Kirk-Othmer Encyclopedia of Chemical Technology.

POWDER METALLURGY

Powder metallurgy (P/M) is both an ancient art and a modern technology on the cutting edge of new materials and manufacturing processes. Powder metallurgy, a worldwide industry, uses metal powders as the raw material from which to manufacture all kinds of products, but chiefly precision metal shapes and parts. These parts perform in many consumer and industrial products such as automobile engines and transmissions, aircraft engines, aerospace hardware, washing machines, power tools, riding lawn mowers, computer disk drives, and surgical implements.

Metal powders are consolidated into shapes through a number of different production processes (Fig. 1). The most widely used powder metallurgy process covers three basic steps for producing conventional density parts: mixing, compacting, and sintering. Elemental or prealloyed metal powders are first mixed with lubricants or other alloy additions to produce a homogeneous mixture of ingredients (see Lubrication and lubricants). A controlled amount of mixed powder is automatically gravity fed into a precision die and compacted, usually at room temperature, at pressures as low as 138 MPa (20,000 psi) or as high as 827 MPa (120,000 psi), depending on the density requirements of the part. Compacting pressures normally range from 414 to 690 MPa (60,000–100,000 psi).

Compacting a loose powder produces a green compact. Using conventional pressing techniques this compact has the size and shape of the finished part when ejected from the die, and sufficient strength for in-process handling and transport to a sintering furnace. Typical compacting techniques use rigid dies set into special mechanical or hydraulic presses.

Tool sets are made of either hardened steel (qv) and/or carbides (qv), and consist of a die body or mold, an upper and lower punch, and in some cases one or more core rods. The pressing cycle for producing a simple part is shown in Figure 2. More specialized compacting and alternative forming methods, such as isostatic pressing, extrusion, injection molding, and slip casting, are sometimes used.

In sintering, the green compact is placed on a wide-mesh belt and slowly moves through a controlled atmosphere furnace (Fig. 3). The parts are heated to below the melting point of the base metal, held at the sintering temperature, and cooled. Basically a solid-state process, sintering transforms mechanical bonds, ie, contact points, between the powder particles in the compact into metallurgical bonds which provide the primary functional properties of the part.

1. History

Powder metallurgy dates to prehistoric times when artisans learned to form a solid structure by hammering gold or iron (qv) particles into metallic objects (1, 2). This occurred long before the advent of furnaces that could even approach the melting point of the metal. Egyptian implements were made from metal particles as early as 3000 BC. Pure iron oxide was heated in a charcoal fire intensified by air blasts from a bellows. The iron was reduced to a spongy metallic form. A more or less solid metallic structure was produced by hammering this porous metal while it was still hot. Final shapes were obtained by forging techniques. The direct reduction of

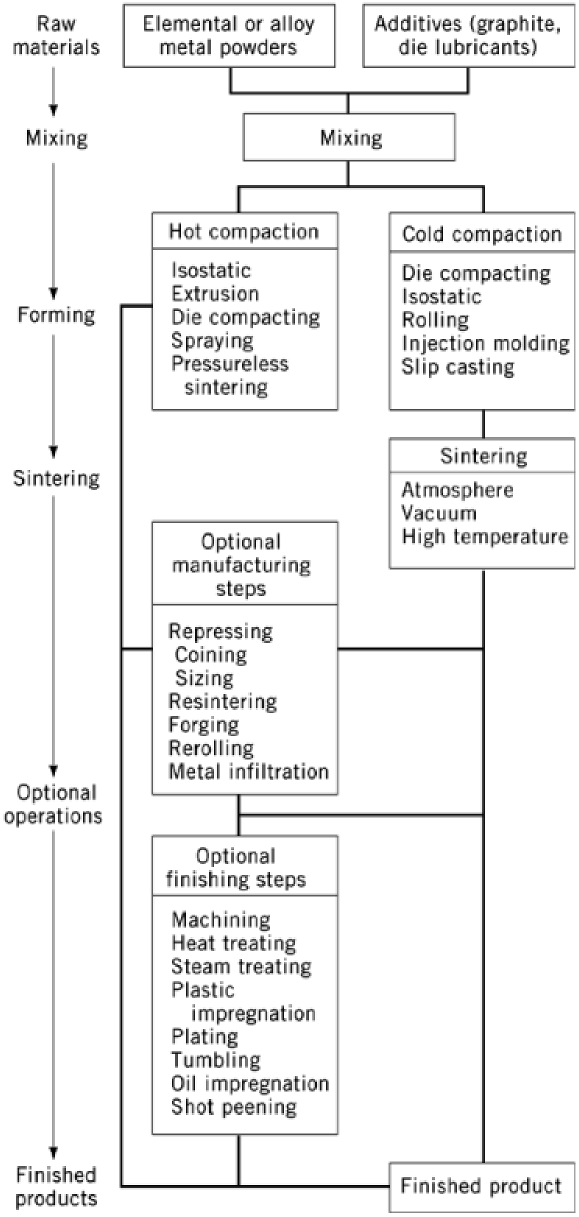

Fig. 1. The P/M process.

iron oxide without fusion dates to 300 AD when the famous Delhi Pillar, weighing almost 5.5 t, was produced (see Iron by direct reduction).

The Incas and their predecessors used powder techniques to form articles from grains of platinum, gold, and silver (3). Until the end of the eighteenth century all platinum was fabricated from granules by variations of the process used by the Incas (see Platinum-group metals). Woolaston worked on producing platinum metal products from sponge powder without liquid-phase sintering in the early nineteenth century. Methods of powder

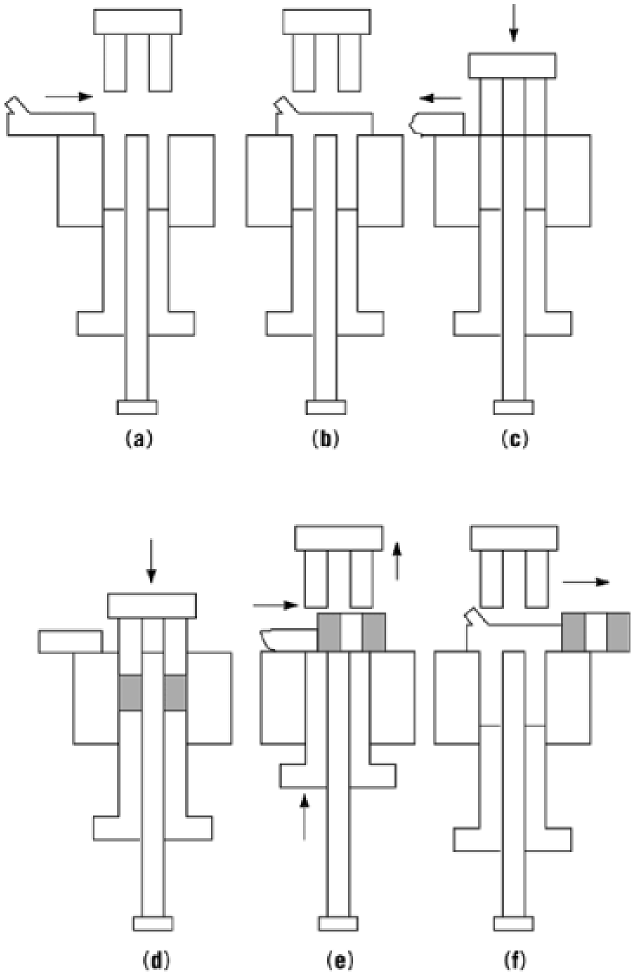

Fig. 2. Pressing cycle for a single level part: (**a**) cycle start; (**b**) charging (filling) die with powder; (**c**) compaction begins; (**d**) compaction completed; (**e**) ejection of part; and (**f**) recharging die.

preparation and compacting were investigated and a horizontal toggle press was developed. In 1830 Osann was recognized for work with copper powder, making shapes by pressing and sintering. The process was also used to make medals out of silver and lead.

The search for a durable filament for the incandescent electric light bulb opened up development work in osmium, tantalum, and tungsten powders. These materials were mixed with a binder, extruded into wire, and sintered. In the early 1900s it was discovered that tungsten could be worked in a certain temperature range yet keep its ductility at room temperature (see Tungsten and tungsten alloys). Sintered tungsten ingots were annealed, swaged, and drawn into very thin and ductile lamp filaments. Next came cemented tungsten carbide, a mixture of tungsten carbide and cobalt powders used to manufacture cutting, forming, and mining tools and wear parts (see Tool materials).

In the 1920s automotive engineers, recognizing the interesting characteristics of powder metallurgy products, designed the oil-impregnated self-lubricated P/M bearing. Conventional P/M bearings can absorb from 10 to 30 vol % of additive-free nonautomotive engine oils. Impregnation takes place by soaking the part

Fig. 3. Sintering of the green compact in a controlled atmosphere furnace.

in heated oil, or by vacuum techniques. When friction heats the part, the oil expands and flows to the bearing surface. On cooling, the oil returns into the pores of the metal by capillary action (see Bearing materials). World War II brought about further commercial applications of powder metallurgy, especially for iron, steel, and copper base P/M parts and products, such as sintered iron bearings, paraffin-impregnated iron driving bands for military ammunition, magnets, bullet cores and fuse-body parts, and magnetic cores (4).

By the 1950s P/M parts were used in postage meters and home appliances. In the 1970s P/M superalloys for aerospace applications were used, followed by steel P/M forgings. The 1980s opened the way for rapid solidification processing, P/M tool steels, and metal injection molded parts.

U.S. annual production has grown from several thousand tons in the late 1940s to several hundred thousand tons in the 1990s. P/M parts, applications, and materials have expanded from simple shapes into complicated components used in high performance environments. The automotive field has been the principal driving force behind the rapid growth of P/M. Each passenger car or light truck contains more than 13.6 kg of P/M parts. Vehicular engines, transmissions, steering, brakes, suspension, seats, and windshield washers contain a myriad of P/M parts such as valves, levers, and gears.

In the 1980s and 1990s P/M forgings, P/M tool steels, rolled-compacted strip, dispersion-strengthened copper (qv), high strength aluminum alloys, metal-matrix composites (MMC) (qv), and materials such as aluminides (see Glassy metals) have all opened up markets for powder metallurgy (5).

The hot forging of P/M products, known as powder forging of metals (P/F), is a recognized technology used to form parts for critical applications, and it is expected to continue to grow. As of this writing, automotive manufacturers are designing P/F connecting rods for operation in new engines. Metal injection molding (MIM) holds great promise for producing complex shapes in large quantities. Spray forming, a single-step gas atomization and deposition process, produces near-net shape products. In this process droplets of molten metal are collected and solidified onto a substrate. Potential applications include tool steel end mills, superalloy tubes, and aerospace turbine disks (6, 7).

The market for lighter weight P/M materials such as aluminum and titanium aluminides is expected to grow, especially for uses in automobiles. P/M processing of titanium aluminides results in more consistent product quality than the conventional casting process, and offers novel alloy/microstructure possibilities and improved ductility. Processing trends include use of high (1200–1350°C) temperature sintering to improve mechanical properties of steel and stainless steel parts.

2. Advantages

The P/M process is cost effective in producing simple or complex parts at, or very close to, final dimensions at hourly production rates that range from a few hundred to several thousand parts. As a result, only minor or no machining is required. P/M parts also may be sized for closer dimensional control and/or coined for both higher density and strength (8). Both ferrous and nonferrous parts can be oil impregnated to function as self-lubricating bearings.

Most P/M parts weigh <2.27 kg (5 lbs), although parts weighing as much as 15.89 kg can be fabricated in conventional P/M equipment. Many early P/M parts such as bushings and bearings were very simple shapes, in contrast to the complex contours and multiple levels often produced economically in the 1990s. The P/M process is not shape-sensitive and normally does not require draft. Parts such as cams, gears, sprockets, and levers are economically produced.

Powder metallurgy is basically a chipless metalworking process that typically uses more than 97% of the starting raw material in the finished part (see Metal treatments). Thus P/M is an energy as well as a materials conserving process. The P/M process eliminates or minimizes machining and scrap losses; maintains close dimensional tolerances; permits use of a wide variety of alloy systems; produces good surface finishes; provides materials which may be heat-treated for increased strength or increased wear resistance; provides controlled porosity for self-lubrication or filtration; facilitates manufacture of complex or unique shapes which would be impractical or impossible with other metalworking processes; is suited to moderate-to-high volume component production requirements; offers long-term performance reliability in critical applications; and is cost effective (9).

