“C” Process
See Croning process.

CAD
Computer Aided (or assisted) Design.

CAM
Computer Aided (or Assisted) Machining (or Manufacture).

Cable
(1) A flexible electrical insulated conductor or group of conduc-
tors twisted (usually multistranded) together for the transmission of
electrical energy. (2) Rope or chain, particularly in marine contexts.

Cadmium
Cadmium (symbol Cd) is a silvery-white crystalline metal that
has a specific gravity of 8.6, is very ductile, and can be rolled or
beaten into thin sheets. It resembles tin and gives the same char-
acteristic cry when bent, but is harder than tin. A small addition
of zinc makes it very brittle. It melts at 320°C and boils at 765°C.
Cadmium is employed as an alloying element in soft solders and in
 fusible alloys, for hardening copper, as a white corrosion-resistant
plating metal, and in its compounds for pigments and chemicals.
It is also used for Ni–Cd batteries and to shield against neutrons
in atomic equipment, but gamma rays are emitted when the neu-
trons are absorbed, and these rays require an additional shielding
of lead.

Most of the consumption of cadmium is for electroplating. For
a corrosion-resistant coating for iron or steel, a cadmium plate of
0.008 mm is equal in effect to a zinc coat of 0.025 mm. The plated
metal has a silvery-white color with a bluish tinge, is denser than
zinc, and harder than tin, but electroplated coatings are subject to
H2 embrittlement, and aircraft parts are usually coated by the vac-
uum process. Cadmium plating is not normally used on copper or
brass since copper is electronegative to it, but when these metals are
employed next to cadmium-plated steel a plate of cadmium may be
used on the copper to lessen deterioration.

Cadmium oxide is used extensively in plastics. In conjunction
with barium it forms a compound used to stabilize the color of fin-
ished plastics. It is also a major constituent of phosphors used in
 television tubes.

Cadmium is mutually soluble in a number of other metallic
elements. It is combined with several of these elements to form a
number of commercial alloys with special properties.

The alloys of cadmium with lead, tin, bismuth, and indium are
unique because of their low melting points. For example:

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Melting Point, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>33% Cd–67% Sn</td>
<td>176</td>
</tr>
<tr>
<td>18% Cd–51.2% Sn–30.6% Pb</td>
<td>145</td>
</tr>
<tr>
<td>40% Cd–60% Bi</td>
<td>144</td>
</tr>
<tr>
<td>20.2% Cd–25.9% Sn–53.9% Bi</td>
<td>103</td>
</tr>
<tr>
<td>10.1% Cd–13.1% Sn–49.5% Bi–27.3% Pb</td>
<td>70</td>
</tr>
<tr>
<td>5.3% Cd–12.6% Sn–47.5% Bi–25.4% Pb–19.1% In</td>
<td>47</td>
</tr>
</tbody>
</table>

These fusible alloys are used in applications ranging from fire-
detection apparatus to accurate proof casting.

Cadmium has limited use in soft solders combined with tin, lead,
and zinc but its major application in the field of joining is for joints
requiring higher-temperature strength than can be obtained with the
soft solders. Cadmium combined with silver, copper, and zinc forms
several brazing filler metals. A typical filler metal contains 35% sil-
ver, 26% copper, 21% zinc, 18% cadmium and has a melting point
of 608°C. Cadmium (0.7%–1%) is added to copper to make a strong
ductile metal that has a high annealing temperature but no serious
loss of electrical conductivity. (Trolley wire is an example of its use.)
The copper above is called cadmium copper or cadmium bronze.
Hitenso is a cadmium bronze of the American Brass Company. It
has 35% greater strength than hard-drawn copper and 85% the con-
ductivity of copper. The cadmium bronze known in England as con-
ductivity bronze, used for electric wires, contains 0.8% cadmium
and 0.6% tin. Tensile strength, hard-drawn, is 586 MPa, and conduc-
tivity is 50% that of copper. Cadmium nitrate, Cd(NO3)2, is a white
powder used for making cadmium yellow and fluorescent pigments,
and as a catalyst. Cadmium sulfide, CdS, is used as a yellow pig-
ment, and when mixed with cadmium selenide, CdSe, a red powder,
it gives a bright-orange pigment. The sulfide is used for growing
cadmium sulfide crystals in plates and rods for semiconductor uses.
Crystals grown at 1922°F (1050°C) are nearly transparent, but those
grown at higher temperatures are dark amber. Cadmium, a carcino-
gen, can be extremely toxic, and caution is required not to create
dust or fumes. Because of its toxicity, use in certain applications—
pigments, for example—has declined considerably.

The importance of cadmium in the nuclear field depends on its
high thermal neutron capture cross section. By absorbing neutrons,
cadmium is employed to control the rate of fission in a nuclear
reaction. Cadmium sulfide exhibits both photosensitivity and elec-
troluminescence, that is, it can convert light to electricity and elec-
tricity to light.

Finally, the fumes of cadmium, its compounds, and solutions of
its compounds are very toxic, and cadmium-plated articles should
not be used in food, nor should cadmium-coated articles be welded
or used in ovens.
Cage
In a bearing, a device that partly surrounds the rolling elements and travels with them, the main purpose of which is to space the rolling elements in proper relation to each other. See also separator.

Cake
(1) A copper or copper alloy casting, rectangular in cross section, used for rolling into sheet or strip. (2) A coalesced mass of unpressed metal powder.

Calcereous Coating or Deposit
A layer consisting of a mixture of calcium carbonate and magnesium hydroxide deposited on surfaces being cathodically protected against corrosion because of the increased pH adjacent to the protected surface.

Calcination
Heating ores, concentrates, precipitates, or residues to decompose carbonates, hydrates, or other compounds.

Calcine
(1) A ceramic material or mixture fired to less than fusion for use as a constituent in a ceramic composition. (2) Refractory material, often fireclay, that has been heated to eliminate volatile constituents and to produce desired physical changes.

Calcite
One of the most common and widely diffused materials, occurring in the form of limestones, marbles, chalks, calcareous marls, and calcareous sandstones. It is a calcium carbonate, CaCO₃, and the natural color is white or colorless, but it may be tinted to almost any shade with impurities. The specific gravity is about 2.72 and Mohs hardness 3. The common black calcite, containing manganese oxide, often also contains silver in proportions high enough to warrant chemical extraction of the metal.

It is a natural mineral, and in its pure form it is transparent and capable of polarizing light.

Calcium
Calcium (symbol Ca) is a metallic element belonging to the group of alkaline earths. It is one of the most abundant materials, occurring in combination in limestones and calcareous clays, and calcareous sandstones. It is a calcium carbonate, CaCO₃, and the natural color is white or colorless, but it may be tinted to almost any shade with impurities. The specific gravity is about 2.72 and Mohs hardness 3. The common black calcite, containing manganese oxide, often also contains silver in proportions high enough to warrant chemical extraction of the metal.

It is a natural mineral, and in its pure form it is transparent and capable of polarizing light.

Edible calcium, for adding calcium to food products, is calcium lactate, a white powder of the composition Ca(C₆H₁₂O₇)₂·5H₂O, derived from milk. Calcium lactobionate is a white powder that readily forms chlorides and other double salts, and is used as a suspending agent in pharmaceuticals. It contains 4.94% available calcium. Calcium phosphate, used in the foodstuffs industry and in medicine, is marketed in several forms. Calcium diphosphate, known as phosphate of lime, is CaHPO₄·2H₂O, or in anhydrous form. It is soluble in dilute citric acid solutions and is used to add calcium and phosphorus to foods, and as a polishing agent in toothpastes.

Calcium oxide is made by the thermal decomposition of carbonates in tall kilns using a continuous-feed process. Care must be taken during the heating to decompose the limestone at a low enough temperature so that the oxide will slake freely with water. If too high a temperature is used, so-called dead-burnt lime is formed. The oxide is used in high-intensity arc lights (limelights) because of its unusual spectral features and as an industrial dehydrating agent. At high temperatures, lime combines with sand and other siliceous material to form fusible slags; hence, the metallurgical industry makes wide use of it during the reduction of ferrous alloys.

Because of the low cost of calcium hydroxide, it is used in many applications where hydroxide ion is needed. Slaked lime is an excellent absorbent for carbon dioxide (CO₂) to produce the carbonate. Because of the great in solubility of the carbonate, gases are easily tested qualitatively for CO₂ by passing them through a saturated lime-water solution and watching for a carbonate cloudiness. The hydroxide is also used in the formation of mortar, which is composed of slaked lime (1 volume), sand (3–4 volumes), and enough water to make a thick paste. The mortar gradually hardens because of the evaporation of the water and the cementing action of the deposition of calcium hydroxide, and because of the absorption of CO₂.

Calcium silicide, CaSi, is an electric-furnace product made from lime, silica, and a carbonaceous reducing agent. This material is useful as a steel deoxidizer because of its ability to form calcium silicate, which has a low melting point.

Calcium carbide is a hard, crystalline substance of grayish-black color, used chiefly for the production of acetylene gas for welding and cutting torches and for lighting. It is made by reducing lime with coke in the electric furnace, at 2000°C–2200°C. It can also be made by heating crushed limestone to a temperature of about 1000°C, flowing a high-methane natural gas through it, and then heating to 1700°C. The composition is CaC₂ and the specific gravity is 2.26. It contains theoretically 37.5% carbon. When water is added to calcium carbide, acetylene gas is formed, leaving a residue of slaked lime. Although calcium carbide is principally used for making acetylene, this market is shrinking as acetylene is recovered increasingly as a by-product in petrochemical plants. A growing application for calcium carbide is desulfurization deoxidation of iron and steel. It is also a raw material for production of calcium cyanamide.

Calcium chloride is a white, crystalline, lumpy or flaky material of composition CaCl₂. The specific gravity is 2.15, the melting point is 1422°F (772°C), and it is highly hygroscopic and diluents with rapid solubility in water. The commercial product contains 75%–80% CaCl₂, with the balance chiefly water of crystallization. Some is marketed in anhydrous form for dehydrating gases. It is also sold in water solution containing 40% calcium chloride. Calcium chloride has been used on roads to aid in surfacing, absorb dust, and prevent cracking from freezing. It is also used for accelerating the setting of mortars, but more than 4% in concrete decreases the strength of the concrete. It is also employed as an antifreeze in fire tanks, for brine refrigeration, for storing solar energy, as an anti-ice agent on street pavements, as a food preservative, and in textile and...
Calendered Sheet

Calendering is the process of forming a continuous sheet of controlled size by squeezing a softened thermoplastic material between two or more horizontal rolls. Along with extrusion and casting, calendering is one of the major techniques used to process thermoplastics into film and sheeting. It also is used in the manufacture of flooring and to apply a plastic coating on paper, textiles, and other supporting materials.

The calendering process is used in the plastics, rubber, linoleum, paper, and metal industries for various roll-forming operations in the manufacture of sheeted materials. This coverage will be concerned only with calendering of thermoplastic materials (plastics and elastomers, the latter of which are calendered in a thermoplastic state prior to vulcanization).

The process consists of five steps: preblending, fluxing, calendering, cooling, and wind-up. Blending of the resin powder with plasticizers, stabilizers, lubricants, colorants, and fillers is usually done in large ribbon blenders. The compound is fluxed, that is heated and worked until it reaches a molten or dough-like consistency.

When a Banbury mill is used, the molten material from it is discharged to a two-roll horizontal mill and thence to the calender either in a continuous strip or in batches. When an extruder is used for fluxing, the extrudate is fed directly to the calender. Alternatively, the preblend can in some cases be fed directly to the calender.

After passage through the calender, the continuous sheet of hot plastic is stripped off the last calender roll with a small, higher-speed stripping roll. The hot sheet is cooled as it travels over a series of cooling drums. The film or sheeting is finally automatically cut into individual sheets or wound up in a continuous roll.

The desired surface finish on the calendered film or sheeting is imparted by the last pair of calender rolls and may range from a high gloss to a heavy matte finish. Extra-high-gloss or special engraved patterns can be made either by having a polished or engraved roll impinge on the last calender roll (contact embossing) or by passing the hot sheeting directly from the calender between an engraved metal roll and a rubber backup roll (in-line embossing). Many attractive patterns are made by these techniques.

The major groups of thermoplastics and elastomers that are calendered into film or sheeting are polyvinyl chloride (PVC) (plasticized and unplasticized) and natural and synthetic rubbers. ABS (acrylonitrile, butadiene, and styrene) polymers, polyolefins, and silicones are also calendered, but in much smaller quantities.

Calendered film is used extensively for floor tile and continuous flooring, rainwear, shower curtains, table covers, pressure-sensitive tape, automotive and furniture upholstery, wall coverings, luminous ceilings, signs and displays, credit cards, etc.

In contrast, calendered rubber—except for some fabric coating—is mainly an intermediate product used in the manufacture of a multitude of articles such as automobile tires, footwear, molded mechanical goods, etc.

In applications that involve the use of calenders for paper and cloth coating, the paper or fabric is fed into the last calender nip so that the plastic or rubber coating is formed on top of the material (calender coating). Frictioning is a variation of this technique by which a thin layer of rubber is squeezed or rubbed into the fabric itself, a technique widely used in the rubber industry for the manufacture of friction tapes and cord fabric for tires.

Production speeds vary greatly with materials, from 10 to 300 fpm (feet per minute). Calenders are heavy, high-precision machines that are made in a variety of designs and with elaborate control equipment that automatically monitors film variations and readjusts the machine to produce the desired thickness.

Calibrate

To determine, by measurement or comparison with a standard, the correct value of each scale reading on a measuring (test) instrument.
Calibration

Determination of the values of the significant parameters by comparison with values indicated by a reference instrument or by a set of reference standards.

Calomel Electrode

(1) An electrode widely used as a reference electrode of known potential in electrometric measurement of acidity and alkalinity, corrosion studies, voltammetry, and measurement of the potentials of other electrodes. (2) A secondary reference electrode of the composition: Pt/Hg–HgCl2/KCl solution. For 1.0 N KCl solution, its potential vs. a hydrogen electrode at 25°C (77°F) at 1 atm is +0.281 V.

Calorie

The quantity of heat required to raise the temperature of 1 g of water by 1°C. The exact value of this depends on the water temperature. The calorie (International Table) is 4.186 J. The dietitians calorie, sometimes termed the large calorie or the kilocalorie is 1000 cal.

Calorimeter

An instrument capable of making absolute measurements of energy deposition (or absorbed dose) in a material by measuring its change in temperature and imparting a knowledge of the characteristics of its material construction.

Calorimetry

The measurement in a calorimeter of heat energy relationships.

Calorizing

A process in which steel is coated with aluminum powder and heated to about 1000°C to form an aluminum oxide coating over an aluminum iron intermetallic layer. The coating offers good oxidation resistance up to about 950°C.

Cam Press

A mechanical forming press in which one or more of the slides are operated by cams; usually, a double-action press in which the blank-holder slide is operated by cams through which the dwell is obtained.

Camber

(1) Deviation from edge straightness, usually referring to the greatest deviation of side edge from a straight line. (2) The tendency of material being sheared from sheet to bend away from the sheet in the same plane. (3) Sometimes used to denote crown in rolls where the center diameter has been increased to compensate for deflection caused by the rolling pressure. (4) The planar deflection of a flat cable or flexible laminate from a straight line of specified length. A flat cable or flexible laminate with camber is similar to the curve of an unbanked racetrack.

Campaign

The period in which a furnace or other equipment is operated between major overhaul such as the replacement of the refractory lining.

Can

A sheeting of soft metal that encloses a sintered metal billet for the purpose of hot working (hot isostatic pressing, hot extrusion) without undue oxidation.

Canada Balsam

The thin resin produced by Canadian firs. It has a refractive index similar to glass and hence is used as an adhesive for multielement lenses.

Cannel Coal

A variety of coal having some of the characteristics of petroleum, valued chiefly for its quick-firing qualities. It consists of coal-like matter intimately mixed with clay and shale, often containing fossil fishes, and probably derived from vegetable matter in lakes. It is compact in texture, dull black, and breaks along joints, often having an appearance similar to black shale. It burns with a long, luminous, smoky flame, from which it derives its old English name meaning candle.

Canning

(1) A dished distortion in a flat or nearly flat sheet metal surface, sometimes referred to as oil canning. (2) Enclosing a highly reactive metal within a relatively inert material for the purpose of hot working without undue oxidation of the active metal. (3) The materials used for canning nuclear fuel elements are selected for low neutron capture cross section, short half-life, good thermal conductivity, compatibility with the working environment, adequate mechanical properties, and forming characteristics. (4) The containment of foodstuffs and other materials in sealed cans made from tin plated steel, aluminum, or other materials.

Cantilever

A loaded beam supported at one end only.

Capacitance (C)

That property of a system of conductors and dielectrics that permits the storage of electrostatically separated charges when potential differences exist between the conductors. It is the ratio of a quantity, Q, of electricity to a potential difference, V. A capacitance value is always positive. The units are farads when the charge is expressed in coulombs and the potential in volts: C = Q/V.

Capacitor

A capacitor is an electrical device capable of storing electrical energy. In general, a capacitor consists of two metal plates insulated from each other by a dielectric. The capacitance of a capacitor depends primarily upon its shape and size and upon the relative permittivity of the medium between the plates. In vacuum, in air, and in most gases, εr ranges from one to several hundred.

One classification of capacitors comes from the physical state of their dielectrics, which may be gas (or vacuum), liquid, solid, or a combination of these. Each of these classifications may be subdivided according to the specific dielectric used. Capacitors may be further classified by their ability to be used in AC or DC circuits with various current levels.
Capacitors are also classified as fixed, adjustable, or variable. Capacitors made with air, gas, or vacuum as the dielectric between plates are constructed with flat parallel metallic plates (or cylindrical concentric metallic plates).

Solid-dielectric types of capacitors use one of several dielectrics such as a ceramic, mica, glass, or plastic film. Alternate plates of metal, or metallic foil, are stacked with the dielectric, or the dielectric may be metal-plated on both sides.

Plastic-film types are capacitors that use dielectrics such as polypropylene, polyester, polycarbonate, or polysulfone with a relative permittivity ranging from 2.2 to 3.2. This plastic film may be used alone or in combination with Kraft paper. The most common electrodes are aluminum or zinc vacuum-deposited on the film, although aluminum foil is also used. Other major types of capacitors can be seen in Table C.1.

The impedance of a capacitor is inversely proportional to the frequency of the voltage impressed; that is, it offers little resistance or impedance to high frequencies, but much to low frequencies.

TABLE C.1
Major Types of Capacitors

<table>
<thead>
<tr>
<th>Type</th>
<th>Capacitance</th>
<th>Voltage (Working Voltage, DC), V</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monolithic ceramics</td>
<td>1 pF–2.2 μF</td>
<td>50–200</td>
<td>Ultrahigh frequency, RF coupling, computers</td>
</tr>
<tr>
<td>Disk and tube ceramics</td>
<td>1 pF–1 μF</td>
<td>50–1000</td>
<td>General, very high frequency</td>
</tr>
<tr>
<td>Paper</td>
<td>0.001–1 μF</td>
<td>200–1600</td>
<td>Motors, power supplies</td>
</tr>
<tr>
<td>Polypropylene</td>
<td>0.0001–0.47 μF</td>
<td>400–1600</td>
<td>Television vertical circuits, RF circuits</td>
</tr>
<tr>
<td>Polyester</td>
<td>0.001–4.7 μF</td>
<td>50–600</td>
<td>Entertainment electronics</td>
</tr>
<tr>
<td>Polystyrene</td>
<td>0.001–1 μF</td>
<td>100–200</td>
<td>General, high stability</td>
</tr>
<tr>
<td>Polycarbonate</td>
<td>0.01–18 μF</td>
<td>50–200</td>
<td>General</td>
</tr>
<tr>
<td>Metallized polypropylene</td>
<td>4–60 μF</td>
<td>400*</td>
<td>Alternating-current motors</td>
</tr>
<tr>
<td>Metallized polyester</td>
<td>0.001–22 μF</td>
<td>100–1000</td>
<td>Coupling, RF filtering</td>
</tr>
<tr>
<td>Aluminum</td>
<td>100.00 μF</td>
<td>5–500</td>
<td>Power supplies, filters</td>
</tr>
<tr>
<td>Tantalum</td>
<td>0.1–2200 μF</td>
<td>3–150</td>
<td>Small space requirement, low leakage</td>
</tr>
<tr>
<td>Gold</td>
<td>0.022–10 μF</td>
<td>2.5–5.5</td>
<td>Memory backup</td>
</tr>
<tr>
<td>Nonpolarized (either aluminum or tantalum)</td>
<td>0.47–1000 μF</td>
<td>10–200</td>
<td>Loudspeaker crossovers</td>
</tr>
<tr>
<td>Mica</td>
<td>330 pF–0.05 μF</td>
<td>50–1000</td>
<td>High frequency</td>
</tr>
<tr>
<td>Silver-mica</td>
<td>5–820 pF</td>
<td>50–500</td>
<td>High frequency</td>
</tr>
<tr>
<td>Ceramic</td>
<td>1–5 to 16–100 pF</td>
<td>200</td>
<td>Radio, television, communications</td>
</tr>
<tr>
<td>Film</td>
<td>0.8–5 to 1.2–30 pF</td>
<td>50</td>
<td>Oscillators, antenna, RF circuits</td>
</tr>
<tr>
<td>Air</td>
<td>10–365 pF</td>
<td>50</td>
<td>Broadcast receiver</td>
</tr>
<tr>
<td>Poly(tetrafluoroethylene)</td>
<td>0.25–1.5 pF</td>
<td>2000</td>
<td>Very high frequency, ultrahigh frequency</td>
</tr>
</tbody>
</table>


a Alternating-current voltage at 60 Hz.

Capacity Number (Cn)
The product of the Sommerfeld number and the square of the length-to-diameter ratio of a journal bearing.

Capillarity
The ability of the material to conduct liquids through its pore structure by the force of surface tension.

Capillary Action
(1) The phenomenon of intrusion of a liquid into interconnected small voids, pores, and channels in a solid, resulting from surface tension. (2) The force by which a liquid, in contact with the solid, is distributed between closely fitted faying surfaces of the joint to be brazed or soldered. (3) It is a consequence of surface tension and depends critically on the liquid wetting the solid surface.

Capillary Attraction
(1) The combined force of adhesion and cohesion that causes liquids, including molten metals, to flow between very closely spaced and solid surfaces, even against gravity. (2) In powder metallurgy, the driving force for the infiltration of the pores of a sintered compact by a liquid.
Capped Steel

A type of steel similar to rimmed steel, usually cast in a bottle-top ingot mold, in which the application of a mechanical or a chemical cap renders the rimming action incomplete by causing the top metal to solidify. The surface condition of capped steel is much like that of rimmed steel, but certain other characteristics are intermediate between those of rimmed steel and those of semi-killed steel.

Capping (of Abrasive Particles)

A mechanism of deterioration of abrasive points in which the points become covered by caps of adherent abrasion debris.

Capping (of Powder Metallurgy Compacts)

Partial or complete separation of a powder metallurgy compact into two or more portions by cracks that originate near the edges of the punch faces and that proceed diagonally into the compact.

Caprolactam

A cyclic amide type of compound containing six carbon atoms. When the range is open, caprolactam is polymerizable into a nylon resin known as type 6 nylon or poly-caprolactam.

Capture Cross Section

The measure of the capability of a material to absorb neutrons without undergoing fission. See atomic structure.

Capture Efficiency

See collection efficiency.

Car Furnace

A batch-type heat-treating furnace using a car on rails to enter and leave the furnace area. Core furnaces are used for lower stress relieving ranges.

Carat

(1) Units of purity of gold, 24 carat being pure. (2) Metric carat, for gemstones, etc. = 200 mg.

Carbanion Ion

Negatively charged organic compound (ion).

Carbide Tip/Tool

Cutting or forming tools of intermetallic compounds usually made from tungsten, titanium, tantalum, or niobium carbides, or a combination of them, in a matrix of cobalt, nickel, or other metals. Carbide tools are characterized by high hardneesses and compressive strengths and may be coated to improve wear resistance. See also cemented carbides.

Carbides

Of the several classes of carbides, only two types need to be considered for engineering applications: the covalent carbides of silicon and boron, and the interstitial carbides of the transition metals—titanium, zirconium, vanadium, niobium (columbium), tantalum, chromium, molybdenum, and tungsten. All of these may be characterized as hard, refractory materials of extreme chemical inertness. Other carbides such as those of aluminum, iron, and manganese are too reactive to be considered for engineering applications. Chemically, all the inert carbides, with the exception of SiC, are unusual in that they exist in their typical form over a range of composition. In this respect, they are more similar to alloys than true chemical compounds.

Structurally, interstitial carbides may be described as metal lattices into which the small carbon atoms have been inserted. In the ideal form, this leads to an fcc (face-centered cubic) structure for all of the metal carbide (MC) types except tungsten carbide (WC), which like the M,C types has a simple hexagonal structure. B,C is rhombohedral, and consists of a distorted B lattice in which part of the boron atoms have been replaced by carbon atoms. SiC exists in a number of crystalline polytypes, both cubic (diamond or zinc blend structures) and hexagonal (wurtzite type). All these structures may be described on the basis that every silicon atom is surrounded tetrahedrally by four carbon atoms and that every carbon atom is surrounded tetrahedrally by four silicon atoms.

Properties of carbides that make them unique are their extreme hardness, exceptional corrosion resistance, extreme refractoriness, high Young’s modulus of elasticity, and high temperature strength.

The simplest method to produce carbides is a direct combination of the metal with carbon, used exclusively in the preparation of carbides where purity is more important than cost considerations. Most carbides are, however, prepared by reduction of metal oxides with carbon.

With the exception of SiC, all carbide bodies are fabricated using powder metallurgical techniques, that is, sintering and hot pressing. SiC bodies are formed by infiltrating a preformed carbonaceous body with elemental silicon, forming SiC in the shape desired.

Complete pump assemblies have been built to transfer molten metals (corrosion resistance); pipes for heat exchangers (high thermal conductivity); cyclone separators and sandblast nozzles (abrasion resistance); rocket nozzles (refractoriness and erosion resistance); electrical-light sources (high melting temperature); and suction box covers for papermaking machines (ability to retain smooth finish without wear).

Several metal carbides mentioned above qualify as engineering ceramics. Most commonly used are B,C and SiC. B,C is noted for its very high hardness and low density—unusual properties for a brittle ceramic—which qualify this ceramic for lightweight, bulletproof armor plate. The material has the best abrasion resistance of any ceramic, so it is also specified for pressure-blasting nozzles and similar high-wear applications. A limitation of B,C is its low strength at high temperatures.

Despite its higher cost, SiC is challenging Al2O3, particularly for the more critical applications. SiC is one of the high-temperature, high-strength “superstars” of the engineering ceramics. It is one of the strongest structural ceramics for high-temperature oxidation-resistant service. However, SiC does not easily self-bond. Consequently, many processing variations have been devised to fabricate parts from this material, creating a number of trade-offs in cost, fabricability, and properties. The ceramic can be consolidated by hot pressing. Under the combination of high temperature and pressure—w ith, in some cases, additives that act as bond-forming catalysts—fully dense material can be formed.

The hot-pressed ceramic is extremely strong and tough at high temperatures, but the manufacturing process is limited to simple shapes, bars, or billets. Complex parts made by hot pressing must be machined to shape—a slow and costly process of ultrasonic machining, EDM (if possible), or diamond grinding.
Carbon Carbon

On the other hand, SiC particles can be bonded without pressure by a number of processes, variously called reaction bonding, recrystallization (for SiC), or reaction sintering. With these processes, “green” parts can be dry or isostatically pressed, extruded, slip-cast, or, in some cases, formed by conventional plastic molding techniques such as injection molding, then sintered. Complex shapes, close to finished size can be produced by these techniques, but the ceramic is only about 80% as dense as the hot-pressed counterpart and has lower strength and poorer thermal shock resistance. SiC—either hot pressed or reaction bonded—is not as strong as Si₃N₄ up to about 1427°C. Si₃N₄ grain boundaries soften, or creep, and strength drops. Above 1427°C, SiC is the stronger ceramic. At 1316°C, however, strength of hot-pressed ceramics nearly equals that of reaction-bonded ceramics.

Hot-pressed SiC is harder and more difficult to EDM than Si₃N₄, which has lower thermal expansion and better thermal shock resistance than SiC. Electrical resistivity of SiC is low at low frequencies and high at high frequencies—an unusual characteristic that qualifies this material as a semiconductor.

Refractory Hard Metals

Refractory hard metals (RHMs) are a ceramic-like class of materials made from metal-carbide particles bonded together by a metal matrix. Often classified as ceramics and sometimes called cemented or sintered carbides, these metals were developed for extreme hard-ness and wear resistance.

The RHMs are more ductile and have better thermal shock resistance and impact resistance than ceramics, but they have lower compressive strength at high temperatures and lower operating temperatures than most ceramics. Generally, properties of RHMs are between those of conventional metals and ceramics. Parts are made by conventional powder metallurgy compacting and sintering methods. Many metal carbides such as SiC and B₄C are not RHMs but are true ceramics. The fine distinction is in particle binding: RHMs are always bonded together by a metal matrix, whereas ceramic particles are self-bonded. Some ceramics have a second metal phase, but the metal is not used primarily for bonding.

Four RHM systems are used for structural applications and, in most cases, several grades are available within each system. WC with a 3%–20% matrix of cobalt is the most common structural RHM. The low-cobalt grades are used for applications requiring wear resistance; the high-cobalt grades serve where impact resistance is required.

TaC and WC combined in a matrix of nickel, cobalt, and/or chromium provide an RHM formulation especially suited for a combination of corrosion and wear resistance. Some grades are almost as corrosion resistant as platinum. Nozzles, orifice plates, and valve components are typical uses.

TiC in a molybdenum and nickel matrix is formulated for high-temperature service. Tensile and compressive strengths, hardness, and oxidation resistance are as high as 1093°C. Critical parts for welding and thermal metalworking tools, valves, seals, and high-temperature gauging equipment are made from grades of this RHM.

Tungsten–titanium carbide (WTiC₂) in cobalt is used primarily for metal-forming applications such as draw dies, tube-sizing mandrels, burnishing rolls, and flaring tools. The WTiC₂ is a gall resistant phase in the RHM containing WC as well as cobalt.

Carbon

Carbon is a nonmetallic element, symbol C, existing naturally in several allotropic forms, and in combination as one of the most widely distributed of all the elements. It is quadrivalent, and has the property of forming chain and ring compounds, and there are more varied and useful compounds of carbon than of all the other elements. The black amorphous carbon has a specific gravity of 1.88: the black crystalline carbon known as graphite has a specific gravity of 2.25; the transparent crystalline carbon, as in the diamond, has a specific gravity of 3.51. Amorphous carbon is not soluble in any known solvent. It is insubstantial, but sublimes at 3500°C, and is stable and chemically inactive at ordinary temperatures. At high temperatures it burns and absorbs O₂, forming the simple oxides CO and CO₂; the latter is the stable oxide present in the atmosphere and a natural plant food. Carbon dissolves easily in some molten metals, notably iron, exerting great influence on them. Steel, with small amounts of chemically combined carbon, and cast iron, with both combined carbon and graphitic carbon, are examples of this.

Carbon occurs as hydrocarbons in petroleum, and as carbohydrates in coal and plant life, and from these natural basic groupings an infinite number of carbon compounds can be made synthetically. Carbon for chemical, metallurgical, or industrial use is marketed in the form of compounds in a large number of different grades, sizes, and shapes; or in master alloys containing high percentages of carbon; or as activated carbons, charcoal, graphite, carbon black, coal-tar carbon, petroleum coke; or as pressed and molded bricks or formed parts with or without binders or metallic inclusions. Natural deposits of graphite, coal tar, and petroleum coke are important sources of elemental carbon.

Combined with carbonaceous binders, such as tars, pitches, and resins, the carbon is compacted by molding or extrusion, and baked at between 816°C and 1649°C to produce what is known as industrial carbon or baked carbon. Conventional industrial graphite (Gr) is made by mixing mined, natural graphite with carbon to produce in effect a C–Gr composite, or baked carbon can be heat treated at about 2985°C, at which temperature the carbon graphitizes.

Manufactured or artificial carbon has a two-phase structure consisting of carbon particles (or grains) in a matrix of binder carbon. Both phases consist essentially of disordered, or uncrystallized, carbon surrounding embryonic carbon crystallites.

Graphites, except for the pyrolytic types, have a two-phase structure similar to that of carbon, but as the result of high-temperature processing contain well-developed graphite crystallites in both phases. These multicyrstalline graphites exhibit many of the properties of single-crystal graphite, such as high electrical conductivity, lubricity, and anisotropy. Compared to carbon, graphite has higher electrical and heat conductivity, better lubricity, and is easier to machine. Because of their more favorable properties, graphites have broader application as engineering materials than do carbons. See graphite.

Types and Forms of Carbon

Elemental carbon exists in two well-defined crystalline allotropic forms, diamond and graphite. Other forms, which are poorly developed in crystallinity, are charcoal, coke, and carbon black.

Charcoal is prepared by the ignition of wood, sugar, blood, and other carbon-containing compounds in the absence of air. X-ray diffraction studies reveal that it has a graphite structure but is not very well developed in crystallinity. The lack of crystallinity is the result of defects in the crystal structure and the high surface area. In the activated state, charcoal adsorbs gases, liquids, and solids.

Coke, another form of amorphous carbon, is prepared by heating coal in the absence of air. It is used primarily for the reduction of metal oxides to the free metals.
Chemically pure carbon is prepared by the thermal decomposition of sugar (sucrose) in the absence of air. Impurities in the carbon are removed by treatment with chlorine (Cl) gas at red heat. The substance is then washed with water and the low residual chlorine is removed by heating in an atmosphere of H₂ gas.

Carbon-13 is one of the isotopes of carbon, used as a tracer in biologic research where its heavy weight makes it distinguished from other carbon. Carbon-14, or radioactive carbon, has a longer life. It exists in the air, formed by the bombardment of N₂ by cosmic rays at high altitudes, and enters into the growth of plants. The half-life is about 6000 years. It is made from N₂ in a cyclotron.

**Carbon fullerences**, such as C₆₀, are a new form of carbon, discovered in the mid-1980s, with considerable potential and diverse applications.

### Carbon Fibers/Yarn/Fabric/Wool

These forms are made by pyrolysis of organic precursor fibers in an inert atmosphere. Pyrolysis temperatures can range from 1000°C to 3000°C; higher process temperatures generally lead to higher-modulus fibers. Only three precursor materials, rayon, polycrylonitrile (PAN), and pitch, have achieved significance in commercial production of carbon fibers (see Table C.2). The first high-strength and high-modulus carbon fibers were based on a rayon precursor. These fibers were obtained by being stretched to several times their original length at temperatures above 2800°C. The second generation of carbon fibers is based on a PAN precursor and has achieved market dominance. In their most common form, these carbon fibers have a tensile strength ranging from 2413 to 3102 MPa, a modulus of 0.2 to 0.5 GPa, and a shear strength of 90 to 117 MPa. This last property controls the traverse strength of composite materials. The high-modulus fibers are highly graphitic in crystalline structure after being processed from PAN at temperatures in excess of 1982°C.

### Table C.2

<table>
<thead>
<tr>
<th>Fiber Strength (10³ psi)</th>
<th>Pan Fibers</th>
<th>Pitch Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiber strength (10³ psi)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>30³</td>
<td>500</td>
<td>33</td>
</tr>
<tr>
<td>40³</td>
<td>820</td>
<td>41</td>
</tr>
<tr>
<td>50³</td>
<td>650</td>
<td>42</td>
</tr>
<tr>
<td>60³</td>
<td>350</td>
<td>57</td>
</tr>
<tr>
<td>70³</td>
<td>300</td>
<td>75</td>
</tr>
<tr>
<td>80³</td>
<td>275</td>
<td>55</td>
</tr>
<tr>
<td>90³</td>
<td>300</td>
<td>75</td>
</tr>
<tr>
<td>100³</td>
<td>360</td>
<td>110</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tensile Modulus (10³ psi)</th>
<th>Pan Fibers</th>
<th>Pitch Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>250</td>
<td>10</td>
</tr>
<tr>
<td>20</td>
<td>470</td>
<td>10</td>
</tr>
<tr>
<td>25</td>
<td>360</td>
<td>10</td>
</tr>
<tr>
<td>40</td>
<td>205</td>
<td>5</td>
</tr>
<tr>
<td>50</td>
<td>110</td>
<td>5</td>
</tr>
<tr>
<td>60</td>
<td>135</td>
<td>5</td>
</tr>
<tr>
<td>70</td>
<td>140</td>
<td>5</td>
</tr>
<tr>
<td>80</td>
<td>180</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Composite Strength (10³ psi)</th>
<th>Pan Fibers</th>
<th>Pitch Fibers</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transverse</td>
<td>25</td>
<td>2</td>
</tr>
<tr>
<td>25</td>
<td>25</td>
<td>1</td>
</tr>
<tr>
<td>35</td>
<td>44</td>
<td>1</td>
</tr>
<tr>
<td>45</td>
<td>35</td>
<td>1</td>
</tr>
<tr>
<td>55</td>
<td>49</td>
<td>1</td>
</tr>
<tr>
<td>65</td>
<td>72</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop 300 (Amoco).</td>
<td></td>
</tr>
<tr>
<td>Thornel T-40.</td>
<td></td>
</tr>
<tr>
<td>Thornel T650/42.</td>
<td></td>
</tr>
<tr>
<td>Thornel 50 PAN.</td>
<td></td>
</tr>
<tr>
<td>Celanese GY-70.</td>
<td></td>
</tr>
<tr>
<td>Thornel P-SSS.</td>
<td></td>
</tr>
<tr>
<td>Thornel P-7SS.</td>
<td></td>
</tr>
<tr>
<td>Thornel P-100SS.</td>
<td></td>
</tr>
</tbody>
</table>

Higher-strength fibers obtained at lower temperatures from rayon feature a higher carbon crystalline content. There are also carbon and graphite fibers of intermediate strength and modulus. The third generation of carbon fibers is based on pitch as a precursor. Ordinary pitch is an isotropic mixture of largely aromatic compounds. Fibers spun from this pitch have little or no preferred orientation and hence low strength and modulus. Pitch is a very inexpensive precursor compared with rayon and PAN. High-strength and high-modulus carbon fibers are obtained from a pitch that has first been converted into a mesophase (liquid crystal). These fibers have a tensile strength of more than 2069 MPa, and a Young’s modulus ranging from 0.38 to 0.52 GPa.

The average filament diameter of continuous yarn is 0.008 mm. Pitch-based carbon and graphite fibers are expected to see essentially the same applications as the more costly PAN and rayon-derived fibers, for example, ablative, insulation, and friction materials and in metals and resin matrices.

Carbon fibers added to thermoplastic resins provide the highest strength, modulus, heat-deflection temperature, creep, and fatigue—endurance values commercially available in composites. These property improvements, coupled with greatly increased thermal conductivity and low friction coefficients, make carbon fibers ideal for wear and frictional applications where the higher cost can be tolerated. In applications where the abrasive nature of glass fibers wears the mating surface, the softer carbon fibers can be substituted to reduce the wear rate. Carbon fibers can also be used in conjunction with internal lubricants to further improve surface characteristics of most thermoplastic resin systems.

Another useful property of carbon-fiber-reinforced thermoplastics is their low volume and surface resistivities. Most resin systems reinforced with 15% or more carbon fibers can effectively dissipate static charge, which is a problem common to gears, slides, and bearings used in business machine, textile, electrical, and conveying equipment.

**Thornel** is a yarn made from these filaments for high-temperature fabrics. It retains its strength to temperatures above 1538°C. Carbon yarn is 99.5% pure carbon. It comes in plies from 2 to 30, with each ply composed of 720 continuous filaments of 0.0076 mm diameter. Each ply has a breaking strength of 0.91 kg. The fiber has the flexibility of wool and maintains dimensional stability to 3150°C. **Ucar** is a conductive carbon fabric made from carbon yarns woven with insulating glass yarns with resistivities from 0.2 to 30 Ω for operating temperatures to 288°C. Carbon wool, for filtering and insulation, is composed of pure carbon fibers made by carbonizing rayon. The fibers, 5–50 μm in diameter, are hard and strong, and can be made into rope and yarn, or the mat can be activated for filter use. **Thornel radiotranslucent carbon fibers**, from Amoco Polymers, allow electrical conduction while remaining invisible to x-rays, permitting babies monitoring equipment to stay intact during x-rays and MRIs. **KIOOX** fiber, from Amoco Performance Products, Inc., is a pitch-carbon fiber for prepreg used to produce composites for thermal management systems in space satellites. **Carbon wool**, for filtering and insulation, is composed of pure-carbon fibers made by carbonizing rayon. **Avceram CS** of FMC Corp., is a composite rayon-silica fiber made with 40% dissolved sodium silicate. A highly heat-resistant fiber, **Avceram CS** is woven into fabric and then pyrolyzed to give a porous interlocked mesh of carbon silica fiber, with a tensile strength of 1138 MPa. **Desan**, of C.H. Dexter and Sons Co., for filtering hot gases and liquids, is a carbon filter paper made from carbon fibers pressed into a paper-like mat, 0.007–0.050 in. (0.18–0.127 mm) thick, and impregnated with activated carbon.

In a process developed by Mitsubishi Gas Chemical Co. (Japan), naphthalene is used as the feedstock for mesophase pitch, called...
AR-Resin, to produce carbon fiber. Conoco, Inc. uses a mesophase pitch to make carbon-fiber mat. This pitch has an anisotropic molecular structure rather than the more amorphous one of the PAN precursor.

Carbon brushes for electric motors and generators and carbon electrodes are made of carbon in the form of graphite, petroleum coke, lamplblack, or other nearly pure carbon, sometimes mixed with copper powder to increase the electric conductivity, and then pressed into blocks or shapes and sintered. Carbon–graphite brushes contain no metals but are made from carbon–graphite powder and, after pressing, are subjected to a temperature of 5000°F (2760°C), which produces a harder and denser structure, permitting current densities up to 125 A/in.² (1538 A/m²). Carbon brick, used as a lining in the chemical processing industries, is carbon compressed with a bituminous binder and then carbonized by sintering. If the binder is capable of being completely carbonized, the bricks are impervious and dense. Graphite brick, made in the same manner from graphite, is more resistant to oxidation than carbon bricks and has a higher thermal conductivity but it is softer. The binder may also be a furfural resin polymerized in the pores. Karbate No. 1 is a carbon-base brick, and Karbate No. 2 is a graphite brick. Impervious carbon is used for lining pumps, for valves, and for acid-resistant parts. It is carbon-base–graphite-impregnated with a chemically resistant resin and molded to any shape. It can be machined. Porous carbon is used for the filtration of corrosive liquids and gases. It consists of uniform particles of carbon pressed into plates, tubes, or disks without a binder, leaving interconnecting pores of about 0.001–0.007 in. (0.025–0.190 mm) in diameter. The porosity of the material is 48%, tensile strength of 1 MPa, and compressive strength about 3.5 MPa. Porous graphite has graphitic instead of carbon particles and is more resistant to oxidation but is lower in strength.

**Diamond**

Diamond is the cubic crystalline form of carbon. When pure, diamond is water clear, but impurities add shades of opaqueness including black. It is the hardest natural material with a hardness on the Knoop scale ranging from 5500 to 7000. It will scratch and be scratched by the hardest anthropogenic material Borazon. It has a specific gravity of 3.5. Diamond has a melting point of 3871°C, at which point it will graphitize and then vaporize. Diamonds are generally electrical insulators and nonmagnetic. Synthetic diamonds are produced from graphite at extremely high pressures (5,444–12,359.9 MPa) and temperatures from 1204°C to 2427°C. They are up to 0.01 carat in size and are comparable to the quality of industrial diamonds. In powder form, they are used in cutting wheels. Of all diamonds mined, about 80% by weight are used in industry. Roughly 45% of the total industrial use is in grinding wheels. Tests have shown that under many conditions synthetic diamonds are better than mined diamonds in this application.

**Composites**

Carbon composites, which comprise carbon fibers in a carbon matrix, are noted for their heat resistance, high-temperature strength, high thermal conductivity, light weight, low thermal expansivity, and resistance to air fuel mixtures. However, they are costly to produce. Also, they react with oxygen at temperatures above 800°F (427°C), necessitating oxygen-barrier coatings. Silicon carbide, 0.005–0.007 in. (0.127–0.178 mm) thick, serves as such a coating for applications in the nose cone and wing leading edges of the Space Shuttle. Other uses include the brakes of large commercial aircraft, clutches and brakes of Formula One race cars, and rocket nozzles.

Carbon films, usually made by chemical vapor deposition (CVD) at 2012°F (1100°C), can strengthen and toughen ceramic–matrix composites but are not readily adaptable to coating fibers, platelets, or powder. The Japanese have developed what is said to be a more economical method using silicon carbide and other ceramics. Nanometer-to-micrometer thick films are formed on these forms including silicon carbide single crystals, by treating them with water under pressure at 572°F–1472°F (300°C–800°C). This treatment transforms the surface layer to carbon.

The so-called carbons used for electric-light arc electrodes are pressed from coal-tar carbon, but are usually mixed with other elements to bring the balance of light rays within the visible spectrum. Solid carbons have limited current-carrying capacity, but when the carbon has a center of metal compounds such as the fluorides of the rare earths, the current capacity is greatly increased. It then forms a deep positive crater in front of which is a flame five times the brilliance of that with a low-current arc. The sunshine carbon, used in electric-light carbons to give approximately the same spectrum as some light, is molded coal-tar carbon with a core of cerium metals to introduce more blue into the light. Arc carbons are also made to give other types of light, and to produce special rays for medicinal and other purposes. B carbon, of National Carbon Co., Inc., contains iron in the core and gives a strong emission of rays which are the antirachitic radiations. The light seen by the eye is only one-fourth the total radiation since the strong rays are invisible. C carbon contains iron, nickel, and aluminum in the core and gives off powerful lower-zone ultraviolet rays. It is used in light therapy and for industrial applications. E carbon, to produce penetrating infrared radiation, contains strontium. Electrode carbon, used for arc furnaces, is molded in various shapes from carbon paste.

**Carbides**

Carbon forms binary compounds known as carbides with elements less electronegative than carbon (C–H₂ compounds are excluded). Effectively then, carbides are composed of metal–carbon compounds if boron and silicon are included among the normal metals. Essentially no volatile compounds (except AlC) are known because decomposition sets in at higher temperatures before volatilization of the carbide as such can occur.

Most carbides can be prepared by heating a mixture of the powdered metal and carbon, usually to high temperatures, but not necessarily as high as the melting point. Generally, the same result is possible by heating a mixture of the oxide of the metal with carbon.

It is useful to classify carbides as ionic (salt-like), metallic (interstitial), and covalent. The more electropositive elements (groups I, II, and III, and to some extent, members of the lanthanide and actinide series of the periodic system) form ionic carbides with transparent (or salt-like) crystals.

Highly refractory covalent carbides are formed with silicon and boron. SiC (diamond structure) is formed from a mixture of SiO₂ and coke. The very hard B₄C can be made similarly from its oxide; it is unusual both structurally and in having a fairly high electrical conductivity.

The carbides of chromium, manganese, iron, cobalt, and nickel are intermediate between the interstitial and covalent types, but are much nearer the former in properties. The presence of Fe₃C in iron is an important factor in the properties of steel.

**Mechanical/Thermal/Electrical/Other Properties**

Compared to metals and most polymers, room-temperature tensile strengths of conventional carbon and graphite are low, ranging from 6.8 to 9.16 MPa. Compressive strengths range from 20.6 to 54.9 MPa. These are generally with-grain values (i.e., specimen length is parallel to the grain).
Carbon Arc Cutting (CAC)

Carbon and graphite do not have a true melting point. They sublime at 4399°C. Conventional graphite have exceptionally high thermal conductivity at room temperature, whereas carbon has only fair conductivity. Conductivity with the grain in graphite is comparable to that of aluminum; across the grain it is about the same as brass. Conductivity increases with temperature up to about 0°C; it then remains relatively high, but decreases slowly over a broad temperature range, before it drops sharply. In pyrolytic graphite, thermal conductivity with the grain approaches that of copper; across grain, it serves as a thermal insulator and is comparable to that of ceramics.

Thermal expansion of carbon and graphite is quite low (1 to 1.5 × 10⁻⁶/°F)—less than one third that of many metals. Expansion of graphite across grain increases with increasing density, whereas along the grain it decreases with increasing density. But expansion increases in both directions with increasing temperatures.

The electrical characteristics associated with carbon and graphite use as electrodes or anodes are relatively well known. Carbon and graphite are actually semiconductors, with their electrical resistivity, or conductivity, falling between those of common metals and common semiconductors. At temperatures approaching absolute zero, carbon and graphite have few conducting electrons, the number increasing with increasing temperature. Thus, electrical resistivity decreases with increasing temperature. On the other hand, although increasing electron density tends to reduce resistivity as temperature rises, scattering effects may become dominant at certain temperatures in the range of 982°C and thus modify or even reverse this trend. Pyrolytic graphite with its higher density has improved electrical conductivity (along the grain). Further, its high degree of anisotropy results in a high degree of electrical resistivity across the grain.

Other properties of graphite are excellent lubricity and relatively low surface hardness; carbon has fair lubricity and relatively high surface hardness. Further, certain types of carbon graphitize relatively easily; others do not. Consequently, a wide variety of carbon, C–Gr, and graphite materials are available, each designed to provide specific types of surface characteristics for such uses as bearings and seals. Grades are also available impregnated with a wide variety of substances, from synthetic resin or oil to a bearing metal. The nuclear grades of carbon and graphite are of exceptionally high purity. As a moderator and reflector in nuclear reactors, they have no equal because of their low thermal neutron absorption cross section and high scattering cross section coupled with high strength at elevated temperatures and thermal stability in nonoxidizing environments. In general, the properties of carbon and graphite are improved by exposure to nuclear radiation. Hardness and strength increase while thermal and electrical conductivity decrease.

Applications

The free element of carbon has many uses, ranging from ornamental applications of the diamond in jewelry to the black-colored pigment of carbon black in automobile tires and printing inks. Another form of carbon, graphite, is used for high-temperature crucibles, arc-light processes, and as a decolorizing agent.

Carbon Arc Cutting (CAC) is an arc welding process that produces coalescence of metals by heat-impingement of the gas and a chamber. The carbon black made by the first process is called channel black, taking the name from the channel iron used as the depositing surface. The modern method, called the impingement process, uses many small flames with the fineness of particles size controlled by flame size. The air-to-gas ratio is high, giving oxidized surfaces and acid properties. No water is used for cooling, keeping the ash content low. The supergrade of channel black has a particle size as low as 512 μm. CO2 is used for the carbonation of beverages, for fire extinguishers, and in the solid state as a refrigerant. CO finds use as a reducing agent for many metallurgical processes. Carbon tetrachloride and carbon disulfide are important solvents for industrial uses. Gaseous dichlorodi-fluoromethane, commonly known as Freon, is used in refrigeration devices. Calcium carbide is used to prepare acetylene, which is used for the welding and cutting of metals as well as for the preparation of other organic compounds. Other metal carbides find important uses as refractories and metal cutters.

Carbon nanotubes may one day be used to construct extremely small-scale circuits. Scientists have observed ballistic conduction-electrons passing through a conductor without heating it—at room temperature in 5 μm carbon nanotubes. Because the nanotubes remain cool, extremely large current densities can flow through them.

The most common use of manufactured carbon is as sliding elements in mechanical devices. It is used as the primary rubbing face in most mechanical seals. Used as a brush, it transfers electrical current to the rotating commutator on small electric motors. Carbon vanes, piston rings, or cylinder liners are used in most small air pumps and drink-dispenser pumps. Carbon is also used for pistons in chemical-metering pumps and for metering valves in gasoline pumps. All these applications require the carbon to slide on metal with a coefficient of friction below 0.2 and a wear rate below 0.001 in. per million inches rubbed.

Bearings are another significant application area for manufactured carbon. In many cases, characteristics of the carbon bearing are tailored to satisfy a wide range of requirements. This is done by impregnating the porous, as-baked or as-graphitized carbon with various materials—for example, resin, babbitt, copper, or glass—or by combining impregnation with chemical conversion of the carbon surface (to hard SiC). These self-lubricating materials are particularly suited for environments containing dust or lint, repeated steam cleaning, solvents or corrosive fluids, low or high temperatures, high static loads, or hard vacuums. Some of these conditions require impregnants in the carbon material. Other applications using manufactured carbon bearings are those inaccessible for lubrication or where product contamination (from lubricants) cannot be tolerated.

Carbon Arc Cutting (CAC)

An arc cutting process in which metals are severed by melting them with the heat of an arc between a carbon electrode and the base metal. To melt the metal along the line of cut.

Carbon Arc Welding (CAW)

An arc welding process that produces coalescence of metals by heating them with an arc between a carbon electrode and the work or struck between two carbon electrodes. No shielding is used although gases produced by the burning of the carbon may offer protection.

Carbon Black

An amorphous powdered carbon resulting from the incomplete combustion of a gas, usually deposited by contact of the flame on a metallic surface, but also made by the incomplete combustion of the gas and a chamber. The carbon black made by the first process is called channel black, taking the name from the channel iron used as the depositing surface. The modern method, called the impingement process, uses many small flames with the fineness of particles size controlled by flame size. The air-to-gas ratio is high, giving oxidized surfaces and acid properties. No water is used for cooling, keeping the ash content low. The supergrade of channel black has a particle size as low as 512 μm. (13 μm) and a pH of 3–4.2. Carbon black made by other processes is called soft black and is weaker in color strength, not so useful as a pigment. Furnace black is made
Carbon Dioxide

Carbon Dioxide

Also called carbonic anhydride, and in its solid state, dry ice. A colorless, odorless gas of composition CO₂, which liquefies at −85°F (−65°C) and solidifies at −108.8°F (−78.2°C). Release of CO₂ into the atmosphere by the burning of fossil fuels is said to be causing global warming by the process known as the greenhouse effect. It is recovered primarily as a by-product of the steam reforming of natural gas to make hydrogen or synthesis gas in petroleum and fertilizer plants. Smaller quantities are obtained by purifying flue gases generated from burning hydrocarbons or lime and from distilleries. Its biggest uses are captive, as a chemical raw material for making urea and in enhanced oil recovery operations in petroleum production. Merchant CO₂ is more than 99.9% pure, with less than 500 ppm (parts per million) of nonvolatile residues. In liquid form it is marketed in cylinders and is used in fire extinguishers, in spray painting, in refrigeration, for inert atmospheres, for the manufacture of carbonated beverages, and in many industrial processes. It is also marketed as dry ice, a white, snow-like solid used for refrigeration and transporting food products.

Cardox Corp. for liquid carbon dioxide in storage units at 30 lb/in.² (0.21 MPa) pressure for fire-fighting equipment. Other uses include hardening of foundry cores, neutralization of industrial wastes, and production of salicylic acid for aspirin. Carbon dioxide is a key lasting gas and carbon dioxide lasers is also used as a shielding gas in some MIG welding applications for steel, and as a foaming agent in producing plastic foam products. It can behave as a supercritical fluid, in which state it can be used to foam plastics and extract hazardous substances and waste treatment processes and in soil remediation. CO₂ is used to wash brownstock in the pulp and paper industry, thereby sending cleaner pulp onto bleaching. In cooling systems, it is an alternative to halogenated-carbon refrigerants. CO₂ “snow,” pellets that is, is used to cool freshly laid eggs, cuts of meat and poultry, and flour in baking. Dry ice pellets are blasted on molds to clean them of plastic residuals. Liquid carbon dioxide is used in SuperFuge, an immersion system by Deflex Corp. to rid products of surface contaminants.

Carbon Dioxide Process (Sodium Silicate/CO₂)

In foundry practice, a process for hardening molds or cores in which carbon dioxide gas is blown through dry clay-free silica sand to precipitate silica in the form of a gel from the sodium silicate binder.

Carbon Dioxide Welding

A gas metal-arc welding (GMAW) process for steel in which carbon dioxide is fit into the arc vicinity to protect the weld zone from atmospheric contamination. Carbon dioxide is effectively inert in these circumstances and its choice, rather than argon, arises from its favorable effect on arc characteristics as well as the economic factor.

Carbon Edges

Carbonaceous deposits in a wavy pattern along the edges of a steel sheet or strip; also known as snaky edges.

Carbon Electrode

A nonfiller material electrode used in arc welding or cutting, consisting of a carbon or graphite rod, which may be coated with copper or other coatings.
Carbon Equivalent

(1) The measure of the effect of one or more alloying elements in cast iron or steel expressed in terms of the amount of carbon that would have the same effect. For example, the alloying elements in steel effect characteristics such as hardenability, and hence weldability, or microstructure in a way which reinforces or detracts from the effect of carbon. The element can therefore be ascribed as a factor reflecting its potency relative to carbon, taken as unity. This factor is termed the carbon equivalent of the element. In any iron or steel, individual alloy contents multiplied by their respective carbon equivalents can be added together to provide a total carbon equivalent for the material. (2) One of a number of formulae for predicting weldability of low alloy steels is:

\[ CE = C + \frac{Mn}{20} + \frac{Ni}{15} + \frac{Cr,Mo,V}{10} \]

Also see Schaeffler Diagram for an example of carbon equivalents related to microstructure. (3) For cast iron, an empirical relationship of the total carbon, silicon, and phosphorus contents expressed by the formula:

\[ CE = \%C + 0.3(\%Si) + 0.33(\%P) - 0.027(\%Mn) + 0.4(\%S) \]

(4) For rating of weldability:

\[ CE = C + \frac{Mn}{6} + \frac{Ni}{15} + \frac{Cu}{15} + \frac{Cr}{5} + \frac{Mo}{5} + \frac{V}{5} \]

Carbon Extraction Replica

See extraction replica.

Carbon Fiber

(1) Fiber produced by the pyrolysis of organic precursor fibers, such as rayon, polyacrylonitrile (PAN), and pitch, in an inert environment. The term is often used interchangeably with the term graphite; however, carbon fibers and graphite fibers differ. The basic differences lie in the temperature at which the fibers are made and heat-treated, and in the amount of elemental carbon produced. Carbon fibers typically are carbonized in the region of 1315°C (2400°F) and assayed at 93%–95% carbon, while graphite fibers are graphitized at 1900°C–2480°C (3450°F–4500°F) and assay at more than 99% elemental carbon. (2) A filament comprised of nearly pure carbon typically up to 10 µm diameter used for reinforcement epoxy or other plastics to form carbon fiber composite materials. See also pyrolysis.

Carbon Flotation

In casting, segregation in which free graphite has separated from the molten iron. This defect tends to occur at the upper surfaces of the cope of the castings.

Carbon Monoxide

Carbon monoxide (CO) is a product of incomplete combustion, and is very reactive. It is one of the desirable products in synthesis gas for making chemicals; the synthesis gas made from coal contains at least 37% CO. It is also recovered from top-blown O₂ furnaces in steel mills. It reacts with H₂ to form methanol, which is then catalyzed by zeolites into gasoline. Acetic acid is made by methanol carbonylation and acid catalysts result from the reaction of CO, acetylene, and methanol. CO forms a host of neutral, anionic, and cationic carbonyls, with such metals as iron, cobalt, nickel, molybdenum, chromium, rhodium, and ruthenium. These metals are from groups I, II, VI, VII, and VIII of the periodic table. The metal carbonyls can be prepared by the direct combination of the metal with CO, although several of the compounds require fairly high pressures. The metal carbonyls react with the halogens to produce metal carbonyl halides. With H₂, a similar reaction takes place to form metal carbonyl hydrides.

Nickel carbonyl finds application in purification and separation of nickel from other metals. Iron carbonyl has been used in anti-knock gasoline preparations and to prepare high-purity iron metal.

CO is an intense poison when inhaled and is extremely toxic even in the small amounts from the exhausts of internal-combustion engines.

With chlorine, in the presence of sunlight, CO forms highly poisonous phosgene, COCl₂; with sulfur, carbonyl sulfide, COS, is obtained.

Carbon Nitride

Traditional materials synthesis techniques, which require high-temperature conditions to facilitate diffusion of atoms in the solid state, generally preclude the rational assembly of atoms since the products are restricted to those phases stable at high temperature. For example, heating graphite in molecular N₂ does not provide carbon nitride (C–N) solids. However, binary C–N solids are desirable materials to prepare and study because they may possess extreme hardness and high thermal conductivity. Extreme hardness is important in thin-film coatings of cutting tools used for machining and in bearing surfaces used in a variety of high-performance mechanical devices, whereas high thermal conductivity is important to the fabrication of advanced microelectronics devices. To overcome the limitations imposed by classical methodologies of solid-state chemistry and provide access to these potentially exciting materials requires better control of the reactants and reactions that might lead to C–N solids. A new experimental approach that meets these requirements and has provided access to C–N materials utilizes pulsed-laser evaporation of graphite to generate reactive carbon fragments and an atomic Nₐ beam as a source of N₂ that can readily react with the carbon fragments.

The atomic Nₐ beam is generated by using a radio-frequency discharge within an Al₂O₃ nozzle through which N₂ seeded in helium flows. This process produces a very high flux of atomic N₂. Furthermore, by varying the N₂:He ratio and the radio-frequency power, it is possible to control both the flux and energy of this critical reactant. Hence, this synthetic approach provides a ready means of producing reactants that are free from impurities and that have controllable energies.

Structure

The structural properties of the C–N materials produced by the laser ablation approach have been investigated and show that carbon and N₂ are bound covalently within this solid but cannot provide information about the three-dimensional structure. Diffraction ring patterns suggest that a single crystalline C–N phase was obtained by using the new synthetic strategy.
Other Key Properties

The new C–N materials also exhibit interesting physical properties that may be attractive for high-performance engineering applications. Qualitative scratch tests indicate that C–N materials produced by the new laser ablation technique are hard. For example, rubbing C–N and hard amorphous carbon surfaces against one another produces damage in the carbon but not the C–N material.

Studies have shown that C–N is an excellent electrical insulator, and that these electrical properties are stable to thermal cycling. Because C–N is also expected to exhibit good thermal conductivity, it could be an attractive candidate for the dielectric in advanced microelectronic devices where thermally conducting electrical insulators are needed to enable further miniaturization of devices.

Carbon Potential

A measure of the ability of an environment containing active carbon to alter or maintain, under prescribed conditions, the carbon level of the steel. In any particular environment, the carbon level attained will depend on such factors as temperature, time, and steel composition.

Carbon Refractory

A manufactured refractory comprised substantially or entirely of carbon (including graphite).

Carbon Restoration

Replacing the carbon lost in the surface layer from previous processing of the steel by carburizing this layer to substantially the original carbon level. Sometimes called re-carburizing.

Carbon Steel

Carbon (C) steel, also called plain carbon steel, is a malleable, iron-based metal containing carbon, small amounts of manganese, and other elements that are inherently present. The old shop names, machine steel and machinery steel, are still used to mean any easily worked low-carbon steel. By definition, plain carbon steels are those that contain up to about 1% carbon, not more than 1.65% manganese, 0.60% silicon, and 0.60% copper, and only residual amounts of other elements, such as sulfur (0.05% max) and phosphorus (0.04% max). They are identified by means of a four-digit numerical system established by the American Iron and Steel Institute (AISI). The digits are preceded by either “AISI” or “SAE.” The first digit is the number 1 for all carbon steels. A 0 after the 1 indicates non-phosphorized grades. The last two digits give the nominal carbon level established by the American Iron and Steel Institute (AISI).

DQ hot-rolled sheet: Rb 40 to 72, 276 to 414 MPa, 186 to 310 MPa, and 34% to 46%.

DQ hot-rolled sheet: Rb 40 to 75 and tensile properties range from ultimate strengths of 276 to 469 MPa, yield strengths of 193 to 331 MPa and elongations of 14% to 43%.

For DQ hot-rolled sheet: Rb 40 to 72, 276 to 414 MPa, 186 to 310 MPa, and 28% to 48% respectively. For CQ hot-rolled sheet: Rb 35 to 60, 290 to 393 MPa, 159 to 262 MPa, and 30% to 45%. And for DQ cold-rolled sheet: Rb 32 to 52, 262 to 345 MPa, 138 to 234 MPa, and 34% to 46%.

Low-carbon steels 1018-1025 in cold-drawn bar (16–22 mm thick) have minimum tensile properties of about 483 MPa ultimate hardening effect. At the same time, it lowers ductility, as evidenced by a decrease in elongation and reduction of area. In addition, increasing carbon content decreases machinability and weldability, but improves wear resistance. The amount of carbon present also affects physical properties and corrosion resistance. With an increase in carbon content, thermal and electric conductivity decline, magnetic permeability decreases drastically, and corrosion resistance is less.

Carbon steels may be specified by chemical composition, mechanical properties, method of oxidation, or thermal treatment (and the resulting microstructure). Carbon steels are available in most wrought mill forms, including bar, sheet, plate, and tubing. Sheet is primarily a low-carbon-steel product, but virtually all grades are available in bar and plate. Plate, usually a low-carbon or medium-carbon product, is used mainly in the hot-finished condition, although it also can be supplied heat-treated. Bar products, such as rounds, squares, hexagonals, and flats (rectangular cross sections), are also mainly low-carbon and medium-carbon products and are supplied hot-rolled or hot-rolled and cold-finished. Cold finishing may be by drawing (cold-drawn bars are the most widely used); turning (machining) and polishing; drawing, grinding, and polishing; or turning, grinding, and polishing. Bar products are also available in various quality designations, such as merchant quality (M), cold-forging quality, cold-heading quality, and several others.

Sheet products also have quality designations as noted in low-carbon steels, which follow. Plain carbon steels are commonly divided into three groups, according to carbon content: low carbon, up to 0.30%; medium carbon, 0.31%–0.55%; and high carbon, 0.56%–1%.

Low-carbon steels are the grades AISI 1005-1030. Sometimes referred to as mild steels, they are characterized by low strength and high ductility, and are nonhardenable by heat treatment except by surface-hardening processes. Because of their good ductility, low-carbon steels are readily formed into intricate shapes. These steels are also readily welded without danger of hardening and embrittlement in the weld zone. Although low-carbon steels cannot be through-hardened, they are frequently surface-hardened by various methods (carburizing, carbonitriding, and cyaniding, for example) that diffuse carbon into the surface. Upon quenching, a hard, wear-resistant surface is obtained.

Low-carbon sheet and strip steels (1008-1012) are widely used in cars, trucks, appliances, and many other applications. Hot-rolled products are usually produced on continuous hot strip mills. Cold-rolled products are then made from the hot-rolled products, reducing thickness and enhancing surface quality. Unless the fully work-hardened product is desired, it is then annealed to improve formability and temper-rolled to further enhance surface quality. Hot-rolled sheet and strip and cold-rolled sheet are designated commercial quality (CQ), drawing quality (DQ), drawing quality special killed (DQS), and structural quality (SQ). The first three designations refer, respectively, to steels of increasing formability and mechanical property uniformity. SQ, which refers to steels produced to specified ranges of mechanical properties and/or hardenability values, does not pertain to cold-rolled strip, which is produced to several tempers related to hardness and bendability. Typically, the hardness of CQ hot-rolled sheet ranges from Rb 40 to 75 and tensile properties range from ultimate strengths of 276 to 469 MPa, yield strengths of 193 to 331 MPa, and elongations of 14% to 43%.

