technical report

COPPER • BRASS • BRONZE

powder metals— properties and applications

COPPER DEVELOPMENT ASSOCIATION INC.

COPPER AND COPPER ALLOY POWDER METALLURGY
PROPERTIES AND APPLICATIONS

by

John L. Everhart

Metal Powder Industries Federation
P. O. Box 2054
Princeton, N.J. 08540

Copper Development Association Inc.
405 Lexington Avenue
New York, N.Y. 10017

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COPPER AND COPPER ALLOY POWDER METALLURGY PROPERTIES AND APPLICATIONS

INTRODUCTION

Powder metallurgy, the technology of utilizing metal powders, offers the engineer a means of conserving materials, reducing machining, and securing a uniform product at a reasonable cost. This unique metal forming method permits the production of parts with close tolerances and a minimum of scrap and the development of products that cannot be produced by any other method. By proper selection of powders, the powder metallurgy (P/M) specialist can control the density of the products over a wide range and secure a wide range of mechanical and physical properties. He can produce mixtures of metals that are insoluble in each other or of metals and nonmetals that combine the properties of both.

Density can be controlled to produce parts with porosities as high as 60% or, conversely, those that are practically pore-free and have densities approaching the theoretical density of the metal. It is even possible to vary the density in a single part. By producing parts with interconnected pores, the metallurgist can obtain a skeleton that can be impregnated with oils, plastics or a metal having a lower melting point.

Metals and alloys in finely divided form, having a maximum dimension in any direction of one millimeter, are known as metal powders. These are highly engineered materials produced by a number of methods to meet rigidly controlled chemical and physical standards. A number of metal powders, including copper, are available commercially in tonnage lots and any metal, except mercury, can be made in powder form.

Copper and copper alloy powders have been used in industrial applications for many years. Probably the best known is the self-lubricating bearing which was the first major application and still accounts for about 70% of the granular copper powder used. This application takes advantage of the ability to produce a component with controlled interconnected and surface-connected porosity. Advantage of this property is taken also in the production of metallic filters.

Pure copper powder is used in the electrical and electronic industries because of its excellent electrical and thermal conductivities. Alloyed with tin, zinc, nickel and other elements, copper in powder form is used in structural parts and friction materials. Brasses, bronzes and other copper alloys produced by powder metallurgy methods have the physical and mechanical properties of their cast or wrought counterparts. Copper is used also as an alloying element in iron powder components to enhance the mechanical properties and control dimensional changes during sintering, the addition being made either by mixing or by infiltration.

In addition to the above applications of granular copper powder a large quantity of copper and copper alloy powder is used in flake form, i.e., as a powder whose thickness is small in relation to its other dimensions. Such powders are used, for example, in anti-fouling paints, decorative and protective coatings and printing inks.

Copper and copper alloy powders are also used in such non-structural applications as brazing, cold soldering, mechanical plating, and for medals and medallions, metal-plastic decorative products, and chemical and medical purposes.

PRODUCTION AND PROPERTIES OF COPPER AND COPPER ALLOY POWDERS

Granular copper powder can be produced by a number of methods, the most important being atomization, electrolysis, hydrometallurgy and solid state reduction. Each method yields a powder having certain inherent characteristics.

Atomization

Typically, copper is melted and the liquid metal flows through an orifice where it is struck by a high velocity stream of gas or liquid, usually water, thus breaking the molten metal into particles which solidify rapidly. Particle size and shape are influenced particularly by the atomizing medium, the pressure and the flow rate. Controlled small additions of deoxidizing elements, such as phosphorus, also influence the particle size and shape. After atomization and annealing in a reducing atmosphere to decrease any surface oxide formed during atomization, the product is milled, classified and blended to achieve the particle size distribution required.

The purity of the product depends on that of the raw material since refining of the melt prior to atomization is generally not practiced. Purity is generally over 99%. The powder can be made either spherical or irregular in shape. Particle size and shape, apparent density,* flow and green strength are influenced not only by atomization variables

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*See Glossary for definitions of technical terms.

but also by controlling oxidation during atomization, subsequent reduction during annealing, and by final processing. Typical particle shapes are shown in Figure 1.

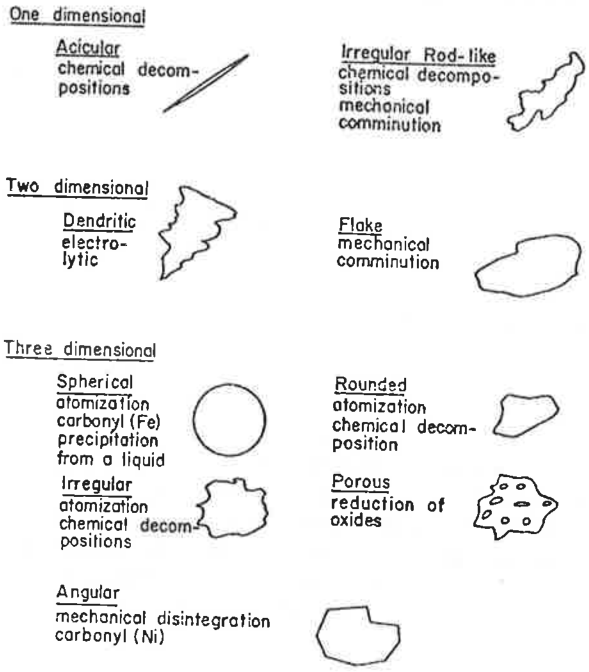

FIGURE 1. PARTICLE SHAPES

Electrolysis

Electrolytic copper powder is produced by following principles used in electroplating with the conditions changed to produce a loose powdery deposit rather than a smooth adherently solid layer. The formation of powder deposits that adhere loosely to the cathode is favored by low copper ion concentration in the electrolyte, high acid concentration and high cathode current density. The addition of colloids, such as glucose, results in the formation of a uniform copper deposit. The starting material is pure cathode copper. Properties of the powder depend on a number of variables including the concentration of sulfuric acid and copper sulfate, type and quantity of the addition agent, temperature of the electrolyte, the current density and the frequency of brush-down. After deposition, the powder is washed to remove all traces of the electrolyte, annealed in a reducing atmosphere, fed to high velocity impact mills to break up clusters, screened, classified and blended to the desired particle size distribution. The properties are influenced also by the temperature used in reducing the powder.

The copper powder obtained by electrolysis is high purity material, averaging more than 99% copper. The powder is dendritic in shape as indicated in Figure 1. A wide range of powders having different apparent densities and high green strengths can be obtained by this method.

Hydrometallurgy

The hydrometallurgy process can be used to produce copper powder from cement copper, concentrates or scrap copper. The copper is leached from these materials with sulfuric acid or ammoniacal solutions and the pregnant solution is separated from the residue by filtration. The copper is precipitated from solution by reduction with hydrogen under pressure. In one process, for example, reduction is accomplished in an autoclave at 225–280F (107–138C) in one hour under a partial pressure of hydrogen of 400 psig (total pressure 425 psig) with a thickening agent added to minimize plating and control the particle size. During reduction, 90–95% of the copper is precipitated as powder. The powder is pumped as a slurry to a centrifuge where the powder is separated from the liquid and washed. The wet copper powder is dried in a reducing atmosphere, milled, classified and blended to achieve the particle size distribution desired. The physical characteristics of the powder can be varied over a considerable range. Temperature and time of reduction and the quantity of acrysol addition have a marked influence on the powder properties.

The process yields a high purity powder, averaging more than 99% copper. Generally, the powder obtained has fine particle sizes with relatively low apparent densities and high green strength. The particle shape is indicated in Figure 1.

Solid State Reduction

In this method, oxides including mill scale are first ground to control particle size and then reduced by a gas, usually carbon monoxide, hydrogen or cracked natural gas at temperatures below the melting point of copper. Particle size and shape can be controlled within rather wide limits by varying the particle size and shape of the oxides, the reducing temperature, pressure and flow of the gas. The resulting powder is milled, classified and blended to the desired specifications.

The purity of the product depends on the purity of the oxide since there is no refining during the reduction process. Generally, the powders produced by this method tend to be porous and have high apparent densities and green strength. An irregular particle shape is obtained as is indicated in Figure 1.

Production of Alloy Powders

Most alloy powders are produced by atomization. Preblended powders are mixtures of the desired composition, with or without lubricant, which will form the alloy during sintering. Pre-alloyed powders are produced by atomization of the alloy composition by the methods mentioned for the production of copper powder. Prealloyed powder can also be produced by sintering a blend and grinding to obtain powder with desired characteristics.

Alloy powders are available commercially in various materials. They include brasses ranging from 95Cu-5Zn to 60Cu-40Zn (and leaded versions of these alloys), nickel silvers, tin bronzes, aluminum bronzes and beryllium bronzes. As mentioned previously, any copper alloy can be produced in powder form.

Production of Flake Powders

The powders discussed previously have been granular in form and are used primarily for the production of P/M parts. Flake powders are used for other purposes. Although pure copper powder is produced in flake form, most flake powder, the so-called "gold bronze" powders, is produced from alloys of copper with zinc and aluminum. Special colors are produced by modifying the base alloys with tin or nickel.

The alloy is powdered by atomization or is melted to produce spatter and the particles are charged into ball mills with a lubricant such as stearic acid and reduced to the desired fineness. Alternately, the Hall paste process involving ball milling in mineral spirits or the Hametag modification of ball milling can be employed. After milling, additional lubricant is added and the powder is polished in drums and stored to develop suitable leafing properties.

Production of Copper Compounds

Cuprous oxide (Cu_2O), cupric oxide (CuO) and cuprous sulfide (Cu_2S) are produced as powders by the controlled reaction of oxygen with copper powder. The products are used in antifouling paints (Cu_2O), reagents in chemical reactions, catalysts in the production of silicone compounds and in foundries for hydrogen degassing of nonferrous melts.

Properties of Copper Powder

The properties of the granular copper powders produced by the methods described are indicated in Table 1. As has been noted, the purity is influenced by the purity of the raw material and the method of preparation. Electrolytic powder is produced from high purity cathode copper and the powder is consistently more than 99% pure. Powder produced by the hydrometallurgical process, in which copper is dissolved preferentially from the raw material, also is a high purity product consistently greater than 99% copper. No refining occurs during atomization or solid state reduction and the purity of the powder depends on that of the raw material used as feed, which is selected to produce powder with 99% purity.

In addition to analysis for trace elements, other chemical characteristics are indicated by loss of weight in hydrogen and "acid insolubles." Loss of weight in hydrogen, indicated in the table, is a measure of the oxygen content of the material—the finer the powder, the greater the oxygen content because of the greater surface area. The acid insolubles value is a measure of the amount of material insoluble in mineral acid. In copper, a large part of this material is found to be complex compounds of copper with other elements.

Particle shape depends on the production method. Copper powders, produced by the methods discussed, can be spherical, irregular or dendritic. The shape influences the density, surface area, permeability and flow characteristics.

Porosity also varies with the production method and influences the density. Internal pores reduce the density but make no contribution to the activity of the particle. Pores connected with the surface reduce the density but also increase the effective surface and the activity.

The surface area depends on the size, shape and surface conditions of the particles and the particle size distribution. The finer the particles the greater the specific surface. An irregular shaped particle will have a greater surface area than a spherical powder of the same size. Surface roughness and surface connected porosity can increase the specific surface many times more than the area associated only with size and shape factors. The activity of a particle generally increases with increasing surface area. Specific surface is significant because reactions, such as sintering, begin at the surface. Activity influences chemical properties and diffusion.

TABLE 1. TYPICAL PROPERTIES OF COPPER POWDER PRODUCED BY VARIOUS METHODS

	Atomized	Electrolytic	Hydro-metallurgy	Solid State Reduction
Copper, %	99–99.5	99–99.5	99–99.5	98–99
Weight Loss in H_2, %	0.1–0.75	0.1–0.75	0.1–0.75	0.1–0.75
Acid Insoluble, %	0.5–0.1 max	0.03 max	0.03 max	0.3 max
Apparent Density, g/cm^3	2–4	1.5–4	1.5–2.5	2–4
Flow, sec/50 g	20–35	30–40	none	20–35
Green Strength, psi	nil-2500	400–6000	nil-10,000	nil-2500
MPa	nil-17.2	2.8–41.3	nil-68.9	nil-17.2
–325 mesh, %	25–80	5–90	60–95	25–50

Source: Reference 1.

Bulk Properties

The properties are also influenced by the characteristics of a mass of powder. The particle size can be varied over wide ranges and the average particle size is the statistical average of all particles in the mass. The particle size distribution is influential in determining the flow and packing of powders.

The apparent density is the weight of a unit volume of the powder under specified conditions. It is a function of the size, shape and particle size distribution and is also influenced by the relative surface area and the packing properties of the powders. Apparent density is important in pressing operations because the die is generally filled by volume.

Flow is a measure of the time required for a specified quantity of powder to flow through an orifice of specified dimensions. It is a function of particle size distribution and shape but is also influenced by friction and other variables. Flow determines the time required to fill a die and thus determines the production rate that can be achieved.

Green strength is determined by compacting a mass of powder under specified conditions and breaking the compact. The strength is calculated from the dimensions of the compact and the breaking load. It is a measure of the strength of the compact before sintering.

As indicated in Table 1, considerable variation in properties can be obtained with various types of powders. Although various types can be used interchangeably, individual characteristics give certain powders distinct advantages in some applications.

For example, atomized copper powder is suitable for most P/M applications because it has a high flow rate and good strength. It can be used in electronic and electrical applications requiring high conductivity provided high purity copper powder is specified.

Electrolytic copper powder, because of its high purity, is particularly suited for P/M components in the electronic and electrical industries where high electrical and thermal conductivities are required. However, it is suitable for most other P/M applications as well.

Hydrometallurgical processing generally yields a powder having fine particle sizes, low apparent density and high strength. With these properties, it is particularly suited for use in friction materials.

Powders produced by solid state reduction have characteristics similar to those of atomized powders and are suitable for the same applications.

COPPER POWDER CONSOLIDATION TECHNIQUES

Compaction

The consolidation of a mass of powder is usually performed in a closed die although other means such as roll compaction, isostatic compaction, extrusion or forging can be used. Parts can also be produced by slip casting using the techniques employed in pottery making. Regardless of the technique employed, each produces densification of the powder mass that can be related to the density of the solid metal as its upper limit.

Most granular copper powder is used in the production of P/M parts and, generally, a closed die is used to form a specific shape. As pressure is applied, the operation proceeds in a series of stages: (1) slippage of the particles with little deformation, (2) elastic compression of contact points between particles, (3) plastic deformation of these points to form contact areas of gradually increasing size and (4) massive deformation of the entire powder mass.[2] To achieve uniform densification it is necessary to select a particle size distribution which will permit uniform packing in the die. It is also necessary to select suitable pressing conditions.

Different materials require different compacting pressures. Pure copper P/M parts are produced with relatively low pressures. An initial compacting pressure of 34 to 40 ksi (234–276 MPa)* has been recommended for thin sections although higher pressures can be used for heavier sections.[3] The objective is to permit the escape of gases and water vapor formed by the internal reduction of oxides during sintering. Compacting pressures that are too high will prevent proper sintering of the center of the compact and reduce the electrical conductivity and the strength. Recommended pressures and compression ratios for some copper and copper alloy compacts are given in Table 2.