Powder metallurgy competes with such conventional metal-forming processes as casting, stamping, screw-machining, forging, and permanent mold casting. Although most metals are more expensive in powdered form than in other forms, the powders themselves are less expensive to fabricate into finished precision metal products. Metal powders are precisely engineered materials that meet a wide range of performance requirements. These powders are available in numerous types and grades designed for the P/M process.

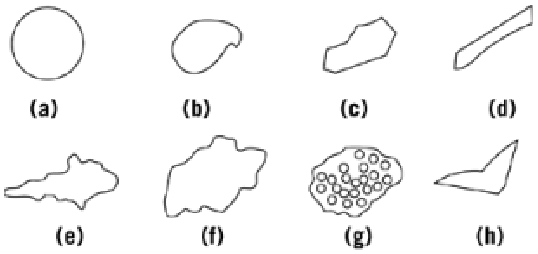

Fig. 4. Shapes of metal powder particles: (**a**) spherical; (**b**) rounded; (**c**) angular; (**d**) acicular; (**e**) dendritic; (**f**) irregular; (**g**) porous; and (**h**) fragmented.

3. Powder Characteristics

3.1. Individual Particles

3.1.1. Size

The precise determination of particle size, usually referred to as the particle diameter, can actually be made only for spherical particles. For any other particle shape, a precise determination is practically impossible and particle size represents an approximation only, based on an agreement between producer and consumer with respect to the testing methods (see Size measurement of particles).

Particles smaller than 44 μm (−325 mesh) are called fines; 44 μm is the finest sieve used on a large-volume basis (U.S. Standard). Size determination of fines is described elsewhere (10, 11).

3.1.2. Shape

Metal powder particles are produced in a variety of shapes, as shown in Figure 4. The desired shape usually depends to a large extent on the method of fabrication. Shape can be expressed as a deviation from a sphere of identical volume, or as the ratio between length, width, and thickness of a particle, as well as in terms of some shape factors.

3.1.3. Density

The density of a metal powder particle is not necessarily identical to the density of the material from which it is produced because of the particles' internal porosity. Therefore, it is difficult to determine the actual particle size and specific BET surface area.

3.1.4. Surface

Any reaction between two powder particles starts on the surface. The amount of surface area compared to the volume of the particle is, therefore, an important factor in powder technology. The particle–surface configuration, whether it is smooth or contains sharp angles, is another. The particle surface area depends strongly on the method of production, as shown in Table 1. The method of production usually determines the particle shape.

3.1.5. Microstructure

Powder particles may consist of a single crystal or many crystal grains of various sizes. The microstructure, ie, the crystal grain size, shape, and orientation, depend also on the method of powder fabrication. However, in many cases a correlation exists between particle size and grain size. In metal powders made by atomization, the smaller atomized particles solidify faster than the larger ones, and therefore in small-sized atomized powder particles there is usually less grain growth, producing smaller grains rather than coarse ones. The grain

Table 1. Particle Shapes and Surface Areas of Fabricated Powder Particles1

Process	Particle shape	Approximate surface area2
carbonyl process	uniform spherical	πd^2
atomization	round irregular spheroids	$1.5–2\pi d^2$
reduction of oxides	irregular spongy	$7–12\pi d^2$
electrolytic process	dendritic	
mechanical comminution		
crushing	angular	$3–4\pi d^2$
ball milling	flakes or leaves	varies over wide range

[a] Ref. 12.

[b] d = diameter.

Table 2. Particle Thickness and Oxide Content of Aluminum Flake Powder

Particle thickness, μm	Oxide content, vol %	Particle thickness, μm	Oxide content, vol %
0.1	30	100	0.03
1.0	3	1000	0.003
10	0.3		

structure affects the activity of the powder particle, and to a certain extent the amount of material transported by grain-boundary diffusion.

A faster cooling rate increases dendrite nuclei formation, resulting in smaller dendrites. Small dendrites produce a microstructure that is easier to homogenize during sintering. The finer the constituents, the more uniform the properties of the powder.

3.1.6. Surface Oxide Layer

The possibility of reducing surface oxide layers in a reducing gas atmosphere (Cu, Fe, Ni, W, Mo, etc) depends on the type of metal. For a given thickness of the oxide layer, the amount of oxide in a powder changes with the particle size (Table 2). The thickness of the oxide layer on an individual particle depends on the conditions under which oxidation occurs. For metals where the oxide layers can be reduced during sintering, the type and amount of oxide crystals converted to metal crystals greatly affect the activity of the particle surface. This is because of the increased mobility of atoms during the conversion of the crystal structure from the oxide to the metallic state. In many cases, an optimum amount of oxide determines the sinterability of the respective powders and their physical properties after sintering.

3.1.7. Particle Activity

Particle activity determines the type and rate of the reaction of a powder particle with its environment.

The total activity of a powder particle consists of the activity of the bulk and that of the surface. Both depend on the type and number of defects in the crystal structure. These defects are usually present in large numbers on the surface. Surface activity increases with increasing ratio of surface area-to-volume. Small particles, therefore, usually show greater activity than larger ones. The shape and surface configuration of the particle also influence the activity. Particles having sharp-angled corners are more active than particles having rounded smooth surfaces.

Because grain boundaries contribute to the activity of a particle, particles having small crystal grains are more active than particles consisting of larger grains. With respect to diffusion, the activity of particles

Table 3. Characteristics of Iron Powders[a]

		Particle size distribution,[b,c] %					
Fabrication method	Average particle size, μm	>100 μm (150)	>74 – <100 μm (200 to −150)	>44 – <74μm (325 to −200)	<44μm (−325)	Specific surface area,[b] cm^2/g	Apparent density,[b] g/cm^3
reduction	68	28.5	15.5	54.5	1.5	516	3.03
	51		6.5	81.5	12.0	945	2.19
	6	3.5	2.0	13.5	81.0	5160	0.97
from iron carbonyl	7	2.5	0.1	1.0	96.4	3460	3.40
atomization	75	28.3	20.4	29.5	21.8	355	2.90
	83	30.7	21.5	26.7	21.1	320	2.95
	89	35.4	25.5	25.3	13.8	284	3.00

[a] Refs. (4–12).
[b] Values given are typical of iron powder samples.
[c] Numbers in parentheses represent mesh sizes.

consisting of single grains is much lower than that of multicrystal particles. The activity of a powder particle determines the rate of material transport by bulk and surface diffusion, the rate of adsorption (qv) and absorption (qv), and other reactions with the environment.

3.2. Powder Mass

A mass of powder consists of a large quantity of particles. The characteristics of some iron powders are shown in Table 3. The most important properties of a good molding-grade powder are flow rate, particle size, and size distribution, apparent density, green strength, compressibility, and dimensional stability during sintering. A powder must flow well in order to fill all parts of the die cavity evenly and move through the automatic equipment (see Powders handling). The particle size and size distribution must maximize the compact density. There is a close relationship between particle size distribution and such factors as powder flow, apparent density, and compressibility. Because the amount of powder needed for each compact is charged to a cavity of constant volume, the apparent density becomes extremely important. Although changes in the depth of a die cavity can be made with ease, it is most desirable that the powder has uniform apparent density batch-to-batch and hour-to-hour.

High compressibility is another desired property of metal powders. Compressibility is the density to which a powder may be pressed at any given pressure. As the compressibility of a powder increases, the pressure needed to obtain any given density decreases. Lower pressures result in lower tool and machine wear. Under the same compacting conditions, higher compressibility powders compact to a higher green strength. This is desirable because the compact must have enough strength to be transported either mechanically or by hand. Green strength of a pressed compact, like density, is generally considered a property of the powder.

3.2.1. Average Particle Size

Average particle size refers to a statistical diameter, the value of which depends to a certain extent on the method of determination. The average particle size can be calculated from the particle-size distribution (see Size measurement of particles).

Table 4. Effect of Particle Shape on Apparent and Tap Density[a]

	Density, g/cm^3		
Particle shape	Apparent	Tap[b]	Increase, %
spherical	4.5	5.3	18
irregular	2.3	3.14	36
flake	0.4	0.7	75

[a] Ref. 4.
[b] Density after tapping the sample.

3.2.2. Particle Size Distribution

For many P/M processes, the average particle size is not necessarily a decisive factor, whereas the distribution of the particles of various sizes in the powder mass is. The distribution curve can be irregular, show a rather regular distribution with one maximum, have more than one maximum, or be perfectly uniform.

3.2.3. Specific Surface

The total surface area of 1 g of powder measured in cm^2/g is called its specific surface. The specific surface area is an excellent indicator for the conditions under which a reaction is initiated and also for the rate of the reaction. It correlates in general with the average particle size. The great difference in surface area between 6-μm reduced iron powder and 7-μm carbonyl iron powder (Table 3) cannot be explained in terms of particle size, but mainly by the difference between the very irregular-shaped reduced and the spherical carbonyl iron powders.

Determination of the specific surface area can be made by a variety of adsorption measurements or by air-permeability determinations. It is customary to calculate average particle size from the values of specific surface by making assumptions regarding particle size distribution and particle shape, ie, assume it is spherical.

3.2.4. Apparent Density

This term refers to the weight of a unit volume of loose powder, usually expressed in g/cm^3 (13). The apparent density of a powder depends on the friction conditions between the powder particles, which are a function of the relative surface area of the particles and the surface conditions. It depends, furthermore, on the packing arrangement of the particles, which depends on the particle size, but mainly on particle size distribution and the shape of the particles.

The characteristics of a powder that determine its apparent density are rather complex, but some general statements with respect to powder variables and their effect on the density of the loose powder can be made. (*1*) The smaller the particles, the greater the specific surface area of the powder. This increases the friction between the particles and lowers the apparent density but enhances the rate of sintering. (*2*) Powders having very irregular-shaped particles are usually characterized by a lower apparent density than more regular or spherical ones. This is shown in Table 4 for three different types of copper powders having identical particle size distribution but different particle shape. These data illustrate the decisive influence of particle shape on apparent density. (*3*) In any mixture of coarse and fine powder particles, an optimum mixture results in maximum apparent density. This optimum mixture is reached when the fine particles fill the voids between the coarse particles.

3.2.5. Tap Density

Tapping a mass of loose powder, or more specifically, the application of vibration to the powder mass, separates the powder particles intermittently, and thus overcomes friction. This short-time lowering of friction results in an improved powder packing between particles and in a higher apparent density of the powder mass. Tap density is always higher than apparent density. The amount of increase from apparent to tap density depends mainly on particle size and shape (see Table 4).

3.2.6. Flow

The free flow of a powder through an orifice depends on the orifice which is standardized for the testing of the powder (14). Flow, therefore, depends not only on friction between powder particles, but also on friction between the particles and the wall of the orifice. Flow is usually expressed by the time necessary for a specific amount of powder (usually 50 g) to flow through the orifice.

Inasmuch as friction conditions determine the flow characteristics of a powder, coarser powder particles of spherical shape flow fastest and powder particles of identical diameter but irregular shape flow more slowly. Finer particles may start to flow, but stop after a short time. Tapping is needed in order to start the flow again. Very fine powders ($<$ca 20μm) do not flow at all. Addition of fine powder particles to coarser ones may increase the apparent density, but usually decreases the flow quality. Metal powders having a thin oxide film may flow well. When the oxide film is removed and the friction between the particles therefore increases, these powders may flow poorly.

The free flow of a powder is necessary for automatically filled compacting dies. Powders having low flow rates need vibratory filling in order to overcome friction. Powders that do not flow at all can be used only for manual filling of the die cavity.

4. Manufacture

The manufacture of metal in powder form is a complex and highly engineered operation. It is dominated by the variables of the powder, namely those that are closely connected with an individual powder particle, those that refer to the mass of particles which form the powder, and those that refer to the voids in the particles themselves. In a mass of loosely piled powder, $\geq 60\%$ of the volume consists of voids. The primary methods for the manufacture of metal powders are atomization, the reduction of metal oxides, and electrolytic deposition (15, 16). Typical metal powder particle shapes are shown in Figure 5.