For DQ hot-rolled sheet: Rb 40 to 72, 276 to 414 MPa, 186 to 310 MPa, and 28% to 48% respectively. For CQ cold-rolled sheet: Rb 35 to 60, 290 to 393 MPa, 159 to 262 MPa, and 30% to 45%. And for DQ cold-rolled sheet: Rb 32 to 52, 262 to 345 MPa, 138 to 234 MPa, and 34% to 46%.
<table>
<thead>
<tr>
<th>AISI-SAE Designation</th>
<th>UNS Designation</th>
<th>Heat Composition Ranges and Limits, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Mn</td>
</tr>
<tr>
<td>1006</td>
<td>G10060</td>
<td>……0.08 max 0.25–0.45</td>
</tr>
<tr>
<td>1008</td>
<td>G10080</td>
<td>……0.10 max 0.25–0.50</td>
</tr>
<tr>
<td>1009</td>
<td>G10090</td>
<td>……0.15 max 0.60 max</td>
</tr>
<tr>
<td>1010</td>
<td>G10100</td>
<td>……0.08–0.13 0.30–0.60</td>
</tr>
<tr>
<td>1012</td>
<td>G10120</td>
<td>……0.10–0.15 0.30–0.60</td>
</tr>
<tr>
<td>1015</td>
<td>G10150</td>
<td>……0.12–0.18 0.30–0.60</td>
</tr>
<tr>
<td>1016</td>
<td>G10160</td>
<td>……0.12–0.18 0.60–0.90</td>
</tr>
<tr>
<td>1017</td>
<td>G10170</td>
<td>……0.14–0.20 0.30–0.60</td>
</tr>
<tr>
<td>1018</td>
<td>G10180</td>
<td>……0.14–0.20 0.60–0.90</td>
</tr>
<tr>
<td>1019</td>
<td>G10190</td>
<td>……0.17–0.23 0.70–1.00</td>
</tr>
<tr>
<td>1020</td>
<td>G10200</td>
<td>……0.17–0.23 0.30–0.60</td>
</tr>
<tr>
<td>1021</td>
<td>G10210</td>
<td>……0.17–0.23 0.60–0.90</td>
</tr>
<tr>
<td>1022</td>
<td>G10220</td>
<td>……0.19–0.25 0.70–1.00</td>
</tr>
<tr>
<td>1023</td>
<td>G10230</td>
<td>……0.22–0.28 0.30–0.60</td>
</tr>
<tr>
<td>1024</td>
<td>G10240</td>
<td>……0.22–0.28 0.60–0.90</td>
</tr>
<tr>
<td>1025</td>
<td>G10250</td>
<td>……0.27–0.34 0.60–0.90</td>
</tr>
<tr>
<td>1026</td>
<td>G10260</td>
<td>……0.29–0.36 0.70–1.00</td>
</tr>
<tr>
<td>1027</td>
<td>G10270</td>
<td>……0.31–0.38 0.60–0.90</td>
</tr>
<tr>
<td>1028</td>
<td>G10280</td>
<td>……0.31–0.38 0.70–1.00</td>
</tr>
<tr>
<td>1029</td>
<td>G10290</td>
<td>……0.34–0.42 0.60–0.90</td>
</tr>
<tr>
<td>1030</td>
<td>G10300</td>
<td>……0.36–0.44 0.70–1.00</td>
</tr>
<tr>
<td>1031</td>
<td>G10310</td>
<td>……0.36–0.44 0.60–0.90</td>
</tr>
<tr>
<td>1032</td>
<td>G10320</td>
<td>……0.39–0.47 0.60–0.90</td>
</tr>
<tr>
<td>1033</td>
<td>G10330</td>
<td>……0.39–0.47 0.70–1.00</td>
</tr>
<tr>
<td>1034</td>
<td>G10340</td>
<td>……0.42–0.50 0.60–0.90</td>
</tr>
<tr>
<td>1035</td>
<td>G10350</td>
<td>……0.42–0.50 0.70–1.00</td>
</tr>
<tr>
<td>1036</td>
<td>G10360</td>
<td>……0.45–0.53 0.60–0.90</td>
</tr>
<tr>
<td>1037</td>
<td>G10370</td>
<td>……0.47–0.55 0.60–0.90</td>
</tr>
<tr>
<td>1038</td>
<td>G10380</td>
<td>……0.52–0.60 0.60–0.90</td>
</tr>
<tr>
<td>1039</td>
<td>G10390</td>
<td>……0.55–0.66 0.60–0.90</td>
</tr>
<tr>
<td>1040</td>
<td>G10400</td>
<td>……0.59–0.70 0.60–0.90</td>
</tr>
<tr>
<td>1041</td>
<td>G10410</td>
<td>……0.59–0.70 0.60–0.90</td>
</tr>
<tr>
<td>1042</td>
<td>G10420</td>
<td>……0.65–0.76 0.60–0.90</td>
</tr>
<tr>
<td>1043</td>
<td>G10430</td>
<td>……0.69–0.80 0.60–0.90</td>
</tr>
<tr>
<td>1044</td>
<td>G10440</td>
<td>……0.72–0.86 0.60–0.90</td>
</tr>
<tr>
<td>1045</td>
<td>G10450</td>
<td>……0.74–0.88 0.60–0.90</td>
</tr>
<tr>
<td>1046</td>
<td>G10460</td>
<td>……0.80–0.94 0.60–0.90</td>
</tr>
<tr>
<td>1047</td>
<td>G10470</td>
<td>……0.80–0.94 0.70–1.00</td>
</tr>
<tr>
<td>1048</td>
<td>G10480</td>
<td>……0.80–0.94 0.30–0.50</td>
</tr>
<tr>
<td>1049</td>
<td>G10490</td>
<td>……0.80–0.94 0.60–0.90</td>
</tr>
<tr>
<td>1050</td>
<td>G10500</td>
<td>……0.84–0.98 0.60–0.90</td>
</tr>
<tr>
<td>1055</td>
<td>G10550</td>
<td>……0.90–1.04 0.60–0.90</td>
</tr>
<tr>
<td>1060</td>
<td>G10600</td>
<td>……1.18–1.25 1.30–1.65</td>
</tr>
<tr>
<td>1061</td>
<td>G10610</td>
<td>……1.22–1.29 1.20–1.55</td>
</tr>
<tr>
<td>1062</td>
<td>G10620</td>
<td>……1.30–1.38 1.20–1.55</td>
</tr>
<tr>
<td>1063</td>
<td>G10630</td>
<td>……1.36–1.45 1.30–1.65</td>
</tr>
<tr>
<td>1064</td>
<td>G10640</td>
<td>……1.43–1.52 1.05–1.40</td>
</tr>
<tr>
<td>1065</td>
<td>G10650</td>
<td>……1.46–1.55 1.20–1.55</td>
</tr>
</tbody>
</table>

* Limits on phosphorus and sulfur contents are typically 0.040% maximum phosphorus and 0.050% maximum sulfur. Silicon contents range from 0.080% to approximately 2%. Steels listed in this table can be produced with additions of lead or boron. Leaded steels typically contain 0.15%–0.35% lead and are identified by inserting the letter “L” in the designation—11L17; boron steels can be expected to contain 0.0005%–0.003% boron and are identified by inserting the letter “B” in the designation—15B41. Formerly designated 10xx grade.
strength, 413 MPa yield strength, and 18% elongation. Properties decrease somewhat with increasing section size, to, for example, 379 MPa, 310 MPa and 15%, respectively, for 50–76 mm cross sections.

Medium-carbon steels are the grades AISI 1030-1055. They usually are produced as killed, semikilled, or capped steels, and are hardenable by heat treatment. However, hardenability is limited to thin sections or to the thin outer layer on thick parts. Medium-carbon steels in the quenched and tempered condition provide a good balance of strength and ductility. Strength can be further increased by cold work. The highest hardness practical for medium-carbon steels is about 550 Bhn (Rockwell C55). Because of the good combination of properties, they are the most widely used steels for structural applications, where moderate mechanical properties are required. Quenched and tempered, their tensile strengths range from about 517 to over 1034 MPa.

Medium-carbon steel 1035 in cold-drawn bar 16–22 mm thick has minimum tensile properties of about 586 MPa ultimate strength, 517 MPa yield strength, and 13% elongation. Strength increases and ductility decreases with increasing carbon content, to, for example, 689 MPa, 621 MPa, and 11%, respectively, for medium-carbon steel 1050. Properties decrease somewhat with increasing section size, to, for example, 483 MPa, 414 MPa, and 10%, respectively, for 1035 steel 50–76 mm cross sections.

High-carbon steels are the grades AISI 1060-1095. They are, of course, hardenable with a maximum surface hardness of about Rockwell C64 achieved in the 1095 grade. These steels are thus suitable for wear-resistant parts. So-called spring steels are high-carbon steels available in annealed and pretempered strip and wire. In addition to their spring applications, these steels are used for such items as piano wire and saw blades. Quenched and tempered, high-carbon steels approach tensile strengths of 1378 MPa.

Free-machining carbon steels are low-carbon and medium-carbon grades with additions usually of sulfur (0.08%–0.13%), S–P combinations, and/or lead to improve machinability. They are AISI 1108-1151 for sulfur grades, and AISI 1211-1215 for phosphorus and sulfur grades. The latter may also contain bismuth and be lead free. The presence of relatively large amounts of sulfur and phosphorus can reduce ductility, cold formability, forgeability, weldability, as well as toughness and fatigue strength. Calcium deoxidized steels (carbon and alloy) have good machinability, and are used for carburized or through-hardened gears, worms, and pinions.

Low-temperature carbon steels have been developed chiefly for use in low-temperature equipment and especially for welded pressure vessels. They are low-carbon to medium-carbon (0.20%–0.30%), high-manganese (0.70%–1.60%), silicon (0.15%–0.60%) steels, which have a fine-grain structure with uniform carbide dispersion. They feature moderate strength with toughness down to −46°C.

For grain refinement and to improve formability and weldability, carbon steels may contain 0.01%–0.04% columbium. Called columbium steels, they are used for shafts, forgings, gears, machine parts, and dies and gauges. Up to 0.15% sulfur, or 0.045% phosphorus, makes them free-machining, but reduces strength.

Rail steel, for railway rails, is characterized by an increase of carbon with the weight of the rail. Railway engineering standards call for 0.50%–0.63% carbon and 0.60% manganese in a 27 kg rail, and 0.69%–0.82% carbon and 0.70%–1.0% manganese in a 64 kg rail. Rail steels are produced under rigid control conditions from deoxidized steels, with phosphorus kept below 0.04%, and silicon 0.10%–0.23%. Guaranteed minimum tensile strength of 551 MPa is specified, but it is usually much higher.

Sometimes, a machinery steel may be required with a small amount of alloying element to give a particular characteristic and still not be marketed as an alloy steel, although trade names are usually applied to such steels. Superplastic steels, developed at Stanford University, with 1.3%–1.9% carbon, fall between high-carbon steels and cast irons. They have elongations approaching 500% at warm working temperatures of 538°C–650°C, and 4%–15% elongation at room temperature. Tensile strengths range from 1034 to over 1378 MPa. The extra-high ductility is a result of a fine, equiaxed grain structure obtained by special thermomechanical processing.

Damascus steels are 1%–2% carbon steels used for ancient swords made by blacksmiths using hot and warm forging, which developed layered patterns. The swords were eminent for their strength and sharp cutting edge. With carbon in the form of iron carbide, the forged products were free of surface markings. With carbon in the form of spherical carbide, the products could exhibit surface markings. So-called welded Damascus steels, also referred to as pattern welded steels, also exhibit surface markings. Superplasticity may be inherent in all of these steels.

Production Types

Steelmaking processes and methods used to produce mill products, such as plate, sheet, and bars, have an important effect on the properties and characteristics of the steel.

Deoxidation Practice

Steels are often identified in terms of the degree of deoxidation resulting during steel production. Killed steels, because they are strongly deoxidized, are characterized by high composition and property uniformity. They are used for forging, carburizing, and heat-treating applications. Semikilled steels have variable degrees of uniformity, intermediate between those of killed and rimmed steels. They are used for plate, structural sections, and galvanized sheets and strip. Rimmed steels are deoxidized only slightly during solidification. Carbon is highest at the center of the ingot. Because the outer layer of the ingot is relatively ductile, these steels are ideal for rolling. Sheet and strip made from rimmed steels have excellent surface quality and cold-forming characteristics. Capped steels have a thin low-carbon rim, which gives them surface qualities similar to rimmed steels. Their cross section uniformity approaches that of semikilled steels.

Melting Practice

Steels are also classified as air melted, vacuum melted, or vacuum degassed. Air-melted steels are produced by conventional melting methods, such as open hearth, basic O₂, and electric furnace. Vacuum-melted steels encompass those produced by induction vacuum melting and consumable electrode vacuum melting. Vacuum-degassed steels are air-melted steels that are vacuum processed before solidification. Compared with air-melted steels, those produced by vacuum-melting processes have lower gas content, fewer nonmetallic inclusions, and less center porosity and segregation. They are more costly, but have better mechanical properties, such as ductility and impact and fatigue strengths.

Rolling Practice

Steel mill products are produced from various primary forms such as heated blooms, billets, and slabs. These primary forms are first reduced to finished or semi-finished shape by hot-working operations. If the final shape is produced by hot-working processes, the steel is known as hot rolled. If it is finally shaped cold, the steel is known as cold finished, or more specifically as cold rolled or cold drawn. Hot-rolled mill products are usually limited to low and
medium, non-heat-treated, carbon steel grades. They are the most economical steels, have good formability and weldability, and are used widely for large structural shapes. Cold-finish shapes, compared with hot-rolled products, have higher strength and hardness and better surface finish, but are lower in ductility.

Carbon Tetrachloride
A heavy, colorless liquid of composition CCl₄, tetrachloromethane, which is one of a group of chlorinated hydrocarbons. It is an important solvent for fats, asphalt, rubber, bitumens, and gums. It is more expensive than the aromatic solvents, but it is notable as a nonflammable solvent for many materials sold in solution and is widely used as a degreasing and cleaning agent in the dry-cleaning and textile industries. Since the fumes are highly toxic, it is no longer permitted in compounds for home use. It is used as a chemical in fire extinguishers such as Pyrene; but when it falls on hot metal, it forms a poisonous gas phosgene. It is also used as a disinfectant, and because of its high dielectric strength has been employed in transformers. Carbon tetrachloride is obtained by the chlorination of carbon disulfide. The specific gravity is 1.595, boiling point 169°F (76°C), and the freezing point 73°F (23°C). Chlorobromomethane, Br-CH₂Cl, is also used in fire extinguishers, as it is less corrosive and more than twice as efficient as an extinguisher. It is a colorless, heavy liquid with a sweet odor, a specific gravity 1.925, boiling point 153°F (67°C), and a freezing point −85°F (−65°C). It is also used as the high-gravity flotation agent.

Carbon Tube Furnace
An electric furnace that has a carbon retort for a resistor element and is especially suitable for the batch or continuous sintering of carbon-insensitive materials such as cement and carbides.

Carbonaceous
A material that contains carbon in any or all of its several allotropic forms.

Carbon–Carbon Composites
Carbon–carbon composites (C–C) provide high-strength, light weight, and resistance to high temperature and corrosion for pistons in both stationary and mobile engines.

Advantages in using carbon–carbon for both gasoline and diesel engines include increased performance (higher power output and faster engine acceleration); higher temperature operation for improved fuel economy; reduced levels of air pollutant emissions; and reduced noise, vibration, and harshness (NVH) levels. These benefits also could provide lower operational costs and reduced environmental impact.

Another carbon–carbon originally developed for use as rocket nozzles is now a replacement for graphite, quartz, and ceramic furnace components used in Czochralski crystal pulling, a processing step in semiconductor manufacturing. The material has a high strength-to-weight ratio, maintains its strength and rigidity despite high temperatures, resists wear, and is relatively chemically inert. When used in Czochralski furnaces, the thermal properties of the material lead to a 10% reduction in energy use and a 50% cut in cooling times. Because of the purity of the material, chipmakers achieve a 7% increase in wafer yields compared to furnaces with graphite components. See composite materials.

Carbonitriding
A case hardening process in which a suitable ferrous material is heated above the lower transformation temperature in a gaseous atmosphere of such composition as to cause simultaneous absorption of carbon and nitrogen by the surface and, by diffusion, create a concentration gradient. The heat-treating process is completed by cooling at a rate that produces the desired properties and the workpiece. See case hardening.

Carbonium Ion
Positively charged organic compound (ion).

Carbonization
The conversion of an organic substance into elemental carbon in an inert atmosphere at temperatures ranging from 800°C to 1600°C (1470°F to 2910°F) and higher, but usually at about 1315°C (2340°F). Range is influenced by precursor, processing of the individual manufacturer, and properties desired. Should not be confused with carburization.

Carbonizing Flame (in Gas Welding)
Same as carburizing flame. See preferred term reducing flame.

Carbonyl Powder
Metal powders prepared by the thermal decomposition of a metal carbonyl compound such as nickel tetracarbonyl Ni(CO)₄ or iron pentacarbonyl Fe(CO)₅. See also thermal decomposition.

Carbonyl Process
A process in which a metal carbonyl gas is heated to form a purified metal powder.

Carborundum
Silicon carbide, particularly as an abrasive.

Carburizing
(1) Absorption and diffusion of carbon into solid ferrous alloys by heating to a temperature usually above Ac₃, in contact with a suitable carbonaceous material. A form of case hardening that produces a carbon gradient extending inward from the surface, enabling the surface layer to be hardened either by quenching directly from the carburizing temperature or by cooling to room temperature, then reaustenitizing and quenching. (2) The process by which carbon diffuses into the steel. The process can be deliberately induced by appropriate treatments. It can occur accidentally during some manufacturing processes with potentially adverse consequences for the component.

Carburizing Flame
A gas flame that will introduce carbon into some heated metals, as during a gas welding operation. A carburizing flame is a reducing flame, but a reducing flame is not necessarily a carburizing flame. Carburizing flames have a long feathery inner cone and a relatively low temperature.
Carburizing Secondary-Hardening Steels

Case-carburized steels subsequently hardened and strengthened by precipitation of 
M_7C_3 carbide. Three steels developed by QuesTek Innovations LLC, include Ferrium C862 stainless steel, GearMet C61%, and GearMet C69% for gears and bearings. Ferrium C862 nominally contains 15% cobalt, 9.0% chromium, 1.5% nickel, 0.2% vanadium, 0.08% core carbon, balance iron. It is targeted at matching the surface properties of standard nonstainless gear steels, maintaining sufficient core strength and toughness, and having better corrosion resistance than 440C stainless steel. Core hardness is 50 Rockwell C, core toughness 1740 MPa mm⁻¹/₂, and surface hardness 62 Rockwell C. GearMet C61% has 18 cobalt, 9.5 nickel, 3.5 chromium, 1.1 molybdenum, 0.16 core carbon, balance iron. It is designed to provide surface properties similar to conventional gear steels and an ultrahigh strength core with superior fracture toughness. Core hardness is 54 Rockwell C, core toughness of more than 2610 MPa mm⁻¹/₂, and surface hardness 61 Rockwell C. GearMet C69% has 27.8–28.2 cobalt, 5–5.2 chromium, 2.9–3.1 nickel, 2.4–2.6 molybdenum, 0.09–0.11 core carbon, 0.015–0.025 vanadium, balance iron. It combines a tough ductile core with an ultrahard case. Core hardness is 50 Rockwell C and surface hardness 69 Rockwell C.

Cascade Sequence

A welding sequence in which a continuous multiple-pass weld is built up by depositing weld beads in overlapping layers, usually laid in a back step sequence. Compare with block sequence.

Case

In heat treating, that portion of the ferrous alloy, extending inward from the surface, whose composition has been altered during case hardening. Typically considered to be a portion of an alloy (a) whose composition has been measurably altered from the original composition, (b) that appears light when etched, or (c) that has a higher hardness value than the core. Contrast with core.

Case Crushing

A term used to denote longitudinal gouges arising from fracture in case-hardened gears.

Case-Hardening Materials

Case-hardening materials are those for adding carbon or other elements to the surface of low-carbon or medium-carbon steels or to iron so that upon quenching a hardened case is obtained, the center of the steel remaining soft and ductile. The material may be plain charcoal, raw bone, or mixtures marketed as carburizing compounds. A common mixture is about 60% charcoal and 40% barium carbonate. The latter decomposes, yielding CO₂, which is reduced to CO in contact with the hot charcoal. If charcoal is used alone, the action is slow and spotty. Coal or coke can be used, but the action is slow, and the sulfur in these materials is detrimental. Salt is sometimes added to aid the carburizing action. By proper selection of the carburizing material, the carbon content may be varied in the steel from 0.80% to 1.20%. The carburizing temperature for carbon steels typically ranges from 850°C to 950°C but maybe as low as 790°C or as high as 1095°C. The articles to be carburized for case hardening are packed in metallic boxes for heating in a furnace, and the process is called pack hardening, as distinct from the older method of burying the red-hot metal in charcoal.

Steels are also case-hardened by the diffusion of carbon and N₂, called carbo-nitriding, or N₂ alone, called nitriding. Case-hardening, also known as dry cyaniding, gas cyaniding, liquid cyaniding, nica-riding, and nitrocarburizing, involves the diffusion of carbon and N₂ into the case. Nitriding also may be done by gas or liquid methods. In carbonitriding, the steel may be exposed to a carrier gas containing carbon and as much as 10% ammonia (NH₃), the N₂ source, or a molten cyanide salt, which provides both elements. NH₃ from gaseous or liquid salts, is also the N₂ source for nitriding. Although low- and medium-carbon steels are commonly used for carburizing and carbonitriding, nitriding is usually applied only to alloy steels containing nitride-forming elements, such as aluminum, chromium, molybdenum, or vanadium. In ion nitriding, or glow-discharge nitriding, electric current is used to ionize low-pressure N₂ gas. The ions are accelerated to the workpiece by the electric potential, and the workpiece is heated by the impinging ions, obviating an additional heat source. Of the three principal case-hardening methods, all provide a hard wear-resistant case. Carburizing, however, which gives the greater case depth, provides the best contact-load capacity. Nitriding provides the best dimensional control and carbonitriding is intermediate in this respect.
The principal liquid-carburizing material is sodium cyanide, which is melted in a pot that the articles are dipped in, or the cyanide is rubbed on the hot steel. Cyanide hardening gives an extremely hard but superficial case. N₂ as well as carbon is added to the steel by this process. Gases rich in carbon, such as methane, may also be used for carburizing, bypassing the gas through the box in the furnace. When NH₃ gas is used to impart N₂ to the steel, the process is not called carburizing but is referred to as nitriding.

Chromized steel is steel surface-alkloyed with chromium by diffusion from a chromium salt at high temperature. The reaction of the salt produces an alloyed surface containing about 40% chromium.

Metalliding is a diffusion coating process involving an electrolytic technique similar to electroplating, but done at higher temperatures (816°C–1093°C). The process uses a molten fluoride salt bath to diffuse metals and metalloids into the surface of other metals and alloys. As many as 25 different metals have been used as diffusing metals, and more than 40 as substrates. For example, boride coatings are applied to steels, nickel-base alloys, and refractory metals. Beryllide coatings can also be applied to many different metals by this process. The coatings are pore-free and can be controlled to a tolerance of 0.025 mm.

**Casein**

A whitish to yellowish, granular or lumpy protein precipitated from skim milk by the action of a dilute acid, or coagulated by rennet, or precipitated with whey from a previous batch. Casein is precipitated from sour milk by pepsin. Casein is rubbed on the hot steel. As many as 25 different metals have been used as diffusing metals, and more than 40 as substrates. For example, boride coatings are applied to steels, nickel-base alloys, and refractory metals. Beryllide coatings can also be applied to many different metals by this process. The coatings are pore-free and can be controlled to a tolerance of 0.025 mm.

**Casein Adhesive**

An aqueous colloidal dispersion of casein that may be prepared with or without heat that may contain modifiers, inhibitors, and secondary binders to provide specific adhesive properties; and that includes a subclass, usually identified as casein glue, that is based on a dry blend of casein, lime, and sodium salts, mixed with water prepared without heat.

**Casein Plastics**

A group of thermoplastic molding materials made usually by the action of formaldehyde on rennet casein. The process was invented in 1885, and the first commercial casein plastic was called Galalith, meaning milk stone. Casein plastics are easily molded, machine easily, are nonflammable, withstand temperatures up to 300°F (150°C) and are easily dyed to light shades. But they are soft, have a high water absorption (7%–14%), and so often when exposed to alkalies. They are thus not suitable for many mechanical or electrical parts. They are used for ornamental parts, buttons, and such articles as fountain-pen holders. Casein fiber is made by treating casein with chemicals to extract the albumen and salts, forcing it through spinnersets, and again treating it to make it soft and silk-like. The fiber is superior to wool in silkiness and resistant to moth attack, but is inferior in general properties. It is blended with wool and fabrics and in hat felts.

**CASS Test**

Abbreviation for copper-accelerated salt-spray test.

**Cassette**

A holder used to contain radiographic film storing exposure to x-rays or gamma rays, that may or may not contain intensifying or filter screens, or both. A distinction is often made between a cassette, which is a positive means for ensuring contact between screens and film and is usually rigid, and an exposure holder, which is rather flexible.

**Cast**

(1) The practice of pouring molten metal into a mold and allowing it to solidify. If the resultant item is of approximately the final shape, requiring only final machining and other treatments that do not involve significant deformation, it will be described as a casting. If the cast item is to be wrought to shape by rolling, forging, etc., it will usually be described as an ingot. See also continuous casting.

(2) The natural curved form that a wire takes as it is drawn from a reel and allowed to lie unrestrained. Its measure is the diameter of the circle formed when a sufficiently is allowed to lie freely on a horizontal surface.
Cast (Plastics)

To form a “plastic” object by pouring a fluid monomer–polymer solution into an open mold where it finishes polymerizing. Forming plastic film and sheet by pouring the liquid resin onto a moving belt or by precipitation in a chemical bath.

Cast Corrosion-Resistant Stainless Steels

High chromium-containing (11%–30% Cr) cast steels have been specified for liquid corrosion service at temperatures below 650°C (1200°F). Corrosion-resistant, or C-type steel castings are classified on the basis of composition using the designation system of the High Alloy Product Group of the Steel Founder’s Society of America. The first letter of the designation (C) indicates that the alloy is intended for liquid corrosion service. The second letter indicates the nickel content; as the nickel content increases, the second letter of the designation changes from A to Z.

Cast Film

A film made by depositing a layer of liquid plastic onto a surface and stabilizing this film by the evaporation of solvent, by fusing after deposition, or by allowing a melt to cool. Cast films are usually made from solutions or dispersions.

Cast Heat-Resistant Stainless Steels

Iron–chromium, iron–chromium–nickel, and iron–nickel–chromium steel castings have been specified for service at temperatures 650°C (1200°F) to approximately 980°C (1800°F). Designated similarly to cast corrosion-resistant stainless steels, H-type steels (the “H” denoting high-temperature service) have nickel contents ranging from 0% to 68%.

Cast Iron

Alloys of iron containing, at the time they are cast, carbon in the range from about 2% to 4%. This contrasts with steel which is also an iron-carbon alloy but which contains considerably less carbon. It is common for the term “cast” to be omitted in description such as “Grey (cast) Iron,” “Malleable (cast) Iron” or even “(cast) Irons.” Iron is common for the term “cast” to be omitted in description such as “Cast Iron.” Iron–carbon alloy but which contains considerably less carbon. It is common for the term “cast” to be omitted in description such as “Grey (cast) Iron,” “Malleable (cast) Iron” or even “(cast) Irons.”

TABLE C.4

Range of Compositions for Typical Unalloyed Common Cast Irons

<table>
<thead>
<tr>
<th>Type of Iron</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray (FG)</td>
<td>2.5–4.0</td>
<td>1.0–3.0</td>
<td>0.2–1.0</td>
<td>0.002–1.0</td>
<td>0.02–0.25</td>
</tr>
<tr>
<td>Compacted graphite (CG)</td>
<td>2.5–4.0</td>
<td>1.0–3.0</td>
<td>0.2–1.0</td>
<td>0.01–0.1</td>
<td>0.01–0.03</td>
</tr>
<tr>
<td>Ductile (SG)</td>
<td>3.0–4.0</td>
<td>1.8–2.8</td>
<td>0.1–1.0</td>
<td>0.01–0.1</td>
<td>0.01–0.03</td>
</tr>
<tr>
<td>White</td>
<td>1.8–3.6</td>
<td>0.5–1.9</td>
<td>0.25–0.8</td>
<td>0.06–0.2</td>
<td>0.06–0.2</td>
</tr>
<tr>
<td>Malleable (TG)</td>
<td>2.2–2.9</td>
<td>0.9–1.9</td>
<td>0.15–1.2</td>
<td>0.02–0.2</td>
<td>0.02–0.2</td>
</tr>
</tbody>
</table>

The mechanical properties, particularly ductility and malleability, of white irons can be improved by various heat treatments to form Malleable Irons. Heating a white iron at about 850°C–950°C in a nonreactive environment for a long period (up to a week) causes the cementite to decompose producing a microstructure of ferrite with temper carbon, i.e., graphite in a nodular or rosette form which is not so damaging as flake. These carbon nodules are more prolific toward the center of this section so the appearance of the fracture surface leads to the term Blackheart (Malleable) Iron. A variation on this process requires a second heating to 900°C allowing some of the carbon to redissolve in the austenite so that pearlite is produced on cooling, hence the term Pearlitic Malleable Iron. Such irons can be heat-treated just like steel. An alternative malleablizing treatment involves heating white iron at about 950°C in an oxidizing environment for up to 100 h during which most of the carbon diffuses to the surface to react with oxygen-forming carbon dioxide. The resulting structure is largely ferritic or pearlitic, with a little temper carbon at the center (more in large castings), hence the name Whiteheart (Malleable) Iron. An alternative approach to producing more ductile irons is to modify the form of the graphite in the as-cast state, usually by small additions of magnesium or cerium to the molten iron. These promote the formation of graphite in the nodular or spheroidal form which, compared with the flake form, has only a slightly adverse effect on the mechanical properties. These materials are referred to as Ductile Irons, Nodular Irons, Spheroidal Graphite Irons (SG Irons). See Tables C.4 and C.5.
In some cases, iron microstructure may be all ferrite—the same constituent that makes low-carbon steels soft and easily machined. But the ferrite of iron is different because it contains sufficient dissolved silicon to eliminate the characteristic gummy nature of low-carbon steel. Thus, cast irons containing ferrite do not require sulfur or lead additions in order to be free machining.

Because the size and shape of a casting control its solidification rate and strength, design of the casting and the casting process involved must be considered in selecting the type of iron to be specified. Although most other metals are specified by a standard chemical analysis, a single analysis of cast iron can produce several entirely different types of iron, depending upon foundry practice and size and shape of the casting, all of which influence cooling rate. Thus, iron is usually specified by mechanical properties. For applications involving high temperatures or requiring specific corrosion resistance, however, some analysis requirements may also be specified.

Pattern making is no longer a necessary step in manufacturing cast iron parts. Many gray, ductile, and alloy-iron components can be machined directly from bar that is continuously cast to near-net shape. Not only does this “parts-without-patterns” method save the time and expense of pattern making, continuous cast iron also produces a uniformly dense, finer-grained structure, essentially free from porosity, sand, or other inclusions. Keys to the uniform microstructure of the metal are the ferrostatic pressure and the temperature-controlled solidification that are unique to the process.

For each basic type of cast iron, there are a number of grades with widely differing chemical properties. These variations are caused by differences in the microstructure of the metal that surrounds the graphite (or iron carbides). Two different structures can exist in the same casting. The microstructure of cast iron can be controlled by heat treatment, but once graphite is formed, it remains.

Pearlitic cast iron grades consist of alternating layers of soft ferrite and hard iron carbide. This lamellated structure—which pearlite—is strong and wear resistant, but still quite machinable. As laminations become finer, hardness and strength of the iron increase. Laminations size can be controlled by heat treatment or cooling rate.

Cast irons that are flame-hardened, induction-hardened, or furnace-heated and subsequently oil-quenched contain a martensite structure. When tempered, this structure provides machinability with maximum strengths and good wear resistance.

**Gray Iron**

This is a supersaturated solution of carbon in an iron matrix. The excess carbon precipitates out in the form of graphite flakes. Gray iron is specified by a two-digit designation; Class 20, for example, specifies a minimum tensile strength of 138 MPa. In addition, gray iron is specified by the cross section and minimum strength of a test bar. Usually, the test bar cross section matches or is related to a particular critical section of the casting. This second specification is necessary because the strength of gray iron is highly sensitive to cross section (the smaller the cross section, the faster the cooling rate and the higher the strength). Impact strength of gray iron is lower than that of most other cast ferrous metals. In addition, gray iron does not have a distinct yield point (as defined by classical formulas) and should not be used when permanent, plastic deformation is preferred to fracture. Another important characteristic of gray iron—particularly for precision machinery—is its ability to damp vibration. Damping capacity is determined principally by the amount and type of graphite flakes. As graphite decreases, damping capacity also decreases.

The high compressive strength of gray iron—three to five times tensile strength—can be used to advantage in certain situations. For example, placing ribs on the compression side of a plate instead of the tension side produces a stronger, lighter component. Gray irons have excellent wear resistance. Even the softer grades perform well under certain borderline lubrication conditions (as in the upper cylinder walls of internal-combustion engines, for example).

To increase the hardness of gray iron for abrasive-wear applications, alloying elements can be added, special foundry techniques can be used, or the iron can be heat-treated. Gray iron can be hardened by flame or induction methods, or the foundry can use a chill in the mold to produce hardened, “white-iron” surfaces. Typical applications of gray iron include automotive engine blocks, gears, flywheels, brake disks and drums, and machine bases. Gray iron serves well in machinery applications because of its good fatigue resistance.

**Ductile Iron**

Ductile, or nodular iron, contains trace amounts of magnesium which, by reacting with the sulfur and oxygen in the molten iron, precipitates out carbon in the form of small spheres. These spheres improve the stiffness, strength, and shock resistance of ductile iron over gray iron. Different grades are produced by controlling the matrix structure around the graphite, either as-cast or by subsequent heat treatment.

A three-part designation system is used to specify ductile iron. The designation of a typical alloy, 60–40–18, for example, specifies a minimum tensile strength of 414 MPa, a minimum yield strength of 276 MPa, and 18% elongation in 5.08 mm.  

---

**TABLE C.5**  
**Classification of Cast Iron by Commercial Designation, Microstructure, and Fracture**

<table>
<thead>
<tr>
<th>Commercial Designation</th>
<th>Carbon-Rich Phase</th>
<th>Matrix</th>
<th>Fracture</th>
<th>Final Structure After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray iron</td>
<td>Lamellar graphite</td>
<td>P</td>
<td>Gray</td>
<td>Solidification</td>
</tr>
<tr>
<td>Ductile iron</td>
<td>Spheroidal graphite</td>
<td>F, P, A</td>
<td>Silver-gray</td>
<td>Solidification or heat treatment</td>
</tr>
<tr>
<td>Compacted graphite iron</td>
<td>Compacted vermicular graphite</td>
<td>F, P</td>
<td>Gray</td>
<td>Solidification</td>
</tr>
<tr>
<td>White iron</td>
<td>Fe₃C</td>
<td>P, M</td>
<td>White</td>
<td>Solidification and heat treatment(ab)</td>
</tr>
<tr>
<td>Mottled iron</td>
<td>Lamellar Gr + Fe₃C</td>
<td>P</td>
<td>Mottled</td>
<td>Solidification</td>
</tr>
<tr>
<td>Malleable ductile iron</td>
<td>Temper graphite</td>
<td>F, P</td>
<td>Silver-gray</td>
<td>Heat treatment</td>
</tr>
<tr>
<td>Austempered ductile iron</td>
<td>Spheroidal graphite</td>
<td>At</td>
<td>Silver-gray</td>
<td>Heat treatment</td>
</tr>
</tbody>
</table>

---

* a: Ferrite; p: pearlite; A: austenite; m: martensite; at: austempered (bainite).
* b: White irons are not usually heat treated, except for stress relief and to continue austenite transformation.
Ductile iron is used in applications such as crankshafts because of its good machinability, fatigue strength, and high modulus of elasticity; in heavy-duty gears because of its high yield strength and wear resistance; and in automobile door hinges because of its ductility. Because it contains magnesium as an additional alloying element, ductile iron is stronger and more shock resistant than gray iron. But although ductile iron also has a higher modulus of elasticity, its damping capacity and thermal conductivity are lower than those of gray iron.

By weight, ductile iron castings are more expensive than gray iron. Because they offer higher strength and provide better impact resistance, however, overall part costs may be about the same.

Although it is not a new treatment for ductile iron, austempering has become increasingly known to the engineering community in the past 5–10 years. Austempering does not produce the same type of structure as it does in steel because of the high carbon and silicon content of iron. The matrix structure of austempered ductile iron (ADI) sets it apart from other cast irons, making it truly a separate class of engineering materials.

In terms of properties, the ADI matrix almost doubles the strength of conventional ductile iron while retaining its excellent toughness. Like ductile iron, ADI is not a single material; rather, it is a family of materials having various combinations of strength, toughness, and wear resistance. Unfortunately, the absence of a standard specification for the materials has restricted its widespread acceptance and use. To help eliminate this problem, the Ductile Iron Society has proposed property specifications for four grades of austempered ductile iron.

Most current applications for ADI are in transportation equipment—automobiles, trucks, and railroad and military vehicles. The same improved performance and cost savings are expected to make these materials attractive in equipment for other industries such as mining, earthmoving, agriculture, construction, and machine tools.

White Iron

White iron is produced by “chilling” selected areas of a casting in the mold, which prevents graphitic carbon from precipitating out. Both gray and ductile iron can be chilled to produce a surface of white iron, consisting of iron carbide, or cementite, which is hard and brittle. In castings that are white iron throughout, however, the composition of iron is selected according to part size to ensure that the volume of metal involved can solidify rapidly enough to produce the white-iron structure.

The principal disadvantage of white iron is its brittleness. This can be reduced somewhat by reducing the carbon content or by thoroughly stress-relieving the casting to spheroidize the carbides in the matrix. However, these measures increase cost and reduce hardness. Chilling should not be confused with heat-treat hardening, which involves an entirely different metallurgical mechanism. White iron, so-called because of its very white structure, can be formed only by solidification. It will not soften except by extended annealing and it retains its hardness even above 538°C.

White irons are used primarily for applications requiring wear and abrasion resistance such as mill liners and shot-blasting nozzles. Other uses include railroad brake shoes, rolling-mill rolls, clay-mixing and brickmaking equipment, and crushers and pulverizers. Generally, plain (unalloyed) white iron costs less than other cast irons.

Compacted Graphite Iron

Until recently, compacted graphite iron (CGI), also known as vermicular iron, has been primarily a laboratory curiosity. Long known as an intermediate between gray and ductile iron, it possesses many of the favorable properties of each. However, because of process-control difficulties and the necessity of keeping alloy additions within very tight limits, CGI has been extremely difficult to produce successfully on a commercial scale. For example, if the magnesium addition varied by as little as 0.005%, results would be unsatisfactory.

Processing problems have been solved by an alloy-addition package that provides the essential alloying ingredients—magnesium, titanium, and rare earths—in exactly the right proportions. Strength of CGI parts approaches that of ductile cast iron. CGI also offers high thermal conductivity, and its damping capacity is almost as good as that of gray iron; fatigue resistance and ductility are similar to those properties in ductile iron. Machinability is superior to that of ductile iron, and casting yields are high because shrinkage and feeding characteristics are more like gray iron.

The combination of high strength and high thermal conductivity suggests the use of CGI in engine blocks, brake drums, and exhaust manifolds of vehicles. CGI gear plates have replaced aluminum in high-pressure gear pumps because of the ability of the iron to maintain dimensional stability at pressures above 10.3 MPa.

Malleable Iron

Malleable iron castings are often used for heavy-duty bearing surfaces in automobiles, trucks, railroad rolling stock, and farm and construction machinery. Pearlitic grades are highly wear resistant, with hardnesses ranging from 152 to over 300 Bhn. Applications are limited, however, to relatively thin-sectioned castings because of the high shrinkage rate and the need for rapid cooling to produce white iron.

High-Alloy Irons

High alloy-irons are ductile, gray, or white irons that contain 3% to more than 30% alloy content. Properties are significantly different from those of unalloyed irons. These irons are usually specified by chemical composition as well as by various mechanical properties.

White high-alloy irons containing nickel and chromium develop a microstructure with a martensite matrix around primary chromium carbides. This structure provides a high hardness with extreme wear and abrasion resistance. High-chromium irons (typically, about 16%) combine wear and oxidation resistance with toughness. Irons containing from 14% to 24% nickel are austenitic; they provide excellent corrosion resistance for nonmagnetic applications. The 35% nickel irons have an extremely low coefficient of thermal expansion and are also nonmagnetic and corrosion resistant.
Aluminum and Its Alloys

Aluminum and its alloys continue to grow in acceptance, particularly in the automotive industry. The electronics industry is another major user of cast aluminum for chassis, enclosures, terminals, etc.

Most metallic elements can be alloyed readily with aluminum, but only a few are commercially important—among them copper, lithium, magnesium, manganese, silicon, and zinc. Many other elements serve as supplementary alloying additions to improve properties and metallurgical characteristics.

Aluminum can be cast by virtually all of the common casting processes—particularly diecasting, sand mold, permanent mold, expendable pattern (lost foam) casting, etc.

Aluminum alloy castings are produced by virtually all commercial processes in a range of compositions possessing a wide variety of useful engineering properties.

- Al–Mg alloys offer excellent corrosion resistance, good machinability, and an attractive appearance when anodized. Careful gating and risering are required.
- Binary Al–Si alloys exhibit good weldability, high corrosion resistance, and low specific gravity.
- Al–Zn alloys have good machinability characteristics and age at room temperature to moderately high strengths in a relatively short period of time without solution heat treatment.
- Al–Sn alloys were developed for bearings and bushings with high load-carrying capacity and fatigue strength. Corrosion resistance is superior, but there is a susceptibility to hot cracking.
- Al–Li alloys are of recent commercial significance because of their good mechanical properties. They are believed to have many potential aerospace applications, and alloy development is widespread.

Copper Casting Alloys

These alloys are grouped according to composition by these general categories: pure copper, high-copper alloys, brasses, leaded brasses, bronzes, aluminum bronzes, silicon bronzes, Cu–Ni alloys, and Cu–Zn–Al alloys known as “nickel silvers.” The UNS designations for copper-base casting alloys range from C80000 through C99900.

In brasses, zinc is the principal alloying element. For cast brass, there are Cu–Zn–Sn alloys (red, semi-red, and yellow brasses), leaded and unleaded manganese bronze alloys (high-strength yellow brasses), and Cu–Zn–Si alloys.

In zinc, the principal alloying element in cast bronze alloys, which consist of four families: tin bronzes, leaded and highly leaded tin bronzes, Ni–Sn bronzes, and aluminum bronzes.

Zinc Alloys

Zinc has a low melting temperature and is readily and economically diecast. In recent years, zinc “foundry alloys” known as the ZA-8, ZA-12, and ZA-27 (containing 8%, 12%, and 27% aluminum, respectively) have been developed. They are finding wide application as gravity-cast sand and permanent mold castings as well as diecastings.

Zinc alloys can be cast in thin sections and with tight dimensional control. The principal alloys used for diecastings contain low percentages of magnesium, 3.9%–4.3% aluminum, and small controlled quantities of impurities such as tin, lead, and cadmium. Copper, and nickel are significant alloying additions.

Magnesium Alloys

The usefulness of magnesium, lightest of the commercial metals, is enhanced considerably by alloying. Magnesium can be used for sand and permanent mold castings and diecastings. Hot-chamber diecasting is a more recent development that is finding wider application each year. With the help of different heat treatments, alloy tensile strength ranges from 136 to 262 MPa, yield strengths from 69 to 262 MPa, and elongations from 1% to 15%.

Magnesium foundry technology has advanced significantly in recent years. Complex components are successfully made as sand castings, with wall thicknesses down to 3.5 mm and tolerances to ±0.6 mm for automotive, aircraft, and electronics applications.

Titanium Castings

Applications are broadening. Titanium is particularly suitable for withstanding corrosive environments or applications that take advantage of its light weight, high strength-to-weight ratio, and nonmagnetic properties. Long applied in military aircraft, titanium alloys are now solving problems in nonmilitary equipment and jewelry.

Metal Matrix Composites (MMC)

MMCs are an important new technology. These compounds consist of an inorganic reinforcement-particle filament, or whisker, in a metal matrix. Nearly all metals can be used as a matrix, but current applications center around aluminum, magnesium, and titanium. The lighter metals offer the best weight-to-strength ratio. MMCs also show improved wear resistance and allow adjustment of the coefficient of thermal expansion to meet varying requirements.

Superalloys

Superalloys are nickel, Fe–Ni, and cobalt-base alloys generally used at temperatures above about 538°C. The Fe–Ni-base superalloys are an extension of stainless steel technology and generally are wrought, whereas cobalt-base and nickel-base superalloys can be wrought or cast.

The more highly alloyed compositions normally are processed as castings. Fabricated cast structures can be built up by welding or brazing, but many highly alloyed compositions containing a high amount of hardening phase are difficult to weld. Properties can be controlled by adjustments in composition and by processing including heat treatment.

Cast Plastics

Plastics casting materials can be generally classified in two groups: (1) those resins, usually thermosetting, that are cast as liquids and cured by chemical cross-linking either at room temperature or elevated temperatures, and (2) thermoplastics that are supplied essentially in suspension or monomeric form and fused or polymerized at elevated temperatures.

Materials

Each casting resin has a unique combination of properties, such as heat resistance, strength, electrical properties, chemical resistance, cost, and shrinkage, which dictate their use for specific applications.
The most commonly used casting resins are phenolics, polyesters, and epoxies. Others are phenolics, acrylics, and urethane elastomers. Following is a brief description of each major type.

Phenolic Resins
Phenolic resins are used for low-cost parts requiring good electrical insulating properties, heat resistance, or chemical resistance. The average shelf life of this resin is about 1 month at 21.1°C. This can be extended by storing it in a refrigerator at 1.6°C–10°C. Varying the catalyst (according to the thickness of the cast) and raising the cure temperature to 93°C will alter the cure time from as long as 8 h to as short as 15 min.

Some shrinkage occurs in the finished casting (0.012–0.6 mm/mm), depending on the quantity of filler, amount of catalyst, and the rate of cure. Faster cure cycles produce a higher rate of shrinkage. Since the cure cycle can be accelerated, phenolics are used in short-run casting operations.

Cast phenolic parts are easily removed from the mold if the parting agents recommended by the supplier are used. Postcuring improves the basic properties of the finished casting.

Polyester Resins
Polyester resins are primarily used in large castings such as those required in the motion picture industry or for large sculptures for museums, parks, and display purposes. Since polyester shrinkage is about 0.024–0.032 mm/mm, castings are usually reinforced with glass cloth or mat and are generally cast in a flexible mold. Catalysts used to initiate the cure are peroxides or hydroperoxides and activators are cobalt naphthanate, alkyl mercaptans, or dialkyl aromatic amines. Recently, isophthalic polyesters have been introduced containing isophthalic acid, which provides improved heat, chemical, and impact resistance.

Clear polyester castings can be made using diallyl or triallyl cyanurate type polyester. Triallyl cyanurate polyesters are used in casting clear sheets because they have excellent scratch and heat resistance.

Acrylic Resins
The process involved in casting acrylic resins is complex and forms a specialized field. The methyl-methacrylate monomer contains inhibitors that must be removed before adding the catalyst. The resin must be cured under very accurately controlled conditions. The primary use of cast acrylics is in optically clear sheet, rod, or tube stock and in the embedment of specimens for museums and display of industrial parts, as well as for the embedment of decorative motifs in the jewelry industry.

Vinyls
Plasticized vinyls (polyvinyl chloride, or PVC) are used in industry in a variety of plastisol processing techniques, for example, slush casting and rotational casting. Electroformed molds are commonly used for this purpose. Since the conversion of the semiliquid vinyl plastisol to a solid consists of fusing the suspended vinyl particles to each other, it is only necessary to raise the temperature of the mass to 82°C–177°C according to the formulation. Cast-vinyl prototype parts can be produced that are comparable with molded parts.

Epoxy Resins
Most cast epoxy resins, other than those used in plastic tooling, are used in encapsulating electrical components and in casting prototype parts. The variations in properties possible make them very versatile materials. They can be made to have almost infinite shelf life, can be varied from a liquid to a thixotropic gel, and can be highly flexibilized by the addition of polylithanes and polyamides. They can be formulated to provide heat resistance up to 260°C.

Cure cycles may range from 1 to 16 h, at which time the casting is removed from the mold. Epoxy resins for casting are available in transparent water-white, semitransparent, and opaque formulations. Room-temperature cures are effected when aliphatic amines are added to the resin in exact amounts. Heat resistance of such systems is about 82°C. Cure is relatively rapid; therefore, exothermic reaction produces relatively high temperatures. Thus, casting must generally be limited in thickness.

Proprietary amine hardeners and epoxy resin systems are available whose heat resistance is about 121°C–177°C. The use of liquid anhydrides yields castings with heat resistance above 204°C. Such systems permit casting in large masses because the exothermic reaction and the curing temperatures are low (about 121°C). The pot life is several days, because elevated temperatures are required to initiate the reaction.

Several facts are basic in the use of these systems. Because it is necessary to use acidic catalysts in order to achieve heat resistance, castings tend to be more brittle; also, more difficulty is encountered in releasing the cast from the mold. The use of the proper release agent with a given resin system is necessary to overcome this tendency.

Cast Replica
In metallography, a reproduction of a surface in plastic made by the evaporation of the solvent from a solution of the plastic or by polymerization of a monomer on the surface. See also replica.

Cast Steels
The general nature and characteristics of cast steels are, in most respects, closely comparable to wrought steels. Cast and wrought steels of equivalent composition respond similarly to heat treatment and have fairly similar properties. A major difference between them is that cast steel is more isotropic in structure. Therefore, properties tend to be more uniform in all directions in contrast to wrought steel, whose properties generally vary, depending on the direction of hot or cold working.

Five basic steel groups are available:

1. Carbon steels
2. Low-alloy steels
3. High-alloy steels
4. Tool steels
5. Stainless steels

The most common types of steels used in castings are the carbon steels, which contain only carbon as their principal alloying element. Other elements are present in small quantities, including those added for deoxidation. Silicon and manganese in cast carbon steels typically range from 0.25% to about 0.8% silicon and 0.50% to 1% manganese, respectively.

Cast plain carbon steels can be divided into three groups—low, medium, and high carbon. However, cast steel is usually specified by mechanical properties, primarily tensile strength, rather than composition. Standard classes are 414, 483, 586, and 690 MPa. Low-carbon grades, used mainly in the annealed and normalized conditions, have tensile strength ranging from 380 to 448 MPa. Medium-carbon grades, annealed and normalized, range from 483 to 690 MPa. When quenched and tempered, strength exceeds 690 MPa.

Cast Replica
Ductility and impact properties of cast steels are comparable, on average, to those of wrought carbon steel. However, the longitudinal properties of rolled and forged steels are higher than those of cast steel. Endurance limit strength ranges between 40% and 50% of ultimate tensile strength.

By definition, low-alloy steels contain alloying elements, in addition to carbon, up to a total content of 8%. A casting containing more than 8% alloy content is classified as a high-alloy steel. Technically, tool steels and stainless steels are high-alloy steels but are normally classified separately. Small quantities of titanium and aluminum are also used for grain refinement in cast low-alloy steels.

Stainless steels are grouped in three classes: martensitic, ferritic, and austenitic. They are all more resistant to corrosion than plain carbon steels or lower alloy steels, and they contain either significant amounts of chromium or chromium and nickel. Cast stainless steel grades are designated in general as either heat resistant or corrosion resistant. Stainless steel castings are specified by ACI designations.

The C series of ACI stainless grades designates corrosion-resistant steels; the H series designates heat-resistant steels that are suitable for service temperatures in the 649°C–1204°C range. Typical casting applications for C-series grades are valves, pumps, and fittings. H-series grades are used for furnace parts, turbine engine components, and other high-temperature requirements.

Interest has renewed in cast duplex stainless steels because the 50% ferritic and 50% austenitic metallographic structure of these grades makes them extremely resistant to stress corrosion cracking. In addition, they have twice the yield strength of austenitic grades and may cost less.

Although the basic properties of cast duplex alloys are determined primarily by the 50/50 mixture of ferrite and austenite, the metallurgy can be complex because of the numerous carbides, nitrides, and intermetallic phases or compounds that can form. Ferrite formation is a function of cooling rate and chemistry, and austenizing temperature affects strength.

Hardenability of cast steels does not vary significantly from that of wrought steels of similar composition. The one principal difference between wrought and cast steels is the effect of the casting surface. It may contain scale and oxides and may not be chemically or structurally equivalent to the base metal; see Table C.6.

A few of the industries and some of the specific products that are being made from cast steel are: automotive (frames, wheels, gears); electrical manufacturing (rotors, bases, housings, frames, shafts); transportation (couplings, drawbars, brake shoes, wheel truck frames); marine (rotors, sterns, anchor chains, ornamental fittings, capstans); off-the-road equipment (crawler side frames, levers, shafts, tread links, turntables, buckets, dipper teeth); municipal (fire hydrants, catch basins, manhole frames and covers); miscellaneous (ingot and pig molds, rolling mill rolls, blast-furnace ingot buggies, engine housings, cylinder blocks and heads, crankshafts, flanges and valves).

**Cast Structure**

The metallographic structure of a casting evidenced by shape and orientation of grains and by segregation of impurities. Other features include grains that are very coarse, possibly cored or dendritic, extensive columnar grains at the exterior and large quantities of internal voids.

**Castability**

(1) A complex combination of liquid-metal properties and solidification characteristics that promotes accurate and sound final castings.

(2) The relative ease with which a molten metal flows through a mold or casting die.

**Castable**

In casting, a combination of refractory grain and suitable bonding agent that, after the addition of a proper liquid, is generally poured into place to form a refractory shape or structure which becomes rigid because of chemical action.

**Cast-Alloy Tool**

A cutting tool made by casting a cobalt-based alloy and used at machining speeds between those for high-speed steels and cemented carbide. Nominal compositions for two commercially available grades are as follows in Table C.7.

**Casting Copper**

Fire-refined tough pitch copper usually cast from melted secondary metal into ingot bars only, and used for making foundry castings but not wrought products.

**Casting Defect**

Any imperfection in a casting that does not satisfy one or more of the required design or quality specifications. This term is often used in a limited sense for those floors formed by improper casting solidification.

**Casting Section Thickness**

The wall thickness of the casting. Because the casting may not have a uniform thickness, the section thickness may be specified at a specific place on the casting. Also, it is sometimes useful to use the average, minimum, or typical wall thickness to describe the casting.

**Casting Shrinkage**

The amount of dimensional change per unit length of the casting as it solidifies in the mold or die and cools to room temperature after removal from the mold or die. There are three distinct types of casting shrinkage. Liquid shrinkage refers to the reduction in volume or liquid metal as it cools to the liquidus. Solidification shrinkage is the reduction in volume of metal from the beginning to the end of solidification. Solid shrinkage involves a reduction in volume of metal from the solidus to room temperature.

**Casting Strains**

Strains in a casting caused by casting stresses that develop as a casting cools.

**Casting Stresses**

Residual stresses set up when the shape of a casting impedes contraction of the solidified casting during cooling.

**Casting Thickness**

See casting section thickness.
Casting Volume
The total cubic units (mm$^3$ or in.$^3$) of cast metal in the casting.

Casting Yield
The weight of a casting(s) divided by the total weight of metal poured into the mold, expressed as a percentage.

Casting Wheel
A wheel carrying at its edge a number of molds which are filled as they pass beneath the molten metal stream. As the wheel rotates the molds are replaced or emptied if sufficiently cool.

Casting
Strength and performance of a cast part do not depend solely on part geometry. Proper alloy selection is crucial to a cost-effective casting design and trouble-free engineering and manufacturing. Materials
TABLE C.7
Two Cast-Alloy Tool Compositions

<table>
<thead>
<tr>
<th>Element</th>
<th>Tantung G, %</th>
<th>Tantung 144, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobalt</td>
<td>42–47</td>
<td>40–45</td>
</tr>
<tr>
<td>Chromium</td>
<td>27–32</td>
<td>25–30</td>
</tr>
<tr>
<td>Tungsten</td>
<td>14–19</td>
<td>16–21</td>
</tr>
<tr>
<td>Carbon</td>
<td>2–4</td>
<td>2–4</td>
</tr>
<tr>
<td>Tantalum or niobium</td>
<td>2–7</td>
<td>3–8</td>
</tr>
<tr>
<td>Manganese</td>
<td>1–3</td>
<td>1–3</td>
</tr>
<tr>
<td>Iron</td>
<td>2–5</td>
<td>2–5</td>
</tr>
<tr>
<td>Nickel</td>
<td>7a</td>
<td>7a</td>
</tr>
</tbody>
</table>

*a Maximum.

Castings
146

selection software has been developed to help meet the need for information about alloys. Because the packages are in a database format, users can search through the data to choose those materials that meet their requirements. Once the basic material selection has been made, three-dimensional (3-D) modeling, casting simulation, and finite-element analysis (FEA) software can be used to confirm the behavior of that material/part combination during manufacture and in service.

Rapid Prototyping
Computer technologies known as rapid prototyping allow manufacturers to fabricate 3-D models, prototypes, patterns, tooling, and production parts directly from computer-aided design (CAD) data in a fraction of the total time and cost of conventional methods. Several practical rapid prototyping systems are commercially available, and their use by OEM product parts designers as well as producers of cast metal parts and tooling shops are becoming widespread.

Each technology shares the same basic approach: A computer analyzes a 3-D CAD file that defines the object to be fabricated and “slices” the object into thin cross sections. The cross sections are then systematically recreated and combined to form a 3-D object.

Here’s a thumbnail sketch of how they work: Stereolithography recreates the object by sequentially solidifying layers of photoactive liquid polymer by exposing the liquid to ultraviolet light.

Ultimately, scientists hope to develop numerical simulations that provide enough information to optimize all the variables in a casting operation. To improve understanding of the process and to improve gating design, researchers use an x-ray system that makes images of the molten metal as it fills the mold. Computer codes that predict mechanical properties are then compared with experimental results and modified to match the behavior of specific alloys.

Metal-Casting Processes
Expendable molds are for use only once (sand castings); other molds (or dies) are made of metal (permanent molding and diecasting) and can be used repeatedly. The pattern must be removable from the mold without damage, and the casting must be removable from the mold or die without damage to either the die or the casting.

Sand Casting Processes
More than 80% of all castings made in the United States are produced by green sand molding. (The term green sand does not refer to color, but to the fact that a raw sand and binder mixture has been tempered with water.) Sand molding is a versatile metal-forming process that provides freedom of design with respect to size, shape, and product quality.

Permanent Molding
In permanent mold casting, which also is referred to as gravity diecasting, a metal mold (or die) consisting of at least two parts is used repeatedly, usually for components that require relatively high production. Molds usually are made of cast iron, although steel, graphite, copper, and aluminum have been used as mold materials with varying degrees of success.

When molten metal is poured into a permanent mold, it cools more rapidly than in a sand mold and produces a finer-grained structure, a sounder and denser casting, and enhanced mechanical properties.

Diecasting Process
The diecasting process is used widely for high production of zinc, lead, tin, aluminum, copper, and magnesium cast components of intricate design. Molten alloy is poured manually or automatically into a shot well and injected into the die under pressure. An important factor in diecasting machine operation is the locking force (in tons), in which case the die is firmly closed against the injection pressure exerted by the plunger as it injects the molten metal.

There are two basic types of diecasting machines—hot chamber and cold chamber. The hot-chamber machine makes shots automatically and is used for low-melting-point materials, such as zinc alloys. The cold-chamber method, for higher-melting-point materials, such as aluminum and magnesium, holds molten metal at a constant temperature in a holding furnace of the bailout type. Metal is poured into the shot well either by hand or by automatic devices.

Vacuum diecasting sometimes is used to evacuate the die cavity. Its objectives are reduction of porosity, assisting metal flow in thin sections, and improving surface finish while at the same time permitting the use of injection pressures lower than those normally applied.

It should be noted that the meanings of the term diecasting in the United States and in European usage are different. Diecasting in Europe is any casting made in a metal mold. Pressure diecasting in Europe is a casting made in a metal mold in which the metal is injected under high pressure. In the United States, this is simply “diecasting.” Gravity diecasting in Europe is a casting poured in a metal mold by gravity, with no application of pressure. In the United States, this is “permanent molding.”

Investment Casting
In investment casting, a ceramic slurry is poured around a disposable pattern (normally of modified paraffin waxes, but also of plastics) and allowed to harden to form a disposable mold. The pattern is destroyed when it melts out during the firing of the ceramic mold. Later, molten metal is poured into the ceramic mold, and after the metal solidifies, the mold is broken up to remove the casting.

Two processes are used to produce investment casting molds—the solid mold and the ceramic shell methods. The ceramic shell method has become the predominant production technique today. The solid investment process is used primarily to produce dental and jewelry castings. Ceramic shell molds are used primarily for the investment casting of carbon and alloy steels, stainless steels,
heat-resistant alloys, and other alloys with melting points above 1093°C. The process can be mechanized.

Almost any degree of internal and complexity can be accommodated, the only limitation is the state of the art in ceramic core manufacturing. Many problems inherent in producing a component by forging, machining, or multiple-piece fabricated assembly can be solved by utilizing the investment casting process. Sheet metal components, assembled by riveting, brazing, soldering, or welding, have been investment-cast as a single unit. Advantages realized include weight savings and better soundness.

**Shell Molding Process**

The essential feature of the shell, or Croning, process is the use of thin-walled molds and cores. Thermosetting resin-bonded silica sand is placed on a heated pattern for a predetermined length of time. Heating cures the resin, causing the sand grains to adhere to each other to form a sturdy shell that constitutes half the mold. Because of pattern costs, this method is best suited to volume production of cast metal components. The complete assembly is preheated to 177°C–204°C and the surface treated with a parting compound (silicone emulsion). The cured resin binders are nonhygroscopic, permitting prolonged storage of shell molds and allowing flexibility for production scheduling.

Castings made by the shell molding process may be more accurate dimensionally than conventional sand castings. A high degree of reproducibility as well as dimensional accuracy can be achieved with a minimum of dependence on the craftsmanship that sometimes is required with other molding processes. Only metal patterns and metal core boxes can be used in the shell process.

**Lost Foam Casting**

This process is also referred to as expanded polystyrene (EPS) molding, expandable pattern casting, evaporative foam casting, the full mold process, the cavityless casting process, and the cavityless EPS casting process. The process is an economical method of producing complex, close-tolerance castings, and uses unbonded sand; the pattern material is EPS.

The process involves attaching patterns to allow heating systems also made of EPS, then applying a refractory coating to the total assembly. Molten metal poured into the down-sprue vaporizes the polystyrene instantly and reproduces the pattern exactly. Gases formed from the vaporized pattern escape through the pattern coating, the sand, and the flask vents. A separate pattern is required for each casting.

To the designer, a major advantage of the process is that no cores are required. Cast-in features and reduced finishing stock usually are benefits of using the lost foam process. Inserts can be cast into the metal, and bimetallic castings can be made commercially.

**Vacuum Molding**

The vacuum molding process, popularly known as the V-process, is a sand molding process in which no binders are used to retain the shape of the mold cavity. Instead, unbonded sand is positioned between two sheets of thin plastic that are held in place by the application of a vacuum.

**Replicast Process**

The replicast process is said to overcome the shortcomings of another process that is prone to cause the formation of lustrous carbon defects in steel castings, as well as undesirable carbon pickup. Outstanding features of the replicast process include surface finish comparable to that obtainable on investment castings, elimination of cores through the use of core inserts in pattern-making tooling, improved casting yields because of absence of spruce and runners, and high quality levels with regard to casting integrity and dimensional accuracy.

**Other Casting Processes**

Other molding systems and casting processes are used to make metal castings. For example, certain types of castings are produced in centrifugal casting machines. Plaster mold casting is another specialized casting process used to produce nonferrous castings that is said to offer certain advantages over other processes.

Certain techniques are used to make castings in ceramic molds that are different from ceramic shell investment molding. The main difference is that the ceramic molds consist of a cope and a drag or, if the casting shape permits, a drag only.

Squeeze casting, also known as liquid-metal forging, is a process by which molten metal (ferrous or nonferrous) solidifies under pressure within closed dies positioned between the plates of a hydraulic press. The applied pressure and the instant contact of the molten metal with the die surface produce a rapid heat transfer condition that reportedly yields a pore-free, finer-grained casting with good mechanical properties.

**CAT Scanning**

See computed tomography.

**Cat’s Tongue (Surface)**

A rough surface texture comprised of strong spikes and ridges separated by deep tapered pits. The texture often has a “lay,” that is, it lies at an angle to the original surface and hence feels very rough when stroked in one direction but relatively smooth in the opposite direction, as does a cat’s tongue. As the damage progresses the texture becomes increasingly coarse although, in terms of weight loss, the rate of damage may fall. The effect is characteristic of damage caused by repeated impact particles including water droplets. The damage mechanism is not a form of cutting abrasion but results from a fatigue action by the repeated impacts producing surface mechanical damage.

**Catalyst**

A substance capable of changing the rate of a reaction without itself undergoing any net change. A substance that markedly speeds up a reaction is called a catalyst. Catalysts are used for liquid reactions such as the hydrogenation of fats and oils. Chemical catalysts are usually liquid compounds, especially such acids as sulfuric and hydrochloric.
Various metals, especially platinum and nickel, are used to catalyze or promote chemical action in the manufacture of synthetics. Nitrogen in the presence of oxygen can be “fixed” or combined in chemicals at ordinary temperatures by the use of ruthenium as a catalyst. Acids may be used to aid in the polymerization of synthetic resins. Mineral soaps are used to speed up the oxidation of vegetable oils. Cobalt oxide is used for the oxidation of ammonia. Cobalt and thorium are used for synthesizing gasoline from coal. All of these are classified as inorganic catalysts. Sometimes, more complex chemicals are employed, silicate of soda being used as a catalyst for high-octane gasoline. In the use of potassium persulfate, $K_2S_2O_8$, as a catalyst in the manufacture of some synthetic rubbers, the material releases 5.8% active oxygen, and it is the nascent oxygen that is the catalyst. Sodium methylate, also called sodium methoxide, CH$_3$·O·Na, used as a catalyst for ester-exchange reactions in the rearrangement of edible oils, is a white powder soluble in fats but violently decomposed in water. Transition-metal complexes, dispersed uniformly in solution, are called homogeneous catalysts. The most common ones are organometallic complexes, such as the carboxyls. They are more resistant to poisoning than solid heterogeneous catalysts, and they are highly active, specific, and selective. Magnetite, a magnetic iron ore, is used as a catalyst in the synthesis of ammonia. In a system from M.W. Kellogg Co., ruthenium, supported on a proprietary graphite structure, is more active, increasing ammonia production by 12%–16% over magnetite.

Metalloenes, organometallic coordination compounds obtained as cyclopentadienyl derivatives of a transition metal or metal hydride, are recent catalysts in the production of various plastics. Also referred to as single-site catalysts, they allow closer control of molecular weight and comonomer distribution, permitting monomers and comonomers previously considered incompatible to be combined. They also allow production of plastics in iso-tactic and syndiotactic forms and have been applied to polyethylene, ethylene copolymers, ethylene terpolymers (including ethylene–propylene–syndiotactic forms and have been applied to polyethylene, ethylene comonomers, ethylene terpolymers (including ethylene–propylene–diene elastomers), polypropylene, and polystyrene.

Aluminum chloride, AlCl$_3$, in gray granular crystals, is used as a catalyst for high-octane gasoline and synthetic rubber and in the synthesis of dyes and pharmaceuticals. Antimony trichloride, SbCl$_3$, is a yellowish solid, used as a catalyst in petroleum processing to convert normal butane to isobutane. Bead catalysts of activated alumina have the alumina contained in beads of silica gel.

Molecular sieve zeolites are crystalline aluminosilicates of alkali and alkali-earth metals. The aluminum and silicon atoms form regular tetrahedral structures that have large voids interconnected by open three-dimensional channels. The microporous may amount to 50% of the volume, resulting in crystals with some of the highest internal surface areas. The alkaline cations are mobile and may be ion-exchanged with metals with catalytic properties. Only reactants of the right molecular size may enter the channels and be catalyzed by the metal cations in the voids. As molecular sieves, zeolite catalysts are used as desiccants and absorbers and drying and purifying gases. Natural zeolites are more effective than synthetic ones. Catalyst carriers are porous inert materials used to support the catalysts, usually in a bed through which a liquid or gas may flow. Materials used are generally alumina, silica carbide, or mullite, and they are usually in the form of graded porous granules or irregular polsasurface pellets. High surface area, low bulk density, and good adherence of the catalyst are important qualities. Pellets are bonded with a ceramic that fuses around the granules with minute necks that hold the mass together as complex silicates and aluminates with no trace elements exposed to the action of a catalyst or chemicals. Catalyst carriers are usually bonded to make them about 40% porous. The pellets may be 15 mesh finer, or they may be in sizes as large as 1 in. (2.5 cm). Platinum, palladium, and rhodium supported on activated alumina carriers are used in the catalytic converters of automobiles to clean up exhaust gases. A catalyst of precious metals supported on zeolite removes hydrocarbons, carbon monoxide, and nitrogen oxides from auto exhaust gases even in the presence of excess oxygen, as is the case for lean-burn engines. Developed by Mazda Motor of Japan, it could improve fuel efficiency of such engines by 5%–8%.

### Catastrophic Failure

Sudden failure of a component or assembly that frequently results in extensive secondary damage to adjacent components or assemblies.

### Catastrophic Period

In cavitation or liquid impingement erosion, a stage during which the erosion rate increases so dramatically that continued exposure threatens or causes gross disintegration of the exposed surface.

### Catastrophic Wear

Sudden surface damage, deterioration, or change of shape caused by wear to such an extent that the life of the part is appreciably shortened or action is impaired.

### Catchment Efficiency

See collection efficiency.

### Catenary

A measure of the difference in length of reinforcing strands in a specified length of roving caused by unequal tension. The tendency of some strands in a taut horizontal roving to sag more than the others.