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*Throughout the report strength properties and stresses are given in U.S. units of thousand pounds per square inch (ksi) and in metric (S.I.) units of megapascals (MPa).

TABLE 2. TYPICAL COMPACTING PRESSURE AND COMPRESSION RATIOS FOR VARIOUS COPPER POWDER PRODUCTS

Typical P/M Part	Compacting Pressure tons/sq. in	Compacting Pressure MPa	Compression Ratio
Brass Parts	30–50	414–690	2.4–2.6:1
Bronze Bearings	15–20	207–276	2.5–2.7:1
Copper-Graphite Brushes	25–30	345–414	2.0–3.0:1
Copper Parts	15–18	207–248	2.6–2.8:1

Solid State Sintering

Sintering is the bonding of particles in a mass of powder by atomic or molecular attraction in the solid state through the application of heat. Powders differ from massive metals in having a much greater ratio of surface area to volume. Consequently, the surface energy is greater. During sintering, changes in the shapes of the pores and a reduction in their volume reduces the surface energy.

Sintering can be considered to proceed in three stages. During the first, neck growth proceeds rapidly but powder particles remain discrete. During the second, most densification occurs, the structure recrystallizes and particles diffuse into each other. During the third, isolated pores tend to become spheroidized and densification continues at a much lower rate.[5] Figure 2 illustrates the progress of densification of compacted copper powder as a function of time and temperature.

The rate of sintering has a significant effect on compact properties and can be modified by either physical or chemical treatments of the powder or compact or by incorporating reactive gases in the sintering atmosphere. These treatments are known as activated sintering. The favorable influence of reducible oxide films on copper powder compacts has been known for years. The activation effect is shown by improvements in densification, strength and electrical conductivity of the compacts.

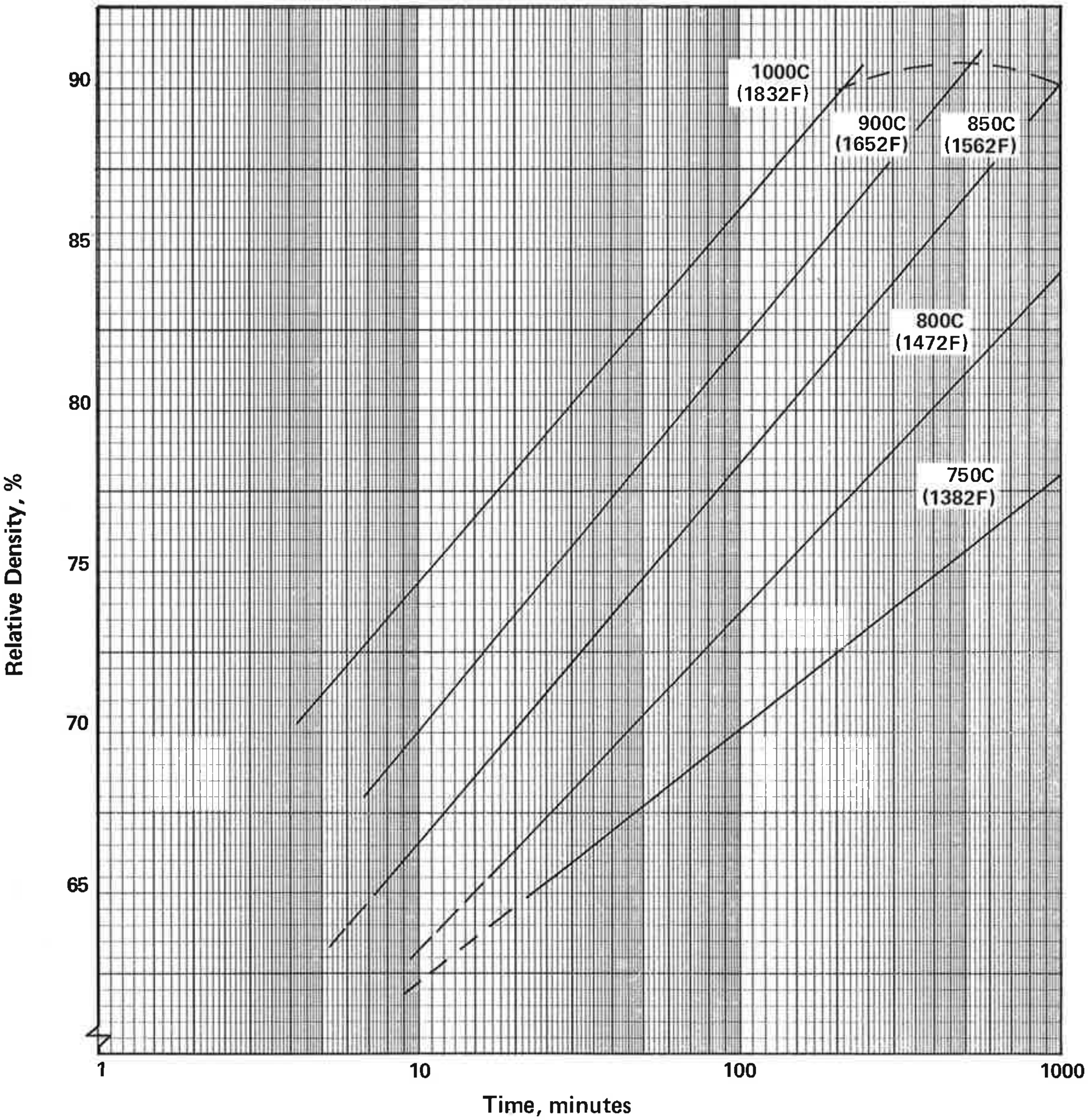

FIGURE 2. EFFECT OF SINTERING TEMPERATURE AND TIME ON DENSIFICATION OF COPPER POWDER COMPACTS. Source: Reference 6.

As an example of chemical treatments, improvements in densification of copper powder treated with aqueous formic acid are indicated in Figure 3.

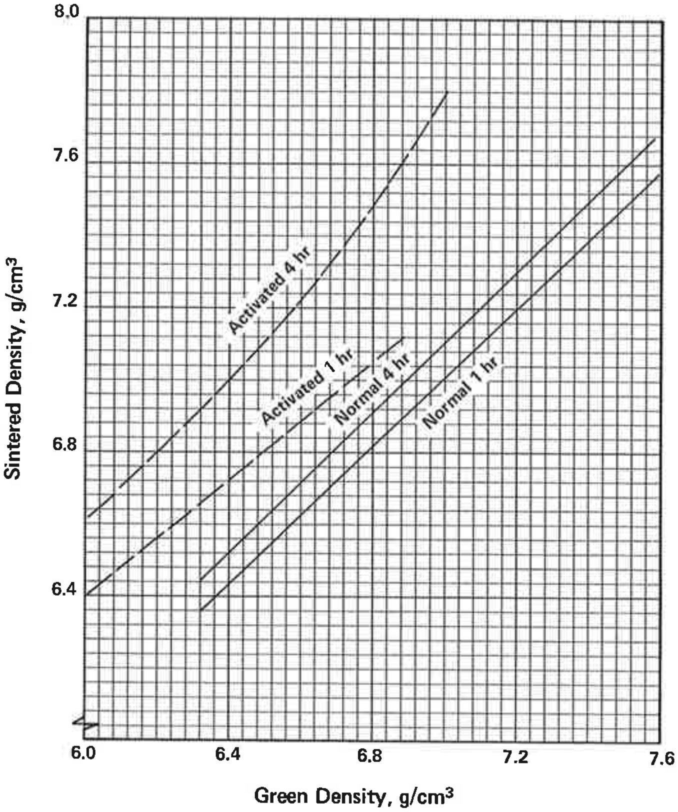

FIGURE 3. EFFECT OF ACTIVATED SINTERING ON DENSITY OF SINTERED COPPER.
Source: Reference 7.

Liquid Phase Sintering

In liquid phase sintering a mixture of two or more powders is sintered at a temperature below the melting point of the high-melting constituent but above that of the low-melting constituent.

Liquid phase sintering applies to pre-mixed powders of copper-tin and iron-copper, for example. If the constituents are properly mixed, the behavior on sintering depends on the wetting properties of the two metals. The mechanism of liquid phase sintering can be explained by considering three overlapping actions: (1) the liquid phase allows rearrangement and rapid shrinkage of the solid material, (2) dissolution and re-precipitation occur with accompanying densification and (3) coalescense occurs when the liquid phase disappears.[5]

In the copper-tin system, the tin melts and alloys with the copper to form a bronze with the accompanying expansion of the compact. Figure 4 is a photomicrograph showing the structure of a typical sintered bronze part. In the iron-copper system, the copper melts, becoming saturated with iron, and the copper-iron alloy diffuses into the iron skeleton, causing expansion of the skeleton. Pores remain at the sites vacated by the copper.

In both the copper-tin and the iron-copper systems, growth or shrinkage of compacts can be modified by the addition of carbon in the form of graphite. Thus, graphite can be used to control dimensional changes in these systems. In the copper-tin-carbon system, sintering is inhibited by mechanical separation of the constituents and, as a result, expansion increases. In the iron-copper-carbon system, the proportion of the liquid phase is increased by the formation of a ternary iron-copper-carbon eutectic which restricts expansion.

CHARACTERISTICS AND PROPERTIES OF COPPER AND COPPER ALLOY P/M MATERIALS

Pure Copper P/M Parts

The physical properties of pure copper in massive form are given in Table 3. Outstanding are the electrical and thermal conductivities which are markedly higher than those of any other base metal and are exceeded only by silver. A copper powder with a purity exceeding 99.95% is available and, of course, the individual particles have the same properties as massive copper. However, it is impractical to achieve a density of 8.94 g/cm^3 by pressing and sintering alone and, therefore, the properties of P/M parts are influenced by the density attained. Densification can be increased by additional operations such as double pressing-double sintering or forging, for example, and the properties of the P/M part approach those of the massive metal as a limit.

The final sintered density has a significant effect on the conductivity of a P/M product. Conductivity is directly affected by porosity; the greater the void content, the lower the conductivity. Since the conductivity of a pore is

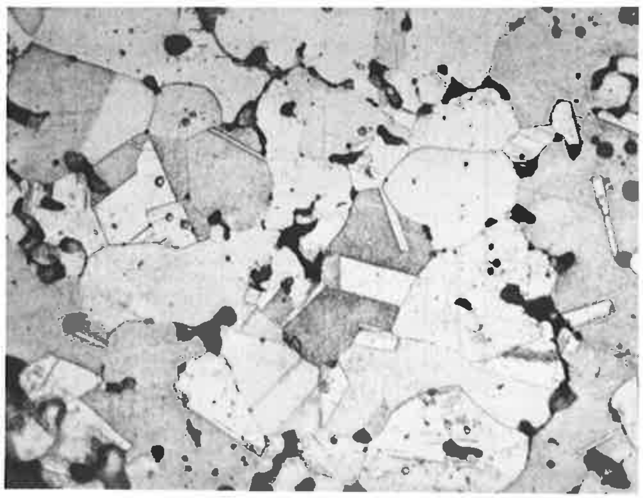

FIGURE 4. MICRO STRUCTURE OF SINTERED BRONZE (Magnification: 200X).

TABLE 3. PHYSICAL PROPERTIES OF MASSIVE (FULLY DENSE) COPPER

	English Units	C.G.S. Units
Melting Point	1981 F	1083 C
Density	0.323 lb/in^3 @ 68 F	8.94 g/cm,^{3} @ 20 C
Coef. Thermal Expansion	9.4 x 10^6/F (68–212 F)	17.0 x 10^6/C (20–100 C)
Thermal Conductivity	226 Btu/ft^2/ft/hr/F@ 68 F	0.934 cal/cm^2/cm/sec/C @ 20 C
Electrical Resistivity	10.3 ohms (circ mil/ft)@ 68 F	1.71 microhm-cm @ 20 C
Electrical Conductivity*	101% IACS @ 68 F	0.586 megmho-cm @ 20 C
Specific Heat	0.092 Btu/lb/F @ 68 F	0.092 cal/g/C @ 20 C
Modulus of Elasticity (Tension)	17,000 ksi	117,000 MPa
Modulus of Rigidity	6,400 ksi	44,000 MPa

*Volume Basis
Source: Reference 8.

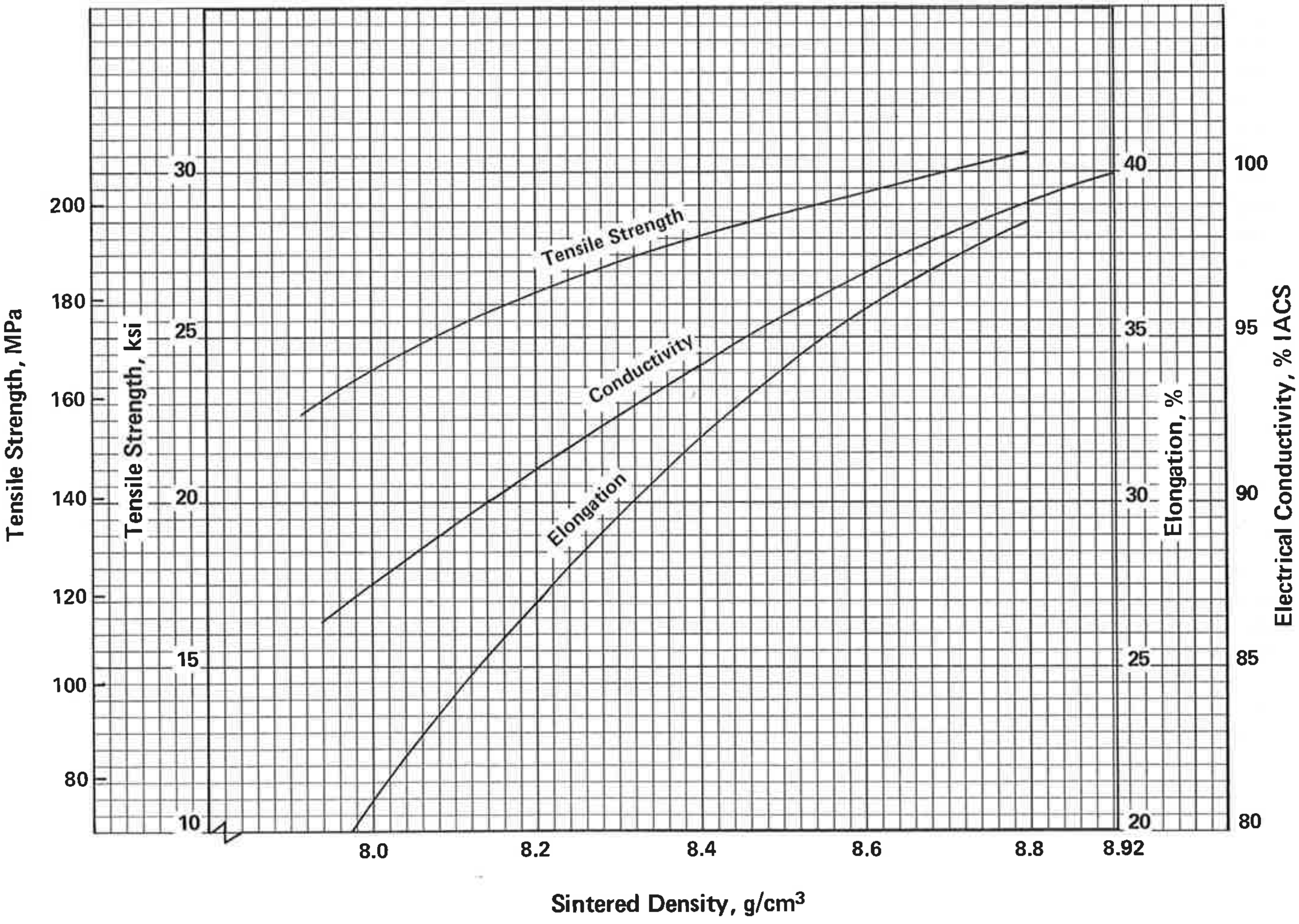

FIGURE 5. EFFECT OF DENSITY ON THE PROPERTIES OF SINTERED COPPER. Source: Reference 3.

zero, the relationship between porosity and conductivity is given by the equation:[9]

$$K = K_s(1\text{-}f)$$

where K = thermal or electrical conductivity of the P/M part
K_s = intrinsic thermal or electrical conductivity of the massive metal
f = fractional porosity

As pressed and sintered, the electrical conductivity of pure copper parts can range from 80 to 90% IACS and higher conductivities can be achieved by additional working of the parts. The effect of sintered density on the electrical conductivity and mechanical properties of sintered copper is indicated in Figure 5.