In atomization, a stream of molten metal is struck with air or water jets. The particles formed are collected, sieved, and annealed. This is the most common commercial method in use for all powders. Reduction of iron oxides or other compounds in solid or gaseous media gives sponge iron or hydrogen-reduced mill scale. Decomposition of liquid or gaseous metal carbonyls (qv) (iron or nickel) yields a fine powder (see Nickel and nickel alloys). Electrolytic deposition from molten salts or solutions either gives powder directly, or an adherent mass that has to be mechanically comminuted.

Metals can be precipitated from the liquid or gas phase. For example, nickel ammonium carbonate gives nickel powder when subjected to hydrogen in an autoclave. Copper, cobalt, molybdenum, and titanium powders can also be formed by precipitation.

In spinning or rotating electrode metal powder formation, molten metal droplets are centrifuged from a spinning electrode in a closed chamber. In high energy impaction, brittle coarse shapes are impinged against a tungsten carbide target at high velocity and ambient or lower temperatures.

Mechanical comminution may be used to form metal powders. Relatively coarse particles are produced by machining, whereas ball mills, impact mills, gyratory crushers, and eddy mills give fine powders of brittle materials.

Condensation of metal vapors followed by deposition on cooler surfaces yields metal powders as does decomposition of metal hydrides. Vacuum treatment of metal hydrides gives powders of fine particle size.

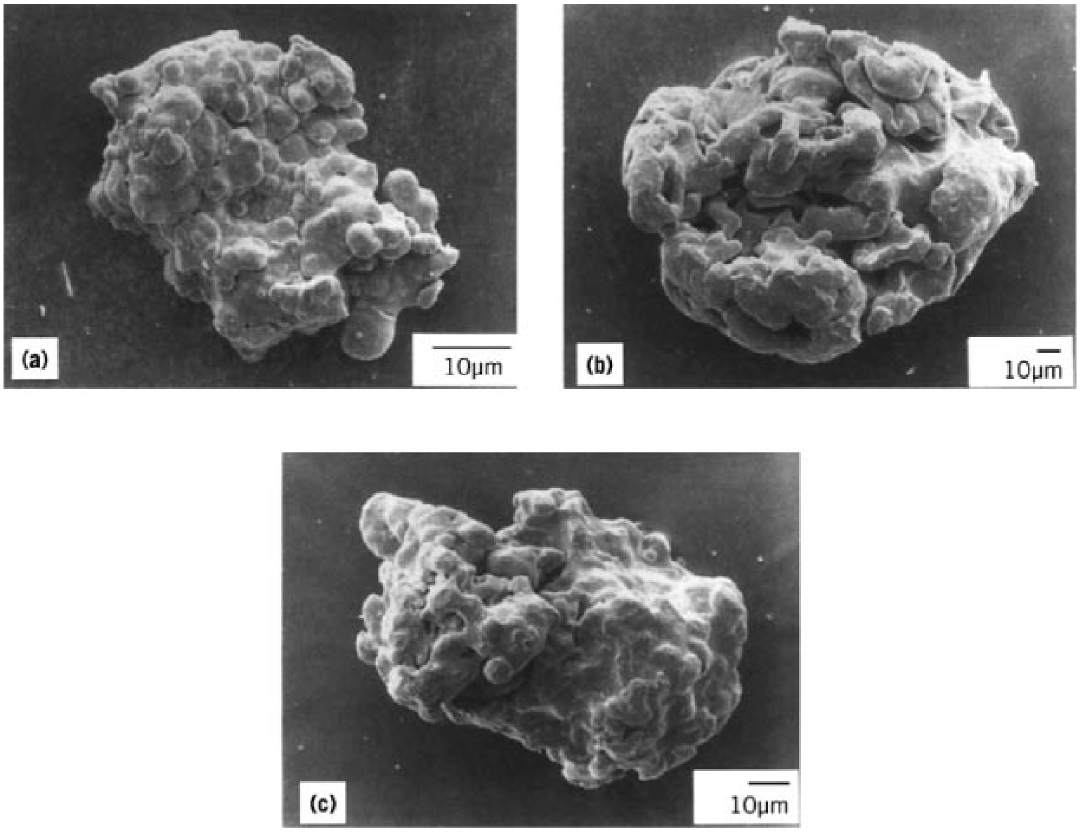

Fig. 5. Metal powder particle shapes: (**a**) atomized copper; (**b**) sponge iron; and (**c**) atomized iron.

Reaction of a metal halide and molten magnesium, known as the Kroll process, is used for titanium and zirconium. This results in a sponge-like product.

Using rapid solidification technology molten metal is quench cast at a cooling rate up to 10^{6}°C/s as a continuous ribbon. This ribbon is subsequently pulverized to an amorphous powder. RST powders include aluminum alloys, nickel-based superalloys, and nanoscale powders. RST conditions can also exist in powder atomization.

Other methods of metal powder manufacture are also employed for specific metals. Selective corrosion of carbide-rich grain boundaries in stainless steel, a process called intergranular corrosion, also yields a powder.

5. Processing

5.1. Consolidation

Metal powders are consolidated by heat or by pressure followed by heat, or by heating during the application of pressure (17). Consolidation produces a coherent mass of definitive size and shape for further working, heat treating, or use as is.

During pressure application, the powder particles are first rearranged or packed. Then elastic and plastic deformation takes place, and finally, the particles are cold-worked. Many attempts have been made to develop a mathematical relationship between compacting pressure and density and strength of the compact and strength of the sintered compact (18–21). Such a relationship has not been found to be of great practical significance. Particles bond and form a coherent mass under pressure because of liquid surface cementation; interatomic forces such as surface adhesion, cold welding, and surface tension; and mechanical interlocking of particles (22).

Plasticity of the metal crystals plays a dominant role in interparticle bonding. This is a characteristic of each metal. It is affected to a large extent by the condition of the individual powder particles. Gold, silver, lead, and iron are highly ductile (plastic) metals, whereas chromium and tungsten deform with great difficulty. Plasticity also depends on nature and history of the powder, impurities present (especially on the surface), and friction conditions between the particles. Powders that exhibit a high degree of plastic deformation form many areas of metal contact and therefore many interparticle bonds, whereas powders composed of harder particles form relatively few such bonds.

Probably the most important powder property governing the formation of atomic bonds is the surface condition of the particles, especially with respect to the presence of oxide films. If heavy oxide layers are present, they must be penetrated by projections on the particles. This results in only local rather than widespread bonding. A ductile metal such as iron which has a heavy oxide layer may not form as strong or as many bonds as a less ductile metal.

5.1.1. Mechanical Interlocking

The fact that irregularly shaped powder particles form denser and stronger compacts under pressure than regularly shaped powder particles leads to the theory of interlocking particles. Interlocking is probably the principal strengthening mechanism in the compact prior to sintering and is probably also responsible for providing increased surface contact for cold welding. This mechanism plays an important role in the strengthening of compacts made from metals such as tungsten and chromium, which normally are not plastic at room temperature.

The characteristics of a pressed compact are influenced by the characteristics of the powder: rate and manner of pressure application, maximum pressure applied and for what period of time, shape of die cavity, temperature during compaction, additives such as lubricants and alloy agents, and die material and surface condition. The effect of various compaction variables on the pressed compact are shown in Figure 6.

5.2. Consolidation Techniques

5.2.1. Unidirectional Compaction

Uniaxial pressing of metal powders in a die of specific dimensions and configuration is the most frequently used technique for the consolidation of powders in the manufacture of P/M products. Powder flows automatically into a die cavity; the bottom punch or punches act as its bottom. An upper punch seals the top and pressure can be applied parallel to the direction of powder flow into the cavity by forcing the punches together. In single action either the bottom or the top punch is held rigid, whereas the other corresponding punch moves to press the powder. In double action both punches move. Double-acting punches produce a more uniformly dense compact.

After pressure application, the top punch is removed and the compact is ejected from the cavity by the bottom punch. The cavity is then refilled and is ready for another charge. This cycle is repeated automatically at a rate that varies with the part and size and the complexity and flowability of the powder. Pressing equipment producing relatively small, simple parts can operate at up to 200 parts/min. Rotary presses with multiple die sets are even faster. Table 5 gives the ranges of pressures used for various materials during die compaction.

Compacting tools must be properly designed, constructed, and fitted to the press. These may be made of heat-treated steel or cemented carbide, depending on the economics and number of parts to be produced. Carbide tools are more expensive; however, they can be used much longer than steel tools.

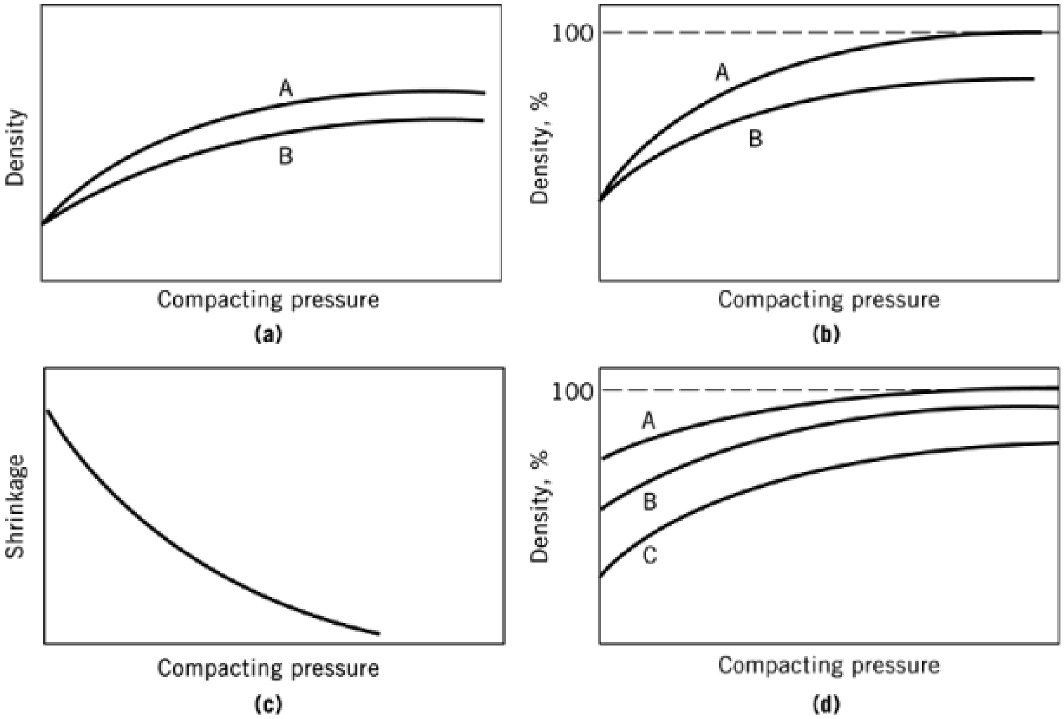

Fig. 6. Effects on the pressed compact of (**a**) speed, where A is low and B, high speed compacting; (**b**) powders, where A is soft and B, hard powders; (**c**) dimensional change after sintering; and (**d**) sintering temperatures, where A is high, B, medium, and C room temperature.

5.2.2. Isostatic Pressing

Isostatic pressing generally is used to produce P/M parts to near-net sizes and shapes of varied complexity (8, 23). Unlike conventional press compaction or molding, isostatic pressing is performed in a pressurized fluid such as oil, gas, or water. As shown in Figure 7, a flexible membrane or hermetic container surrounds the powder mass and provides a pressure differential between its contents and the pressurizing medium. Among the benefits of isostatic pressing are capability to produce complex shapes; minimized expensive powder input; applicability to difficult-to-compact materials; and uniform density and properties of products.

5.2.2.1. Cold Isostatic Pressing. Cold or room temperature compaction, known as cold isostatic pressing (CIP), is carried out in liquid systems at pressures commonly reaching 414 MPa (60,000 psi). Metal powder can be packed into complex shaped rubber or elastomeric molds before compacting. Free of die frictional forces, the powder compact reaches a higher and more uniform density at its external surfaces. Powders having spherical or rounded particles are not cold compacted because of the inability to form a strong green body. Sintering can be performed by any of the conventional methods.