### Cathode

The negative electrode of an electrolytic cell at which reduction is the principal reaction. (Electrons flow toward the cathode and the external circuit.) Typical cathodic processes are cations taking up electrons and being discharged, oxygen being reduced, and the reduction of an element or group of elements from a higher to a lower valence state. Contrast with anode.

### Cathode Compartment

In an electrolytic cell, the enclosure formed by a diaphragm around the cathode.

### Cathode Copper

Copper in slab form produced by electrolytic refining. It is subsequently re-melted to produce high conductivity grades such as electrolytic tough pitch, high conductivity copper, and oxygen-free high conductivity copper. It is also the basis for high conductivity copper castings and high conductivity alloys.

### Cathode Efficiency

Current efficiency at the cathode.
Cathode Film

The portion of solution in immediate contact with the cathode during electrolysis.

Cathode-Ray Tube (CRT)

An electronic device in which a stream of electrons, that is, the negatively charged cathode ray, is formed and directed at a fluorescent screen. The path of the ray is deflected by electromagnetic coils to produce the screen display.

Cathodic Cleaning

Electrolytic cleaning in which the work is the cathode.

Cathodic Corrosion

Corrosion resulting from a cathodic condition of a structure usually caused by the reaction of an amphoteric metal and the alkaline products of electrolysis.

Cathodic Disbondment

The destruction of adhesion between a coating and its substrate by products of a cathodic reaction.

Cathodic Etching

See ion etching.

Cathodic Inhibitor

A corrosion protection, a chemical substance or mixture that prevents or reduces the rate of the cathodic or reduction reaction.

Cathodic Polarization

The change of the electrode potential in the active (negative) direction due to current flow. See also polarization.

Cathodic Protection

(1) Reduction of corrosion rate by shifting the corrosion potential of the electrode toward a less oxidizing potential by applying an external electromotive force. (2) Partial or complete protection of a metal from corrosion by making it a cathode, using either a galvanic or an impressed current. (3) Electrical currents can develop the metal components exposed to wet environments and corrosion will occur at the end anodic areas (see electrochemistry). However, attack may be prevented by inducing a reverse current that causes the component to be cathodic with respect to some external anode. One technique is to impose a DC electrical current from an external power source—termed Impressed Current cathodic protection. Alternatively, the component may be protected by attaching to it another metal that is more anodic. For example, steel was protected by zinc either in the form of plating, (galvanizing) or as large blocks of zinc bolted to, or buried close to, and in electrical circuit with, the component. These anodes will be progressively consumed by corrosion, hence the term Sacrificial Cathodic Protection but the rate of anode loss, in practical cases, is acceptably economic and the main component will be preserved. Contrast with anodic protection.

Cathodic Reaction

Electrode reaction equivalent to a transfer of negative charge from the electronic to the ionic conductor. A cathode reaction is a reduction process.

Cathodoluminescence

A radioactive transition wherein low-energy light photons are really storing electron irradiation.

Catholyte

The electrolyte adjacent to the cathode of an electrolytic cell.

Cation

A positively charged ion that migrates through the electrolyte toward the cathode under the influence of a potential gradient. See also anion and ion.

Cationic Detergent

A detergent in which the cation is the active part.

Caul

In adhesive bonding, a sheet of material employed singly or in pairs in the hot or cold pressing of assemblies being bonded. A caul is used to protect either the faces of the assembly or the press platens, or both, against marring and staining in order to prevent sticking, facilitate press loading, impact a desired surface texture or finish, and provide uniform pressure distribution. A caul may be made of any suitable material such as aluminum, stainless steel, hardboard, fiberboard, or plastic, the length and width dimensions generally being the same as those of the plates of the press where it is used.

Caul Plates

In fabrication of composites, smooth metal plates, free of surface defects, that are the same size and shape as a composite lay-up, and that contact the lay-up during the curing process in order to transmit normal pressure and temperature, and to provide a smooth surface on the finish laminate.

Cauliflower

A growth of material on the exterior, particularly the top, of an ingot as a result of inverse segregation.

Caulk

See caulking.

Caulk Weld

See preferred term seal weld.
**Caustic**

(1) Burning or corrosive. (2) A hydroxide of a light metal, such as sodium hydroxide or potassium hydroxide.

**Caustic Attack**

Generally, any corrosion caused by caustic alkali. The term often refers specifically to the attack on the water side of steam generating tubes and power plants. The cause is excessive sodium hydroxide resulting either from the introduction of quantities well in excess of that required for normal feed water treatment or from local concentration affects. Factors promoting concentration are very high levels of heat input and bore irregularities such as deposits or the crevice produced when the internal projection of a flash butt weld is smeared along the bore rather than being cleanly cut away. When such factors are present, the tube bore facing toward the fire develops a persistent steam blanket rather than the normal bubbles of steam which can be swept away. The caustic concentrates in this area and the normally protective magnetite film is disrupted leading to severe corrosion and in some cases to hydrogen embrittlement. In some cases, the corrosive attack produces deep grooves along the tube leading to terms such as *caustic grooving* or *gouging*.

**Caustic Cracking**

A form of *stress-corrosion cracking* most frequently encountered in carbon steels or iron–chromium–nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of (200°C–250°C) (400°F–480°F). Also known as caustic embrittlement.

**Caustic Dip**

A strongly alkaline solution into which metal is immersed for etching, for neutralizing acid, or for removing organic materials such as greases or paints.

**Caustic Embrittlement**

(1) An obsolete historical term denoting a form of *stress-corrosion cracking* most frequently encountered in carbon steels or iron–chromium–nickel alloys that are exposed to concentrated hydroxide solutions at temperatures of (200°C–250°C) (400°F–480°F). (2) Cracking, intergranular stress corrosion cracking of steel in caustic, alkaline, solutions. It usually only occurs above about 70°C and in fairly high alkaline conditions. However, it can be a serious problem in cases where the solution is now only 2 weeks to have any significant effect but where an inadvertent concentration mechanism is active. For example, to allow a concentration to develop in the leak path interface as water evaporates at the exterior face.

**Caustic Quenching**

Quenching with aqueous solutions of 5%–10% sodium hydroxide.

**Caustic Soda**

Sodium hydroxide.

**Cavitation**

The formation and collapse, within a liquid of cavities or bubbles that contain vapor or gas or both. In general, cavitation originates from a decrease in the static pressure in the liquid. It is distinguished in this way from boiling, which originates from an increase in the liquid temperature. There are certain situations where it may be difficult to make a clear distinction between cavitation in boiling, and the more general definition that is given here is therefore to be preferred. In order to erode a solid surface by cavitation, it is necessary for the cavitation bubbles to collapse on or close to that surface.

**Cavitation Cloud**

A collection of a large number of cavitation bubbles. The bubbles in a cloud are small, typically less than 1 mm in cross section.

**Cavitation Corrosion**

A process involving conjoint corrosion and cavitation.

**Cavitation Damage**

The degradation of a solid body resulting from its exposure to cavitation. This may include loss of material, surface deformation, or changes in properties or appearance.

**Cavitation Erosion/Damage**

The removal of metal from an immersed surface as a result of local severe pressure fluctuations associated with turbulent flow. Water subjected to a sudden pressure drop will form cavities, i.e., bubbles. These rapidly collapse producing shockwaves which damage adjacent surfaces by various mechanisms including a direct mechanical action, a fatigue action or by disrupting protective films. The development of local pits exacerbates cavity quality and size so metal loss is accelerated. Pumps and propellers are commonly affected.

**Cavitation Tunnel**

A flow cavitation test facility in which liquid is pumped through a pipe or tunnel, and cavitation is induced in a test section by conducting the flow through a constriction, or around an obstacle, or a combination of these.

**Cavity (Metals)**

The mold or die impression that gives a casting its external shape.

**Cavity (Plastics)**

The space inside a mold into which a resin or molding compound is poured or injected. The female portion of a mold. The portion of the mold that encloses the molded article (often referred to as the die). Depending on a number of such depressions, molds are designated as single cavity or multiple cavity.
Cavity Retainer Plates

In forming of plastics, plates in a mold that hold the cavities and forces. These plates are at the mold parting line and usually contain the guide pins and bushings. Also called force retainer plates.

CCP

Cubic close-packed crystallographic structure. Same as face-centered cubic.

CCT Diagram (Continuous Cooling Transformation Diagram)

See Isothermal Transformation Diagram.

Ceiling

The maximum that should not be exceeded in the process in question.

Cell

In honeycomb core, a cell is a single honeycomb unit, usually in a hexagonal shape.

Cell (Electrochemistry)

Electrochemical system consisting of an anode and a cathode immersed in an electrolyte. The anode and cathode may be separate metals or dissimilar areas on the same metal. The cell includes the external circuit, which permits the flow of electrons from the anode toward the cathode. See also electrochemical cell.

Cell (Plastics)

A single cavity formed by gaseous displacement in a plastic material. See also cellular plastic.

Cell Feed

The material supplied to the cell in the electrolytic production of metals.

Cell Size

The diameter of an inscribed circle within a cell of honeycomb core.

Cellular

A network comprising a large number of associated cells of broadly similar characteristics.

Cellular Adhesive

Synonym for foamed adhesive.

Cellular Plastic

A plastic with greatly decreased density because of the presence of numerous cells or bubbles dispersed throughout its mass. See also cell (plastics), foamed plastics, and syntactic cellular plastics.

Cellulose

Cellulose is the main constituent of the structure of plants (natural polymer) that, when extracted, is employed for making paper, plastics, and in many combinations. Cellulose is made up of long-chain molecules in which the complex unit C₆H₁₀O₅ is repeated as many as 2000 times. It consists of glucose molecules with three hydroxyl groups for each glucose unit.

Cellulose is the most abundant of the nonprotein natural organic products. It is highly resistant to attack by the common microorganisms. However, the cellulose digests it easily, and this substance is used for making paper pulp, for clarifying beer and citrus juices, and for the production of citric acid and other chemicals from cellulose. Cellulose is a white powder insoluble in water, sodium hydroxide, or alcohol, but it is dissolved by sulfuric acid.

One of the simplest forms of cellulose used industrially is regenerated cellulose, in which the chemical composition of the finished product is similar to that of the original cellulose. It is made from wood or cotton pulp digested in a caustic solution. Cellophane is a regenerated cellulose in thin sheets for wrapping and other special uses include windings on wire and cable.

Cellulose Plastics

For plastics, pure cellulose from wood pulp or cotton linters (pieces too short for textile use) is reacted with acids or alkalis and alkyl halides to produce a basic flake. Depending upon the reactants, any one of four esters of cellulose (acetate, propionate, acetate butyrate, or nitrate) or a cellulose ether (ethyl cellulose) may result. The basic flake is used for producing both solvent cast films and molding powders.

Ethyl cellulose plastics are thermoplastic and are noted for their ease of molding, lightweight, and good dielectric strength, 15–20.5 × 10⁶ V/m, and retention of flexibility over a wide range of temperature from −57°C to 66°C, the softening point. They are the toughest, the lightest, and have the lowest water absorption of the cellulosic plastics. But they are softer and lower in strength than cellulose-acetate plastics. Typical ethyl cellulose applications include football helmets, equipment housings, refrigerator parts, and luggage.

For molding powders, the flake is then compounded with plasticizers, pigments, and sometimes other additives. At this stage of manufacture, the plastics producer is able to adjust hardness, toughness, flow, and other processing characteristics and properties. In general, these qualities are spoken of together as flow grades. The flow of a cellulose plastic is determined by the temperature at which a specific amount of the material will flow through a standard orifice under a specified pressure. Manufacturers offer cellulosic molding materials in a large number of standard flow grades, and, for an application requiring a nonstandard combination of properties, are often able to tailor a compound to fit. Cellulose can be made into a film (cellophane) or into a fiber (rayon), but it must be chemically modified to produce a thermoplastic material.

Cellulosics are synthetic plastics, but they are not synthetic polymers; see Table C.8.

Because the cellulosics can be compounded with many different plasticizers in widely varying concentrations, property ranges are broad. These materials are normally specified by flow, defined in American Society for Testing and Materials (ASTM) D509, which is controlled by plasticizer content. Hard flows (low plasticizer content) are relatively hard, rigid, and strong. Soft flows (higher plasticizer content) are tough, but less hard, less rigid, and less strong. They also process at lower temperatures. Thus, within available

...
property ranges listed, no one formulation can provide all properties to the maximum degree. Most commonly used formulations are in the middle flow ranges.

Molded cellulosic parts can be used in service over broad temperature ranges and are particularly tough at very low temperatures. Ethyl cellulose is outstanding in this respect. These materials have low specific heat and low thermal conductivity—characteristics that give them a pleasant feel.

Dimensional stability of butyrate, propionate, and ethyl cellulose is excellent. Plasticizers used in these materials do not evaporate significantly and are virtually immune to extraction by water. Water absorption (which causes dimensional change) is also low, with that of ethyl cellulose the lowest. The plasticizers in acetate are not as permanent as those in other plastics, however, and water absorption of this material is slightly higher.

Butyrate and propionate are highly resistant to water and most aqueous solutions except strong acids and strong bases. They resist nonpolar materials such as aliphatic hydrocarbons and ethers, but they swell or dissolve in low-molecular-weight polar compounds such as alcohols, esters, and ketones, as well as in aromatic and chlorinated hydrocarbons. Acetate is slightly less resistant than butyrate and propionate to water and aqueous solutions, and slightly more resistant to organic materials. Ethyl cellulose dissolves in all the common solvents for this polymer, as well as in such solvents as cyclohexane and diethyl ether. Like the cellulose esters, ethyl cellulose is highly resistant to water.

Although unprotected cellulosics are generally not suitable for continuous outdoor use, special formulations of butyrate and propionate are available for such service. Acetate and ethyl cellulose are not recommended for outdoor use.

<table>
<thead>
<tr>
<th>Table C.8</th>
<th>Properties of Cellulosics</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM or UL Test</td>
<td>Property</td>
</tr>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>D792</td>
<td>Specific gravity</td>
</tr>
<tr>
<td>D792</td>
<td>Specific volume (in.³/lb)</td>
</tr>
<tr>
<td>D570</td>
<td>Water absorption, 24 h, 1/8 in. thick (%)</td>
</tr>
<tr>
<td><strong>Mechanical</strong></td>
<td></td>
</tr>
<tr>
<td>D638</td>
<td>Tensile strength (psi)</td>
</tr>
<tr>
<td>D638</td>
<td>Tensile modulus (10⁵ psi)</td>
</tr>
<tr>
<td>D790</td>
<td>Flexural strength (psi)</td>
</tr>
<tr>
<td>D790</td>
<td>Flexural modulus (10⁵ psi)</td>
</tr>
<tr>
<td>D256</td>
<td>Impact strength, Izod (ft lb/in. of notch)</td>
</tr>
<tr>
<td>D785</td>
<td>Hardness, Rockwell R</td>
</tr>
<tr>
<td><strong>Thermal</strong></td>
<td></td>
</tr>
<tr>
<td>C177</td>
<td>Thermal conductivity (10⁻¹⁴ cal cm/s cm² °C)</td>
</tr>
<tr>
<td>D696</td>
<td>Coefficient of thermal expansion (10⁻⁴ in./in. °C)</td>
</tr>
<tr>
<td>D648</td>
<td>Deflection temperature (°F)</td>
</tr>
<tr>
<td></td>
<td>At 66 psi</td>
</tr>
<tr>
<td>UL94</td>
<td>Flammability rating</td>
</tr>
<tr>
<td><strong>Electrical</strong></td>
<td></td>
</tr>
<tr>
<td>D149</td>
<td>Dielectric strength (V/mil) Short time, 1/8 in. thick</td>
</tr>
<tr>
<td>D150</td>
<td>Dielectric constant at 1 kHz</td>
</tr>
<tr>
<td>D150</td>
<td>Dissipation factor at 1 kHz</td>
</tr>
<tr>
<td>D257</td>
<td>Volume resistivity (Ω cm) at 73°F, 50% RH</td>
</tr>
<tr>
<td>D495</td>
<td>Arc resistance(s)</td>
</tr>
<tr>
<td><strong>Optical</strong></td>
<td></td>
</tr>
<tr>
<td>D542</td>
<td>Refractive Index</td>
</tr>
<tr>
<td>D1003</td>
<td>Transmittance (%)</td>
</tr>
</tbody>
</table>


* At 500 V/s rate of rise.
* For 1/8 in. thick specimen.
Applications

Acetate applications include extruded and cast film and sheet for packaging and thermoforming.

Cellulose Acetate

Cellulose acetate is an amber-colored, transparent material made by the reaction of cellulose and acetic acid or acetic anhydride in the presence of sulfuric acid.

It is thermoplastic and easily molded. The molded parts or sheets are tough, easily machined, and resistant to oils and many chemicals. In coatings and lacquers, the material is adhesive, tough, and resilient, and does not discolor easily. Cellulose acetate fiber for rayons can be made in fine filaments that are strong and flexible, nonflammable, mildew proof, and easily dyed. Standard cellulose acetate for molding is marketed in flake form.

In practical use, cellulose acetate moldings exhibit toughness superior to most other general-purpose plastics. Flame-resistant formulations are currently specified for small appliance housings and for other uses requiring this property. Uses for cellulose acetate molding materials include toys, buttons, knobs, and other parts where the combination of toughness and clear transparency is a requirement.

Extruded film and sheet of cellulose acetate packaging materials maintain their properties over long periods. Here also the toughness of the material is advantageously used in blister packages, skin packs, window boxes, and over wraps. It is a breathing wrap and is solvent and heat sealable.

Large end uses for cellulose acetate films and sheets include photographic film base, protective cover sheets for notebook pages and documents, index tabs, sound recording tape, as well as the laminating of book covers. The grease resistance of cellulose acetate sheet allows its use in packaging industrial parts with enclosed oil for protection.

For eyeglass frames, cellulose acetate is the material in widest current use. Because fashion requires varied and sometimes novel effects, sheets of clear, pearlescent, and colored cellulose acetate are laminated to make special sheets from which optical frames are fabricated.

The electrical properties of cellulosic films combined with their easy bonding, good aging, and available flame resistance bring about their specification for a broad range of electrical applications. Among these are as insulations for capacitors; communications cable; oil windings; in miniaturized components (where circuits may be vacuum metallized); and as fuse windows.

Cellulose triacetate is widely used as a solvent cast film of excellent physical properties and good dimensional stability. Used as photographic film base and for other critical dimensional work such as graphic arts, cellulose triacetate is not moldable.

Cellulose Propionate

Cellulose propionate, commonly called “CP” or propionate, is made by the same general method as cellulose acetate, but propionic acid is used in the reaction. Propionate offers several advantages over cellulose acetate for many applications. Because it is “internally” plasticized by the longer-chain propionate radical, it requires less plasticizer than is required for cellulose acetate of equivalent toughness.

Cellulose propionate absorbs much less moisture from the air and is thus more dimensionally stable than cellulose acetate. Because of better dimensional stability, cellulose propionate is often selected where metal inserts and close tolerances are specified.

Largest-volume uses for cellulose propionate are as industrial parts (automotive steering wheels, armrests, and knobs, etc.), telephones, toys, findings, ladies’ shoe heels, pen and pencil barrels, and toothbrushes.

Cellulose Acetate Butyrate

Commonly called butyrate or CAB, it is somewhat tougher and has lower moisture absorption and a higher softening point than acetate. CAB is made by the esterification of cellulose with acetic acid and butyric acid in the presence of a catalyst. It is particularly valued for coatings, insulating types, varnishes, and lacquers.

Special formulations with good weathering characteristics plus transparency are used for outdoor applications such as signs, light globes, and lawn sprinklers. Clear sheets of butyrate are available for vacuum-forming applications. Other typical uses include transparent dial covers, television screen shields, tool handles, and type-writer keys. Extruded pipe is used for electric conduits, pneumatic tubing, and low-pressure waste lines. Cellulose acetate butyrate also is used for cable coverings and coatings. It is more soluble than cellulose acetate and more miscible with gums. It forms durable and flexible films. A liquid cellulose acetate butyrate is used for glossy lacquers, chemical-resistant fabric coatings, and wire-screen windows. It transmits ultraviolet light without yellowing or having and is weather-resistant.

Cellulose Acetate Propionate

This substance is similar to butyrate in both cost and properties. Some grades have slightly higher strength and modulus of elasticity. Propionate has better molding characteristics, but lower weatherability than butyrate. Molded parts include steering wheels, fuel filter bowls, and appliance housings. Transparent sheeting is used for blister packaging and food containers.

Cellulose Nitrate

Cellulose nitrates are materials made by treating cellulose with a mixture of nitric and sulfuric acids, washing free of acid, bleaching, stabilizing, and dehydrating. For sheets, rods, and tubes it is mixed with plasticizers and pigments and rolled or drawn to the shape desired. The lower nitrates are very inflammable, but they do not explode like the high nitrates, and they are the ones used for plastics, rayons, and lacquers, although their use for clothing fabrics is restricted by law. The names cellulose nitrate and pyroxylin are used for the compounds of lower nitration, and the term nitrocellulose is used for the explosives.

Cellulose nitrate is the toughest of the thermoplastics. It has a specific gravity of 1.35–1.45, tensile strength of 41–52 MPa, elongation 30%–50%, compressive strength 137–206 MPa, Brinell hardness 8–11, and dielectric strength 9.9–21.7 × 106 V/m. The softening point is 71°C, and it is easy to mold and easy to machine. It also is readily dyed to any color. It is not light stable, and is therefore no longer used for laminated glass. It is resistant to many chemicals, but has the disadvantage that it is inflammable. The molding is limited to pressing from flat shapes.

Among thermoplastics, it is remarkable for toughness. For many applications today, however, cellulose nitrate is not practical because of serious property shortcomings: heat sensitivity, poor outdoor aging, and very rapid burning.

Cellulose nitrate cannot be injection-molded or extruded by the nonsolvent process because it is unable to withstand the temperatures these processes require. It is sold as films, sheets, rods, or tubes, from which end products may then be fabricated.

Cellulose nitrate yellows with age; if continuously exposed to direct sunlight, it yellows faster and the surface cracks. Its rapid burning must be considered for each potential application to avoid unnecessary hazard.
The outstanding toughness properties of cellulose nitrate lead to its continuing use in such applications as optical frames, shoe eyelets, ping-pong balls, and pen barrels.

**Cellulosic Electrode (for Welding)**

See electrode (welding).

**Cellulosic Plastics**

Plastics based on cellulose compounds, such as esters (cellulose acetate) and ethers (ethyl cellulose). See Table C.8.

**Celsius**

The SI recommended scale of temperature based on reference points including 0°C as a freezing point of water and 100°C as the boiling point of water. It is essentially identical to centigrade.

**Cement**

Cement is a synthetic mineral mixture that, when ground to a powder and mixed with water, forms a stone-like mass. This mass results from a series of chemical reactions whereby the crystalline constituents hydrate, forming a material of high hardness that is extremely resistant to compressive loading. The main uses of cement are in civil engineering, for which, since the late nineteenth century, it has become indispensable.

The history of cement dates back to the Romans, who found that mixtures of volcanic ash, lime, and clay would harden when wet, and who used it extensively to build structures. In 1757, it was found that burned and ground high calcific clays would harden when placed in water. In 1824, a patent was granted to a British bricklayer who formulated a new type of cement with improved hardness. Because the color of the material reminded him of the limestone on the Isle of Portland, he named the product portland cement. This cement was made by lightly calcining small batches of lime and clay and grinding the product of fine powder.

The modern manufacturing process is very basic and has not been radically changed since its inception except for the use of computer-controlled equipment, which has greatly improved the consistency of the final product. The four basic cement processing operations are: (1) quarrying and crushing of raw materials, (2) grinding to high fineness and carefully proportioning the mineral constituents, (3) pyroprocessing the raw materials in a rotary calciner; and (4) cooling and grinding the calcined product, or clinker, to obtain a fine powder.

There are four main compounds that compose portland cement: tricalcium silicate, 3CaO·SiO₂ (C₃S); dicalcium silicate, 2CaO·SiO₂ (C₂S); tricalcium aluminate, 3CaO·Al₂O₃ (C₃A); and tetracalcium aluminoferrite, 4CaO·Al₂O₃·Fe₂O₃ (C₄AF). In the United States, Portland cements are manufactured to comply with the ASTM Standard Specification for Portland Cement, ASTM C150. This specification defines five main types of portland cement. Type I, which is made in the greatest quantity, is intended for general-purpose use when the special properties of the other types are not required. The special properties of the other types when used in concrete are: Type II, moderate sulfate resistance or moderate heat of hydration; Type III, high early strength; Type IV, low heat of hydration; Type V, high sulfate resistance. The chemical and physical differences between the types that produce their special properties lie in the proportions of the cement compounds and in the fineness to which the cement is ground.

**Oxchloride cement, or Sorel cement,** is composed of magnesium chloride, MgCl₂, and calcined magnesia. It is strong and hard and, with various fillers, is used for floors and stucco. Magnesia cement is magnesium oxide, prepared by heating the chloride or carbonate to redness. When mixed with water, it sets to a friable mass but of sufficient strength for covering steam pipes or furnaces. It is usually mixed with asbestos fibers to give strength and added heat resistance. The term 85% magnesia means 85% magnesia cement and 15% asbestos fibers. The cement will withstand temperatures up to 600°F (316°C).

**Keene's cement,** also known as flooring cement and tiling plaster, is a gypsum cement. It is made by burning gypsum at about 1100°F (593°C), to drive off the chemically combined water, grinding to a fine powder, and adding alum to accelerate the set. It will keep better than ordinary gypsum cement, has high strength, is white, and takes a good polish. Parian cement is similar, except that borax is used instead of alum. Martin's cement is made with potassium carbonate instead of alum. These cements are also called hard-finish plaster, and they will set very hard and white. They are used for flooring and to imitate tiling. An ancient natural cement is pozzolana cement. It is a volcanic material found near Pozzuoli, Italy, and in several other places in Europe. It is a volcanic lava modified by steam or gases so that it is powdery and has acquired hydraulic properties. The chief components are silica and alumina, and the color varies greatly, being white, yellow, brown, or black. It has been employed as a construction cement since ancient times. Slag cement is made by grinding blast-furnace slag with portland cement. Pozzolans are siliceous materials which will combine with lime in the presence of water to form compounds having cementing properties. Fly ash is an artificial pozzolan composed principally of amorphous silica with varying amounts of the oxides of aluminium and iron and traces of other oxides. It is a fine, dark powder of spheroid particles produced as the by-product of combustion of pulverized coal, and collected at the base of the stack. As an admix, it improves the workability of concrete, and in large amounts its pozzolanic action adds to the compressive strength. A fire-resistant cement, developed by Arthur D. Little, Inc., is made of magnesium oxychlorides and magnesium oxysulfates. This inorganic resin foam cement contains 40%–50% bond water that is released when the material is exposed to high temperatures and absorbs heat. It is said not to burn, smoke, or produce poisonous fumes when subjected to a direct flame.

**Cement Copper**

In pure copper recovered by chemical deposition when iron (most often shredded steel scrap) is brought into prolonged contact with a dilute copper sulfate solution.

**Cementation**

The introduction of one or more elements into the outer portion of a metal object by means of the fusion at high temperature. See carburizing.

**Cementation Process**

An obsolete process in which wrought iron-activated charcoal is heated at about 900°C for a few days allowing carbon to diffuse into the low carbon iron to produce steel.
Cemented Carbides

Referred to as hard metals, belong to a class of hard, wear-resistant, refractory materials in which the hard carbide particles are bound together, or cemented, by a soft and ductile metal binder. The first cemented carbide produced was tungsten carbide (WC) with a cobalt binder. Over the years, the basic WC–Co material has been modified to produce a variety of cemented carbides, which are used in a wide range of applications, including metal cutting, mining, construction, rock drilling, metal-forming, structural components, and wear parts. Tungsten carbide-based materials with nickel or steel binders have also been produced for specialized applications.

Tungsten carbides are manufactured by powder metallurgy process consisting of (1) processing of the ore in the preparation of the WC powder, (2) preparation (ball milling) of WC powders and grade (alloying) powders, (3) the addition of suitable binder material, (4) powder consolidation, and (5) sintering of the compacted part at temperatures between 1300°C and 1600°C (2370°F and 2910°F), most often in vacuum. The sintered product can be directly used or can be ground, polished, and coated to suit a given application.

Approximately 50% of all carbide production is used for machining applications, and a wide variety of compositions are available. “Straight” grades, which consist of WC particles bonded with cobalt, generally contain 3%–12% Co and carbide grain sizes range from 0.5 to >5 μm. Alloy grades, or steel-cutting grades, contain titanium carbide (TiC), titanium carbonitride (TiCN), titanium nitride (TiN), and/or niobium carbide (NbC). Improved wear resistance of cemented carbide tools is achieved by multilayer hard coatings of TiC, TiCN, TiN, alumina (Al₂O₃), and occasionally hafnium carbide (HfC). These coatings are commonly applied by chemical vapor deposition.

Cemented carbides are also being used increasingly for nonmetallic mining, oil and gas drilling, transportation and construction, metal-forming, structural and fluid-handling components, and forestry tools. Straight WC–Co grades are used for the majority of these applications. In general, cobalt contents range from 5% to 30% and WC grain sizes range from <1 to >8 μm.

Cementite

A hard (~800 HV), brittle compound of iron and carbon, known chemically as iron carbide and having the approximate chemical formula Fe₃C is characterized by an orthorhombic crystal structure. When it occurs as a phase in steel, the chemical composition will be altered by the presence of manganese and other carbide-forming elements. The cementite content in steel, the chemical composition will be altered by the presence of manganese and other carbide-forming elements. The highest cementite contents are observed in white cast irons, which are used in applications where high wear resistance is required.

Centane Number

A measure of the ignition quality of a fuel or petroleum product with reference to normal centane high-ignition quality fuel with an arbitrary number of 100.

Center Drilling

Drilling a short, conical hole in the end of a workpiece—a hole to be used to center the workpiece for turning on a lathe.

Center-Gated Mold

An injection or transfer mold in which the cavity is filled with plastic molding material, through a sprue or gate, directly into the center of the part.

Centering Plug

A plug fitting both spindle and cutter to ensure concentricity of the cutter mounting.

Centerless Grinding

Grinding the outside or inside diameter of a cylindrical piece which is supported on a work support blade instead of being held between centers and which is rotated by a so-called regulating or feed wheel.

Centerline Shrinkage

Shrinkage or porosity occurring along the central plane or axis of a cast part.

Centigrade

The original metric measure of temperature. Identical to Celsius in the SI system.

Centrifugal Casting (Plastics)

A method of forming thermoplastic resins in which the granular resin is placed in a rotatable container, heated to a molten condition by the transferor heat through the walls of the container, and rotated such that the centrifugal force induced will force the molten resin to conform to the configuration of the interior surface of the container. Used to fabricate large-diameter pipes and similar cylindrical items.

Centrifugal Castings

Centrifugal castings can be produced economically and with excellent soundness. They are used in the automotive, aviation, chemical, and process industries for a variety of parts having a hollow, cylindrical form or for sections or segments obtainable from such a form.

There are three modifications of centrifugal casting: (1) true centrifugal casting, (2) semicentrifugal casting, and (3) centrifuging.

1. True centrifugal casting is used for the production of cylindrical parts. The mold is rotated, usually in a horizontal plane, and the molten metal is held against the wall by centrifugal force until it solidifies.

2. Semicentrifugal casting is used for disk- and wheel-shaped parts. The mold is spun on a vertical axis, the metal is introduced at the center of the mold, and centrifugal force throws the metal to the periphery.

3. Centrifuging is used to produce irregular-shaped pieces. The method differs from static casting only in that the mold is rotated. Mold cavities are fastened at the periphery of a revolving turntable, the metal is introduced at the center, and thrown into the molds through radial ingates.

The nature of the centrifugal casting process ensures a dense, homogeneous cast structure free from porosity. Because the metal solidifies in a spinning mold under centrifugal force, it tends to be forced against the mold wall while impurities, such as sand, slag, and gases, are forced toward the inside of the tube. Another advantage of centrifugal casting is that recovery can run as high as 90% of the metal poured.

Certain types of castings are produced in centrifugal casting machines. There are essentially two types of those machines—the
horizontal type that rotates about a horizontal axis and the vertical type that rotates about a vertical axis. In general, horizontal machines are used to make pipe, tubes, bushings, cylinder sleeves, and other cylindrical or tubular castings that are simple in shape. Castings that are not cylindrical, or even symmetrical, can be made using vertical centrifugal casting machines.

**Ferrous Castings**

Centrifugal castings can be made of many of the ferrous metals—cast irons, carbon and low-alloy steels, and duplex metals.

**Mechanical Properties**

Regardless of alloy content, the tensile properties of irons cast centrifugally are reported to be higher than those of static castings produced from the same heat. Hydrostatic tests of cylinder liners produced by both methods show that centrifugally cast liners withstand about 20% more pressure than statically cast liners.

Freedom from directionality is one of the advantages that centrifugal castings have over forgings. Properties of longitudinal and tangential specimens of several stainless grades are substantially equal.

**Shapes, Sizes, Tolerances**

The external contours of centrifugal castings are not limited to circular forms. The contours can be elliptical, hexagonal, or fluted, for example. However, the nature of the true centrifugal casting process limits the bore to a circular cross section.

Iron and steel centrifugally cast tubes and cylinders are produced commercially with diameters ranging from 28.6 to 1500 mm, wall thickness of 0.25–102 mm, and in lengths up to 14.30 m. Generally it is impractical to produce castings with a ratio of the outside diameter to the inside diameter greater than about 4–1. The upper limit in size is governed by the cost of the massive equipment required to produce heavy castings.

As-cast tolerances for centrifugal castings are about the same as those for static castings. For example, tolerances on the outside diameter of centrifugally cast gray iron pipe range from 0.3 mm for 76 mm diameter to ±0.6 mm for 1.2 m diameter. Inside-diameter tolerances are greater, because they depend not only on the mold diameter, but also on the quantity of metal cast; the latter varies from one casting to another. These tolerances are generally about 50% greater than those on outside diameters. Casting tolerances depend to some extent also on the shrinkage allowance for the metal being cast.

The figures given earlier apply to castings to be used in the machined state. For castings requiring machining, it is customary to allow 2.35–3.2 mm on small castings and up to 6.4 mm on larger castings. If the end-use requires a sliding fit, broader tolerances are generally specified to permit additional machining on the inside surface.

**Cast Irons**

Large tonnages of gray iron are cast centrifugally. The relatively low pouring temperatures and good fluidity of the common grades make them readily adaptable to the process. Various alloy grades that yield pearlitic, acicular, and chill irons are also used. In addition, specialty iron alloys such as “Ni-Hard” and “Ni-Resist,” have been cast successfully.

**Carbon and Low-Alloy Steels**

Centrifugal castings are produced from carbon steels having carbon contents ranging from 0.05% to 0.90%. Practically all of the AISI standard low-alloy grades have also been cast.

Small-diameter centrifugally cast tubing in the usual carbon steel grades is not competitive in price with mechanical tubing having normal wall thicknesses. However, centrifugally cast tubing is less expensive than statically cast material.

**High-Alloy Steels**

Most of the AISI stainless and heat-resisting grades can be cast centrifugally. A particular advantage of the process is its use in producing tubes and cylinders from alloy compositions that are difficult to pierce and to forge or roll.

The excellent ductility resulting in the stainless alloys from centrifugal casting makes it possible to reduce the rough cast tubes to smaller-diameter tubing by hot- or cold-working methods. For example, billets of 18-8 stainless steel, 114.5 mm outside diameter by 16 mm inside diameter, have been reduced to 27-gauge capillary tubing without difficulty.

**Duplex Metals**

Centrifugal castings with one metal on the outside and another on the inside are also in commercial production. Combinations of hard and soft cast iron, carbon steel, and stainless steel have been produced successfully.

Duplex metal parts have been centrifugally cast by two methods. In one, the internal member of the pair is cast within a shell of the other. This method has been used to produce aircraft brake drums by centrifugally cast iron into a steel shell.

In the second method, both sections of the casting are produced centrifugally; the metal that is to form the outer portion of the combination is poured into the mold and solidified and the second metal is introduced before the first has cooled. The major limitation of this method is that the solidification temperature of the second metal poured must be the same or lower than that of the first. This method is used to form a strongly bonded duplex casting.

The possibilities of this duplex method for producing tubing for corrosion-resistant applications and chemical pressure service have been developed.

**Nonferrous Castings**

Nonferrous centrifugal castings are produced from copper alloys, nickel alloys, and tin- and lead-base bearing metals. Only limited application of the process is made to light metals because it is questionable whether any property improvement is achieved; for example, differences in density between aluminum and its normal impurities are smaller than in the heavy metals and consequently separation of the oxides, a major advantage of the process, is not so successful.

**Shapes, Sizes, Tolerances**

As with ferrous alloys, the external shapes of nonferrous centrifugal castings can be elliptical, hexagonal, or fluted, as well as round. However, the greatest overall tonnage of nonferrous castings is produced in plain or semiplain cylinders. The inside diameter of the casting is limited to a straight bore or one that can be machined to the required contour with minimum machining cost.

Nonferrous castings are produced commercially in outside diameters ranging from about 25.4 mm to 1.8 m and in lengths up to 8.1 m. Weights of individual castings range from 0.2268 to 27,300 kg.

Although tolerances on as-cast parts are about the same as those for sand castings, most centrifugal castings are finished by machining. An advantage of centrifugal casting is that normally only a small machining allowance is required; this allowance varies from...
as little as 1.53 mm on small castings to 6.4 mm on the outside diameter of large-diameter castings. A slightly larger machining allowance is required on the bore to permit removal of dross and other impurities that segregate in this area.

Copper Alloys
A wide range of copper casting alloys is used in the production of centrifugal castings. The alloys include the plain brasses, leaded brasses and bronzes, tin bronzes, aluminum bronzes, silicon bronzes, manganese bronzes, nickel silvers, and beryllium copper. The ASTM lists 32 copper alloys for centrifugal casting; in addition, there are a number of proprietary compositions that are regularly produced by centrifugal casting.

Most of these alloys can be cast without difficulty. Some trouble with segregation has been reported in casting the high leaded (over 10% lead) alloys. However, alloys containing up to 20% lead are being cast by some foundries; the requirements are (1) rapid chilling to prevent excessive lead segregation and (2) close control of speed.

The mechanical properties of centrifugally cast copper alloys vary with the composition and are affected by the mold material used. Centrifugal castings produced in chill molds have higher mechanical properties than those obtained by casting in sand molds. However, centrifugal castings made in sand molds have properties about 10% higher than those obtained on equivalent sections of castings produced in static sand molds. (Castings produced in centrifugal chill molds have properties 20%–40% higher than those produced in static sand molds.)

Nickel Alloys
Centrifugal castings of nickel 210, 213, and 305; “Monel” alloys 410, 505, and 506; and “Inconel” alloys 610 and 705 are commercially available in cylindrical tubes. Centrifugal castings are also produced from the heat-resisting alloys 60% nickel–12% chromium and 66% nickel–17% chromium. These alloys should behave like other materials and show improved density with accompanying improvement in mechanical properties. The nickel alloys are employed for service under severe corrosion, abrasion, and galling conditions.

Bearing Metals
Centrifugal casting is a standard method of producing lined bearings. Steel cylinders, after being cleaned, pickled, and tinned, are rotated while tin- or lead-base bearing alloys are cast into them. The composite cylinder is then cut lengthwise, machined, and finished into split bearings.

Centrifuge
A mechanism in which a material is spun either by having a swirl induced in it or by being contained in a vessel that is spun at high speed. In either case, the intention is to apply high gravitational forces that separate materials of different densities.

Centrifuge Casting
A casting technique in which mold cavities are spaced symmetrically about a vertical axial common downgate. The entire assembly is rotated about that axis during pouring and solidification.

Ceramic (Adjective)
(1) Of or pertaining to ceramics, that is, inorganic nonmetallic as opposed to organic or metallic. (2) Pertaining to products manufactured from inorganic nonmetallic substances which are subjected to a high temperature during manufacture or use. (3) Pertaining to the manufacture or use of such articles or materials, such as ceramic process or ceramic science.

Ceramic Color Glaze
An opaque colored glass of satin or gloss finish obtained by spraying the clay body with a compound of metallic oxides, chemicals, and clays. It is fired at high temperatures, fusing the glaze to the body, making them inseparable.

Ceramic Fibers
Alumina–silica (Al₂O₃–SiO₂) fibers, frequently referred to as ceramic fibers, are formed by subjecting a molten stream to a fiberizing force. Such force may be developed by high-velocity gas jets or rotors or intricate combinations of these. The molten stream is produced by melting high-purity Al₂O₃ and SiO₂, plus suitable fluxing agents, and then pouring this melt through an orifice. The jet or rotor atomizes the molten stream and attenuates the small particles into fine fibers as supercooling occurs.

The resulting fibrous material is a versatile high-temperature insulation for continuous service in the 538°C–1260°C range. It thus bridges the gap between conventional inorganic fiber insulating materials (e.g., asbestos, mineral wool, and glass) and insulating refractories.

Al₂O₃–SiO₂ fibers have a maximum continuous use temperature of 1093°C–1260°C, and a melting point of over 1760°C for extended periods of time, a phenomenon called devitrification occurs. This is a change in the orientation of the molecular structure of the material from the amorphous state (random orientation) to the crystalline state (definitely arranged pattern). Insulating properties are not affected by this phase change but the material becomes more brittle.

Most ceramic fibers have an Al₂O₃ content from 40% to 60%, and an SiO₂ content from 40% to 60%. Also contained in the fibers are from 1.5% to 7% oxides of sodium, boron, magnesium, calcium, titanium, zirconium, and iron.

Fibers as formed resemble a cotton-like mass with individual fiber length varying from short to 254 mm, and diameters from less than 1 to 10 μm. Larger-diameter fibers are produced for specific applications. In all processes, some unfiberized particles are formed that have diameters up to 40 μm.

Low density, excellent thermal shock resistance, and very low thermal conductivity are the properties of Al₂O₃–SiO₂ fibers that make them an excellent high-temperature insulating material. Available in a variety of forms, ceramic fiber is in ever-increasing demand due to higher and higher temperatures now found in industrial and research processes.

Applications
Ceramic fibers were originally developed for application in insulating jet engines. Now, this is only one of numerous uses for this material. It can be found in aircraft and missile applications where a high-temperature insulating medium is necessary to withstand the searing heat developed by rockets and supersonic aircraft. Employed as a thermal-balance and pressure-distribution material, ceramic fiber in the form of paper has made possible the efficient brazing of metallic honeycomb-sandwich structures.

Successful trials have been conducted in aluminum processing where this versatile product in paper or molded form has been used
Ceramic Glass Decorations
Ceramic glass enamels fused to glassware at temperatures above 245°C (800°F) to produce a decoration.

Ceramic Glass Enamels
Predominantly colored, silicate glass fluxes used to decorate glassware. Also referred to as ceramic enamels or glass enamels.

Ceramic Molding
A precision casting process that employs permanent patterns and fine-grain slurry for making molds. Unlike monolithic investment molds, which are similar in composition, ceramic molds consist of a cope and a drag or, if the casting shape permits a drag only.

Ceramic Printed Board
A printed board made from ceramic dielectric and cermet materials.

Ceramic Process
The production of articles or coatings from essentially inorganic, nonmetallic materials, the article or coating being made permanent and suitable for utilitarian and decorative purposes by the action of heat at temperatures sufficient to cause sintering, solid-state reactions, bonding, or conversion partially or wholly to the glassy state.

Ceramic Rod Flame Spraying
A thermal spraying process variation in which the material to be sprayed is a ceramic rod form. See also flame spraying.

SiC Fibers
These fibers, capable of withstanding temperatures to about 1200°C, are manufactured from a polymer precursor. The polymer is spun into a fine thread, then pyrolyzed to form a 15 μm ceramic fiber consisting of fine SiC crystallites and an amorphous phase. An advantage of the process is that it uses technology developed for commercial fiber products such as nylon and polyester. Two commercial SiC fiber products are the Ube Industries Tyranno fiber and the Nippon Carbon Nicalon fiber.

Ceramic Glass Decorations
Ceramic Glass Decorations
Silica, have also been produced, the latter material being used for larger radome structures on ballistic missiles.

Ceramic Whiteware
A fired ware consisting of glazed or unglazed ceramic body which is commonly white and of fine texture. This term designates such product classifications as tile, china, porcelain, semi-vitreous ware, and earthenware. See also traditional ceramics.

Ceramic(s) (Noun)
Any of the class of inorganic nonmetallic products which are subjected to a high temperature during manufacture or use (high temperature usually means a temperature above a barely visible red, approximately 540°C, or 1000°F). Typically, but not exclusively, a ceramic is a metallic oxide, boride, carbide, or nitride, or a mixture or compound of such materials; that is, it includes anions that play important roles in atomic structures and properties.

See also advanced ceramics, electronic ceramics, refractories, structural ceramics, and traditional ceramics.

Ceramic–Matrix Composite
The class of materials known as ceramic–matrix composites, or CMCs, shows considerable promise for providing fracture-toughness values similar to those for metals such as cast iron. Two kinds of damage-tolerant ceramic–ceramic composites have been developed. One incorporates a continuous reinforcing phase, such as a fiber; the other, a discontinuous reinforcement, such as whiskers. The major difference between the two is in their failure behavior. Continuous-fiber-reinforced materials do not fail catastrophically. After matrix failure, the fiber can still support a load. A fibrous failure is similar to that which occurs in wood.

CMCs are candidate materials for high-performance engines and wear-resistant parts. Interest in ceramic composites has been stimulated by the realization that carbon–carbon composites (CCC) are difficult to protect from oxidation, and that metal–matrix composites (MMCs) have end-use temperature limitations that are below the level needed for engine components.

A wide variety of reinforcing materials, matrices, and corresponding processing methods have been studied. The most successful fiber-reinforced composites have been produced by hot pressing, chemical vapor infiltration, or directed metal oxidation, which is a process that uses accelerated oxidation reactions of molten metals to grow ceramic matrices around preplaced fiber or reinforcement material preforms. Much of the work has been on glass and glass-ceramic matrices reinforced with carbon fibers. Because of the low axial coefficient of thermal expansion (CTE) of carbon fibers and the requirements for CTE matching, the more successful composites have been produced with low CTE matrices, such as borosilicate glass (CTE = 3.5 × 10⁻⁶ K⁻¹) and lithium aluminosilicate glass-ceramics (CTE = 1.5 × 10⁻⁶ K⁻¹).

Other fiber-reinforced ceramic composites include silicon carbide fibers in SiC produced by chemical vapor infiltration and deposition, and SiC fiber reinforced alumina (Al₂O₃) and zirconium diboride (ZrB₂) reinforced zirconium carbide (ZrC) composites produced by direct metal oxidation. Multidirectionally reinforced ceramics, such as fused quartz reinforced silica and Al₂O₃ reinforced silica, have also been produced, the latter material being used for larger radome structures on ballistic missiles.
Incorporating whiskers into a ceramic matrix improves resistance to crack growth, making the composite less sensitive to flaws. These materials are commonly described as being flaw tolerant. However, once a crack begins to propagate, failure is catastrophic.

Composed of fine equiaxed Al₂O₃ grains and needle-like SiC whiskers, SiC₆₋₅Al₂O₃ composites exhibit promising fracture toughness (6.5 MPa√m, or 5.9 ksi√in.) and strength (600 MPa or 57 ksi) properties. SiC₆₋₅Al₂O₃ composites have been used in cutting-tool applications. Composites with whisker loadings higher than 8 vol% must be hot pressed.

Of particular importance to the technology of toughened ceramics has been the development of high-temperature SiC reinforcements.

**SiC Filaments**

SiC filaments are prepared by chemical vapor deposition. A thick layer of SiC is deposited on a thin fiber substrate of tungsten or carbon. Diameter of the final product is about 140 μm.

Although developed initially to reinforce aluminum and titanium matrices SiC filaments have since been used as reinforcement in Si₃N₄.

**SiC Whiskers**

SiC whiskers consist of a fine (0.5–5 μm-diameter) single-crystal structure in lengths to 100 μm. The material is strong (to 15.9 GPa) and is stable at temperatures to 1800°C. Whiskers can be produced by heating SiO₂ and carbon sources with a metal catalyst in the proper environments.

Although these materials are relatively new, at least one successful commercial product is already being marketed. An SiC-whisker-reinforced Al₂O₃ cutting-tool material is being used to machine nickel-based superalloys. In addition, considerable interest has been generated in reinforcing other matrices such as mullite, SiC, and Si₃N₄ for possible applications in automotive and aerospace industries.

The excellent high-temperature strength, oxidation resistance, thermal shock resistance, and fracture toughness of silicon nitride has led to the development of SiC₆₋₅ reinforced Si₃N₄. The major phase, Si₃N₄, offers many favorable properties, and the SiC whiskers provide significant improvement in the fracture toughness of the composite. Whisker-reinforced Si₃N₄ is a leading candidate material for hot-sections of ceramic-engine components.

**DIMOX Process**

CMCs are steadily moving from the laboratory to initial commercial applications. For example, engineers are currently evaluating these materials as refractories, glass, brick, cement and plaster, abrasives, and dielectrics. Diameter of the final product is about 140 μm.

Examples of ceramic matrices that can be produced by the DIMOX directed metal oxidation process include Al₂O₃, Al₃Ti₃, Al₂O₃, Ti₃C, and ZrC. Filler materials can be anything chemically compatible with the ceramic, parent metal, and growth atmosphere.

The first step in the process involves making a shaped preform of the filler material. Preforms consisting of particles are fabricated with traditional ceramic-forming techniques, while fiber preforms are made by weaving, braiding, or laying up woven cloth. Next, the preform is put in contact with the parent metal alloy. A gas-permeable growth barrier is applied to the surfaces of this assembly to limit its shape and size.

The assembly, supported in a suitable refractory container, is then heated in a furnace. For aluminum systems, temperatures typically range from 899°C to 1149°C. The parent metal reacts with the surrounding gas atmosphere to grow the ceramic reaction product through and around the filler to form a CMC.

Capillary action within the growing ceramic matrix continues to supply molten alloy to the growth front. There, the reaction continues until the growing matrix reaches the barrier. At this point, growth stops, and the part is cooled to ambient temperature. To recover the part, the growth barrier and any residual parent metal are removed. However, some of the parent metal (5%–15% by volume) remains within the final composite in micron-sized interconnected channels.

Traditional ceramic processes use sintering or hot pressing to make a solid CMC out of ceramic powders and filler. Part size and shapes are limited by equipment size and the shrinkage that occurs during densification of the powders can make sintering unfeasible. Larger parts pose the biggest shrinkage problem. Advantages of the directed metal oxidation process include low shrinkage because matrix formation occurs by a growth process. As a result, tolerance control and large part fabrication can be easier with directed metal oxidation.

In addition, the growth process forms a matrix whose grain boundaries are free of impurities or sintering aids. Traditional methods often incorporate these additives, which reduce high-temperature properties. And cost comparisons show the newer process is a promising replacement for traditional methods.
Ceramics are included in this family. These are carbon and graphite, mica, and asbestos. Also, intermetallic compounds, such as aluminaides and beryllides, which are classified as metals, and cermet, are usually thought of as ceramic materials because of similar physical characteristics to certain ceramics.

Ceramic materials can be subdivided into traditional and advanced ceramics. Traditional ceramics include clay-base materials such as brick, tile, sanitaryware, dinnerware, clay pipe, and electrical porcelain. Common-use glass, cement, abrasives, and refractories are also important classes of traditional ceramics.

Advanced materials technology is often cited as an “enabling” technology, enabling engineers to design and build advanced systems for applications in fields such as aerospace, automotive, and electronics. Advanced ceramics are tailored to have premium properties through application of advanced materials science and technology to control composition and internal structure. Examples of advanced ceramic materials are Si₃N₄, SiC, toughened ZrO₂, ZrO₂-toughened Al₂O₃, AIM, PbMg niobate, PbLa titanate, SiC-whisker-reinforced Al₂O₃, carbon-fiber-reinforced glass ceramic, SiC-fiber-reinforced SiC, and high-temperature superconductors.

Advanced ceramics can be viewed as a class of the broader field of advanced materials, which can be divided into ceramics, metals, polymers, composites, and electronic materials. There is considerable overlap among these classes of materials.

Advanced ceramics can be subdivided into structural and electronic ceramics based on primary function or application. Optical and magnetic materials are usually included in the electronic classification. Structural applications include engine components, cutting tools, bearings, valves, wear- and corrosion-resistant parts, heat exchangers, fibers and whiskers, and biological implants. The electronic-magnetic-optic functions include electronic substrates, heat exchangers, fibers and whiskers, and biological implants. The electronic-magnetic-optic functions include electronic substrates, electronic packages, capacitors, transducers, magnets, waveguides, lamp envelopes, displays, sensors, and ceramic superconductors.

Thermal insulation, membranes, and filters are important advanced ceramic product areas that do not fit well into either the structural or the electronic class of advanced ceramics.

Advanced ceramics are differentiated from traditional ceramics such as brick and porcelain by their higher strength, higher operating temperatures, improved toughness, and tailorable properties. Also known as engineered ceramics, these materials are replacing metals in applications where reduced density and higher melting points can increase efficiency and speed of operation. The nature of the bond between ceramic particles helps differentiate engineering ceramics from conventional ceramics. Most particles within an engineering ceramic are self-bonded, that is, joined at grain boundaries by the same energy-equilibrium mechanism that bonds metal grains together. In contrast, most nonengineering ceramic particles are joined by a so-called ceramic bond, which is a weaker, mechanical linking or interlocking of particles. Generally, impurities and nonengineering ceramics prevent the particles from self-bonding.

A broad range of metallic and nonmetallic elements are the primary ingredients in ceramic materials. Some of the common metals are aluminum, silicon, magnesium, beryllium, titanium, and boron. Nonmetallic elements with which they are commonly combined are O₂, carbon, or N₂. Ceramics can be either simple, one-phase materials composed of one compound, or multiphase, consisting of a combination of two or more compounds. Two of the most common are single oxide ceramics, such as alumina (Al₂O₃) and magnesium (MgO), and mixed oxide ceramics, such as cordierite (magnesia alumina silica) and forsterite (magnesia silica). Other newer ceramic compounds include borides, nitrides, carbides, and silicides. Macrostructurally, there are essentially three types of ceramics: crystalline bodies with a glassy matrix; crystalline bodies, sometimes referred to as holocrystalline; and glasses.

The specific gravities of ceramics range roughly from 2 to 3. As a class, ceramics are low-tensile-strength, relatively brittle materials. A few have strengths above 172 MPa, but most have less than that. Ceramics are notable for the wide difference between their tensile and compressive strengths. They are normally much stronger under compressive loading than in tension. It is not unusual for a compressive strength to be 5–10 times that of the tensile strength. Tensile strength varies considerably depending on composition and porosity.

One of the major distinguishing characteristics of ceramics, as compared to metals, is their almost total absence of ductility. They fail in a brittle fashion. Lack of ductility is also reflected in low impact strength, although impact strength depends to a large extent on the shape of the part. Parts with thin or sharp edges or curves and with notches have considerably lower impact resistance than those with thick edges and gently curving contours.

Ceramics are the most rigid of all materials. A majority of them are stiffer than most metals, and the modulus of elasticity in tension of a number of types runs as high as 0.3–0.4 million MPa compared with 0.2 million MPa for steel. In general, they are considerably harder than most other materials, making them especially useful as wear-resistant parts and for abrasives and cutting tools.

Ceramics have the highest known melting points of materials. Hafnium and TaC, for example, have melting points slightly above 3870°C, compared to 3424°C for tungsten. The more conventional ceramic types, such as Al₂O₃, melt at temperatures above 1927°C, which is still considerably higher than the melting point of all commonly used metals. Thermal conductivities of ceramic materials fall between those of metals and polymers. However, thermal conductivity varies widely among ceramics. A two-order magnitude of variation is possible between different types, or even between different grades of the same ceramic. Compared to metals and plastics, the thermal expansion of ceramics is relatively low, although like thermal conductivity it varies widely between different types and grades. Because the compressive strengths of ceramic materials are 5–10 times greater than tensile strength, and because of relatively low heat conductivity, ceramics have fairly low thermal-shock resistance. However, in a number of ceramics, the low thermal expansion coefficient succeeds in counteracting to a considerable degree the effects of thermal conductivity and tensile–compressive-strength differences.

Practically all ceramic materials have excellent chemical resistance, and are relatively inert to all chemicals except hydrofluoric acid and, to some extent, hot caustic solutions. Organic solvents do not affect them. Their high surface hardness tends to prevent breakdown by abrasion, thereby retarding chemical attack. All technical ceramics will withstand prolonged heating at a minimum of 999°C. Therefore, atmospheres, gases, and chemicals cannot penetrate the material surface and produce internal reactions that are normally accelerated by heat.

Unlike metals, ceramics have relatively few free electrons and therefore are essentially nonconductive and considered to be dielectric. In general, dielectric strengths, which range between 7.8 × 10⁵ and 13.8 × 10⁵ V/m, are lower than those of plastics. Electrical resistivity of many ceramics decreases rather than increases with an increase in impurities, and is markedly affected by temperature.

**Fabrication Process**

A wide variety of processes are used to fabricate ceramics. The process chosen for a particular product is based on the material, shape, complexity, property requirements, and cost. Ceramic fabrication
processes can be divided into four generic categories: powder, vapor, chemical, and melt processes.

**Powder Processes**

Transitional clay-base ceramics and most refractories are fabricated by powder processes as are the majority of advanced ceramics. Powder processing involves a number of sequential steps. These are preparation of the starting powders, forming the desired shape (green forming), removal of water and organics, heating with or without application of pressure to densify the powder, and finishing.

**Vapor Processes**

The primary vapor processes used to fabricate ceramics are chemical vapor deposition (CVD) and sputtering. Vapor processes have been finding an increasing number of applications. CVD involves bringing gases containing the atoms to contact the ceramic and then into contact with a heated surface, where the gases react to form a coating. This process is used to apply ceramic coatings to metal and tungsten carbide cutting tools as well as to apply a wide variety of other coatings for wear, electronic, and corrosion applications. CVD can also be used to form monolithic ceramics by building up thick coatings. A form of CVD known as chemical vapor infiltration (CVI) has been developed to infiltrate and coat the surfaces of fibers in woven preforms.

Several variations of sputtering and other vacuum-coating processes can be used to form coatings of ceramic materials. The most common process is reactive sputtering, used to form coatings such as TiN on tool steel.

**Chemical Processes**

A number of different chemical processes are used to fabricate advanced ceramics. The CVD process described earlier as a vapor process is also a chemical process. Two other chemical processes finding increasing application in advanced ceramics are polymer pyrolysis and sol–gel technology.

**Melt-Processes**

These are used to manufacture glass, to fuse-cast refractories for use in furnace linings, and to grow single crystals. Thermal spraying can also be classified as a melt process. In this process a plasma-spray gun is used to apply ceramic coatings by melting and spraying powders onto a substrate.

**Metal Oxide Ceramics**

Although most metals form at least one chemical compound with O₂, only a few oxides are useful as the principal constituent of a ceramic. And of these, only three are used in their fairly pure form as engineering ceramics: Al₂O₃, BeO, and ZrO₂.

The natural alloying element in the Al₂O₃ system is SiO₂. However, Al₂O₃ can be alloyed with chromium (which forms a second phase with the Al₂O₃ and strengthens the ceramic) or with various oxides of silicon, magnesium, or calcium.

Al₂O₃s serve well at temperatures as high as 1550°C provided they are not exposed to thermal shock, impact, or highly corrosive atmospheres. Above 2038°C, strength of Al₂O₃ drops. Consequently, many applications are in steady-state, high-temperature environments, but not where abrupt temperature changes would cause failure from thermal shock. Al₂O₃s have good creep resistance up to about 816°C above which other ceramics perform better. In addition, Al₂O₃s are susceptible to corrosion from strong acids, steam, and sodium. See Aluminum.

BeO ceramics are efficient heat dissipaters and excellent electrical insulators. They are used in electrical and electronics applications, such as microelectronic substrates, transistor bases, and resistor cores. BeO has excellent thermal shock resistance (some grades can withstand 816°C/s changes), a very low coefficient of thermal expansion (CTE), and a high thermal conductivity. It is expensive, however, and is an allergen to which some persons are sensitive. See Beryllium.

ZrO₂ is used primarily for its extreme inertness to most metals. ZrO₂ ceramics retain strength nearly up to their melting point—well over 2205°C, the highest of all ceramics. Applications for fused or sintered ZrO₂ include crucibles and furnace bricks. See Zirconium.

Transformation-toughened ZrO₂ ceramics are among the strongest and toughest ceramics made. These materials are of three main types: Mg-PSZ (ZrO₂ partially stabilized with MgO), Y-TZP (Y₂O₃ stabilized tetragonal ZrO₂ poly crystals), and ZTA (ZrO₂-toughened Al₂O₃).

Applications of Mg-PSZ ceramics are principally in low- and moderate-temperature abrasive and corrosive environments—pump and valve parts, seals, bushings, impellers, and knife blades. Y-TZP ceramics (stronger than Mg-PSZ but less flaw tolerant) are used for pump and valve components requiring wear and corrosion resistance in room-temperature service. ZTA ceramics, which have lower density, better thermal shock resistance, and lower cost than the other two, are used in transportation equipment where they need to withstand corrosion, erosion, abrasion, and thermal shock.

Many engineering ceramics have multioxide crystalline phases. An especially useful one is cordierite (MgO–Al₂O₃–SiO₂), which is used in cellular ceramic form as a support for a wash-coat and catalyst in catalytic converters in automobile emission systems. Its low CTE is a necessary property for resistance to thermal fracture.

**Glass Ceramics**

Glass ceramics are formed from molten glass and subsequently crystallized by heat treatment. They are composed of several oxides that form complex, multiphase microstructures. Glass ceramics do not have the strength-limiting porosity of conventional sintered ceramics. Properties can be tailored by control of the crystalline structure in the host glass matrix. Major applications are cooking vessels, tableware, smooth cooktops, and various technical products such as radomes.

The three common glass ceramics, Li–Al–SiO₂ (LAS, or beta spodumene), Mg–Al–SiO₂ (MAS, or cordierite), and Al–SiO₂ (AS, or aluminous keatite), are stable at high temperatures, have near-zero CTEs, and resist various forms of high-temperature corosion, especially oxidation. LAS and AS have essentially no measurable thermal expansion up to 427°C. The high SiO₂ content of LAS is responsible for the low thermal expansion, but the SiO₂ also decreases strength. LAS is attacked by sulfur and sodium.

MAS is stronger and more corrosion resistant than LAS. A multiphased version of this material, MAS with Al₂TiO₅, has good corrosion resistance up to 1093°C.

AS, produced by leaching lithium out of LAS particles prior to forming, is both strong and corrosion resistant. It has been used, for example, in an experimental rotating regenerator for a turbine engine.

A proprietary ceramic (Macor) called machinable glass ceramic (MGC), is about as strong as Al₂O₃. It also has many of
the high-temperature and electrical properties of the glass ceramics. The main virtue of this material is that it can be machined with conventional tools. It is available in bars, or it can be rough-formed, then finish-machined. Machined parts do not require firing.

A similar glass ceramic is based on chemically machinable glass that, in its initial state, is photosensitive. After the glass is sensitized by light to create a pattern, it is chemically machined (etched) to form the desired article. The part can then be used in its glassy state, or it can be fired to convert it to a glass ceramic. This material/process combination is used where precision tolerances are required and where a close match to thermal expansion characteristics of metals is needed. Typical applications are sliders for disk-memory read/write heads, wire guides for dot-matrix printers, cell sheets for gas-discharge displays, and substrates for thick-film and thin-film metallization.

Another ceramic-like material, glass-bonded mica, the moldable/machinable ceramic, is also called a “ceramoplasic” because its properties are similar to those of ceramics, but it can be machined and molded like a plastic material. A glass/mica mixture is pressed into a preform, heated to make the glass flow, then transfer- or compression-molded to the desired shape. The material is also formed into sheets and rods that can be machined with conventional carbide tooling. No firing is required after machining.

The thermal expansion coefficient of glass-bonded mica is close to that of many metals. This property, along with its extremely low shrinkage during molding, allows metal inserts to be molded into the material and also ensures close dimensional tolerances. Molding tolerances as close as ±0.01 mm/mm can be held. Continuous service temperatures for glass-bonded mica range from cryogenic to 371°C or 704°F depending upon material grade.

**Aluminum-Ceramic Coatings**

These coatings are used to protect aircraft-turbine and other turbomachinery parts from corrosion and heat at temperatures to 2000°F (1093°C) and greater. For compressor applications in ground-based turbines, aluminum-filled, chrome-silicate-phosphate coatings sealed with a ceramic topcoat have more than doubled service life. Aluminum-ceramic coatings are also alternatives to cadmium plating of fasteners and other products and used for galvanic protection of dissimilar materials. Nickel-ceramic coatings, with silicon carbide or silicon carbide and phosphorus added to the nickel matrix for hardness and hexagonal boron nitride or silicon nitride for lubricity are used in Japan on cylinder bores and pistons of outboard-marine, motorcycle, and snowmobile engines to increase wear resistance. Paintable ceramic coatings, especially of Zyp Coatings, Inc., combined corrosion resistance with heat resistance to 2000°F (1093°C).

**Piezoelectric Ceramics**

These ceramics produce voltage proportional to applied mechanical force and, conversely, mechanical force when electric voltage is applied. The ceramics are classified as materials into hard, soft, and custom groups. Lead zirconate titanate ceramics encompass both “hard” and “soft” groups. The hard, such as PZT-4, 4D, and 8, can withstand high levels of electrical excitation and stress. They are suited for high-voltage or high-powered generators and transducers. The soft, such as PZT-5A, 4B, 5H, 5L, and 5R as well as 7A and 7D feature greater sensitivity and permittivity. Under high drive conditions, however, they are susceptible to self-heating beyond their operating temperature range. They are used in sensors, low-power motor-type transducers, receivers, low-power generators, hydrophones, accelerometers, vibration pickups, inkjet printers, and towed array lines. Modified lead metaniobate, PZT-1 and 2, features higher operating temperatures and is used in accelerometers, flow detectors, and thickness gages. All are available as rods, tubes, disks, plates, rings, and blocks as well as in custom shapes.

Because of their extreme hardness, hot hardness, wear resistance, and chemical inertness, ceramics are used for cutting tools, mainly in the form of inserts fixed to a tool-holder, to increase machining speeds or metal-removal rates, and to enhance machining of certain metals and alloys relative to traditional cutting-tool materials. On the other hand, the materials are more costly and brittle. The most commonly used ceramics for cutting tools are based on alumina or silicon nitride. Various other ceramics are added to the powder mix to enhance sintering mechanical properties, toughness primarily. Principal alumina-based materials, for example, contain titanium carbide, zirconia, or silicon carbide. Other additives include titanium nitride, titanium boride, titanium carbonitride, and zirconium carbonitride. Silicon nitride is generally stronger and tougher than the alumina but alumina, aluminum nitride, or silica is required as a sintering additive to achieve dense material. SIALONs consist of various amounts of alumina and silicon nitride, sometimes with zirconia or yttria additives.

**Larsenite**, of Blasch Precision Ceramics, Inc., is a ceramic composite of alumina and silicon carbide. It is more resistant to thermal shock than alumina and resists oxidation at higher temperatures over 3000°F (1649°C) than the carbide. It is made by firing alumina and a particular grain size of silicon carbide, which then forms a lattice and improves the thermal shock resistance of the alumina. The composite has been used instead of fused silica for nozzles used in atomizing metals into powder. Sulfide ceramics, developed at Argonne National Laboratory, hold promise for effective bonding of difficult-to-join materials, such as ceramics to metals. Because they form at lower temperatures than traditional welds, joints are stronger and less brittle. Materials having coefficients of thermal expansion differing by as much as 200% have been joined. The ceramics are candidates for use in lithium-iron sulfide batteries being developed for battery-powered cars.

**Eco-ceramics** is the term given to silicon carbide ceramics developed from renewable resources and environmental waste (natural wood and sawdust) at the National Aeronautics and Space Administration Glenn Research Center. Parts are to net shape, pyrolyzed at 1800°F (982°C), and infiltrated with molten silicon or silicon alloys.

**Cereal**

An organic binder, usually cornflower.

**Cerium**

A chemical element, cerium (Ce) is the most abundant metallic element of the rare earth group in the periodic table. Cerium occurs mixed with other rare earths in many minerals, particularly monazite and bastnasite, and is found among the products of the fission of uranium, thorium, and plutonium. It is a strong reducing agent used as a getter and thermionic valves and in a number of refining processes usually in the form of Misch Metal, and impure mixture of about 50% cerium and other rare earths. With 50% iron, it forms a pyrophoric alloy for products such as cigarette lighter “flints.” Small additions are made to aluminum and magnesium to improve their strength and ductility and to cast irons to promote the formation of nodular graphite. See cast iron.