The high electrical conductivity and excellent ductility that can be achieved in copper P/M compacts lead to the selection of pure copper powder for P/M parts for electronic and electrical applications where conductivity is essential. Such parts include commutator rings, contacts, shading coils, nose cones and twist-type electrical plugs. A specific application is a diode used as the base of the silicon rectifier for the alternator charging systems in automobiles.

Copper powders are used in copper-graphite compositions, which have low contact resistance, high current-carrying capacity and high thermal conductivity for brushes in motors and generators and as moving parts of rheostats, switches and current-carrying washers. These powders are also used to produce electrode tools for electrical discharge machining of complex dies. Copper powder is selected for its high electrical and thermal conductivity.

Pure copper is also used in non-electrical P/M applications. An interesting example is a copper blade shank which is impregnated with grease to increase the service life of a pocket knife.

Bronze P/M Parts

Most tin bronze parts are produced from pre-mixes although some are made from pre-alloyed powder. Since pre-alloyed powders have higher yield strengths and work hardening rates than pre-mixed powders, the pressing loads required to achieve a given green density are higher than those required when pressing elemental powders. The differences in pressing characteristics of pre-mixed and pre-alloyed powders are indicated in Figure 6.

Processing variables influence the properties. In an investigation in which 90Cu-10Sn and 88.6Cu-9.9Sn-1.5C (graphite) pre-mixed powders were used, the optimum strength was achieved when the tin-rich phase was completely alloyed with the copper but little grain growth had occurred. Figure 7 shows the effect of density and graphite content on the strength of the bronze.

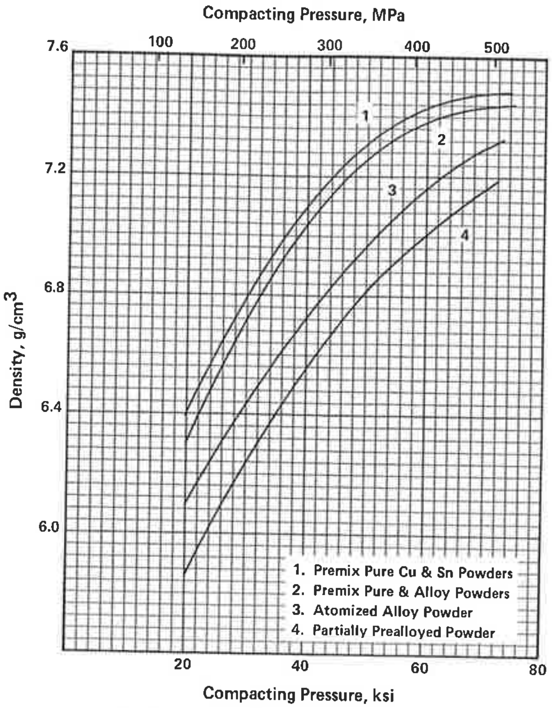

FIGURE 6. PRESSING CHARACTERISTICS OF PRE-MIXED AND PRE-ALLOYED 90Cu-10Sn POWDERS. Source: Reference 10.

Properties of tin bronze P/M parts are influenced also by such factors as heating rate and sintering time and temperature. Faster heating rates tend to produce greater growth than slow heating rates. Sintering temperature influences both growth and strength. Sintering time influences dimensional control and strength; rapid growth occurs at the beginning of sintering and is followed by a period of predictable slow shrinkage. By completing sintering in the shrinkage range, it is possible to maintain dimensional control over the bronze P/M product.

Bearings—A unique attribute of powder metallurgy is the ability to produce porous products with interconnected porosity. This attribute made possible the development of the self-lubricating bronze bearing, an early P/M product, the first having been used in a Buick automobile in the 1920's. Depending on the sintered density, these bearings can absorb from 10 to 30% by volume of oil and can supply a continuous lubricating film even at low speeds. Porous bronze bearings also have the advantage that they are sufficiently ductile to permit assembly by ring staking.

Development of these bearings revolutionized the home appliance industry. By eliminating the requirement of periodic lubrication, the self-lubricating bearing assured many years of trouble-free operation of home appliances and led to a great expansion of the industry. New applications continue to be found and the self-lubricating bronze bearing industry consumes a major portion of the copper powder produced each year.

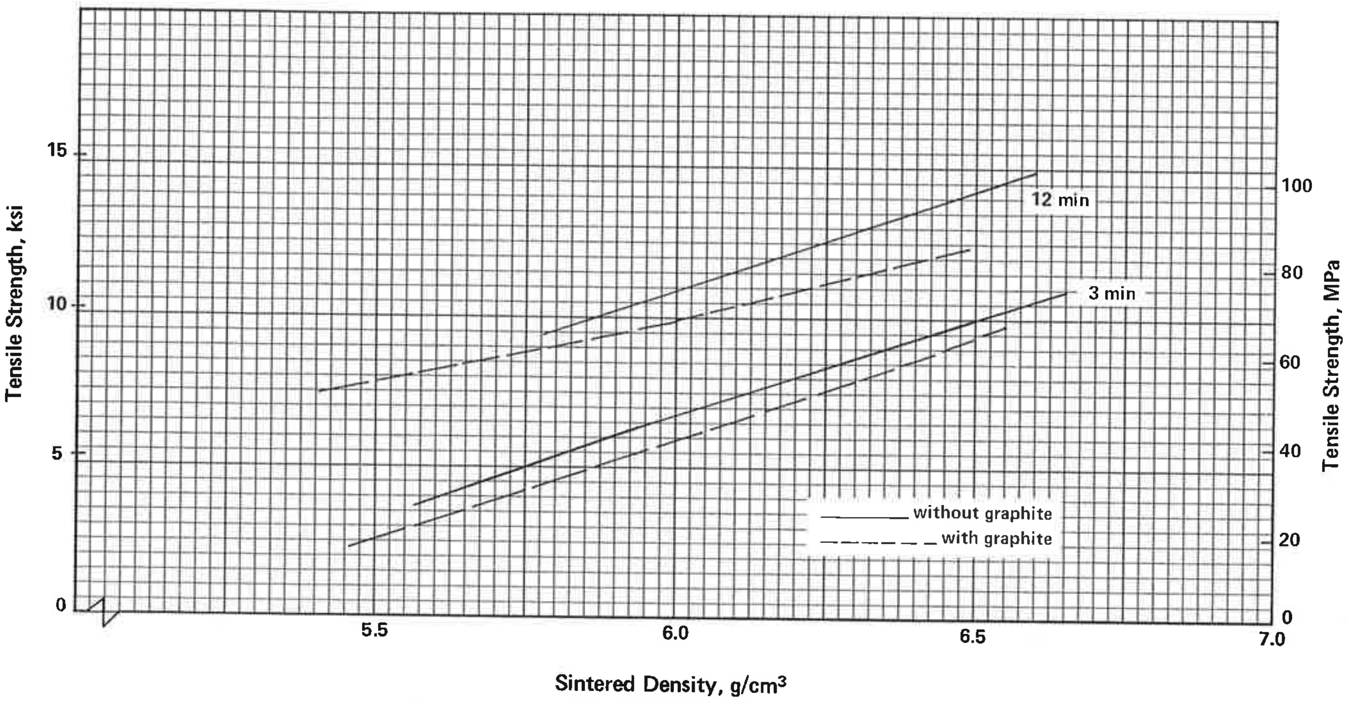

FIGURE 7. EFFECT OF DENSITY ON THE STRENGTH OF COPPER-TIN AND COPPER-TIN-GRAPHITE COMPACTS. Source: Reference 11.

Self-lubricating porous bronze bearings depend on conduction and convection for heat dissipation during service. The frictional heat developed is proportional to PV μ where P is the pressure on the bearing, V is the surface velocity and μ is the coefficient of friction. Practical limits for safe operation of these bearings are often set at a PV factor of 50–60 ksi (345–414 MPa). These bearings are installed by pressing into rigid reamed or bored housings.

Porous bronze bearings are used widely in automotive service, household appliances, automatic machines and industrial equipment in two types of applications:

> (1) For low-duty shaft bearings where the static load carrying capacity is adequate; where lubrication is impossible; and where the only requirement is low cost and avoidance of heating, seizure or squeaking throughout the life of the appliance or machine.
>
> (2) As an alternate to an oil bottle or ball bearing in medium to heavy duty applications. In these applications, facilities for relubrication must be supplied.[12]

There are many other uses for these bearings. For example, in space vehicles, bronze P/M bearings have been used as sleeve bearings for attitude control mechanisms, solar panel hinges and stepping device bushings in tape recorders and commutators.

Filters—The ability to achieve close control of porosity and pore size is the basis for the use of metal powders as filters. Most producers prefer spherical powder of closely controlled particle size to permit the production of filters within the desired pore size range. Tin bronze is probably the most widely used filter material but nickel silver and copper-nickel-tin alloys are also used. The effective pore size can be varied widely but for P/M filters generally ranges from 5 to 125 microns. P/M bronze filters can be obtained with tensile strengths ranging from 3 to 20 ksi (21–138 MPa) and appreciable ductility, up to 20% elongation. In addition, P/M bronze has the same corrosion resistance as cast bronze of the same composition and therefore can be used in a wide range of environments.

P/M bronze filters are used to filter gases, oils, refrigerants and chemical solutions. They have been used in fluid systems of space vehicles to remove particles as small as one micron. Bronze diaphragms can be used to separate air from liquids or mixtures of liquids that are not emulsified. Only liquids capable of wetting the pore surface can pass through the porous metal part.

Bronze filter materials can be used as flame arrestors on electrical equipment operating in flammable atmospheres where the high thermal conductivity of the bronze prevents ignition. They can also be used on vent pipes on tanks containing flammable liquids. Here again, heat is conducted away so rapidly that the ignition temperature is not reached.

Aluminum bronze P/M parts containing from 5 to 11% aluminum are prepared from blends of the elemental powders. Alloys containing from 5 to 9% aluminum are single-phase materials and have excellent ductility. They can be strengthened by cold working. Alloys containing from 9 to 11% are two-phase materials which are less ductile than the alloys of lower aluminum content. However, they can be heat treated to increase their strengths.

The sintered yield strength increases from 11 ksi (26 MPa) at 7% aluminum to 40 ksi (276 MPa) at 11% aluminum; heat treatment of the latter alloy increases the yield strength to 60 ksi (414 MPa). Tensile strengths increase uniformly from 32 ksi (221 MPa) for the 7% alloy to 65 ksi (448 MPa) for the heat treated 11% alloy. Elongations of the 5 to 9% alloys are in the 25 to 35% range; the two-phase alloys are considerably less ductile.[13] These properties make the P/M aluminum bronzes suitable for the production of parts where the strength requirements are too high to be met by the tin bronzes.

Limited corrosion data indicate that these P/M aluminum bronzes have properties similar to those of the cast and wrought counterparts. With this combination of strength and corrosion resistance the alloys can be used for the production of P/M parts such as impellers, gears, connecting rods and similar components.

Brass and Nickel Silver P/M Parts

Commercial brass powders are available in the simple brasses ranging from 95Cu-5Zn to 60Cu-40Zn and leaded versions of these brasses, and in modified brasses containing such elements as phosphorus, manganese and silicon. Nickel silver powders containing 64Cu-18Ni-18Zn and 64Cu-18Ni-16.5Zn-1.5Pb are also available on the commercial market. These powders are produced by atomizing alloy melts.

Optimum properties are attained by preheating to drive off lubricants and sintering in a cracked ammonia atmosphere. The P/M parts produced by such procedures have mechanical properties comparable with those of the corresponding cast alloys. Typical properties of representative brasses and nickel silvers are given in Table 4. These P/M alloys have moderate strength with good ductility.

Next to bronze bearings, the brasses and nickel silvers are the most widely used materials for structural P/M parts. Examples of the many applications are hardware for latch bolts and cylinders for locks; shutter components for cameras; gears, cams and actuator bars in timing assemblies; small generator drive assemblies; and decorative trim and medallions.

Copper Nickel P/M Materials

Copper nickel P/M alloys containing 75Cu-25Ni and 90Cu-10Ni have been developed for coinage and corrosion resisting applications. The 75Cu-25Ni alloy pressed at 112 ksi (690 MPa) has a green density of 89% of theoretical. After sintering at 2000F (1090C) in dissociated ammonia, the elongation was 14% and the apparent Rockwell hardness B20. A repressing at 112 ksi (690 MPa) increased the density to 95%. This alloy has the color of stainless steel and can be burnished to a high luster. The 90Cu-10Ni under similar pressing and sintering conditions has a final density of 99.4%. It has a bright bronze color and can also be burnished to a high luster.[15]

In one method of producing coins, medals and medallions, a mixture of 75Cu-25Ni powders with zinc stearate

TABLE 4. TYPICAL MECHANICAL PROPERTIES OF BRASS AND NICKEL SILVER P/M COMPACTS PRESSED AT 30 TONS/SQ. IN. (414 MPa)

Nominal Composition	Sintered Density g/cm^3	Tensile ksi	Strength MPa	Elongation % in 1 in.	Rockwell Hardness
Brass					
90Cu-10Zn	8.1	30	207	20	H77
85Cu-15Zn	8.2	31.5	217	20	H82
70Cu-30Zn	8.1	38	262	21	H87
88.5Cu-10Zn-1.5Pb	8.4	30	207	25	H76
80Cu-18.5Zn-1.5Pb	8.2	34.5	238	31	H82
68.5Cu-30Zn-1.5Pb	7.7	34.6	239	29	H71
Nickel Silver					
64Cu-18Ni-18Zn	7.9	34	234	12	B83
64Cu-18Ni-16.5Zn-1.5Pb	7.8	28	193	11	B84

Source: Reference 14.

lubricant is compressed, sintered, coined and resintered to produce blanks suitable for striking. These blanks have the advantage over rolled blanks of being softer because they are produced from high purity material. Therefore, they can be coined at relatively low pressures and achieve greater relief depth with decreased die wear.