5.2.2.2. Hot Isostatic Pressing. Hot isostatic pressing (HIP) is performed in a gaseous (inert argon or helium) atmosphere contained within the pressure vessel. Usually the gaseous atmosphere as well as the part to be pressed are heated by a furnace within the vessel (8, 24, 25). Common pressure levels extend upward to 103 MPa (15,000 psi) and combined temperatures to about 1250°C. Processing volumes reach to diameters of 1.2 m by 2.7 m long. Higher pressures and temperatures may be used but at the expense of reduced work volumes. The powder to be hot compacted is hermetically sealed, usually within an iron or glass container or

Table 5. Pressure Requirements and Compression Ratios[a] for Powder Products

Type of compact	Pressure, MPa[b]	Compression ratio
brass parts	413–690	2.4–2.6:1
bronze bearings	207–276	2.5–2.7:1
carbon products	138–165	3.0:1
carbides	138–414	2.0–3.0:1
iron bearings	207–345	2.2:1
iron parts		
low density	345–483	2.0–2.4:1
medium density	483–552	2.1–2.5:1
high density	483–828	2.4–2.8:1
iron powder cores	138–690	1.5–3.5:1
tungsten	69–138	2.5:1
tantalum	69–138	2.5:1

[a] Compression ratio is the dimensional relationship between the loose and compacted powder at a given compacting pressure.
[b] To convert MPa to psi, multiply by 145.

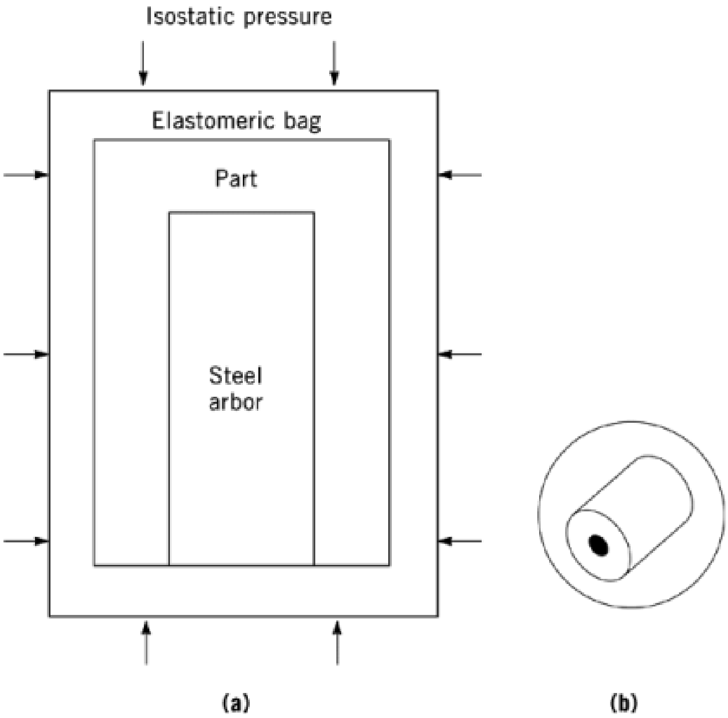

Fig. 7. (**a**) Isostatic compacting and (**b**) the shape of the completed part.

envelope which deforms plastically at elevated temperatures. Prior to sealing, the container is evacuated to eliminate residual gases in the powder mass.

In contrast to the cold isostatic pressing process, the hot process can readily employ powders having spherical or noninterlocking particles. The powder is simply poured in and vibration packed into a container of desired shape. The powder mass is then simultaneously compacted and bonded during the treatment.

Densification to what is practically full density is achievable for most materials. The resulting mechanical properties are equivalent to wrought parts in similar condition. In some materials, the properties of the HIP product are superior because of reduced anisotropy.

Depending on the material being compacted, removal of the HIP container may be by chemical leaching, machining, or other mechanical methods. As for cold isostatic pressing, mandrels can form internal contours. Parting agents are generally used to prevent bonding. Differential thermal contraction eases mandrel removal for simple, regular shapes. Mandrels with locking-in features are removable by methods used for container removal (26).

5.2.3. Powder Rolling

Powder conveyed either horizontally or vertically through a set of steel rolls is compacted in the roll gap and emerges as a porous sheet (27). This sheet is then sintered, rerolled (warm or cold, depending on the material), annealed, and rolled again in a finishing operation. The rolling mills and furnaces are arranged for continuous production. Green strength of the sheet, as it emerges from the roll gap, is the limiting factor for both the thickness and width of the sheet. Roll size, roll gap, roll speed, and rate of powder feed have to be controlled. Compaction occurs essentially in only one direction because very little pressure is transmitted laterally.

Assuming a cost-effective starting material, powder rolling eliminates much of the equipment needed for the usual melting, casting, and rolling to produce thin sheet. Sheet can be rolled closely to finished size with a minimum loss of material. Most scrap generated by this process can be reclaimed as powder. This technique also permits the production of clad materials by using a metal strip as the carrier for the powder through the roll gap. Roll compacting of nickel powder produces strips from which blanks are made for coins. In the United States, large quantities of nickel and nickel–iron–cobalt powders are rolled into strip for glass-sealing alloys and various electronic applications. Multiple-ply strips may also be rolled directly by metallurgical sintering of the layered components in the roll gap. This process is used commercially to make tri-ply strip box composite bearings.

5.2.4. P/M Forging

Even after conventional repressing of a P/M component, it is still difficult to increase density above 95%. However, full density in a P/M part improves its properties. Hot isostatic pressing in autoclaves works well, especially for titanium and superalloy components, but the capital equipment is expensive and production rates are slow.

For ordinary materials and higher production rates, P/M forging can be used (26, 28). After parts are compacted and sintered to medium density, they are reheated, lubricated, and fed into a hot-forming or P/M-forging press. The part is formed by one stroke of the press in a closed precision die. A typical hot-forming press setup includes die sets, automatic die cooling and lubrication, transfer mechanism, an induction heating unit for preforms, and controls.

P/M forged parts with dimensions up to 120 cm^2 and weighing up to 4.5 kg are produced on hot-forming presses in the 500–2500 t range. Usually the process is used for parts weighing 0.35–4.5 kg. Properties are generally equal or superior to those of conventional forgings. P/M forgings usually have a minimum density of 99% of theoretical and depending on alloy composition, can exhibit tensile strengths $>$ 1.38 GPa (200,000 psi) after heat treatment. Oil quenching and tempering at 230°C, for example, produces tensile strengths of ca 1.5 GPa (215,000 psi) (ultimate) and ca 1.25 GPa (185,000 psi) (yield) with 7% elongation and RC 43 hardness (qv). Heat treating at 650°C reduces strength and hardness values by 50% but triples elongation. The cups and cones for tapered roller bearings are forged from grade 4600 powder (2 wt % nickel, 1/2 wt % molybdenum alloy), which corresponds to AISI 4600 grade steel. These perform at least equal to and up to eight times longer than the same part produced from wrought steel.

The automotive industry is the principal user of P/M forgings, primarily for transmission and differential components, but also for engine parts. Other markets are in power tools and farm machinery. Cost effectiveness is generally the reason for substituting P/M forgings for conventionally forged, cast, or machined parts.

5.2.5. High Energy Rate Compaction

Metal powders can be rapidly compacted in rigid dies by the application of high pressures at high speed (29). Special presses employ a pressure upsetting system for rapid movement of the compacting tools. Explosives are also used. Single- and double-acting presses are capable of generating pressures on the order of several GPa (10^6 psi) for a time. The rams in presses employing explosives move at the rate of more than 1000 m/s, causing compaction to occur in microseconds. Shock fronts from explosives generate pressures close to 14 GPa (2×10^6 psi).

Higher energy rate-forming techniques have been used mainly for laboratory studies or to produce compacts with special properties, but these techniques are not of commercial interest.

5.2.6. Slip Casting

Slip casting of metal powders into useful articles is an interesting process but has only limited industrial application (30, 31). It is sometimes used to produce large, very complicated parts from refractory metals (see Refractories).

Slip casting of metal powders closely follows ceramic slip casting techniques (see Ceramics). Slip, which is a viscous liquid containing finely divided metal particles in a stable suspension, is poured into a plaster-of-Paris mold of the shape desired. As the liquid is absorbed by the mold, the metal particles are carried to the wall and deposited there. This occurs equally in all directions and equally for metal particles of all sizes which gives a uniformly thick layer of powder deposited at the mold wall.

5.2.7. Vibratory Consolidation

Powders are vibrated in a mold or other container in which they will be sintered, or in a metal container that will be used for extrusion or other metalworking process (31). Vibratory consolidation produces packings of UO_2 particles up to 95% of theoretical density.

5.2.8. Hot Pressing

Hot pressing may be used either to consolidate a powder that has poor compactability at room temperature, or to combine compaction and sintering in one operation. The technique is essentially the same as described for unidirectional die compacting. The powder is heated by either heating the entire die assembly in a furnace or by induction heating. In most instances, a protective atmosphere must be supplied.

Hot pressing produces compacts that have superior properties, mainly because of higher density and finer grain size. Closer dimensional tolerances than can be obtained with pressing at room temperature are also possible. Hot pressing is used only where the higher cost can be justified. It has been useful in producing reactive materials. One use is the combination of P/M and composites to produce hot-pressed parts that are fiber reinforced. However, the technique is mainly employed in the laboratory.

5.2.9. Extrusion, Swaging, or Rolling

Metal powders first formed into ingots by isostatic pressing, or metal powders encased in a suitable container may be subjected to any number of operations such as extrusion, swaging, or rolling. In the absence of a container, a protective atmosphere is essential. This type of consolidation is usually performed at elevated temperature. For contained powder, the case becomes a sheath during working, which is subsequently removed by either machining or chemical methods. Canned extrusion is used commercially for tool steels, superalloys, and beryllium.

5.2.10. Metal Injection Molding

Metal injection molding (MIM) offers a manufacturing capability for producing complex parts in large quantities (8, 26). The process utilizes fine metal powders, typically $< 20\ \mu$m, which are intimately mixed with various thermoplastics, waxes (qv), and other ingredients. In contrast to conventional powder metallurgy, these polymeric binder materials may comprise as much as 40 vol % of the mixture. The resulting feedstock is granulated and can then be fed into a conventional injection molding machine. Multiple cavity tooling is commonly employed. Most but not all of the binder is then removed from the molded (green) components by thermal or solvent processing, or a combination of both. The exact method chosen is dependent on the binders used for molding and the cross sections of the part. Following binder removal, parts are sintered in either an atmosphere or vacuum, during which the remaining traces of binder are removed. Sintering temperatures are usually in excess of 1260°C. Final relative densities are generally 95–98% with interconnected porosity $< 1\%$.

Parts weighing up to 100 g are commonly produced. Cross sections are generally under 6.35 mm. Parts are not restricted to this combination of mass/cross section, however, and larger parts are in production. Processing is normally to a tolerance of $\pm\ 0.3\%$, although specific dimensions may be held as close as $\pm\ 0.1\%$. Common secondary operations, such as plating, coloring, or heat treating, are often employed. Because interconnected porosity is so low, parts do not have to be resin impregnated for plating and close control over case depth is possible in carburizing.

The injection molding process eliminates the restriction of straight-sided components required when parts are ejected from a die, and offers opportunities for external undercuts and threads. A wide variety of alloys can be processed, including alloy steels and stainless steels. Material properties of injection molded parts are available (32).

Process details may be summarized: powder sizes are fine (usually $< 20\ \mu$m); low (generally < 69 MPa (10,000 psi)) injection pressure; low (ca 149°C) molding temperature; shrinkage (molded part to finished size) typically 20%; final part densities are usually 95–98% + of maximum pore-free density; and ductility is exceptionally high, elongation values are $\geq 30\%$.

5.3. Compacting Lubricants

The surface area of most moldable metal powders is in the range of 500–700 cm^2/g. Finer powders can have a surface area as high as 1500 cm^2/g (33). A very large number of individual particles is involved. For example, 1 cm^3 uniformly filled with 2-μm spherical particles having a surface area of 1200 cm^2/g contains ca 1.2×10^9 particles. Because of this large surface area, a considerable amount of friction has to be overcome during powder consolidation. To one degree or another, friction is present in all consolidation methods.

Dry lubricants are usually added to the powder in order to decrease the friction effects. The more common lubricants include zinc stearate [557-05-1], lithium stearate [4485-12-5], calcium stearate [1592-23-0], stearic acid [57-11-4], paraffin, graphite, and molybdenum disulfide [1317-33-5]. Lubricants are generally added to the powder in a dry state in amounts of 0.25–1.0 wt % of the metal powder. Some lubricants are added by drying and screening a slurry of powder and lubricant. In some instances, lubricants are applied in liquid form to the die wall.