Ceritic oxide, CeO₂, is the oxide usually obtained when cerium salts of volatile acids are heated. CeO₂ is an almost white powder
Cermets

A composite material made up of ceramic particles (or grains) dispersed in a metal matrix. Particle size is greater than 1 μm, and the volume fraction is over 25% and can go as high as 90%. Bonding between the constituents results from a small amount of mutual or partial solubility. Some systems, however, such as the metal oxides, exhibit poor bonding between phases and require additions to serve as bonding agents. Cermet parts are produced by powder–metallurgy (P/M) techniques. They have a wide range of properties, depending on the composition and relative volumes of the metal and ceramic constituents. Some cermets are also produced by impregnating a porous ceramic structure with a metallic matrix binder. Cermets can also be used in powder form as coatings. The powdered mixture is sprayed through an acetylene flame, and it fuses to the base material. Although a great variety of cermets have been produced on a small scale, only a few types have significant commercial use. These fall into two main groups: oxide-base and carbide-base cermets. Other important types include the TiC-base cermets, Al2O3-base cermets, and UO2 cermets specially developed for nuclear reactors.

The most common type of oxide-base cermets contains Al2O3 ceramic particles (ranging from 30% to 70% volume fraction) and a chromium or chromium-oxide alloy matrix. In general, oxide-base cermets have specific gravities between 4.5 and 9.0, and tensile strengths ranging from 144 to 268 MPa. Their modulus of elasticity ranges between 0.25 and 0.34 million MPa, and their hardness range is A 70 to 90 on the Rockwell scale. The outstanding characteristic of oxide-base cermets is that the metal or ceramic can be either the particle or the matrix constituent. The 6MgO–94Cr cermets reverse the roles of the oxide and chromium, that is, the magnesium is added to improve the fabrication and performance of the chromium. Chromium is not ductile at room temperature. Adding MgO not only permits press-forging at room temperature but also increases oxidation resistance to five times that of pure chromium. Of the cermets, the oxide-base alloys are probably the simplest to fabricate. Normal P/M or ceramic techniques can be used to form shapes, but these materials can also be machined or forged. The oxide-base cermets are used as a tool material for high-speed cutting of difficult-to-machine materials. Other uses include thermocouple-protection tubes, molten-metal-processing equipment parts, mechanical seals, gas-turbine flame holders (resistance to flame erosion), and flow control pins (because of Cr–Al2O3’s resistance to wetting and erosion by many molten metals and to thermal shock).

There are three major groups of carbide-base cermets: tungsten carbide, aluminum carbide, and titanium carbide. Each of these groups is made up of a variety of compositional types or grades. WC cermets contain up to about 30% cobalt as the matrix binder. They are the heaviest type of cermet (specific gravity is 11–15). Their outstanding properties include high rigidity, compressive strength, hardness, and abrasion resistance. Their modulus of elasticity ranges between 0.45 and 0.65 million MPa; and they have a Rockwell hardness of about A88. They have superior resistance to oxidation, excellent corrosion resistance, and relatively low density (specific gravity is 7.0). Their high rigidity and abrasion resistance make them suitable for gauges, oil-well check valves, valve liners, spray nozzles, bearing seal rings, and pump rotors.

Other cermets are barium-carbonate–nickel and tungsten–thoria, which are used in higher-power pulse magnetrons. Some proprietary compositions are used as friction materials. In brake applications, they combine the thermal conductivity and toughness of metals with the hardness and refractory properties of ceramics. UO2 cermets have been developed for use in nuclear reactors. Cermets play an important role in sandwich-plate fuel elements, and the finished element is a siliconized SiC with a core containing UO2. Control rods have been fabricated from B4C–stainless steel and rare earth oxides–stainless steel. Other cermets developed for use in nuclear equipment include Cr–Al2O3 cermets, Ni–MgO cermets, and Fe–ZrC cermets. Nonmagnetic compositions can be formulated for use where magnetic materials cannot be tolerated.

Interactions

The reactions taking place between the metallic and ceramic components during fabrication of cermets may be briefly classified and described as follows:

1. Heterogeneous mixtures with no chemical reaction between the components, characterized by a mechanical interlocking of the components without formation of a new phase, no penetration of the metallic component into the ceramic component, and vice versa, and no alteration of either component (e.g., MgO–Ni).
2. Surface reaction resulting in the formation of a new phase as an interfacial layer that is not soluble in the component materials. The thickness of this layer depends on the diffusion rate, temperature, and time of the reaction (e.g., Al2O3–Be).
3. Complete reaction between the components, resulting in the formation of a solid solution characterized by a polyatomic structure of the ceramic and the metallic component (e.g., TiC–Ni).
4. Penetration along grain boundaries without the formation of interfacial layers (e.g., Al2O3–Mo).

Bonding Behavior

One important factor in the selection of metallic and ceramic components in cermets is their bonding behavior. Bonding maybe by surface interaction or by bulk interaction. In cermets of the
Cesium Chafing Fatigue

Chafing Fatigue

Fatigue initiated in a surface damage by rubbing against another body. See also fretting.

Applications

Aside from the high-temperature applications in turbine buckets, nozzle vanes, and impellers for auxiliary power turbines, there is a wide variety of applications for cermets based on various other properties. One of the most successful applications for the TiC-base cermets is in elements of temperature sensing and controlling thermostats where their oxidation resistance together with their low coefficient of thermal expansion as compared with nickel-base alloys are the important properties. Their ability to be welded directly to the alloys is also important.

The TiC-base cermets are also used for bearings and thrust runners in liquid metal pumps, hot flash trimming and hot spinning tools, hot rod mill guides, antifriction and sleeve-type bearings, hot glass pinch jaws, rotary seals for hot gases, oil well valve balls, etc.

The size of the ceramic component varies, depending on the system and application. It can be as coarse as 50–100 μm, as in some type of cermets based on uranium dioxide (UO₂) that are used for nuclear reactor fuel elements, or as fine as 1–2 μm, as in the microgran type of cemented carbides. It should be noted, technically, all metal-bonded tungsten carbide materials should fall into the category of cermets. However, it has been customary in the cutting tool industry to designate all cobalt-bonded tungsten carbide compositions as cemented carbides. If the ceramic component is even finer and is present in small amounts, the material is considered a dispersion-strengthened material and therefore falls outside the accepted definition of cermets.

Like cemented carbides, cermets contain a metal binder and are produced by powder metallurgy techniques. The metallic binder phase can consist of a variety of elements, alone or in combination, such as nickel, cobalt, iron, chromium, molybdenum, and tungsten; it can also contain other metals, such as stainless steel, superalloys, titanium, zirconium, or some of the lower-melting-point copper or aluminum alloys. The volume fraction of the binder phase depends entirely on the intended properties and end use of the material. It can range anywhere from 15% to 85%, but it is generally kept at the lower half of the scale (e.g., 10%–15%).

Cermets have proven their value in a variety of applications. The most important use of cermets is in cutting tools based on titanium carbide (TiC) or titanium carbonitride (TiC,N). Steel-bonded carbides consisting of 45 vol% TiC are used in wear-resistant parts and in dies and other forming equipment components. Cermets based on UO₂, as well as those based on uranium carbide (UC), offer potential for advanced fuel elements. Cermets based on zirconium boride (ZrB₂) or silicon carbide (SiC), and others containing alumina (Al₂O₃), silicon dioxide (SiO₂), boron carbide (B₄C), or refractory compounds combined with diamonds, possess unique properties. Several are used commercially in a wide range of applications, including hot-machining tools, shaft seals, valve components and wear parts, ultrahigh-temperature exposed ducts, nozzles, and other rocket engine components, furnace fixtures and hearth elements, grinding wheels, and diamond-containing drill heads and saw teeth.

Cesium

A chemical element, cesium (symbol Cs) is the heaviest of the alkali metals in group 1. It is a soft, light, very low melting temperature metal. It is the most reactive of the alkali metals and indeed is the most electropositive and the most reactive of all the elements.

Cesium oxidizes easily in the air, ignites at ordinary temperatures, and decomposes water with explosive violence. It can be contained in vacuum, inert gas, or anhydrous liquid hydrocarbons protected from O₂ and air. The specific gravity is 1.903, melting point 28.5°C, and boiling point 670°C. It is used in low-voltage tubes to scavenge the last traces of air. It is usually marketed in the form of its compounds such as cesium nitrate, CsNO₃, cesium fluoride, CsF, or cesium carbonate, Cs₂CO₃. In the form of cesium chloride, CsCl, it is used on the filaments of radio tubes to increase sensitivity. It interacts with the thorium of the filament to produce positive ions. In photoelectric cells, CsCl is used for a photosensitive deposit on the cathode, since cesium releases its outer electron under the action of ordinary light, and its color sensitivity is higher than that of other alkali metals. The high-voltage rectifying tube for changing AC to DC has cesium metal coated on the nickel cathode, and has cesium vapor for current carrying. The cesium metal gives off a copious flow of electrons and is continuously renewed from the vapor. Cesium vapor is also used in the infrared signaling lamp as it produces infrared waves without visible light. Cesium salts have been used medicinally as antishock agents after administration of arsenic drugs.

Cesium metal is generally made by thermochemical processes. The carbonate can be reduced by metallic magnesium, or the chloride can be reduced by CaC. Metallic cesium volatile lodges from the reaction mixture and is collected by cooling the vapor.

C-Frame Press

Same as a gap-frame press.

CFRP

Carbon Fiber Reinforced Plastics.

C-Glass

A glass with a soda-lime-borosilicate composition that is used for its chemical stability and corrosive environments.

Chafing

(1) Repeated rubbing between two solid bodies that can result in surface damage and/or wear. (2) Local abrasion or sometimes an alternative term for fretting.

Chafing Fatigue

Fatigue initiated in a surface damage by rubbing against another body. See also fretting.
Chain

A length of interlinked loops intended to carry tensile loads and, sometimes transmit drive between toothed chain wheels. (2) A string of linked atoms forming, usually, an organic molecule.

Chain Intermittent Weld

A weld made intermittently along the two sides of a joint, for example, a T fillet weld, with the welds on the two sides lying opposite each other. Where the welds on one side lie opposite the gaps on the other the joint is termed a Staggered Intermittent Weld. Contrast with staggered-intermittent fillet welding.

Chain Length

In plastics, the length of the stretched linear macromolecule, most often expressed by the number of identical links.

Chain Reaction

Any continuing process occurring in repeating steps where each step initiates the next. The term often refers to nuclear reactions where fission of one atom releases neutrons that cause fission in further atoms and so on.

Chain Transfer Agent

In plastics, a molecule from which an atom, such as hydrogen, may be readily abstracted by a free radical.

Chalcogenide

A binary or ternary compound containing a chalcogen (sulfur, selenium, or tellurium) and a more electoral positive element. Ternary molybdenum chalcogenides, Mn–Mo6X8, where M is a cation and X is a chalcogen, are superconducting materials.

Chalk

A fine-grained, limestone, or a soft, earthy form of calcium carbonate, CaCO3, composed of finely pulverized marine shells. The natural chalk comes largely from the southern coast of England and the north of France, but high-calcium marbles and limestones are the sources of most U.S. chalk and precipitated calcium carbonate. Chalk is employed in putty, crayons, paints, and rubber goods, linoleum, calcimine, and as a mild abrasive in polishes. Chalk that have been ground and washed for use in paints, inks, and putty. French chalk is a high grade of massive talc cut to shape and used for marking. Chalk should be white, but it may be colored gray or yellowish by impurities. The commercial grades depend on the purity, color, and fineness of the grains. The specific gravity may be as low as 1.8.

Precipitated calcium carbonate is the whitest of the pigment extenders. Kalite, of Diamond Alkali Co., is a precipitated calcium carbonate of R.T. Vanderbilt Co., Inc., are precipitated calcium carbonates. A highly purified calcium carbonate for use in medicine as an antacid is Amitone.

Chalking

(1) Dry, chalk-like appearance of deposit on the surface of a plastic. (2) The development of loose removable powder at the surface of an organic coating usually caused by weathering.

Chamber Furnace

Powder metallurgy, a batch sintering furnace usually equipped with a retort that can be sealed gas tight.

Chamfer

(1) A beveled surface to eliminate an otherwise sharp corner. (2) A relieved angular cutting edge at a tooth corner.

Chamfer Angle

(1) The angle between a reference surface and the bevel. (2) On a milling contour, the angle between a beveled surface and the axis of the cutter.

Chamfering

Making a sloping surface on the edge of a member. Also called beveling. See also bevel angle.

Channeling

(1) The tendency of a grease or viscous oil to form air channels in a bearing or gear system, resulting in an incomplete lubricant film. (2) The tendency of a grease to form a channel by working down in a bearing or distribution system, leaving shoulders to act as a reservoir and seal.

Channeling Pattern

A pattern of lines observed in a scanning electron image of a single-crystal surface caused by preferential penetration, or channeling, of the incident beam between rows of atoms at certain orientations. The pattern provides information on the structure and orientation of the crystal.

Chaplet

Metal support that holds a core in place within a casting mold; molten metal solidifies around a chaplet and fuses it into the finished casting. They are made of similar metal to the casting.

Characteristic

A property of items in a sample or population that when measured, counted, or otherwise observed helps to distinguish between the items.
Characteristic Electron Energy Loss Phenomena

The inelastic scattering of electrons in solids that produces a discrete energy loss determined by the characteristics of the material. The most probable form is due to excitation of valence electrons.

Characteristic Radiation

Electromagnetic radiation of a particular set of wavelengths, produced by and characteristic of a particular element whenever its excitation potential is exceeded. Electromagnetic radiation is emitted as a result of electron transitions between the various energy levels (electron shells) of atoms; of atoms whose wavelengths depend only on the element concerned and the energy levels involved.

Charcoal

An amorphous form of carbon, made by enclosing billets in a retort and exposing them to a red heat for 4 or 5 h. It is also made by covering large heaps of wood with earth and permitting them to burn slowly for about a month. Much charcoal is now produced as a by-product in the distillation of wood, a retort charge of 10 cords of wood yielding an average of 2,650 gal (10,030 L) of pyroliognous liquor, 11,000 lb (4,950 kg) of gas, and 6 tons (5.4 metric tons) of charcoal. Wood charcoal is used as a fuel, for carbonizing steel, and for making activated charcoal for filtering and absorbent purposes. Gunpowder charcoal is made from alder, willow, or hazelwood. Commercial wood charcoal is usually about 25% of the original weight of the wood and is not pure carbon. The average composition is 95% carbon and 3% ash. It is an excellent fuel, burning with a glow at low temperatures and with a pale-blue flame at high temperatures. Until about 1850, it was used in blast furnaces for melting iron, and it produces a superior iron with less sulfur and phosphorus than when coke is used. Red charcoal is an impure charcoal made at a low temperature that retains much oxygen and hydrogen.

Charge

(1) All the solid materials fed into a furnace. (2) Weights of various liquid and solid materials put into a furnace during one feeding cycle. (3) The weight of plastic material used to load a mold at one time or during one cycle. (4) In the case of smelting processes this includes, ore, flux and (solid) fuel but not liquid fuel or air. In the case of secondary production processes, it includes the components being treated and usually any individual support systems but not usually items such as bogies or removable hearths that are a basic part of the furnace. (5) Any process of adding material to a body or system, of imposing a static electric field or of introducing a quantity of electricity to a battery or similar equipment. See also static charge.

Charging

(1) For a lap, impregnating the surface with fine abrasive. (2) Placing materials into a furnace.

Charpy Test

An impact test in which a V-notched, keyhole-notched, or U-notched specimen, supported at both ends, is struck behind the notch by a striker mounted at the lower end of a bar that can swing as a pendulum. The energy that is absorbed in fracture is calculated from the height to which the striker would have risen had there been no specimen and the height to which it actually rises after fracture of the specimen. Contrast with Izod test and impact test.

Charring

The heating of a reinforced plastic or composite in air to reduce the polymer matrix to ash, allowing the fiber content to be determined by weight.

Chase (Machining)

To make a series of cuts each, except for the first, following in the path of the cut preceding it, as in chasing a thread.

Chase (Plastic)

In plastic part making, an enclosure of any shape, used to shrink-fit parts of a mold cavity in place, prevent spreading or distortion in hobbing, or enclose an assembly of two or more parts in a split cavity block.

Chatter

In machining or grinding, (1) A vibration of the tool, wheel, or workpiece producing a wavy surface on the work and causes noise or local surface damage. More specifically vibration and judder of a cutting tool at the point of metal removal. This causes poor surface quality termed chatter marks. (2) The finish produced by such vibration. (3) In tribology, elastic vibrations resulting from frictional or other instability.

Chatter Marks

Surface imperfections on the work being ground, usually caused by vibrations transferred from the wheel–work interface during grinding.

Check

The intermediate section of a flask that is used between the cope and the drag when molding a shape that requires more than one parting plane.

Checked Edges

Sawtooth edges seen after hot rolling and/or cold rolling.

Checkers

In a chamber associated with a metallurgical furnace, bricks stacked openly so that heat may be absorbed from the combustion products and later transferred to incoming air when the direction of flow is reversed.

Checking

The development of slight breaks in a coating that do not penetrate to the underlying surface. See also checks (1) and craze cracking.
Checks

(1) Numerous, very fine cracks in a coating or at the surface of a metal part. Checks may appear during processing or during service and are most often associated with thermal treatment or thermal cycling. (2) The shallow surface cracking, often extensive is the result of thermal shock resulting from the stresses associated with temperature transients. Also called check marks, checking, or heat checks. (3) Minute cracks in the surface of a casting caused by unequal expansion or contraction during cooling. (4) Cracks in a die impression corner, generally due to forging strains or pressure, localized at some relatively sharp corner. Die blocks too hard for the depth of the die impression have a tendency to check or develop cracks in impression corners. (5) A series of small cracks resulting from thermal fatigue of hot forging dies.

Cheesecloth

A thin, coarse-woven cotton fabric of plain weave, 40–32 count, and of coarse yarns. It was originally used for wrapping cheese, but is now employed for wrapping, lining, interlining, filtering, as a polishing cloth, and as a backing for lining and wrapping papers. The cloth is not sized and may be either bleached or unbleached. It comes usually 36 in. (0.91 m) wide. The grade known as beef cloth, originally used for wrapping meats, is also the preferred grade for polishing enameled parts. It is made of No. 22 yarn or finer. For covering meats the packing plants now use a heavily napped knitted fabric known as stockinet. It is made either as a flat fabric or in seamless tube form, and it is also used for covering inking and oiling rolls in machinery. Later grades of cheesecloth, with very open weave, known as gauze, are used for surgical dressings and for backings for paper and maps. Baling paper is made by coating cheesecloth with asphalt and pasting to one side of heavy craft or Manila paper. Cable paper, for wrapping cables, is sometimes made in the same way but with insulating varnish instead of asphalt. Buckram is a coarse, plain-woven open fabric similar to cheesecloth but heavier and highly sized with water-resistant resins. It is usually made of cotton, but may be of linen, and is white or in plain colors. It is used as a stiffening material, for bookbindings, inner soles, and interlinings. Cotton bunting is a thin, soft, flimsy fabric of finer yarn and tighter weave than cheesecloth, used for flags, industrial linings and declarations. It is dyed in solid colors or printed. But usually, the word bunting alone refers to a more durable, and nonfading, lightweight, worsted fabric in plain weave.

Chelant/Chelate Corrosion Attack

Corrosion on the water side of steam generating tubes resulting from excessive quantities, generally or locally, of chelating agent in the same manner as caustic attack. Corrosion may also be promoted by excess oxygen, turbulence, and high water velocities.

Chelate

(1) Five- or six-membered ring formation based on intramolecular attraction of H, O, or N atoms. (2) A molecular structure in which a heterocyclic ring can be formed by the unshared electrons of neighboring atoms. (3) A coordination compound in which a heterocyclic ring is formed by a metal down to two atoms of the associated ligand. See also complexation.

Chelating Agent

(1) An organic compound in which atoms form more than one coordinate bond with metals and solution. (2) A substance used in metal finishing to control or eliminate certain metallic ions present in undesirable quantities. Same as chelant.

Chelating Agents

Also called chelants and used to capture undesirable metal ions in water solutions, affect their chemical reactivity, dissolve metal compounds, increase color intensity in organic dyes, treat waters and organic acids, and preserve quality of food products and pharmaceuticals. Three major classes of organic chelants are aminopolycarboxylic acids (APCAs), phosphonic acids, and polycarboxylic acids. The polycarboxylic acids include citrates, gluconates, polyacrylates, and polyaspartates. APCAs are stable at high temperatures and pH values, have a strong attraction for metals, and are not too costly. Their chelate stability surpasses that of the other two classes; they are useful in most industrial applications including metal cleaning, gas treatment by sulfur removal, and pulp and wood processing. The phosphonic acids are more costly but are stable over a wide range of temperature and pH values. They are used to treat waters to inhibit corrosion of storage vessels and for metals and plastics processing. The polycarboxylic acids are weak and less stable, but inexpensive and useful for alkaline-earth and hardness-ion control. In the United States, the major chelant produces are Dow Chemical, Akzo-Nobel, and BASF. Phosphates have been severely restricted for environmental reasons, especially in household detergents. EDTA has been implicated for raising metal concentrations in rivers by remobilizing metals in sludge. Citrates, which are biodegradable, are being used increasingly as substitutes for phosphates in liquid laundry detergents. NTA, a biodegradable member of EDTA, has largely replaced phosphates and detergents in Canada but is listed as a suspected carcinogen in the United States. Zeolites, though not chelants, serve as phosphate substitutes in detergents but are not as effective in removing magnesium. Polyelectrolytes, lightweight polymers of acrylic acid and maleic anhydride, reduce scale formation by dispersing calcium as fine particles.

Chelation

A chemical process involving formation of a heterocyclic ring compound that contains at least one metal cation or hydrogen ion in the ring.

Chemical Adsorption

See chemisorption.

Chemical Attack

An imprecise term implying any adverse effect resulting from a chemical reaction between a material and its environment. Such effects include chemical dissolution or combination with a component of the environment resulting in oxidation, scaling, rusting, pitting, etc., the term usually does not include damage mechanisms with a nonchemical component such as stress corrosion cracking or corrosion fatigue cracking.

Chemical Blowing Agent

In processing of plastics, an agent that readily decomposes to produce a gas.
Chemical Bonding
The joining together of atoms to form molecules. See also molecule and interatomic bonding.

Chemical Cleaning
The removal of surface films, rust and other contamination by the immersion in, or application of, appropriate chemicals.

Chemical Compound
A substance that comprises two or more elements joined in an interatomic bond in fixed weight ratios.

Chemical Conversion Coating
A protective or decorative nonmetallic coating produced in situ by chemical reaction of a metal with a chosen environment. It is often used to prepare the surface prior to the application of an organic coating.

Chemical Decomposition
The separating of a compound into its constituents.

Chemical Deposition
(1) The precipitation or plating-out of a metal from solutions of its salts through the introduction of another metal or reagent to the solution. (2) The deposition of a coating on an immersed surface by a chemical reaction between constituents of the solution or between the constituents in the surface.

Chemical Equivalent (of an Element)
The atomic weight divided by the valence.

Chemical Etching
The dissolution of the material of a surface by subjecting it to the corrosive action of an acid or an alkali.

Chemical Flux Cutting
An oxygen cutting process in which metals are severed using a chemical flux to facilitate cutting.

Chemical Indicators
Dyestuffs that have one color in acid solutions and a different color in basic or alkaline solutions. They are used to indicate the relative acidity of chemical solutions, as the different materials have different ranges of action on the acidity scale. The materials are mostly weak acids, but some are weak bases. The best known is litmus, which is red below a pH of 3.8 and blue above a pH of 8.3 and is used to test strong acids or alkalies. It is a natural dye prepared from several varieties of lichen, Variolaria, chiefly Rocella tinctoria, by allowing them to ferment in the presence of ammonia and potassium carbonate. When fermented, the mass has a blue-color and is mixed with chalk and made into tablets of papers. It is used also as a textile dye, wood stain, and food colorant.

Some coal-tar indicators are malachite green, which is yellow below a pH of 0.5 and green above 1.5; phenolphthalein, which is colorless below 8.3 and magenta above 10.0; and methyl red, which is red below 4.4 and yellow above 6.0. A universal indicator is a mixture of a number of indicators that gives a whole range of color changes, thereby indicating the entire pH range. But such indicators must be compared with a standard to determine the pH value. The change in color is caused by a slight rearrangement of the atoms of the molecule. Some of the indicators, such as thymol blue, exhibit two color changes at different acidity ranges because of the presence of more than one chromophore arrangement of atoms. These can thus be used to indicate two separate ranges on the pH scale. Test papers are strips of absorbent paper that have been saturated with an indicator and dried. They are used for testing for acidic or basic solutions, and not for accurate determination of acidity range or hydrogen-ion concentration, such as is possible with direct use of the indicators. Litmus paper is used for acidity testing. Starch-iodide paper is paper dipped in starch paste containing potassium iodide. It is used to test for halogens and oxidizing agents such as hydrogen peroxide.

Chemical Lead
Lead, usually as sheet, high purity, 99.9% or better, for chemical reaction vessels or linings.

Chemical Machining
Removing metal stock by controlled selective chemical dissolution.

Chemical Metallurgy
See process metallurgy.

Chemical Milled Parts
Chemical milling is the process of producing metal parts to predetermined dimensions by chemical removal of metal from the surface. It is a machining process in which metal is formed into intricate shapes by masking certain portions and then etching away the unwanted material. Acid or alkaline, pickling, or etching baths have been formulated to remove metal uniformly from surfaces without excessive etching, roughening, or grain boundary attack. Simple immersion of a metal part will result in uniform removal from all surfaces exposed to the chemical solution. Selective milling is accomplished by use of a mask to protect the areas where no metal is to be removed. By such means optimum strength per unit of construction weight is achieved. Nonuniform milling can be done by the protective masking procedure or by programmed withdrawal of the part from the milling bath. Complex milling is done by multiple masking and milling or withdrawal steps.

Versatility Offered
The aircraft industry, as an example, utilizes production chemical milling for weight reduction of large parts by means of precise etching. The process is the most economical means of removal of metal from large areas, nonplanar surfaces, or complex shapes. A further advantage is that metal is just as easily removed from fully hardened as from annealed parts. The advantages of chemical milling result from the fact that metal removal takes place on
Chemical Polishing

all surfaces contacted by the etching solution. The solution will easily mill inside and reentrant surfaces as well as thin metal parts or parts that are multiple racked. The method does not require elaborate fixturing or precision setups, and parts are just as easily milled after forming as in the flat. Job lots and salvage are treated, as well as production runs.

Maximum weight reduction is possible through a process of etching, milling, measuring, and remilling with steps repeated as necessary. Planned processing is the key to production of integrally stiffened structures milled so that optimum support of stresses is attained without the use of stiffening by attachment, welding, or riveting.

A level of ability comparable to that required for electroplating is necessary to produce chemically milled parts. Planned processing, solution control, and developed skill in masking and handling of the work are requisite to success. Periods to train personnel, however, are relatively short as compared to training for other precision metal-removal processes.

Tooling requirements are simple. Chemicals, tanks, racks, templates, a hoist, hangers, and a few special hand and measuring tools are required.

Although chemical milling skill can be acquired without extensive training, it is not feasible to expect to produce the extremes of complexity and precision without an accumulation of considerable experience. However, a number of organizations are available that will produce engineering quality parts on a job shop basis. The processes are well established, commercially, either in or out of the plant.

Specific Etchants Needed

It is anticipated that any metal or alloy can be chemically milled. On the other hand, it does take time to develop a specific process and only those metals can be milled for which an etchant has been developed, tested, and made available. Aluminum alloys have been milled for many years. Steel, stainless steel, nickel alloys, titanium alloys, and superalloys have been milled commercially and a great number of other metals and alloys have been milled experimentally on a small commercial scale.

It is advantageous to be able to mill a metal without changing the heat-treated condition or temper, as can be done chemically. Defective or nonhomogeneous metal, however, can respond unfavorably. Porous castings will develop holes during milling and mechanically or thermally stressed parts will change in shape as stressed metal is removed. Good-quality metal and controlled heat treating, tempering, and stress relieving are essential to uniformity and reproducibility.

Process Characteristics

Almost any metal size or shape can be milled; limitations are imposed only by extreme conditions such as complex shapes with inverted pockets that will trap gases released during milling, or very thin metal foil that is too flimsy to handle. Shapes can be milled that are completely impractical to machine. For example, the inside of a bent pipe could easily be reduced in section by chemical removal of metal. This possibility is used to advantage to reduce weight on many difficult-to-machine areas such as webs of forgings or walls of tubing. Thin sections are produced by milling when alternate machining methods are excessively costly and the optimum in design demands thin metal shapes that are beyond commercial casting, drawing, or extruding capabilities.

Surface roughness is often reduced during milling from a rough-machined, cast, or forged surface to a semimatte finish. The milled finish may vary from about 30 to 250 μin., depending on the original finish, the alloy, and the etchant. In some instances, the production of an attractive finish reduces finishing steps and is a cost advantage. So-called etching that takes place during milling often causes a brightened finish and etchants have been developed that do not result in a loss of mechanical properties.

Complement Machining

Chemical milling has flourished in the aircraft industry where paring away of every ounce of weight is important. It has spread to instrument industries where weight or balance of working parts is important to the forces required to initiate and sustain motion. It has also become a factor in the design of modern weight-limited portable equipment.

A realistic appraisal of the limitations and advantages of the process is essential to optimum designs. The best designs result from complementing mechanical, thermal, and chemical processes. Chemical milling is not a substitute for mechanical methods but, rather, is more likely as an alternative where machining is difficult or economically unfeasible. It does not compete with low-cost, mass production mechanical methods but, rather, is successful where other methods are limited due to the configuration of the part.

Tolerances

It is good design practice to allow a complex shape to be manufactured by the most economical combinations of mechanical and chemical means. To allow this, print tolerances must reflect allowances that are necessary to apply chemical milling. Chemical milling will produce less well-defined cuts, radii, and surface finishes. The tolerance of a milled cut will vary with the depth of the cut. For 2.5 mm cut, a tolerance in depth of cut of ±0.10 m is commercial. This must be allowed in addition to the original sheet tolerance. Line definition (deviation from a straight line) is usually ±0.8 mm. Unmilled lands between two milled areas should be 0.004 mm minimum. Greater precision can be had at a premium price.

In general, milling rates are about 0.0004 mm/s and depth of cut is controlled by the immersion time. Cuts up to 12.7 mm are not unrealistic although costs should be investigated before designs are made that are dependent on deep cuts.

Limitations

There are limitations to the process. Deep cuts on opposite sides of a part should not be taken simultaneously. One side can be milled at a time but it is less costly to design for one cut rather than two. Complex parts can be made by step milling or by programmed removal of parts to produce tapers. In general, step milling is less expensive and more reliable. Chemical milling engineers should be consulted relative to the feasibility and cost of complex design. Very close tolerance parts can be produced by milling, checking, masking, and re-milling but such a multiple-step process could be more costly than machining.

Chemical Polishing

A process that produces a polished surface by the action of a chemical etching solution. The etching solution is compounded so that peaks in the topography of the surface are dissolved preferentially.
The chemical dissolution is performed without the assistance of abrasives or an external electric current.

**Chemical Potential**

In a thermodynamic system of several constituents, the rate of change of the Gibbs function of the system with respect to the change in the number of moles of a particular constituent.

**Chemical Vapor Deposited (CVD) Carbon**

Carbon deposited on a substrate by pyrolysis of a hydrocarbon, such as methane.

**Chemical Vapor Deposition (CVD)**

(1) A coating process, similar to gas carburizing and carbonnitriding, whereby a reactant atmosphere gas is fed into a processing chamber where it decomposes at the surface of the workpiece, liberating one material for either absorption by, or accumulation on, the workpiece. A second material is liberated in gas form and is removed from the processing chamber, along with excess atmosphere gas. (2) Process used in manufacture of several composite reinforcements, especially boron and silicon carbide, in which desired reinforcement material is deposited from vapor phase onto a continuous core, for example, boron on tungsten wire (core).

**Chemical Wear**

See corrosive wear.

**Chemically Precipitated Powder**

A metal powder that is produced as a fine precipitate by chemical displacement.

**Chemically Strengthened**

Glass that has been ion-exchanged to produce a compressive stress layer at the treated surface.

**Chemisorption**

(1) The taking up of a liquid or gas or of a dissolved substance, only one molecular layer in thickness, wherein a new chemical compound or bond is formed between the sorbent surface atoms and those of the sorbate. (2) The binding of an adsorbate to the surface of a solid by forces whose energy levels approximate those of a chemical bond. Contrast with physisorption.

**Chevron Pattern**

A fractographic pattern of radial marks (shear ledges) that look like nested letters “V”; sometimes called a herringbone pattern. Chevron patterns are typically found on brittle fracture surfaces in parts whose widths are considerably greater than their thicknesses. The points of the chevrons can be traced back to the fracture origin.

**Chill**

(1) A metal or graphite insert embedded in the surface of a casting sand mold or core or placed in a mold cavity to increase the cooling rate at that point. (2) White iron occurring on a gray or ductile iron casting, such as the chill in the wedge test. See also chilled iron. Compare with inverse chill.

**Chill Casting**

Any casting technique which promotes rapid cooling when particularly casting into metal molds. See also splat casting.

**Chill Coating**

In casting, applying a coating to a chill that forms part of the mold cavity so that the metal does not adhere to it, or applying a special coating to the sand surface of the mold that causes the iron to undercool.

**Chill Crystals**

The first fine crystals formed on the faces of castings as a result of solidification initiating at the large number of nuclei that result from the local undercooling, i.e., chilling, by the cold mold surface.

**Chill Mark**

A wrinkled surface condition on glassware resulting from uneven cooling in the forming process.

**Chill Plate (in Welding)**

A substantial piece of material held in good thermal contact with a more flimsy component to protect that component from overheating during welding.

**Chill Ring**

See preferred term backing ring.

**Chill Roll**

A cored roll, usually temperature controlled by circulating water, that cools the web before winding. For chill roll plastic (cast) film, the surface of the roll is highly polished. In extrusion coating, either a polished or matte surface may be used, depending on the surface desired on the finish coating.

**Chill Roll Extrusion**

The extruded plastic film is cooled while being drawn around two or more highly polished chill rolls cored for water cooling for exact temperature control. Also called cast film extrusion.

**Chill Time**

See preferred term quenched time.

**Chilled Iron**

Cast iron that is poured into a metal mold or against a mold insert so as to cause the rapid solidification that often tends to produce a white iron structure in the casting.
Chin (Ceramics and Glasses)

(1) Area along an edge or corner where the material has broken off. (2) An imperfection due to breakage of a small fragment out of an otherwise regular surface.

China

A glazed or unglazed vitreous ceramic whiteware use for nontechnical purposes. This term designates such products as dinnerware, sanitary ware, and artware when they are vitreous.

Chinese-Script Eutectic

A configuration of eutectic constituents, found particularly in some cast alloys of aluminum containing iron and silicon and in magnesium alloys containing silicon, that resembles the characters in Chinese script.

Chip

(1) Small metal particles cut away during machining. (2) A integrated circuit comprising a series of interconnected electronic devices such as transistors, resistors, etc. A large number of chips are formed together on a wafer, that is, a sheet of, usually, silicon.

Chip Breaker

(1) Notch or groove in the face of a tool parallel to the cutting edge, designed to break the continuity of the chip. (2) A step formed by an adjustable component clamped to the face of the cutting tool. (3) Features in the microstructure, particularly inclusions, which provide a plane of weakness causing breakup of the material removed during machining operations. See free machining. (4) Details on the profile of a machining tool that promote material removal as chips rather than continuous strands.

Chipping

(1) Removing seams and other surface imperfections in metals manually with a chisel or gouge, or by a continuous machine, before further processing. (2) Similarly, removing excessive metal.

Chips (Composites)

Minor damage to a protruded surface of a composite material that removes material but does not cause a crack or craze.

Chips (Metals)

Pieces of material removed from a workpiece by cutting tools or by an abrasive medium.

Chisel Steel

Any steel used for chisels and similar tools. Handheld carpenter chisels are typically high carbon steels, larger chisels for more onerous duty may be of various low alloy steels. They will be hardened and tempered as appropriate to the work. See steel.

Chitin

A cellulose-like polysaccharide, it holds together the shells of such crustaceans as shrimp, crab, and lobster; and it is also found in insects, mollusks, and even some mushrooms. It ranks after cellulose as nature’s most abundant polymer. Deacetylation of chitin, a poly-N-acetyl glucose amine, yields chitosan, a cationic electrolyte that finds occasional use as a replacement for some cellulose materials. Chitosan may serve as a flocculant and wastewater treatment, thickener or extender in foods, coagulant for healing wounds in medicine, and coating for moisture proof films. Chitin is insoluble in most solvents, whereas chitosan, although insoluble in water, organic solvents, and solutions above pH 6.5, is soluble in most organic acids and dilute mineral acids. For removing heavy metals from wastewater, Manville Corp, immobilizes bacteria on diatomaceous earth and then coats the complex with chitosan; the bacteria degrade organic material, and the chitosan absorbs heavy metals, such as nickel, zinc, chromium, and arsenic.

Chloride of Lime

A white powder, a calcium chloride hypochlorite, having a strong chloride order. It decomposes easily in water and is used as a source of chlorine for cleaning and bleaching. It is produced by passing chlorine gas through slaked lime. Chloride of lime, or chlorinated lime, is also known as bleaching powder, although commercial bleaching powder may also be a mixture of calcium chloride and calcium hypochlorite, and the term bleach is used for many chlorinated compounds.

Chlorinated Hydrocarbons

A large group of materials that have been used as solvents for oils and fats, for metal degreasing, dry cleaning of textiles, as refrigerants, in insecticides and fire extinguishers, and as foam-blowing agents. They range from the gaseous methyl chloride to the solid hexachloroethane, with most of them liquid. The increase in the number of chlorine atoms increases the specific gravity, boiling point, and some other properties. They may be divided into four groups: the methane group, including methyl chloride, chloroform, and carbon tetrachloride; the ethylene group, including dichloroethylene; the ethane group, including ethyl chloride and dichloroethane; and the propane group. All of these are toxic, and the fumes are injurious when breathed or absorbed through the skin. Some decompose in light and heat to form more toxic compounds. Some are very inflammable, while others do not support combustion. In general, they are corrosive to metals. Some have been implicated in the depletion of ozone in the stratosphere.

Chloroform, or trichloromethane or methenyl trichloride, is a liquid of composition CHCl₃. Used industrially as a solvent for greases and resins and in medicine as an anesthetic. It decomposes easily in the presence of light to form phosgene, and a small amount of ethyl alcohol is added to prevent decomposition. Ethyl chloride is a gas used in making ethyl fuel for gasoline, as a local anesthetic in dentistry, as a catalyst in rubber and plastics processing, and as a refrigerant and household refrigerators. It is marketed compressed into cylinders as a colorless liquid. Its disadvantage as a refrigerant is that it is highly inflammable, and there is no simple test for leaks. Methyl chloride is a gas which is compressed into cylinders as a colorless liquid. Methyl chloride is one of the simplest and cheapest chemicals for methylation. In water solution, it is a good solvent. It is also used as a catalyst in rubber processing, as a restraining gas in high-heat thermometers,
and as a refrigerant. Monochlorobenzene is a colorless liquid, not soluble in water. It is used as a solvent for lacquers and resins, as a heat-transfer medium, and for making other chemicals. Trichloro cumene, or isopropyl trichlorobenzene, is valued as a hydraulic fluid and dielectric fluid because of its high dielectric strength, low solubility in water, and resistance to oxidation. It is a colorless liquid. Halane, used in processing textiles and paper, is a white powder containing 66% available chlorine.

Chlorinated Lubricant

A lubricant containing a chlorine compound that reacts with a rubbing surface at elevated temperatures to protect it from sliding damage. See also extreme-pressure lubricant, sulfochlorinated lubricant, and sulfurized lubricant.

Chlorinated Polyether

Chlorinated polyether is a thermoplastic resin used in the manufacture of process equipment. Chemically, it is a chlorinated polyether of high molecular weight, crystalline in character, and is extremely resistant to thermal degradation at molding and extrusion temperatures. It possesses a unique combination of mechanical, electrical, and chemical-resistant properties, and can be molded in conventional injection and extrusion equipment.

Properties

Chlorinated polyether provides a balance of properties to meet severe operating requirements. It is second only to the fluorocarbons in chemical and heat resistance and is suitable for high-temperature corrosion service.

Mechanical Properties

A major difference between chlorinated polyether and other thermoplastics is its ability to maintain its mechanical strength properties at elevated temperatures. Heat distortion temperatures are above those usually found in thermoplastics and dimensional stability is exceptional even under the adverse conditions found in chemical plant operations. Resistance to creep is significantly high and in sharp contrast to the lower values of other corrosion-resistant thermoplastics. Water absorption is negligible, assuring no change in molded shapes between wet and dry environments.

Chemical Properties

Chlorinated polyether offers resistance to more than 300 chemicals and chemical reagents, at temperatures up to 121°C and higher, depending on environmental conditions. It has a spectrum of corrosion resistance second only to certain of the fluorocarbons.

In steel construction of chemical processing equipment, chlorinated polyether liners or coatings on steel substrates provide the combination of protection against corrosion plus structural strength of metal.

Electrical Properties

Along with the mechanical capabilities and chemical resistance, chlorinated polyether has good dielectric properties. Loss factors are somewhat higher than those of polystyrenes, fluorocarbons, and polyethylenes, but are lower than many other thermoplastics.

Dielectric strength is high and electrical values show a high degree of consistency over a range of frequencies and temperatures.

Fabrication

The material is available as a molding powder for injection-molding and extrusion applications. It can also be obtained in stock shapes such as sheet, rods, tubes, or pipe, and blocks for use in lining tanks and other equipment, and for machining gears, plugs, etc. In the form of a finely divided powder, it is used in a variety of different coating processes.

The material can be injection-molded by conventional procedures and equipment. Molding cycles are comparable to those of other thermoplastics. Rods, sheet, tubes, pipe, blocks, and wire coatings can be readily extruded on conventional equipment and by normal production techniques. Parts can be machined from blocks, rods, and tubes on conventional metalworking equipment.

Sheet can be used to convert carbon steel tanks into vessels capable of handling highly corrosive liquids at elevated temperatures. Using a conventional adhesive system and hot gas welding, sheet can be adhered to sandblasted metal surfaces.

Coatings of a finely divided powder can be applied by several coating processes and offer chemical processors an effective and economical means for corrosion control. Using the fluidized bed process, pretreated, preheated metal parts are dipped in an air-suspended bed of finely divided powder to produce coatings, which after baking are tough, pinhole free and highly resistant to abrasion and chemical attack. Parts clad by this process are protected against corrosion both internally and externally.

Uses

Complete anticorrosive systems are available with chlorinated polyether, and lined or coated components, including pipe and fittings, tanks and processing vessels, valves, pumps, and meters.

Rigid uniform pipe extruded from solid material is available in sizes ranging from 12.7 to 50.8 mm in either Schedule 40 or 80, and in lengths up to 6 m. This pipe can be used with injection-molded fittings with socket or threaded connections.

Lined tanks and vessels are useful in obtaining maximum corrosion and abrasion resistance in a broad range of chemical exposure conditions. Storage tanks, as well as processing vessels protected with this impervious barrier, offer a reasonably priced solution to many processing requirements.

A number of valve constructions can be readily obtained from leading valve manufacturers. Solid injection-molded ball valves, coated diaphragm, and plug valves are among the variety available. Also available are diaphragm valves with solid chlorinated polyether bodies.

Chlorinated Polyethylene

This family of elastomers is produced by the random chlorination of high-density polyethylene. Because of the high degree of chemical saturation of the polymer chain, the most desirable properties are obtained by cross-linking with the use of peroxides or by radiation. Sulfur donor cure systems are available that produce vulcanizates with only minor performance losses compared to that of peroxide cures. However, the free radical cross-linking by means of peroxides is most commonly used and permits easy and safe processing, with outstanding shelf stability and optimum cured properties.
Chlorinated Rubber

An ivory-colored or white powder produced by the reaction of chlorine and rubber. It contains about 67% by weight of rubber, although it is a mixture of two products, one having a CH₂ linkage instead of a CHCl. Chlorinated rubber is used in acid-resistant and corrosion-resistant paints, in adhesives, and in plastics.

The uncompounded film is brittle, and for paints chlorinated rubber is plasticized to produce a hard, tough, adhesive coating, resistant to oils, acids, and alkalies. It is soluble in hydrocarbons, carbon tetrachloride, and esters, but insoluble in water. The unplasticized material has a high dielectric strength, up to 2300 V/mil (90.6 x 10⁶ V/m). Pliofilm, of Goodyear Tire and Rubber Company, is a rubber hydrochloride made by saturating the rubber molecule with hydrochloric acid. It is made into transparent sheet wrapping material which heat-seals at 221°F–266°F (105°C–130°C), or is used as a coating material for fabrics and paper. It gives a tough, flexible, water-resistant film. Betacote 95 is a maintenance paint for chemical processing plants which is based on chlorinated rubber. It adheres to metals, cements, and wood and is rapid-drying; the coating is resistant to acids, alkalies, and solvents.

Chlorination

(1) Roasting ore in contact with chlorine or a chloride salt to produce chlorides. (2) Removing dissolved gases and entrapped oxides by passing chlorine gas through molten metal such as aluminum and magnesium. (3) The most common is chlorination of water to kill bacteria. (4) In a metallurgical context, chlorine may be injected into molten magnesium as a deoxidizing and degassing agent.

Chlorine

An elementary material, symbol Cl₂, which at ordinary temperatures is a gas. It occurs in nature in great abundance and combinations, and in such compounds as common salt. A yellowish-green gas, it has a powerful suffocating odor and is strongly corrosive to organic tissues and to metals. During World War I, it was used as a poison gas under the name Bertholite. An important use for liquid chlorine is for bleaching textiles and paper pulp, but is also used for the manufacture of many chemicals. It is a primary raw material for chlorinated hydrocarbons and for such inorganic chemicals as titanium tetrachloride. Chlorine is used extensively for treating potable, process, and wastewaters. Its use as a biocide has declined due to toxicological and safety issues. A key issue is the chlorinated organics, such as trihalomethanes (THMs), that form when chlorine reacts with organics and water. One alternative to chlorine biocides for process waters is FMC Corp.’s tetra alkyl phosphonium chloride, a strong biocide containing a surface-active agent that cleans surfaces fouled by biofilm. Use of chlorine in fluorocarbons has decreased as chlorofluorocarbons have been replaced with non-ozone-depleting compounds. Its use in chlorofluorocarbons, such as CFC-11 and CFC-12, is decreasing, as these are replaced with more environmentally acceptable refrigerants. Chlorine’s used in bleach also has declined. For bleaching, it has been widely employed in the form of compounds easily broken up. The other two oxides of chlorine are also unstable. Chlorine monoxide, or hypochlorous anhydride, Cl₂O₃, is a highly explosive gas. Chlorine heptoxide, or perchloric anhydride, Cl₇O₇, is an explosive liquid. The chlorinating agents, therefore, are largely limited to the more stable compounds. Dry chlorines are used in cleansing powders and for detinning steel, where the by-product is tin tetrachloride.

Chloride may be made by the electrolysis of common salt. The gas is an irritant and not a cumulative poison, but breathing large amounts destroys the tissues. Commercial chlorine is produced in making caustic soda, by treatment of salt with nitric acid, and as a by-product in the production of magnesium metal from seawater or brines. The chlorine yield is from 1.8 to 2.7 times the weight of the magnesium produced.

Chlorine Extraction

Removal of phases by formation of a volatile chloride. See also extraction.

Chlorofluorocarbon Plastics

Plastics based on polymers made with monomers composed of chlorine, fluorine, and carbon only.

Chlorofluorohydrocarbon Plastics

Plastics based on polymers made with monomers composed of chlorine, fluorine, hydrogen, and carbon only.

Chlorosulfonated Polyethylene

This material, more commonly known as Hypalon, can be compounded to have an excellent combination of properties including virtually total resistance to ozone and excellent resistance to abrasion, weather, heat, flame, oxidizing chemicals, and crack growth. In addition, the material has low moisture absorption, good dielectric properties, and can be made in a wide range of colors because it does not require carbon black for reinforcement. Resistance to oil is similar to that of neoprene. Low-temperature flexibility is fair at −40°C. The material is made by reacting polyethylene with chlorine and SO₂ to yield chlorosulfonated polyethylene. The reaction changes the thermoplastic polyethylene into a synthetic elastomer that can be compounded and vulcanized. The reaction changes the thermoplastic polyethylene into a synthetic elastomer that can be compounded and vulcanized. The reaction changes the thermoplastic polyethylene into a synthetic elastomer that can be compounded and vulcanized. The reaction changes the thermoplastic polyethylene into a synthetic elastomer that can be compounded and vulcanized.

Selection

Hypalon is a special-purpose rubber, not particularly recommended for dynamic applications. The elastomer is produced in various types, with generally similar properties. The design engineer can best rely on the rubber formulator to select the appropriate type for a given application, based on the nature of the part, the properties required, the exposure, and the performance necessary for successful use.

In combination with properly selected compounding ingredients, the polymer can be extruded, molded, or calendered. In addition, it can be dissolved to form solutions suitable for protective or decorative coatings.
Chord Modulus

Initially used in pump and tank linings, tubing, and comparable applications where chemical resistance was of prime importance, this synthetic rubber is now finding many uses where its weatherability, its colorability, its heat, ozone, and abrasion resistance, and its electrical properties are of importance. Included are jacketing and insulation for utility distribution cable, control cable for atomic reactors, automotive primary and ignition wire, and linemen’s blankets. Among heavy-duty applications are conveyor belts for high-temperature use and industrial rolls exposed to heat, chemicals, or abrasion.

Interior, exterior, and underhood parts for cars and commercial vehicles are an increasingly important area of use. Representative automotive applications are headliners, window seals, spark plug boots, and tractor seat coverings.

Chlorosulfonated polyethylene is used in a variety of mechanical goods, such as V-belts, motor mounts, O-rings, seals, and gaskets, as well as in consumer products like shoe soles and garden hose. It is also used in white sidewalls on automobile tires. In solution, it is used for fluid-applied roofing systems and pool liners, for masonry coatings, and various protective-coating applications. It can also be extruded as a protective and decorative veneer for such products as sealing and glazing strips.

Chord Modulus

The slope of the chord drawn between any two specific points on a stress–strain curve. See also modulus of elasticity.

Chromatography

The separation, especially of closely related compounds, caused by allowing a solution or mixture to seep through an absorbent (such as clay, gel, or paper) such that each compound becomes absorbed in a separate, often colored, layer.

Chrome Plating

(1) Producing a chromate conversion coating on magnesium for temporary protection or for a paint base. (2) The solution heat produces the conversion coating. (3) Is widely used where extreme hardness or resistance to corrosion is required. When plated on a highly polished metal, it gives a smooth surface that has no capillary attraction to water or oil, and chromium-plated bearing surfaces can be run without oil. For decorative purposes, chromium plates as thin as 0.0002 in. (0.0006 cm) may be used.

Chromel

(1) A 90Ni–10Cr alloy used in thermocouples. (2) A series of nickel–chromium alloys, some with iron, used for heat-resistant applications. (3) The most well-known that, with Alumel, is widely used for thermocouples.

Chromia

Formula Cr₂O₃, a compound having many properties and derivatives similar to those of alumina. Useful either pure or impure (e.g., as chrome ore) in both basic and high-alumina refractories.

Chromic Acid

A name given to the red, crystalline, strongly acid material of composition CrO₃ known also as chromium trioxide or as chromic anhydride. It is, in reality, not the acid until dissolved in water, forming a true chromic acid of composition H₂CrO₄. It is marketed in the form of porous lumps. It is produced by treating sodium or potassium dichromate with sulfuric acid. The dust is irritating and the fumes of the solutions are injurious to the nose and throat because the acid is a powerful oxidizing agent. Chronic acid is used in chromium-plating baths, for etching copper, and electric batteries, and in tanning leather.

Chrome oxide green is a chromic oxide in the form of dry powder or ground in oil, used in paints and lacquers and for coloring rubber. It is a bright-green crystalline powder of composition Cr₂O₃ and insoluble in water. The dry powder has a Cr₂O₃ content of 97% minimum and is 325 mesh. The paste contains 85% pigment and 15% linseed oil. Chrome oxide green is not as bright in color as chrome green but is more permanent.

Chromium

An elementary metal, chromium (symbol Cr) is used in stainless steels, heat-resistant alloys, high-strength alloy steels, electrical-resistance alloys, wear-resistant and decorative electroplating, and, in its compounds, for pigments, chemicals, and refractories. The specific gravity is 6.92, melting point 1510°C, and boiling point 2200°C. The color is silvery white with a bluish tinge. It is an extremely hard metal; the electrodeposited plates have a hardness of 9 Mohs. It is resistant to oxidation, is inert to HNO₃, but dissolves in HCl and slowly in H₂SO₄. At temperatures above 816°C, it is subject to intergranular corrosion.
Chromium Alloys and Steels

Chromium occurs in nature only in combination. Its chief ore is chromite, from which it is obtained by reduction and electrolysis. It is marketed for use principally in the form of master alloys with iron or copper.

Most pure chromium is used for alloying purposes such as the production of Ni–Cr or other nonferrous alloys where the use of the cheaper ferrochrome grades of metal is not possible. In metallurgical operations such as the production of low-alloy and stainless steels, the chromium is added in the form of ferrochrome, an electric-arc furnace product that is the form in which most chromium is consumed.

Uses

Its bright color and resistance to corrosion make chromium highly desirable for plating plumbing fixtures, automobile radiators and bumpers, and other decorative pieces. Unfortunately, chrome plating is difficult and expensive. It must be done by electrolytic reduction of dichromate in \( \text{H}_2\text{SO}_4 \) solution. It is customary, therefore, to first plate the object with copper, then with nickel, and finally, with chromium.

Alloys

In alloys with iron, nickel, and other metals, chromium has many desirable properties. Chrome steel is hard and strong and resists corrosion to a marked degree. Stainless steel contains roughly 18% chromium and 8% nickel. Some chrome steels can be hardened by heat treatment and find use in cutlery; still others are used in jet engines. Nichrome and chromel consist largely of nickel and chromium; they have low electrical conductivity and resist corrosion, even at red heat, so they are used for heating coils in space heaters, toasters, and similar devices. Other important alloys are Hastelloys—chromium, molybdenum, tungsten, iron, nickel—used in chemical equipment that is in contact with \( \text{HCl} \), oxidizing acids, and hypochlorite. Stellite—cobalt, chromium, nickel, carbon, tungsten (or molybdenum)—noted for its hardness and abrasion resistance at high temperatures, is used for lathes and engine valves, and Inconel—chromium, iron, nickel—is used in heat treating and corrosion-resistant equipment in the chemical industry.

Biological Aspects

Chromium is essential to life. A deficiency (in rats and monkeys) has been shown to impair glucose tolerance, decrease glycogen reserve, and inhibit the utilization of amino acids. It has also been found that inclusion of chromium in the diet of humans sometimes, but not always, improves glucose tolerance.

On the other hand, chromates and dichromates are severe irritants to the skin and mucous membranes, so workers who handle large amounts of these materials must be protected against dusts and mists. Continued breathing of the dusts finally leads to ulceration and perforation of the nasal septum. Contact of cuts or abrasions with chromate may lead to serious ulceration. Even on normal skin, dermatitis frequently results.

Chromium Alloys and Steels

Chromium Copper

A name applied to master alloys of copper with chromium used in the foundry for introducing chromium into nonferrous alloys or to copper–chromium alloys, or chromium copper alloys, which are high-copper alloys. A chromium–copper master alloy, Electromet chromium copper, contains 8%–11% chromium, 88%–90% copper, and a maximum of 1% iron and 0.50% silicon.

Wrought chromium copper alloys are designated C18200, C18400, and C18500, and contain 0.4%–1.0% chromium. Soft, thus ductile, in the solution-treated condition, these alloys are readily cold-worked and can be subsequently precipitation-hardened. Depending on such treatments, tensile properties range from 35,000 to 70,000 lb/\( \text{in}^2 \) (241 to 483 MPa) ultimate strength, 15,000 to 62,000 lb/\( \text{in}^2 \) (103 to 427 MPa) yield strength, and 15% to 42% in elongation. Electrical conductivity ranges from 40% to 85% that of copper. Chromium copper alloys are used for resistance-welding electrodes, cable connectors and electrical parts.

Cr–Mo Steel

This is any alloy steel containing chromium and molybdenum as key alloying elements. However, the term usually refers specifically to steels in the American Iron and Steel Institute (AISI) 41XX series, which contain only 0.30%–1.20% chromium and 0.08%–0.35% molybdenum. Chromium imparts oxidation and corrosion resistance, hardenability, and high-temperature strength. Molybdenum also increases strength, controls hardenability, and reduces the tendency to temper embrittlement. AISI 4130 steel, which contains 0.30% carbon, and 4140 (0.40%) are probably the most common and can provide tensile strengths well above 1379 MPa. Many other steels have greater chromium and/or molybdenum content, including high-pressure boiler steels, most tool steels, and stainless steels. Croloy 2, which is used for boiler tubes for high-pressure superheated steam, contains 2% chromium and 0.50% max molybdenum, and is for temperatures to 621°C, and Croloy 5, which has 5% chromium and 0.50% max molybdenum, is for temperatures to 649°C and higher pressures as well as Croloy 7, which has 7% chromium and 0.50% molybdenum.

Chromium Steels

Any steel containing chromium as the predominating alloying element may be termed chromium steel, but the name usually refers to the hard, wear-resisting steels that derive the property chiefly from the chromium content. Straight chromium steels refer to low-alloy steels in the AISI 50XX, 51XX, and 61XX series. Chromium combines with the carbon of steel to form a hard \( \text{CrC} \), and it restricts graphitization. When other carbide-forming elements are present, double or complex carbides are formed. Chromium refines the structure, provides deep-hardening, increases the elastic limit, and gives a slight red-hardness so that the steels retain their hardness at more elevated temperatures. Chromium steels have great resistance to wear. They also withstand quenching in oil or water without much deformation. Up to about 2% chromium may be included in tool steels to add hardness, wear resistance, and nondeforming qualities. When the chromium is high, the carbon may be much higher than in ordinary steels without making the steel brittle. Steels with 12%–17% chromium and about 2.5% carbon have remarkable wear-resisting qualities and are used for cold-forming dies for hard metals, for broaches, and for rolls. However, chromium narrows the hardening range of steels unless balanced with nickel. Such steels also work-harden rapidly unless modified with other elements. The high-chromium steels are corrosion resistant and heat resistant but are not to be confused with the high-chromium stainless steels that are low in carbon, although the non-nickel 4XX stainless steels are very definitely chromium steels. Thus, the term is indefinite but...
may be restricted to the high-chromium steels used for dies, and to those with lower chromium used for wear-resistant parts such as ball bearings.

Chromium steels are not especially corrosion resistant unless the chromium content is at least 4%. Plain chromium steels with more than 10% chromium are corrosion resistant even at elevated temperatures and are in the class of stainless steels, but are difficult to weld because of the formation of hard brittle martensite along the weld.

Chromium steels with about 1% chromium are used for gears, shafts, and bearings. One of the most widely used bearing steels is AISI 52100, which contains 1.3%–1.6% chromium. Many other chromium steels have greater chromium content and, often, appreciable amounts of other alloying elements. They are used mainly for applications requiring corrosion, heat, and/or wear resistance.

**Cr–V Steels**

Alloy steel containing a small amount of chromium and vanadium, the latter having the effect of intensifying the action of the chromium and the manganese in the steel and controlling grain growth. It also aids in formation of carbides, hardening the alloy, and in increasing ductility by the deoxidizing effect.

The amount of vanadium is usually 0.15%–0.25%. These steels are valued where a combination of strength and ductility is desired. They resemble those with chromium alone, with the advantage of the homogenizing influence of the vanadium. A Cr–V steel with 0.92% chromium, 0.20% vanadium, and 0.25% carbon has a tensile strength up to 689 MPa, and when heat-treated has a strength up to 1034 MPa and elongation 16%. Cr–V steels are used for such parts as crankshafts, propeller shafts, and locomotive frames. High-carbon Cr–V steels are the mild-alloy tool steels of high strength, toughness, and fatigue resistance. The chromium content is usually about 0.80%, with 0.20% vanadium, and with carbon up to 1%.

**Chromium–Molybdenum Heat-Resistant Steels**

Alloy steels containing 0.5%–9% Cr and 0.5%–1.10% Mo with a carbon content usually below 0.20%. The chromium provides improved oxidation and corrosion resistance, and the molybdenum increases strength at elevated temperatures. Chromium–molybdenum steels are widely used in the oil and gas industries and fossil fuel and nuclear power plants.

**Chromizing**

(1) A surface treatment at elevated temperature, generally carried out in pack, vapor, or salt baths, in which an alloy is formed by the inward diffusion of chromium into the base metal. (2) Usually at elevated temperature, which causes chromium to diffuse into the surface to improve corrosion resistance.

**Chuck**

A device for holding work or tools on a machine so that the part can be held or rotated during machining or grinding.

**Chucking Hog**

A projection forged or cast onto a part to act as a positive means of driving or locating the part during machining.

**Circuit Breaker**

In powder metallurgy, a feeding trough for powder to pass from a fill hopper to the die cavity and an automatic press.

**CIL Flow Test**

A method of determining the rheology or flow properties of thermoplastic resins. In this test, the amount of the molten resin that is forced through a specified size orifice per unit of time when a specified variable force is applied gives a relative indication of the flow properties of various resins.

**CIP**

The acronym for cold isostatic pressing.

**Circle Grid**

A regular pattern of circles, often 2.5 mm (0.1 in.) in diameter, marked on a sheet metal blank.

**Circle Grinding**

Either cylindrical grinding or internal grinding; the preferred terms.

**Circle Shear**

A shearing machine with two rotary disc cutters mounted on parallel shafts driven in unison and equipped with an attachment for cutting circles where the desired piece of material is inside the circle. It cannot be employed to cut circles where the desired material is outside the circle.

**Circle-Grid Analysis**

The analysis of deformed circles to determine the severity with which a sheet metal blank has been deformed.

**Circuit**

(1) In filament winding of composites, one complete traverse of a winding band from one arbitrary point along the winding path to another point on a plane through the starting point and perpendicular to the axis. (2) The interconnection of a number of components in one or more closed pairs to perform a desired electrical or electronic function.

**Circuit Board**

In electronics, a sheet of insulating material laminated to foil that is etched to produce a circuit pattern on one or both sides. Also called printed circuit board or printed wiring board.

**Circuit Breaker**

A device designed to open and close a circuit by nonautomatic means and to open the circuit automatically on a predetermined overload of current, without injury to itself, when properly applied within its rating.
Circular Electrode

See resistance welding electrode.

Circular Field

The magnetic field that (a) surrounds a nonmagnetic conductor of electricity, (b) is completely contained within a magnetic conductor of electricity, or (c) both exists within and surrounds a magnetic conductor. Generally applied to the magnetic field within any magnetic conductor resulting from a current being passed through the part or through a section of the part. Compare with bipolar field.

Circular Mill

A measurement used to determine the area of wire. The area of a circle that is one one-thousandth inch in diameter.

Circular Resistance Seam Welding

See preferred term transverse resistance seam welding.

Circular-Step Bearing

A flat circular hydrostatic bearing with a central circular recess. See also step bearing.

Circumferential ("Circ") Winding

In filament-wound reinforced plastics, a winding with the filaments essentially perpendicular to the axis (90° or level winding).

Circumferential Resistance Seam Welding

See preferred term transverse resistance seam welding.

CIS Stereoisomer

In engineering plastics, a stereoisomer in which side chains or side atoms are arranged on the same side of a double bond present in a chain of atoms.

Citric Acid

C₆H₈O₇, produced from lemons, limes, and pineapples, is a colorless, odorless, crystalline powder of specific gravity 1.66 and melting point 307°F (153°C). It is also produced by the fermentation of blackstrap molasses. It is used as an acidulent in effervescent salts in medicine, and jams, jellies, and carbonated beverages in the food industry. Acetyl tributyl citrate is a vinyl resin plasticizer. It is also used in inks, etching, and as a resist in textile dyeing and printing. It is a good antioxidant and stabilizer for tableau and other fats and greases, but is poorly soluble in fats. Citric acid is also used as a preservative in frozen fruits to prevent discoloration and storage. Its salt, sodium citrate, is a water-soluble crystalline powder used in soft drinks to give a nippy saline taste, and it is also used in plating baths. Citric acid is a strong chelant and finds use in regenerating ion-exchange resins, recovering metals and spent baths, decontaminating radioactive materials, and controlling metal-ion catalysis. For example, it can be used to extract metal contaminants from incinerator ash and to treat uranium-contaminated soils.

Circular Electrode Clad Metals

Combinations

The following clad materials are in common use:

- Stainless steel on steel: Provides corrosion resistance and attractive surface at low cost for food display cases, chemical-processing equipment, sterilizers, and decorative trim.
- Stainless steel on copper: Combines surface protection and high thermal conductivity for pots and pans, and for heat exchangers for chemical processes.
• **Copper on aluminum**: Reduces cost of electrical conductors and saves copper on appliance wiring.
• **Copper on steel**: Adds electrical conductivity and corrosion resistance needed in immersion heaters and electrical switch parts; facilitates soldering.
• **Nickel or Monel on steel**: Provides resistance to corrosion and erosion for furnace parts, blowers, chemical equipment, toys, brush ferrules, and many mechanical parts in industrial and business machines; more durable than electroplating.
• **Titanium on steel**: Supplies high-temperature corrosion resistance. Bonding requires a thin sheet of vanadium between titanium and steel.
• **Bronze on copper**: Usually clad on both sides, for current-carrying springs and switch blades; combines good electrical conductivity and good spring properties.
• **Silver on copper**: Provides oxidation resistance to surface of conductors, for high-frequency electrical coils, conductors, and braiding.
• **Silver on bronze or nickle**: Adds current-carrying capacity to low-conductivity spring material; cladding sometimes is in form of stripes or inlays with silver areas serving as built-in electrical contacts.
• **Gold on copper**: Supplies chemical resistance to a low-cost base metal for chemical processing equipment.
• **Gold on nickel or brass**: Adds chemical resistance to a stronger base metal than copper; also used for jewelry, wristbands, and watchcases.

**Applications**

Gold-filled jewelry has long been made by the cladding process: the surface is gold, the base metal bronze or brass with the cladding thickness usually 5%. The process is used to add corrosion resistance to steel and to add electrical or thermal conductivity, or good bearing properties, to strong metals. One of the first industrial applications was the use of a nickel-clad steel plate for a railroad tank car to transport caustic soda; stainless clad steels are used for food and pharmaceutical equipment. Corrosion-resistant pure aluminum is clad to a strong duralumin base, and many other combinations of metals are widely used in cladding; there is also a technique for cladding titanium to steel for jet engine parts.

Today’s coinage uses clad metals as a replacement for rare silver. Dimes and quarters have been minted from composite sheet consisting of a copper core with Cu–Ni facing. The proportion of core and facing used duplicates the weight and electrical conductivity of silver so the composite coins are acceptable in vending machines.

A three-metal composite sole plate for domestic steam irons provides a thin layer of stainless steel on the outside to resist wear and corrosion. A thick core of aluminum contributes thermal conductivity and reduces weight, and a thin zinc layer on the inside aids in bonding the sole plate to the body of the iron during casting.

Clad metals have been applied in nuclear power reactor pressure vessels in submarines as well as in civilian power plants.

Other applications where use of clad is increasing are in such fields as fertilizer, chemicals, mining, food processing, and even seagoing wine tanks.

Producers see a market for clad metal curtain wall building panels, and even stainless clad bus and automobile bumpers.

Aluminum-clad wire for electric coils is copper wire coated with aluminum to prevent deterioration of the enamel insulation caused by copper oxide. Solder-clad aluminum strip, developed by Heraeus Holding, GmbH, has soft solder adhesive-bonded to both sides and is intended for heat exchangers and other products.

DuPont cladding has been applied by explosive bonding and Bethlehem Lukens just as well by roll bonding. Clad plate includes carbon, alloy, and stainless-steel plate clad with stainless steel, copper or nickel alloys, titanium, tantalum, or zirconium. Clad-plate transition joints are made by DuPont. Other products include clad wire, clad rivets, and clad welding tapes.

**Composite tool steel**, used for shear blades and die parts, is not a laminated metal. The term refers to bar steel machined along the entire length and having an insert of tool steel welded to the backing of mild steel. Clad steels are available regularly in large sheets and plates. They are clad with nickel, stainless steel, Monel metal, aluminum, or special alloys on one or both sides of the sheet. Where heat and pressure are used in the processing, there is chemical bonding between the metals. For some uses the cladding metal on one side will be 10%–20% of the weight of the sheet. A composite plate having an 18-8 stainless steel cladding to a thickness of 20% on one side saves 100 and 144 lb (65 kg) of chromium and 64 lb (29 kg) of nickel per 1000 lb (454 kg) of total plate. The clads may also be extremely thin.