In another procedure, organic binder is mixed with copper or copper nickel powders and rolled into "green" sheets. Individual copper and copper-nickel sheets are pressed together to form a laminate and blanks are punched from it. The blanks are heated in hydrogen to remove the organic binder and sinter the material. The density of the "green" blanks is low, being only about 45% of theoretical, but coining increases the density to 97%. After pressing, the blanks are annealed to improve ductility and coinability.[16]

Copper-Lead and Copper-Lead-Tin P/M Materials

Metals such as copper and lead which have very limited solubilities in each other are difficult to alloy by conventional means but copper-lead powder mixtures have excellent cold pressing properties. They can be compacted at pressures as low as 11 ksi (76 MPa) to densities as high as 80% and, after sintering, can be repressed at pressures as low as 22 ksi (152 MPa) to produce essentially non-porous bearings.

Copper-lead sintered bearing materials with a lead content of 40–45% have tensile strengths of about 11 ksi (76 MPa), Vickers hardness values of about 32 and a fatigue strength of 3 ksi (21 MPa),which is almost double that of a white metal bearing. The surface properties are good enough to permit use in an automobile engine without an overlay.

Copper-lead alloys containing about 30% lead are stronger but have less satisfactory surface properties and are usually used with a thin lead-tin overlay.

If the copper-lead alloys do not have sufficient load-carrying capacity, the lead content is reduced and tin is added to improve the strength. Typical is a 74Cu-22Pb-4Sn composite. This material has a tensile strength of 17 ksi (117 MPa) and a Vickers hardness of 50. Its fatigue strength of 5 ksi (34 MPa) is almost three times that of white metal liners. However, an overlay is required if this alloy is to be used in an automobile engine.

Where still greater strength and hardness are required, an 80Cu-10Pb-10Sn alloy is used. This composition usually has a Vickers hardness of 60 to 80 but can be cold worked to a hardness as high as Vickers 130. It has a tendency to seize, however, and is normally used with grease rather than oil lubrication.

Steel-backed copper or copper-lead-tin P/M materials are being used in an increasing number of applications to replace solid bronze bearings. They are produced by spreading the powder in a predetermined thickness on a steel strip, sintering, rolling to theoretical density, resintering and annealing. The final product has a residual porosity of about 0.25%. Blanks of suitable size are cut from the bimetallic strip, formed and drilled with oil holes or machined to form suitable grooves. These materials are represented by four groups:

(1) A Cu-25Pb-0.5Sn alloy is used with an overlay plate for high load applications.
(2) A Cu-25Pb-3.5Sn alloy is used widely for such applications as cam bearings, turbine bearings, pump bushings and high speed thrust washers.
(3) A Cu-10Pb-10Sn alloy is used for shock and oscillating loading applications such as piston pin bushings, rocker arm bushings, wear plates and thrust washers.
(4) A Cu-50Pb-1.5Sn alloy is used for intermediate duty applications.[17]

Dispersion-Strengthened P/M Materials

Copper P/M products can be strengthened by incorporating finely dispersed particles of oxides such as alumina, titania, beryllia, thoria or yttria in the matrix. Dispersions can be made by mechanical mixing, internal oxidation or co-precipitation. For example, the Bureau of Mines prepared copper-alumina dispersions by co-precipitation of the nitrates of copper and aluminum with ammonia, conversion of the product to oxides, reduction by hydrogen, compaction and extrusion.[18] Others have consolidated dispersion-strengthened copper by hot forging or rolling.

Dispersion strengthening has a number of advantages. Since the oxides are inert, they reduce the electrical conductivity only to the extent that they reduce the cross-section of the material. Thus, electrical conductivities on the order of 80 to 95% IACS can be achieved. However, the major value of dispersion strengthening is to produce a material that resists softening and grain growth at temperatures approaching the melting point of copper. Dispersion-strengthened materials are superior in structural stability to the precipitation hardenable alloys such as copper-chromium or copper-beryllium because the oxides have no tendency to dissolve at high temperatures, a characteristic of the precipitation hardenable alloys.

For example, a commercial copper-alumina alloy now available has an electrical conductivity of 85% IACS and a room temperature tensile strength of 85 ksi (586 MPa). Approximately 90% of the strength is retained with no loss in conductivity after one hour exposure at 1700F (925C). The precipitation hardenable alloys would be completely soft after a similar treatment.

P/M Friction Materials

A basic attribute of powder metallurgy is the ability to combine materials in powder form that are otherwise immiscible. This unique advantage allows the production of friction materials in which copper and other metal powders are combined with solid lubricants, oxides and other compounds. Metallic friction materials can be operated at higher loads and temperatures than organic friction materials.

P/M friction materials are used as clutches and brakes. Dry applications may include both but wet applications are normally confined to clutches. For brake and clutch facings, powders having high green strength are essential. Such powders characteristically also have high internal porosity, low apparent density and irregular shapes.

There is no definite relation between the physical properties of the brake material and the performance as a friction material. Further, there are so many intangibles that influence friction and wear that the selection of a P/M friction material is still empirical.

Generally, the major portion of the matrix is copper with about 5–15% low melting metal such as tin; 5–25% lubricant which may be lead, litharge, graphite, or galena; up to 20% friction material such as silica, alumina, magnetite, silicon carbide or aluminum silicide; and up to 10% wear resistant materials such as cast iron grit or shot.

Typical compositions are:

- For dry clutches and brakes: 75Cu-6Pb-7Sn-5graphite-4molybdenum disulfide-3feldspar.
- For wet clutches and brakes: 74Cu-3.5Sn-2Sb-16graphite-4.5galena.

Copper-base friction materials perform best under wet conditions. They are also suitable for dry friction applications under relatively mild operating conditions with moderate loads, speeds and temperatures.

Dry clutches are used in highway trucks, machine tools, farm tractors and industrial presses. Dry brakes are used in automobiles and industrial presses. Wet clutches are used for automatic transmissions, machine tools and tractors. Wet brakes are used for off-highway vehicles and military service.

Copper-Tungsten P/M Materials

Copper, nickel and tungsten powders are used in the production of so-called heavy metal, which contains from 80 to 95% tungsten. The alloys are prepared by the liquid-phase sintering of mixed elemental powders during which part of the tungsten dissolves in the copper-nickel liquid. The product is a two-phase material consisting of rounded tungsten grains and a matrix of copper-nickel-tungsten containing up to 17% tungsten.

The density of the alloys ranges from 17 to 18 g/cm^3 and the electrical conductivity is quite low, on the order of 17% IACS. The mechanical properties are strongly influenced by the nickel-copper ratio and by the post-sintering heat treatment. Tensile strengths range from 45 to 125 ksi (310–862 MPa) and elongations from 2 to 8%.

These alloys are used in such applications as gyro rotors, instrument counterweights, airframe counterweights, jet aircraft wing edges and balancing weights for rotating elements in machinery, golf clubs and self-winding wrist watches.

COPPER IN IRON AND STEEL P/M PARTS

Pre-mixes

Copper, which has been used for many years to modify the properties of steels and cast irons, is receiving increasing attention as an alloying element in iron-base P/M parts. These parts can be produced by pressing and sintering mixed elemental powders. Carbon, in the form of graphite, is frequently used to produce steels. Control of dimensions during sintering and optimum mechanical properties are achieved by adjusting the iron-copper or iron-copper-graphite composition. Pre-alloyed powder obtained by atomizing a suitable iron or steel composition can also be used to produce P/M parts, to which metallic copper can be added by mixing. Premixes of iron and copper, with or without graphite, are made by simple blending. These pre-mixes can be fabricated to produce a wide variety of density and strength levels by conventional pressing and sintering. A practical maximum pressure of 90 to 112 ksi (621–772 MPa) for iron-copper pre-mixes without graphite yields a strength range of 40–50 ksi (276–344 MPa) and a density of 6.2–6.4 g/mm^2. With graphite under the same pressing conditions, strength levels of 75 ksi (517 MPa) can be achieved. The properties of iron-base P/M parts containing carbon can be enhanced by heat treatments such as those used for conventional irons and steels.

The properties of iron-copper parts produced from premixed powders are influenced by the type of iron powder. As shown in Figure 8, there can be considerable variation in the strength properties and dimensional

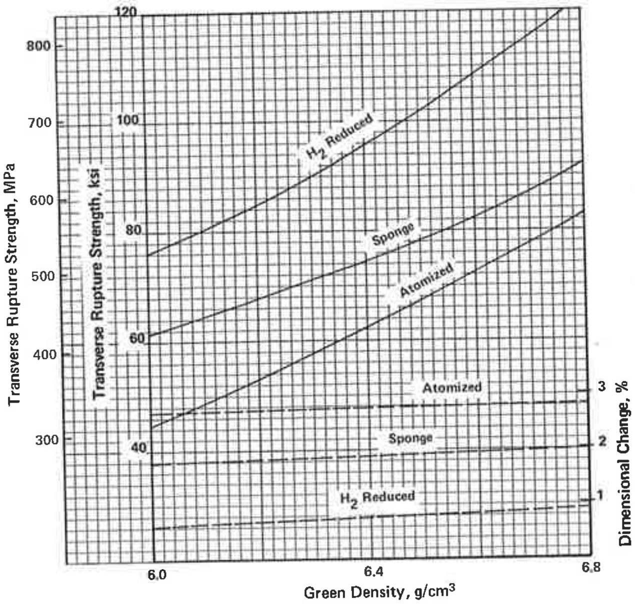

FIGURE 8. EFFECT OF TYPE OF POWDER ON PRE-MIXED IRON—7% COPPER COMPACTS.
Source: Reference 1.

TABLE 5. PROPERTIES OF PRE-MIXED IRON-COPPER AND IRON-COPPER-CARBON P/M COMPACTS

Nominal Composition	Condition	Sintered Density g/cm^3	Tensile ksi	Strength MPa	Yield ksi	Strength MPa	Elongation % in 1 in.	Rockwell Hardness
Cu 1.5–3.9	As sintered	6.6	30	207	21	145	4	B15
C 0.3 max	As sintered	7.0	37	255	23	159	7	B30
Cu 1.5–3.9	As sintered	6.6	50	345	38	262	1.5	B70
C 0.3–0.6*	Heat treated	6.6	85	586	81	558	0.5	C30
	As sintered	7.0	62	428	45	310	3.0	B80
	Heat treated	7.0	100	690	95	655	0.5	C35
Cu 1.5–3.9	As sintered	6.6	60	414	48	331	1.0	B70
C 0.6–1.0*	Heat treated	6.6	80	552	—	—	0.5	C35
	As sintered	7.0	80	552	57	393	1.5	B80
	Heat treated	7.0	100	690	95	655	0.5	C40

*Combined
Source: Reference 19.

changes in P/M parts produced with a constant copper content depending on the type of iron powder used.

Typical mechanical properties of a series of iron-copper-carbon P/M compacts produced from pre-mixed powders are given in Table 5. The effect of carbon on the as-sintered compacts and the property improvements obtainable by heat treatment are apparent.

Pre-mixes of iron-copper and of iron-copper-carbon (graphite) are in use in an increasing number of applications. In wide use is an alloy containing about 2% copper and 0.7% carbon. This alloy is in use in automotive applications such as camshaft drive sprockets, valve rocker arms, lifter parts and oil pump gears. It is used also in chain saw engine connecting rods, differential gears for garden tractors and piston rings for small bore engines and many similar applications.

To cite a few other examples: A low carbon copper P/M steel is used for a 16 mm projector sprocket. A similar steel is used for the eccentric for an automatic dryer belt adjustment. A cam for a business machine, an application requiring high strength and impact resistance together with sufficient porosity for oil impregnation, was produced from a 2%copper-0.6%carbon steel at a density of 6.4 g/cm^3. Cable grips with teeth sufficiently hard to bite into high strength alloy steel cables on a power transmission line support were produced from a similar steel at a minimum density of 6.4 g/cm^3 which was carbonitrided to achieve the required hardness.

Infiltrated Parts

Iron-base P/M parts can be infiltrated with copper or a copper alloy by placing slugs of the infiltrant (which has a lower melting point than the porous body) on the compact prior to sintering. Upon melting, the infiltrant is completely absorbed as a liquid into the pores by capillary action to produce a component with a composite structure. The resulting properties generally depend upon the metals which constitute the structure of the infiltrated part and the manner and proportion in which they are combined.

Infiltration has a number of advantages. It increases the density with a resulting improvement in mechanical properties, improves the corrosion resistance by closing the pores, and improves machinability and brazability. It is possible to achieve tensile strengths in the range 70–90 ksi (482–621 MPa) in iron porous bodies infiltrated with 15 to 25% copper.

Erosion of the porous iron body is a major problem with infiltration. The effect is greatest with pure copper and can be minimized by using a copper-iron alloy to which other elements such as manganese, nickel and aluminum have been added to lower the melting point and act as deoxidants during infiltration. The properties of the infiltrated part are influenced by the type of iron powder, infiltrant type and composition, furnace conditions and any heat treatment performed after infiltration.

Table 6 indicates the properties obtainable in infiltrated iron parts with and without carbon additions. The presence of carbon results in a considerable increase in strength even in the as-sintered condition but at a reduction in ductility. Ductility in the carbon-free alloy can be improved greatly by normalizing and there is little reduction in strength. Heat treatment of the alloy containing carbon produces parts with excellent strength accompanied by ductility that is superior to that obtained in premixed material of similar carbon content.

Copper-infiltrated iron parts are particularly suitable for applications requiring good resistance to shock loading and good fatigue strength accompanied by resistance to wear. Some examples are:

A clutch hub for an automatic transmission, formerly produced by machining internal and external splines on a forging, was switched to a copper-infiltrated iron P/M part with a cost reduction of 25%.

TABLE 6. PROPERTIES OF INFILTRATED 75% IRON-25% COPPER COMPACTS

Carbon %	Heat Treatment	Sintered Density g/cm^3	Tensile ksi	Strength MPa	Reduction of Area %	Elongation % in 1 in.	Rockwell Hardness	Izod Impact ft-lb
0	None	8.02	68	469	13	8	B74	5.0
1*	None	7.96	105	724	4.8	4	B93	1.0
0	Norm 1800F (980C); 950F(510C), 4 hr	7.95	60	414	20.5	18	B71	11.3
0	Norm 1800F (980C); 950F (510C), 4 hr; 1300F (700C) 2 hr	8.01	58	400	44.3	25	B70	14.9
1*	Norm 1800F (980C); 1550F (840C), w.q.	7.98	159	1096	3.7	3.2	B110	1.0
1*	Norm 1800F (980C); 1550F (840C), w.q.; temper 930F (500C)	7.97	140	965	4.7	4.0	B106	2.3

*Combined, Infiltrant 90% Cu-5%Fe-5%Mn.
Source: Reference 20.

A printing press paper gripper for use on an offset press was required to resist high wear under light impact conditions. It was produced of copper-infiltrated iron and had a tensile strength of 75 ksi (517 MPa), an elongation of 11% and a hardness of Rockwell C 17–20 without heat treatment.