Lubricants protect die and punch surfaces from wear and burn-out of the compact during sintering without objectionable effects or residues. They must have small particle size, and overcome the main share of friction generated between tool surfaces and powder particles during compaction and ejection. They must mix easily with the powder, and must not excessively impede powder flow (see Lubrication and lubricants).

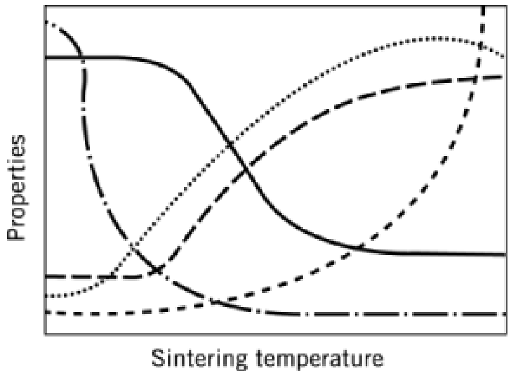

Fig. 8. Effect on sintering on (▬▬) porosity, (▬ ▬ ▬) density, (▬•▬) electrical resistivity, (...) strength, and (- - -) grain size.

5.4. Sintering

Basically a solid-state process, sintering transforms compacted mechanical bonds between the powder particle into metallurgical bonds (23, 34–38).

During the sintering treatment, which usually occurs below the melting point of the metal powder except for liquid-phase sintering of some powder mixtures, material transport takes place in the solid state. This results in some changes of the properties of the compacted powder, as shown in Figure 8. With increasing temperature and time, the strength of the powder mass increases, electrical resistivity and porosity decrease, and density, therefore, increases. The grain structure also undergoes some changes, and recrystallization and grain growth occur. In order to avoid oxidation of the metal powder mass during the high temperature treatment, either a neutral or a reducing atmosphere is provided. The movement or transport of material during sintering is caused by surface diffusion, volume or lattice diffusion, grain-boundary diffusion, evaporation and condensation, and plastic or viscous flow (37, 39). Probably several of these mechanisms act simultaneously, depending on the type of powder, its particle size and shape, and especially the temperature.

Diffusion is based mainly on the diffusion of vacancies; grain boundaries may act as sinks for these vacancies. This vacancy movement and annihilation cause the porosity of the powder compact to decrease during sintering.

Pressed powder (green) compacts are characterized by a porosity, or total pore volume, of approximately 10–40%. The number and size of the pores can be correlated with the size and shape of the powder particles from which the compact has been prepared, and the pressure applied during compacting. During sintering, the porosity undergoes a number of changes: with increasing sintering temperature or time, the total porosity decreases, the pores that originally are irregular or angular in shape become spherical; the average pore size becomes larger; the total number of pores decreases; the smaller pores disappear first; and the number of larger pores increases slightly.

The decrease of porosity during sintering results in shrinkage and, accordingly, in the densification of the powder compact. Density and densification rate during sintering are strongly affected by the particle size, the pressure applied during compacting (Fig. 9), and the sintering temperature and time. They depend further on the type of metal from which the powder has been prepared. The average sintering temperatures for various types of metals depend on their melting points (Table 6).

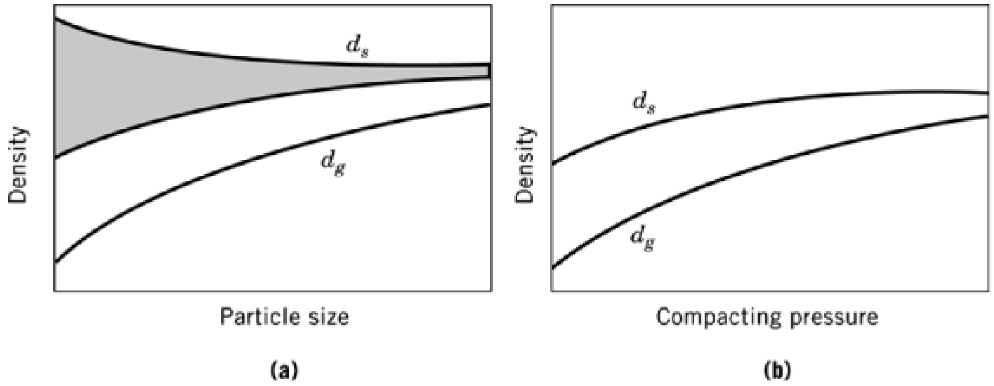

Fig. 9. Effect of density, where d_g is density as compacted and d_s is density as sintered, for (**a**) particle size and (**b**) compacting pressure.

Table 6. Material Sintering Temperature and Time[a, b]

Material	Temp, °C	Time, min
bronze	760–871	10–20
copper	843–899	10–30
brass	843–899	10–30
iron, iron–graphite, etc	1010–1149	15–30
nickel	1010–1149	30–45
stainless steel	1288–1316	20–30
Alnico magnets	1204–1302	121–150
90% tungsten–6% nickel–4% copper	1343–1593	10–120
tungsten carbide	1426–1482	20–30
molybdenum	2054	120[c]
tungsten	2343	480[c]
tantalum	2400[c]	480[c]

[a] Ref. 23.
[b] In high heat chamber.
[c] Value given is approximate.

5.4.1. Liquid-Phase Sintering

Sintering in the liquid state refers to the sintering of a powder mixture of two or more components, of which at least one has a melting temperature lower than the others. The sintering temperature is then selected in such a manner that a liquid phase is formed in which the solid powder particles of the other components rearrange. A high density powder compact is the result.

The properties of the sintered product depend to a large extent on the surrounding atmosphere. There are reducing atmospheres (hydrogen, dissociated ammonia, carbon monoxide, nitrogen plus hydrocarbons, or hydrocarbons) and neutral atmospheres (vacuum, argon, helium, or nitrogen). Metal powders susceptible to

Table 7. Heating Methods and Element Material Temperature Limits[a]

Method	Temperature, °C
gas	1150
resistance wire heating	
Nichrome A	1175
Kanthal A	1400
molybdenum	1550
tungsten	2500
silicon carbide	1538
carbon short-circuit tube[b]	3300
induction heating	3000

[a] Temperature limit depends on furnace atmosphere.
[b] Current goes directly through the furnace tube and no other heating elements are necessary.

surface oxidation must be sintered in a reducing atmosphere in order to remove the oxide films. The selection of the atmosphere depends on the type of material to be sintered, whether a reaction between the metal and the atmosphere is desired, and the type of reaction desired. Cost is also a factor.

Both batch and continuous furnaces may be employed. The maximum temperature that can be reached in a sintering furnace depends on the furnace and the heating methods (Table 7) (23).

5.4.2. Infiltration

In infiltration, the pores of a sintered solid are filled with a liquid metal or alloy (24). The most common application is the infiltration of a porous sintered steel matrix with copper, to give a copper-infiltrated P/M part. The aims of infiltration are to obtain higher strength and a pore-free structure for plating, machining, and sealing of pressure-tight applications. The liquid and the solid must not react to form a solid compound or alloy having a specific volume as great as or greater than their combined preinfiltration specific volumes. The porosity in the porous matrix should be interconnected. Ideally, the matrix material should be insoluble in the liquid infiltrant. Simple liquid-phase sintering does not give pore-free structures; infiltration does, provided the pores are interconnected.

The process is used for ferrous P/M structural parts that have densities of at least 7.4 g/cm^3 and mechanical properties superior than those of parts that have been only compacted and sintered. Depending on the application, the porous matrix may be infiltrated only partially or almost completely. Copper-base alloy infiltrants have been developed to minimize erosion of the iron matrix.

In one method, the matrix component has already been sintered and the green compact of infiltrant powders is positioned on or underneath it. The assembly is then heated to the infiltration temperature. Alternatively, sintering of the matrix and infiltration may be combined into one operation by positioning the green compact of the infiltrant on the green compact of the iron or steel matrix. This operation is called sintrating. By controlling the rate of heating, the matrix is adequately sintered by the time the melting point of the infiltrant is reached. If only part of the matrix is to be infiltrated, eg, the teeth of an infiltrated gear, the matrix may be positioned in a graphite container in which space is provided adjacent to the gear teeth to be preferentially infiltrated. The space is then filled with the appropriate amount of infiltrant in powder form. Tungsten for electrical contacts is often infiltrated in this manner with copper or silver.

5.5. Post-Sintering Treatments

The sintering process concludes the powder metallurgy processes of production and consolidation. However, some P/M parts may require a number of further operations.

5.5.1. Working Treatments

Restricted plastic deformation takes place entirely within the confines of a closed die cavity. A sintered part may be placed in the die cavity and pressure applied to the part. This pressure generally is of the same magnitude as the original compaction pressure. This second application of pressure can be categorized as follows.

5.5.1.1. Sizing. The desired size is obtained by a final pressing of a sintered compact. During sintering, the compact may have expanded, shrunk, or changed dimensions slightly, which is corrected by the sizing operation.

5.5.1.2. Repressing. Pressure is applied to a previously pressed and sintered compact, usually for the purpose of improving a physical property, such as tensile strength, hardness, or density.

5.5.1.3. Coining. The sintered compact is pressed to obtain a definite surface configuration which changes the shape of the article. In some instances, the sintered piece is used as a blank with most of the surface configuration produced by coining such as in striking coins or medallions.

In general, sizing, repressing, and coining are performed at room temperature. With elevated temperatures, a protective atmosphere must be provided.

Unrestricted plastic deformation includes all of the metalworking procedures generally applied to cast metals. P/M ingots made by die pressing and sintering, or isostatic pressing and sintering, may be forged, swaged, drawn, rolled, or extruded. These processes may also be applied to a mass of loose or loosely sintered powder. In most instances, the P/M ingot being worked has lower density and lower workability than cast ingots; temperatures are generally higher. In many cases a neutral atmosphere is provided by enclosing the operation in a protective gas or in a sheath and providing the proper atmosphere within the sheath.

5.5.2. Heat Treatments

If the inherent porosity is taken into consideration, heat treatments performed on P/M parts do not differ substantially from the same treatments performed on cast or wrought metal. Results are also similar.

The most common heating operation is resintering, usually under conditions similar to those of the first sintering operation, but at higher temperature. Resintering relieves stress or removes the effects of cold work imparted during coining or repressing. Resintering is also undertaken for further densification. Cold-working, as in repressing or coining, reduces porosity and ruptures oxide films within the compact, which creates new metal-contact areas. A resumption of sintering enables diffusion to proceed with fewer obstructions at a lower temperature. In general, it increases ductility and density with some loss in strength; however, hardness, tensile strength, and ductility are usually much improved.

Sintered metals may be softened or hardened by a number of procedures common in treating cast or wrought metals. Pure copper or silver may be annealed by heating above the recrystallization temperature. Certain copper-base alloys are precipitation hardened, such as copper–beryllium, copper–chromium, and copper–zirconium by solution-treatment quenching and coining (see Copper alloys). Precipitation hardening is practiced on aluminum alloys that contain up to 5 wt % copper and 1.5 wt % silicon, or 0.5 wt % magnesium and 0.5 wt % manganese.

P/M steels can be heat treated in the same manner as cast or wrought steels. They may be austenitized, quenched, and tempered. Surface hardening includes pack or gas carburization or nitriding, ie, heating in a nitrogen-containing atmosphere. Because of the greater amount of exposed surface area in the form of porosity, a protective atmosphere is needed (see Metal surface treatments).

5.5.3. Finishing

Finishing treatments include shaping operations such as machining, broaching, sizing, burnishing, grinding, straightening, deburring, and abrading, as well as surface treatments, such as steam oxidizing, coloring, plating, impregnating, dipping, or spraying.

Steam treatment imparts increased corrosion resistance for ferrous P/M parts. The parts are heated to 400–600°C and then exposed to superheated steam. After cooling, the parts are usually oil dipped to further increase corrosion and wear resistance, and to enhance appearance (see Corrosion and corrosion control). Heat treated parts are seldom steam treated because annealing reduces hardness and tensile strength.

The blue-black iron oxide formed in this process fills some of the interconnecting porosity and much of the surface. Hence the density is increased, resulting in higher compressive strength. Furthermore, the oxide coating increases hardness (qv) and wear resistance.

5.5.3.1. Bluing. Ferrous P/M parts can be colored by several methods. To enhance corrosion resistance, the parts are blued, ie, blackened, by heating in a furnace to the bluing temperature and then cooled. Oil dipping deepens the color and improves corrosion resistance. A dry-to-touch oil may leave a dry film on the parts.