Stainless-clad copper is copper sheet with stainless steel on both sides, used for making cooking utensils and food processing equipment. With stainless steel alone, heat remains localized and causes sticking and burning of foodstuffs. Copper has high heat conductivity, is corroded by some foods, and has an injurious catalytic action on milk products. Thus, the stainless-clad copper gives a conductivity of copper with the protection of stainless steel. The internal layer of copper also makes the metal easier to draw and form.

**Cladding**

(1) A layer of material, usually metallic, that is mechanically or metallurgically bonded to a substrate. Cladding may be bonded to the substrate by any of several processes, such as roll-cladding and explosive forming. (2) A relatively thick layer (>1 mm, or 0.04 in.) of material applied by surfacing for the purpose of improved corrosion resistance or other properties. (3) The application of a substantial coating of one type of metal to a substrate of another. For example, a strong, corrosion-prone aluminum alloy plate can be clad with a corrosion-resistant but weak “pure” aluminum. Such cladding is accomplished by rolling either a pair of the materials or a sandwich comprising a slab of the alloy between two slabs of “pure” material. Rolled gold is another example. See also coating, surfacing, and hard facing.

**Clamping Pressure**

In injection molding and transfer molding of plastics, the pressure that is applied to the mold to keep it closed in opposition to the fluid pressure of the compressed molding material, within the mold cavity (cavities) and the runner system. In blow molding, the pressure exerted on the two mold halves (by the locking mechanism of the blowing table) to keep the mold closed during formation of the container. Normally, this pressure or force is expressed in tons.

**Clamshell Marks**

Same as beach marks.

**Classification**

(1) The separation of ores into fractions according to size and specific gravity, generally in accordance with Stokes’ law of sedimentation. (2) Separation of a metal powder into fractions according to particle size.
Clay

Clay is composed of naturally occurring sediments that are produced by chemical actions resulting during the weathering of rocks. Often clay is the general term used to identify all earths that form a paste with water and harden when heated. The primary clays are those located in their place of formation. Secondary clays are those that have been moved after formation to other locations by natural forces, such as water, wind, and ice. Most clays are composed chiefly of SiO₂ and Al₂O₃. Clays are used for making pottery, tiles, brick, and pipes, but more particularly the better grade of clays are used for pottery and molded articles not including the fireclays and fine porcelain clays. Kaolins are the purest forms of clay. Clay is a natural mineral aggregate, consisting essentially of hydrous aluminum silicates. It is plastic when sufficiently wetted, rigid when dried en masse, and vitreous when fired to a sufficiently high temperature.

The fineness of the grain of a clay influences not only its plasticity but also such properties as drying performance, drying shrinkage, warping, and tensile, transverse, and bonding strength. For example, the greater the proportion of fine material, the slower the drying rate, the greater the shrinkage, and the greater the tendency to warping and cracking during this stage. Clays with a high fines content usually are mixed with coarser materials to avoid these problems.

For two clays with different degrees of plasticity, the more plastic one will require more water to make it workable, and water loss during drying will be more gradual because of its more extensive capillary system. The high-plasticity clay also will shrink more and will be more likely to crack.

The most important clays in the pottery industry are the ball clays and china clays (kaolin).

Commercial Clay

Commercial clays, or clays utilized as raw material in manufacturing, are among the most important nonmetallic mineral resources. The value of clays is related to their mineralogical and chemical composition, particularly the clay mineral constituents kaolinite, montmorillonite, illite, chlorite, and attapulgite. The presence of minor amounts of mineral or soluble salt impurities in clays can restrict their use. The more common mineral impurities are quartz, mica, carbonates, iron oxides and sulfides, and feldspar. In addition, many clays contain some organic material.

Mining and Processing

Almost all the commercial clays are mined by open-pit methods, with overburden-to-clay ratios ranging as high as 10⁻¹. The overburden is removed by motorized scrapers, bulldozers, shovels, or draglines. The clay is removed with draglines, shovels, or bucket loaders, and transported to the processing plants by truck, rail, aerial trainways, or belt conveyors, or as slurry in pipelines.

The clay is processed dry or, in some cases, wet. The dry process usually consists of crushing, drying, and pulverizing. The clay is crushed to egg or fist size or smaller and dried usually in rotary driers. After drying, it is pulverized to a specified mesh size such as 90% retained on a 200-mesh screen with the largest particle passing a 30-mesh screen. In other cases, the material may have to be pulverized to 99.9% finer than 325 mesh. The material is shipped in bulk or in bags. All clays are produced by this method.

Properties

Most clays become plastic when mixed with varying proportions of water. Plasticity of a material can be defined as the ability of the material to undergo permanent deformation in any direction without rupture under a stress beyond that of elastic yielding. Clays range from those that are very plastic, called fat clay, to those that are barely plastic, called lean clay. The type of clay mineral, particle size and shape, organic matter, soluble salts, adsorbed ions, and the amount and type of nonclay minerals all affect the plastic properties of a clay.

Strength

Green strength and dry strength properties are very important because most structural clay products are handled at least once and must be strong enough to maintain shape. Green strength is the strength of the clay material in the wet, plastic state. Dry strength is the strength of the clay after it has been dried.

Shrinkage

Both drying and firing shrinkages are important properties of clay used for structural clay products. Shrinkage is the loss in volume of a clay when it dries or when it is fired. Drying shrinkage is dependent on the water content, the character of the clay minerals, and the particle size of the constituents. Drying shrinkage is high in most very plastic clays and tends to produce cracking and warping. It is low in sandy clays or clays of low plasticity and tends to produce a weak, porous body.

Color

Color is important in most structural clay products, particularly the maintenance of uniform color. The color of a product is influenced by the state of oxidation of iron, the state of division of the iron minerals, the firing temperature and degree of vitrification, the proportion of Al₂O₃, lime, and MgO in the clay material, and the composition of the fire gases during the burning operation.

Uses

All types of clay and shale are used in the structural products industry but, in general, the clays that are used are considered to be relatively low grade. Clays that are used for conduit tile, glazed tile, and sewer pipe are underclays and shales that contain large proportions of kaolinite and illite. Clays used for brick and drain tile must be plastic enough to be shaped. In addition, color and vitrification range are very important. For common brick, drain tile, and terra-cotta, shales and surface clays are usually suitable, but for high-quality face bricks, shales and underclays are used.

Clean Surface

A service that is free of foreign material, both visible and invisible.

Cleanup Allowance

See finish allowance.
Clearance
(1) The gap or space between two mating parts. (2) Space provided between the relief of a cutting tool and the surface that has been cut.

Clearance Angle
The angle between a plane containing the flank of the tool and a plane passing through the cutting edge in the direction of relative motion between the cutting edge and the work. See also the terms face mill and single-point tool.

Clearance Fit
Any of various classes of fit between mating parts where there is a positive allowance (gap) between the parts, even when they are made to the respective extremes of individual tolerances that enable the tightest fit between the parts. Contrast with interference fit.

Clearance Ratio
In a bearing, the ratio of radial clearance to shaft radius.

Cleavage
(1) Fracture of a crystal by crack propagation across a crystallographic plane of low index or low ductility fracture. (2) The tendency to cleave or split along definite crystallographic planes. (3) Breakage of covalent bonds. (4) The effect can be visualized as layers of atoms peeling apart in contrast to ductile shear failure where the layers slide across one another. The relevant atomic planes are referred to as cleavage planes and the resultant cracks as brittle, flat, or cleavage fractures.

Cleavage Crack (Crystalline)
A crack that proceeds across the grain, that is, a transgranular crack in a single crystal or in a single grain of a polycrystalline material.

Cleavage Crack (Glass)
Damage produced by the translation of a hard, sharp object across a glass surface. This fracture system typically includes a plastically deformed groove on the damage surface, together with median and lateral cracks emanating from this groove.

Cleavage Fracture
A fracture, usually of a polycrystalline metal, in which most of the grains have failed by cleavage, resulting in bright reflecting facets. It is one type of crystalline fracture and is associated with low-energy brittle fracture. Contrast was shear fracture.

Cleavage Plane
A characteristic crystallographic plane or set of planes in a crystal on which cleavage fracture occurs easily.

Cleavage Strength
In testing of adhesive bonded assemblies, the tensile load and terms of kgf/mm (lbf/in.) of width required to cause the separation of a test specimen 25 mm (1 in.) in length.

Clenching/Clinching
The final process of tightening a mechanical joint by tightening a bolt, bending over the projecting point of a nail closing over the shank of a rivet.

Climb Cutting
Analogous to climb milling.

Climb Milling
Milling in which the cutter moves in the direction of feed at the point of contact.

Clink, Clinking
The noise of a crack occurring in metals, usually steel, during heating or cooling. The cracks themselves may be termed clinks. They result from restraint of thermal expansion or contraction or, during cooling from hydrogen damage.

Clinker
Generally a fused or partly fused by-product of the combustion of coal as opposed to fine ash but also including lava and portland cement clinker, and partly vitrified slag and brick.

Clip and Shave
In forging, a dual operation in which one cutting surface in the clipping die removes the flash and then another shapes and sizes the piece.

Close Packed Hexagonal
A crystal structure in which atoms are close packed, i.e., in contact with six others in the same layer and with three others on the layers above and below, and in which the atoms in alternate layers are aligned. Face-centered cubic, also termed cubic close packed, is similar except that every third layer is aligned.

Close(d) Annealing
Annealing in a sealed box to minimize reaction with air. In the case of steel the term may also imply subcritical annealing as opposed to full annealing. Same as box annealing.

Close(d) Joint
A joint in which the component faces to be welded are in contact prior to welding.
Closed Assembly Time
The time interval between completion of assembly of the parts for adhesive bonding and the application of pressure or heat, or both, to the assembly.

Closed Dies
Forging or forming impression dies designed to restrict the flow of metal to the cavity within the die set, as opposed to open dies, in which there is little or no restriction to lateral flow.

Closed Pass
A pass of metal through rolls where the bottom roll has a groove deeper than the bar being rolled and the top roll has a collar fitting into the groove, thus producing the desired shape free from flash or fin.

Closed Porosity
The volume fraction of all pores within a solid mass that are closed off by surrounding dense solid, and hence are inaccessible to each other and to the external surface; they thus are not detectable by gas or liquid penetration. In contrast, open pore material allows lubricant to permeate the material.

Closed-Cell Cellular Plastics
Cellular plastics in which almost all the cells are non-interconnecting.

Closed-Die Forging
The shaping of hot metal completely within the walls or cavities of two dies that come together to enclose the workpiece on all sides. The impression for the forging can be entirely either die or divided between the top and bottom dies. Impression-die forgings, often used interchangeably with the term closed-die forging, refers to a closed-die operation in which the dies contain a provision for controlling the flow of excess material, or flash, that is generated. By contrast, in flashless forging, the material is deformed in a cavity that allows little or no escape of excess material. See forge.

Close-Packed
A geometric arrangement in which a collection of equally sized spheres (atoms) may be packed together in a minimum total volume.

Close-Tolerance Forging
A forging held to unusually close dimensional tolerances so that little or no machining is required after forging. See also precision forging.

Closure
In fabricating of reinforced plastics, the complete coverage of a mandrel with one layer (two plies) of fiber. When the last tape circuit that completes mandrel coverage lays down adjacent to the first without gaps or overlaps, the wind pattern is said to have closed.

Coagulation
Precipitation of a polymer dispersed in a latex.
Coal

A general name for a black mineral formed of ancient vegetable matter, and employed as a fuel and for destructive distillation to obtain gas, coke, oils, and coal-tar chemicals. Coal is composed largely of carbon with smaller amounts of hydrogen, nitrogen, oxygen, and sulfur. It was formed in various geological ages and under varying conditions, and it occurs in several distinct forms. Peat is the first stage, followed by lignite, bituminous coal, and anthracite, with various intermediate grades. The mineral is widely distributed in many parts of the world. The value of coal for combustion purposes is judged by its fixed carbon content, volatile matter, and lack of ash. It is also graded by the size and percentage of lumps. The percentage of volatile matter declines from peat to anthracite, and the fixed carbon increases. A good grade of coal for industrial powerplant use should contain 55%–60% fixed carbon and not exceed 8% ash. Finely ground coal, or powdered coal, is used for burning in an air blast-like oil, or it may be mixed with oil. Coal in its natural state absorbs large amounts of water and also, because of the impurities in irregular sizes, is not so efficient a fuel as the reconstructed coal made by crushing and briquetting lignite or coal and waterproofing with a coating of pitch. Anthracite powder is used as a filler in plastics.

Low-sulfur coal burns cleaner than regular coal, but its heating value is much less so that it is uneconomical as a fuel. Increasing amounts of coal are being used for production of gas and chemicals. By the hydrogenation of coal much greater quantities of phenols, cresols, aniline, and nitrogen-bearing amines can be obtained than by means of by-product coking, and low grades of coal can be used. The finely crushed coal is slurried to a paste with oil, mixed with a catalyst, and reacted at high temperature and pressure. Synthesis gas, used for producing gasoline and chemicals, is essentially a mixture of carbon monoxide and hydrogen. It is made from low-grade coals.

Coalesced Copper

Massive oxygen-free copper made by briquetting ground, brittle cathode copper, then sintering the briquettes in a pressurized reducing atmosphere, followed by hot working.

Coalescence

(1) The union of particles of a dispersed phase into larger units, usually affected at temperatures below the fusion point. (2) Growth of grains at the expense of the remainder by absorption or the growth of a phase or particle at the expense of the remainder by absorption or reprecipitation. (3) Examples include the coalescence of voids during creep or the coalescence of carbides in steel, where a large number of fine particles can, by a process of diffusion, coalesced to a small number of coarse particles. (4) The bonding that results when powders are sintered. (5) In the context of welded or brazed joints, the term indicates a satisfactory bond between components.

Coarse Fraction

The large particles in a metal powder spectrum.

Coarse Grains

Grains larger than normal for the particular wrought metal or alloy or of a size that produces a surface roughening known as orange peel or alligator skin.

Coarsening

An increase in grain size, usually, but not necessarily, by grain growth.

Coarsening

The increase in grain size by the process of grain growth or, in steel, the increase in size, with associated reduction in number, of carbide particles or pearlite plates. See steel.

Coated Abrasive

An abrasive product (sandpaper, for example) in which a layer of abrasive particles is firmly attached to a paper, cloth, or fiber backing by means of glue or synthetic-resin adhesive.

Coated Electrode

See preferred term covered electrode and lightly coated electrode.

Coated Fabrics

The first coated fabric was a rubberized fabric produced in Scotland by Charles Macintosh in 1823 and known as Macintosh cloth for rainwear use. The cloth was made by coating two layers of fabric with rubber dissolved in naphtha and pressing them together, making a double fabric impervious to water. Rubberized fabrics are made by coating fabrics, usually cotton, with compounded rubber and passing between rollers under pressure. The vulcanized coating may be no more than 0.003 in. (0.008 cm) thick, and the resultant fabric is flexible and waterproof. But most coated fabrics are now made with synthetic rubbers or plastics, and the base fabric may be of synthetic fibers, or a thin plastic film may be laminated to the fabric.

Coated fabrics now have many uses in industrial applications, and the number of variations with different resins and backing materials is infinite. They are usually sold under trade names and are used for upholstery, linings, rainwear, bag covers, book covers, tarpaulins, outerwear, wall coverings, window shades, gaskets, and diaphragms. Vinyl-type resins are most commonly used, but for special purposes other resins are selected to give resistance to wear, oils, or chemicals.

Vinyl-coated fabrics are usually tough and elastic and are low cost, but unless specially compounded are not durable. Many plastics in the form of latex or emulsion are marketed especially for coating textiles. Water dispersions of acrylic resins are specifically made for this purpose. Coatings cure at room temperature, and have high heat and light stability, give softness flexibility to the fabric, and withstand repeated dry-cleaning. A water emulsion of a copolymer of vinyl pyrrolidone with ethyl acrylate forms an adherent, tough, and chemical-resistant coating. Geon latex is a water dispersion of polyvinyl chloride resin. Polyvinyl chloride of high molecular weight is resistant to staining, abrasion, and tearing and is used for upholstery fabrics. The base cloth may be of various weights from light sheetings to heavy ducks. They may be embossed with designs to imitate leather.

One of the first upholstery fabrics to replace leather was Fabrikoid, of DuPont. It was coated with a cellulose plastic and came in various weights, colors, and designs, especially for automobile seating and book covers. Armalon is twill or sateen fabric coated with ethylene plastic for upholstery. For some uses, such as...
Coatings

for draperies or industrial fabrics, the fabric is not actually coated, but is impregnated, either on the fiber or in the finished cloth, to make it water-repellent, immune to insect attack, and easily cleaned. Impregnated fabrics may have only a thin, almost undetectable surface coating on the fibers to make them water-repellent and immune to bacterial attack, or they may be treated with fungicides or with flame-resistant chemicals or waterproofing resins. Stabilized fabrics, however, are not waterproofed or coated, but are fabrics of cotton, linen, or wool that have been treated with a water solution of urea formaldehyde or other thermosetting resin to give them greater resiliency with resistance to creasing and resistance to shrinking and washing. Shrinkproof fabrics are likewise not coated fabrics, but have a light impregnation of resins that usually remains only in the core of the fibers. The fabric retains its softness, texture, and appearance, but the fibers have increased stability. Various resin materials are marketed under trade names for creaseproofing and shrinkproofing fabrics.

Under the general name of protective fabrics, coated fabrics are now marketed by use characteristics rather than by coating designation since resin formulations vary greatly in quality. For example, the low-cost grades of vinyl resins may be hard and brittle at low temperatures and soft and rubbery in hot weather, and thus unsuitable for all-weather tarps. Special weaves of fabrics are used to give a high tear strength with light weight, and the plastic may be impregnated, coated on one side or both, bonded with an adhesive or electronically bonded, or some combination of all these. Flame resistance and static-free qualities may also be needed. Many companies have complete lines to meet definite needs.

Coating

(1) A relatively thin layer (<1 mm, or 0.04 in.) of material applied by surfacing for the purpose of corrosion prevention, resistance to high-temperature scaling, wear resistance, lubrication, or other purposes. (2) Any process of applying a surface layer to a component, or the layer itself. The term is sometimes used in contrast to cladding to imply a relatively thin surface layer, less than about 1 mm. (3) The layer of flux and other materials on some welding electrodes.

Coating Density

The ratio of the determined density of a coating to the theoretical density of the material used in the coating process. Usually expressed as percent of theoretical density.

Coating Strength

A measure of the cohesive bond within a coating, as opposed to coating-to-coating substrate bond; the tensile strength of a coating.

Coating Stress

The stresses in a coating resulting from rapid cooling of molten or semi-molten particles as they impact the substrate.

Coatings

Plastic, metal, or ceramic coatings can be applied to the surface of a material in a variety of ways to achieve desired properties. Coatings improve adherence, corrosion resistance, abrasion resistance, and electrical or optical properties. They can be applied by wet or dry techniques, with simple or complex equipment.

The choices are almost limitless because almost any coating material offers some degree of protection as long as it retains its integrity. If it provides a continuous barrier between the substrate and the environment, even a thin, decorative coating can do the job in a relatively dry and mild environment.

Metal Coatings

Many new materials have been developed, but steel remains the principal construction material for automobiles, appliances, and industrial machinery. Because of the vulnerability of steel to attack by aggressive chemical environments or even from simple atmospheric oxidation, coatings are necessary to provide various degrees of protection. They range from hot-dipped and electroplated metals to tough polymers and flame-sprayed ceramics.

In general, corrosive environments contain more than one active material, and the coating must resist penetration by a combination of oxidizers, solvents, or both. Thus, the best barrier is one that resists “broadband” corrosion.

Physical integrity of the coating is as important as its chemical barrier properties in many applications. For instance, coatings on impellers that mix abrasive slurries can be abraded quickly; coatings on pipe joints will cold-flow away from a loaded area if the creep rate is not low; and coatings on flanges and support brackets can be chipped or penetrated during assembly if impact strength is inadequate. Selecting the best coating for an application requires evaluating all effects of the specific environment, including thermal and mechanical conditions.

Zinc

One of the most common and inexpensive protection methods for steel is provided by zinc. Zinc-coated, or galvanized, steel is produced by various hot-dipping techniques, but more steel companies have moved into electrogalvanizing so they can provide both.

Oxidation protection of steel by zinc operates in two ways—first as a barrier coating, then as a sacrificial coating. If the zinc coating is scratched or penetrated, it continues to provide protection by galvanic action until the zinc layer is depleted. This sacrificial action also prevents corrosion around punched holes and at cut edges.

The grades of zinc-coated steel commercialized in recent years have been designed to overcome the drawbacks of traditional galvanized steel, which has been difficult to weld and to paint to a smooth finish. The newer materials are intended specifically for stamped automotive components, which are usually joined by spot welding and which require a smooth, Class A painted finish.

Aluminum

Two types of aluminum-coated steel are produced, each a different kind of corrosion protection. Type 1 has a hot-dipped Al–Si coating to provide resistance to both heat and corrosion. Type 2 has a hot-dipped coating of commercially pure aluminum, which provides excellent durability and protection from atmospheric corrosion. Both grades are usually used unpainted.

Type 1 aluminum-coated steel resist heat scaling to 677°C and has excellent heat reflectivity to 482°C. Nominal aluminum-alloy coating is about 1 mil on each side. The sheet is supplied with a soft, satiny finish. Typical applications include reflectors and housings for industrial heater panels, interior panels and heat exchangers for residential furnaces, microwave ovens, automobile and truck muffler systems, heat shields for catalytic converters, and pollution-control equipment.
Type 2 aluminized steel, with an aluminum coating of about 1.5 mil on each side, resists atmospheric corrosion and is claimed to outlast zinc-coated sheet in industrial environments by as much as 5–1. Typical applications are industrial and commercial roofing and siding, drying ovens, silo roofs, and housings for outdoor lighting fixtures and air-conditioners.

**Electroplating**

Use of protective electroplated metals has changed in recent years, mainly because of rulings by the Environmental Protection Agency (EPA). Cyanide plating solutions and cadmium and lead-bearing finishes are severely restricted or banned entirely. Chromium and nickel platings are much in use, however, applied both by conventional electroplating techniques and by new, more efficient methods such as fast rate electrodeposition (FRED), which has also been used successfully to deposit stainless steel on ferrous substrates.

Functional chromium, or “hard chrome,” plating is used for anti-galling and low-friction characteristics as well as for corrosion protection. These platings are usually applied without copper or nickel underplates in thicknesses from about 0.3 to 2 mil. Hard-chrome plating is recommended for use in saline environments to protect ferrous components.

Nickel platings, in thickness from 0.12 to 3 mil, are used in food-handling equipment, on wear surfaces in packaging machinery, and for cladding in reaction vessels. Electroless nickel plating, in contrast to conventional electroplating, operates chemically instead of using an electric current to deposit metal. The electroless process deposits a uniform coating regardless of substrate shape, overcoming a major drawback of electroplating—the difficulty of uniformly plating irregularly shaped components. Conforming anodes and complex fixturing are unnecessary in the electroless process. Deposit thickness is controlled simply by controlling immersion time. The deposition process is autocatalytic, producing thicknesses from 0.1 to 5 mil.

Proprietary electroless-plating systems contain, in addition to nickel, elements such as phosphorous, boron, and/or thallium. A relatively new composition, called the polyalloy, features three or four elements in the bath. These products are claimed to provide superior wear resistance, hardness, and other properties, compared with those of generic electroless-plating methods.

One polyalloy contains nickel, thallium, and boron. Originally developed for aircraft gas turbine engines, it offers excellent wear resistance. Comparative tests show that relative wear for a polyalloy-coated part is significantly less than that for hard chromium and Ni–P coatings.

In general, Ni–B coatings are nodular. As coating thickness increases, nodule size also increases. Because the columnar structure of the coating flexes as the substrate moves, Ni–B resists chipping and wear.

Adhesion quality depends on factors such as substrate material, part preparation, and contamination. Although it is excellent for tool steels, stainless steel, high-performance nickel- and cobalt-base alloys, and titanium, a few metal substrates are not compatible. These include metals with high zinc or molybdenum content, aluminum, magnesium, and tungsten carbide. Modifications can, however, eliminate this incompatibility.

Another trend in composite electroless plating appears to be toward codeposition of particulate matter within a metal matrix. These coatings are commercially available with just a few types of particulates—diamond, SiC, Al2O3, and polytetrafluoroethylene (PTFE)—with diamond heading the list in popularity.

These coatings can be applied to most metals, including iron, carbon steel, cast iron, aluminum alloys, copper, brass, bronze, stainless steel, and high-alloy steels.

**Conversion Coatings**

Electroless platings are more accurately described as conversion coatings, because they produce a protective layer or film on the metal surface by means of a chemical reaction. Another conversion process, the black oxide finish, has been making progress in applications ranging from fasteners to aerospace. Black oxide is gaining in popularity because it provides corrosion resistance and aesthetic appeal without changing part dimensions.

On a chemical level, black oxidizing occurs when the Fe within the surface of the steel reacts to form magnetite (Fe₃O₄). Processors use inorganic blackening solutions to produce the reaction. Oxidizing salts are first dissolved in water, then boiled and held at 138°C–140°C. The product surface is cleaned in an alkaline soak and then rinsed before immersion in the blackening solution. After a second rinse, the finish is sealed with rust preventatives, which can produce finishes that vary from slightly oily to hard and dry.

Black oxidizing produces a microporous surface that readily bonds with a topcoat. For example, a supplemental oil topcoat can be added to boost salt-spray resistance to the same level as that of zinc plate with a clear chrome coating (100–200 b).

Black oxide can be used with mild steel, stainless steel, brass, bronze, and copper. As long as parts are scale free and do not require pickling, the finish will not produce hydrogen embrittlement or change part dimensions. Operating temperatures range from cryogenic to 538°C.

Chromate conversion coatings are formed by the chemical reaction that takes place when certain metals are brought in contact with acidified aqueous solutions containing basically water-soluble chromium compounds in addition to other active radicals. Although the majority of the coatings are formed by simple immersion, a similar type of coating can be formed by an electrolytic method.

Protective chromate conversion coatings are available for zinc and zinc alloys, cadmium, aluminum and aluminum alloys, copper and copper alloys, silver, magnesium and magnesium alloys. The appearance and protective value of the coatings depends on the base metal and on the treatment used.

Chromate conversion coatings both protect metals against corrosion and provide decorative appeal. They also have the characteristics of low electrical resistance, excellent bonding characteristics with organic finishes, and can be applied easily and economically. For these reasons the coatings have developed rapidly, and they are now one of the most commonly used finishing systems. They are particularly applicable where metal is subjected to storage environments such as high humidity, salt, and marine conditions.

The greatest majority of chromate conversion coatings are supplied as proprietary materials and processes. These are available usually as liquid concentrates or powdered compounds that are mixed with water. In the case of the powdered compounds, they are often adjusted with additions of acid for normal operation.

Chromate conversion coatings are formed immersing the metal in an aqueous acidified chromate solution consisting substantially of chromic acid or water-soluble salts of H₂CrO₄ together with various catalysts or activators. The chromate solutions, which contain either organic or inorganic active radicals or both, must be acid and must be operated within a prescribed pH range.

Maximum corrosion protection is obtained by using drab or dark bronze coatings on zinc and cadmium surfaces, and yellow to brown-colored coatings on the other metals. Lighter iridescent
yellow type coatings generally provide medium protection, and the clear-bright type coatings, produced either in one dip or by leaching, provide the least protection.

Chromate conversion coatings provide maximum corrosion protection in salt spray or marine types of environment, and in high humidity such as encountered in storage, particularly where stale air with entrapped water may be present. They also provide excellent protection against tarnishing, staining, and finger marking, or other conditions that normally produce surface oxidation.

Olive drab type coatings are widely used on military equipment because of their high degree of corrosion protection coupled with a nonreflective surface. Iridescent yellow coatings are widely used for corrosion protection where appearance is not a deciding factor. The clear-bright chemically polishing type coatings for zinc and cadmium have been widely used to simulate nickel and chromium electroplate and are primarily used for decorative appeal rather than corrosion protection. Where additional corrosion protection or abrasion resistance is desired, these clear coatings act as an excellent base for a subsequent clear organic finish.

Heavy olive drab and yellow coatings for zinc, cadmium, and aluminum can be dyed various colors. Generally speaking, the dyed colors are used for identification purposes only since they are not lightfast and will fade upon exposure to direct sunlight or other sources of ultraviolet.

Because of their low electrical resistance, chromate conversion coatings are widely used for electronics equipment. Surface resistance depends on the type and thickness of the film deposited, the pressure exerted at the contact, and the nature of the contact. Low-resistance coatings are particularly important on aluminum, silver, magnesium, and copper surfaces.

Chromate conversion coatings can also be soldered and welded. A chromate coating on aluminum, for example, facilitates heliac welding. Because of the slight increase in electrical resistance, an adjustment in current (depending upon the thickness of the coating) must be made to satisfactorily spot-weld. Soldering, using rosin fluxes, can be performed on cadmium-plated surfaces that have been treated with clear bright chromate conversion coatings. Clear, bright coatings on zinc-plate surfaces and colored coatings on both zinc and cadmium necessitate the use of an acid flux or removal of the film by an increase in soldering iron temperature, which burns through the coating, or by mechanical abrasion, which removes the film and provides a clean metal surface for the soldered joint.

Most chromate conversion treatments are applied by simple immersion in an acidified chromate solution. Because no electrical contacts need be made during immersion, the coatings can be applied by rack, bulk, or strip line operation. Under special situations, swabbing or brush coating can be used where small areas must be coated, as in a touch-up operation.

Chromate conversion coatings can also be applied by an electrolytic method in which the electrolyte is composed essentially of water-soluble chromium compounds and other radicals operated at neutral or slightly alkaline pH. This type of application is limited primarily to rack-type operation.

In general, processing can be placed in two categories: (1) over freshly electroplated surfaces; and (2) over electroplated surfaces that have been aged or oxidized, or other metal surfaces such as zinc diecastings, wrought metals, or hot-dipped surfaces.

**Sputtering**

Formally used primarily to produce integrated-circuit components, sputtering has moved on to large, production-line jobs such as “plating” of automotive trim parts. The process deposits thin, adherent films, usually of metal, in a plasma environment on virtually any substrate.

Sputtering offers several advantages to automotive manufacturers for an economical replacement for conventional chrome plating. Sputtering lines are less expensive to set up and operate than plating systems. And because sputtered coatings are uniform as well as thin, less coating material is required to produce an acceptable finish. Also, pollution controls are unnecessary because the process does not produce any effluents. Finally, sputtering requires less energy than conventional plating systems.

Chrome coating of plastics and metals is only one application for sputtering. The technique is not limited to depositing metal films. PTFE has successfully been sputtered on metal, glass, paper, and wood surfaces. In another application, cattle bone was sputtered on metallic prosthetic devices for use as hip-bone replacements. The sputtered bone film promotes bone growth and attachment to living bone.

Sputtering is the only deposition method that does not depend on melting points and vapor pressures of refractory compounds such as carbides, nitrides, silicides, and borides. As a result, films of these materials can be sputtered directly onto surfaces without altering substrate properties.

Much sputtering has been aimed at producing solid-film lubricants and hard, wear-resistant refractory compounds. NASA is interested in these tribological applications because coatings can be sputter-deposited without a binder, with strong adherence, and with controlled thickness on curved and complex-shaped surfaces such as gears and bearing retainers, races, and balls. Also, because sputtering is not limited by thermodynamic criteria (unlike most conventional processes that involve heat input), film properties can be tailored in ways not available with other deposition methods.

Most research on sputtered solid-lubricant films has been done with MoS₂. Other films that have been sputtered are WC, TiN, PbO₂, gold, silver, tin, lead, indium, cadmium, PTFE, and polyimide (PI). Of these coatings, the gold-colored TiN coatings are most prominent.

TiN coatings are changing both the appearance and performance of high-speed steel metal-cutting tools. Life of TiN-coated tools, according to producers’ claims, increases by as much as tenfold, metal-removal rates can be doubled, and more regrinds are possible before a tool is discarded or rebuilt.

**Sputtering**

The SCX™ sputter coating process, a proprietary, computer-aided process developed by Engelhard-CLAL, Carteret, NJ, a producer of high-purity materials, enables the coating of base or refractory metals with precious metals. The source of the coating material can be almost any metallic composition. A major benefit of sputtering is the ability to deposit alloys or compounds that cannot be mechanically worked or alloyed as is required in the cladding process. By fabricating a segmented target comprising of two or more individual elements, a deposition can be made that is a uniformly dispersed “alloy” of the constituents.

SCX sputtering is conducted at low temperatures (<300°C), permitting deposition on plastics and other temperature-sensitive materials in addition to metals. Conducted at reduced pressures of inert gases, entrapped gases are kept to a minimum. Finally, by replacing the inert gas with a reactive gas such as H₂, N₂, or O₂, a compound formed by the gas can be deposited. This permits the reaction of very interesting coatings, such as nitrides, hydrides, and oxides. The unique sputter coating process makes it possible to attain very thin as well as relatively thick coatings equally as well in the range of ½ to over 6 μm.
Typical substrate dimensions are: wire: 0.08–1 mm diameter, continuous lengths up to 3000 m at 0.08 mm diameter, and 300 m at 0.89 mm diameter; ribbon: 0.017–0.50 mm thick and widths from 0.25 to 3.2 mm, continuous lengths from 120 to 500 m; rods: 3.2 mm diameter by 508 mm long; metallic foil: 0.05 mm thick and up, to 102 × 508 mm window dimension; polymeric: 0.25 mm thick and up, to 102 × 508 mm window; rigid metallic and nonmetallic: up to 127 mm thick and up to 102 × 508 mm window dimension. Flexible and discrete parts can be coated selectively on one or both sides.

**Application to Power Tube Grids**

Power tube grids control the flow of tube current by providing a bias between the cathode and anode. Semiconductor devices have replaced the bulk of electron tube usage, especially in receiving applications. However, in extremely high-power applications, the triode style thermal emissions tube still finds global use. The electron tube is expected to provide long-lasting, high-quality performance throughout the typical frequency range of 20 kHz to over 20 GHz, with grid temperatures from 600°C to 1300°C, depending on the application. Secondary electron emission is of major concern to tube designers. Without controls or limits, a tube could easily become unstable and quickly self-destruct.

Platinum-coated molybdenum and tungsten are traditional materials for grid construction. Traditional platinum-clad molybdenum grid wire is produced with very thick precious metal coatings because it is difficult to produce claddings without base material breakthrough, and the molybdenum tends to diffuse through the platinum, embrittling the grid as well as causing an increase in emission. The SCX-PC sputter coating process accomplishes the same function as cladding, but with a precious metal savings of 15%–30%. This is achieved by introducing a diffusion barrier into the coating during the manufacturing process, which effectively prohibits the interdiffusion of the core and the coating.

Other unique coatings include SCXPZC, which includes zirconium in the deposition process to permit higher-temperature grid usage with closer cathode spacing, and SCX-TH, which produces titanium-hydride (TiHₓ) coatings to control primary and secondary emissions and enables the grid to act as a getter for nascent gas molecules.

**Ion Plating**

The basic difference between sputtering and ion plating is that sputtered material is generated by impact evaporation and transferred by a momentum transfer process. In ion plating, the evaporant is generated by thermal evaporation. Ion plating combines the high throwing power of electroplating, the high deposition rates of thermal evaporation, and the high energy impingement of ions and energetic atoms of sputtering and ion-implantation processes.

The excellent film adherence of ion-plated films is attributed to the formation of a graded interface between the film and substrate, even where the two materials are incompatible. The graded interface also strengthens the surface and subsurface zones and increases fatigue life.

The high throwing power and excellent adherence makes possible the plating of complex three-dimensional configurations such as internal and external tubing, gear teeth, ball bearings, and fasteners. Gears for space applications, for example, have been ion plated with 0.12–0.2 μm of gold for lubrication and to prevent cold welding of the gear pitch line. Ion plating has also been used, on a production basis to plate aluminum on aircraft landing-gear components for corrosion protection.

Ion plating is also one of the two methods used to deposit diamond-like coatings (DLCs). A relative newcomer to the coatings field, DLCs are commonly made from hydrocarbon (often methane) and H₂ gases heated to 2000°C. The carbon coatings are prized for their wear resistance, as well as electrical and optical properties. Although they represent a huge potential, present DLCs are at the earliest stages of commercialization. However, their wide range of properties, along with their relatively low-cost, leads many to predict huge growth in DLCs.

Researchers have proposed that the coatings be used to improve wear resistance in tool bits, as electronic heat sinks, and to boost wear and corrosion resistance in optical materials.

Chemical vapor deposition (CVD) is the method most often used to deposit DLCs. Adjusting deposition conditions allows the processor to change the coating from graphite to diamond-like. One process used at Battelle deposits the DLC in a gas atmosphere at reduced pressure without a fixed target. This plasma-assisted CVD allows large workpieces to be coated on all sides without turning. However, substrates must be heated to roughly 800°C when using CVD.

Reduced substrate temperatures are offered by dual ion-beam-enhanced deposition. Substrate temperature reaches only 66°C, and the dual ion-beam process does not rely on epitaxial growth for its formation as CVD does. Epitaxial growth requires a crystalline substrate; because dual ion-beam processing is free of this need, it enables amorphous materials to be coated as well.

Materials that are compatible with the Dicond process include ferrous and nonferrous metals, glasses, ceramics, plastics, and composites. In addition to the Dicond coating, dual ion-beam enhanced deposition can apply metallic coatings to fiber-reinforced carbon-carbon materials.

The basic ion-implantation process sends beams of elemental atoms (produced in a particle accelerator) into the surface of the target component. With dual ion-beam enhanced deposition, two simultaneous beams are used. One beam continuously sputters carbon onto the surface, providing the carbon material necessary to grow a diamond film. A second beam, consisting of inert gas at higher energy, drives some of the diamond layer into the interface zone. Then, the energy of the second beam is reduced to allow diamond growth. Implanting diamond material within the interface zone optimizes adhesion.

Technologies developed for electronic and optical thin films are often transferred into the engineering coatings sector, leading to a wider use of ion- and plasma-based techniques.

A novel nonequilibrium plasma treatment method with unusual characteristics is now being developed by EA Technology Ltd. of Capenhurst, near Chester, Great Britain. The process acts like a low-pressure, nontemperature glow discharge. Although it appears to provide many of the conditions needed for plasma surface engineering, the process runs at atmospheric pressure. Atmospheric deposition is generally much simpler than traditional vacuum plasma deposition, and its higher reactant concentrations make it much faster and, therefore, more cost-effective.

The equipment needed for this new approach is little more than a modified commercial microwave oven in which the plasma is sustained within a flask by microwave energy. Processing can be done either within the plasma or in a downstream gas that flows through the flask. In-plasma treatment is more energetic. Those materials that can withstand high temperatures can be coated within the flask.

Downstream processing is easier and particularly effective at coating epoxies and polymers such as polymethyl methacrylate with materials such as TiO₂. This technique improves the wear resistance of the surface. The plasma can even be used to break down noxious gases such as volatile organics with more than 97% efficiency.
Vacuum Plasma Processing

This is the heart of advanced physical vapor deposition (PVD) coatings used on tools such as molds, dies, drills, and cutters. Although TiN is the most widely used of these coatings, many demanding applications now use TiAlN. High-quality PVD coatings are produced when electron beams evaporate the coating material while N2-rich plasma bombard the substrates. Electron beams cannot be used to evaporate alloys such as TiAlN, since the vapor pressure of aluminum is 100 times higher than that of titanium. However, to overcome this problem, a new control technology has been developed for electron-beam deposition systems. This technology measures optical emissions from elements in the plasma, picking up characteristic titanium and aluminum emission lines. These are used to control individual electron-beam sources for alloy elements.

As a result, users can control the composition of the alloy coating—they can even modify the gradation of the coating chemistry, a technique not possible with alloy are and sputter sources.

C-coated components, when compared to nitrided, nickel, and chromium coatings, exhibit improved wear-resisting performance. In particular, Balinit® C WC/C coatings are claimed to offer the proper combination of low coefficient of friction and high hardness needed by highly loaded automotive and machine parts.

Balinit C WC/C coatings are made of hard WC particles in a soft amorphous carbon matrix. Ion bombardment of a WC target removes coating material for deposition onto component surfaces under controlled conditions. Several applications demonstrate the ability of the material to solve wear problems:

- A coating of WC/C, specifically developed for highly stressed machine components operating under less-than-optimum lubricating conditions, has given design engineers a way out of such predicaments. Produced by PVD, WC/C is said to improve seizure resistance and reduce wear—this technology allows them to control the composition of the coating.
- Pump pistons coated with Balinit C operate longer than nitrided pistons or nickel- and chromium-coated pistons. Replacement of sliding shoes made from bronze with nitrided pistons or nickel- and chromium-coated pistons. WC/C is said to improve wear-resistance coating material that lends itself to forming amorphous/microcrystalline phases when plasma sprayed. The resultant coating provides excellent corrosion resistance with minimal application results in a low coefficient of friction and “smoothing” of the surface of the part. Hardness measures 1000 VHN (25 g); thickness is approximately 3 μm.
- Balinit C WC/C coatings, with a maximum working temperature of 300°C, are at present used in racing, as well as industrial gear systems.

In tribological tests conducted on CrN, TiAIN, TiAlCN, TiCN, TiCN + C, TiN + C, TiB2, WC, and molybdenum coatings for load capacitance, adhesion power, abrasion force, hardness, and fatigue strength showed TiAIN, the very hard, metallic coating used on cutting tool inserts, gave the best results. Unlike cutting tools, however, bearing components cannot be coated in a standard CVD process at temperatures over 500°C. Even with a specially developed PVD process, which deposits hard coatings with high adhesion power at a temperature level of only 160°C, bearing rings must undergo special annealing after final grinding at a temperature of approximately 240°C to achieve the roundness deviation after coating within the normal manufacturing tolerance range.

Thermal Spraying

Arc spraying, a form of thermal spraying of metals, is done on a prepared (usually grit-blasted) metal surface, using a wire-arc gun. The coating metal is in the form of two wires that are fed at rates that maintain a constant distance between their tips. An electric arc liquefies the metal, and an air spray propels it onto the substrate. Because particle velocity can be varied considerably, the process can produce a range of coating finishes from a fine to a coarse texture. Arc-sprayed coatings are somewhat porous, as they are composed of many overlapping platelets. Used in applications where appearance is important, thermally sprayed coatings can be sealed with pigmented vinyl copolymers or paints, which usually increase the life of the metal coating. Arc-sprayed coatings are thicker than those applied by hot dipping, ranging from 3 to 5 mil for light-duty, low-temperature applications to 7 to 12 mil for severe service.

Because zinc and aluminum are, under most conditions, more corrosion resistant than steel, they are the most widely used spray-coating metals. In addition, since both metals are anodic to steel, they act galvanically to protect ferrous substrates.

In general, aluminum is more durable in acidic environments, and zinc performs better in alkaline conditions. For protecting steel in gas or chemical plants, where temperatures might reach 204°C, aluminum is recommended. Zinc is preferred for protecting steel in fresh, cold waters; in aqueous solutions above 66°C, aluminum is the usual choice.

For service to 538°C, a thermally sprayed aluminum coating should be sealed with a silicone–aluminum paint. Between 538°C and 899°C, the aluminum coating fuses and reacts with the steel base metal, forming a coating that, without being sealed, protects the structure from an oxidizing environment. And, for continuous service to 982°C, a nickel-oxide alloy is used, sometimes followed by aluminum.

In Europe, where thermally sprayed metal coatings for corrosion protection have been far more widely used than in the United States, many structures such as bridges are still in good condition after as long as 40 years, with minimum maintenance. Other applications include exhaust-gas stacks, boat hulls, masts, and many outdoor structures.

Thermal spraying has become much more than a process for rebuilding worn metal surfaces. Thanks to sophisticated equipment and precision control, it is now factored into the design process, producing uniform coatings of metals and ceramics. With some of the processes, even graded coatings can be applied. This is done by coating the substrate with a material that provides a good bond and that has compatible expansion characteristics, then switching gradually to a second material to produce the required surface quality such as wear resistance, solderability, or thermal-barrier characteristics.

Plasma Spraying

Plasma-spray coating relies on a hot, high-speed plasma flame (N2, H2, or argon) to melt a powdered material and spray it onto the substrate. A DC arc is maintained to excite gases into the plasma state. The high-heat plasma (in excess of 7075°C) enables this process to handle a variety of coating materials—most metals, ceramics, carbides, and plastics. Although most coating materials are heated to well beyond their melting points, substrate temperatures commonly remain below 121°C.

This process has found wide acceptance in the aircraft industry. Plasma-sprayed metallic coatings protect turbine blades from corrosion, and sprayed ceramics provide thermal-barrier protection for other engine parts.

Proprietary refinements in plasma-spray technology include a wear-resistance coating material that lends itself to forming amorphous/microcrystalline phases when plasma sprayed. The resultant coating provides excellent corrosion resistance with minimal...
Coatings Coatings

Coatings Coatings

C... boilers, and jet engines. Performance of formulations containing ceramic frits approaches that of ceramic materials.

thermal fatigue and chemical attack.

high CTE correlates well with the base metals to which ZrO₂ is substrate oxidation and corrosion. As a class, these materials are substrate both to enhance bonding and to provide a barrier that prevents oxidation at higher temperatures. This promises to eliminate problems of work-hardened crystalline coatings that chip or delaminate in response to stress, which have previously been taken care of by expensive alloying elements.

Another amorphous alloy development involves a crystalline material that, upon abrasive wear, transforms to an amorphous hard-phase alloy. The top layer, 3–5 μm thick, results in hardness levels over 1300 Vickers. Wear tests have indicated this material is superior to more expensive WC coatings.

Detonation gun coatings considered by many to be an industry standard, use a detonation wave to heat and accelerate powdered material to 732 mm/s. In the line-of-sight process, each individual detonation deposits a circle of coating with a 2.54 cm diameter and 2 μm thickness. Coatings, thus, consist of multiple layers of densely packed lenticular particles tightly bonded to the surface.

The Super D-Gun has been developed to increase particle velocities. New coatings (the UCAR 2000 Series) applied with the gun offer improved wear resistance without affecting fatigue performance. The system has been targeted for fatigue-sensitive aircraft components.

Other low-pressure plasma-spray (LPPS) coatings protect turbine vanes by improving the sulfidation and oxidation resistance of complex components. Inert-atmosphere LPPS systems are an effective means for applying complex corrosion-resistant coatings such as NiCoCrAlY to high-temperature engine components.

PS300 is a self-lubricating solid coating material for use in sliding contacts at temperatures up to 800°C. PS300 is a composite of metal-bonded CrO₂ with BaF₂/CaF₂ eutectic and silver as solid lubricant additives. The “PS” in the name of this and other self-lubricating, high-temperature composite materials signifies that the material is applied to a substrate by plasma spraying of a powder blend of its constituents.

Spray Coatings

Stabilized Zirconia (ZrO₂)

Yttria-stabilized zirconia (YZP) represents the bulk of all sprayed ceramics. This material is used primarily for thermal barrier coatings (TBCs) in aircraft, rocket, and reciprocating engines. TBCs are applied to engine components to lower substrate temperatures so that combustion gas temperatures can be higher, thereby increasing engine power and efficiency and lowering emissions. Stabilized ZrO₂ is unique for its high CTE and low thermal conductivity. The high CTE correlates well with the base metals to which ZrO₂ is commonly applied, reducing stresses that are induced by differential expansion. Plasma-sprayed YZP is also reasonably resistant to thermal fatigue and chemical attack.

Other elements used to stabilize ZrO₂ include the oxides of magnesium, calcium, and cerium. Phase stabilization is used to mitigate the large volume change that ZrO₂ undergoes during heating to and cooling from service temperatures. The phase transformation from low-temperature monoclinic to high-temperature tetragonal can be arrested by the inclusion of stabilizing components such as Y₂O₃. Fully stabilized ZrO₂ maintains a cubic structure throughout heating. Partially stabilized ZrO₂, which has both cubic and tetragonal phases, is reported to be tougher and to have a better match of CTE with engine materials.

MCRALYS

Metallic coatings are used between the ceramic coating and substrate both to enhance bonding and to provide a barrier that prevents substrate oxidation and corrosion. As a class, these materials are denoted by the term MCRALYS, which is derived from the components: a base metal (M), chromium (CR), aluminum (AL), and yttria (Y). The M component is iron (Fe), cobalt (Co), or nickel (Ni), singly or in combination. The coatings are then called FECRALY, COCRALY, NICRALY, and so forth.

Recent advances in thermal spraying have focused on controls. Process control includes barfeedstock, materials, and processing parameters. Historically, thermal spray coatings have been applied at a confidence level of around 70.

Applications

Common use of thermally sprayed YZP involves net-shape manufacturing. O₂ sensors for automobile emission control systems are manufactured by applying the coatings of YZP to remove mandrels. When the mandrel is removed, a free-standing shape is left.

Net- and near-net-shape (NNS) techniques facilitate the fabrication of parts that is not practical by other means. Freestanding net-shape ion engines have been manufactured from tungsten by using load chamber, plasma-arc spray. Plasma spraying in an argon atmosphere eliminates oxidation of reaction materials, such as tungsten. Precision Al₂O₃ tubes (0.75 mm) wall thickness, 75 mm diameter, and 1.2 m length would be difficult, if not impossible, to fabricate by casting and grinding; however, they have been successfully fabricated by thermal-spray net-shape techniques. On the other extreme, multilayer ceramic tubes with 1-mm inside diameter have been made to join blood vessels.

Ceramic coatings are applied to medical instruments used for endoscopic and other forms of minimal invasive surgery.

Polymer Coatings

Polymeric coatings designed for corrosion protection are usually tougher and are applied in heavier films than are appearance coatings. Requirements of such coatings are much more stringent: They must adhere well to the substrate and must not chip easily or degrade from heat, moisture, salt, or chemicals.

Environmental factors also drive the technology behind polymer coatings replacing chromium and cadmium coatings. This is partly due to increasing concern about heavy metals. Also, automakers must now contend with acid rain in addition to salt spray, and polymers surpass chromium and cadmium in acid rain resistance.

Acrylics and alkyds are widely used for farm equipment and industrial products requiring good corrosion protection at a moderate cost. Alkyd resins, particularly, play a major role in maintenance painting because of their good weathering characteristics and ease of application with low-cost, low-toxicity solvents. Alkyd paints are also relatively high in solids, permitting good buildup of a paint film with a minimum number of coats.

Silicone modification of organic resins improves overall weatherability and durability. Compared to organic coatings in general, silicones have greater heat stability, longer life, better resistance to deterioration from sunlight and moisture, and greater biological and chemical inertness.

For optimum weatherability, silicone content should be 25%–30%. Performance of the waterborne formulations is proving to be almost identical to that of the solvent-based coatings.

For coatings requiring higher heat resistance, silicone resins can be used alone for the paint vehicles, or they can be blended with various organic resins. These finishes are used on space heaters, clothes dryers, and barbecue grills. Similar formulations are used on smoke-stacks, incinerators, boilers, and jet engines. Performance of formulations containing ceramic frits approaches that of ceramic materials.
Polyurethane enamels are characterized by excellent toughness, durability, and corrosion resistance. These thermosetting materials, available in both one- and two-part formulations, cost more than the alkyds and acrylics.

Urethane chemistry is versatile enough to provide a hard, durable, environmentally resistant film, a tough, elastomeric coating, or a surface somewhere between. Urethanes have traditionally been available as solvent-based coatings containing 25%–45% solids, but environmental concerns have prompted manufacturers to also supply them in high solids, 100% solids, and waterborne formulations.

Coating thickness of polyurethanes ranges from about 2 mil for average requirements to as much as 30 mil for applications requiring impact and/or abrasion resistance as well as corrosion resistance. Typical uses are on conveyor equipment, aircraft radomes, tugboats, road-building machinery, and motorcycle parts. Abrasion-resistant coatings of urethanes are applied on railroad hopper cars, and linings are used in sandblasting cabinets and slurry pipes.

Epoxies finish have better adhesion to metal substrates than do most other organic materials. Epoxies are attractive economically because they are effective against corrosion in thinner films than are most other finishing materials. They are often used as primers under other materials that have good barrier properties but marginal adhesive characteristics.

Epoxies can vary from 1 mil for light-duty protection to as much as 20 mil for service involving the handling of corrosive chemicals or abrasive materials. Performance of epoxies is limited in the heavier thickness, however, because they are more brittle than other organic materials.

Nylon 11 coatings provide attractive appearance as well as protection from chemicals, abrasion, and impact. Applied by electrostatic spray in thicknesses from 2.5 to 8 mil, nylon coatings are used on office and outdoor furniture, hospital beds, vending-machine parts, and building railings. Heavier coatings—to 50 mil—are applied by the fluidized-bed method and are used to protect dishwasher baskets, food-processing machinery, farm and material-handling equipment, and industrial equipment such as pipe, fittings, and valves.

Fluorocarbons are more nearly inert to chemicals and solvents than all other polymers. The most effective barriers among the fluorocarbons for a variety of corrosive conditions are PFA, PTFE, ECTFE, FEP, and PVDF.

Ethylene-chlorotrifluoroethylene (ECTFE) is a member of the fluoropolymer family of resins. This high-temperature coating provides corrosion resistance and mechanical and electrical qualities up to 149°C. It is easy to apply and has excellent release and low-friction properties. Multiple layers of ECTFE can be applied up to 100 mil. Although more expensive than other powders, its performance often justifies a higher cost. ECTFE has a smooth surface as applied and is therefore used in water handling systems to minimize bacterial buildup.

Fluorinated ethylene propylene (FEP) is a soft fluoropolymer coating similar to PTFE and PFA. It has the best release properties among powder coatings. The corrosion-resistant qualities of FEP are better than PTFE, but FEP does not stand up to high temperatures as well.

Perfluoralkoxy (PFA) is another member of the fluoropolymer family that resists corrosion and has better release and nonwetting qualities than PTFE. With wide temperature limits, PFA can be used in applications ranging from cryogenic levels to 260°C. It is typically used for coating molding cavities, and this food-grade-quality powder can also be used for baking surfaces.

Polytetrafluoroethylene (PTFE) is a soft and waxy material that has release properties similar to PFA. The high-temperature coating protects against corrosion in environments reaching 260°C. However, its softness limits it to nonabrasive and moderately abrasive applications.

Polyvinylidenefluoride (PVDF) is the hardest powder coating with qualities similar to PPS, making it ideal for high-load and higher-modulus applications. The coating works well in corrosive environments for components in pulp mills, waste treatment plants, and petrochemical facilities. Once applied, PVDF coatings can be removed only with heat. The coating has a surface temperature limit of 130°C and is not commonly used for release and low-friction applications.

For impact service, PVDF and ECTFE coatings are recommended, in that order. PTFE, FEP, and PFA are also suitable, but they have a greater tendency to creep under load. For abrasive conditions, PVDF is outstanding among the fluorocarbons. Recommended for high surface temperatures—drying ovens and steam-handling equipment, for example—are PFA and PVDF. These materials are also used on engine components and welders. PVDF also has the highest compressive strength of the fluorocarbons. PTFE has the highest allowable service temperature (316°C) of the fluorocarbons.

Coatings based on PTFE are being used to reduce wear in the US automotive industry. Fluoropolymer coatings prevent binding and galling in disk brake systems at temperatures over 100°C. PTFE is also used as a dry lubricant. In addition, PTFE can be used as a coating on automotive fasteners, and a new process uses PTFE to prevent seizure in valve springs. This process is FluoroPlate impingement, a process whereby a mixture of inorganic and organic particles bombard the spring surface, thus relieving internal stresses and reducing surface flaws. The coating also helps the springs to repel oil.

A new class of coating—an alloy of fluoropolymer and other resins—has a different viscosity behavior than that of the earlier organics. Viscosity of “fastener-class” coating resins decreases sharply as film shear increases (as in application by the dip/spin process). Then, when the spinning basket stops, viscosity returns almost instantaneously to its original value. Thus, when applied by the dip/spin process, the coating clings to sharp edges, threads, and points.

Film thickness typically ranges from 0.5 to 0.7 mil, but formulations can be adjusted to provide films of 0.3–0.4 mil for parts with fine threads or other intricate features. Not only do these extremely tough coatings provide a more uniform barrier to corrosives, but they are also based on polymers that are inherently stable in the presence of a wide spectrum of acids, bases, and aqueous solutions.

Combination coatings blend the advantages of anodizing or hard-coat platings with the controlled infusion of low-friction polymers and/or dry lubricants. The coatings become an integral part of the top layers of metal substrates, providing increased hardness and other surface properties.

These coatings are different for each class of metals. For example, a Tufram coating for aluminum combines the hardness of Al2O3 and the protection of a fluorocarbon topcoat to impart increased hardness, wear and corrosion resistance, and permanent lubricity.

In the multistep process, the surface is first converted to Al2O3. Submicron particles of PTFE are then fused into the porous anodized surface, forming a continuous plastic/ceramic surface that does not chip, peel, or delaminate. The coating is claimed to have greater abrasion resistance than case-hardened steel or hard chromium plate.

Another proprietary coating that penetrates PTFE into precision hardcoat anodizing is Nituflf. The coating achieves a self-curing, self-lubricating surface with low friction, high corrosion resistance, and dielectric properties superior to ordinary hardcoat anodizing. It is used extensively in aerospace, textile, food processing, packaging, and other industries, where it allows manufacturers to benefit from the lightweight and easy machinability of aluminum enhanced by the durability, cleanliness, and dry lubrication of the Nituflf surface.
Other proprietary combination coatings have been developed for steel, stainless steel, copper, magnesium, and titanium that provide similar surface improvement. Coatings are also available that enhance specific properties such as lubricity, corrosion resistance, or wear resistance.

**Powder Coatings**

Powder coatings are generally much thicker than fluids, typically greater than 5 mil compared to 1 or 2 mil for fluids. Powders commonly protect substrates from corrosion and erosion wear, or provide release or aesthetic qualities. Fluid coatings, in contrast, are preferred for friction, abrasion, and spalling wear—corrosion applications that require low friction and release.

In addition to performance attributes, powder coatings also provide processing advantages over fluids. Powders are environmentally friendly because they do not contain volatile organic compounds (VOCs) that attack the ozone layer.

The powder coating combines properties of both plastics and paints. The coatings are manufactured using typical plastics-industry equipment. They are first sent through a melt-mix extruder and then ground. When applied as a coating, however, the powder becomes a coating film that is exactly like paint.

These coatings have been developed in response to pressures to reduce VOC emissions, which have increased over the past few years. Overspray from liquid paints contains solvents that are released into the atmosphere. Even with recovery systems, some volatile components escape. Powder coatings, on the other hand, are completely recyclable. Overspray can be collected easily and reused. If a small amount becomes too contaminated for recycling, safe disposal techniques are available.

Powder coatings also show promise as a substitute for clear coats in the automotive industry. Present solvent-based paints could be replaced by a clear powder coating that cures at roughly the same temperature as conventional paints. Powder coatings may also replace the baked-on porcelain enamel used for appliance parts. Washer and dryer lids are now powder-coated in industry.

Applications are not all that is new, however. Materials have changed. The majority of powder coatings have relied on either an epoxy or polyester resin base. Acrylics, however, are becoming more important, and other possible bases include nylon, vinyl, and various fluoropolymers.

Two processes for applying coatings have undergone refinements. With electrostatic spraying, the most popular method, powder is given a charge and sprayed onto electrically grounded parts. Baking then completes the cure. Nonconductive parts must be primed or heated to provide them with more electrostatic attraction.

In the fluid-bed process, air passes through a porous membrane at the bottom of a tank and aerates the powder so that it swirls around in the tank. A part is then heated and dipped into the tank, so that the powder melts on the surface. This process is used for thick-film protection coatings, and is suitable only for metal parts that can retain heat long enough to be coated.

**Liquid Layers**

Despite strict governmental restrictions that continue to thwart the amount of VOCs released into the atmosphere, the use of high-performance fluid coatings remains widespread. Unlike powder coatings, fluids can be applied in films as thin as 0.2 mil without affecting their integrity. Powder coatings, in contrast, require more clearance between components to accommodate thicknesses greater than 5 mil.
Coaxing Cobalt

C ... give excellent abrasion and wear resistance and are used as hard-facing alloys and for aircraft jet engine parts.

Under high loads or extreme wear, the topcoat may wear away, exposing the substrate material. However, because the fluid coat remains in the asperities of the base metal, the composite coating maintains a low-friction surface while the steel helps resist wear. Typical applications are large locking and fastening mechanisms, tumblers, agitators, and parts subjected to high abrasive wear.

Conformal Coatings

Printed circuit board (PCB) assemblies used in avionics, marine, automotive, and military applications generally perform in environments affected by heat, moisture, industrial pollutants, manual handling, and process residues, which typically magnifies such effects.

The PCB designer must determine if and how the assembly must be protected with a worst-case environment in mind. Consequences ranging from malfunction to product failure will devolve from this decision. Other factors include feasibility and cost of implementation of such protection, but the designer will have several options: reducing circuit sensitivity through designed signal characteristics, increasing conductor spacing, and using buried vias. Other protective options include sealing the circuit in a box pressurized with inert gas or in a polymer via potting or molding, or employing an electrically insulating barrier between conductors and the ambient environment.

Using a polymeric-film barrier for board protection is the most common and practical approach. There are, however, limitations and peculiarities accompanying the two categories of coatings:

1. Bare-board coatings, or “permanent soldermasks,” are applied during the board fabrication process as liquids or dry films over conductive finishes or bare copper, and polymerized (cured) either by heat or ultraviolet light.
2. Assembly coatings offer protective coverage against water in the form of atmospheric humidity and condensation. They are commonly referred to as “conformal” coatings, implying compliance of the film to the contour line of the assembly. However, this term may be a misnomer, since newer application techniques permit only specific areas be coated to eliminate the cost of masking.

The use of conformal coating materials is provided in four basic material types (acrylic, epoxy, silicone, and urethane resins) for liquid-applied coatings, and one (paraxylylene) for vapor deposition. As a result, a coating must be selected on the basis of electrical, thermal, mechanical, and other pertinent properties as dictated by requirements for circuit performance and characteristics, type and degree of environmental exposure, and consequences of failure.

Coaxing

Improvement of the fatigue strength of a specimen by the application of a gradually increasing stress amplitude, usually starting below the fatigue limit.

Cobalt

Cobalt (symbol Co) is a lustrous, silver-blue metallic chemical element, resembling nickel but with a bluish tinge instead of the yellow of nickel. It is rarer and costlier than nickel and its price has varied widely in recent years. Although allied to nickel, it has distinctive differences. It is more active chemically than nickel. It is dissolved by dilute H$_2$SO$_4$, HNO$_3$, or HCl acids, and is attacked slowly by alkanal. The oxidation rate of pure cobalt is 25 times that of nickel. Its power of whitening copper alloys is inferior to that of nickel, but small amounts in Ni–Cu alloys will neutralize the yellowish tinge of the nickel and make them whiter. The metal is diatomic like nickel, but it has three times the maximum permeability. Like tungsten, it imparts red-hardness to tool steels. It also hardens alloys to a greater extent than nickel, especially in the presence of carbon, and can form more chemical compounds in alloys than nickel.

Its chemical properties resemble, in part, those of both nickel and iron. Cobalt has the metal with the highest Curie temperature (1121°C) and the lowest allotropic transformation temperature (399°C). Below 421°C, cobalt is close-packed hexagonal; above, it is face-centered cubic.

Properties

Cobalt has a specific gravity of 8.756, a melting point of 1495°C, 85 Brinell hardness, and an electrical conductivity about 16% that of copper. The ultimate tensile strength of pure cast cobalt is 234 MPa, but with 0.25% carbon it is increased to 427 MPa. Strength can be increased slightly by annealing and appreciably by swaging or zone refining. The metal is used in tool-steel cutters, in magnet alloys, and high-permeability alloys, and as a catalyst, and its compounds are used as pigments and for producing many chemicals.

The natural cobalt is cobalt-59, which is stable and nonradioactive, but the other isotopes from 54 to 64 are all radioactive, emitting beta and gamma rays. Most have very short life except cobalt-57, which has a half-life of 270 days, cobalt-56 with a half-life of 80 days, and cobalt-58 with a half-life of 72 days. Cobalt-60, with a half-life of 5.3 years, is used for radiographic inspection. It is also used for irradiating plastics, and as a catalyst for the saponification of paraffin oils because the gamma rays cause the reaction of SO$_2$ and liquid paraffin. Co 60 emits gamma rays of 1.1–1.3 MeV energy, which gives high penetration for irradiation. The decay loss in a year is about 12%, the cobalt changing to nickel.

The best-known cobalt alloys are the cobalt-base superalloys used for aircraft turbine parts. The desirable high-temperature properties of low creep, high stress-rupture strength, and high thermal-shock resistance are attributed to the allotropic change of cobalt to a face-centered cubic structure at high temperatures. Besides containing 36%–65% cobalt, usually more than 50%, most of these alloys also contain about 20% chromium for oxidation resistance and substantial amounts of nickel, tungsten, tantalum, molybdenum, iron, and/or aluminum, and small amounts of still other ingredients. Carbon content is in the 0.05%–1% range. These alloys include L-605; S-816; V-36; WI-52; X-40; J-1650; Haynes 21 and 151; AlResist 13, 213, and 215; and MAR-M 302, 322, and 918. Their 1000 h stress-rupture strengths range from about 276 to 483 MPa at 649°C and from about 28 to 103 MPa at 982°C. Cobalt is also an important alloying element in some nickel-base superalloys, other high-temperature alloys, and alloy steels. Besides tool steels, the maraging steels are a good example. Although cobalt-free grades have been developed, due to the scarcity of this metal at times, most maraging steels contain cobalt, as much as 12%. Cobalt is also a key element in magnet steels, increasing residual magnetism and coercive force, and in nonferrous-base magnetic alloys.

An important group of cobalt alloys is the stellite types. They contain chromium and various other elements such as tungsten, molybdenum, and silicon. The extremely hard alloy carbides in a fairly hard matrix give excellent abrasion and wear resistance and are used as hard-facing alloys and for aircraft jet engine parts.
The interesting properties of cobalt-containing permanent, soft, and constant-permeability magnets are a result of the electronic configuration of cobalt and its high Curie temperature. In addition, cobalt in well-known Alnico magnet alloys decreases grain size and increases coercive force and residual magnetism.

Cobalt is a significant element in many glass-to-metal sealing alloys and low-expansion alloys. One iron-base alloy containing 31% nickel and 5% cobalt provides a lower CTE than the iron–36% nickel alloy called Invar, and is less sensitive to variations in heat treatment. Co–Cr alloys are used in dental and surgical applications because they are not attacked by body fluids. Alloys named Vitallium are used as bone replacements and are ductile enough to permit anchoring of dentures on neighboring teeth. They contain about 65% cobalt.

Cobalt is a necessary material in human and animal metabolism, and is used in fertilizers.

### Applications

The major uses of cobalt are in cobalt-base and cobalt-containing materials for high-temperature alloys, permanent magnets, and steels. In addition, cemented carbides, which are considered cutting tools, are used in balls for ballpoint pens and high-temperature ball bearings.

The hard-facing alloys are useful because of their resistance to corrosion, abrasion, and oxidation at high temperatures for plowshares, oil bits, crushing equipment, tractor treads, rolling mill guides, knives, punches, shears, billet scrapers, valves for high-pressure steam, oil refineries, and diesel and auto engines.

The superalloys have found use as searchlight reflectors, and are also useful under the severe operating conditions of high-temperature nuclear reactors. Their superior elevated-temperature properties compensate, to some extent, for the high thermal-neutron absorption for cobalt. They are used in reactors in certain wear-resistant components as guides for control rods. In nuclear submarines, these alloys are used where severe wear in contact with seawater is encountered.

Although the main application of Alnico permanent magnets is in motors, generators, regulating devices, radar, and loudspeakers, some are used in games, novelties, and door latches. Cobalt-containing tool and high-speed steels are also used for dies.

### Cobalt Oxide

A steel-gray to blue-black powder employed as a base pigment for ceramic lasers on metal, as a colorant for glass, as a chemical catalyst. It gives excellent adhesion to metals and is valued as an undercoat for vitreous enamels. It is the most stable blue, as it is not changed by ordinary oxidizing or reducing conditions. It is also one of the most powerful colorants for glass, 1 part in 20,000 parts of a batch giving a distinct blue color. Cobalt oxide is produced from the cobalt-nickel and pyrite ores, and the commercial oxide may be a mixture of the three oxides. Cobaltous oxide, CoO, is called gray cobalt oxide but varies from greenish to reddish. It is the easiest to reduce to the metal, and it reacts easily with silica and alumina in ceramics. Cobaltic oxide, CoO, occurs in the mixture only as the unstable hydrate, and it changes to the stable black cobalt oxide, or cobalto-cobaltic oxide, Co₃O₄ on heating. Above about 1652°F (900°C) this oxide loses oxygen to form cobaltous oxide.

### Cockling/Cockles

The wavy edge of rolled sheet and plate.