An automatic transmission part consisting of an SAE 1112 steel pin and a body of P/M iron infiltrated with copper had to meet medium shock, medium torque, load bearing wear and high strength requirements. The pin was bonded to the body during sintering. The assembly was carbonitrided and hardened. After this treatment, the body had a tensile strength of 120 ksi (827 MPa) and was file hard.

ADVANTAGES AND APPLICATIONS OF COPPER AND COPPER ALLOY P/M PARTS

The outstanding characteristics of copper, which apply also to copper P/M parts, are high electrical and thermal conductivities, ductility and corrosion resistance. Many applications of copper and copper alloy P/M parts are based on these characteristics.

Copper powder with a purity of more than 99% copper is available commercially and parts produced from these powders have electrical conductivities of 80 to 95% IACS as pressed and sintered. Higher conductivities, approaching 100% IACS can be achieved by further densification. High electrical conductivity also means high thermal conductivity. Thus copper P/M parts have a significant advantage for the production of electronic and electrical components where electrical or thermal conductivity is an essential attribute.

Copper is a very ductile and malleable metal. Parts produced from copper and copper alloy powders also have excellent ductility. The elongation of pressed and sintered P/M copper, brass and nickel silver parts ranges up to 35% in one inch.

Copper and copper-base alloys are resistant to a wide variety of corrosive environments. P/M parts produced from copper, bronze, brass, nickel silver and copper-nickel have corrosion resistance properties essentially equivalent to those of their wrought or cast counterparts.

The applications of these P/M materials are based on a combination of properties, rather than on a single one. The following case histories indicate that selection is based not only on conductivity, ductility and corrosion resistance but on strength, ability to hold close tolerances and cost reduction.

Copper P/M Parts

Components for switch gears were converted to copper P/M parts from wrought copper to achieve a considerable reduction in cost while still maintaining good electrical conductivity. The components are used in switch boxes with capacities up to 600 amperes.

Because of its excellent thermal conductivity, a P/M copper component weighing 1/2 pound was selected for a heat sink in an electronic application.

Components for 150 and 250 ampere fuse blow-outs, used in coal mining equipment were converted from machined copper bar stock to a P/M copper part. Although drilling and tapping were still required, the conversion resulted in cost savings of about 25%.

Bronze P/M Parts

A P/M bronze cam was developed to advance the film, frame by frame, at the rate of 24 frames per second for 8 and 16 mm projectors. The shape was a circular arc with a 126-degree dwell surface. Wear resistance was a requirement because the cam operated against hardened and polished cam shoes. A leaded bronze was selected which met the close tolerances demanded of this part without machining.

A P/M bronze gear and ratchet for dial telephones was selected as a replacement for a cast and machined brass assembly and by eliminating machining, reduced costs by 25%.

P/M bronze pantograph shoes are used on Japanese railroads because they offer low contact resistance, high strength, and low maintenance cost. For normal use, the alloy is 80Cu-10Sn-5Fe-5graphite. In areas where corrosion is a factor, the iron content is increased and nickel is added with a corresponding reduction in the copper content.

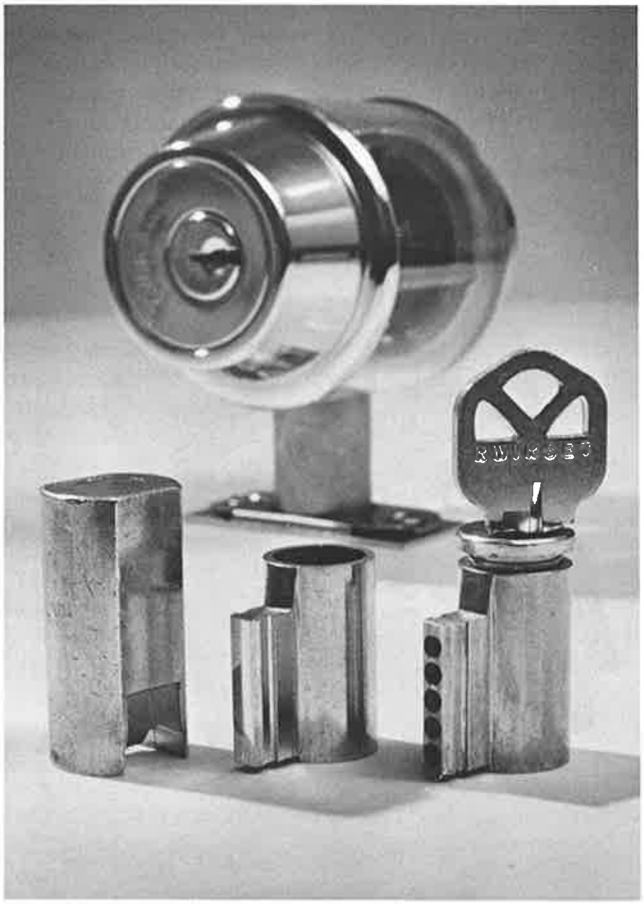

FIGURE 9. BRASS CYLINDER AND LATCH BOLT USED IN HIGH SECURITY LOCK.

Brass P/M Parts

Leaded brass (78Cu-20.5Zn-1.5Pb) was selected for a latch bolt and cylinder for an extra security double cylinder lock. Redesigned from die cast and machined parts, the P/M components provided improved strength and tolerances and a better design at an economical cost. The latch bolt is compacted, sintered, coined and annealed to a density of 7.8 g/cm^3 with critical tolerances held to 6–8 mils. The bolt houses a 3/8-in. hardened steel pin to prevent sawing. The bolt can withstand a 450-pound blow without breaking. The cylinder body is compacted, sintered and coined for dimensional control and has a minimum density of 7.6 g/cm^3. The lock, which is surrounded by two free-turning P/M steel rings and has tempered P/M steel cylinder guards, has passed rigid break-in tests and meets HUD requirements.

A P/M brass diverter valve body is used in a home water-softening and purification faucet unit. The unit removes chlorine, sulfur, rust, scale, algae and most additive chemicals. The complicated part has eight levels and is fabricated from brass powder to a minimum density of 7.6 g/cm^3. It is impregnated with a plastic to assure pressure tightness and is finished by chrome plating.

A leaded brass (78Cu-20.5Zn-1.5Pb) was selected for the rotor of a clockwork delay mechanism of a fuze for a 40 mm projectile used in shoulder-fired weapons. The part prevents detonation of the round before it has reached a safe distance from the muzzle of the weapon. The rotor is fabricated to a minimum density of 7.7 g/cm^3. It is produced at high production rates to tolerances of 2 mils on both the solid hub and the hollow hub.

A similar leaded brass was selected for the gear rotor in the timing mechanism of a mechanical fuze which serves as a safety and arming device for 40 mm projectiles used in

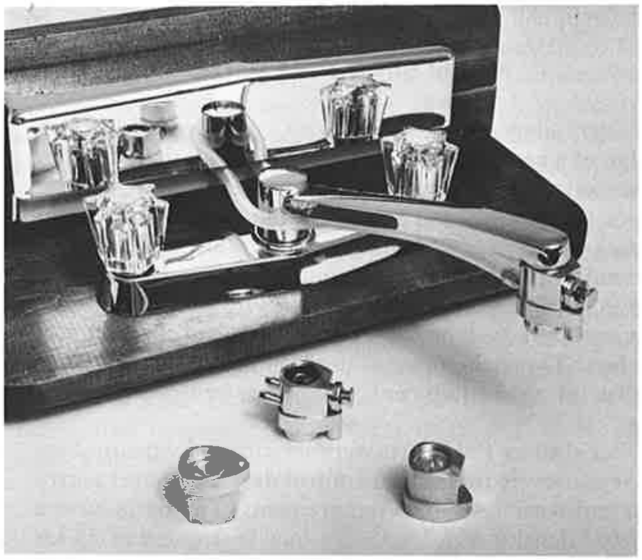

FIGURE 10. BRASS DIVERTER VALVE BODIES AND ASSEMBLED VALVE FOR WATER PURIFIER UNIT.

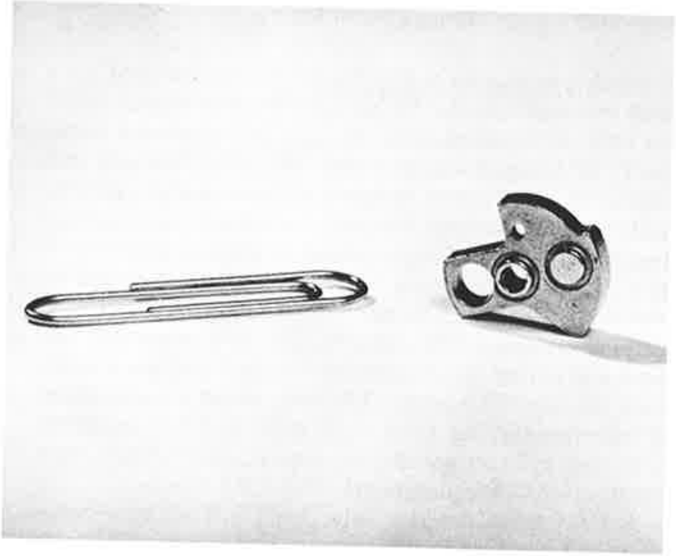

FIGURE 11. BRASS ROTOR FOR ORDNANCE FUZE.

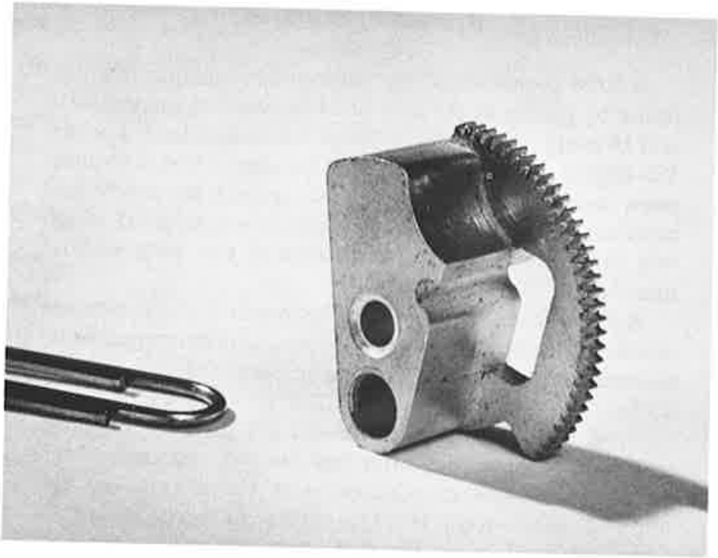

FIGURE 12. BRASS GEAR ROTOR FOR TIMING MECHANISM IN MECHANICAL FUZE.

helicopter cannon. The part is fabricated to a density of 7.7 g/cm^3 and tolerances are held to 0.8 mils on gear teeth that are only 0.013-in. thick.

A gland to prevent the turning of a valve stem with subsequent grinding of the seat washer against the seat was originally made of extruded brass stock. A non-circular hole was shaped during extrusion but required broaching and all shaping was done on a screw machine. Converted to a brass P/M part, no machining was required with a resulting cost reduction of 40%.

P/M brass (85Cu-15Zn) has been pressed, sintered and coined to produce blanks that have excellent coinability and produce sharp impressions in the production of medallions.

Nickel Silver P/M Parts

Nickel silver (64Cu-18Ni-18Zn) was selected for a new design of a gear and cam that replaced more than 21 parts in an automotive recording tachometer. The P/M part drives the pointer and recording unit and offers a cam surface which acts as a contact and ground to turn on an internal warning light and an audible warning signal. The part is fabricated to a density of 7.2–7.6 g/cm^3 and close tolerances are held on the 22 gear teeth and the center of the hub. The tachometer is used on heavy long-distance trucks, off-road equipment, emergency vehicles and fleet cars.

Nickel silver P/M parts were selected for activator bars for repeat-cycle timing and control devices to meet corrosion and wear resistance requirements. The parts have a sintered density of 7.7 g/cm^3, a tensile strength of 35 ksi (241 MPa) and an elongation of 35% in one inch. They are used in electromechanisms for aircraft, scientific equipment and pre-set motor operations.

A brush holder for a miniature D.C. motor, rated 0.045 hp at 16,000 rpm, is 1.875 inches long and 1.250 inches in diameter. Produced from nickel silver powder, the part meets the requirements for corrosion resistance and a component life test of 3000 hours without fatigue failure.

A thrust bearing assembly for a submersible gasoline pump consists of a face plate and an angle plate produced from nickel silver powder. These parts were originally

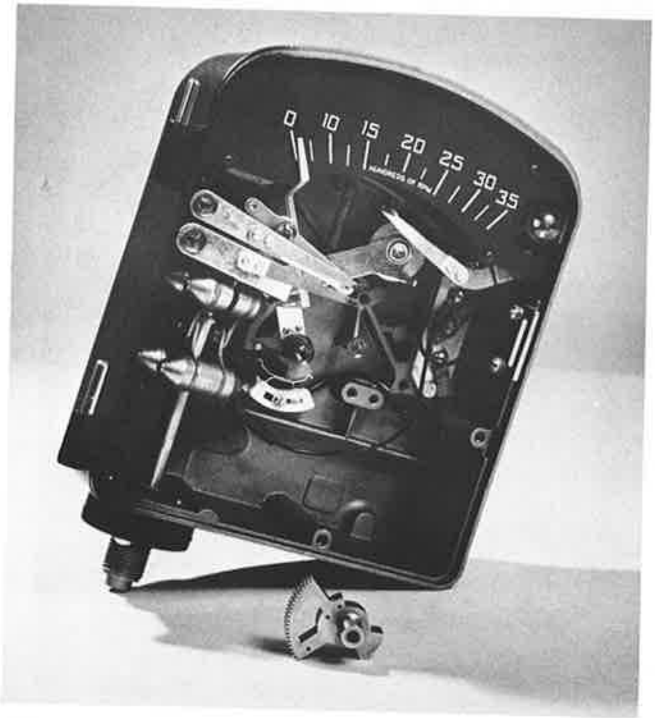

FIGURE 13. NICKEL SILVER GEAR AND CAM FOR AUTOMOTIVE RECORDING TACHOMETER.

machined from stainless steel. Production by P/M procedures eliminated machining and produced equivalent hardness and wear resistance at a saving of over $2 per set.

An insert to provide contact points for the stator winding of a synchro-motor assembly was converted from an assembly of 13 parts to a single nickel silver P/M part. In the new design, the P/M insert is embedded in a molded plastic block. The ends of the block and the base of the nickel silver part are machined to leave exposed metal segments which are drilled and tapped for wiring connections.

NON-STRUCTURAL APPLICATIONS OF COPPER AND COPPER ALLOY POWDERS

Although the major applications of copper and copper alloy powders are in structural components, significant quantities of the powders are employed in non-structural applications. These range from the strictly utilitarian to the purely ornamental. As the advantages of using these powders to improve the properties of nonmetallic materials become more apparent, new applications continue to develop. Currently, copper and copper alloy powders are used in paints, coatings and inks, plastics-metal combinations, brazing pastes and in a variety of other applications.