Ferrous P/M parts can also be blackened chemically, using one of several commercial liquid salt baths. If the parts are below a density of 7.3 g/cm^3, entrapment of salt is avoided by impregnating the parts before blackening with a resin that does not break down in the bath. Nickel- or copper-bearing parts tend to adversely affect most blackening baths. Furthermore these materials seriously affect color. As for furnace blackening, an oil dip improves appearance and corrosion resistance. However, the process causes a slight change in size and makes the parts more brittle and more difficult to machine.

5.5.3.2. Plating. All types of plating in general use, including copper, nickel, chromium, cadmium, and zinc, can be applied on P/M parts. High (7.2 g/cm^3) density and infiltrated parts can be plated by the same methods as wrought parts. To avoid entrapment of plating solutions in the pores, lower density parts should be sealed with resin. Before resin impregnation, the oil must be removed from all pores and surfaces. Electroless nickel plating can also be used, and peen (mechanical) plating is applicable to nonimpregnated ferrous parts with a density of 6.6–7.2 g/cm^3 (see Electroless plating; Electroplating).

6. Economic Aspects

Powder metallurgy is a worldwide industry. The P/M parts and products industry in North America has an estimated annual sales of about $3 billion. It is comprised of approximately 150 companies that make conventional P/M parts and products from iron and copper-base powders plus about 50 other companies that make specialty P/M products. Specialty products include superalloys, tool steels, porous products, friction materials, strip for electronic applications, high strength permanent magnets, magnetic powder cores and ferrites (qv), tungsten carbide cutting tools and wear parts, tungsten alloy parts, and metal injection molded parts.

The United States has the largest metal powder producing and consuming industry of any country. The value of U.S. metal powder shipments, including paste and flake, was $1.243 billion in 1992. Approximately 307,000 t of iron and steel powder and 21,000 t of copper and copper-base powders were shipped in North America in 1994. Estimated annual world metal powder production exceeds 950,000 t.

About 88% of iron powder production is used in the manufacture of P/M parts and friction materials. Detailed statistical data are available (16). About 86% of the copper and copper-base powder produced is used in the production of self-lubricating bearings and P/M parts.

In the production of automotive parts, powder metallurgy offers strong competition to fine-blanking, stamping, screw machining, gray iron, and die casting. Automotive applications of P/M parts are expected to continue to dominate the industry through the end of twentieth century. Auto makers are specifying more P/M parts in engines, transmissions, and subassemblies. P/M also offers weight reduction in parts, a characteristic that is becoming the single most important way to boost auto fuel economy.

7. Health and Safety

Metal powders possess an immensely high ratio of specific surface area to volume. This characteristic contributes to several potentially hazardous properties such as pyrophoricity, explosiveness, and toxicity (40–42). The problems associated with the fine particles can be minimized or eliminated with proper handling and good housekeeping procedures, such as storage in appropriate containers, processing in sparkproof equipment, avoiding exposure to open flames, and minimizing airborne particulates (see Powders HANDLING). Investigations of various commercial metal powders with respect to ignition temperature, minimum explosive concentration, minimum ignition temperature for dust clouds, maximum pressure, and rate of pressure rise are available (40, 43). The prevention of dust explosions is covered in codes issued by the National Fire Protection Association (42).

The toxicity of a metal in powder form may vary from that of the massive metals in that fine particles can be ingested or inhaled more readily (41). The metal powder producing or consuming industries must conform to OSHA requirements. The limits of airborne particulates are set by NIOSH.

There are no fumes or effluents generated in the processing of powders and the requirements of state and federal environmental protection agencies are met without difficulty. However, the production of powders has been subjected to the same concerns as most other metal refining and smelting operations.

Safety in the P/M industry workplace is also a concern regarding the operation of compacting presses. Guarding devices are required by OSHA to prevent injuries. Those devices applying specifically to metal powder compacting presses are described in a standard issued by the Metal Powder Industries Federation.

8. Applications

8.1. Structural Parts

P/M parts can be made from a range of materials including iron, steels, low and high brass, bronze, nickel and nickel-base alloys, copper, aluminum, titanium, and various alloys including refractory metals (Fig. 10). P/M parts can be made smaller than a ball point on a pen or as large as bearing weighing more than 50 kg. Because parts are formed in precision dies under high pressure at room temperature, reproducibility is a great advantage.

The tensile properties of sintered (nonheat treated) conventional P/M parts are generally similar to cast metals of the same composition. Fatigue strength is about 38% of tensile values, whereas in wrought metals, such as carbon and alloy steels, it is about 50%. Toughness, as a measure of impact strength determined by Izod or Charpy methods, is density dependent. The higher the density, the higher the toughness.

Most P/M parts are manufactured on a custom engineered basis and orders are filled according to customer specifications. In addition, most manufacturers offer secondary operations such as plating, machining, heat treating, steam treating, plastic impregnation, sizing or coining, or grinding. Physical properties can match those of machined, cast, or even forged parts. Properties range from low density, porous, self-lubricating bearings, to high density structural parts with tensile strengths exceeding 1241 N/mm^2 (180,000 psi). P/M parts can be made hard and dense in one section and porous for self-lubrication in another. Although the P/M process is most amenable for the production of large quantities of parts in order to amortize tooling costs, short runs in quantities of below 10,000 pieces are possible.

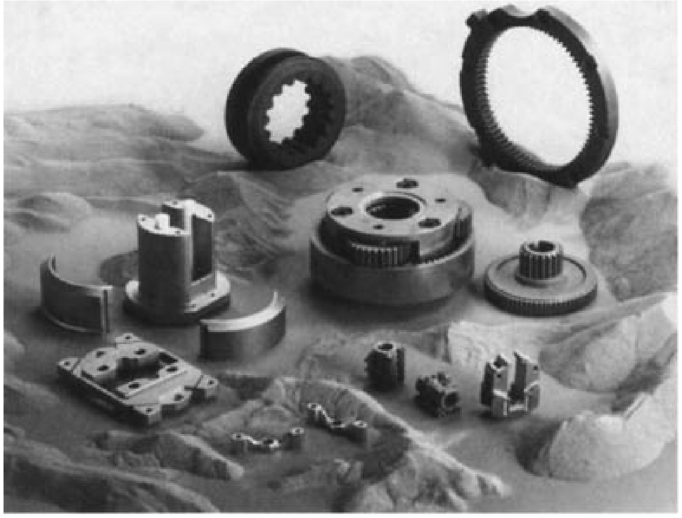

Fig. 10. Structural P/M parts made from iron- and copper-based powders. Other P/M parts can be made from a range of materials. See text.

Most properties of the P/M part are closely related to the final density of the part expressed in g/cm^3. Normally, density of mechanical and structural parts is reported on a dry unimpregnated basis; density of bearings is reported on a fully oil impregnated basis. Density may be calculated by any of several means. The commonly used method is given (44).

Density may also be expressed as relative density, defined as the ratio of the P/M part density to that of its pore-free equivalent. Generally, P/M parts $<75\%$ or relative density are considered low density, those $>90\%$ are high density, and those in between these two ranges are medium density. Structural and mechanical parts usually have relative densities ranging from 80 to $>95\%$. Forgings and HIP products often exceed 99%. Many self-lubricating bearings have relative densities on the order of 75%; filter parts usually have relative densities of 50%. As for wrought and cast metals, chemical composition of P/M parts strongly influences the mechanical properties. In P/M parts, however, density, particle size, extent of sintering, pore size, shape, and distribution also play a role.

8.1.1. Processing

Metal powders for structural parts are blended or mixed with each other and with a lubricating agent, then fed into automatic molding presses where the mixture is shaped into a compact. The compact is heated at a specific temperature under a protective gas atmosphere, generally 1120°C for iron and steel, 1260°C for stainless steel, and 982°C for copper and copper alloys (qv). In some instances, a separate presintering treatment (burn-off) at a lower temperature is applied in order to volatilize the pressing lubricant and to sinter the compact to a specific degree for subsequent repressing. In general, the part is completed after a single sintering. Occasionally, coining or various heat treatments are necessary.

Changes in configuration may occur during sintering. Dimensional changes are generally a function of the powder; shape changes are a function of density inequalities. Configuration changes are controlled either by a combination of powder properties or post-sintering treatments such as sizing or machining; the latter, however, increase costs.

8.2. Porous Materials

In porous materials, the void space that determines the porosity is controlled as to amount, type, and degree of interconnection (25, 45–47). Porous parts include self-lubricating bearings, bushings, certain types of P/M parts, and metallic filters. Their manufacture represents an important aspect of the P/M industry. The main applications for porous metals are in filters for separating combinations of solids, liquids, and gases; surge dampeners and flame arrestors for use with gases and liquids; metering devices and distribution manifolds; and storage reservoirs for liquids. These last include self-lubricating bearings. In addition, porous metals are used for the diffusion of air for aeration (qv) of liquids, and the physical separation of immiscible liquids such as gasoline and water, pressure gauge equalizers in instrumentation, flow control, flame arrestors, and sound deadeners.

Porous parts and bearings are made by both the press and sinter techniques, whereas filters are made by loose powder sintering. The metals most commonly used for P/M porous products are bronze, stainless steel (type 316), nickel-base alloys (Monel, Inconel, nickel), titanium, and aluminum.

8.2.1. Processing

Porous metal products are made by compacting and sintering, isostatic compacting, gravity sintering, sheet forming, and metal spraying.

Gravity (loose powder sintering) is employed to make porous metal parts from powders that bond easily by diffusion, eg, bronze. No outside pressure is applied to shape the part. The appropriate material, graded for size, is poured into a steel or graphite mold that is heated to the sintering temperature of the metal; at this point bonding takes place. The part tolerances are necessarily liberal, although the inside diameters tend to be predictable because the material usually shrinks to the core during sintering. Design tolerances of ±2% for the outside diameter and ±3% for the part length are typical.

In the sheet-forming process, stainless steel, bronze, nickel-base alloys, or titanium powders are mixed with a thermosetting plastic and presintered to polymerize the plastic. Sintering takes place in wide, shallow trays. The specified porosity is achieved by selecting the proper particle size of the powder. Sheet is available in a variety of thicknesses between 16 × 30 mm and as much as 60 × 150 cm. A sheet can be sheared, rolled, and welded into different configurations.

Porous metal structures can also be created by spraying molten metal onto a base. Porosity is controlled by spraying conditions or by an additive that may be removed later.

Porous P/M products can be sinter bonded to solid metals. They can also be welded, brazed, or soldered. Filling the voids with flux or molten metal has to be avoided. P/M porous products can be machined, but blocking of the porous passages has to be avoided. Press fitting and epoxy bonding are commonly used.

8.2.2. Self-Lubricating Parts

Self-lubrication depends on the presence of oil within the pores of the bearing or bushing. A built-in oil reservoir provides a protective oil film that separates the bearing from the shaft, for example in a motor, and prevents metal-to-metal contact. During operation, the rotating shaft draws the oil in the bearing to the surface through capillary action. When not under load, most of the oil is drawn back into the bearing, leaving a layer of oil between the two metal parts.

Most bearing materials (qv) are made from bronze powders. Compositions may be 5–12 wt % tin and up to 6 wt % graphite. Standard compositions are 90.5 wt % Cu–7 wt % Sn–2.5 wt % graphite; 89 wt % Cu–7 wt % Sn–4 wt % graphite; 93 wt % Cu–7 wt % Sn; 96 wt % Cu–4 wt % graphite; and 100 wt % Cu. Compositions containing copper with up to 8 wt % Pb or up to 40 wt % Zn are also available.

Self-lubricating bearings are also made from iron usually containing 36 wt % Cu and 4 wt % Sn. Iron–lead alloys contain 2–6 wt % Pb and 2–4 wt % graphite. Iron-base materials offer increased hardness and strength;

in addition, their coefficient of thermal expansion is close to that of the steel shaft. However, iron-base materials are generally not rated as high as copper-base materials for self-lubricating bearing materials.

8.2.2.1. Processing. Simple self-lubricating parts are produced on an automatic, rapid, high volume basis. The powder mixtures usually contain a few percent of organic lubricants. They are molded unidirectionally in a closed die cavity at pressures of 276–552 MPa (40,000–80,000 psi). During sintering, the lubricant volatilizes which facilitates some control over interconnection of the voids. Porosity is increased by volatile pore-forming agents that are added during sintering.