### Cocoa

In fretting wear, a powdery form of debris, usually consisting of red iron oxides, that is expelled from a ferrous metal joint near the location where fretting wear is occurring. Also known as red mud. Fe₂O₃ is formed by fretting of iron and steel.

### Co-Curing

The act of curing a composite laminate and simultaneously bonding it to some other prepared surface, or curing together an inner and outer tube of similar or dissimilar fiber–resin combinations after each has been wound or wrapped separately. See also secondary bonding.

### COD Crack Opening Displacement

See fracture toughness.

### Coefficient

A factor defining the relationship between two components. For example, the coefficient of thermal expansion is a measure of the change in dimensions resulting from a unit change in temperature.

### Coefficient of Adhesion

(1) The ratio of the normal force required to separate two bodies to the normal load with which they were previously placed together.

(2) In railway engineering, sometimes used to signify the coefficient of (limiting) static friction.

### Coefficient of Compressibility

See bulk modulus of elasticity.

### Coefficient of Elasticity

The reciprocal of Young’s modulus in a tension test. See also compliance.

### Coefficient of Expansion

A measure of the change in length or volume of an object, specifically, a change measured by the increase in length or volume of an object per unit length or volume.

### Coefficient of Friction

The dimensionless ratio of the friction force (F) between two bodies to the normal force (N) pressing these bodies together: \( \mu = F/N \).

### Coefficient of Thermal Expansion

(1) Change in unit of length (or volume) accompanying a unit change of temperature, at a specified temperature. (2) The linear or volume expansion of a given material per degree rise of temperature, expressed at an arbitrary base temperature or as a more complicated equation applicable to a wide range of temperatures.
Coefficient of Wear

See wear coefficient.

Coercive Force

The magnetizing force that must be applied in the direction opposite to that of the previous magnetizing force in order to reduce magnetic flux density to zero; thus, a measure of the magnetic retentivity of magnetic materials.

Coextruded

An extrusion process in which two materials are extruded simultaneously so that one forms a surface layer around the other. The process is, for example, applied to tubes which require a combination of strength and corrosion resistance not obtainable in a single material.

Coextrusion Welding

A solid-state welding process which produces coalescence of the faying surfaces by heating and forcing materials through an extrusion die.

Cogging

The first reducing operation in working an ingot into a billet with a forging hammer or a forging press. See cogging mill.

Cogging Mill

A blooming mill.

Coherency

(1) The state in which the lattices of a precipitate and its surrounding parent matrix remains substantially in alignment but are distorted in the vicinity of the interface. (2) The parent phase (solvent) maintained by mutual strain and not separated by a phase boundary.

Coherent (Precipitate)

(1) An intermediate stage of precipitation, preceding formation of a distinct and separate phase, in which the lattices of the solution and the emerging precipitate are still in alignment but distorted. (2) A crystalline precipitate that forms from solid solution with an orientation that maintains continuity between the crystal lattice of the precipitate and the lattice of the matrix, usually accompanied by some strain in both lattices. Because the lattices fit at the interface between precipitate and matrix, there is no discernible phase boundary.

Coherent Radiation

Radiation in which the phase difference between any two points in the radiation field is constant throughout the duration of the radiation.

Coherent Scattering

In materials characterization, a type of x-ray or electron scattering in which the phase of the scattered beam has a definite (not random) relationship to the phase of the incident beam. Also termed unmodified scattering. See also incoherent scattering.

Cohesion

(1) The state in which the particles of a single substance are held together by primary or secondary valence forces. As used in the adhesive field, the state in which the particles of the adhesive (or adherend) are held together. (2) Force of attraction between the molecules (or atoms) within a single phase. Contrast with adhesion.

Cohesive Blocking

The blocking of two similar, potentially adhesive faces.

Cohesive Failure

Failure of an adhesive joint occurring primarily in an adhesive layer.

Cohesive Strength

(1) The hypothetical stress causing tensile fracture without plastic deformation. (2) The stress corresponding to the forces between atoms. (3) Intrinsic strength of an adhesive. (4) Same as technical cohesive strength. (5) Same as disruptive strength.

Coil

(1) An assembly consisting of one or more magnet wire windings. (2) Rolled metal sheet or strip.

Coil Breaks

Greases or ridges in sheet or strip that appear as parallel lines across the directions of rolling and that generally extend the full width of the sheet or strip.

Coil Winding

An electrically continuous length of insulated wire wound on a bobbin/spool, or form.

Coil with Support

A filler metal package type consisting of a continuous length of electrode in coil form wound on an internal support which is a simple cylindrical section without flanges.

Coil without Support

A filler metal package type consisting of a continuous length of electrode in coil form without an internal support. It is appropriately bound to maintain its shape.

Coin Silver

An alloy containing 90% silver, with copper being the usual alloying element.

Coin Straightening

A combination coining and straightening operation performed in special cavity dies assigned to impart a specific amount of working in specified areas of a forging to relieve the stresses developed during heat treatment.
Coinage Metals

Metals used for currency coinage because of their availability, durability and perceived value, originally gold, silver, copper and bronze, now presumably including aluminum, nickel, etc.

Coining

(1) A closed-die squeezing operation, usually performed cold, in which all surfaces of the work are confined or restrained, resulting in a well-defined imprint of the die upon the work. (2) A restriking operation used to sharpen or change an existing radius or profile. (3) The final pressing of a sintered powder metallurgy compact to obtain a definite surface configuration (not to be confused with re-pressing or sizing).

Coining Dies

Dies in which the coining or sizing operation is performed.

Coke

The poorest, gray, infusible residue left after the volatile matter is driven out of bituminous coal. The coal is heated to a temperature of 2192°F–2552°F (1200°C–1400°C), without allowing air to burn it, and the volatile matter expelled. The residue, which is mainly fixed carbon and ash, is a cellular mass of greater strength than the original coal. Its nature and structure make it a valuable fuel for blast furnaces, burning rapidly and supporting a heavy charge of metal without packing. Soft, or bituminous, coals are designated as coping or noncooking, according to their capacity for being converted to coke. Coal low in carbon and high in ash will produce a coke that is friable and not strong enough for furnace use, or the ash may have low-melting-point constituents that leave glassy slag in the coke. Coke is produced in the beehive and by-product ovens, or is a by-product of gas plants. Coke is also used as a fuel in cupola melting.

The fixed carbon of good coke should be at least 86%, and sulfur not more than 1%. The porosity may vary from 40% to 60%, and the apparent specific gravity should not be less than 0.8. Foundry coke should have an ignition point of about 1000°F (538°C), with sulfur below 0.7%, and the pieces should be strong enough to carry the burden of ore and limestone. Coke suitable for foundry use is also made from low-grade coals by reducing them to a semi-coke, or char, and briquetting, but semi-coke and smokeless fuel are generally coals carbonized at low temperatures and briquetted for household use. These fuels are sold under trade names such as Coalite and Carbolux, and they are really by-products of the chemical industry since much greater quantities of liquids and more lighter fractions in the tar are obtained in the process.

Pitch coke, made by distilling coal tar, has a high carbon content, above 99%, with low sulfur and ash, and is used for making carbon electrodes. Petroleum coke is the final residue in the distillation of petroleum and forms about 5% of the weight of the crude oil. With the sand and impurities removed, it is about 99% pure carbon and is used for molded carbon products. Calcined coke is petroleum coke that has been calcined at 2400°F (1316°C) to remove volatile matter. It is used for electrodes. Carbonite is a natural coke found in England and in Virginia. It is a coke-like mineral formed by the baking action of igneous rocks on seams of bituminous coal.

Coke Breeze

In foundry practice, fines from coke screenings, used in blacking mixes after grinding; also briquetted for cupola use.

Coke Furnace

Type of pot or crucible furnace that uses coke as a fuel.

Coke Oven

The furnace in which coal is tightly packed and heated to form coke.

Coke Oven Gas

The gas produced in the manufacture of coke. It is a mixture of carbon monoxide, methane and hydrogen plus numerous other volatile constituents.

Coke Test

In foundry practice, the first layer of coke placed in the cupola. Also the coke used as a foundation and constructing a large mold in a flask or pit.

Cold Anodizing

A process for increasing the thickness of the normal oxide film on aluminum by immersing it in cold 50% nitric acid for a few minutes. Also see anodizing.

Cold Bend Test

A test in which a bar of metal is bent to some specified degree as a test of ductility or, especially in the case of tests that include a weld zone, to confirm freedom from cracking. The specimen may be plain or notched. See also bend test.

Cold Box Process

In foundry practice, a two-part organic resin binder system mixed in conventional mixers and blown into shell or solid core shapes at room temperature. A vapor mixed with air is blown into the core, permitting instant setting and immediate pouring of metal around it.

Cold Cast

A term used, dubiously, for a technique where a metal powder such as bronze is mixed with liquid resin and poured into a mold to solidify. The resultant item is then described as Cold Cast Bronze.

Cold Chamber Machine

A diecasting machine with an injection system that is charged with liquid metal from a separate furnace. Compare with hot chamber machine.

Cold Chisel

A chisel or relatively short length, substantial cross section and relatively obtuse angled cutting edge for cutting materials such as metal or brick as opposed to timber. It has no handle and the flat, beveled edge, head is struck with a hammer.

Cold Coined Forging

A forging that has been restruck cold in order to hold closer face distance tolerances, sharpen corners or outlines, reduce section thickness, flatten some particular surface, or in nonheat-treatable alloys, increase hardness.
Cold Compacting
See preferred term cold pressing.

Cold Cracking
(1) Cracks in cold or nearly cold cast metal due to excessive internal stress caused by contraction. Often brought about when the mold is too hard or the casting is of unsuitable design. (2) A type of weld cracking that usually occurs below 400°F (205°C). Cracking may occur during or after cooling to room temperature, sometimes with a considerable time delay. Three factors combine to produce cold cracks: stress (for example, from thermal expansion and contraction), hydrogen (from hydrogen-containing welding consumables), and a susceptible microstructure (plate martensite is most susceptible to cracking, ferritic and bainitic structures least susceptible). See also hot cracking, lamellar tearing, and stress-relief cracking.

Cold Die Quenching
A quench utilizing cold, flat, or shaped dies to extract heat from a part. Cold die quenching is slow, expensive, and is limited to smaller parts with large surface areas.

Cold Drawing
Technique for using standard metalworking equipment and systems for forming thermoplastic sheet at room temperature.

Cold Dry Die Quenching
Same as cold die quenching.

Cold Etching
Development of microstructure at room temperature and below.

Cold Extrusion
See extrusion.

Cold Extrusion/Forming/Drawing, etc.
See Cold Work, etc. Extrusion and Drawing, etc. In some cases of the terms there is an implication of close dimensional control of the product.

Cold Finger
In materials characterization, a liquid-nitrogen-cooled cold trap used to reduce contamination levels in vacuum chambers.

Cold Flow
The distortion that takes place in polymeric materials under continuous load at temperatures within the working range of the material without a phase or chemical change.

Cold Form Tapping
Producing internal threads by displacing material rather than removing it as either the tap or the workpiece is rotated. The thread form is produced by a tool, which has neither flutes nor cutting edges, that resembles a simple screw when viewed from the side but the end view shows that both the major and minor diameters have irregular contours for displacing the work material.

Cold Forming
See cold working.

Cold Galvanizing
Painting with zinc rich paint or a similar immersion process in an attempt to obtain the protection offered by hot dip or electrogalvanizing. The coating must have good adhesion and provide electrical continuity between zinc particles and the underlying steel if any cathodic protection is to be obtained. The term has also been used of electrogalvanizing although this latter term is normally to be preferred, if only because of the likely superior protection compared with a paint or similar film.

Cold Hardening—Natural Aging
See precipitation hardening.

Cold Heading
(1) Working metal at room temperature such that the cross-sectional area of a portion or all of the stock is increased. (2) Cold forging the heads of bolts by an upsetting process. See also heading and upsetting.

Cold Hearth Melting
The use of a furnace with a water cooled hearth, usually copper, on which to melt materials to avoid contamination by refractories.

Cold Inspection
A visual (usually final) inspection of forgings for visible imperfections, dimensions, weight, and surface condition at room temperature. The term may also be used to describe certain nondestructive tests such as magnetic-particle, dye-penetrant, and sonic inspection.

Cold Isostatic Pressing
Forming technique in which high fluid pressure is applied to a powder (metal or ceramic) part at ambient temperature. Water or oil is used as the pressure medium.

Cold Joint (Soldered or Brazed)
A joint with inadequate bonding resulting from insufficient heating of the parent components. See also dry joint.

Cold Junction
The cold end datum point of the pair of wires forming a thermocouple.

Cold Lap
(1) Wrinkled markings on the surface of an ingot or casting from incipient freezing of the surface and too low a casting temperature.
Cold Mill
A mill for cold rolling of sheet or strip.

Cold Parison Blow Molding
A plastic forming technique in which parisons are extruded or injection molded separately and then stored for subsequent transportation to the blow molding machine for blowing. See also blow molding.

Cold Pressing (Plastics)
A bonding operation in which a plastic assembly is subjected to pressure without the application of heat.

Cold Pressing (Powder Metallurgy)
Forming a powder metallurgy compact at a temperature low enough to avoid sintering, usually room temperature. Contrast with hot pressing.

Cold Rolled Sheets
A metal mill product produced from a hot-rolled pickled coil that has been given substantial cold reduction at room temperature. The resulting product usually requires further processing to make it suitable for most common applications. The usual end product is characterized by improved surface, greater uniformity in thickness, and improved mechanical properties compared with hot rolled sheet.

Cold Rolling
(1) Cold working, by rolling, of sheet, bar, etc., to affect a size change. (2) Local rolling, of surface features such as crankshaft radii, with hardened steel wheels or rollers to induce surface hardening with beneficial residual stresses.

Cold Short
Having poor ductility and hence a susceptibility to cracking during cold working operations.

Cold Shortness
Brittleness that exists in some metals at temperatures below the recrystallization temperature.

Cold Shot
(1) A portion of the surface of an ingot or casting showing premature solidification; caused by splashing of molten metal onto a cold mold wall during pouring. (2) Small globule of metal embedded in, but not entirely fused with, the casting.

Cold Shut
(1) Any process of plastic deformation in which the component does not recrystallize but becomes progressively harder and stronger but less ductile up to some limit. The temperature will normally be at about ambient. If it is deliberately and significantly higher, but still below the recrystallization temperature, the process may be termed warm working. (2) Permanent strain in a metal accompanied by strain hardening.

Cold Welding
(1) Welding, without any heating, between two surfaces in intimate contact. In practice high pressures and very clean, oxide free surfaces are required. Also termed adhesion, galling and seizure. (2) The application of special procedures allowing fusion welding, in particular arc welding, without preheat and, or postheat, in circumstances where they would normally be expected. For example, alloy steels in restrained thick sections. (3) A solid-state welding process in which pressure is used at room temperature to produce coalescence of metals with substantial deformation at the weld. Compare with hot pressure welding, diffusion welding, and forge welding.

Cold Work
(1) A flaw that results when a workpiece fails to fill the die cavity during the first forging. A seam is formed as subsequent dies force metal over this gap to leave a seam on the workpiece surface. See also cold shut.

Cold Press
The first plastic material to enter an injection mold; so-called because in passing through a sprue orifice it is cooled below the effective molding temperature.

Cold Soldered Joint
A joint with incomplete coalescence caused by insufficient application of heat to the base metal during soldering.

Cold Stretch
A pulling operation with little or no heat, usually on extruded filaments, to increase tensile properties of composite materials.

Cold Test
A test in which the pour point of an oil is determined.

Cold Treatment
Exposing steel to suitable subzero temperatures (−85°C or −120°F) for the purposes of obtaining desired conditions or properties such as dimensional or microstructural stability. When the treatment involves the transformation of retained austenite, it is usually followed by tempering.

Cold Trimming
The removal of flash or excess metal from a forging at room temperature in a trimming press.
Cold Working

Deforming metal plastically under conditions of temperature and strain rate that induce strain hardening. Usually, but not necessarily, conducted at room temperature. Contrast with hot working.

Cold-Molded Plastics

Cold-molded plastics are one of the oldest of the so-called plastic materials; they were introduced in the United States in 1908. For the first time they provided the electrical engineer with materials that could be molded into more complicated shapes than could porcelain or hard rubber, providing better heat resistance than hard rubber, and better impact strength than porcelain. They could also incorporate metal inserts.

A procedure in which a plastic is shaped at room temperature and subsequently cured by baking.

General Nature and Properties

So-called cold-molded plastics are formulated and mixed by the molder (usually in a proprietary formulation). The materials fall into two general categories: inorganic or refractory materials, and organic or nonrefractory materials.

Inorganic cold-molded plastics consist of asbestos fiber filler and either an SiO₂-lime cement or portland cement binder. Clay is sometimes added to improve plasticity. The SiO₂-lime materials are easier to mold although they are lower in strength than the portland cement types.

In general, advantages of these materials include high arc resistance, heat resistance, good dielectric properties, comparatively low-cost, rapid molding cycles, high production with single-cavity molds (thus low tool cost), and no need for heating of molds. On the other hand, they are relatively heavy, cannot be produced to highly accurate dimensions, are limited in color, and can be produced only with a relatively dull finish. They have been used generally for arc chutes, arc barriers, supports for heating coils, underground fuse shells, and similar applications.

Organic cold-molded plastics consist of asbestos fiber filler materials bound with bituminous (asphalt, pitches, and oils), phenolic, or melamine binders. The binder materials are mixed with solvents to obtain proper viscosities, then thoroughly mixed with the asbestos, ground and screened to form molding compounds. The bituminous-bound compounds are lowest in cost and can be molded more rapidly than the inorganic compounds; the phenolic and melamine-bound compounds have better mechanical and electrical properties than the bituminous compounds and have better surfaces as well as being lighter in color. Like the inorganic compounds, organic compounds are cold-molded, followed by oven curing.

Compounds with melamine binders are similar to the phenolics, except that melamines have greater arc resistance, lower water absorption, are nontracking, and have higher dielectric strength.

Major disadvantages of these materials, again, are relatively high specific gravity, limited colors, and inability to be molded to accurate dimensions. Also, they can be produced only with a relatively dull finish.

Compounds with bituminous binders are used for switch bases, wiring devices, connector plugs, handles, knobs, and fuse cores. Phenolic and melamine compounds are used for similar applications where better strength and electrical properties are required.

An important benefit of cold-molded plastics is the relatively low tooling cost usually involved for short-run production. Most molding is done in single-cavity molds, in conventional compression-molding presses equipped for manual, semiautomatic, or fully automatic operation.

Cold-Rolled Steel

Cold-rolled steels are flat steel products produced by cold-rolling hot-rolled products. The hot-rolled product is cleaned of oxide scale by pickling and passed through a cold-reduction mill to reduce and more uniformly control thickness and to enhance surface finish. Cold rolling also increases hardness, reducing ductility. Although the steel is sometimes used as rolled, it is often subsequently annealed to improve formability and then temper-rolled or roller-leveled for flatness. Cold-rolled steels are available in carbon and alloy grades as well as high-alloy grades, such as stainless steels. For plain carbon steels, carbon content is usually 0.25% maximum, often less. Quality designations include commercial quality (CQ) steel, which is produced from rimmed, capped, or semikilled steel; drawing quality (DQ), which is made from specially processed steel and is more ductile and uniform in forming characteristics; and drawing-quality special-killed (DQSK) steel, which is still more ductile and more uniform in forming characteristics. Cold-rolled structural-quality (SQ) steel refers to cold-rolled steel produced to specific mechanical properties. Bar and rod products are often cold-drawn through dies and called cold-drawn bar steel, or cold-finished in other ways and called cold-finished bar steel.

A series of SQ ultrahigh-strength steels featuring minimum tensile strength levels of between 1000 and 1400 MPa combine superior performance with low weight. Named Docol UHS, the new steels are particularly applicable to the automotive industry. Their high-energy-absorbing properties, for example, make them useful as structural members and for components used in a car’s crumple zone.

Since the steel is hardened prior to leaving the factory, industries using these steels no longer require their own warm-up plants and hardening furnaces. Cutting, shaping, and welding are achieved with traditional methods. The Docol UHS series consists of three standard steels: Docol 1000 DP, Docol 1200 DP, and Docol 1400 DP. Numbers relate to maximum loads measured in megapascals, MPa.
Cold-Runner Molding

In plastic part making, a mold in which the sprue-and-runner system (the manifold section) is insulated from the rest of the mold and temperature-controlled to keep the plastic in the manifold fluid. This mold design eliminates scrap loss from sprues and runners.

Cold-Setting Adhesive

An adhesive that sets at temperatures below 20°C (68°F). See also hot-setting adhesive, intermediate-temperature-setting adhesive, and room-temperature-setting adhesive.

Cold-Setting Process

In foundry practice, any of several systems for bonding mold or core aggregates by means of organic binders, relying on the use of catalysts rather than heat for polymerization (setting).

Cold-Slug Well

In plastic part making, the space provided directly opposite the sprue opening in an injection mold to trap the cold slug.

Coldstream Process

In powder metallurgy, a method of producing cleavage fractures in hard particles through particle impingements in a high-velocity cold gas stream. Also referred to as impact crushing.

Cold-Worked Structure

A microstructure resulting from plastic deformation of the metal or alloy below its recrystallization temperature.

Collapse

Inadvertent densification of cellular plastic material during manufacture resulting from the breakdown of cell structure.

Collapsibility

The tendency of a sand mixture to break down under the pressures and temperatures developed during casting.

Collapsible Tool

A press tool that can be easily disabled.

Collar

The reinforcing metal of a nonpressure thermit weld.

Collar Oiler

A collar on a shaft that extends into the oil reservoir and carries oil into a bearing as the shaft rotates. Wipers are usually provided to direct the oil into the bearing.

Collaring (Thermal Spraying)

Adding a shoulder to a shaft or similar component as a protective confining wall for the thermal spray deposit.

Collection Efficiency

The cross-sectional area of undisturbed fluid containing particles that will ultimately impinge on a given solid surface, divided by the projected area of the solid surface. Also known as collision efficiency, capture efficiency, catchment efficiency, and impaction ratio.

Collet

A split sleeve used to hold work or tools during machining or grinding.

Colligative Properties

Properties of plastics based on the number of molecules present. Most important are certain solution properties extensively used in molecular weight characterization.

Collimate

To make parallel to a certain line or direction.

Collimated

Rendered parallel.

Collimated Roving

Roving for reinforced plastics that has been made using a special process (usually parallel wound), such that the strands are more parallel than in standard roving.

Collimation

The degree of parallelism of light rays from a given source. A light source with good collimation produces parallel light rays, whereas a poor light source produces divergent, nonparallel light rays.

Collimator

The x-ray system component that confines the x-ray beam to the required shape. An additional collimator can be located in front of the x-ray detector to further define the portion of the x-ray beam to be measured.

Collision Efficiency

See collection efficiency.

Collodian Replica

In metallography, a replica of a surface cast in nitrocellulose.

Colloid

A stable (nonsettling) finely particulate suspension of some material within a fluid host, the dimensions of the former usually being about ±1 μm. Fogs, smokes, foams, emulsions, sols, and gels are examples.
Colloidal

A state of suspension in a liquid medium in which extremely small particles are suspended and dispersed but not dissolved.

Colonies (Titanium)

Regions within prior-β grains with α Platelets having nearly identical orientations. In commercially pure titanium, colonies often have serrated boundaries. Colonies arise as transformation products during cooling from the β field at cooling rates that induce platelet nucleation and growth.

Colophony

See rosin.

Color Buffing

Producing a final high luster by buffing. Sometimes called coloring.

Color Center

In materials characterization, a point lattice defect that produces optical absorption bands in an otherwise transparent crystal.

Color Concentrate

A measured amount of dye or pigment incorporated into a predetermined amount of plastic. The pigmented or colored plastic is then mixed into larger quantities of plastic material to be used for molding articles to be molded. This mixture is added to the bulk of plastic and measured quantity in order to produce a precise, predetermined color of finished articles to be molded.

Color Filter

In metallography, a device that transmits principally a predetermined range of wavelengths. See also contrast filter and filter.

Color Temperature

The temperature in degrees Kelvin at which a blackbody must be operated to provide a color equivalent to that of the source in question. See also blackbody.

Colorimeter

An instrument for measuring the hue, purity, and brightness of a color.

Coloring

Producing desired colors on metal by a chemical or electrochemical reaction. See also color buffing.

Columbium and Alloys

One of the basic elements, columbium (Cb) is also known as niobium and occurs in the minerals columbite and tantalite. A refractory metal, it closely resembles tantalum, is yellowish-white in color, has a specific gravity of 8.57, a melting point of 2468°C, and an electrical conductivity 13.2% relative to copper. It is quite ductile when pure or essentially free of interstitials and impurities, notably N₂, O₂, and H₂, which are limited to very small amounts. Tensile properties depend largely on purity, and columbium, with a total interstitial content of 100–200 ppm, provides about 276 MPa ultimate strength, 207 MPa yield strength, 30% elongation, and 105,000 MPa elastic modulus. Drawn wire having an ultimate tensile strength of 896 MPa has been produced. The metal is corrosion resistant to many aqueous media, including dilute mineral and organic acids, and to some liquid metals, notably lithium, sodium, and NaK. It is strongly attacked, however, by strong dilute alkalis, hot concentrated mineral acids, and HF acid. At elevated temperatures, gaseous atmospheres attack the metal primarily by oxidation even if O₂ content is low, with the attack especially severe at 399°C and higher temperatures, necessitating the use of protective coatings. Columbium tends to gall and seize easily in fabrication. Sulfonated tallow and various waxes are the preferred lubricants in forming, and carbon tetrachloride in machining. Ferro-columbium is used to add the metal to steel. Columbium is also an important alloying element in non-ferrous alloys.

Secondary Fabrication

Pure columbium is considered one of the most workable of the refractory metals, and commercially fabricated columbium can be forged, rolled, swaged, drawn, and stamped by existing commercial techniques. In the primary or mill fabrication, and ingot is hot-worked by forging or extruding, following which the surface is conditioned to remove the contaminated layer, annealed in vacuum or an inert atmosphere to obtain a recrystallized structure, and then cold-worked (with intermediate anneals, if required) by any desired technique to final shape and size. Columbium metal containing less than a total of 0.12% combined O₂, N₂, and carbon can be given a cold reduction of over 90% in cross-sectional area. Secondary fabrication is done cold to avoid O₂ contamination, and lubrication is used to minimize galling or seizing on the working tools.

Vapor degreasing is an effective way to remove oils or grease from columbium parts, while immersion in various hot acids can be used for surface cleaning.

Columbium Alloys

These alloys are noted mainly for their heat resistance at temperatures far greater than those that can be sustained by most metals, but protective coatings are required for oxidation resistance. Thus, they find use for aircraft turbine components and in rocket engines, aerospace reentry vehicles, and for thermal and radiation shields. Cb–Sn and Cb–Ti alloys have found use as superconductors, and Cb–1Zr, a columbium–1% zirconium alloy, as has been used for high-temperature components, liquid-metal containers, sodium or magnesium vapor-lamp parts, and nuclear applications. It has a tensile yield strength of about 255 MPa at 21°C and 165 MPa at 1093°C. Thin cold-rolled sheet of columbium alloy C-103, which contains 10% hafnium and 1% titanium, has a tensile yield strength of 648 MPa at 21°C and 172 MPa at 1093°C. After recrystallization at 1315°C, however, yield strength drops to 345 MPa at 21°C and 124 MPa at 1093°C. The room-temperature tensile properties of the 10% tungsten, 10% hafnium, 0.1% yttrium columbium alloy, known as columbium alloy C-129, are 620 MPa ultimate strength, 517 MPa yield strength, 25% elongation, and 110,000 MPa elastic modulus.

Its strength falls rapidly with increasing temperatures; tensile yield
Columnar Grains/Structure

A coarse structure of parallel elongated grains formed by unidirectional growth, most often observed in castings, but sometimes seen in structures resulting from diffusional growth accompanied by a solid-state transformation.

Coma

In materials characterization, a lens aberration occurring in that part of the image field that is some distance from the principal axis of the system. It results from different magnification in the various lens zones. Extra-axial object points appear as short cone-like images with the brighter small head toward the center of the field (positive coma) or away from the center (negative coma).

Combination Die

(1) A die-casting die having two or more different cavities for different castings. (2) For forming, see compound die.

Combination Mill

(1) An arrangement of a continuous mill for roughing and a guide mill or looping mill for shaping. (2) A rolling mill in which the initial coggling mill is followed immediately by a further series of rolls to complete the hot rolling process.

Formation of Cast Iron

A group of comparatively deep unidirectional scratches that form adjacent to a microstructural discontinuity doing mechanical polishing. They have the general shape of a comet tail. Comet tails form only when a unidirectional motion is maintained between the surface being polished and the polishing cloth.

Comminution

(1) The production of fine powder by various processes including pulverizing, attrition, chemical or electrochemical techniques. (2) Breaking up or grinding an ore into small fragments. (3) Reducing metal to powder by mechanical means. (4) The act or process of reduction of powder particle size, usually but not necessarily by grinding or milling. See also pulverization.

Common Brass

Alloy of 63% copper and 37% zinc. The highest zinc level and hence the cheapest alloy that remains single, (alpha) phase allowing it to be cold worked.

Commutator-Controlled Welding

Spot or projection welding in which several electrodes, in simultaneous contact with the work, function progressively under the control of an electrical commutating device.

Compact (Noun)

The object produced by the compression of metal powder, generally while confined in a die.

Compact (Verb)

The operation or process of producing a compact; sometimes called pressing.

Compact Tension Specimen (CTS)

See fracture toughness.

Compacted Graphite Cast Iron

Cast iron having a graphite shape intermediate between the flake form typical of gray cast iron and the spherical form of fully
Compactibility

An acceptable compacted graphite iron structure is one that contains no flake graphite, <20% spheroidal graphite, and 80% compacted graphite (ASTM A247, type IV). Also known as CG iron or vermicular iron, compacted graphite cast iron is produced in a manner similar to that for ductile cast iron, but using a technique that inhibits the formation of fully spherulitic graphite nodules. Typical nominal compositions of CG irons containing 3.1%–4.0% C, 1.7%–3.0% Si, and 0.1%–0.6% Mn.

Compatibility

See compressibility.

Compacting Crack

A crack in a powder metallurgy compact that is generated during the major phases of the pressing cycle, such as load application, load release, and ejection.

Compacting Force

The force that acts on a powder to be densified expressed in newtons or tons.

Compacting Pressure

In powder metallurgy, the specific compacting force related to the area of contact with the press punch expressed in megapascals, meganewtons per square meter, or tons per square inch.

Compacting Tool Set

See die.

Compaction

(1) The act of forcing particulate or granular material together (consolidation) under pressure or impact to yield a relatively dense mass or formed object. Usually followed by drying, curing, or firing in refractory or other ceramic or powder metallurgy processing. (2) In ceramics or powder metallurgy, the preparation of a compact or object produced by the compression of a powder, generally while confined in a die, with or without the inclusion of lubricants, binders, etc., and with or without the concurrent applications of heat. (3) In reinforced plastics and composites, the application of a temporary vacuum bag and vacuum to remove trapped air and compact the lay-up.

Comparison Standard

In metallography, a standard micrograph or a series of micrographs, usually taken at 75x–100x, used to determine grain size by direct comparison with the image.

Compatibility (Frictional)

In tribology, materials that exhibit good sliding behavior, including resistance to adhesive wear, are termed frictionally compatible. Under some conditions materials that are not normally considered compatible in a metallurgical sense (for example, silver and iron) may be very compatible in the frictional sense.

Compatibility (Lubricant)

In tribology, a measure of the degree to which lubricants or lubricant components can be mixed without harmful effects such as formation of deposits.

Compatibility (Metallurgical)

A measure of the extent to which materials are mutually soluble in the solid state.

Compatibility (Plastics)

The ability of two or more substances combined with one another to form a homogeneous composition having useful plastic properties; for example, the suitability of a sizing or finish for use with certain general resin types. Nonreactivity or negligible reactivity between materials and contact.

Compensating Eyepiece

In metallography, an eyepiece design for use with apochromatic objectives. They are also used to advantage with high-power (oil-immersion) achromatic objectives. Because apochromatic objectives are undercorrected chromatically, these eyepieces are overcorrected. See also apochromatic objective.

Compensating Leads

The electrical conductor wires between a thermocouple and the instrument measuring the e.m.f. The wire materials are selected to have the same thermoelectric characteristics as their respective thermocouple wires over the temperature range that the lead experiences. The benefits offered are that the lead can be stranded to improve flexibility and it can be of cheaper material than the thermocouple.

Complete Fusion

Fusion which has occurred over the entire base material surfaces intended for welding and between all layers and weld beads.

Complete Joint Fusion

Joint penetration in which the weld metal completely fills the groove and is fused to the base metal throughout its total thickness.

Complete Penetration

See preferred term complete joint penetration.

Complex Ion

An ion that may be formed by the additional reaction of two or more other ions.

Complex Modulus

The ratio of stress to strain in which each is a vector that may be represented by a complex number. May be measured in tension or flexure, compression, or shear.
**Complex Shear Modulus**
The vectorial sum of the shear modulus and the loss modulus.

**Complex Silicate Inclusions**
A general term describing silicate inclusions containing visible constituents in addition to the silicate matrix. An example is corundum or spinel crystals occurring in a silicate matrix in steel.

**Complex Young’s Modulus**
The vectorial sum of Young’s modulus and the loss modulus.

**Complexation**
The formation of complex chemical species by the coordination of groups of atoms termed ligands to a central ion, commonly a metal ion. Generally, the ligand coordinates by providing a pair of electrons that forms an ionic or covalent bond to the central ion. See also chelate, coordination compound, and ligand.

**Complexing Agent**
A substance that is an electron donor and that will combine with a metal ion to form a soluble complex ion.

**Compliance**
(1) Tensile compliance is the reciprocal of Young’s modulus. Shear compliance is the reciprocal of shear modulus. The term is also used in the evaluation of stiffness and deflection. (2) The measure of the ability of a shaft or similar body to flex elastically.

**Component**
(1) One of the elements or compounds used to define a chemical (or alloy) system, including all phases, in terms of the fewest substances possible. (2) One of the individual parts of a vector as referred to a system of coordinates. (3) An individual functional element in a physically independent body that cannot be further reduced or divided without destroying its stated function, for example, a resistor, capacitor, diode, or transistor.

**Component of Variance**
A part of the total variance identified with a specified source of variability.

**Composite**
See composite material.

**Composite Bearing Material**
A solid material composed of a continuous or particulate solid lubricant dispersed throughout a load-bearing matrix to provide continuous replenishment of solid lubricant films as wear occurs, and effective heat transfer from the friction surface.

**Composite Coating**
A coating on a metal or nonmetal that consists of two or more components, one of which is often particulate in form. Example: a cermet composite coating on a cemented carbide cutting tool. Also known as multilayer coating.

**Composite Compact**
A metal powder compact consisting of two or more adhering layers, rings, or other shapes of different metals or alloys with each material retaining its original identity.

**Composite Electrode**
A welding electrode made from two or more distinct components, at least one of which is filler metal. A composite electrode may exist in any of various physical forms, such as stranded wires, filled tubes, or covered wire.

**Composite Joint**
A joint in which welding is used in conjunction with mechanical joining.

**Composite Material**
Composite materials are based on the controlled distribution of one or more reinforcement materials in a continuous matrix. Plastics are the most common matrix materials, although metals, ceramics, and intermetallics are also used. Reinforcements include ceramics, glass, polymers, carbon, and metals. They can be in the shape of filaments, spheres, irregularly shaped particles, short fibers known as whiskers, or flat particles known as flakes.

Composites are also found in nature. Wood is a composite of cellulose fibers bonded by a matrix of natural polymers, mainly lignin. Egyptians reinforced mud with straw to make bricks. Concrete can be classified as a ceramic composite in which stones are dispersed among cement. And in the 1940s, short glass fibers impregnated with thermosetting resins, known as fiberglass, became the first composite with a plastic matrix.

In a properly designed composite, the reinforcement compensates for low properties of the matrix. Furthermore, in many cases synergism enables the reinforcing material to improve properties in the matrix. Composites also offer the capability of placing specific properties where they are needed on the part.

All these developments mean a larger and more-complicated choice of materials. This diversity has made plastics applicable to a broad range of consumer, industrial, automotive, and aerospace products. It has also made the job of selecting the best materials from such a huge array of candidates quite challenging.

**Definition**
Composite materials are macroscopic combinations of two or more distinct materials with a discrete and recognizable interface separating them.

**Constituents and Construction**
In principle, composites can be constructed of any combination of two or more materials-metallic, organic, or inorganic; but the constituent forms are more restricted. The matrix is the body constituent serving to enclose the composite and give it bulk form. Major structural constituents are fibers, particles, laminae or layers, flakes,
Composite Material

203

Composite Material

fillers, and matrices. They determine the internal structure of the composite. Usually, they are the additive phase.

Because the different constituents are intermixed or combined, there is always a contiguous region. It may simply be an interface, that is, the surface forming the common boundary of the constituents. An interface is in some ways analogous to the grain boundaries in monolithic materials. In some cases, however, the contiguous region is a distinct added phase, called an interphase. Examples are the coating on the glass fibers in reinforced plastics and the adhesive that bonds the layers of a laminate together. When such an interphase is present, there are two interfaces, one between the matrix and the interphase and one between the fiber and the interface.

Interfaces are among the most important yet least understood components of a composite material. In particular, there is a lack of understanding of processes occurring at the atomic level of interfaces, and how these processes influence the global material behavior. There is a close relationship between processes that occur on the atomic, microscopic, and macroscopic levels. In fact, knowledge of the sequence of events occurring on these different levels is important in understanding the nature of interfacial phenomena. Interfaces in composites, often considered as surfaces, are in fact zones of compositional, structural, and property gradients, typically varying in width from a single atom layer to micrometers. Characterization of the mechanical properties of interfacial zones is necessary for understanding mechanical behavior.

Nature and Performance

Several classification systems for composites have been developed, including classification by (1) basic material combinations, for example, metal-organic or metal-inorganic; (2) bulk-form characteristics, such as matrix systems or laminates; (3) distribution of the constituents, that is, continuous or discontinuous; and (4) function, for example, electrical or structural.

There are five classes under the classification of basic material combinations: (1) fiber composites, composed of fibers with or without a matrix; (2) flake composites, composed of flat flakes with or without a matrix; (3) particulate composites, composed of particles with or without a matrix; (4) filled (or skeletal) composites, composed of a continuous skeletal matrix filled by a second material; and (5) laminar composites, composed of layer or laminar constituents.

There is also a classification based on dimensions. The dimensions of some of the components of composite materials vary widely and overlap the dimensions of the microstructural features of common conventional materials. They range from extremely small particles or fine whiskers to the large aggregate particles or rods in reinforced concrete.

The behavior and properties of composites are determined by the composition, form and arrangements, and interaction between the constituents. The intrinsic properties of the materials of which the constituents are composed largely determine the general order or range of properties of the composite. Structural and geometrical characteristics—that is, the shape and size of the individual constituents, their structural arrangement and distribution, and the relative amount of each—contribute to overall performance. Of far-reaching importance are the effects produced by the combination and interaction of the constituents. The basic principle is that by using different constituents it is possible to obtain combinations of properties and property values that are different from those of the individual constituents.

A performance index is a property or group of properties that measures the effectiveness of a material in performing a given function. The values of performance indices for a composite differ from those of the constituents.

Fiber–Matrix Composites

Fiber–matrix composites have two constituents and usually a bonding phase as well.

Fibers

The performance of a fiber–matrix composite depends on orientation, length, shape, and composition of the fibers; mechanical properties of the matrix; and integrity of the bond between fibers and matrix. Of these, orientation of the fibers is perhaps most important.

Fiber orientation determines the mechanical strength of the composite and the direction of greatest strength. Fiber orientation can be one-dimensional, planar (two-dimensional), or three-dimensional. The one-dimensional type has maximum composite strength and modulus in the direction of the fiber axis. The planar type exhibits different strengths in each direction of fiber orientation; and the three-dimensional type is isotropic but has greatly decreased reinforcing values. The mechanical properties in any one direction are proportional to the amount of fiber by volume oriented in that direction. As fiber orientation becomes more random, the mechanical properties in any one direction become lower.

Fiber length also impacts mechanical properties. Fibers in the matrix can be either continuous or short. Composites made from short fibers, if they could be properly oriented, could have substantially greater strengths than those made from continuous fibers. This is particularly true of whiskers, which have uniform high tensile strengths. Both short and long fibers are also called chopped fibers. Fiber length also has a bearing on the processibility of the composite. In general, continuous fibers are easier to handle but have more design limitations than short fibers.

Bonding

Fiber composites are able to withstand higher stresses than their individual constituents because the fibers and matrix interact, resulting in redistribution of the stresses. The ability of constituents to exchange stresses depends on the effectiveness of the coupling or bonding between them. Bonding can sometimes be achieved by direct contact of the two phases, but usually a specially treated fiber must be used to ensure a receptive adherent surface. This requirement has led to the development of fiber finishes, known as coupling agents. Both chemical and mechanical bonding interactions occur for coupling agents.

Voids (air pockets) in the matrix are one cause of failure. A fiber passing through the void is not supported by resin. Under load, the fiber may buckle and transfer stress to the resin, which readily cracks. Another cause of early failure is weak or incomplete bonding. The fiber–matrix bond is often in a state of shear when the material is under load. When this bond is broken, the fiber separates from the matrix and leaves discontinuities that may cause failure. Coupling agents can be used to strengthen these bonds against shear forces.

Reinforced Plastics

Probably the greatest potential for lightweight high-strength composites is represented by the inorganic fiber-organic matrix composites, and no composite of this type has proved as successful as glass-fiber-reinforced composites. As a group, glass-fiber-plastic composites have the advantages of good physical properties, including strength, elasticity, impact resistance, and dimensional stability; high strength-to-weight ratio; good electrical properties; resistance to chemical attack and outdoor weathering; and resistance to moderately high temperatures (about 260°C).

A critical factor in reinforced plastics is the strength of the bond between the fiber and the polymer matrix; weak bonding causes fiber
pullout and delamination of the structure, particularly under adverse environmental conditions. Bonding can be improved by coatings and the use of coupling agents. Glass fibers, for example, are treated with silane (SiH₄) for improved wetting and bonding between the fiber and the matrix.

Generally, the greatest stiffness and strength in reinforced plastics are obtained when the fibers are aligned in the direction of the tension force. Other properties of the composite, such as creep resistance, thermal and electrical conductivity, and thermal expansion, are anisotropic. The transverse properties of such a unidirectionally reinforced structure are much lower than the longitudinal. Seven mechanical and thermal properties are of direct interest in assessing the potential of a new composite: density, modulus, strength, toughness, thermal conductivity, expansion coefficient, and heat capacity; others, such as fracture toughness and thermal diffusivity, are calculated from them.

**Tailoring Properties**

The ideal way to develop a product made of composites is to model and analyze it extensively by computer before a prototype is built. But this is difficult because most computer programs were developed for metals and do not work well with composites.

Many new applications for composites are structural. Since the objective of structural parts generally is to maximize strength-to-weight ratios, a key design objective is to optimize configurations as well as materials.

After a design is defined, manufacturing is the next challenge. Building a single part normally is not technically taxing. The trick comes in fabricating composite parts reliably in mass production. Manufacturing operations tend to be expensive because fabrication is labor-intensive, and the labor must be skilled.

The processes for fabricating composites also may produce built-in defects. For this reason, provisions for nondestructive testing should go hand-in-hand with fabrication. Unfortunately, available methods for nondestructive testing often leave a lot to be desired.

All these problems are being combated. Better guidelines are being developed to help designers select a composite and define its shape. Software is being developed to cope with the analytical complexities posed by composites and to help with the optimization process. Finally, major efforts are being exerted to automate fabrication processes and refine nondestructive testing operations.

**Thermoplastic Composites**

No longer is product design a constraint to the property limits and performance characteristics of unmodified grades of resins. Thermoplastics that are reinforced with high-strength, high-modulus fibers provide dramatic increases in strength and stiffness, toughness, and dimensional stability. The performance gain of these composites usually more than compensates for their higher cost. Processing usually involves the same methods used for unreinforced resins.

**Glass and Mineral Fibers**

Glass fibers used in reinforced compounds are high-strength, textile-type fibers, coated with a binder and coupling agent to improve compatibility with the resin and a lubricant to minimize abrasion between filaments. Glass-reinforced thermoplastics are usually supplied as ready-to-mold compounds. Molded products may contain as little as 5% and as much as 60% glass by weight. Pultruded shapes (usually using a polyester matrix) sometimes have higher glass contents. Most molding compounds, for best cost/performance ratios, contain 20%–40% glass.

Practically all thermoplastic resins are available in glass-reinforced compounds. Those used in largest volumes are nylon, polypropylene, polystyrene, ABS, and SAN, probably because most experience with reinforced thermoplastics has been based on these resins. The higher-performance resins—PES, PEI, PPS, PEEK, and PEEK, for example—are also available in glass-fiber-reinforced composites, and some with carbon or aramid fibers as well.

Glass-fiber reinforcement improves most mechanical properties of plastics by a factor of two or more. Tensile strength of nylon, for example, can be increased from about 70 MPa to over 210 MPa, and deflection temperature to almost 260°C, from 77°C. A 40% glass-fortified acetyl has a flexural modulus of 1.89 MPa, a tensile strength of 150.5 MPa, and a deflection temperature of 168°C. Reinforced polyester has double the tensile and impact strength and four times the flexural modulus of the unreinforced resin.

Also improved in reinforced compounds are tensile modulus, dimensional stability, hydrolytic stability, and fatigue endurance.

Fiber reinforcement of a resin always changes its impact behavior and notch sensitivity. The change may be in either direction, depending on the specific resin involved. But even when the change is an improvement, these properties may not be high enough for certain demanding applications. This need has led to the development of impact-modified compounds—specifically, nylon 6 and 6/6 alloys, a nylon 6/6 copolymer, and a polypropylene copolymer—with up to 50% improvement over reinforced unmodified compounds. Although the impact properties of a glass-reinforced compound are not always superior to those of the unreinforced compound, the reinforced modified compounds are always superior to the reinforced unmodified grades.

**Applications**

Molded glass-reinforced and mineral-reinforced plastics are used in a broad range of structural and mechanical parts. For example, glass-reinforced nylon, because of its strength and stiffness, is used in gears and automotive under-the-hood components, whereas mineral-reinforced nylon is used in housings and body parts because it is tougher and has low warpage characteristics. Polypropylene applications include automotive air-cleaner housings and dishwasher tubs and inner doors. Polycarbonate is used in housings for water meters and power tools. Polyester applications include motor components—brush holders and fans—high-voltage enclosures, television tuner gears, electrical connectors, and automobile exterior panels.

**Advanced Composites**

Advanced composites comprise structural materials that have been developed for high-technology applications, such as airframe structures, for which other materials are not sufficiently stiff. In these materials, extremely stiff and strong continuous or discontinuous fibers, whiskers, or small particles are dispersed in the matrix. A number of matrix materials are available including carbon, glass, ceramics, metals, and polymers. Advanced composites possess enhanced stiffness and lower density compared to fiberglass and conventional monolithic materials. Although composite strength is primarily a function of the reinforcement, the ability of the matrix to support the fibers or particles and to transfer load to the reinforcement, is equally important. Also, the matrix frequently dictates service conditions, for example, the upper temperature limit of the composite.
Reinforcements

Continuous filamentary materials that are used as reinforcing constituents in advanced composites are carbonaceous fibers, organic fibers, inorganic fibers, ceramic fibers, and metal wires. Reinforcing inorganic materials are used in the form of discontinuous fibers and whiskers.

Carbon and graphite fibers offer high modulus and the highest strength of all reinforcing fibers. These fibers are produced in a pyrolysis chamber from three different precursor materials—rayon, polyacrylonitrile (PAN), and pitch. High-modulus carbon fibers are available in an array of yarns and bundles of continuous filaments (tows) with differing moduli, strengths, cross-sectional areas, twists, and plies.

Almost any polymer fiber can be used in a composite structure, but the first one with high-enough tensile modulus and strength to be used as a reinforcement in advanced composites was an aramid, or aromatic polyamide, fiber. Aramid fibers have been the predominant organic reinforcing fiber; graphite is a close second.

The most important inorganic continuous fibers for reinforcement of advanced composites are boron and SiC, both of which exhibit high stiffness, high strength, and low density. Continuous fibers are made by chemical vapor deposition (CVD) processes. Other inorganic compounds that provide stiff, strong discontinuous fibers that predominate as reinforcements for metal–matrix composites (MMC) are SiC, Al2O3, graphite, Si3N4, TiC, and boron carbide.

Polycrystalline Al2O3 is a commercial continuous fiber that exhibits high stiffness, high strength, high melting point, and exceptional resistance to corrosive environments. One method to produce the fibers is dry spinning followed by heat treatment.

Whiskers are single crystals that exhibit fibrous characteristics. Compared to continuous or discontinuous polycrystalline fibers, they exhibit exceptionally high strength and stiffness. SiC whiskers are prepared by chemical processes or by pyrolysis of rice hulls. Whiskers made of Al2O3 and Si3N4 are also available. Particulates vary widely in size, characteristics, and function, and since particulate composites are usually isotropic, their distribution is usually random rather than controlled.

Organic–Matrix Composites

In many advanced composites the matrix is organic, but metal matrices are also used. Organic matrix materials are lighter than metals, adhere better to the fibers, and offer more flexibility in shaping and forming. Ceramic–matrix composites (CMC), carbon–carbon composites (C–C), and intermetallic–matrix composites (IMC) have applications where organic or metal matrix systems are unsuitable.

Materials

Epoxy resins have been used extensively as the matrix material. However, bismaleimide (BMI) resins and polyimide (PI) resins have been developed to enhance in-service temperatures. Thermoplastic resins, PEK, and polyphenylene sulfide (PPS) are in limited use.

The continuous reinforcing fibers for organic matrices are available in the forms of monofilaments, multifilament fiber bundles, unidirectional ribbons, roving (slightly twisted fiber), and single-layer and multilayer fabric mats. Frequently, the continuous reinforcing fibers and matrix resins are combined into a nonfinal form known as a prepreg.

The matrix material generally governs the service temperature. For PMCs, thermosets are the common matrix material. Epoxy, the most widely used, allows service temperatures up to about 300°F (149°C). Bismaleimide (BMI), which has replaced epoxy to some extent in military aircraft applications, permits use to about 350°F (177°C). Cycom 5250-4, 5260, and 5270-1 are BMIs from Cytec Fiberte. The 5250-4 and toughened 5260 have service temperatures to about 350°F (177°C), the 5270-1 to as high as 450°F (232°C). Cycom 5250-4 RTM is used for resin-transfer-molding applications.

Polyimide, with a maximum service temperature of at least 500°F (260°C), is used to a much more limited extent. The principal load-bearing elements, however, are the fibers, typically continuous, contained by the matrix. These include aramid, Kevlar mainly, boron, glass, and graphite. PMCs are lightweight, strong, and rigid, thus providing high strength-to-weight ratios (specific strength) and high rigidity-to-weight ratios (specific stiffness). Other thermosets include cyanate esters, which feature good moisture and heat resistance and better electrical properties; polyetheretherketone (PEEK), polyetherimide (PEI), and polyphenylene sulfide (PPS). Another advantage is that fiber direction can be oriented to suit applied load direction. Such composites are made by manual or automatic layout of thin (0.010 in. [0.254 mm]) prepreg plies or by filament winding, followed by curing in autoclaves or presses. Prepreg is a partially cured and somewhat tacky fiber-reinforced resin, which must be kept in refrigerated storage to keep from spoiling. Filament winding involves winding a tow of fibers or a series of tows (band) around a mandrel of the shape of the part to be produced. In “dry winding,” tows of prepreg are used. In “wet winding,” the tows or bands are first drawn through a resin bath.

C-Bar, or composite rebar, is a PMC bar developed by Marshall Industries Composites for reinforcing concrete. Intended to compete with epoxy-coated steel rebar, it consists of a protruded rod core of fiber-reinforced urethane-modified vinyl ester with a helically ribbed exterior of compression-molded, urethane-modified sheet molding compound to bond to concrete. The fibers, originally of E-glass, can also be aramid or graphite. The rebar is not conductive or corrodible, has a coefficient of thermal expansion closer to that of concrete than steel, and weighs about one-fourth as much as a comparable steel rod. Protruded fiber-reinforced epoxy plates are adhesive-bonded to form glulams—glued laminated beams—and used to locally reinforce wood glulams typically made of hemlock or Douglas fir plates.

Fabrication

Many processes are available for the fabrication of organic matrix composites. The first process is contact molding in order to orient the unidirectional layers at discrete angles to one another. Contact molding is a wet method, in which the reinforcement is impregnated with the resin at the time of molding. The simplest method is hand layup, whereby the materials are placed and formed in the mold by hand and the squeezing action expels any trapped air and compacts the part.

Molding may also be done by spraying, but these processes are relatively slow and labor costs are high, even though they can be automated. Many types of boats, as well as buckets for power-line servicing equipment, are made by this process.

Another process is vacuum-bag molding, where prepregs are laid in mold to form the desired shape. In this case, the pressure required to form the shape and achieve good bonding is obtained by covering the layup with a plastic bag and creating a vacuum. If additional heat and pressure are desired, the entire assembly is put into an autoclave. To prevent the resin from sticking to the vacuum bag and to facilitate...
removal of excess resin, various materials are placed on top of the prepreg sheets. The molds can be made of metal, usually aluminum, but more often are made from the same resin (with reinforcement) as the material to be cured. This eliminates any problem with differential thermal expansion between the mold and the part.

In filament winding, the resin and fibers are combined at the time of curing. Axisymmetric parts, such as pipes and storage tanks, are produced on a rotating mandrel. The reinforcing filament, tape, or roving is wrapped continuously around the form. The reinforcements are impregnated by passing them through a polymer bath. However, the process can be modified by wrapping the mandrel with prepreg material. The products made by filament winding are very strong because of their highly reinforced structure. For example, filament winding can be used directly over solid-rocket-propellant forms.

Pultrusion is a process used to produce long shapes with constant profiles, such as rods or tubing, similar to extruded metal products. Individual fibers are often combined into a tow, yarns, or rovings, which consists of a number of tows or yarns collected into a parallel bundle without twisting (or only slightly so). Filaments can also be arranged in a parallel array called a tape and held together by a binder. Yarns or tows are often processed further by weaving, braiding, and knitting or by forming them into a sheet-like mat consisting of randomly oriented chopped fibers or swirled continuous fibers held together by a binder.

Weaving to produce a fabric is a very effective means of introducing fibers into a composite. There are five commonly used patterns, which include box or plain, basket, crowfoot, long-shaft, and leno weave. Although weaving is usually thought of as a two-dimensional process, three-dimensional weaving is often employed.

Knitting is a process of interlooping chains of tow or yarn. Advantages of this process are that the tow or yarn is not cramped as happens in weaving, and higher mechanical properties are often observed in the reinforced product. Also, knitted fabrics are easy to handle and can be cut without falling apart.

In braiding, layers of helically wound yarn or tow are interlaced in a cylindrical shape, and interlocks can be produced at every intersection of fibers. During the process, a mandrel is fed through the center of a braiding machine at a uniform rate, and the yarn or tow from carriers is braided around the mandrel at a controlled angle. The machine operates like a maypole, the carriers working in pairs to accomplish the over-and-under sequencing. The braiding process is most effective for cylindrical geometries. It is used for missile heat shields, lightweight ducts, fluid-sealing components such as packings and sleeving, and tubes for insulation.

Metal–Matrix Composites (MMCs)

MMCs are usually made with alloys of aluminum, magnesium, or titanium, and the reinforcement is typically a ceramic in the form of particulates, platelets, whiskers, or fibers, although other systems may be used. MMCs are often classified as discontinuous or continuous depending on the geometry of the reinforcement. Particulates, platelets, and whiskers are in the discontinuous category, whereas the continuous category is reserved for fibers and wires. The type of reinforcement is important in the selection of an MMC because it determines virtually every aspect of the product, including mechanical properties, cost, and processing method. The primary methods for processing of discontinuous MMCs are powder metallurgy, liquid metal infiltration, squeeze or pressure casting, and conventional casting; however, most of these methods do not result in finished parts. Therefore, most discontinuously reinforced MMCs require secondary processing, which includes conventional wrought metallurgy operations such as extrusion, forging, and rolling; standard and nonstandard machining operations; and joining techniques such as brazing and welding.

MMCs, like PMCs, were in use long before this term was coined. Examples include cermets, or ceramic-reinforced metals, such as tungsten-carbide particles in a cobalt matrix for cutting tools and titanium-carbide particles in steel for heat- and wear-resistant parts. MMCs may contain continuous or discontinuous fibers, particulates, whiskers or preforms as a reinforcing constituent. As a class, they are far more heat-resistant than PMCs. Among the MMCs that have been made are aluminum, copper, cobalt, lead, and magnesium reinforced with graphite. Boron has served as a reinforcement for aluminum, magnesium, and titanium; silicon carbide for aluminum, titanium, and tungsten; and alumina for aluminum. Compared with PMCs, applications so far have been limited, and these are largely limited to aluminum. Aluminum reinforced with continuous boron fibers is used for struts in the Space Shuttle, and aluminum reinforced with continuous graphite fibers is used for the Hubble telescope masts. Fiber preforms have been used to selectively reinforce cast aluminum products. Brake rotors made of 30% alumina in a 1%-magnesium aluminum alloy can operate at temperatures up to 1000°F (540°C) and 360 aluminum alloy with 30% silicon carbide has withstood 840°F (450°C). For semiconductor packaging, die-cast aluminum alloy with 70% silicon carbide provides low thermal expansion and high heat-dissipating thermal conductivity for superior reliability. Titanium–matrix composites are candidates for aircraft gas-turbine-engine parts. Pressure infiltration, mainly with either aluminum or magnesium alloys in porous ceramic, carbide, nitride, carbon, or graphite preforms, is used by Metal Matrix Cast Composites, Inc., to make MMCs. Pressureless infiltration is also used. For example, with the Primax Cast process, infiltrating a 30% by volume silicon carbide preform with Loxane 92-2050, an aluminum, 10% silicon, 1% magnesium, 1% iron alloy results in an MMC with the density of 0.101 lb/in.3 (2796 kg/m3). Aluminum alloys reinforced with alumina, boron carbide, or silicon carbide particulates are commercially available as wrought and foundry products.

Ceramic–Matrix Composites (CMCs)

One type of CMC incorporates a continuous fiber, and another type a discontinuous reinforcement such as whiskers. Both approaches enhance fracture resistance, but the mechanism is substantially different. Continuous-fiber-reinforced ceramics resist catastrophic failure because, after the matrix fails, the fiber supports the load. When whiskers are used as reinforcements, the resistance to crack propagation is enhanced and hence the composite is less sensitive to flaws. However, once a crack begins to propagate, the failure will be catastrophic.

CMCs and IMCs are largely developmental. Both are promising for still greater heat resistance, although the inherent brittleness of the CMCs may limit their use in structural applications. Allied Signal makes CMCs using directed metal oxidation or chemical vapor infiltration techniques. Components include silicon carbide-particulate-reinforced alumina tubes and connecting sleeves for high-temperature air heaters and silicon carbide–reinforced silicon carbide panels for the vortex finder of a cyclone high-performance particle separator. The SiC/SCS panels were made by fabricating fiber preforms woven, braided, or wound to shape and infiltrating them with chemical vapors reacting at high temperature to form the silicon carbide matrix on and between the fibers. Matrix materials for discontinuously reinforced CMCs made by Triton Systems include silicon carbide, hafnium carbide, tantalum carbide, boron nitride,
or silicon nitride, and refractory borides. Continuous fiber CMCs include carbon-reinforced silicon carbide, alumina-reinforced silicon carbide, and SiC/SiC. Silcomp, from General Electric, comprises SiC fibers in an SiC and silicon matrix. It features low porosity, for oxidation and heat resistance, strength, and rigidity and may be suitable for gas-turbine-engine combustor liners and shrouds. A glass-fiber-reinforced CMC serves as armor in the U.S. Army’s Crusader ground combat vehicle. Silicon nitride-coated fibers in a barium–strontium–aluminum-silicate glass that converts to a strong and tough glass ceramic on processing features low permittivity and electromagnetic absorption.

IMCs are seen as potential candidates for aircraft, aircraft-engine, and spacecraft components exposed to temperatures above 2000°F (1093°C). Promising matrix materials include molybdenum disilicide (MoSi₂), nickel aluminides, and titanium aluminides. Reinforcements include particles, whiskers, and continuous or discontinuous fibers of alumina or silicon carbide. MoSi₂, which excels in corrosion and oxidation resistance, has a brittle-to-ductile transition temperature of about 1832°F (1000°C), but alloying with tungsten disilicide (WSi₂) improves toughness at lower temperatures. The nickel aluminide, NiAl, with 0.5% boron and reinforced with alumina fibers, has a potential service temperature of 1500°F (816°C) or greater. For titanium aluminide, TiAl, reinforced with alumina, this temperature may approach 1900°F (1038°C), and for Ti₃Al with columbium, reinforced with silicon-carbide fibers, it is within the range of 1472°F–1562°F (800°C–850°C). An SiC/SiC composite from Allied Chemical is highly resistant to high concentrations of potassium and sodium both in chlorides and sulfides as well as to more complex compounds such as coal ash at temperatures up to 2100°F (1150°C).

Carbon–Carbon Composites (C–C)

Carbon–carbon composite is a specialized material made by reinforcing a carbon matrix with continuous carbon fiber. This type of composite has outstanding properties over a wide range of temperatures in both vacuum and inert atmospheres. It will even perform well at elevated temperatures in an oxidizing environment for short times. It has high strength, modulus, and toughness up to 2000°C; high thermal conductivity; and a low coefficient of thermal expansion. A material with such properties is excellent for rocket motor nozzles and exit cones, which require high-temperature strength as well as resistance to thermal shock. Carbon–carbon composites are also used for aircraft and other high-performance brake applications that take advantage of the fact that C–C composites have the highest energy capability of any known material. If a carbon–carbon composite is exposed to an O₂-containing atmosphere above 600°C for an appreciable time, it oxidizes, and therefore it must be protected by coatings.

C–Cs are noted for their lightweight and good strength and low thermal expansion at temperatures greater than 3600°F (2000°C). A carbon-fiber-reinforced carbon piston developed at NASA Langley Research Center maintains high strength and stiffness at operating temperatures to over 2500°F (1371°C). C–Cs also have high thermal stability and nonoxidizing environments, are nonmelting and nonflammable, and possess low ablation and erosion rates. They are also tough and resistant to abrasion and corrosion, have a high thermal and electrical conductivity and high temperatures, and have excellent resistance to thermal shock. With silicon carbide as the oxygen-barrier coating, C–Cs service thermal-protection systems in the nose cone and wing leading edges of the Space Shuttle. Aircraft brake disks, 8–20 in. (200–500 mm) in diameter and 1–2 in. (25–50 mm) thick, are by far the largest-production use. Other applications include race-car brake and clutch components, heat sinks for electronic circuit boards, solid- and liquid-propellant rocket-motor sections, aerospace-vehicle components, thermal insulation for spacecraft and vacuum or inert-gas furnaces, furnace trays and baskets, glass-production equipment, and high-temperature bolts, nuts, and rods.

Applications

The use of fiber-reinforced materials in engineering applications has grown rapidly. Selection of composites rather than monolithic materials is dictated by the choice of properties. The high values of specific stiffness and specific strength may be the determining factor, but in some applications wear resistance or strength retention at elevated temperatures is more important. A composite must be selected by more than one criterion, although one may dominate.

Components fabricated from advanced organic–matrix-fiber-reinforced composites are used extensively on commercial aircraft as well as for military transports, fighters, and bombers. The propulsion system, which includes engines and fuel, makes up a significant fraction of aircraft weight (frequently 50%) and must provide a good thrust-to-weight ratio and efficient fuel consumption. The primary means of improving engine efficiency are to take advantage of the high specific stiffness and strength of composites for weight reduction, especially in rotating components, where material density directly affects both stress levels and critical dynamic characteristics, such as natural frequency and flutter speed.

Composites consisting of resin matrices reinforced with discontinuous glass fibers and continuous glass-fiber mats are widely used in truck and automobile components bearing light loads, such as interior and exterior panels, pistons for diesel engines, drive shafts, rotors, brakes, leaf springs, wheels, and clutch plates.

The excellent electrical insulation, formability, and low cost of glass-fiber-reinforced plastics have led to their widespread use in electrical and electronic applications ranging from motors and generators to antennas and printed circuit boards.

Composites are also used for leisure and sporting products such as the frames of rackets, fishing rods, skis, golf club shafts, archery bows and arrows, sailboats, racing cars, and bicycles.

Advanced composites are used in a variety of other applications, including cutting tools for machining of superalloys and cast iron and laser mirrors for outer-space applications. They have made it possible to mimic the properties of human bone, leading to development of biocompatible prostheses for bone replacements and joint implants. In engineering, composites are used as replacements for fiber-reinforced cements and cables for suspension bridges. See also carbon–carbon composites, ceramics–matrix composites, metal–matrix composites and resin–matrix composites.

Composite Plate

An electrodeposit consisting of layers of at least two different compositions.

Composite Powder

A powder in which each particle consists of two or more different materials.

Composite Structure

A structural member (such as a panel, plate, pipe, or other shape) that is built up by bonding together two or more distinct components,
Composition Metal

Also called composition brass, although it does not have the characteristics of a true brass. A general name for casting alloys, such as copper alloy C83600, that are in a midposition between the brasses and bronzes. The most widely used standard composition metal is ounce metal, containing 85% copper, 5% zinc, 5% tin, and 5% lead. It makes a good average bearing metal, and because it gives a dense casting that will withstand liquid pressures, it is also used for valves, pumps, and carburetor parts. It cast well, machines easily, and takes a good polish, so that is widely employed for mechanical castings. It has about the same coefficient of expansion as copper and can thus be used for pipe fitting. ASTM alloy No. 2 is this metal, and it may also contain up to 1% nickel and small amounts of iron, either as intentional additions to increase strength or as impurities. This alloy has also been called red casting brass, hydraulic bronze, and steam brass, and it has also been used for forgings, producing parts with a tensile strength of 227 MPa and 25% elongation.

Compositional Depth Profile

In materials characterization, the atomic concentration measured as a function of the perpendicular distance from the surface.

Compound

(1) In chemistry, a substance of relatively fixed composition and properties, whose ultimate structural unit (molecule or repeat unit) is comprised of atoms of two or more elements. The number of atoms of each kind in this ultimate unit is determined by natural laws and is part of the identification of the compound. (2) In reinforced plastics and composites, the intimate admixture of a polymer with other ingredients, such as fillers, softeners, plasticizers, reinforcements, catalysts, pigments, or dyes. A thermoset compound usually contains all the ingredients necessary for the finished product, while a thermoplastic compound may require subsequent addition of pigments, blowing agents, and so forth.

Compound Compact

A powder metallurgy compact consisting of mixed metals, the particles of which are joined by pressing or sintering, or both, with each metal particle retaining substantially its original composition.

Compound Die

Any die designed to perform more than one operation on a part with one stroke of the press, such as blanking and piercing, in which all functions are performed simultaneously within the confines of the blank size being worked.

Compressibility

(1) The ability of a powder to be formed into a compact having well-defined contours and structural stability at a given temperature and pressure; and measure of the plasticity of powder particles. (2) A density ratio determined under definite testing conditions. Also referred to as compactibility.

Compressibility Curve

A plot of the green density of a powder compact with increasing pressure.

Compressibility Test

In powder metallurgy, a test to determine the behavior of a powder under applied pressure. It indicates the degree of densification and cohesiveness of a compact as a function of the magnitude of the pressure.

Compression and Transfer Molded Plastics

Compression and transfer molding techniques are the most commonly used methods of molding thermosetting molding compounds as well as rubber parts. They may also be used for forming thermoplastic materials (e.g., compression molding of vinyl phonograph records), but usually other methods are more economical for molding thermoplastics.

The two processes are somewhat similar in terms of sizes and shapes produced. The major difference lies in the greater control of material flow permitted in transfer molding, allowing use of more delicate inserts and production of somewhat more complicated shapes.

Compression Molding

A technique of thermoset molding in which the plastic molding compound (generally preheated) is placed in the heated open mold cavity, the mold is closed under pressure (usually in a hydraulic press), causing the material to flow and completely fill the cavity, and then pressure is held until the material has cured.

The materials to be molded are generally softened by preheating in conventional ovens or, more frequently, in a dielectric preheating unit prior to placement in the mold.

Compression molding techniques are used most extensively for the manufacture of products made from thermosetting plastic materials and rubbers. These materials require the relatively high pressures and temperatures afforded by the compression molding process. Such materials include the phenolics, the melamines, the ureas, and the polyester resins. Under special circumstances, thermoplastics are compression-molded, but the injection molding process is usually more economical for the production of thermoplastic parts.