Paints, Coatings and Inks

Pigments are made by flaking copper, copper-zinc or copper-zinc-aluminum alloy powder in ball mills. Colors range from copper red through pink to various shades of gold. Additional color modifications can be achieved by adding such elements as nickel or tin to the alloys or by heating under controlled conditions. The alloy pigments are generally known as "gold bronze."

To produce a highly metallic luster on a surface, the flakes must float to the surface of the film and orient themselves to form a continuous metal film, a phenomenon known as leafing. The coverage of the coating and the gloss generally depend on the particle size and shape.

The leafing properties depend on the formulation of the base material. Metallic coated paper, for example, is produced by applying flake powder in a thin film to paper stock coated usually with a casein or pyroxylin coating. This paper is used for menus, greeting cards, tags, box wrapping and other printed pieces.

Dusting is a process used to put "gold" rims on labels. The area to be bronzed is printed with an ink of tacky consistency, bronze powder is dusted on the surface and adheres to the inked areas, and the excess is shaken off.

Bronze powder is used also in printing wall paper; in silk screening to apply designs to paper, glass, cloth or leather; in hot stamping, a process of roll transfer of flakes to produce stamped or embossed impressions; and in paints.

A major application of gold bronze pigments is in the printing industry. These metallic printing inks are used for both rotogravure and letterpress printing.

Copper powder and cuprous oxide are used in the formulation of vinyl paints for use in marine applications to prevent or delay the fouling of metal ships and buoys by marine organisms. Copper-filled epoxy paint is used in similar applications.

Metallizing guns are fed with copper or bronze powder to form a corrosion resistant coating on the workpiece. A recent development is the use of copper and tin powder to produce coatings by plasma spraying.

Mechanical (peen) plating is a process of depositing a metal coating on a metal surface without the use of electricity. The process consists of tumbling the parts to be plated in a rubber-lined barrel containing a slurry of metal powder, glass beads and a promoter chemical. During the operation, the powders are peened flat and cold welded to the surfaces of the parts. The process is used to plate small ferrous parts such as stampings, fasteners and washers with various soft metals, including brass and copper. As an example, copper powder is mechanically plated on parts which are to be brazed.

Plastics-Metal Combinations

The use of copper and copper alloy powders in combination with various plastics is growing in importance. A large quantity of bronze powder is used with vinyl resins for floor and wall tile. Similar powder is added to acetyls or nylon to produce thermally or electrically conductive moldings that can be plated if desired. These bronzes are also used with polyethylene, styrene and other plastics in extrusion and injection molding applications for decorative effects.

Epoxy resins filled with copper or bronze powder are used as repair and patching pastes for brass and bronze castings and stampings. Bronze-filled epoxy pastes have been used for years to repair condenser tubes.

Epoxy resins, highly filled with copper or bronze powder, are used to cast forming tools. Ornamental statuettes and other decorative pieces are also cast of filled plastics.

Copper-polyethylene mixtures have been developed for self-lubricating bearing applications. A composition containing 76% copper powder and 24% high molecular weight, high density polyethylene has exhibited good bearing properties.[21]

The addition of bronze powder to TFE (polytetrafluoroethylene) increases the hardness and compressive strength, improves dimensional stability, and lowers cold flow, creep and wear. Improvements are progressive up to a maximum of about 70% bronze. However, the addition of bronze makes the TFE unsuitable for electrical applications and for applications in environments that are corrosive to bronze. Bronze-fortified TFE is used for self-lubricating bearings, compression rings, cup seals, rod seals, valve seats and liners.

Brazing

Copper and copper alloy powders in paste form are used as filler metals for brazing steel and copper alloy parts. A brazing alloy paste consists of copper or copper alloy powder (55–90%) and a neutral binder (10–35%). It may or may not contain a flux (up to 10%). Fluxing is not required, for example, in certain controlled atmosphere brazing operations. Pastes range in consistency from those that can be sprayed to those resembling putty.

The major advantage of using a paste in furnace brazing is the ability to deposit a controlled quantity of the paste in the area desired with automatic or manual applicators. If a flux is required, it is combined with the paste, speeding preparation of the assembly and reducing labor costs. Paste alloys can also be dispensed in irregular shapes, an advantage over preforms.

The major use of copper brazing paste is in the furnace brazing of carbon and alloy steel parts. They can be brazed in a variety of reducing atmospheres or in vacuum using fluxless paste. Stainless steels can also be brazed in hydrogen or vacuum with fluxless pastes. Pastes containing fluxes can be used for brazing of low carbon, low alloy and stainless steels in inert gas atmospheres.

Brazing with copper requires temperatures on the order of 2050F (1130C). Copper alloy powders can be used where a lower temperature is desirable for brazing. Copper-tin (90Cu-10Sn) bronze pastes can be used at 1925F (1150C) for brazing steel parts and copper-nickel alloys. Copper-zinc-tin (59.25Cu-40Zn-0.75Sn) can be used at about 1700F (925C) for brazing steels, copper-base and nickel-base alloys. However, fluxes are required with the copper-zinc-tin alloy.

Chemical Applications

Copper powder is used as a catalyst in various chemical operations. In one process, the addition of activated copper powder to solutions containing cyanides and tartrates causes the precipitation of lead, bismuth, tin, cadmium and silver but zinc, cobalt, nickel, copper and aluminum remain in solution.

Other Applications

Advantage is taken of the excellent electrical conductivity of copper powder to prepare some printed circuits for use in radio and television applications.

Copper powder confers non-sparking and fungicidal properties to oxychloride cements.

A compound containing copper, lead and zinc powders is used to coat the threads of petroleum drilling pipe to aid in breaking the threads when the equipment is dismantled.

Brass powder is added to the compound used in making poker chips to increase the weight of the chips.

ENGINEERING/PRODUCTION/ECONOMIC ADVANTAGES OF POWDER METALLURGY

Copper and copper alloy P/M parts can be pressed and sintered to their final shape and size, usually with the desired surface finish and with no draft angles. They can also be sized to close tolerances by coining or repressing, thus eliminating much of the machining required when other metal forming procedures are used. They can be machined, plated and joined by brazing and some of the alloys can be heat treated to enhance their properties.

Using commercial automatic presses, copper and copper alloy P/M parts can be produced rapidly and accurately at an average rate of 1000 parts per hour. Some very simple shapes have been produced on rotary compacting presses at rates as high as 63,000 parts per hour. Sizes can range from miniature parts smaller than the ball of a ball-point pen to bearings weighing over 100 pounds.

The physical and mechanical properties of copper and copper alloy P/M parts are comparable with those of cast and wrought copper-base materials of similar composition. However, the P/M process permits a flexibility that the other processes do not possess. Parts can be produced that vary in density from the low-density required for self-lubricating bearings or filters to almost theoretical density of wrought parts.

P/M parts are produced with a minimum of raw material loss and greatly reduced processing wastes resulting in a new approach toward lower overall costs. As a further advantage, there is no pollution of the environment in the production of P/M parts.

Some of the basic advantages of powder metallurgy are:

- Metal powders are high purity materials
- Close dimensional tolerances can be maintained
- High volume process with excellent reproducibility
- Quality control is inherent in the process
- Low labor input
- Machining is eliminated or reduced
- Scrap losses are eliminated or reduced
- Segregation is avoided
- Controllable porosity and density can be precisely controlled
- Combines immiscible metals
- Complex shapes can be produced

APPLICATIONS OF COPPER-BASE POWDER METALS

Abrasive Wheels	
Bonding	Copper
Agriculture	
Fungicides	Copper
Lawn and Garden Equipment	Bronze
Soil Conditioning	Copper
Aerospace	
Brake Linings	Copper
Counterweights	Copper-tungsten
Filters	Bronze
Automotive	
Brake Bands, Liners	Copper, brass, copper-lead, copper-lead-tin
Bushings	Bronze
Instruments	Nickel silver
Building and Construction	
Conductive and Non-sparking Floors	Copper
Decorative Plastics	Copper, bronze, brass
Domestic Water Filters	Brass
Lock Components	Brass
Pipe Joint Compounds	Copper
Chemical	
Catalysts	Copper
Filters	Bronze
Valve and Pump Parts	Copper-nickel
Coatings	
Anti-fouling Paints	Copper
Conductive Paints and Plastics	Copper, brass
Decorative Paints	Copper, brass, bronze
Lacquers	Brass, bronze
Mechanical (Peen) Plating	Copper, brass
Spray Coating	Copper, brass
Vacuum Metallizing	Copper
Coins, Medals, Medallions	Copper-nickel, brass
Electrical and Electronic	
Brushes	Copper
Brush Holders	Nickel silver
Contacts	Copper
Heat Sinks	Copper, dispersion-strengthened copper
Printed Circuits	Copper
Semi-conductor Stud Bases	Copper, dispersion-strengthened copper
Telephone Components	Brass, bronze
Hardware	
Lock Components	Brass, bronze
Industrial, General	
Balancing Weights	Copper-tungsten
Bearings and Bushings	Bronze, copper-lead, copper-lead-tin
Filters, Liquid and Gas	Bronze
Flame Arrestors	Bronze
Instruments, Control	Nickel silver
Joining	
Brazing Compounds	Copper,bronze,brass
Resistance Welding Electrodes	Copper, dispersion-strengthened copper
Lubricants	
Anti-galling Pipe Joint Compounds	Copper
Copper Lubricants	Copper
Plastic-Filled Metal	Copper, bronze
Machining	
Electrical Discharge Machining (EDM)	Copper
Electrochemical Machining (ECM)	Copper
Office Equipment	
Business Machines	Brass
Ordnance	
Armor-piercing Cores	Copper
Fuze Parts	Brass
Projectile Rotating Bands	Copper, brass
Personal Products	
Cordless Electric Toothbrush and Razor	Copper
Fingernail Lacquer	Copper
Photographic Equipment	Bronze, brass, nickel silver
Poker Chips	Brass, bronze, copper-nickel
Printing Inks	
Metallic Inks for Offset, Letterpress, Gravure	Copper, brass
Radio and Television	
Printed Circuits	Copper
Railroads	
Brake Linings	Bronze, copper-lead, copper-lead-tin
Friction Strips on Pantographs	Copper
Self-lubricating Parts	
Oil-filled	Bronze
Plastic-filled	Copper
Ships	
Anti-fouling Paint	Copper

REFERENCES

1. P.W. Taubenblat, "Importance of Copper in Powder Metallurgy," Int. J. Powder Met. & Powder Technology 10:169 (July 1974).
2. P.J. James, "Fundamental Aspects of the Consolidation of Powders," Powder Met. Int. 4:82 (1972).
3. P.W. Taubenblat, W.E. Smith and C.E. Evans, "Production of P/M Parts from Copper Powder," Precision Metal 30(4):41 (1972).
4. H.H. Hausner quoted by Taubenblat, Reference 1.
5. F. Thummler and W. Thomma, "The Sintering Process," Metallurgical Reviews No. 115, June (1967).
6. R.I. Cable and T.K. Gupta, "Intermediate Stage Sintering," in Sintering and Related Phenomena, New York, Gordon and Breach, 1967.
7. A.S. Reshamwala and G.S. Tendolkar, "Activated Sintering," Powder Met. Int. 3(3):15 (1970).
8. Standards Handbook, Part 2, Alloy Data. New York, Copper Development Association Inc., 1973.
9. J.S. Hirschhorn, Introduction to Powder Metallurgy. New York, American Powder Metallurgy Institute, 1969.
10. A. Price and J. Oakley, "Factors in the Production of 90/10 Tin Bronze Compacts of Higher Density (7.49g/cm^3)," Powder Met. 8:201 (1965).
11. A.K.S. Rowley, E.C.C. Wasser and M.J. Nash, "The Effect of Some Variables on the Structure and Mechanical Properties of Sintered Bronze," Powder Met. Int. 4(2):71 (1971).
12. V. Morgan, "Applications of Porous Metal Bearings," Industrial Lubrication & Tribology 24(3):129–138 (1972).
13. P.E. Matthews, "Cubraloy, A New Development in Aluminum Bronze Powder Metallurgy," Proc. Fall 1971 Powder Metallurgy Conference, Metal Powder Industries Federation.
14. Data from New Jersey Zinc Company and U.S. Bronze Powders, Inc.
15. P.E. Matthews, "The Mechanical Properties of Brass and Developmental Nonferrous P/M Materials," Int. J. Powder Met. & Powder Technology 5(4):59 (1969).
16. T.R. Bergdtrom and B.G. Harrison, "Laminated Cupronickel/Copper Coin Blanks from Metal Powders," Int. J. Powder Met. & Powder Technology 3(4):47 (1967).
17. D.N. Lisson, "A Metallurgical Review of Plain Bearings," paper presented at Coppermetal Bearings Symposium, Melbourne, Australia, Oct. 29, 1969.
18. D.H. Desy, "Dispersion Strengthened Copper," Bureau of Mines R.I. 7228 (1969).
19. Metal Powder Industries Federation data.
20. R.L. Pettibone, "Properties and Performance of Infiltrated Powder Metallurgy Parts," Progress in Powder Metallurgy 19:86 (1963).
21. P.M. Kamath, S. Stregeusky and C.A. Sprang, "Development of Applications for Copper Plastic Combinations," Summary Report to International Copper Research Association, 1966.

APPENDIX A

BIBLIOGRAPHY OF COPPER AND COPPER ALLOY POWDER METALLURGY

Production Methods

Atomization

N.J. Grant and V.K. Sarin, "Powder Methods for Production of Wrought High Strength High Conductivity Thermally Stable Copper Base Alloys," Final Report to International Copper Research Association, Nov. 1971.

H. Lubanska, "Correlation of Spray Ring Data for Gas Atomization of Liquid Metals," J. Metals 22(2):45–49 (1970).

R.L. Probst, "Spherical Metal Powders-Production and Characteristics," in New Types of Metal Powders, AIME Met. Soc. Conf. 23:45 (1964).

K. Tamura and S. Wanikawa, "Variables in the Production of Metal Powder by Liquid Atomization," Trans. Nat. Research Inst. Metals, Japan 11(3):196 (1969).

K. Tamura and S. Wanikawa, "On the Manufacture of Porous Bronze Powder by Atomization," Trans. Nat. Research Inst. Metals, Japan 11(3):198–200 (1969).

J.F. Watkinson, "Atomization of Metal and Alloy Powders," Powder Met. 1:13–23 (1958).

Electrolysis

"Bibliography on Electrolytic Production of Copper Powder," Tech. Report No. 134. International Copper Development Council, Jan. 1967.

S. Harper and A.A. Marks, "Electrodeposition of Copper Powder with the Aid of Surfactants," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.

C.L. Mantell, "Electrodeposition of Powders for Powder Metallurgy," J. Electrochem. Soc. 106:70–74 (1959).

H.J.V. Tyrrell, "Some Aspects of the Production and Heat-Treatment of Electrolytic Copper Powder," J. Inst. Metals 76:17–42 (1949–50).

F. Wills and E.J. Clugston, "Production of Electrolytic Copper Powder," J. Electrochem. Soc. 106:362 (1959).

Hydrometallurgy

R.O. Groves, J.K. Winter and L.G. Evans, "Preparing Copper Powder from Cement Copper," U.S. Bur. Mines R.I. 7548 (1971).