The sintering of bronze bearings is an example of liquid-phase sintering in which the liquid is present only during part of the sintering time. Alloying causes the liquid to solidify. Bronze bearings are sometimes presintered at 370–480°C in order to control the degassing lubricants. During this treatment, the bronze alloy is formed by the diffusion of liquid tin into the copper, and it solidifies in the furnace. When the temperature is raised, the tin-rich phase liquefies and is absorbed by the copper-rich matrix.

After sintering, P/M bearings are usually sized for dimensional accuracy on the same type of equipment used for molding. This produces a smooth surface and involves forcing the part back into a cavity of the dimensions desired. Lubricating oil is impregnated into the part either before or after sizing. The resulting part is an oil-impregnated bearing containing approximately 20 vol % oil.

A broad range of ferrous and nonferrous compositions is utilized in self-lubricating finished P/M parts. Among these materials are iron, brass, low carbon and low nickel steel, copper, nickel–silver, and stainless steel. Processing is essentially the same as for conventional bearings. P/M parts differ from conventional bearings only in shape and in the capability to withstand shear and compressive stresses considerably greater than those that bearings must withstand.

An important application of self-lubricating P/M parts is the oil-pump gear used in automotive engines. This part is made from a steel of eutectic composition containing 0.3 wt % carbon and 2 wt % copper; it is hardened after sintering. The gear teeth are resistant to wear and plastic deformation. The oil flowing through the interconnected pores lubricates the gear and increases corrosion resistance. High strength nonporous sections can be combined with other sections having lower density and self-lubricating characteristics such as ratchet-and-cam combinations.

8.2.3. Filters

Compared to screens, metallic filters offer a tortuous path through which the fluid must flow and thus provide depth filtration (qv). Compared to glass (qv) or ceramic filters, P/M filters are strong and particles of the filtered material cannot break away in service and enter the filtrate. The P/M filters are ductile and do not fracture under mechanical or thermal shocks. They can be fitted into housings by rolling, machining, press-fitting, or welding. In vibrating applications, the limited fatigue resistance of P/M filters must be taken into consideration (25). A wide range of design possibilities, permitting filtration at 0.5–200 μm and flow rates from a trickle to high volumes, is possible.

8.2.3.1. Porosity Measurement. Porosity is difficult to define precisely because the total interconnected porosity reflects not only a range of hole diameters but also passages of varying lengths and tortuosity. Maximum pore size is determined by the bubble-point test. It measures the pressure at which a bubble forms at the part surface when submerged in alcohol. The micrometer rating is roughly related to the ability of the filter to retain or remove particles. The lower the rating, the finer the powder used to make the part and the higher the pressure drop. For filter design, the maximum size particles in micrometers that is acceptable in the filtrant is specified. The minimum pressure drop at that micrometer rating should be attained.

8.3. P/M Tool Steels

In conventionally produced high alloy tool steels (slowly cooled cast ingots), carbide tends to segregate (48). Segregated clusters of carbide persist even after hot working, and cause undesirable effects on tool fabrication and tool performance. P/M tool steels, on the other hand, provide very fine and uniform carbides in the compact, the final bar stock, and the tools. Several tool steel suppliers consolidate gas-atomized tool steel powder by HIP to intermediate shapes, which are then hot-worked to final mill shapes. Water-atomized tool steel powder is also available (see also Tool materials).

Small complex tool steel parts are being made by conventional compaction and sintering in vacuum to near theoretical density. Applications include spade drills, knife blades, slotting cutters, insert blades for gear cutters, reamer blades, and cutting tool inserts.

8.4. Friction Materials

Sintered friction materials are classified as metal– nonmetal combinations (49, 50). These are best manufactured by the P/M process. Clutch plates, brake bands, brake blocks, and packing compositions are examples of friction materials (see Brake linings and clutch facings).

A sintered friction material is composed of a metal matrix, generally mainly copper, to which a number of other metals such as tin, zinc, lead, and iron are added. Important constituents include graphite and friction-producing components such as silica, emery, or asbestos.

Copper, with its high heat conductivity, resists frictional heat during service and is readily moldable. It is generally used as a base metal, at 60–75 wt %, whereas tin or zinc powders are present at 5–10 wt %. Tin and zinc are soluble in the copper, and strengthen the matrix through the formation of a solid solution during sintering.

Iron or other higher melting metals insoluble in copper are added in amounts of 5–10 wt %. Harder particles, such as iron embedded in the soft copper base, increase the coefficient of friction and also exert a scouring action on the surface. Lead, which is also insoluble in copper, is added in amounts of 5–15 wt %. Dispersed in the matrix, it acts as a lubricant during molding and as a lubricating film during operation of the friction material if the surface temperature is such that the lead liquefies. In addition, lead enhances the smooth engagement of sliding surfaces, which prevents erratic brake or clutch action. Graphite, 5–10 wt %, has effects similar to lead. Silica, emery, or other similar friction-producing materials are added at 2–7 wt %. Minute quantities affect the coefficient of friction. A typical composition of friction–P/M material, in wt %, is Cu, 62; Pb, 12; Fe, 8; graphite, 7; and silica, 4.

Friction materials have to be able to wear the surface away in a uniform manner in order to provide new friction-producing conditions at the surface.

8.4.1. Processing

Friction materials are manufactured by cold pressing a mixture of the ingredients at relatively low (138–276 MPa (20,000–40,000 psi)) pressures. Large parts are sintered in bell-type furnaces, whereas small parts are sintered in conventional furnaces. The pressed compact is bonded to a backing plate during sintering. A number of compact steel plate assemblies are stacked on top of each other and pressure is applied to the stacked assemblies during sintering. Post-sintering treatments such as bending to shape, drilling holes, or machining to dimensions are usually necessary.

8.5. Electrical and Electronic Applications

8.5.1. Contact Materials

Electrical contact materials are produced by either slicing rod made from metal powder, infiltrating a porous refractory skeleton, or compaction and sintering of powders (see Electrical connectors) (51–53).

Tungsten contacts cut from rod are resistant to deformation under a large number of cycles at relatively high forces, have high hardness and strength, the ability to switch high currents without detrimental arcing or welding, and vaporize very little in an arc (if one should form). These contacts meet the requirements of many

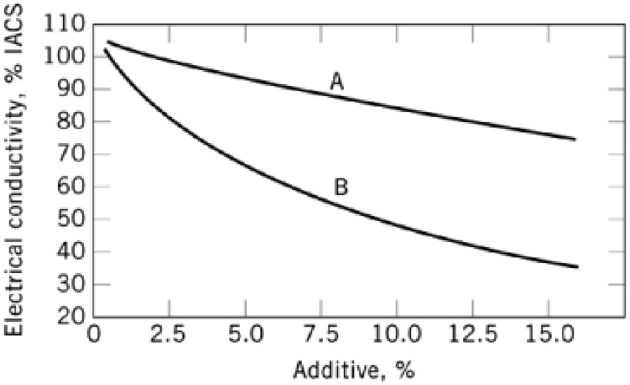

Fig. 11. Conductivity of A, silver semirefractory compositions and B, solid-solution alloys of the same metals. Copper gives 100% IACS (International Annealed Copper Standard).

automotive, aviation, and appliance applications; they are, however, limited in use because an insulating oxide film forms during switching.

Copper and silver combined with refractory metals, such as tungsten, tungsten carbide, and molybdenum, are the principal materials for electrical contacts. A mixture of the powders is pressed and sintered, or a previously pressed and sintered refractory matrix is infiltrated with molten copper or silver in a separate heating operation. The composition is controlled by the porosity of the refractory matrix. Copper–tungsten contacts are used primarily in power-circuit breakers and transformer-tap charges. They are confined to an oil bath because of the rapid oxidation of copper in air. Copper–tungsten carbide compositions are used where greater mechanical wear resistance is necessary.

Tungsten–silver contacts are made similarly, but can be operated in air because of the greater stability of silver. The three standard compositions of this class include tungsten–silver, tungsten carbide–silver, and molybdenum–silver.

A third group includes silver–nickel, silver–cadmium oxide, and silver–graphite combinations. These materials are characterized by low contact resistance, some resistance to arc erosion, and excellent nonsticking characteristics. They can be considered intermediate in overall properties between silver alloys and silver or copper–refractory compositions. Silver–cadmium oxide compositions, the most popular of this class, have wide application in aircraft relays, motor controllers, and line starters and controls.

Figure 11 illustrates the superior conductivity of P/M silver–nickel or silver–cadmium oxide contacts when compared with contacts made by standard melting techniques and formed from solid-solution alloys.

So-called sliding contacts transfer current in motors and generators. Sliding contacts are often called brushes. High electrical conductivity, wear resistance, lubricating qualities, and some arc-erosion resistance are the characteristics required by high current applications. Compositions are usually of copper and 5–7% graphite, silver and graphite, or bronze and graphite.

8.5.2. Magnets

Permanent magnets known as Alnico magnets are made by pressing and sintering powder mixtures (51). These materials are alloys of aluminum, nickel, and iron with additives such as cobalt, copper, and titanium. Sintered Alnico as compared to cast Alnico offers greater mechanical strength and closer tolerances without costly finishing operations. Other P/M magnetic materials include barium and strontium hard ferrites (qv) and iron–neodymium–boron, Fe–Nd–B.

Soft magnetic parts include iron pole pieces for small d-c motors or generators, armatures for generators, and sintered and rolled iron–nickel alloys for radio transformers, measuring instruments, and similar applications. The highest (358.1 T·kA/m (45 MG·Oe)) energy product magnets, made from Fe–Nd–B, are used in cars, appliances, and electric motors (see Magnetic materials).

8.5.2.1. Rare-Earth Magnets. The combination of rare earths and cobalt exhibits magnetic flux 4–19 times greater than conventional Alnico magnets (54). Because it is necessary to press the metal powders in a magnetic field to align the fine particles, $\leq$10 micrometers in size, powder metallurgy is the only practical way to obtain such superalloys. The rare-earth–cobalt alloy powders are compacted in a mechanical press and sintered in argon or nitrogen at 1100–1200°C (see Cobalt and cobalt alloys). Samarium, mischmetal, and praseodymium are mostly used (see Lanthanides).

8.5.3. Cores

Iron powder cores are manufactured for a-c self-inductance coils for high frequency applications in telephone, radio, and television systems. In the production of radio and television cores, iron powder is coated with an electrically insulating material, compacted in conventional P/M presses, ejected, and baked to fuse the coated particles together. Such a core can afford a large change of inductance by a simple movement in one direction in or out of a wire-wound coil. Fine iron powders of the electrolytic or carbonyl types are employed. These cores exhibit minimum eddy-current and hysteresis losses and the magnetic permeability returns to its original value after application of large magnetizing forces. Cores are also made from molybdenum–permalloy materials.

8.5.4. Electrolytic Capacitors

Tantalum, because of its high melting point of 2850°C, is produced as a metal powder. As such, it is molded, sintered, and worked to wire and foil, and used to build certain types of tantalum capacitors (51). Other capacitors are made by compacting and sintering the tantalum powder.

8.5.5. Batteries

In the nickel–cadmium rechargeable storage battery, the nickel powder forms a porous sheet around a woven wire grid (see Batteries). The sheet, with up to 90% porosity, is used as a reservoir for nickel and cadmium compounds and as an electron take-off. It offers a large surface area per unit weight or volume. The porous sheet is made either by sifting nickel powder into a ceramic mold of the correct size and containing the woven screen, or by applying a slurry to a thin perforated nickel-plated iron sheet. The composite is then sintered at a temperature that effects strengthening but not densification.

Dry-battery mercury anodes are pressed compacts of zinc–mercury amalgam. They were first developed and produced during World War II for walkie-talkie communication systems. Practically all hearing aids employ this type of battery in the 1990s.

8.5.6. Incandescent Lamps, Electronic Tubes, and Resistance Elements

Articles fashioned in any form from molybdenum and tungsten usually fall within the bounds of powder metallurgy. These metals normally are first produced as a powder. Both molybdenum and tungsten are used as targets in x-ray tubes, for structural shapes such as lead and grid wires in electron tubes, and as resistance elements in furnaces.