The process is ideal for the production of such items as thermosetting radio cabinets, television cabinets, trays, and other products that require resistance to heat. The size of the compression molded articles is generally limited only by the plate size and tonnage capacity of the presses used. Through the use of multicavity molds, small electrical components such as switch plates and terminal blocks may be produced economically. Compression molding is also used to produce extremely large parts such as fiberglass boat hulls and the complete fuselage for radio-controlled target aircraft.

Compression molding is not practical for many intricate products where complicated molds are required. Thermosetting materials are extremely stiff or viscous plastic masses during the mold-closing period. The internal pressures developed by these materials tend to distort or break delicate core pins and other
small mold components. The process also may be unsatisfactory for the production of extremely close tolerance articles, particularly where critical dimensions are influenced by the mold parting line. Flash thickness produced at the mold parting line tends to vary from cycle to cycle, thus changing the dimensions in the direction of the stroke of the press.

Molding pressures range from as low as 0.35 MPa for certain polyester compounds to as high as 2.3 kg/mm² for stiff high-impact phenolic materials. Process temperatures range from 121°C to 177°C depending upon the material used.

Thickness of the molded part influences production rates. A general rule of thumb allows a minute of mold close-time for each 3.2 mm of wall thickness. Standard dimensional tolerances are usually figured at ±0.05 mm⁻¹, although closer tolerances can be held under special circumstances. Where phenolic and urea materials are to be molded, hardened steel is used for the mold construction. Such molds are usually carburized and hardened to about 50 Rockwell C. For use with polyester materials, where pressure requirements are not high, prehardened steel at about 38 Rockwell C is usually satisfactory.

Transfer Molding

Transfer molding is best described as a closed-mold technique wherein the material is injected or transferred into a closed mold through a gate or runner system. Essentially, transfer molding is a one-shot injection molding technique. The process is particularly adaptable again to thermosetting materials, since these materials retain their plastic condition after preheating for only a short length of time.

Generally, the comments made regarding compression molding apply to this process as well. The distinct advantage in the transfer molding process lies in the fact that the mold is completely closed and under clamping pressure before the material is injected into the mold cavity. This results in little or no flash and accurate control of dimensions.

A preweighted material charge is plasticized generally in a dielectric preheating unit. The charge is then placed in a pot that is usually positioned above the closed mold. A ram enters the pot and forces the material through an orifice into the closed mold. The transfer plunger and mold are kept under pressure for a predetermined time to allow the chemical/heat hardening process to proceed. When the mold is opened, the small amount of material remaining in the transfer pot and that which has filled the orifice is removed as a cull and discarded.

Transfer molding generally operates at faster cycles than compression molding. Because of the highly plastic condition of the material, complex part designs involving cores, undercuts, and moving die parts are best adapted to this process. Molded-in inserts can be held in position more easily in the transfer molding operation. Mold cavity. This results in little or no flash and accurate control of dimensions.

With a properly designed mold, transfer molded articles require fewer finishing operations with a resultant lower net cost.

The process results in higher material costs due to the loss of material in the transfer pot and runner system. High-impact phenolic materials have generally lower physical properties when transfer molded compared with those obtained by compression molding.

Transfer molding techniques are used in the manufacture of a wide range of product shapes and sizes. Small, complex electrical components with molded-in terminals are made by this process. Radio and television cabinets weighing up to 1.7 kg have been transfer molded from phenolic materials.
Compressometer

Instrument for measuring change in length over a given gauge length caused by application or removal of a force. Commonly used in compression testing of metal specimens.

Compton Scattering

In materials characterization, the elastic scattering of photons by electrons. Contrast with Rayleigh scattering.

Computed Tomography (CT)

The collection of transmission data through an object and the subsequent reconstruction of an image corresponding to a cross section through this object. Also known as computerized axial tomography, computer-assisted tomography, CAT scanning, or industrial computed tomography.

Computer Aided (Assisted) Design (CAD)

Design techniques employing computer-based mathematical and graphics programs to assist in matters such as stress determination, computer layout, and product appearance.

Computer Aided (Assisted) Manufacture (Machining) (CAM)

Processes employing computers to assist in matters such as monitoring of product dimensions, rectification of deviations, etc.

ConCast

Continuously cast material or the continuous casting process.

Concave Grating

In materials characterization, a diffraction grating on a concave mirror surface. See also diffraction grating and plane grating.

Concave Root

An indentation along the line of the weld root. Same as root concavity.

Concave Root Surface

A root surface which is concave.

Concave Weld

Any weld including butt and fillet in which the exposed weld surface falls below a line joining the points where the weld metal meets the parent metal.

Concavity

The maximum distance from the face of a concave fillet weld perpendicular to a line joining the toes.

Concentration

(1) The mass of a substance contained in a unit volume of sample, for example, grams per liter. (2) A process for enrichment of an ore in valuable mineral content by separation and removal of waste material, or gangue. (3) The quantity of one substance contained in another, usually as a percentage.

Concentration Cell

An electrolytic cell, the electromotive force of which is caused by a difference in concentration of some component in the electrolyte. This difference leads to the formation of discrete cathode and anode regions.

Concentration Gradient

A variation, from point-to-point, and the proportion of two or more elements. The gradient may be a sharp step, as at the boundary between two phases, or it may be a shallow slope as in coring.

Concentration Polarization

That portion of the polarization of a cell produced by concentration changes resulting from passage of current through the electrolyte.

Conchoidal Markings

Concentric marks on the surface of a fatigue fracture. They are visible to the unaided eye and marked the crack front at irregularities in the load cycling such as interruptions in cycling or an abnormal load. Also termed beach marks, shell marks or arrest marks. Compare with striations.

Concrete

(1) A composite material that consists essentially of a binding medium within which are embedded particles or fragments of aggregates (maximum aggregate size >5 mm, or 0.2 in.). In hydraulic cement concrete, the binder is formed from a mixture of hydraulic cement and water. (2) A homogenous mixture of portland cement, aggregates, and water and which may contain admixtures. See also cement.

Concrete is a construction material composed of portland cement and water combined with sand, gravel, crushed stone, or other inert material such as expanded slag or vermiculite. The cement and water form a paste that hardens by chemical reaction into a strong stone-like mass. The inert materials are called aggregates, and for economy no more cement paste is used than is necessary to coat all the aggregate surfaces and fill all the voids. The concrete paste is plastic and easily molded into any form or troweled to produce a smooth surface. Hardening begins immediately, but precautions are taken, usually by covering, to avoid rapid loss of moisture because the presence of water is necessary to continue the chemical reaction and increase the strength. Too much water, however, produces a concrete that is more porous and weaker. The quality of the paste formed by the cement and water largely determines the character of the concrete.

Proportioning of the ingredients of concrete is referred to as designing the mixture, and for most structural work the concrete is designed to give compressive strengths of 16–34 MPa. A rich mixture for columns may be in the proportion of 1 volume of cement to...
Concrete

1 of sand and 3 of stone, whereas a lean mixture for foundations may be in the proportion of 1:3:6. Concrete may be produced as a dense mass that is practically artificial rock, and chemicals may be added to make it waterproof, or it can be made porous and highly permeable for such use as filter beds. An air-entraining chemical may be added to produce minute bubbles for porosity or light weight. Normally, the full hardening period of concrete is at least 7 days. The gradual increase in strength is due to the hydration of the tricalcium aluminates and silicates. Sand used in concrete was originally specified as roughly angular, but rounded grains are now preferred. The stone is usually sharply broken. The weight of concrete varies with the type and amount of rock and sand. A concrete with trap rock may weigh 2483 kg/m³. Concrete is stronger in compression than in tension, and steel bars or mesh are embedded in structural members to increase the tensile and flexural strengths. In addition to the structural uses, concrete is widely used in precast units such as block, tile, sewer and water pipe, and ornamental products.

Concrete may be classified as flexible or rigid. These characteristics are determined mainly by the cementitious materials used to bond the aggregates. Flexible concretes tend to deform plastically under heavy loads or when heated. Rigid concretes are considerably stronger in compression than in tension and tend to be brittle. To overcome this deficiency, strong reinforcement may be incorporated in the concrete, or prestress may be applied to keep the concrete under compression.

Flexible Concretes

Usually, bituminous or asphaltic concretes are used when a flexible concrete is desired. The main use of such concretes is for pavements. The aggregates generally used are sand, gravel or crushed stone, and mineral dust; the binder is asphalt cement, an asphalt specially refined for the purpose. A semisolid at normal temperatures, the asphalt cement may be heated until liquefied for bonding the aggregates. Ingredients usually are mixed mechanically in a pug mill, which has pairs of blades revolving in opposite directions. While the mix is still hot and plastic, it can be spread to a specified thickness and shaped with a paving machine and compacted with a roller or by tamping to a desired density. When the mix cools, it hardens sufficiently to withstand heavy loads. Sulfur, rubber, or hydrated lime may be added to an asphalt-concrete mix to improve the performance of the product.

Rigid Concretes

Ordinary rigid concretes are made with portland cement, sand, and stone, or crushed gravel. The mixes incorporate water to hydrate the cement to bond the aggregates into a solid mass. Admixtures may be added to the mix to impart specific properties to it or to the hardened concrete. Other types of rigid concretes include nailable concretes; insulating concretes; heavyweight concretes; lightweight concretes; fiber-reinforced concretes, in which short steel or glass fibers are embedded for resistance to tensile stresses; polymer and pozzolan concretes, which exhibit improvement in several properties; and silica-fume concretes, which possess high strength. Air-entrained concrete formulations, in which tiny air bubbles have been incorporated, may be considered variations of ordinary concrete.

Stress and Reinforcement

Because ordinary concrete is much weaker in tension than in compression, it is usually reinforced or prestressed with a much stronger material, such as steel, to resist tension. Use of plain, or unreinforced, concrete is restricted to structures in which tensile stresses will be small, such as massive dams, heavy foundations, and unit-masonry walls. For reinforcement of other types of structures, steel bars or structural steel shapes may be incorporated in the concrete.

Cementitious Materials

These are for general-purpose cements, cements modified to achieve low heat of hydration and to produce a concrete resistant to sulfate attack, high-early-strength cement, and air-entraining cement. Several other types of cement are sometimes used instead of portland cement for specific applications—for example, hydraulic cements, which can set and harden underwater. Included in this category, in addition to, are aluminous, natural, and white portland cements, and blends, such as portland blast-furnace slag, portland-pozzolan, and slag cements.

Aggregates for Ordinary Concrete

Aggregates should be inert, dimensionally stable particles, preferably hard, tough, and round or cubical. They should be free of clay, silt, organic matter, and salts.

Polymer Concretes

Polymers are used in several ways to improve concrete properties; they are impregnated in hardened concrete, are incorporated in a mix, or replace portland cement. Impregnation is sometimes used for concrete road surfaces. It can more than double compressive strength and elastic modulus, decrease creep, and improve resistance to freezing and thawing. Monomers and polymers added as admixtures are used for restoring and resurfacing deteriorated roads. The concrete hardens more rapidly than ordinary concrete, enabling faster return of roads to service. Polymer concretes in which a polymer replaces portland cement possess strength and other properties similar to those of impregnated concrete. After curing for a relatively short time, for example, overnight at room temperatures, polymer concretes are ready for use; in comparison, ordinary concrete may have to cure for a week or more before exposure to service loads.

Casting

There are various methods employed for casting ordinary concrete. For very small projects, sacks of prepared mixes may be purchased and mixed on the site with water, usually in a drum-type, portable, mechanical mixer. For larger projects, mix ingredients are weighed separately and deposited in a stationary batch mixer, a truck mixer, or a continuous mixer. Concrete mixture agitated in a truck is called ready-mixed concrete. Paving mixes are self-propelled, track-mounted machines that move at about 0.45 m/s while mixing.
Concurrent Heating

At the site, concrete may be conveyed to the forms in wheelbarrows, carts, trucks, chutes, conveyor belts, buckets, or pipelines. Where chutes or belts are used, the flow of material is maintained as continuous as possible. On large projects, concrete may be delivered to the formwork in dump buckets by cableways or by cranes. In many instances, direct pumping through pipelines is used to convey concrete from the mixer or hopper to the point of placement.

Condensate

Same as condensation except that the term usually implies bulk liquid such as would be produced in a condenser.

Condensation

(1) A chemical reaction in which two or more molecules combine, with the resulting separation of water or some other simple substance; the process is called polycondensation if a polymer is formed.
(2) Liquid precipitated from the gaseous phase. The term may imply films were small volumes of liquid. See also polymerization.

Condensation Polymerization

In plastics technology, a stepwise chemical reaction in which two or more molecules combine, often but not necessarily accompanied by the separation of water or some other simple substance. If a polymer is formed, the process is called polycondensation. See also polymerization.

Condensation Ratio

A resin formed by polycondensation, for example, the alkyd, phenylaldehyde, and urea–formaldehyde resins.

Condenser

(1) A heat exchanger, in which a gas, often steam, is cooled causing it to revert to the liquid state. In a tube condenser cooling water is circulated through tubes to condense the steam exhausting from a steam turbine or other cycle. In a jet condenser the cooling water is injected into the exhaust steam; this requires high-quality cooling water. (2) An electrical capacitor. (3) A term applied to lenses or mirrors designed to collect, control, and concentrate radiation in an illumination system, such as an optical or scanning electron microscope.

Condenser Aperture

In electron microscopy, and opening in the condenser lens controlling the number of electrons entering the lens and the angular aperture of the illuminating beam.

Condenser Foil

Metal foil, usually aluminum or tin base, used for electrical capacitors, i.e., condensers. The foil may be varnished or, in the case of aluminum anodized, to provide an insulating surface to avoid the need for a nonconducting interleaf when rolled to form the capacitor.

Condenser Lens

See condenser.

Conditioning

Subjecting a material to a prescribed environmental and/or stress history before testing.

Conditioning Heat Treatment

A preliminary heat treatment used to prepare a material for a desired reaction to a subsequent heat treatment. For the term to be meaningful, the exact heat treatment must be specified.

Conditioning Time

See joint-conditioning time, curing time, and setting time.

Conductance (Electrical)

A measure of the ability of any material to conduct an electrical charge. Conductance is the ratio of the current flow to the potential difference. The reciprocal of electrical resistance.

Conductance (Thermal)

The time rate of heat flow through a unit area of a body, induced by a unit temperature difference between the body surfaces.

Conduction Band/Electrons

See Band Theory.

Conductive (Electrical) Polymers and Elastomers

These are polymers made electrically conductive by the addition of carbon black, nickel, silver, or other metals. Volume resistivities of plastics and rubbers, which normally are in excess of $10^9$ Ω/cm, can be lowered to between $10^{-3}$ and $10^5$ Ω/cm by addition of conductive materials. Carbon black is the most widely used filler. The relationship of carbon black loading and volume resistivity is not proportioned. Up to a 25% loading, conductivity significantly increases, but it falls off sharply thereafter. Generally, the addition of carbon black lowers the mechanical properties of the polymer. However, the use of carbon fibers to enhance conductivity improves mechanical properties.

Polyethylene and polyvinyl chloride resins loaded with carbon black are perhaps the most widely used conductive plastics. Plastics often made conductive by adding up to 30% carbon fiber are polysulfone, polyester, polyphenylene sulfide, nylon 6/6, ethylene tetrafluoroethylene, and vinylidene fluoride–polytetrafluoroethylene. Although silicone is the most widely used base polymer for conductive rubber, other rubbers frequently used in compounding conductive elastomers include SBR, EPDM, TPR, and neoprene.
Conductivity (Electrical)

The reciprocal of volume resistivity. The electrical or thermal conductance of a unit cube of any material (conductivity per unit volume).

Conductivity (Thermal)

The time rate of heat flow through unit thickness of an infinite slab of a homogeneous material in a direction perpendicular to the surface, induced by unit temperature difference. Recommended SI units: W/m K. See also IACS.

Conductors

This term is usually applied to materials (wire, cable, or other body), generally metals, used to conduct electric current, although heat conductors and sound conductors have important uses. Good conductors of electricity tend to be good conductors of heat, as well. Silver is the best conductor of electricity, but copper is the most commonly used. The conductivity of pure copper is 97.6% that of silver. The electric conductivity of metals is often expressed as a percentage of the electric conductivity of copper, which is arbitrarily set at 100%. Copper with a high-pitch copper is the standard conductivity metal, and it is designated as the International Annealed Copper Standard (IACS).

Because of the low conductivity of zinc, the brasses have low current-carrying capacity, but are widely used for electric connections and parts because of their workability and strength. The electric conductivity of aluminum is only 63% that of copper, but it is higher than that of most brasses. Copper wire for electric conductors in high-temperature environments has a plating of heat-resistant metal. Aluminum wire with a steel core is used for power transmission because of the long spans possible. Steel has a conductivity only about 12% that of copper, but the current in a wire tends to travel near the surface, and the small steel core does not reduce greatly the current-carrying capacity. Aluminum is now widely used to replace brass in switches and other parts. Aluminum wire for electric equipment is usually commercially pure aluminum with small amounts of alloying elements, such as magnesium, which give strength without appreciably reducing the conductivity. Plastics, glass, and other nonconductors are given conductive capacity with coatings of transparent lacquer containing metal powder, but conductive glass usually is made by spraying on at high temperature an extremely thin invisible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO. Coated glass panels are available with various conductible coating of SnO.
Connected Porosity

The volume fraction of all pores, voids, and channels within a solid mass that are interconnected with each other and communicate with the external surface, and thus are measurable by gas or liquid penetration. Contrast with closed porosity.

Consistency

(1) In adhesives, that property of a liquid adhesive by virtue of which it tends to resist deformation. Consistency is not a fundamental property but is composed of viscosity, plasticity, and other phenomena. See also viscosity and viscosity coefficient. (2) An imprecise measure of the degree to which a grease resists deformation under the application of a force.

Consolidation

In metal–matrix or thermoplastic composites, a processing step in which fiber and matrix are compressed by one of several methods to reduce voids and achieve desired density.

Constant Life Fatigue Diagram

In failure analysis, a plot (usually on rectangular coordinates) of a family of curves, each of which is for a single fatigue life (number of cycles), relating alternating stress, maximum stress, minimum stress, and mean stress. The constant life fatigue diagram is generally derived from a family of $S$–$N$ curves, each of which represents a different stress ratio for a 50% probability of survival. See also nominal stress, maximum stress, minimum stress, $S$–$N$ curve, fatigue life, and stress ratio.

Constantan

An alloy of 60% copper with 40% nickel having high electrical resistivity, about 48 $\mu$Ω cm, a low temperature coefficient of resistivity up to about 450°C and good corrosion resistance. It is used for various electrical purposes, such as resistors and thermocouples. See resistance alloys.

Constituent

(1) One of the ingredients that make up the chemical system. (2) A phase or a combination of phases that occurs in a characteristic configuration in an alloy microstructure. (3) In composites, the principal constituents are the fibers in the matrix.

Constraint

(1) Any restriction that limits the transverse contraction normally associated with a longitudinal tension, and that hence causes a secondary tension in the transverse direction; usually used in connection with welding. Contrast with restraint. (2) (of deformation) Localized restriction of deformation resulting from the Poisson effect, i.e., as the material is extended along one axis it has to contract across the transverse axes. At notches and other stress concentrations the material at the highly stressed notch tip is constrained from contraction in the transverse axes by the surrounding large volume of lower stress material. This gives rise to complex triaxial stresses at the notch tip. The effect is usually confined to small volumes of material while stresses are in the elastic range but large volumes may be involved if plastic deformation has occurred.

Constricted Arc (Plasma Arc Welding and Cutting)

A plasma arc column that is shaped by a constricting nozzle orifice. See also plasma arc welding.

Constricting Nozzle (Plasma Arc Welding and Cutting)

A water-cooled copper nozzle surrounding the electrode and containing the constricting orifice. See also cutting torch (plasma arc).

Constricting Orifice (Plasma Arc Welding and Cutting)

The hole in the constricting nozzle through which the arc passes. See also multi-port nozzle.

Constriction Resistance

In electrical contact theory, the resistance that arises from the constriction of current flow lines in order to pass through small areas of contact (a-spots) at the interface of two connecting bodies. See also a-spot, contact resistance, and film resistance.

Consumable Electrode

A general term for any arc welding electrode made chiefly of filler metal. Use of specific names such as covered electrode, bare electrode, flux-cored electrode, and lightly coated electrode is preferred.

Consumable Guide Electroslag Welding

In electroslag welding process variation in which filler metal is supplied by an electrode and its guiding member. See also electroslag welding.

Consumable Insert (of Weld)

A preplaced filler having specific dimensions that is located in the root of a joint to be made from one side. It is intended to be fully fused to become an integral part of the joint and is not normally machined following welding. Same as fusible insert.

Consumable-Electrode Remelting

A process for refining metals in which an electric current passes between electrode made of the metal to be refined in an ingot of the refined metal, which is contained in a water-cooled mold. As a result of the passage of electric current, droplets of molten metal form on the electrode and fall to the ingot. The refining action occurs from contact with the atmosphere, vacuum, or slag through which the drop falls. See also electro slag remelting and vacuum arc remelting.

Contact Adhesive

An adhesive that is apparently dry to the touch and that will adhere to itself simultaneously upon contact. An adhesive that, when applied to both adherends and allowed to dry, develops a bond when the adherends are brought together without sustained pressure.
Contact Angle

(1) See roll angle. (2) The angle formed at the junction between a solid and a liquid. If the liquid “wets” the solid as with water on clean glass the angle is acute, if it does not wet as with water droplets on a wax car body the angle is obtuse. (3) (in a bearing). See angle of contact.

Contact Area

The common area between a conductor and a connector across which the flow of electricity takes place.

Contact Bond Adhesive

Synonym for contact adhesive.

Contact Corrosion

(1) Corrosion in the vicinity of the point of contact between dissimilar metals in electrolyte. (2) A term primarily used in Europe to describe galvanic corrosion between dissimilar metals.

Contact Electrode (for Welding)

An electrode, the coating of which during the welding operation maintains a cup profile projecting slightly beyond the tip of the metal electrode. The edge of the cup is rested against the component being welded to maintain a fixed arc length.

Contact Fatigue

Cracking and subsequent pitting of a surface subjected to alternating Hertzian stresses such as those produced under rolling contact or combined rolling and sliding. The phenomenon of contact fatigue is encountered most often in rolling-element bearings or in gears, where the surface stresses are high due to the concentrated loads and are repeated many times during normal operation.

Contact Infiltration

In powder metallurgy, the process of infiltration whereby the initially solid infiltrant is placed in direct contact with the compact and the pores are filled with the liquid phase by capillary force after the infiltrant has become molten. See also infiltrant and infiltration.

Contact Material

A metal, composite, or alloy made by the melt-cast method or manufactured by powder metallurgy that is used in devices that make and break electrical circuits or welding electrodes. A majority of contact applications in the electrical industry utilize silver-type contacts, which include the pure metal, alloys, and powder metal combinations. Silver, which has the highest electrical and thermal conductivity of all metals, is also used as a plated, brazed, or mechanically bonded overlay on other contact materials—notably, copper and copper-base materials. Other types of contacts used include the platinum group metals, tungsten, molybdenum, copper, copper alloys, and mercury. See also electrode (welding).

Contact Molding

A process for molding reinforced plastics in which reinforcement and resin are placed in a mold. Cure is either at room temperature using a catalyst-promoter system or by heating in an oven, without additional pressure. Also referred to as hand lay-up.

Contact Plating

(1) The plated-on material applied to the basic metal of an electrical contact to provide for required contact resistance and/or specified wear resistance characteristics. (2) A metal plating process wherein the plating current is provided by galvanic action between the work metal and a second metal, without the use of an external source of current.

Contact Potential

In corrosion technology, the potential difference at the junction of two dissimilar substances.

Contact Pressure Resins

Liquid resins that thicken or polymerize upon heating, and, when used for bonding laminates, require little or no pressure.

Contact Resistance

(1) It reflects aspects such as contact area, roughness, interfacial pressure and contamination. (2) The electrical resistance of metallic surfaces at their interface in the contact area under specified conditions. (3) The electrical resistance between two contacting bodies, which is the sum of the constriction resistance and the film resistance.

Contact Scanning

In ultrasonic inspection, a planned systematic movement of the beam relative to the object being inspected, the search unit being in contact with and coupled to this object by a thin film of coupling material.

Contact Stress

Stress that results near the surfaces of two contacting solid bodies when they are placed against one another under a nonzero normal force. This term is not sufficiently precise because it does not indicate the type of stress, although common usage usually implies elastic or Hertz stress.

Contact Stress (Glass)

The tensile stress component imposed at a glass surface immediately surrounding the contact area between the glass surface and an object generating a locally applied force.

Contact Tube

A device which transfers current to a continuous welding electrode.
Contact Weld

(1) The point of attachment of a contact to its support when accomplished by resistance welding. (2) A contacting failure due to the fusing of contacting surfaces under load conditions to the point that the contacts failed to separate when expected.

Contacting Ring Seal

A type of circumferential seal that utilizes a ring-spring loaded radially against the shaft. The ring is either gapped or segmented, in order to have radial flexibility. The seal has overlapping joints for blocking leakage at the gaps. An axial spring load seats the ring against the wall of its containing cartridge.

Container

The chamber into which an ingot or billet is inserted prior to extrusion. The container for backward extrusion of cups or cans is sometimes called a die.

Contaminant

An impurity or foreign substance present in a material or environment that affects one or more properties of the material.

Context Root Surface

A root surface which is convex.

Continuous Furnace (Glass)

A glass furnace in which the level of glass remains substantially constant because the feeding of batch continuously replaces the glass withdrawn.

Continuity Bond

In corrosion protection, a metallic connection that provides electrical continuity between metal structures.

Continuous Casting

Any system using a mold open at both ends such that solid metal is steadily drawn out of the bottom while molten metal continues to enter the top. The mold can be in various forms including a simple die or rolls and is usually water cooled. Often, equipment beyond the mold cuts the ingot, bar, tube, etc., into lengths allowing the process to continue virtually indefinitely. If the process is occasionally interrupted to allow removal of the ingot the process may be termed Semi-continuous casting. Used chiefly to produce semi-finished mill products such as billets, blooms, ingots, slabs, strip, and tubes. See also strand casting.

Continuous Compaction

In powder metallurgy, the production of relatively long compacts having a uniform cross-section, such as sheet, rod, tube, etc. By direct extrusion or rolling of loose powder.

Continuous Cooling Transformation (CCT) Diagram

Set of curves drawn using logarithmic time and linear temperature as coordinates, which define, for each cooling curve of an alloy, the beginning and end of the transformation of the initial phase. See Isothermal Transformation Diagram.

Continuous Covered Electrode

Welding electrode filler wire, supplied as coils, comprising a central main filler wire carrying an external coating and helical wire(s) which reinforced the coating and act as current pickup.

Continuous Filament Yarn

Yarn formed by twisting two or more continuous filaments into a single, continuous strand.

Continuous Furnace

A furnace which operates continually with materials being charged at one end and discharged at the other. A variation is the Rotary Hearth where the charge and discharge points are a short distance apart around the radius.

Continuous Furnace (Powder Metallurgy)

A furnace used for the uninterrupted sintering of compacts.

Continuous Mill

A rolling mill consisting of a number of strands of synchronized rolls (in tandem) in which metal undergoes successive reductions as it passes through the various strands.

Continuous Phase

In an alloy or portion of an alloy containing more than one phase, the phase that forms the matrix in which the other phase or phases are dispersed.

Continuous Precipitation

Precipitation from a supersaturated solid solution in which the precipitate particles grow by long-range diffusion without recrystallization of the matrix. Continuous precipitates grow from nuclei distributed more or less uniformly throughout the matrix. They usually are randomly oriented, but may form a Widmanstätten structure. Also called general precipitation. Should be compared with discontinuous precipitation and localized precipitation.

Continuous Sequence

A longitudinal welding sequence in which each pass is made continuously from one end of the joint to the other. See also backstep sequence and longitudinal sequence.

Continuous Sintering

In powder metallurgy, presintering or sintering in such a manner that the objects are advanced through a furnace at a fixed rate by manual or mechanical means; sometimes called stoking.
Continuous Spectrum (X-Rays)
In materials characterization, the polychromatic radiation emitted by the target of an x-ray tube. It contains all wavelengths above a certain minimum value, known as the short wavelength limit.

Continuous Weld
A weld extending continuously from one end of a joint to the other or, where the joint is essentially circular, completely around the joint. Contrast with intermittent weld.

Continuous-Type Furnace
A furnace used for heat treating materials that progress continuously through the furnace, entering one door and being discharged from another. See also belt furnace, direct-fired tunnel-type furnace, rotary-retort furnace, and shaker-hearth furnace.

Continuum
In materials characterization, the noncharacteristic rays emitted upon irradiation of a specimen and caused by deceleration of the incident electrons by interaction with the electrons and nuclei of the specimen. Also termed bremsstrahlung and white radiation.

Contour Forming
See roll forming, stretch forming, tangent bending, and wiper forming.

Contour Machining
Machining of irregular surfaces, such as those generated in tracer turning, tracer boring, and tracer milling.

Contour Milling
Milling of irregular surfaces. See also tracer milling.

Contraction
The volume change that occurs in metals and alloys upon solidification and cooling to room temperature. See shrinkage.

Contrast Enhancement (Electron Optics)
In electron microscopy, an improvement of electron image contrast by the use of an objective aperture diaphragm, shadow casting, or other means. See also shadowing.

Contrast Filter
In metallography, a color filter, usually with strong absorption, that uses the special absorption bands of the object to control the contrast of the image by exaggerating or diminishing the brightness difference between differently colored areas.

Contrast Perception
In metallography, the ability to differentiate various components of the object structure by various intensity levels in the image.

Controlled Atmosphere
(1) A specified inert gas or mixture of gases at a predetermined temperature in which selected processes take place. (2) As applied to sintering, to prevent oxidation and destruction of the powder compacts.

Controlled Atmosphere Chamber
An inert-gas-filled enclosure or cabinet in which plasma spraying or welding can be performed to minimize (or prevent) oxidation of the coating or substrate. The enclosure is usually fitted with viewing ports, glove ports to permit manipulations, and a small separate airlock for introducing or removing components without loss of atmosphere.

Controlled Cooling
Any cooling at a prescribed rate but it is usually implicit that the rate is slower than would occur naturally, as opposed to quenching. It is imposed after heat treatment, welding or hot working for various reasons including avoiding hardening, minimizing residual stresses or allowing dissolved hydrogen to escape.

Controlled Etching
Electrolytic etching with selection of suitable etchant and voltage resulting in a balance between current and dissolved metal ions.

Controlled Rolling
A hot-rolling process in which the temperature of the steel is closely controlled, particularly during the final rolling passes, to produce a fine-grain microstructure.

Controlled Thermal Severity Test
A test of the weldability of steels, in particular the relationship between cooling rate and susceptibility to cracking. For the test, a 3 in.$^2$ steel plate is bolted to a much larger and thicker steel plate and substantial fillet welds deposited along two opposite sides. Two test welds are then deposited, in sequence, on the remaining sides. The concept is that when the first test weld is deposited the cooling rate is controlled by the conduction of heat through the two assembly welds while the cooling rate for the second test weld is controlled by conduction through the previous three welds. The severity of the test is defined in terms of Thermal Severity Number, TSN, which is the number of conduction paths multiplied by the plate thickness in units of 0.25 in. For example, with quarter inch plate the TSNs of the test welds would be 2 and 3, and with half inch plate they would be 4 and 6.

Controlled-Potential Coulometry
Measurement of the number of coulombs required for an electrochemical reaction occurring under conditions where the working electrode potential is precisely controlled.

Controlled-Pressure Cycle
A forming cycle during which the hydraulic pressure in the forming cavity is controlled by an adjustable cam that is coordinated with the punch travel.
Convection
The motion resulting in a fluid from the differences in density and the action of gravity. In heat transmission, this meaning has been extended to include both forced and natural motion or circulation.

Conventional Forging
A forging characteristic by design complexity and tolerances that fall within the broad range of general forging practice.

Conventional Milling
Milling in which the cutter moves in the direction opposite to the feed at the point of contact. Contrast with climb milling.

Conventional Strain
See engineering strain and strain.

Conventional Stress
The stress calculated on the original cross-sectional area, as opposed to the Real Stress. See tensile test and engineering stress and stress.

Convergent-Beam Electron Diffraction (CBED)
In analytical electron microscopy, a technique of impinging a highly convergent electron beam on a crystal to produce a diffraction pattern composed of disks of intensity. In addition to d-spacing and crystal orientation information, the technique can provide information on crystallographic point or space group symmetry.

Conversion Coating
(1) A coating consisting of a compound of the surface metal, produced by chemical or electrochemical treatments of the metal. Examples include chromate coatings on zinc, cadmium, magnesiuim, and aluminum, and oxide and phosphate coatings on steel. It forms a compound between the applied material and the base metal rather than merely depositing a layer. Anodizing, chromizing, and phosphating are examples. See also chromate treatment and phosphating.

Conversion Coatings
Surface transformations formed naturally by chemical or electrochemical methods on ferrous and nonferrous metals and alloys. Natural conversion coatings, usually oxides, include rust, the ferric oxide and hydroxide that forms on iron and plain carbon steels in air or moisture, and the adherent and protective oxides that forms on aluminum, copper, and other metals. Chemical conversion coatings are mainly phosphates, chromates, and oxides induced by the reaction of specific chemicals with metal surfaces. Electrochemical conversion coatings are formed by anodic oxidation, or anodizing, in an electrolytic cell in which the metal being treated is the anode. Phosphate conversion coatings are formed on iron, steel, galvanized steel, and aluminum by chemicals containing phosphoric acid and its salts. Zinc phosphates, one of three major types, are applied by immersion or spray in a wide variety of coating weights and crystal sizes. The microstructure type enhances paint adhesion, minimizes paint consumption, and improves bonding to plastics and rubber.

The heavy kind are quite absorbent, thus capable of retaining forming lubricants and rust-preventive oils. They also reduce friction and enhance wear resistance and corrosion resistance. Iron phosphates, similarly applied, are produced from alkali-metal phosphate solutions. When amorphous or of fine crystal size, they are used mainly to improve paint adhesion and to increase resistance to paint flaking from impact or flexing. Manganese phosphates, applied only by immersion, are used to retain oil so as to facilitate part break-in and prevent galling of mating surfaces. Phosphate coatings have specific colors, depending on the chemicals used and the metal to which they are applied. Special colors can be developed by pretreatments and posttreatments.

Chromate conversion coatings are formed on aluminum, cadmium, copper, magnesium, silver, zinc, and their alloys by immersion or spray using aqueous solutions of chromic acid, chromium salts such as sodium or potassium chromate or dichromate, and hydrofluoric, phosphoric, or other mineral acids. Generally, the basic ingredients are hexavalent chromium and sufficient acid for the desired pH. Solutions of trivalent chromium are used for clear coatings on electroplated cadmium and zinc. Chromate–phosphate mixtures are used to produce combination coatings on aluminum. Chromates are typically amorphous, pore-free, and gel-like initially but, on drying, harden and become hydrophobic, less soluble, and more abrasion-resistant. They are used primarily to increase corrosion resistance, especially in marine, humid, and tropical atmospheres; but they also serve as a good base for paint. Various colors can be provided, depending on the particular solution and post-treatments. Regarding hexavalent chromium, however, the aim is to eliminate the use because of its carcinogenicity.

Oxide chemical conversion coatings are the bluish, black, or brown oxides formed on iron or steel with hot caustic or alkaline solutions, and the black or brown oxides formed on cadmium, copper, iron, steel, or zinc alloys with acidic solutions. Although they are used mainly for abrasion resistance and anesthetics, some add a modest degree of corrosion protection. Alkaline chromate solutions as fused-salt solutions, for example, impart corrosion resistance and abrasion resistance to iron and steel.

Electrochemical conversion coatings, or anodic coatings, pertain mainly to aluminum alloys or magnesium alloys, although several other metals are also anodized. Anodized aluminum is produced primarily in aqueous solutions of sulfuric, chromic, or oxalic acid for a variety of reasons; to improve corrosion resistance, abrasion resistance, paint adhesion, adhesive bonding, or electroplating; to provide decorative finishes, including color; and to impart an electrically insulative surface or a base for photographic or lithographic emulsions. Hard anodic coatings on aluminum alloys, for abrasion resistance, are typically thicker than those for corrosion protection. Anodized magnesium is produced in aqueous solutions of ammonium bifluoride, sodium dichromate, and phosphoric acid or in aqueous solutions of potassium and aluminum hydroxide, trisodium phosphate, potassium fluoride, and potassium manganate or permanganate. Thin coatings serve mainly as a base for paint, thick ones for corrosion resistance and abrasion resistance. Other nonferrous metals are anodized primarily to increase corrosion resistance. Anodizing zinc is produced by immersion in an alkali-carbonate solution and then in a silicate solution, or in a single alkaline solution of sodium silicate, borate, and tungstate. Anodized beryllium is made in an aqueous solution of nitric and chromic acids, and anodized titanium and anodized thorium are made in mixtures of glacial acetic and nitric acids. Anodized zirconium also has been made in such mixtures although, for nuclear applications it and anodized hafnium are made in aqueous solutions of ethanol, glycerine, and lactic, phosphoric, and citric acids, followed by autoclaving.
Converter Cooling Curve

Converter

Anodized columbium and anodized tantalum are produced in solutions of ammonium citrate or borate, with ammonium hydroxide for basicity.

Conversion coatings are also known by various terms and trade names. Among the latter by Allied-Keltec, of Wicco Corp., are Keykote phosphate coatings, Iridite chromate coatings, Iridize zinc and anodic coatings, and Irlac clear coatings. The clear coatings can be applied to the anodic for additional corrosion protection. Other terms and key ingredients applicable to hard-anodizing aluminum are Martin Hard Coat (sulfuric acid). Magnaplate HCR, of General Magnaplate, is a surface treatment to improve the hardness, corrosion resistance, and abrasion resistance of aluminum and aluminum alloys. Nituff, a Teflon-impregnated hard-anodized aluminum, combines hardness and lubricity which markedly increases release properties and wear resistance. One application is chemical polishing tubs used to make sapphire optics.

Convex Fillet Weld

A fillet weld having a convex face.

Convexity

The maximum distance from the face of a convex fillet weld perpendicular to a line joining the toes.

Cool Time (Resistance Welding)

The time interval between successive heat times in multiple-impulse welding or in the making of seam welds.

Coolants

Liquids used to quench metals in heat treating, used to cool and lubricate cutting tools and workpieces in machining, or applied to forming tools and workpieces to assist in forming operations. In the case of machining, they are also called cutting fluids, and in the case of forming, forming lubricants. When water is used for the normal water-hardening steels, it may be modified with soda or other material to give a less drastic and more uniform cooling. A water bath containing 5% sodium hydroxide gives uniform, rapid cooling. Oils are used in cooling or quenching baths to provide a more moderate cooling effect. Quenching oils are usually compounded, although fish oils alone are sometimes employed. Fish oils, however, have offensive odors when heated. Vegetable oils alone are likely to oxidize and become gummy. Animal oils become rancid. Lard and palm oils give low cooling rates, while cottonseed, neatfoot, and fish oils give more rapid cooling. Mineral oils compounded with fish, vegetable, or animal oils are sold under trade names and vary considerably in their content. Oil-quenching baths are usually kept at a temperature of not over 150°F (66°C) by providing cooling pipes. Tempering oils differ from quenching oils only in that they are compounded to withstand temperatures up to about 525°F (274°C).

Coolants for machining are classified into five groups: straight oils, soluble oils, chemical coolants, synthetics, and semisynthetics. Straight oils, which contain no water, are petroleum or mineral oils with or without additional compounding. Without further compounding, they are suitable for light-to moderate-duty cutting on readily machined metals. For more severe machining, they are typically compounded with up to 20% fatty oils, sulfur, chlorine, phosphorus, or combinations thereof. Sulfur, chlorine, and phosphorus are commonly called extreme-pressure additives (EP additives).

For the most severe applications, compounding, mainly with chlorine and sulfurized fatty oils, may exceed 20%. Soluble oils, such as emulsified sulfonated mineral oils, are also suitable for light- and moderate-duty applications. Although they do not match the straight oils in lubricity, they, like water-dilutable fluids in general, are better heat dissipators. Because of their water content, they are usually formulated with additives to prevent corrosion of the workpiece and to resist microbial degradation and souring, necessitating maintenance and service to retain these characteristics. Heavy-duty soluble oils are suitable for most applications for which straight oils are used. Chemical coolants were originally amine nitrates, but amine borates are commonly used now because nitrates in contact with amine form nitrosamine, a suspected carcinogen. They are noted for excellent cooling capacity, inhibiting corrosion, and resisting microbial degradation and souring. They have limited lubricity, however, and are confined to light-duty operations, mainly light grinding. Synthetic coolants, which have been likened to soluble oils without oil, are water-dilutable systems designed for high-cooling capacity, lubricity, corrosion prevention, and easy maintenance. These synthesized materials are chemically similar to mineral-oil derivatives, but can be dispersed in water and are suitable for more severe operations than chemical coolants. They tend to defat human skin, however, causing dermatitis, thus necessitating that workers adhere to prescribed methods of personal hygiene. Semisynthetic coolants contain small dispersions of oil in an otherwise water-dilutable system, are almost transparent, are more broadly applicable than soluble oils, and are easier to maintain.

Straight oils, soluble oils, and synthetics are also used as forming lubricants. They also may contain a wetting agent, or polarity agent, such as animal fats, fatty acids, long-chain polymers, emulsifiers, and EP additives. The straight oils are the most varied in formulation and the most widely used. The soluble oils, however, can match their performance in many applications and, because of their superior cooling effect, sometimes provide better performance. The synthetics, which have been improved in recent years, also feature excellent cooling capacity as well as cleanliness and lubricity, and they have replaced both the straight and soluble oils and many applications. Because of their cleanliness, they are especially useful in forming precoated metals.

Cooling Channels

In plastic part making, chemicals or passageways located within the body of a mold through which a cooling medium can be circulated to control temperature on the mold surface. May also be used for heating a mold by circulating steam, hot oil, or other heated fluid through channels, as in the molding of thermosetting and some thermoplastic materials.

Cooling Curve

A graph showing the relationship between time and temperature during the cooling of a material. It is used to find the temperatures at
which phase changes occur. A property or function other than time may occasionally be used—for example, thermal expansion.

**Cooling Fixture**

In plastic part making, block of metal or wood shape to hold a molded part to maintain the proper shape or dimensional accuracy of the part after it is removed from the mold until it is cooled enough to retain its shape without further appreciable distortion. Also called a shrink fixture.

**Cooling Rate**

The average slope of the time–temperature curve taken over a specified time and temperature interval.

**Cooling Stresses**

Residual stresses in castings resulting from nonuniform distribution of temperature during cooling.

**Cooling Table**

Same as a hot bed.

**Coordinate Bonding**

See Interatomic Bonding.

**Coordination Catalysis**

Ziegler-type of catalysis for processing plastics. See also Ziegler–Natta catalysts.

**Coordination Compound**

A compound with a central atom or ion bound to a group of ions or molecules surrounding it. Also called coordination complex. See also chelate, complexation, and ligand.

**Coordination Number**

(1) Number of items or radicals coordinated with the central atom in a complex covalent compound. (2) Number of nearest neighboring atoms to a selected atom and crystal structure. (3) It is 12 for the close packed hexagonal and face-centered cubic structures, and 8 for body centered cubic structures.

**Cope**

In casting, the upper or topmost section of a flask, mold, or pattern. The lower part is the drag.

**Copolyesters**

These thermoplastic elastomers are generally tougher over a broader temperature range than the urethanes. Also, they are easier and more forgiving in processing. Several grades include Hytrel, Riteflex, and Ecedel, ranging in hardness from 35 to 72 Shore D. These materials can be processed by injection molding, extrusion, rotational molding, flow molding, thermoforming, and melt casting. Powders are also available.

Copolyesters, which along with the urethanes are high-priced elastoplastics, have excellent dynamic properties, high modulus, good elongation and tear strength, and good resistance to flex fatigue at both low and high temperatures. Brittle temperature is below -68°C, and modulus at -40°C is only slightly higher than at room temperature. Heat resistance of 449°C is good.

Resistance of the copolyesters to nonoxidizing acids, some aliphatic hydrocarbons, aromatic fuels, sour gases, alkaline solutions, hydraulic fluids, and hot oils is good to excellent. Thus, they compete with rubbers such as nitriles, epichlorohydrins, and polycrylates. However, hot polar materials, strong mineral acids and bases, chlorinated solvents, phenols, and cresols degrade the copolymers. Weathering resistance is low but can be improved considerably by compounding ultraviolet stabilizers or carbon blacks with the resin.

Copolyester elastomers are not direct substitutes for rubber in existing designs. Rather, such parts must be redesigned to use the higher strength and modulus, and to operate within the elastic limit. Thinner sections can usually be used—typically one-half to one-sixth that of a rubber part.

Applications of copolyester elastomers include hydraulic hose, fire hose, power-transmission belts, flexible couplings, diaphragms, gears, protective boots, seals, oil-field parts, sports-shoe soles, wire and cable insulation, fiber-optic jacketing, electrical connectors, fasteners, knobs, and bushings.

**Copolymer**

A long-chain molecule formed by the reaction of two or more dissimilar monomers. See also polymer.

**Copolymerization**

See polymerization.

**Copper Acetate**

Also known as crystals of Venus. A dark-green, crystalline, poisonous powder. It is soluble in water and alcohol. It is used as a pigment in paints, lacquers, linoleum, and inks and for making artificial verdigris or patina on copper articles. It is used as a catalyst in making phthalic anhydride plastics. When used for mildew-proofing cotton cloth, the copper precipitates out to form the waxate, or copper soap coating. Verdigris is an old name for basic copper acetate as a blue-grain pigment, but the name is now usually applied to the bluish-green corrosion crust on copper. The greenish-brown crust known as patina, forms on bronze, is esteemed as a characteristic of antiquity. It is a basic sulfate of copper, usually with oxides of tin, copper, and lead.

**Copper and Copper Alloys**

Copper (symbol Cu) is one of the most useful of the metals, and probably the one first used by humans. It is found native and in a large number of ores. Its apparent plentifulness is only because it is easy to separate from its ores and is often a by-product from silver and other mining. Copper has a face-centered cubic crystal structure. It is yellowish red in color, tough, ductile, and malleable; gives a brilliant luster when polished; and has a disagreeable taste and a peculiar odor. It is the best conductor of electricity next to silver, with a conductivity 97% that of silver. Copper refers to the
Copper and Copper Alloys

Copper and copper-base alloys are unique in their desirable combination of physical and mechanical properties. The following properties are found or may be developed in these materials:

1. Moderate to high strength and hardness
2. Excellent corrosion resistance
3. Ease of workability both in primary and secondary fabrication operations
4. Pleasing color and wide color range
5. High electrical and thermal conductivity
6. Nonmagnetic properties
7. Superior properties at subnormal temperatures
8. Ease of finishing by polishing, plating
9. Good-to-excellent machinability
10. Excellent resistance to fatigue, abrasion, and wear
11. Relative ease of joining by soldering, brazing, and welding
12. Moderate cost
13. Availability in a wide variety of forms and tempers

The importance of copper and copper-based alloys is in no small part because many other metals, whether singly or in combination, may be alloyed with copper. There are many binary alloys, and ternary and quaternary alloy systems which are quite common. The copper content of alloys in commercial use ranges from about 58% to about 100%. Alloys of 63% to about 100% copper are of the alpha plus beta (two-phase) type and are particularly suited to hot-working processes such as hot rolling, hot extrusion, and hot forging.

Copper alloys in the lower range, 62% and less, are of the alpha plus beta (two-phase) type and are particularly suited to hot-working processes such as hot rolling, hot extrusion, and hot forging.

The chief elements alloyed with copper are zinc, tin, lead, nickel, silicon, and aluminum, and to a lesser extent, beryllium, phosphorus, cobalt, boron, arsenic, zirconium, antimony, cadmium, iron, manganese, chromium, and very recently, mercury.

Cast Products

Foundry alloys are used in the form in which they are originally molded. In general, cast alloys are not easily workable and subsequent operations are limited to such treatment as machining, electroplating, soldering, and brazing. The use of alloys in cast form permits the production of intricate and irregular shapes impractical or impossible to make by other means. The use of cores permits the making of hollow shapes. The alloying metals are generally greater in amount than for wrought alloys. Types of castings in commercial use include sand castings, diecastings, permanent mold, plaster mold, shell mold, and centrifugal and investment castings. The alloy involved, the properties desired, and the quantity to be made govern the choice of casting process. Where regularity of shape permits, a number of foundry alloys are available in the continuous-cast condition and may be either solid or hollow shapes. The classification of copper-base foundry alloys generally follows that used for wrought alloys. As in the wrought-alloy field, the number of cast alloys in commercial use runs well into the hundreds; many are modifications of standard alloys.

Wrought Products

Wrought products are those originally cast into starting shapes such as billets, cakes (slabs), and wire bar, which are further fabricated into useful forms such as sheet, strip, plate, rod, bar, seamless tubes, extruded shapes, and forgings by hot rolling, cold rolling, cold drawing, hot piercing, hot extrusion, or combinations of these primary fabricating processes. Secondary fabricating processes include such operations as machining, bending, spinning, cold heading, hot press forging, soldering, brazing, electroplating, cold extrusion, and operations normally associated with press working (blanking, deep drawing, coining, staking, embossing, drilling).

The various types of copper and the copper-base alloys are not fabricated with equal facility into usable forms or by secondary fabricating processes. This fact, together with the wide range and combination of physical and mechanical properties desirable for end use, accounts for the large number of commercial wrought copper-base alloys. Design considerations usually dictate a compromise between service properties desired, secondary fabricating properties, forms and sizes available, and cost.

The Alloys

In the copper industry, and in the brass mill section of that industry in particular, the alloys of copper have been designated by a sort of "word-terminology" that is often confusing and misleading. Names assigned to various alloys are not always descriptive or indicative of the composition. Several names may be in common use for the same composition. Numerous proprietary names are also used and, in some cases, several names in this category are in general use for essentially the same composition or type of alloy.

Since the more important alloying elements are used effectively in varying amounts, a convenient and logical classification is made possible by separating the alloys into well-recognized groups.
Copper and Copper Alloys

222

according to composition. Literally hundreds of wrought copper alloys are used. Those listed are standard alloys that account for the large majority of tonnage used. Alloys not listed are, in general, modifications of standard alloys often used for very special purposes.

Certain terms require clarification. Brass is an alloy of copper with zinc as the principal alloying element, used with or without additional elements. High brasses are Cu–Zn alloys containing more than 20% zinc, more properly called yellow brasses. Low brasses are alloys containing 20% zinc or less and low brass is a specific alloy, 80% copper and 20% zinc. Rich low brass is a term used for brass containing nominally 85% copper and 15% zinc, more properly called red brass. Straight brasses are those alloys containing copper and zinc only.

The term bronze in modern usage properly requires a modifying adjective. Early bronzes were alloys of copper with tin as the only, or principal, alloying metal, and thus the term bronze has been traditionally associated with alloys of copper and tin. The widespread use of numerous other alloys in recent times requires that a bronze be defined as an alloy of copper with some element, or elements, other than zinc as a chief alloying metal. Thus, “tin-bronze” is the proper name for alloys of copper and tin, silicon-bronze for alloys of copper and silicon, aluminum–silicon-bronze for an alloy of Cu–Al–Si. Tin-bronzes are also commonly called phosphor-bronzes because of the long-established practice of deoxidizing these alloys with phosphorus.

The “coppers” include pure copper and its modified forms, and also certain materials that might more properly be classed as alloys but that are commonly called “coppers” where the alloying element is less than about 1%, e.g., “TeCu”—0.5% tellurium, the balance, copper.

Refractory copper-base alloys are those that, because of their hardness or abrasiveness, require greater dimensional tolerances than those established for nonrefractory alloys. Examples of refractory alloys are the phosphor bronzes, silicon bronzes, aluminum bronzes, and nickel silvers.

Coppers

Many types and variations of commercial copper are available; the differences are slight or important depending upon the method of production or the intentional minor additions of other metals. Two types refer to the method of refining. Fire-refined copper is that finished by furnace refining. Electrolytically refined copper is that finished by electrolytic deposition where the original ore requires such refining because of certain undesirable impurities that can be satisfactorily removed only by this method, or where the original ore contains sufficient quantities of silver and gold, recoverable in electrolytic refining, to make the electrolytic process profitable. Over 85% of all copper is electrolytically refined. Three major types of commercial copper with respect to composition and method of casting are tough pitch, O2-free, and phosphorus deoxidized. Tough-pitch copper contains a small but controlled amount of O2 (about 0.04%) necessary to obtain a level set, i.e., the correct pitch, on the refinery casting (wire bar, cake, billet); the level set is necessary to provide adequate ductility for hot or cold primary fabricating operations, i.e., sufficient “toughness.” Electrolytic tough-pitch copper is the standard copper of industry for electrical and many other purposes. Its low electrical resistance (0.15328 Ω/g m² at 20°C) equivalent to 100% IACS conductivity is the standard with which other metals are compared. Copper has the highest conductivity of any base metal and is exceeded only by that of silver.

Tough-pitch copper has one distinct disadvantage. When heated above about 399°C in atmospheres containing reducing gases, particularly H₂, the CuO₂ is reduced to copper and water vapor, the water changing to steam at the temperatures involved, thus “gassing” or embrittling the copper and destroying its ductility. Hence, the term H₂ embrittlement. Under circumstances where H₂ embrittlement is likely to occur (brazeing, welding, annealing), O2-free copper may be used without sacrifice of conductivity. In cases where some conductivity loss may be tolerated, various types of deoxidized copper may be used. Tough-pitch copper, while ductile enough for most fabricating work, is somewhat lacking in the ductility required for difficult forming operations (severe drawing, edgewise heading) and O₂-free copper is often used in these instances. Also, tough-pitch copper is not as free machining as the varieties made for that purpose, i.e., leaded copper, TeCu, sulfur copper. Silver is added to copper (without sacrifice of conductivity) for the purpose of increasing the recrystallization temperature, thus permitting soldering operations without reduction of strength and hardness. The amount of silver added varies with the application. Lake copper is a general term for silver-bearing copper, having varying but controlled amounts of silver up to about 30 oz/ton.

Phosphorized copper, with excellent hot and cold workability, is the second largest type in use with respect to tonnage and is widely used for pipe and tube for domestic water service and refrigeration equipment.

O₂-free copper is made either by melting and casting copper in the presence of carbon or carbonaceous gases or by extruding compacted, specially prepared cathode copper under a protective atmosphere, so that no O₂ is absorbed. No deoxidizing agent is required; therefore, no residual deoxidants are present, and optimum electrical conductivity is maintained. O₂-free copper is used extensively in the electrical and electronics industries, e.g., metal-to-glass seals.

Wrought Cu Alloys

Copper and zinc melted together in various proportions produce one of the most useful groups of copper alloys, known as the brasses. Six different phases are formed in the complete range of possible compositions. The relationship between composition and phases alpha, beta, gamma, delta, epsilon, and eta are graphically shown in the well-established constitution diagram for the Cu–Zn system. Brasses containing 5%–40% zinc constitute the largest volume of copper alloys. One important alloy, cartridge brass (70% copper, 30% zinc), has innumerable uses, including cartridge cases, automotive radiator cores and tanks, lighting fixtures, eyelets, rivets, screws, springs, and plumbing products. Tensile strength ranges from 310 MPa as annealed to 900 MPa for spring temper wire.

Lead is added to both copper and the brasses, forming an insoluble phase that improves machinability of the material. Free cutting brass (61% copper, 3% lead, 36% zinc) is the most important alloy in the group. In rod form it has a strength of 340–480 MPa, depending on temper and size. It is machined into parts on high-speed (10,000 rpm) automatic screw machines for a multiplicity of uses.

Increased strength and corrosion resistance are obtained by adding up to 2% tin or aluminum to various brasses. Admiralty brass (70% copper, 2% aluminum, 0.02% arsenic, 21.97% zinc) are two useful condenser-tube alloys. The presence of phosphorus, antimony, or arsenic effectively inhibits these alloys from dezincification corrosion.

Alloys of copper, nickel, and zinc are called nickel silvers. Typical alloys contain 65% copper, 10%–18% nickel, and the remainder zinc. Nickel is added to the Cu–Zn alloys primarily because of its influence on the color of the resulting alloys; color ranges from
Copper and Copper Alloys

Copper and Copper Alloys

Yellowish-white, to white with a yellowish tinge, to white. Because of their tarnish resistance, these alloys are used for table flatware, zippers, camera parts, costume jewelry, nameplates, and some electrical switch gear.

Copper forms a continuous series of alloys with nickel in all concentrations. The constitution diagram is a simple all-alpha-phase system.

Nickel slightly hardens copper, increasing its strength without reducing its ductility. Copper with 10% nickel makes an alloy with a pink cast. More nickel makes the alloy appear white.

Three copper-base alloys, containing 10%, 20%, and 30% nickel, with small amounts of manganese and iron added to enhance casting qualities and corrosion resistance, are important commercially. These alloys are known as cupronickels and are well-suited for application in industrial and marine installations as condenser and heat-exchanger tubing because of their high corrosion resistance and particular resistance to impingement attack. Heat-exchanger tubes in desalination plants use the cupronickel 10% alloy.

Cu–Sn alloys (3%–10% tin), deoxidized with phosphorus, form an important group known as phosphorus bronzes. Tin increases strength, hardness, and corrosion resistance, but at the expense of some workability. These alloys are widely used for springs and screens in papermaking machines.

Silicon (1.5%–3.0%), plus smaller amounts of other elements, such as tin, iron, or zinc, increases the strength of copper, making alloys useful for hardware, screws, bolts, and welding rods.

Sulfur (0.35%) and tellurium (0.50%) form insoluble compounds when alloyed with copper resulting in increased ease of machining. Alloys of copper that can be precipitation-hardened have the common characteristic of a decreasing solid solubility of some phase or constituent with decreasing temperature. Precipitation is a decomposition of a solid solution leading to a new phase of different composition to be found in the matrix. In such alloys systems, cooling at the appropriate rapid rate (quenching) from an equilibrium temperature well within the all-alpha field will preserve the alloy as a single solid solution possessing relatively low hardness, strength, and electrical conductivity.

A second heat treatment (aging) at a lower temperature will cause precipitation of the unstable phase. The process is usually accompanied by an increase in hardness, strength, and electrical conductivity. Some 19 elements form copper-base binary alloys that can be age- or precipitation-hardened.

Two commercially important precipitation-hardenable alloys are Be–Cu and Cr–Cu. Be–Cu (2.0%–2.5% beryllium plus cobalt or nickel) can have a strength of 1400 MPa and an electrical conductivity of less than 50% of IACS. Cobalt adds high-temperature stability and nickel acts as a grain refiner. These alloys have found use as springs, diaphragms, and bearing plates and in other applications requiring high strength and resistance to shock and fatigue.

CuCr (1% chromium) can have a strength of 550 MPa and an electrical conductivity of 80%. Cu–Cr alloys are used to make resistance-welding electrodes, structural members for electrical switch gear, current-carrying members, and springs.

Cu–Ni, with silicon or phosphorus added, forms another series of precipitation-hardenable alloys. Typical composition is 2% nickel, 0.6% silicon. Strength of a 30 MPa can be obtained with high ductility and electrical conductivity of 32% IACS.

Zr–Cu is included in this group because it responds to heat treatment, although its strength is primarily developed through application of cold deformation or work. Heat treatment restores high electrical conductivity and ductility and increases surface hardness. Tensile strength of 500 MPa coupled with an electrical conductivity of 88% can be developed. Uses are resistance welding wheels and tips, stud bases for transistors and rectifiers, commutators, and electrical switch gear.

As little as 2% beryllium content, combined with the thermal conductivity of copper, has improved wear resistance to extend mold life and accelerated mold cycle time. Advancements in electrode materials are directly responsible for use of alloys like Be-Cu in mold making.

Conventional EDM performance in Be–Cu alloys with graphite electrodes is similar to that of other copper work metals. However, differences in EDM performance for various grades of Be–Cu alloys are evident at all power levels.

Be–Cu alloys with beryllium contents of 0.2%–0.6% and 1.6%–2.0% have shown that the higher-content group exhibited improved conventional EDM performance over the lower-content group. Testing of EDM with Be–Cu must still be performed relative to the possible health hazards involving fumes or gases, which must be recognized. Adequate EDM tank ventilation and dust collection for machining particulates could eliminate the hazards of inhaling any free beryllium or copper.

**Cast Copper Alloys**

Copper alloy castings of irregular and complex external and internal shapes can be produced by various casting methods, making possible the use of shapes for superior corrosion resistance, electrical conductivity, good bearing quality, and other attractive properties. High-copper alloys with varying amounts of tin, lead, and zinc account for a large percentage of all copper alloys used in the cast form. Tensile strength ranges from 250 to 330 MPa depending on composition and size. Leaded tin-bronzes with 6%–10% tin, about 1% lead and 4% zinc are used for high-grade pressure castings, valve bodies, gears, and ornamental work. Bronzes high in lead and tin (5%–25% lead and 5%–10% zinc) are mostly used for bearings. High tin content is preferred for heavy pressures or shock loading, but lower tin and higher lead is preferred for lighter loads, higher speeds, or where lubrication is less certain. A leaded brass containing 85% copper and 5% each of tin, lead, and zinc is a popular alloy for general use.

High-strength brasses containing 57%–63% copper, small percentages of aluminum and iron, and the balance zinc have tensile strengths from 490 to 830 MPa, high hardness, good ductility, and resistance to corrosion. They are used for valve stems and machinery parts requiring high strength and toughness.

Copper alloys containing less than 2% alloying elements are used when relatively high electrical conductivity is needed. Strength of these alloys is usually notably less than that of other cast alloys.

Aluminum bronzes containing 5%–10.5% aluminum, small amounts of iron, and the balance copper have high strengths even at elevated temperature, high ductility, and excellent corrosion resistance. The higher-aluminum-content castings can be heat-treated, increasing their strength and hardness. These alloys are used for acid-resisting pump parts, pickling baskets, valve seats and guides, and marine propellers.

Additives impart special characteristics. Manganese is added as an alloying element for high-strength brasses where it forms intermetallic compounds with other elements, such as iron and aluminum. Nickel additions refine cast structures and add toughness, strength, and corrosion resistance. Silicon added to copper forms Cu–Si alloys of high strength and high corrosion resistance in acid media. Beryllium or chromium added to copper forms a series of age- or precipitation-hardenable alloys. Cu–Be alloys are among the strongest of the copper-base cast materials.
**Copper and Copper Alloys**

**Copper Alloy Designations**

Copper serves as the base metal for a great variety of wrought and cast alloys and the major wrought and their designations, or alloy numbers, are high-copper alloys (C16200–C19750), which include CdCu, BeCu, and CuCr; CuZn brasses (C20500–C28580); Cu-Zn–Pb leaded brasses (C31200–C38590); Cu–Zn–Sn alloy or tin brasses (C40400–C49080); Cu–Sn phosphor bronzes (C50100–C52400); Cu–Sn–Pb bronze alloys or leaded phosphor bronzes (C53200–C54800); Cu–P alloys and Cu–Ag–P alloys (C55180–C55284); Cu–Al alloys or aluminum bronzes (C60600–C64400); Cu–Si alloys or silicon bronzes (C64700–C66100); miscellaneous Cu–Zn alloys (C66400–C69950); and Cu–Ni–Zn alloys or nickel silvers (C73150–C79900). All told, there are about 300 standard wrought alloys and many have cast counterparts (C81300–C99750). There are about 140 standard cast alloys. Many copper alloys are also available in powder form for powder-metal parts.

Cu–Ni wrought alloys are designated C70100–C72950; cast alloys, C96200–C96800. The alloys also have been referred to as cupronickels, Cu–Ni 20% (or whatever the percent nickel), also 80%–20% (or whatever the percent copper and nickel), nickel content may be as low as 2%–3% (C70200) or as high as 43%–46% (C72150), but intermediate amounts, nominally 10% (C70600 and C96200), 20% (C71000 and C96300), and 30% (C71500 and C96400), are the most common. Most of the alloys also contain small to moderate amounts of iron, zinc, manganese, and other alloying ingredients, and some contain substantial amounts of tin (1.8%–2.8% in C72500; 7.5%–8.5% in C72800).

**The Brasses/Bronzes/Silvers/Cupronickels**

The straight brasses are without question the most useful and widely used of all copper-base alloys. Zinc is used in substantial portions in five of the alloy groups listed. Most of the brasses are within the alpha field of the phase diagrams, thus maintaining good cold-working properties. With a higher zinc content of about 40%, the beta phase facilitates hot working. The addition of zinc decreases the melting point, density, electrical and thermal conductivities, and modulus of elasticity. It increases the coefficient of expansion, strength, and hardness. Work hardening increases with zinc content but 70–30 brass has the best combination of strength and ductility.

The low zinc brasses (20% zinc or less) have excellent corrosion resistance, are highly resistant to stress-corrosion cracking (SCC), and cannot dezincify. All of the low brasses are extensively used where these properties are required, along with good forming characteristics, and moderate strength. Commercial bronze is the standard alloy for domestic screen cloth, rotating bands on shells, and weatherstripping. Red brass is highly corrosion resistant, more so than copper in many cases, and is used for condenser tubes and process piping. The brasses have a pleasing color range varying from the red of copper through bronze and gold colors to the yellow of the high zinc brasses. The alloy 87.5% copper, 12.5% zinc very closely matches the color of 14-karat gold, and the low brasses in particular are used in inexpensive jewelry, for closures, and in other decorative items.

The high brasses, cartridge brass and yellow brass, have excellent ductility and high strength and have innumerable applications for structural and decorative parts that are to be fabricated by drawing, stamping, cold heading, spinning, and etching. Cartridge brass is able to withstand severe cold working in practically all fabricating operations, and derives its name from the deep-drawing operations necessary on small-arms munition cases, for which it is ideally suited. Muntz metal is primarily a hot-working alloy and is cold-formed with difficulty. It is used in applications where cold spinning, drawing, or upsetting are not necessary. A typical use of Muntz metal is for condenser tube plates.

**Silicon, Aluminum, and Manganese Brass**

Silicon red brass has the corrosion resistance of the low brasses, with higher electrical resistance than that normally inherent in those brasses, and is especially suited to applications involving resistance welding. Aluminum brass is a moderate-cost alloy primarily made in tube form for use in condensers and heat exchangers, where its improved resistance to the corrosive and erosive action of high-velocity seawater is desired. Manganese brass serves the same purpose as silicon brass.

**Ledeared Brasses**

The primary purpose in adding lead to any copper alloy is to improve machinability and related operations such as blanking or shearing. Lead also improves antifriction properties and is sometimes useful in that respect. Lead has an adverse effect in that both hot- and cold-working properties are hindered by reduced ductility. Optimum machinability is reached in free-cutting brass rod with 3.25% lead, ideally suited for automatic screw-machine work. Other leaded brasses in rod and other forms, with lead content ranging from 0.5% to over 2%, and with varying copper content, are available to permit varying combinations of corrosion resistance, strength, and hardness, and equally important, secondary fabricating processes (flaring, bending, drawing, stamping, thread rolling). Applications of all these alloys are found throughout industry.

**Tin Brasses**

Tin improves the corrosion resistance and strength of Cu–Zn alloys. Pleasing colors are obtainable when tin is alloyed with the low brasses. The tin brasses in sheet and strip form and with copper content of 80% or greater comprise a group of materials used as low-cost spring materials, for hardware, or for color effect alone, as in inexpensive jewelry, closures, and decorative items. Admiralty brass is the standard alloy for heat exchanger and condenser tubes, with good corrosion resistance to both seawater and domestic-water supplies. The addition of a small amount of antimony, phosphorus, or arsenic inhibits dezincification, a type of corrosion to which the high-zinc alloys are susceptible. Naval brass and manganese bronze are widely used for applications requiring good corrosion resistance and high strength, particularly in marine equipment for shafting and fastenings.

**Phosphor Bronzes**

As a group, these range in tin content from 1.25% to 10% nominal tin content. They have excellent cold-working characteristics, high strength, hardness, and endurance properties, low coefficient of friction, and excellent general corrosion resistance, and hence find wide use as springs, diaphragms, bearing plates, Fourdrinier wire, bellows, and fastenings.

**Aluminum Bronzes**

The alpha aluminum bronzes (containing less than about 8% aluminum) have good hot- and cold-working properties, while the alpha–beta alloys (8%–12% aluminum, with nickel, iron, silicon,
Copper Brazing

Copper and bronzes are used for spark-resistant tools. Certain alloys in this category may be hardened by a heat-treatment process similar to that used for steels. Certain alloys in this group are used for spark-resistant tools.