B. Maddings and D.J.I. Evans, "The Changing Role of Hydrometallurgy," Canadian Mining Met. Bull. 64(2):48–57 (1971).

V.N. Mackiw, "Current Trends in Chemical Metallurgy," Canadian J. Chem. Eng. 46(2):3–15 (1968).

V.N. Mackiw, T.W. Benz and D.J. I. Evans, "Recent Developments in Pressure Hydrometallurgy," Metallurgical Reviews No. 109 (1966).

H. Veltman, S. Pellegrini and V.N. Mackiw, "Direct Acid Leaching of Chalcocite Concentrate," J. Metals 19(2):21–25 (1967).

W.J.Yurko, "A Chemical Copper Refinery," Paper Presented at Annual Operating Conference, Met. Soc. AIME, Philadelphia, Dec. 5, 1966.

Solid State Reduction

E.C. Ellwood and W.A. Waddle, "The Production and Properties of Oxide Reduced Copper Powder," J. Inst. Metals 80:193–206 (1952).

Pre-mixing

"New Powder Developments Stress Processability," Metal Prog. 101(5):90,92 (1972).

V.T. Price, Jr. and F. Wills, "Pre-mixed Metal Powders," Precision Metal 23(10):45–47 (1967).

H. Triffleman, "Method of Manufacture of Homogeneous Compositions," U.S. Patent 2,893,859, July 7, 1959.

Processes Related to Copper and Copper Base Alloys

Die Compaction

R.J. Donachie, Jr., and M.F. Borr, "Effects of Pressing on Metal Powders," J. Metals 15:849–854 (1963).
L.F. Hammond and E.G. Schwartz, "The Effect of Die Rotation on the Compaction of Metal Powders," Int. J. Powder Met. & Powder Technology 6(1):25–36 (1970).
M.C. Kostelnik, F.H. Kludt and J.K. Beddow, "The Initial Stages of Compaction of Metal Powders in a Die," Int. J. Powder Met. & Powder Technology 4(4):19 (1968).
R.J. Sajdak, R.P. McNally, M.D. Nasta and J.K. Beddow, "Two Methods for Characterizing the Compaction and Ejection Behavior of Metal Powders in a Die," Int. J. Powder Met. & Powder Technology 6(4):13–23 (1970).

High Energy Rate Compaction

S.D. Elwakil and R. Davies, "Speed Effects in the Compaction of Copper Powders," Proc. Conf. on The Use of High Energy Rate Methods for Forming, Welding and Compaction 16 (1973).
J.W. Hagemeyer and J.A. Regalbuto, "Dynamic Compaction of Metal Powders with a High Value Impact Device," Int. J. Powder Met. & Powder Technology 4(3):19–25 (1968).
A.K. Hopkins, "On the Response of Mixed Materials to One-Dimensional Shock Waves," Wright-Patterson Air Force Base Tech. Report No. AFML-TR-70–158, July 1970.
J. Pearson, "Metal Working with Explosives," J. Metals 12:673–681 (1960).

Hydrostatic Compaction

H.D. Hanes and P.J. Gripshover, "Porous Mandrels Provide Uniform Deformation in Hydrostatic Powder Metallurgy," NASA Tech. Brief 67–10209, June 1967.
W.R. Morgan and R.C. Sands, "Isostatic Compaction of Metal Powders," Metals & Materials 14(5):85–102 (1969).
R.A. Powell, "Isostatic Compaction of Metal Powders in Conventional Molding Tools," Int. J. Powder Met. & Powder Technology 1(3):13–18 (1965).

Slip Casting

E.J. Thellmann, "Slip Casting, A Versatile P/M Process," Precision Metal 29(5):41–43 (1971).

Forging and Extrusion

"Copper Alloy Forgings from Powder Metal Preforms," Final Report of Industrial Materials Laboratories, Woburn, Mass. to International Copper Research Association, April 1971.
J.S. Hirschhorn and R.B. Bargainnier, "The Forging of Powder Metallurgy Preforms," J. Metals 22(9):21–29 (1970).
E.J. Stefanides, "Extrusion from P/M Blank Improves Forged Parts," Design News 24:40 (Nov. 24, 1969).

Roll Compacting

C.U. Chisholm, "The Effects of Roll Compaction on Copper-Lead and Copper-Lead-Tin Alloys Sintered to Mild Steel," Metal Treatment 33(3):85–90 (1966).
H.S. Nayar, "Strip Products Via Particle Metallurgy," Powder Met. Int. 4:30–36 (1972).
A.K. Patwardham and G.S. Tendolkar, "Roll Compacting of Metal Powders," Trans. Indian Inst. Metals 19:183–188 (1966).
J.H. Tundermann and A.R.E. Singer, "Deformation and Densification During the Rolling of Metal Powders," Powder Met. 12:219–250 (1969).

Sintering

L.K. Barrett and C.S. Yust, "Progressive Shape Changes of the Void During Sintering," Trans. Met. Soc. AIME 239:1172–1179 (1967).
R.W. Boesel and I.S. Yoshioka, "Spark Sintering Tames Exotic Materials," Materials Eng. 70(10):32–35 (1969).
D.S. Buist, "Application of the Method of Quantitative Metallography to the Sintering of Spherical Copper Powder," Refractories J. 44(1):2–3, 6–8 (1968).

J.E. Drapeau, "Sintering Characteristics of Copper Powder in Powder Metallurgy." Cleveland, Ohio, American Society for Metals, 1942.

R.A. Gregg and F.N. Rhines, "Surface Tension and the Sintering Force in Copper," Met. Trans. 4:1365–1374 (1973).

H.H. Hausner, "Pressureless Compacting and Sintering Metal Powders," J. Metals 13:752–758 (1961).

M. Mitkov, E. Kustic and M.M. Ristic, "Influence of Heating Rate on the Sintering of Copper Compacts During Sintering," Powder Met. Int. 5(2):33–35 (1973).

J.R. Moon, "Sintering of Metal Powders," Powder Met. Int. 3(3):147 (1971), 3(4):194 (1971).

P. Ramakrishnan, "Sintering Kinetics of Oxide-Film-Coated Copper Powder," Powder Met. 9:47–53 (1966).

A.S. Reshamwala and G.S. Tendolkar, "Activated Sintering," Powder Met. Int. 1(2):58 (1969), 2(1):15 (1970).

C.B. Shuhmaker and R.M. Fulrath, "Initial Stage Sintering of Copper and Nickel," Paper Presented at International Conference on Sintering and Related Phenomena, University of Notre Dame, June 5–7, 1972.

F. Thummler and W. Thomma, "The Sintering Process," Metallurgical Reviews No. 115, June 1967.

Vacuum Sintering

J.W. Cable, "Engineering Aspects of Present Day Vacuum Technology," Metal Treating 20(1):3 (1969), 20(2):3–16 (1969).

Diffusion

M. Khubaib and K.P. Gupta, "Diffusion of Cu in AuCu Alloy," Scripta Met. 4:605–609 (1970).

W.R. Raja, A.A. Jatkar and G.S. Tendolkar, "Contribution of Grain Boundary Diffusion During Intermediate Stage Sintering of Copper," Int. J. Powder Met. & Powder Technology 6(7):65–73 (1970).

M.J. Salkind, "The Rate of Interfacial Diffusion in the Sintering of Copper," Trans. Met. Soc. AIME 239:119 (1967).

T.L. Wilson and P.G. Shewman, "The Role of Interfacial Diffusion in the Sintering of Copper," Trans. Met. Soc. AIME 236:48 (1966).

Copper and Copper Base Materials

Pure Copper

G. Arthur, "The Porosity and Permeability of Hot Compacted Copper Powder," J. Inst. Metals 84:327–332 (1955–56).

M.K. Carlson and J.S. Hirschhorn, "Stable Neck Pores in Sintered Copper and Copper-Antimony Compacts," Int. J. Powder Met. & Powder Technology 6(1):39–42 (1970).

A. Duffield and P. Grutenhuis, "The Effect of Particle Size on the Sintering of Copper," J. Inst. Metals 87:33–41 (1958–59).

E. Klar, "Relationships Between Pore Characteristics and Compacting Properties of Copper Powder," J. Materials 7:418–424 (1972).

E. Klar and A.B. Michael, "Influence of Impurities, Sintering Atmosphere, Pores and Obstacles on the Electrical Conductivity of Sintered Copper," Trans. Met. Soc. AIME 242:2173–2176 (1968).

O.V. Romar and H.H. Hausner, "Shrinkage of Copper and Iron Powder Compacts During Sintering," Metal Prog. 83:104–108 (1963).

W. Rutkowski, "Some Experiments on Sintering Copper Powder Oxidized Under Various Conditions," Int. J. Powder Met. & Powder Technology 1(3):20–25 (1965).

S.J. Sanderson and P.E. Evans, "Internal Friction in Porous Material," Modern Developments in P/M 7:519–535 (1974).

A.D. Sarkar and A.R. Singh, "Results from Experiments on Compaction and Sintering of Electrolytic Copper Powders," Metallurgia 82(10):131–134 (1970).

J.T. Smith and T. Vasilos, "The Pressure Sintering of Copper," Trans. AIME 233:1431–1437 (1965).

P.W. Taubenblat, "Techniques for Measuring and Attaining High Electrical Conductivity with Copper Powder Compacts," Int. J. Powder Met. 5(4):89–95 (1969).

P.W. Taubenblat and G. Goller, "The Preparation of High Conductivity Compacts from Copper Powder," J. Inst. Metals 98:225–227 (1970).

P.W. Taubenblat, W.E. Smith and C.E. Evans, "Production of P/M Parts from Copper Powder," Precision Metal 30(4):41–44 (1972).

P.W. Taubenblat, F. Wills and W.E. Smith, "Conductivity and Strength in Parts Made from Copper and Cu-Zr Powders," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.

N.F. Vysznikov and S.S. Yermakov, "Powdered Metal Materials and Products," Wright Patterson Air Force Base, Report FTD-HC-23-391-69, May 28, 1970.

Bronzes

"Can Your Product Use Filters," Precision Metal 21(9):48 (1963).

H.L. Andrews and D.A. Hay, "Hot Rollable Phosphor Bronze (Cu-Sn-P) Alloys with Improved Tensile Properties," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.

G.R. Bell, F.B. Weble and R. Woolfall, "Pressing and Sintering Characteristics of Certain Copper and Tin Powder Mixes," Metallurgia 58(11):233 (1958).

D.F. Berry, "Factors Affecting the Growth of 90/10 Copper/Tin Mixes Based on Atomized Powder," Powder Met. 15:247–266 (1972).

G. Clough, "Powder Metallurgy Techniques Applied to the Manufacture of Metal-Graphite Bearing Materials," Powder Met. Int. 1(12):52–57 (1969).

R. Davies and A.D. Sarkar, "Volume Growth of Cu-Sn Compacts Due to Sintering with Sn Content Between 12–20%," Metallurgia and Metal Forming 40(8):260–262 (1973).

E. Deegan and A.D. Sarkar, "Effect of Sintering Variables on the Dimensional Changes of Copper-Tin Compacts up to 10% Tin," Metallurgia and Metal Forming 40(5):148–151 (1973).

F.J. Esper and R. Zeller, "The Sintering Process of 90% Copper-10% Tin Compositions," Powder Met. Int. 2(8):95 (1970).

I. Ferraro and E.I. Sgambetterra, "Properties of Sintered Bronze-Cobalt Bearings," Cobalt No. 18:3–17 (March 1963).

E.L. Fisher and H.D. Ambs, "Dimensional Control in P/M Bronze," Precision Metal 32(4):5 (1974).

N.C. Kothani, "Effect of Nickel Addition on Copper-Tin Alloys Prepared by Powder Metallurgy," Paper Presented at International Powder Metallurgical Conference, Toronto, July 15–20, 1973.

D.N. Lisson, "A Metallurgical Review of Plain Bearings," Paper Presented at Coppermetal Bearings Symposium, Melbourne, Australia, Oct. 29, 1969.

D.N. Lisson, "A Metallurgical Review of Self Lubricating Porous Bronze Bearings," ibid.

P.E. Matthews, "Cubraloy, A New Development in Aluminum Bronze Powder Metallurgy" Proc. Fall 1971 Powder Metallurgy Conference, Metal Powder Industries Federation.

V. Morgan, "Application of Porous Metal Bearings," Industrial Lubrication & Tribology 24(3):129–138 (1972).

S.A. Price and J. Oakley, "Factors in the Production of 90/10 Bronze Components of Higher Density (7.4 g/cm^3)," Powder Met. 8:201 (1965).

E. Peissker, "Pressing and Sintering Characteristics of Powder Mixtures for Sintered Bronze 90/10 Containing Different Amounts of Free Tin," Modern Developments in P/M 7:597–614 (1974).

A.B.S. Rowley, E.C.G. Wasser and M.J. Nash, "The Effect of Some Processing Variables on the Structure and Mechanical Properties of Sintered Bronze," Powder Met. 4(5):71 (1972).

Brass and Nickel Silver

E. Fetz and R.L. Cavanagh, "The Effect of Ternary Elements on the Physical Properties of Air-Atomized 85/15 Copper-Zinc Powders-Green and Sintered Compacts," Paper Presented at International Powder Metallurgy Conference, June 1965.

P.R. Kalisher, "Brass Sinterings Replace Extrusions and Machined Parts," Precision Metal Molding 11(4):34 (1953).

P.E. Matthews, "The Mechanical Properties of Brass and Developmental Nonferrous P/M Alloys," Int. J. Powder Met. 5(4):59 (1969).

W. Rostoker and S.Y.K. Liv, "The Influence of Porosity on the Ductility of Sintered Brass," Technical Report to Frankford Arsenal, Contract No. DAAA 25–68-C-9352, 1969.

R.R. Van Valkenberg, "Fundamentals of Sintering Brass and Nickel Silver Alloys," Precision Metal 29(9):48 (1971).

G.A. Wickham and K.E. Geary, "Sintering Brass P/M Parts in an Endothermic Atmosphere," Int. J. Powder Met. 9(2):103 (1973).

Other Copper-Base Materials

"Antifriction and Friction Cermet Materials," Wright Patterson Air Force Base, Report No. AD 749–637.

T.R. Bergstrom and B.G. Harrison, "Laminated Cupronickel/Copper Coin Blanks from Metal Powders," Int. J. Powder Met. & Powder Technology 3(4):47 (1967).

B.T. Collins and C.P. Schneider, "Sintered Metal Friction Materials," in Modern Developments in Powder Metallurgy, New York, Plenum Press, 1966.

R.L. Crosby and D.H. Desy, "Dispersion-Strengthening in Copper-Alumina and Copper-Yttria Alloys," Bureau of Mines R.I. 7266 (1969).

D.H. Desy, "Dispersion-Strengthened Copper; Its Preparation and Properties," Bureau of Mines R.I. 7228 (1969).

W. Dreizler, F. Aldinger and H.E. Exner, "Preparation and Properties of Sintered Copper-Beryllium Alloys," Modern Developments in P/M 7:505–517 (1974).

R.J. Goodwin, "Dispersion-Hardened Copper Wire," J. Inst. Metals 98:257–264 (1970).