Iron–nickel and iron–nickel–cobalt alloys are prepared in wire and sheet form by either rolling an isostatic-pressed ingot or by directly rolling and sintering the metal powders. These materials have numerous applications in the electronic field as glass-sealing alloys because their coefficient of thermal expansion is close to that of certain glasses. Moreover, their coefficients can be tailored to the application by varying the composition, an easy accomplishment for the powder metallurgist.

8.5.7. Refractory Materials

Extremely high melting metals and those that are more resistant to deformation when hot are considered refractory metals (55). This generally refers to melting above the melting point of iron (1536°C). Tungsten, rhenium, tantalum, molybdenum, and niobium belong to this group and also osmium, boron, titanium, thorium, zirconium, and vanadium. Refractory materials also include alloys of these metals (see High temperature alloys; Refractories).

Refractory metals are associated with powder metallurgy because these metals are not easily melted. Therefore in smelting the ores, the metal is recovered in powder form rather than melted. Refractory metals are used mainly to produce filament wire for incandescent lamps.

8.5.7.1. Processing. Tungsten powder of approximately 5 μm average particle size produced from the hydrogen reduction of tungsten oxides, is compacted into ingots. The bar is extremely weak and must be heated in hydrogen in a standard muffle furnace in order to strengthen it before sintering in a bell-shaped furnace under a hydrogen atmosphere. Heating is by resistance and is carried on until the sintered bar is dense enough to be heated and worked in air. The bar is then worked first at 1550–1650°C and then at gradually decreasing temperatures. Metallurgically, this is cold working because recrystallization does not take place. The material is swaged and drawn with intermediate annealings to wire filaments. During working, the sintered bar increases in tensile strength and ductility and becomes 100% dense.

Metalworking, such as swaging, drawing, rolling, etc, may also be performed on slabs or ingots of other metals prepared by any of the consolidation and sintering techniques described.

8.5.7.2. Refractory Metal Alloys. Alloys of refractory or nonrefractory metals are made by direct mixing of the elemental metal powders or by the incorporation of compounds of the solute in the processing step for subsequent reduction to the metal (56). In most instances, the metals are alloyed by solid-state diffusion during sintering. Tungsten and molybdenum form a continuous series of solid solutions which offer considerably greater workability compared to pure molybdenum and pure tungsten.

Tungsten with the addition of as much as 5% thoria is used for thermionic emission cathode wires and as filaments for vibration-resistant incandescent lamps. Tungsten–rhenium alloys are employed as heating elements and thermocouples. Tantalum and niobium form continuous solid solutions with tungsten. Iron and nickel are used as alloy agents for specialized applications.

8.5.7.3. Heavy Metal. Heavy-metal composition is widely used for containers for shielding radioactive materials, counter-balances in airplane controls, and as cores in armor-piercing projectiles. The tungsten–nickel–iron alloy nominally containing 93 wt % W–5 wt % Ni–2 wt % Fe is considered to be a heavy-metal composition, because its sintered density may exceed 17 g/cm^3. It has sufficient ductility to be worked and can be sintered to full density at 1400°C in contrast to pure tungsten. This alloy is utilized when a high mass having good impact strength, ductility, and tensile strength is needed. Pure tungsten has more mass but is brittle.

8.6. Cemented Carbides

Cemented carbides contain mostly tungsten carbide and lesser amounts of other hard-metal components, embedded in a matrix of cobalt (see Carbides, cemented carbides).

The principal application of cemented carbides is as cutting tools for metals. They are also used in armor-piercing projectile cores and tips, and for carbide shot. Cemented carbides are used for parts requiring corrosion resistance, including burnishing tools and dies, pump valves, sandblast nozzles, gauges, rock and masonry drills, and guides of many types. Carbide compositions containing only tungsten carbide [12070-12-1], and cobalt are unsuitable for machining highly resistant materials. However, tungsten carbide can be replaced with solid solutions of tungsten, molybdenum, and titanium carbides to machine such materials. Various rare-earth carbides have been added to tungsten carbide for special-purpose cutting tools. Tungsten-free compositions have also been developed as well as compositions containing diamonds.

Cemented carbides exhibit extreme hardness and toughness which are retained at the elevated temperatures that may occur between tool and work during cutting.

8.6.1. Processing

Tungsten carbide is made by heating a mixture of lampblack with tungsten powder in such proportions that a compound with a combined carbon of 6.25 wt % is obtained. The ratio of free-to-combined carbon is of extreme importance. Tantalum and titanium carbides are made by heating a mixture of carbon with the metal oxide. Multicarbide powders, such as Mo_2C–WC, TaC–NbC, and TiC–TaC–WC, are made by a variety of methods, the most important of which is carburization of powder mixtures.

These carbides are mixed with fine cobalt powder in a wet ball-milling operation. Water, benzene, or other organic materials may be used. Milling produces an intimate mixture of cobalt attached to the carbide particles. This is followed by mixing with a lubricant or other binder, such as paraffin, camphor, or stearic acid, in a separate operation. Dried and screened, the mass results in a lubricated, flowable powder that can be cold-molded in conventional presses and tooling. A low temperature, presinter treatment is carried out in order to strengthen the part through sintering of the binder metal and to evaporate the pressing lubricant. The presintered part is then formed by machining into the desired shape and dimensions. This is followed by high temperature sintering between 1350 and 1550°C for 1–2 h. Sintering is characterized by solution of the carbides in the liquid phase, and precipitation at areas of low energy. Recrystallized grains of carbide form and are embedded in a matrix of a solution of carbides and matrix metal. Linear dimensional shrinkage of 21–25% occurs.

8.7. Cermets

High temperature applications in space and nuclear technology created a need for materials to fill the gap between cobalt- and nickel-base superalloys and refractory metals such as tungsten and molybdenum. Pure ceramics are strong at elevated temperatures but lack sufficient ductility to be worked at room temperature, whereas metal alloys, although ductile at room temperature, are not strong enough at the higher temperatures. Mixtures of ceramics and metals have both the high temperature strength of ceramics, and sufficient ductility and thermal conductivity contributed by the metal to provide resistance from thermal shock at high temperatures and workability at room temperature. These compositions are termed ceramals and cermets (see Ceramics; High temperature alloys). Actually, the cemented carbides can be considered cermets.

The cermet class of materials contains a large number of compositions (57). Most cermets are carbide-based, eg, WC and titanium carbide [12070-08-5], TiC. Cemented tungsten carbides are widely used for cutting tools and car parts.

Dispersions of flake aluminum powders having surface oxide up to 14 wt % Al_2O_3 have been pressed, sintered, and worked to a material known as sintered aluminum powder (SAP). This product exhibits high strength at elevated temperatures. Nickel containing small additions of thoria, known as TD-nickel, is also a high temperature cermet.

Thoria-dispersed nickel products are obtained by precipitating basic nickel compounds, whereby thoria particles of ca 100 nm are coated with layers of nickel to the extent that the product has a 2% thoria dispersion.

Dispersion-strengthened copper is made by dispersing a thoria or alumina phase through copper powder. The resulting P/M product retains its strength at elevated temperatures. It is used, for example, as the conductor or lead wire that supports the hot filament inside incandescent lamps.

Mechanical alloying is another method of producing dispersion-strengthened metals. In this process, the powdered constituents of the alloy are treated in an attrition mill. A finely distributed layer of the dispersed phase is distributed on particles of the base metal. Subsequent pressing and sintering strengthens the dispersion (25).

8.8. Metal-Matrix Composites

A metal-matrix composite (MMC) is comprised of a metal alloy, less than 50% by volume that is reinforced by one or more constituents with a significantly higher elastic modulus. Reinforcement materials include carbides, oxides, graphite, borides, intermetallics or even polymeric products. These materials can be used in the form of whiskers, continuous or discontinuous fibers, or particles. Matrices can be made from metal alloys of Mg, Al, Ti, Cu, Ni or Fe. In addition, intermetallic compounds such as titanium and nickel aluminides, Ti_3Al and Ni_3Al, respectively, are also used as a matrix material (58, 59). P/M MMC can be formed by a variety of full-density hot consolidation processes, including hot pressing, hot isostatic pressing, extrusion, or forging.

MMCs can offer improved strength and elastic modulus especially at elevated temperatures when compared with metal alloys. For example, titanium–silicon carbide composites have a high strength-to-weight ratio, good elevated temperature creep-rupture strength, and a higher modulus than conventional titanium alloys. Potential applications include gas turbine engine components, and airframe structures in advanced aircraft and auto engine valves and turbocharger rotors (see Metal-matrix composites).

8.9. Space Applications

The growth of powder metallurgy in space technology has arisen from the difficulty of handling many materials in conventional fusion-metallurgy techniques, the need for controlled porosity, and the requirement of many special and unique properties (60, 61). Powder metallurgy is applied in low density components with emphasis on porous tungsten for W–Ag structures, beryllium compounds, titanium and dispersion-hardening systems.

Plates of beryllium metal were used as heat-shield shingles on the cylindrical section of the Mercury spacecraft in some of the first suborbital flights (see Ablative materials). A fairing for the Agena-B space-vehicle interstage structure used beryllium machined from a pressed compact 180-cm in dia and 70-cm high. Beryllium has also been used in the nose cap of the ascent shroud in several of the Ranger-Mariner space probe series and in air- and spaceborne mirrors (62). Beryllium has a favorable stiffness-to-density ratio and good thermal properties which make it acceptable as a shielding material against micrometeorites.

Special tungsten powders have been developed for space applications. Spherical tungsten particles are used to form porous tungsten bodies in the ionizing surface in ion-propulsion engines. Silver-infiltrated tungsten parts have a density before infiltration of 70–80% of theoretical; 90% of the porosity is infiltrated with silver. These parts are used where the ablative cooling provided by the silver during solid–vapor change of state and transpiration cooling through the resulting porosity are desirable, as in reentry vehicles.

Space technology has always demanded materials that can operate at temperatures between those of superalloys and refractory metals and that have high temperature strength during operation and room temperature ductility for fabrication. The development of dispersion-strengthened and oxide alloy systems has solved part of this problem.

Space technology also utilizes sintered magnetic materials such as Alnico, sintered bronze bushings, electrical contacts and tantalum capacitors, and a variety of P/M porous filters. Aluminum and magnesium powders are blended with solid fuels for enhancing rocket-propulsion systems. The space shuttle Columbia is launched using 90,720 kg of aluminum powder plus ammonium perchlorate and oxidizers in each of its two booster rockets. P/M titanium housings are used in guided missiles.

High vacuum is one of the main characteristics of space. Bearings having liquid lubricants would lose the lubricant through evaporation. Bearings produced by powder metallurgy techniques having embedded MoS_2 give good service.

8.10. Nuclear Applications

Powder metallurgy is used in the fabrication of fuel elements as well as control, shielding, moderator, and other components of nuclear-power reactors (63) (see Nuclear reactors). The materials for fuel, moderator, and control parts of a reactor are thermodynamically unstable if heated to melting temperatures. These same materials are stable under P/M process conditions. It is possible, for example, to incorporate uranium or ceramic compounds in a metallic matrix, or to produce parts that are similar in the size and shape desired without effecting drastic changes in either the structure or surface conditions. Only little post-sintering treatment is necessary.

In nuclear technology, the P/M process is applied to beryllium, zirconium, uranium, and thorium. Uranium and thorium are used as fuel materials, beryllium for moderating purposes, and zirconium as construction material. These metals are used in elemental form, as alloys, or in metal–ceramic combinations. The metal powders must be handled somewhat differently from ordinary metal powders. Beryllium powder is extremely toxic, zirconium is highly pyrophoric, and uranium and thorium powders are both toxic and pyrophoric. The vapors eminating from burning uranium are also extremely toxic. These powders are generally handled in closed containers, called dry boxes, usually filled with a protective atmosphere such as argon or helium. Beryllium powders have extremely poor compactability at room temperature and are therefore generally processed by sintering in vacuum or HIP.

Both zirconium hydride and zirconium metal powders compact to fairly high densities at conventional pressures. During sintering the zirconium hydride decomposes and at the temperature of decomposition, zirconium particles start to bond. Sintered zirconium is ductile and can be worked without difficulty. Pure zirconium is seldom used in reactor engineering, but the powder is used in conjunction with uranium powder to form uranium–zirconium alloys by solid-state diffusion. These alloys are important in reactor design because they change less under irradiation and are more resistant to corrosion.

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PETER K. JOHNSON
Metal Powder Industries Federation, APMI International

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