Cupronickels

These are straight Cu–Ni alloys with nickel content ranging from 2.5% to 30% nickel and have increased corrosion resistance with increasing nickel content. Cupronickels are markedly superior in their resistance to the corrosive and erosive effects of high-velocity seawater. They are moderately hard but quite tough and ductile, so that they are particularly suited to the manufacture of tubes for condenser and heat-exchanger use, and have flaring, rolling, and bending characteristics necessary for installation.

Cadmium Bronzes

Alloys of copper and cadmium, with or without small additions of tin, are primarily used for electrical conductors where high electrical conductivity and improved properties are found.

Nickel Silvers

Actually nickel brasses, these alloys contain varying amounts of copper, zinc, and nickel. They have a color ranging from ivory white in the lower nickel alloys to silver white in the higher nickel alloys. Their pleasing silver color, coupled with excellent corrosion resistance and cold formability, makes them ideally suited as a base for silver-plated flatware and hollow-ware, and structural and decorative parts in optical goods, cameras, and costume jewelry. The low-copper 18% nickel alloy is used for springs and other applications where high fatigue strength is desired.

Silicon Bronzes

The silicon bronzes are an extremely versatile series of alloys, having high strength, exceptional corrosion resistance, and excellent weldability, coupled with excellent hot and cold workability. The low silicon bronzes (1.5% silicon) are widely used for electrical hardware. The high silicon bronzes are used for structural parts throughout industry. Al–Si bronze is an important modification with exceptional strength and corrosion resistance, particularly suited to hot working and with better machinability than the regular silicon bronzes.

Copper Alloy Powders

Besides copper, there are a rather large range of compositions of copper alloy powders available, including the brasses, bronzes, and Cu–Ni. Brass powders are the most widely used for powder–metalurgy structural parts. Conventional grades are available with zinc contents from around 10% to 30%. Sintered brass parts have tensile strengths up to around 245 and 280 MPa and elongations of from 15% to around 40% depending on composition, design, and processing. In machinability they are comparable in cost with wrought brass stock of the same composition. Brass P/M parts are well-suited for applications requiring good corrosion resistance, and where free machining properties are desirable. Cu–Ni, or Ni–Ag, powders contain 10% or 18% nickel. Their mechanical properties are rather similar to the brasses, with slightly higher hardness and corrosion resistance. Because they are easily polished, they find considerable use in decorative applications.

Copper and bronze powders are used for filters, bearings, and electrical and friction products. Bronze powders are relatively hard to press to densities to give satisfactory strength for structural parts. Probably the most commonly used bronze contains 10% tin. The strength properties are considerably lower than iron-base and brass powders, usually below 140 MPa.

Miscellaneous Copper Alloys

Narloy Z is a copper–silver–sirconium alloy for high-temperature applications, such as vacuum-plasma-sprayed combustion chambers of rocket engines. It is also a candidate for engine inlets and wing leading edges of the U.S. national aerospace airplane. Powder-metal copper–chromium–columbium alloys Cu–8Cr–4Cb and Cu–6.5Cr–5.8Cb are also candidates for rocket-engine applications as well as heat exchangers, electrical contacts, and resistance welding electrodes. The latter alloy possesses high strength, creep resistance, and thermal conductivity at high temperatures. Besides their use for a great variety of parts, copper alloys are also used for surfacing ferrous and nonferrous parts for bearing applications, for corrosion and erosion resistance, and to rebuild worn parts. There are also memory alloys, or shape-memory alloys, which can be deformed and then revert to their original shape when heated to their transformation temperature. The reusable locknuts, from Memry Corp., are one application. With copper–aluminum–zinc or copper–aluminum–nickel alloy used for an answer, the insert can be deformed to lock the nut in place. When the nut is removed and heated to the alloys transformation temperature, the insert returns to its original shape so that the nut can be reused. An 89Cu–5Al–5Zn–1Sn alloy, referred to as Nordic Gold, is used for several Euro coins. A series of Thermitech copper–tungsten alloys, from Mi-Tech Metals, Inc., are used for thermal heat sinks and electronic circuits.

Copper Brazing

A term improperly used to denote brazing with a copper filler metal. See preferred terms furnace brazing and braze welding.

Copper Loss

The power loss resulting from the resistance in electrical circuit.

Copper Matte

An intermediate stage in the production of copper from sulfide ores; it contains about two-thirds copper.

Copper Oxide

There are several oxides of copper but usually the term refers to red copper oxide, or cuprous oxide, Cu₂O, a reddish crystalline powder formed by the oxidation of copper at high temperatures. It also occurs naturally in cuprite ore. It is insoluble in water but soluble in acids and alkalies. It is used in coloring glass and ceramics red, in electroplating, and in alternating-current rectifiers. Black copper oxide, or cupric oxide, CuO, is a brownish-black amorphous powder. It is used for coloring ceramics green or blue. In its natural ore form, it is called tenorite. Together with the red oxide, it is used as a copper paint for ships’ bottoms.
Cupric oxide, when used in glazes, has a wide range of color. It may be used either as the raw oxide in a raw glaze, as the raw oxide in a fritted glaze, or as part of the frit itself. Cupric oxide is generally preferred in glazes and cuprous oxide in glasses.

*Copper hydroxide,* formed by the action of an alkali on the oxides, is also a poisonous blue powder and is used as a pigment.

**Copper Shortening**

See shortening.

**Copper Steel**

Steel containing up to 0.25% copper and very low in carbon, employed for construction work where mild resistance to corrosion is needed and where the cost of the more resistant chromium steels is not warranted. It is employed in sheet form for culverts, ducts, pipes, and such manufacturing purposes as washing-machine boilers. The alloy steels containing considerable copper for special purposes are not classified as copper steels. The copper neutralizes the corroding influence of the sulfur in the steel and aids in the formation of a fine-grained oxide that retards further corrosion. Copper is not added to unalloyed high-carbon steels because it causes brittleness and hot-shortness. Since the carbon content of copper steel is usually very low, the material is more a copper iron. Unless balancing elements, especially nickel, are present, more than 0.2% copper in steel may cause rolling defects. Molybdenum in small quantities may also be added to give additional corrosion resistance, and the percentage of carbon may be raised to 0.40% when about 0.05% molybdenum is added.

**Copper Sulfate**

Also called blue stone, blue copperas, and blue vitriol. An azure-blue, crystalline, lumpy material. It is soluble in water and insoluble in alcohol. It is produced as a by-product in copper refineries, or by the action of sulfuric acid on copper or copper oxide. A major market for copper sulfate is agriculture, where it is used in fungicides, micronutrients for fertilizers and animal feeds, and seed treatment. In chemical processes, it is used as an algicide in water treatment, for separating sulfide ores, in electroplating, in froth flotation, in leather tanning and hide preservation, and as a raw material for the synthesis of other salts and dyes.

**Copper-Accelerated Salt-Spray (CASS) Test**

An accelerated corrosion test for some electrodeposits and for anodic or coatings on aluminum.

**Copper-Constantan**

A pair of metals used for thermocouples. See *Constantan*.

**Copperhead**

A reddish spot in a porcelain enamel coating caused by iron pickup during enameling, iron oxide left on poorly cleaned basic metal, or burrs on iron or steel basic metal that protrude through the coating and are oxidized during firing.

**Cordierite**

A talc-like mineral of composition $\text{Mg}_2\text{Al}_4\text{Si}_5\text{O}_{18}$ used in ceramics to make refractories, filters and diesel engines, and spark plug insulators. Cordierite has an unusually low coefficient of expansion ($1.4-2.6 \times 10^{-6}/\degree\text{C}$ from $25\degree\text{C}$ to $1000\degree\text{C}$) and high thermal shock resistance.

**Core**

(1) A specially formed material inserted in a mold to shape the interior other part of the casting that cannot be shaped as easily by the pattern. (2) To establish the internal shape of a hollow casting. (3) In a ferrous alloy prepared for case hardening, that portion of the alloy that is not part of the case. Typically considered to be the portion that (a) appears dark (with certain etchants) on an etched cross section (b) has an essentially unaltered chemical composition, or (c) has a hardness, after hardening, less than a specified value. (4) The central member of a sandwich construction (honeycomb material, foamed plastic, or solid sheet to which the faces of the sandwich are attached). (5) The inner material beneath a case hardened, or other surface layer. (6) The central mass of a transformer around which the windings are arranged.

**Core (Plastics)**

(1) In plastic part making, a channel in a mold for circulation of heat transfer media. (2) The part of a complex mold that molds undercut parts. Cores are usually withdrawn before the main sections of the mold are opened. Also called core pin.

**Core Assembly**

In casting, a complex score consisting of a number of sections.

**Core Binder**

In casting, any material used to hold the grains of core sand together.

**Core Blow**

A gas pocket in a casting adjacent to a cored cavity and caused by entrapped gases from the core.

**Core Blower**

A machine for making foundry cores using compressed air to blow and pack the sand into the core box.

**Core Box**

In casting, a wood, metal, or plastic structure containing a shaped cavity into which sand is packed to make a core.

**Core Crush**

A collapse, distortion, or compression of the core of a sandwich construction.

**Core Depression**

A localized indentation or gouge in the core of a sandwich construction.
Core Dryers
In casting, supports used to hold cores in shape during baking; constructed from metal or sand for conventional baking or from plastic material for use with the dielectric core-making equipment.

Core Filler
In casting, a material, such as coke, cinder, and sawdust, used in place of sand in the interiors of large cores; usually added to aid collapsibility.

Core Forging
(1) Displacing metal with a punch to fill a die cavity. (2) The product of such an operation.

Core Knockout Machine
In casting, a mechanical device for removing cores from castings.

Core Oil
In casting, a binder for core sand that sets when baked and is destroyed by the heat from the cooling casting.

Core Pin
In plastic part making, a pin used to mold a hole.

Core Pin Plate
In plastic part making, a plate holding core pins.

Core Plates
In casting, heat-resistant plates used to support cores during baking; may be metallic or nonmetallic, the latter being a requisite for dielectric core baking.

Core Plug
A plug inserted into the wall of a hollow casting to close a hole left by the core support or through which a sand core was extracted.

Core Print
In casting, projections attached to a pattern in order to form recesses in the mold at points where cores are to be supported.

Core Refining
The initial stage of hardening a carburized steel component. The carburizing treatment produces an undesirably large grain size in the component. Good quality work requires a fine grain size in both the low carbon core and the high carbon case. Initially, the component is heated to and quenched from about 880°C which is just within the austenitic region for the typical lower carbon core. This refines, hardens, and toughens the core. Subsequently, the component is heated to and quenched from about 750°C which is just within the austenitic region for the high carbon case. This hardens the case. See Steel and Case Hardening.

Core Rod
In powder metallurgy, a member of a die assembly used in molding a hole in a compact.

Core Sand
In casting, sand for making cores to which a binding material has been added to obtain good cohesion and permeability after drying; usually low in clays.

Core Separation
In a sandwich construction, a partial or complete breaking of the core node bond.

Core Shift
In casting, a variation from the specified dimensions of a cored casting section due to a change in position of the core or misalignment of cores in assembly.

Core Splicing
The joining of segments of a core of a sandwich construction by bonding, or by overlapping each segment and then driving them together.

Core Vents
(1) In casting, a wax product, round or oval in form, used to form the vent passage in a core. Also, a metal screen or slotted piece used to form the vent passage in the core box used in a core blowing machine. (2) Holes made in the core for the escape of gas.

Core Wash
In casting, a suspension of a fine refractory applied to cores by brushing, dipping, or spraying to improve the surface of the cored portion of the casting.

Core Wires or Rods
(1) In casting, reinforcing wires or rods for fragile cores, often for preformed into special shapes. (2) (for welding) The central main wire of a continuous covered electrode.

Cored Bars
In powder metallurgy, a compact of bar shape heated by its own electrical resistance to a temperature high enough to melt its interior.

Cored Mold
In plastic part making, a mold incorporating passages for electrical heating elements, steam, or water.
Cored Solder
A solder wire or bar containing flux as a core.

Coreless Induction Furnace
An electric induction furnace for melting or holding molten metals that does not utilize a steel core to direct the magnetic field which stirs the melt.

Coring
(1) A condition of variable composition between the center and surface of a unit of microstructure (such as a dendrite, grain, carbide particle); results from nonequilibrium solidification, which occurs over a range of temperature. (2) A central cavity at the butt end of a rod extrusion, sometimes called extrusion pipe. (3) A variation in composition from center to edge of individual grains of an alloy solidifying as a solid solution. It is most pronounced where there is a large difference between the liquidus and the solidus and arises during casting because the first material to solidify is relatively rich in one element and the remaining molten material becomes progressively richer in the second element. The change in composition may be so extreme that a nonequilibrium phase precipitates in the latter stages of solidification. See Phase, Lever Rule and Solidification.

Coring (Plastics)
In plastic part making, the removal of excess material from the cross section of a molded part to attain a more uniform wall thickness.

Corner Angle
On face milling cutters, the angle between an angular cutting edge of a cutter tooth and the axis of the cutter, measured by rotation into an axial plane. See face mill.

Corner Joint
A joint between two members located approximately at right angles to each other in the form of an “L.” Usually between 30° and 135°.

Corner-Flange Weld
A flange weld with only one member flanged at the location of welding.

Corona (Resistance Welding)
The area sometimes surrounding the nugget of a spot weld at the faying surfaces which provides a degree of solid-state welding.

Correction
In the case of a testing machine, the difference obtained by subtracting the indicated load from the correct value of the applied load.

Corrodikote Test
An accelerated corrosion test for electrodeposits.

Corrosion
Any process by which a metal reacts chemically or electrochemically with another element in the surrounding environment. It is usually implicit that the consequences will be damaging as opposed to processes such as anodizing. Damage includes loss of bulk section, pitting, rusting, and scaling. See also Electrochemistry and Corrosion Resistance.

Corrosion Effect
A change in any part of the corrosion system caused by corrosion.

Corrosion Embrittlement
Deeply penetrating corrosion damage, essentially cracking, often along grain boundaries. The damage is usually not obvious to a visual inspection but causes a major reduction in load carrying capacity not merely a reduction in toughness. See also hydrogen damage.

Corrosion Fatigue
A cracking mechanism in which corrosion and fatigue act concurrently to reduce significantly the total life that would be expected if fatigue loading and a corrosive environment had acted alone or consecutively. Purists sometimes argue that any fatigue, other than in vacuum, is corrosion fatigue. A more practical approach is to differentiate on the basis of the major difference in life seen in a clean and dry environment compared with that in a moist and contaminated one.

Corrosion Fatigue Strength
The maximum repeated stress that can be endured by a metal without failure under definite conditions of corrosion and fatigue and for a specific number of stress cycles and a specified period of time.

Corrosion Inhibitor
See inhibitor.

Corrosion Potential (Ecorr)
The electrical potential of a corroding surface in an electrolyte, relative to a reference electrode. Also called rest potential, open-circuit potential, or freely corroding potential.

Corrosion Product
Substance formed as a result of corrosion.

Corrosion Protection
Modification of a corrosion system so that corrosion damage is mitigated.

Corrosion Rate
Corrosion effect on a metal per unit of time. The type of corrosion rate used depends on the technical system and on the type
of corrosion effect. Thus, corrosion rate may be expressed as an increase and corrosion depth per unit of time (penetration rate, for example, mil/year) or the mass of metal turned into corrosion products per unit area of surface per unit of time (weight loss, for example, g/m²/year). The corrosion effect may vary with time and may not be the same at all points of the corroding surface. Therefore, reports of corrosion rates should be accompanied by information on the type, time dependency, and location of the corrosion effect.

**Corrosion Resistance**

The ability of a metal to avoid unacceptable reactions with its environment. For metals, this could be pitting or rusting; for organic materials, it could be crazing. Generalizing, metals can be divided into three categories. Some metals such as gold and platinum have inherent resistance, that is, they do not react to any significant extent with the atmosphere and many other environments. Other metals such as aluminum or titanium react very rapidly when exposed to the atmosphere but the oxide film is thin, tightly bonded to the metal and forms an impervious barrier to further attack. This is often termed Acquired Resistance. Finally, metals such as iron and steel in moist environments form a bulky, loosely adherent and porous oxide layer. This does not significantly slow the rate of attack and it may even detach, exposing bare metal for further attack. See also stainless steel.

**Corrosion System**

System consisting of one or more metals and all parts of the environment that influence corrosion.

**Corrosion–Erosion**

A combination of corrosion and erosion. There are considerable similarities with impingement attack and some authorities recognize only one mechanism. Where the two are differentiated, and this may not be easy in some cases, impingement is regarded as having a major electrochemical component arising from the potential difference between uncorroded areas and bare metal exposed by erosion. The term corrosion–erosion would then be confined to cases where the erosion merely serves to remove the products of corrosion which, if undisturbed, could impede further attacks. See also Electrochemistry and Cavitation. See also erosion–corrosion.

**Corrosion-Resistant Alloys**

There are now several corrosion-resistant alloys available that are capable of meeting most difficult design requirements.

**Cast Alloys**

In general, these are the cast counterparts to 3XX and 4XX wrought stainless steels and, thus, are also referred to as cast stainless steels. Designations of the Alloy Casting Institute of the Steel Founders Society of America and the wrought designations to which they roughly correspond (compositions are not identical) include CA-15 (410), CA-40 (420), CB-30 (431), CC-50 (446), CF-30 (312), CF-3 (304L), CF-3M (316L), CF-8 (304), CF-8C (347), CF-8M (316), CF-12M (316), CF-16F (303), CF-20 (302), CG-8M (317), CH-20 (309), and CK-20 (310). There are also other alloys that do not correspond to wrought grades. The cast alloys corresponding to 3XX wrought grades have chromium contents in the range of 17%–30% and nickel contents in the range of 8%–22%. Silicon content is usually 2.00% maximum (1.50 for CE-8M), manganese 1.50% maximum, and carbon 0.08%–0.30% maximum, depending on the alloy. Other common alloying elements include copper and molybdenum. Those corresponding to 4XX grades may contain as much chromium but much less nickel; 1%–5%, depending on the alloy. Manganese and silicon contents are also generally less and carbon may be 0.15%–0.50%, depending on the alloy. All of the alloys are Fe–Cr–Ni alloys and the widest used are CF-8 and CF-8M, which limit carbon content to 0.08%. CN-7M and CN-7MS contain more nickel than chromium and, thus, are referred to as Fe–Cr–Ni alloys.

The alloys are noted primarily for their outstanding corrosion resistance in aqueous solutions and hot gaseous and oxidizing environments. Oxidation resistance stems largely from the chromium. Nickel improves toughness and corrosion resistance in neutral chloride solutions and weak oxidizing acids. Molybdenum enhances resistance to pitting in chloride solutions. Copper increases strength, and permits precipitation hardening to still greater strength. After a 482°C age, for example, the room-temperature tensile properties of CB-7Cu are 1290 MPa ultimate strength, 1100 MPa yield strength, 10% elongation, and 196, 500 MPa elastic modulus. Higher aging temperatures, to 621°C, decrease strength somewhat but markedly increase impact strength. The alloys are widely used for pumps, impellers, housings, and valve bodies in the power-transmission, marine, and petroleum industries, and for chemical, food, pulp and paper, beverage, brewing, and mining equipment.

**Corrosive Flux**

A flux with a residue that chemically attacks the base metal. It may be composed of inorganic salts and acids, organic salts and acids, or activated rosins or resins.

**Corrosive Wear**

Wear in which chemical or electrochemical reaction with the environment is significant. See also oxidative wear.

**Corrosivity**

Tendency of an environment to cause corrosion in a given corrosion system.

**Corrugating**

The forming of sheet metal into a series of straight, parallel alternate ridges and grooves with a rolling mill equipped with matched roller dies or a press brake equipped with a specially shaped punch and die.

**Corundum**

Corundum is a very hard crystalline mineral used chiefly as an abrasive, especially for grinding and polishing optical glass. It is in the alpha, or hexagonal, crystal form, usually containing some lime and other impurities. The physical properties are theoretically the same as for synthetic alpha Al2O3, but they are not uniform. The melting point and the hardness are generally lower because of impurities, and the crystal structure also varies.
Pure corundum is transparent and colorless, but most specimens contain some transition elements substituting for aluminum, resulting in the presence of color. Substitution of chromium results in a deep red color; such red corundum is known as ruby. The term sapphire is used in both a restricted sense for the “cornflower blue” variety containing iron and titanium, and in a general sense for gem-quality corundums of any color other than red.

Corundum is synthesized by a variety of techniques for use as synthetic gems of a variety of colors and as a laser source (ruby). The most important technique is the Verneuil flame-fusion method, but others include the flux-fusion and Czochralski “crystal-pulling” techniques. Native alumina occurring as rhombohedral crystals and also in masses and variously colored grains. Corundum and its artificial counterparts are abrasives especially suited to the grinding of metals.

Cosmetic Pass

A weld pass made primarily for the purpose of enhancing appearance.

Cosworth Process

A process for producing high-quality precision castings. Quality is assured by extreme efforts to avoid entrainment of oxide or other contaminants, in particular, by the use of extended periods of holding the molten metal followed by pumped, up-hill feeding. Precision is achieved by the use of molds of zircon sand having a low expansion coefficient.

Cottoning

The formation of web-like filaments of adhesive between the applicator and substrate surface.

Cottrell Process

Removal of solid particulates from gases with electrostatic precipitation.

Coulomb

The SI unit of quantity of electricity, the electrical charge transported by 1 A flowing for 1 s.

Coulomb Friction

A term used to indicate that the frictional force is proportional to the normal load.

Coulometer

An electrolytic cell arranged to measure the quantity of electricity by the chemical action produced in accordance with Faraday’s law.

Coulometry

In materials characterization, an electrochemical technique in which the total number of coulombs consumed in electrolysis is used to determine the amount of substance electrolyzed.

Coumarone

A colorless, oily liquid of composition C_8H_6O, used chiefly in making synthetic resins. It has a specific gravity of 1.096, is insoluble in water, and is easily oxidized. It can be reacted with butadiene to form an indene–butadiene rubber of superior properties. All of the cumenes are variants of benzene.

The indene resins are classified with the coumarone resins, but they are lighter in color and are used in varnishes. The coumarone resins are made by the action of sulfuric or phosphoric acid on coumarone, are very soluble in organic solvents and are used in lacquers, waterproofing compounds, molding, and adhesives.

Count

For fabric used in composites fabrication, the number of warp and filling yarns per inch and woven cloth. For yarn, size based on relation of length and weight.

Counterblock

A jog in the mating surfaces of dies to prevent lateral die shifting from side thrusts developed in forging irregularly shaped pieces.

Counterblow Equipment

Forging equipment with two opposed rams that are activated simultaneously to strike repeated blows on the workpiece placed midway between them.

Counterblow Forging Equipment

A category of forging equipment in which two opposed rams are activated simultaneously, striking repeated blows on the workpiece at a midway point. Action is vertical or horizontal.

Counterblow Hammer

A forging hammer in which both the ram and the anvil are driven simultaneously toward each other by air or steam pistons.

Counterboring

Removal of material to enlarge a hole for part of its depth with a rotary, pilot guided, end cutting tool having two or more cutting lips and usually having straight or helical flutes for the passage of chips and the admission of a cutting fluid.

Counterelectrode

In emission spectroscopy, the electrode that is used opposite to the self-electrode or supporting electrode and that is not composed of the sample to be analyzed. In voltammetry, the current between the working electrode and counterelectrodes is measured. See also self-electrode, supporting electrode, and auxiliary electrode.

Counterformal Surfaces

Surfaces whose centers of curvature are on the opposite sides of the interface, as in rolling-element bearings or gear teeth. In wear testing, this term is sometimes used to indicate that the test specimen
Countersinking surfaces are not conformal (for example, with a sphere-on-flat or flat block-on-rotating ring configuration). In such cases, the nominal contact area of at least one of the test piece surfaces increases as the amount of wear increases. Contrast with conformal surfaces.

Countersinking Beveling or tapering the work material around the periphery of a hole creating a concentric surface at an angle less than 90° with the centerline of the hole for the purpose of chamfering holes or recessing screw and rivet heads.

Couple The ability of dissimilar metals in electrical contact to produce electrical currents. Similar effects can occur in a single component because of variations, from point-to-point, and the composition of the material or of the environment. See Thermoelectric Effects and galvanic corrosion.

Coupling (1) The degree of mutual interaction between two or more elements resulting from mechanical, acoustical, or electrical linkage. (2) A device or mechanism joining two components or structures, usually for some specific function such as transmitting a fluid, traction or power or such purpose.

Coupon A piece of material from which a test specimen is to be prepared—often an extra piece (as on a casting or forging) or a separate piece made from test purposes (such as a test weldment).

Covalent Bond A bond in which two atoms share a pair of electrons. Contrast with ionic bond. See Interatomic bonding.

Cover Core (1) In casting, a core set in place during the ramming of a mold to cover and complete a cavity partly formed by the withdrawal of a loose part of the pattern. Also used to form part or all of the cope surface of the mold cavity. (2) A core placed over another core to create a flat parting line.

Cover Half The stationary half of a die-casting die.

Cover Pass The final layer of a multilayer well. The term often implies a deposit having a good appearance.

Cover Plate (Welding Eye Protection) A removable pane of colorless glass, plastic-coated glass, or plastic that covers the filter plate and protects it from weld splatter, pitting, or scratching when used in a helmet, hood, or goggles.

Covered Electrode A composite filler metal electrode consisting of a core of a bare electrode or metal cored electrode to which a covering sufficient to provide a slag layer on the weld metal has been applied. The covering may contain materials providing such functions as shielding from the atmosphere, deoxidation, and arc stabilization and can serve as a source of metallic additions to the weld. See electrode welding.

Covering Power (1) The ability of a solution to give satisfactory plating at very low current densities, a condition that exists in recesses and pits. This term suggests an ability to cover, but not necessarily to build up, a uniform coating, whereas throwing power suggests the ability to obtain a coating of uniform thickness on an irregularly shaped object. (2) The degree to which a porcelain enamel coating obscures the underlying surface. (3) The ability of a glaze to uniformly and completely cover the surface of the fired ceramic ware.

Crack (1) A fracture type discontinuity characterized by a sharp tip and high ratio of length and width to opening displacement. (2) A line of fracture without complete separation. (3) A planar defect that has developed in an area that was substantially defect-free. There is often an implication of limited ductility and “Crack” as opposed to “break” tends to be favored where the component has not parted completely. See also brake, rupture, and fracture.

Crack Arrest Temperature The temperature at which a running brittle fracture in steel will cease to propagate. The term may be used in connection with some particular laboratory test such as the Robertson Test. More generally the term refers to the lowest service temperature of a steel component at which a brittle fracture will not propagate further.

Crack Arrestor Any feature, intended or otherwise, that stops a crack from propagating further. Such features may be on a microscopic scale, for example, nonmetallic inclusions, or on a macro scale, for example, reinforcement plates, ductile materials are even holes placed across the path of an advancing crack.

Crack Branching The separation of a material into two or more segments.

Crack Extension (Δο) An increase in crack size. See also crack length, effective crack size, original crack size, and physical crack size.

Crack Growth Rate of propagation of a crack through a material due to a static or dynamic applied load.
Crack Initiator
Any feature, such as a crack, section change or inclusion, which has a local stress raising effect and hence assist the initiation of cracking by any mechanism.

Crack Length (Depth) (α)
In fatigue and stress-corrosion cracking, the physical crack size used to determine the crack growth rate and the stress-intensity factor. For a compact-type specimen, crack length is measured from the line connecting the bearing points of load application. For a center-crack tension specimen, crack length is measured from the perpendicular bisector of the central crack. See also crack size.

Crack Mouth Opening Displacement (CMOD)
See crack opening displacement.

Crack Opening Displacement (COD)
On a \( K_{ic} \) specimen, the opening displacement of the notch surfaces at the notch and in the direction perpendicular to the plane of the notch and the crack. The displacement at the tip is called the crack tip opening displacement (CTOD), at the mouth, it is called the crack mouth opening displacement (CMOD). See also stress-intensity factor for definition of \( K_{ic} \). See fracture toughness and fracture mechanics.

Crack Plane Orientation
An identification of the plane and direction of a fracture in relation to product geometry. This identification is designated by a hyphenated code, the first letter(s) representing the direction normal to the crack plane and the second letter(s) designated the expected direction of crack propagation.

Crack Size (α)
A lineal measure of a principal planar dimension of a crack. This measure is commonly used in the calculation of quantities descriptive of the stress and displacement fields. In practice, the value of crack size is obtained from procedures for measurement of physical crack size, original crack size, or effective crack size, as appropriate to the situation under consideration. See also crack length (depth).

Crack Tip Opening Displacement (CTOD)
See crack opening displacement.

Cracked Gas
A generic term for a gas mixture obtained by thermal decomposition, with or without catalysis, of a gaseous compound. Examples: cracked ammonia (\( \text{NH}_3 \)) is a mixture of nitrogen and hydrogen, and cracked natural gas hydrocarbons such as methane (\( \text{CH}_4 \)) are a mixture of carbon and hydrogen. Cracked ammonia is also known as disassociated ammonia.

Crack-Extension Force (G)
The elastic energy per unit of new separation area that would be made available at the front of an ideal crack in an elastic solid during a virtual increment of forward crack extension. This definition is useful for either static cracks or running cracks. From past usage, crack extension force is commonly associated with linear-elastic methods of analysis. See also \( J \)-integral.

Crack-Extension Resistance (\( K_G \))
A measure of the resistance of a material to crack extension expressed in terms of the stress-intensity factor, the crack-extension force, or values of \( J \) derived from the \( J \)-integral concept.

Cracking
In lubrication technology, that process of converting unwanted long-chain hydrocarbons to shorter molecules by thermal or catalytic action. See fracture toughness and fracture mechanics.

Crackled
Either a craze cracked surface or a severely wrinkled paint coating.

Crack-Tip Plane Strain
A stress–strain field near a crack tip that approaches plane strain to the degree required by empirical criterion.

Crank
Forging shape generally in the form of a “U” with projections at more or less right angles to the upper terminals. Crank shapes are designated by the number of throws (for example, two-throw crank).

Crank Press
A mechanical press who slides are actuated by a crankshaft.

Crankpin Bearing
See big-end bearing.

Crater
In arc welding, a depression or hole at the termination of a weld bead or in the molten weld pool resulting from local shrinkage during solidification.

Crater Crack
A crack in the crater of a weld bead.

Crater Fill Time
The time interval following weld time but prior to meltback time during which arc voltage or current reaches a preset value greater or less than welding values. Weld travel may or may not stop at this point.

Crater Fill Voltage
The arc voltage value during crater fill time.
Crater Wear
The wear that occurs on the rake face of a cutting tool due to contact with the material in the chip that is sliding along that face.

Cratering
Depressions on coated plastic surfaces caused by excess lubricant. Cratering results when paint is too thin and later ruptures, leaving pinholes and other voids. Use of less thinner in the coating can reduce or eliminate cratering, as can less lubricant on the part.

Craze Cracking
Irregular surface cracking of a metal associated with thermal cycling. This term is used more in the United Kingdom than in the United States, where the term checking is used instead.

Crazing
Multiple intersecting surface cracks, usually shallow, arising from various causes but particularly thermal shock.

Crazing (Ceramics)
The cracking which occurs in fired glazes or other ceramic coatings due to critical tensile stresses.

Crazing (Plastics)
Region of ultrafine cracks, which may extend in a network on or under the surface of a resin or plastic material. May appear as a white band. Often found in a filament-wound pressure vessel or bottle. In many plastics, craze growth precedes crack growth because crazes are load bearing.

Creel
In composites fabrication, a spool, along with its supporting structure, that holds the required number of roving balls or supply packages in a desired position for unwinding for the next processing step, that is, weaving, braiding, or filament winding.

Creep
Time-dependent strain occurring under stress. The creep strain occurring at a diminishing rate is called primary creep; that occurring at a minimum and almost constant rate, secondary creep; and that occurring at an accelerating rate, tertiary creep.

Creep Ductility
The elongation at failure of a component failing by creep. See Creep.

Creep Limit
(1) The maximum stress that will cause less than a specified quantity of creep in a given time. (2) The maximum nominal stress under which the creep strain rate decreases continuously with time under constant load and at constant temperature. (3) This term has a range of interpretations and some potential for confusion. The most basic definition is the maximum stress that can be allowed without causing unacceptable damage. Damage, in the context of Creep Limit, may be defined as failure or as some level of strain, in which cases it is necessary also to specify the service temperature and life required. Damage may also be specified as a rate of deformation in which case only the temperature need be specified. See Creep. Sometimes used synonymously with creep strength.

Creep Permanent
Progressive deformation, occurring over a period of time, at loads below the yield stress. Most metals at ambient temperature will carry a stress which is less than the yield stress for, effectively, an indefinite period; when the stress is removed the component will revert to its original dimensions. However, if the temperature of the component is raised above a critical level any significant stress will, over a period of time, cause progressive deformation that remains after the stress has been removed. If the load is maintained for a sufficient period internal voids and cracks will develop and ultimately the component will fail. A typical, perhaps idealized, creep test has the characteristics three stage, strain to time relationship, termed a Creep Curve. In the usually brief primary, or transient stage, deformation is rapid as it is dominated by mechanisms such as dislocation movement and grain boundary slide, i.e., the two neighboring grain faces rotating across each other. This high initial rate then slows as work hardening plays an increasing role. In the longer secondary, or steady-state stage, deformation continues at a lower uniform rate arising from the balance between work hardening and thermal softening. Toward the end of this stage, damage, in the form of grain boundary voids, starts to become visible under the microscope. In the final tertiary or runaway stage, deformation accelerates as voids join up, gross grain boundary cracks develop and the specimen necks prior to failure. This conventional view of creep being accompanied by major deformation is often confirmed by service experience but it is not universal; some metals fail by creep with negligible reduction in area and only a fraction of one percent elongation. Such behavior may be termed Creep Brittle. Creep failure is often termed Creep Rupture but this does not imply any special characteristic of failure; it could equally be termed “creep fracture” or even “creep breakage” although these phrases tend to sound inappropriate to most metallurgists. The temperature at which creep commences is broadly related to the melting point of the metal, it often being suggested that creep of pure metals is significant above half their absolute temperature melting point. For example, lead will creep, at least over decades or centuries, at normal ambient temperature and mild steel will creep at a significant rate above about 400°C. The rate of damage, above the critical temperature, rises with increasing stress and temperature. Creep deformation characteristics, often termed the Stress Rupture Properties, are determined by testing specimens of the material over ranges of stresses and temperatures to establish the time to reach a specified percentage creep strain or to fail. Unfortunately, the results obtained from testing identical specimens under identical conditions are rarely the same. Hence, the results of numerous tests plotted on a graph do not form a neat smooth curve but tend to be scattered over a fairly wide band. This gives rise to such terms as Creep Scatter Band while designs may be made on the basis of Lower Scatter Band (i.e., the lower line enclosing all test results) or 90% Scatter Band (the line enclosing 90% of all results) or Average Stress Rupture properties. See also Stress Rupture and Larsen Miller Parameter for examples of creep data presentation.

Creep Rate
The slope of the creep–time curve at a given time. Deflection with time under a given static load.
Creep Recovery

The time-dependent decrease in strain in a solid, following the removal of force.

Creep Relaxation

The reduction of imposed load as a result of deformation by creep, i.e., by the conversion of elastic strain to plastic strain by a creep mechanism. The phenomenon occurs in assemblies where the loading mechanism is rigid and does not move sufficiently to maintain the stress. One example is high temperature bolts which are tightened to induce a large amount of tensile elastic extension while the flange through which they pass, being of much larger cross section, experiences negligible elastic compression. If the bold creep, assuming it does not fail, the joint closure force will progressively fall. This contrasts with the case of, for example, a boiler tube which experiences a constant internal pressure. If the tube distends the internal pressure remains the same but is carried by a reducing wall thickness so the stress rises. See also preload and displacement control.

Creep Rupture

Failure by Creep. See also Larsen Miller Parameter.

Creep Strain

The time-dependent total strain (extension plus initial gauge length) produced by applied stress during a creep test.

Creep Strength

(1) The stress that will cause a given creep strain in a creep test at a given time in a specified constant environment. (2) Generally, the strength of the material in its creep range. More specifically, the same as creep limit.

Creep Stress

The constant load divided by the original cross-sectional area of the specimen.

Creep Test

A method of determining the extension of metals under a given load at a given temperature. The determination usually involves the plotting of time–elongation curves under constant load; a single test may extend over many months. The results are often expressed as the elongation (in millimeters or inches) per hour on a given gauge length (e.g., 25 mm or 1 in.).

Creep-Feed Grinding

See grinding.

Creep-Rupture Embrittlement

Embrittlement under creep conditions of, for example, aluminum alloys and steels that results in abnormally low rupture ductility. In aluminum alloys, iron and amounts above the solubility limit is known to cause such embrittlement; in steels, the phenomenon is related to the amount of impurities (for example, phosphorus, sulfur, copper, arsenic, antimony, and tin) present. In either case, failure occurs by intergranular cracking of the embrittled material.

Creep-Rupture Strength

The stress that causes fracture in a creep test at a given time, in a specified constant environment. This is sometimes referred to as the stress-rupture strength. In glass technology, this is termed the static fatigue strength.

Creep-Rupture Test

A test in which progressive specimen deformation and the time for rupture are both measured. In general, deformation is much greater than that developed during a creep test. Also known as stress-rupture test.

Creosote

Also called dead oil and pitch oil. A yellowish, poisonous oily liquid obtained from the distillation of coal tar. It has the odor of carbolic acid. The crude creosote oil is used as a wood preservative and as a harsh disinfectant, but its use in these applications is expected to decrease because it has been recently classified as a possible carcinogen. Other applications include use as a fluxing oil for coal-tar pitch and bitumen, production of carbon black, and use in sprays for dormant fruit plants. Creosote is also obtained in the distillation of pinewood tar and is then a yellowish liquid with a smoky odor, a mixture of phenols and derivatives.

Crescent Crack

Damage having the appearance of a crescent, produced in a glass surface by the frictive translation of a hard, blunt object across the glass surface. The crescent shape is concave toward the direction of translation on the damage surface.

Crevice Corrosion

(1) Localized corrosion of a metal surface at, or immediately adjacent to, an area that is shielded from full exposure to the environment because of close proximity between the metal and the surface of another material. (2) Corrosion, occurring within a narrow gap which is severe compared with that on a plain surface exposed to the same environment. The mechanism usually involves the development of variations in environment composition from point to point leading to electrochemical corrosion. The variation may be a concentration effect, for example, of dissolved salts, or it may be a depletion effect, for example, a reduction in oxygen within the crevice.

Crimping

(1) The formation of circumferential corrugations around one side of a tube to induce a bend, more usually termed wrinkle bending. (2) The deliberate kinking of a folded lap joint to lock the joint. (3) The introduction of angular ridges in a sheet surface to improve rigidity. (4) The introduction of multiple transverse indentations in bar to improve grip or to increase its length. See also corrugating.
Critical Anodic Current Density

The maximum anodic current density observed in the active region for a metal or alloy electrode that exhibits active–passive behavior in an environment.

Critical Cooling Rate

The minimum rate of continuous cooling for preventing undesirable transformations. For steel, unless otherwise specified, it is the slowest rate at which austenite can be cooled from above critical temperature to prevent its transformation above the martensite start temperature. See steels.

Critical Current Density

In an electrolytic process, a current density at which an abrupt change occurs in an operating variable or in the nature of an electrodeposited or electrode film.

Critical Curve

In a binary or higher order phase diagram, a line along which the phases of a heterogeneous equilibrium become identical.

Critical Damping

In dynamic mechanical measurement of plastics, that damping required for the borderline condition between oscillatory and non-oscillatory behavior.

Critical Diameter

Diameter of a steel bar that can be fully hardened with 50% martensite at its center.

Critical Dimension

A dimension on a part that must be held within the specified tolerance for the part to function in its application. A noncritical tolerance may be for cost or weight savings or for manufacturing convenience, but is not essential for the products.

Critical Flaw Size

The size of a flaw (defect) in a structure that will cause failure at a particular stress level.

Critical Frequency/Speed

The vibration frequency or rotational speed which coincides with a natural resonance frequency of the component. At this critical condition, perturbations which would normally be innocuous can rapidly increase in severity leading to damage or failure. Examples include gross instability of shafts, collapse of bridges, and rapid fatigue failure of turbine blades. Design and operating practices therefore aim to avoid completely, or to pass rapidly through, the critical stage.

Critical Humidity

The relative humidity above which the atmospheric corrosion rate of some metals increases sharply.

Critical Illumination

In metallography, the formation of an image of the light source in the object field.

Critical Length

In composites fabrication, the minimum fiber length required for shear loading to its ultimate strength by the matrix.

Critical Longitudinal Stress

The longitudinal stress necessary to cause internal slippage and separation of a spun yarn and a fiber-reinforced plastic. The stress necessary to overcome the interfiber friction developed as a result of twist.

Critical Mass

The minimum amount of fissile material required to sustain nuclear fission.

Critical Micelle Concentration

The concentration of a micelle at which the rate of increase of electrical conductance with increase in concentration levels off or proceeds at a much slower rate. See also micelle.

Critical Pitting Potential ($E_{cp}$, $E_p$, $E_{pp}$)

The lowest value of oxidizing potential at which pits nucleate and grow. It is dependent on the test method used.

Critical Point

(1) The temperature or pressure at which a change in crystal structure, phase, or physical properties occurs. Also termed transformation temperature. (2) In an equilibrium diagram, that combination of composition, temperature, and pressure at which the phases of an inhomogeneous system are in equilibrium.

Critical Pressure

That pressure above which the liquid and vapor states are no longer distinguishable.

Critical Rake Angle

The rake angle in which the action of a V-point tool changes from cutting to plowing. See also rake.

Critical Range

In steels it is temperature range between the upper critical and lower critical temperatures. See steel.

Critical Shear Stress

The shear stress required to cause slip in a designated slip direction on a given slip plane. It is called the critical resolved shear stress if the shear stress is induced by tensile or compressive forces acting on the crystal.
**Critical Strain**
The minimum amount of plastic strain, i.e., deformation, required to induce recrystallization. Some metals, such as iron, can develop a completely new grain structure by heating them through a phase transformation. However, in the absence of such a transformation, a metal cannot form a new structure by heating below the melting point, unless it has been plastically deformed by more than a critical amount, the critical strain, typically a few percent. This process of developing a new grain structure with associated reduction in the hardness is termed annealing and, generalizing, the more severe the deformation the finer the subsequent grain size. Consequently, components deformed only slightly more than the critical amount can form structures with exceptionally large grain sizes when annealed. This effect is termed *critical strain grain growth*. (1) In mechanical testing, the strain at the yield point. (2) The strain just sufficient to cause recrystallization. Recrystallization takes place from only a few nuclei, which produces a recrystallized structure consisting of very large grains.

**Critical Strain Energy Release Rate**
The toughness as measured by the energy input required for a crack to continue propagating.

**Critical Stress Intensity Factor**
See *stress-intensity factor* and *fracture toughness*.

**Critical Surface**
In a ternary or higher order *phase diagram*, the area upon which the phases in equilibrium become identical.

**Critical Temperature**
That temperature above which the vapor phase cannot be condensed to liquid by an increase in pressure. Synonymous with *critical point* if pressure is constant.

**Critical Temperature Range**
Synonymous with transformation ranges, which is the preferred term.

**Criticality of a Nuclear Reactor**
The state at which the fission reaction is exactly in balance with the number of neutrons released being just sufficient to maintain the chain reaction.

**Croning Process**
In casting, a shell molding process that uses a phenolic resin binder. Sometimes referred to as C process or *Chronizing*.

**Cropping**
The practice of cutting off and discarding the ends of bars, ingots, etc., as these are the site of defects.

**Cross Breaks**
Same as *coil breaks*.

**Cross Direction**
See *transverse direction*.

**Cross Forging**
Preliminary working of forging stock in flat dies to develop mechanical properties, particularly in the center portions of heavy sections.

**Cross Laminate**
In composites fabrication, a laminate in which some of the layers of material are oriented approximately at right angles to the remaining layers with respect to the grain, or strongest direction in tension. A bidirectional laminate. See also *parallel laminate*.

**Cross Link**
Intermolecular bonds produced between long-chain molecules in a material to increase molecular size and weight by chemical or electron bombardment, resulting in a change in physical properties in the material, usually improved properties.

**Cross Linking**
With thermosetting and certain thermoplastic polymers, the setting up of chemical links between the molecular chains. When extensive, as in most thermosetting resins, cross-linking makes an infusible supermolecule of all the chains. In rubbers, the cross-linking is just enough to join all molecules into a network.

**Cross Rolling**
Rolling of metal or sheet or plate so that the direction of rolling is about 90° from the direction of a previous rolling.

**Cross Slip**
The extension of a dislocation from one slip plane to an adjacent plane.

**Cross-Country Mill**
A rolling mill in which the mill stands are so arranged that their tables are parallel with a transfer (or crossover) table connecting them. Such a mill is used for rolling structural shapes, rails, and any special form of bar stock not rolled in the ordinary bar mill.
Crossed Joint
See bridging.

Cross-Linking, Degree of
The fraction of cross-linked polymeric units in the entire system.

Cross-Ply Laminate
A laminate with plies usually oriented at 0° and 90° only.

Cross-Roll Straightener
A machine having paired rolls of special design for straightening round bars or tubes, the pass being made with the work parallel to the axes of the rolls.

Cross Section
(1) Of a bar, extrusion, etc., it is the shape and dimensions of the face formed by a full transverse cut. (2) In the context of nuclear interactions it is a function of the probability that a particle entering the material in question will meet a particle with which to react. The SI unit is the barn.

Cross-Wire Weld
A weld made at the junction between crossed wires or bars.

Crosswise Direction
In testing of plastics, crosswise refers to the cutting of specimens and to the application of load. For rods and tubes, crosswise is any direction perpendicular to the long axis. For other shapes or materials that are stronger in one direction than in another, crosswise is the direction that is weaker. For materials that are equally strong in both directions, crosswise is an arbitrarily designated direction at right angles to the lengthwise direction.

Crowfoot Satin
In this type of composite fabric weave, there is a three-by-one interlacing; that is, a filling thread floats over three warp threads and then under one. This type of fabric looks different on one side than the other. Fabrics with this weave are more pliable than either the plain or basket weave and, consequently, are easier to form around curves.

Crown
(1) The upper part (head) of a forming press frame. On hydraulic presses, the crown usually contains the cylinder; on mechanical presses, the crown contains the drive mechanism. See also hydraulic press and mechanical press. (2) A shape (crown) ground into a flat roll to ensure flatness of cold (and hot) rolled sheet and strip. (3) A contour on a sheet or roll where the thickness or diameter increases from edge to center.

Crucible
A vessel in which metal is melted.

Crucible Furnace
A melting or holding furnace in which the molten metal is contained in a pot-shaped (hemispherical) shell. Electric heaters or fuel-fired burners outside the shell generate the heat that passes through the shell (crucible) to the molten metal.

Crucible Steel
The term is sometimes still used to refer to steels made in small quantities and, possibly, claimed to have superior characteristics.

Cruciform
Having the geometry of a cross. A cruciform weld joint is formed when two bars or plates are welded in the same plane on either side of, and perpendicular to, another plate. A cruciform test is one in which such a joint is made, inspected and, usually, tested to destruction.

Crud
Originally an American term for solid particulate contamination in the boiler water of steam power plants. The term is now used for any solid suspension or deposition in any liquid.

Crush
(1) Buckling or breaking of a section of a casting mold due to incorrect register when the mold is closed. (2) An indentation in the surface of a casting due to displacement of sand when the mold was closed. (3) In a split-journal bearing, the amount by which a bearing half extends above the horizontal split of the bore before it is assembled. Also known as nip in the United Kingdom.

Crush Forming
Shaping a grinding wheel by forcing a rotating metal roll into its face so as to reproduce the desired contour.

Crushed Strip or Bead
In casting, an indentation in the parting line of a pattern plate that ensures that cope and drag will have good contact by producing a ridge of sand that crushes against the other surface of the mold or core.

Crushing
A process of comminuting large pieces of metal or ore into rough size fractions prior to grinding into powder. A typical machine for this operation is a jaw crusher.

Crushing Test
(1) A radial compressive test applied to tubing, sintered-metal bearings, or other similar products for determining radial crushing strength (maximum load in compression). (2) An axial compressive test for determining quality of tubing, such as soundness of weld and welded tubing.
Cryogenic Treatment

See cold treatment.

Cryogenics

Today’s limited acceptance and use of deep-cryogenic treatment at liquid N\textsubscript{2} temperature (−196°C) is usually attributed to a lack of understanding of the technology, as well as to the absence of generally acceptable practices for deploying it.

When the above two factors are resolved the “science” of deep cryogenics and its potential contributions will be shown. For example, a deep-cryogenic treatment at −196°C between quenching and tempering optimizes the mechanical properties of AISI T15 high-speed steel and dramatically improves its wear resistance, compared with standard heat treatments that do not incorporate a cryogenic step.

When the above is used, deep cryogenics does indeed become a science—results are predictable and the mechanical properties of the heat-treated parts are optimized. This is why it is believed that the use of the process during heat treating should now be standard rather than optional.

In future heat-treating guidelines and practices and procedures it is recommended that when using deep cryogenics as part of the heat treatment, the temperature of the subsequent temper be noted for the specific steel and the hardness vs. tempering temperature.

Cryolite

A mineral of composition Na\textsubscript{3}AlF\textsubscript{6}, found in commercial quantities in Greenland and used as a flux in the electrical production of aluminum, and the making of special glasses and porcelain, as a binder for abrasive wheels, and in insecticides. It acts as a powerful flux because of its solvent power on silicon, aluminum, and calcium oxides. In opal and milky classes, it forms a complex AlF\textsubscript{3} anion, retaining the alumina and preventing loss of the fluorine.

Cryopump

A type of vacuum pump that relies on the condensation of gas molecules and atoms on internal surfaces of the pump, which are maintained at extremely low temperatures.

Crystal

(1) A solid composed of atoms, ions, or molecules arranged in a pattern that is repetitive in three dimensions. (2) That form, or particle, or piece of a substance in which its atoms are distributed in one specific orderly geometrical array, called “lattice,” essentially throughout. Crystals exhibit characteristic optical and other properties and growth or cleavage surfaces, in characteristic directions. (3) “Crystal” is often interchangeably with grain. Unfortunately, there are no widely accepted rules to guide usage but, generalizing, “crystal” tends to be favored in the context of features on an atomic scale, for example crystal lattice, whereas “grain” tends to be favored for larger scale matters, for example grain size. Note however, “Crystalline” is used, when describing a fracture surface, to indicate a bright angular faceted appearance resulting from cleavage along specific crystallographic planes, characteristic of brittle fracture. See crystal structure.

Crystal Analysis

A method for determining crystal structure, for example, the size and shape of the unit cell and the location of all atoms within the unit cell.

Crystal Lattice

See crystal structure.

Crystal Orientation

See orientation.

Crystal Structure

The arrangement of atoms in crystals including virtually all solid metals. Atoms in crystals are arranged in simple, repeating, three-dimensional patterns rather than in the random jumble of amorphous, i.e., noncrystalline, materials. The basic unit of the pattern can be visualized as comprising atoms located at specific points on a simple geometric body, for example the points of the cube. This concept leads to terms such as “Body Centered Cubic” or “Face Centered Cubic” in which atoms lie on the points of the cube and also, respectively, at the center of the body or the center of each face. The basic block is repeated for very large distances, measured on an atomic scale, and the atoms can then be regarded as lying in layers or on atomic planes. The three-dimensional arrangement is termed a lattice. An individual crystal or grain has all of its atoms and atomic planes in continuous alignment. Neighboring crystals will have the same patterns but their planes will not be in alignment. The interfaces between grains are referred to as the crystal boundaries or grain boundaries. Also see ordering and dislocations.

Crystal System

One of seven groups into which all crystals may be divided; triclinic, monoclinic, orthorhombic, hexagonal, rhombohedral, tetragonal, and cubic.

Crystalline

(1) That form of a substance which is comprised predominantly of (one or more) crystals, as opposed to glassy or amorphous. (2) A bright, angular faceted fracture surface. See crystal.

Crystalline Fracture

A pattern of highly reflecting crystal facets on the fracture surface of a polycrystalline metal, resulting from cleavage fracture of many individual crystals. Contrast with fibrous fracture, and silky fracture; see also granular fracture.

Crystalline Plastic

A material having an internal structure in which the atoms are arranged in an orderly three-dimensional configuration. More accurately referred to as a semicrystalline plastic because only a portion of the molecules are in crystalline form.
Crystallinity (Plastics)

A regular arrangement of the atoms of a solid in space. In most polymers, including cellulose, this state is usually imperfectly achieved. The crystalline regions (ordered regions) are submicroscopic volumes in which there is some degree of regularity in the arrangement of the component molecules. In these regions there is sufficient geometric order to obtain definite x-ray diffraction patterns.

Crystallite

An imprecise term which may mean no more than a very small crystal. Alternatively, the term may refer to sub crystals within a grain or small crystals or parts of crystals which do not exhibit all of the characteristics of a crystal.

Crystallization

(1) The separation, usually from a liquid phase on cooling, of a solid crystalline phase. (2) The progressive process in which crystals are first nucleated (started) and then grown in size within a host medium which supplies their atoms. The host may be gas, liquid, or of another crystalline form.

Crystallographic Cleavage

The separation of a crystal along a plane of fixed orientation relative to the three-dimensional crystal structure within which the separation process occurs, with the separation process causing the newly formed surfaces to move away from one another in directions containing major components of motion perpendicular to the fixed plane.

Crystallography

The study of crystal structure.

Crystobalite

An allotropy of quartz. See quartz.

C-Stage

In processing of plastics, the final stage in the reaction of certain thermosetting resins in which the material is practically insoluble and infusible. Also called resite. The resin in a fully cured thermoset molding is in this stage. See also A-stage and B-stage.

CTE Mismatch

The difference in the coefficients of thermal expansion (CTEs) of two materials or components joined together, producing strains and stresses at the joining interfaces or in the attachment structures (solder joints, leads, and so on).

CTOD

See Cracking Opening Displacement.

CTS

(1) Compact tension specimen. See fracture toughness. (2) Controlled thermal severity test.

Cubic Texture

A texture found in wrought metals in the cubic system in which nearly all the crystal grains have a plane of the type (100) parallel or nearly parallel to the plane of working and a direction of the type (100) parallel or nearly parallel to the direction of elongation.

Cubic

Having three mutually perpendicular axes of equal length.

Cubic Boron Nitride (CBN)

An extremely hard ceramic material synthesized by high-pressure sintering of hexagonal boron nitride. CBN is used in the machining and grinding of ferrous material such as tool steels, cast irons, hard-facing alloys, and surface-hardened steels. See also superabrasives.

Cubic Close Packed

See close packed hexagonal.

Cubic Plane

A plane perpendicular to any one of the three crystallographic axes of the cubic (isometric) system; the Miller Indices are (100).

Cull

Plastic material in a transfer chamber after the mold has been filled. Unless there is a slight excess in the charge, the operator cannot be sure the cavity is filled. Charge is generally regulated to control thickness of the cull.

Cumulative Damage

The total amount of damage resulting from a number of damage mechanisms or from a number of exposures to a mechanism. The term is commonly used in the case of fatigue reflecting the variation and stress range or other variables that a component might experience. The basic concept in all cases is that each exposure consumes a fraction of the fatigue life and failure will occur when these fractions total unity.

Cumulative Erosion–Time Curve

A plot of cumulative erosion vs. cumulative exposure duration, usually obtained by periodic interruption of the erosion test and weighing of the specimen. This is the primary record of an erosion test used to derive other characteristics such as incubation period, maximum erosion rate, terminal erosion rate, and the erosion rate–time curve.

Cup

(1) A sheet metal part; the product of the first drawing operation. (2) Any cylindrical part or shell closed at one end.

Cupellation

Oxidation of molten lead containing gold and silver to produce lead oxide, thereby separating the precious metals from the base metal. The rate of oxidation is usually increased by an air jet.
Cupola

A vertical shaft, air blast furnace, lined with refractory, for remelting, in particular, cast iron. The charge of iron with metallurgical coke or charcoal as fuel and a flux are introduced at the top; the molten iron and slags are tapped at the bottom.

Cupping

(1) The first step in deep drawing. (2) Fracture of severely worked rods or wire where one end has the appearance of a cup and the other that of a cone.

Cupping Test

A mechanical test used to determine the ductility and stretching properties of sheet metal. It consists of measuring the maximum part depth that can be formed before fracture. The test is typically carried out by stretching the test piece clamped at its edges into a circular die using a punch with a hemispherical end. See also Erichsen test, Olson ductility test, and Swift cup test.

Cupronickel

Copper-based alloys containing significant amounts of nickel.

Cure

(1) To change the physical properties of a material (usually from a liquid to a solid) by chemical reaction or by the action of heat and catalysts, alone or in combination, with or without pressure. (2) To irreversibly change, usually at elevated temperatures, the properties of a thermosetting resin by chemical reaction, that is, by condensation, ring closure, or addition. Cure may be accomplished by the addition of curing (cross linking) agents, with or without heat and pressure.

Cure Cycle

The time/temperature/pressure cycle used to cure a thermosetting resin system or prepreg.

Cure Monitoring, Electrical

Use of electrical techniques to detect changes in the electrical properties and/or mobility of the resin molecules during cure. A measuring of resin cure.

Cure Stress

A residual internal stress produced during the curing cycle of a composite structure. Normally, these stresses originate when different components of a wet lay-up have different thermal coefficients of expansion. One Curie is the quantity of radionuclide in which the number of disintegrations in 1 s is $3.7 \times 10^9$.

Curie Point/Temperature

For a metal, it is the temperature below which is magnetic (more strictly ferromagnetic) and above which it is nonmagnetic (paramagnetic). For iron it is 770°C.

Current-Carrying Capacity

It is the temperature at which piezoelectric materials lose their electromechanical characteristics. See also ferromagnetism and paramagnetism.

Curing Agent

A catalytic or reactive agent that causes cross linking of a plastic. Also called a hardener.

Curing Temperature

The temperature to which an adhesive or an assembly is subjected to cure the adhesive. The temperature attained by the adhesive in the process of curing (adhesive curing temperature) may differ from the temperature of the atmosphere surrounding the assembly (assembly curing temperature). See also drying temperature and setting temperature.

Curing Time

In plastic part making, the time between the instant of cessation of relative movement between the moving parts of a mold and the instant that pressure is released. Also called molding time.

Curing Time (No Bake)

In foundry practice, the period of time needed before a sand mass reaches maximum hardness.

Curling

Rounding the edge of sheet metal into a closed or partly closed loop.

Current

The net transfer of electric charge per unit time. Also called electric current. See also current density.

Current Decay

In spot, seam, or projection welding, the controlled reduction of the welding current from its peak amplitude to a lower value to prevent excessively rapid cooling of the weld nugget.

Current Density

The current in amps, flowing to or from a unit area of the electrode surface.

Current Efficiency

(1) The ratio of the electrochemical equivalent current density for a specific reaction to the total applied current density. (2) The proportion of current used in a given process to accomplish a desired result; in electroplating, the proportion used in depositing or dissolving metal. See Faraday’s Law.

Current-Carrying Capacity

The maximum current that can be carried continuously, under specified conditions, by a conductor without causing objectionable degradation of electrical or mechanical properties.
Curtain Coating

A method of coating that may be employed with low-viscosity resins or solutions, suspensions, or emulsions of resins in which the substrate to be coated is passed through and perpendicular to a freely falling liquid curtain (or waterfall). The flow rate of the falling liquid and the linear speed of the substrate passing through the curtain are coordinated in accordance with the thickness of coating desired.

Curvature of Field

In metallography, a property of a lens that causes the image of a plane to be focused into a curved surface instead of a plane.

Cushion

Same as die cushion.

Cut

In lubricant technology, a product or fraction obtained by distillation within a specified temperature range.

Cut (Foundry Practice)

(1) To recondition molding sand by mixing on the floor with a shovel or blade-type machine. (2) To form the sprue cavity in a mold. (3) Defect in a casting resulting from erosion of the sand by metal flowing over the mold or cored surface. (4) Apart from obvious meanings it often implies the depth of cut at a single pass of the cutting tool.

Cut Edge

A mechanically sheared edge obtained by slitting, shearing, or blanking.

Cut Layers

With laminated plastics, a condition of the surface of machines or ground rods and tubes and of sanded sheets in which cut edges of the surface layer or lower laminations are revealed.

Cut-and-Carry Method

Stamping method wherein the part remains attached to the strip or is forced back into the strip to be fed through the succeeding stations of a progressive die.

Cutlery Steel

Originally approximately 1% carbon steel used for domestic cutlery and other blades but now usually 12% chromium, 0.3% carbon (martensitic stainless steel).

Cut-Off (Casting)

Removing a casting from the sprue by refractory wheel or saw, arc-air torch, or gas torch.

Cut-Off (Metal Forming)

A pair of blades positioned in dies or equipment (or a section of the die milled to produce the same effect as inserted blades) used to separate the forging from the bar after forging operations are completed. Used only when forgings are produced from relatively long bars instead of from individual, precut multiples or blanks. See also blank and multiple.

Cut-Off (Plastics)

The line where the two halves of a mold come together. Also called groove and pitch-off.

Cut-Off Wheel

A thin disk, coated or impregnated with abrasive, rotating at high speed and often water cooled, for cutting purposes. It can produce a narrow, clean-cut with minimal surface damage even in hard materials. Also variously termed cutting wheel, slitting wheel, elastic wheel, etc.

Cutting Alloys

Usually of complex Co–Cr–W–Fe–Si–C composition, used for lathes and planer tools for cutting hard metals. They form a class distinct from the cemented carbides, which are not true alloys; from the refractory hard metals, which are chemical compounds; and from the cobalt high-speed steels, which are high in iron and usually have less carbon. The hardness is inherent in the alloy and is not obtained by heat treatment, as with the tool steels. Cutting alloys are cast to shape and are usually marketed in the form of tool bits and shear blades. Complex alloys, however, may have heat-transition points at which the metal complexes change structure, limiting the range of use.

Since the development of balanced high-speed steels and cement-type cutting tools, these alloys with a high proportion of the scarcer cobalt have lost their importance as cutting alloys and, because of their high corrosion, heat, and wear resistance, are used chiefly for weld-facing rods and heat-corrosion applications. The first of the commercial cobalt cutting alloys was Stellite, of Haynes Stellite Co., in various composition grades and with trade names, such as J-metal and Star J-metal. Other similar alloys contain boron for added wear resistance. This type of alloy is now used in surgical alloys for surgical tools and dental plates since they are not attacked by body acids and set up no electromotive currents. To make them more workable for this purpose, they usually contain a higher content of cobalt, 60% or more, with a smaller amount of molybdenum instead of tungsten, and with less carbon and silicon.

Cutting Attachment

A device for converting an oxyfuel gas welding torch into an oxygen cutting torch.

Cutting Compound/Fluid/Paste

A substance applied at the cutting edge during machining. Where it is a stream of fluid its primary function is cooling but all of these substances act as a lubricant and limit adhesion to the tool edge. They also contribute to surface finish, tool life and precision.
Cutting Down
Removing roughness or irregularities of a metal surface by abrasive action.

Cutting Edge
The leading edge of a cutting tool (such as a lathe tool, drill or milling cutter) where a line of contact is made with the work during machining. See single-point tool.

Cutting Fluid
A fluid used in metal cutting to improve finish, tool life, or dimensional accuracy. On being flowed over the tool and work, the fluid reduces friction, the heat generated, and tool wear, and prevents galling. It conducts the heat away from the point of generation and also serves to wash the chips away.

Cutting Head
The part of a cutting machine or automatic cutting equipment in which a cutting torch or tip is incorporated.

Cutting Nozzle
See preferred term cutting tip.

Cutting Process
A process which brings about the severing or removal of metals. See also arc cutting and oxygen cutting.

Cutting Speed
The linear or peripheral speed of relative motion between the tool and workpiece in the principal direction of cutting.

Cutting Tip
That part of an oxygen cutting torch from which the gases issue.

Cutting Tools
Polycrystalline diamond (PCD) and polycrystalline cubic boron nitride (PCBN) inserts could be the best means of increasing productivity despite their high cost. In the past, PCD and PCBN cutting tools were difficult to cost-justify, unless they were essential for the machining job.

Today, improvements in quality and reliability make these tools, although still costly, competitive in many machining applications in the automotive, aerospace, and medical equipment industries. More rigid machines and tooling setups enable manufacturers to take full advantage of the potential for improved productivity offered by PCD and PCBN inserts. Also, having more cutting-tool options gives manufacturing engineers an opportunity for cost-effective productivity improvement in various machining applications.

PCBN
New, thicker PCBN solid inserts with larger grain size possess improved wear and impact resistance—the key to effective machining of materials like cast irons containing less than 10% ferrite content. Such performance improvement is especially important when machining alloy cast irons for automotive applications. Previously, manufacturers had to grind these castings.

In roughing operations on alloy cast irons, tools must withstand interrupted cuts due to surface cracks, sand inclusions, and other surface discontinuities inherent to the casting process. Good wear resistance comes into play in finishing operations, where parts containing 28%–30% chromium have a hardness between $R_c 68$ and $R_c 72$.

Solid PCBN inserts provide multiple cutting edges on two sides, reducing insert cost per part produced. PCBN inserts also come in full-face and tipped types. The full-face type has a complete PCBN top face sintered onto a carbide substrate, and provides multiple cutting edges on one side only. These inserts are less expensive than solid PCBN inserts. The tipped style contains a small PCBN segment brazed onto one corner of a carbide insert, providing either a single cutting edge or double cutting edges. Most PCBN inserts used today are tipped. Both full-face and tipped PCBN inserts come in industry-standard sizes and, like the solid insert, can be used in the insert pockets of standard tool-holders and milling cutters.

Inserts made of PCBN work best in hard-part machining applications. In practice, the low end for part hardness falls at about $R_c 45$. Machining softer parts using PCBN produces insert cratering.

In roughing operations, maximum depths of cut using solid-style PCBN inserts range from about 4.76 mm for white iron and other hard, high-chromium irons to about 6.4 mm for unalloyed, “clean” cast irons. Finishing speeds range from 107 to 122 m/min on high-chromium irons to as high as 2134 m/min on gray cast irons. All PCBN operations require the use of very rigid tooling, work fixturing, machine spindles, and machine tools.

Currently, the largest growth area for PCBN inserts is in hard turning/finish turning of alloy steel automotive engine components such as gears, shafts, and bearings with hardeness between $R_c 60$ and $R_c 65$. Traditionally, manufacturers ground these parts to obtain very tight dimensional tolerances and a fine surface finish. Hard turning gives the same results using a CNC lathe.

Insert edge preparation also strongly influences the success of PCBN machining. To promote good tool life, a reinforced cutting edge with the proper edge preparation is a must.
Cutting Torch (Oxyfuel Gas)
A device used for directing the preheating flame produced by the controlled combustion of fuel gases and to direct and control the cutting oxygen.

Cutting Torch (Plasma Arc)
A device used for plasma arc cutting to control the position of the electrode, to transfer current to the arc, and to direct the flow of plasma and shielding gas.

Cutting Wear
See abrasive wear.

CVD Carbon
See chemical vapor deposited (CVD) carbon.

Cyanate Resins
Thermosetting resins that are derived from bisphenols or polyphenols, and are available as monomers, oligomers, blends, and solutions. Also known as cyanate esters, cyanic esters, and triazine esters.

Cyanic Copper
Copper electrodeposited from an alkali-cyanide solution containing a complex ion made up of univalent copper and the cyanide radical; also the solution itself.

Cyanide Slimes
Finely divided metallic precipitates that are formed when precious metals are extracted from their ores using cyanide solutions.

Cyaniding
A case-hardening process in which a ferrous material is heated above the lower transformation temperature range at about 900°C in a molten salt containing cyanide to cause simultaneous absorption of carbon and nitrogen at the surface and, by diffusion, create a concentration gradient. Quench hardening completes the process. See case hardening.

Cyanoacrylate
A thermoplastic monomer adhesive characterized by excellent polymerizing and bonding strength.

Cycle
One complete operation of a plastic molding press from closing time, for example, in one cycle to closing time in the next cycle.

Cycle (N)
In fatigue, one complete sequence of values of applied load that is repeated periodically. See also S–N curve.

Cycle Annealing
An annealing process employing a predetermined and closely controlled time–temperature cycle to produce specific properties or microstructures.

Cycle Hydrocarbons
Cyclic or ring compounds; benzene (C₆H₆) is a classic example.

Cyclic Load
(1) Repetitive loading, as with regularly recurring stresses on a part, that sometimes leads to fatigue fracture. (2) Loads that change value by following a regular repeating sequence of change.

Cyclic Stressing
See cyclic load.

Cyclone
In powder metallurgy, a collector of fractions of a powder from air, water, or other gases or liquids; the device operates with the aid of centrifugal force that acts on the powder suspension in the fluid.

Cylinder Manifold
See preferred term manifold.

Cylindrical Grinding
Grinding the outer cylindrical surface of a rotating part.

Cylindrical Land
Land having zero relief.