R.L. Graham, D.A. Edge and D.C. Moore, "Dispersion-Hardened Copper and Copper Alloys Made From Chemically Prepared Powders," J. Inst. Metals 99:81–92 (1971).

W.V. Knapp and J.D. Shaw, "Coins, Tokens and Medallions Made by Powder Metallurgy," Int. J. Powder Met. & Powder Technology 3(1):57 (1967).

O.A. Nikifurav and T.N. Chang, "Sintering of Copper-Silver-Cadmium Contacts," Paper Presented at Conference on Powders and Sintered Products, Kanpur, India, 1971, p 206–216.

O. Preston and N.J. Grant, "Dispersion Strengthening of Copper by Internal Oxidation," Trans. Met. Soc. AIME 221:164–173 (1961).

V.K. Sarin and N.J. Grant, "Cu-Zr and Cu-Zr-Cr Alloys Produced From Rapidly Quenched Powders," Met. Trans. 3:875–878 (1972).

W. Scheithauer, R.F. Cheney and N.E. Kopatz, "The Manufacture, Properties and Applications of High-Conductivity High-Strength Cu-ThO_2," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.

W.F. Shilling and N.J. Grant, "Oxide Dispersed Copper Alloys by Surface Oxidation," Met. Trans. 1:2205–2210 (1970).

P.W. Taubenblat, F. Wills and W.E. Smith, "Conductivity and Strength in Parts Made From Copper and Cu-Zr Powders," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.

M. Yamazaki and N.J. Grant, "Alumina Dispersion-Strengthened Copper-Nickel Alloys," Trans. Met. Soc. AIME 233:1573–1580 (1965).

T. Wantanabe and K. Yamada, "Effects of Method of Adding Copper on the Strength of Sintered Aluminum Copper Alloys," Int. J. Powder Met. & Powder Technology 4(7):37–47 (1968).

J.E. White, "Alloy and Dispersion Strengthening by Powder Metallurgy," J. Metals 17:587–593 (1965).

K.G. Wikle and N.P. Sarle, "Copper-Beryllium Alloy Powder," in New Types of Metal Powders, AIME Met. Soc. Conf. 23:116 (1964).

Copper In Iron And Steel

Pre-mix and Pre-alloyed Powders

A. Adler, "Nickel, Copper Boost Properties of P/M Steels," Materials Eng. 67(3):32 (1968).

S.K. Barua, P.A. Ainsworth and D.A. Robins, "Sintering of Iron Powder Compacts With Simultaneous Additions of Tin and Copper," Metallurgia 80(9):87–91 (1969).

J.C. Billington, C. Fletcher and P. Smith, "Iron-Copper-Tin Sintered Compacts," Powder Met. 16:327 (1973).

J.M. Capus and A. Maaref, "Influence of Copper and Carbon Levels on the Heat Treatment and Properties of High Purity Iron Powder," Paper Presented at International Powder Metallurgy Conference, Toronto, July 15–20, 1973.

R.T. Holcomb, "The Properties of Prealloyed Iron-Copper Powders Produced From a Melt," 9th Annual Conference Canadian Inst. Mining and Met., Hamilton, Ontario, Aug. 24–26, 1970.

F.V. Lenel and T. Pecanha, "Observations on the Sintering of Compacts From a Mixture of Iron and Copper Powders," Powder Met. 16:351–365 (1973).

J.R. Long, "Tin and Tin-Copper Additives Improve Properties of Sintered Iron Compacts," Metal Progress 101(4):64 (1972).

Y. Trudel and R. Angers, "Comparative Study of Fe-Cu-C Alloys Made From Mixed and Prealloyed Powders," Modern Developments in P/M 6:305–322 (1973).

J. Woodhouse, R. Ganguly, T. Matalis and C. Wert, "Aspects of the Fe-Cu-Co System at 1000C-Liquid Sintering Phenomenon," Paper Presented at 4th Spring Meeting, Metallurgical Society, AIME, Boston, Mass., May 8–11, 1972.

Infiltrants

A. Adler and F. Emley, "Pre-Infiltrated Iron-Copper Powder," Int. J. Powder Met. & Powder Technology 3(1):7 (1967).

B.K. Ganguly, "Microchemistry of Copper Infiltrated Iron Powder Compacts," Dissertation Abstracts International B32(10): 5831-B (1972).

P.L. Pettibone, "Properties and Performance of Infiltrated Powder Metallurgy Parts," Progress in Powder Met. 19:86 (1963).

E. Snape, "Infiltration of Iron Compacts with Ni-Containing Copper," Powder Met. Int. 6(1):20 (1974).

P.W. Taubenblat, R. Lewis and W.E. Smith, "An Infiltration System for Achieving High Strength Iron P/M Parts," Modern Developments in P/M 8:149–162 (1974).

M.V. Veidis, "The Selection of Protective Atmosphere for Two-Step Copper Infiltration," Int. J. Powder Met. & Powder Technology 9(4):187–189 (1973).

Non-Structural Applications of Copper and Copper Alloy Powders

Brazing Materials

P.D. Johnson and A.B. Backensto, "Copper Base Brazing Pastes," Paper Presented at CDA-ASM Conference on Copper, Cleveland, Ohio, Oct. 16–19, 1972.
R.J. MacDonald, "Metal Powders—Their Role in Brazing," Welding J. 50(5):327–331 (1971).
B.R. Williams, "Furnace Brazing with Paste Alloys," Tech. Paper No. AD69–182, Am. Soc. Tool & Mfg. Engr. (1969).

Paints, Coatings and Inks

Metalligraphics. Metallic Pigments Council, Mar. 28, 1968.
R.J. Dick, "Anti-Fouling Coatings; Parts 1 and 2," Paint and Varnish Products 60(11):35–40; 60(12):43–48 (1970).
S. Gurusnamy, N. Shanmugan, V. Yegaraman and R. Rajugopal, "Numerous Colors Are Possible in Electro-Organic Coatings," Metal Finishing 70(9):61 (1972).

Other Applications

"Literature Survey on Copper-Base Cermets," Report No. 87. International Copper Development Council, Oct. 29, 1965.
A.M. Czikk and P.S. O'Neill, "Application of Enhanced Heat Transfer Surface to VTE Process Plant," Office of Saline Water Symposium on Enhanced Tubes for Desalination Plants, Washington, D.C., 1969.
R.D. Deanin, B.J. Skowronski and L.A. Wheeler, "Cement Copper in Injection Moldable Plastic Composites," Final Summary Report to International Copper Research Association, June 30, 1965.
P.A. Kamuth, S. Strageusky and C.A. Sprang, "Development of Applications for Copper Plastic Combinations," Summary Report to International Copper Research Association, 1966.

General Properties

"Corrosion Resistance of Sintered Metals," Design News Mar. 30, 1966, p. 122.
D.A. Armstrong, "Tolerance Factors in P/M Parts Production," Int. J. Powder Met. & Powder Technology 4(4):35–41 (1968).
E. Ariel, J. Barta and D. Brandon, "Preparation and Properties of Heavy Metals," Powder Met. Int. 5(1):126 (1973).
J.W. Caputo and A.R. Pels, "What Controlled Density Means to the Design Engineer," Int. J. Powder Met. & Powder Technology 3(2):17 (1967).
H.H. Hausner, "Friction Conditions in a Mass of Metal Powder," Int. J. Powder Met. & Powder Technology 3(10):7–14 (1967).
R. Haynes, "Fatigue Behavior of Sintered Metals and Alloys," Powder Met. 13:465–510 (1970).
R. Kunkel, "P/M-Profitable Tooling for Powdered Metal Parts," Manufacturing Engineering and Management 64(5):37–41 (1970).
W.B. Maass, "Unsolved Corrosion Problems," Metal Finishing 68(10):60 (1970).
W.M. Shafer and E. Klar, "On the Nature of Green Strength; Parts I and II," Int. J. Powder Met. & Powder Technology 5(4):5–10; 5(10):5–16 (1969).

APPENDIX B

GLOSSARY OF TERMS USED IN POWDER METALLURGY

Absolute Pore Size-The maximum pore opening of a porous material, such as a filter through which no larger particle will pass. Synonymous with Maximum Pore Size.

Acicular Powder-Needle shaped particles.

Acrysol-A trademark for aqueous solutions of acrylic polymers.

Air Classification-The separation of powder into particle size fractions by means of an air stream of controlled velocity.

Alloy Powder-A powder all particles of which are composed of the same alloy of two or more metals. See Metal Powder.

Apparent Density-The weight of a unit volume of powder, usually expressed as grams per cubic centimeter, determined by a specified method.

Apparent Hardness-The value obtained by testing a sintered material with standard indentation hardness equipment. Since the reading is a composite of pores and solid material, it is usually lower than that of solid material of the same composition and condition. Not to be confused with particle hardness.

Arborescent Powder-See Dendritic Powder.

Atomization-The disintegration of a molten metal into particles by a rapidly moving gas or liquid stream or by mechanical means.

Atomized Metal Powder-Metal powder produced by the disintegration of a molten metal by a rapidly moving gas or liquid stream, or by mechanical means.

Average Pore Size-The average pore diameter of a porous material, such as a filter, which conforms to specific particle removal requirements, usually the removal of 95% to 100% of a given particle size distribution. Synonymous with Nominal Pore Size.

Binder-A cementing medium; either a material added to the powder to increase the green strength of the compact, and which is expelled during sintering; or a material (usually of relatively lower melting point) added to a powder mixture for the specific purpose of cementing together powder particles which alone would not sinter into a strong body.

Blank-A pressed, presintered or fully sintered compact, usually in the unfinished condition, requiring cutting, machining, or some other operation to give it its final shape. See Preforming.

Blending-The thorough intermingling of powders of the same nominal composition (not to be confused with mixing).

Bridging-The formation of arched cavities in a powder mass.

Briquet-See Compact.

Bulk Density-Synonymous with Apparent Density (U.S.), and Loading Weight (British).

Burn Off-That stage of a sintering cycle referring to the time and temperature necessary to remove ingredients used to assist the forming of a powder metallurgy part, such as binders or die lubricants.

Cake-A coalesced mass of unpressed metal powder.

Carbonyl Powder-A metal powder prepared by the thermal decomposition of a metal carbonyl.

Cement Copper-Copper precipitated by iron from copper sulfate solutions.

Chemically Precipitated Metal Powder-Powder produced by the replacement of one metal from a solution of its salts by the addition of another element higher in the electrochemical series, or by other reducing agent.

Classification-Separation of a powder into fractions according to particle size.

Coining-The pressing of a sintered compact to obtain a definite surface configuration (not to be confused with Repressing or Sizing).

Cold Pressing-The forming of a compact at room temperature.

Cold Welding-Cohesion between two surfaces of metal, generally under the influence of externally applied pressure at room temperature.

Compact-An object produced by the compression of metal powder, generally while confined in die, with or without the inclusion of nonmetallic constituents. Synonymous with Briquet.

Compacting Tool Set-See Die.

Composite Compact-A metal powder compact consisting of two or more adhering layers, rings, or other shapes of different metals or alloys with each layer retaining its original identity.

Compound Compact-A metal powder compact consisting of mixed metals, the particles of which are joined by pressing or sintering or both, with each metal particle retaining substantially its original composition.

Compressibility-A density ratio determined under definite testing conditions.

Compression Ratio-The ratio of the volume of the loose powder to the volume of the compact made from it. Synonymous with Fill Ratio.

Continuous Sintering-Presintering, or sintering, in such manner that the objects are advanced through the furnace at a fixed rate by manual or mechanical means. Synonymous with Stoking.

Core Rod-The separate member of the compacting tool set or die that forms a hole in the compact.

Cored Bar-A compact of bar shape heated by its own electrical resistance to a temperature high enough to melt its interior.

Cracked Ammonia-See Dissociated Ammonia.

Cut-See Fraction.

Dendritic Powder-Particles, usually of electrolytic origin, having the typical pine tree structure. Synonymous with Arborescent Powder.

Density (Dry)-The weight per unit volume of an unimpregnated P/M part.

Density (Wet)-The weight per unit volume of a P/M part impregnated with oil or other non metallic materials.

Density Ratio-The ratio of the determined density of a compact to the absolute density of metal of the same composition, usually expressed as a percentage.

Die-The part or parts making up the confining form in which a powder is pressed. The parts of the die may be some or all of the following: Die body, punches, and core rods. Synonymous with Mold and Compacting Tool Set.

Die Body-The Stationary or fixed part of a die.

Die Insert-A removable liner or part of a die body or punch. Synonymous with Die Liner.

Die Liner-See Die Insert.

Die Lubricant-A lubricant mixed with the powder or applied to the walls of the die and punches to facilitate the pressing and ejection of the compact.

Die Set-The parts of a press that hold and locate the die in proper relation to the punches.

Dissociated Ammonia-A reducing gas produced by the thermal decomposition of anhydrous ammonia over a catalyst, resulting in a gas of 75% hydrogen and 25% nitrogen. Synonymous with Cracked Ammonia.

Disintegration-The reduction of massive material to powder.

Electrolytic Powder-Powder produced by electrolytic deposition or the pulverization of an electrodeposit.

Endothermic Atmosphere (Gas)-A reducing gas atmosphere used in sintering and produced by the reaction of a hydrocarbon fuel gas and air over a catalyst with the aid of an external heat source. It is low in carbon dioxide and water vapor with relatively large percentages of hydrogen and carbon monoxide. Maximum combustibles approximately 60%.

Equiaxed Powder-See Granular Powder.

Exothermic Atmosphere (Gas)-A reducing gas atmosphere used in sintering and produced by partial or complete combustion of a hydrocarbon fuel gas and air. Maximum combustibles approximately 25%.

Exudation-The action by which all or a portion of the low melting constituent of a compact is forced to the surface during sintering. Sometimes referred to as "bleed out". Synonymous with Sweating.

Fill Ratio-See Compression Ratio.

Fines-The portion of a powder composed of particles which are smaller than a specified size, currently less than 44 microns. See also Superfines.

Flake Powder-Flat or scale-like particles whose thickness is small compared with the other dimensions.

Flow Rate-The time required for a powder sample of standard weight to flow through an orifice in a standard instrument according to a specified procedure.

Fraction-That portion of a powder sample which lies between two stated particle sizes. Synonymous with Cut.

Gas Classification-The separation of powder into particle size fractions by means of a gas stream of controlled velocity.

Granular Powder-Particles having approximately equidimensional nonspherical shapes.

Granulation-The production of coarse metal particles by pouring the molten metal through a screen into water (shotting), or by violent agitation of the molten metal while solidifying. Not to be confused with Granulation as used in pharmaceutical terminology.

Green-Unsintered (not sintered); for example: Green compact, green density, green strength.

Growth-An increase in dimensions of a compact which may occur during sintering (converse of Shrinkage).

Hall Paste Process-A ball milling process for powder production in which a liquid hydrocarbon is used as a suspension medium.

Hametag Process-A ball milling method of powder production in which an inert gas atmosphere is used to prevent oxidation of the powder.

Hot Pressing-The simultaneous heating and molding of a compact.

Hydrogen Loss-The loss in weight of metal powder or of a compact caused by heating a representative sample for a specified time and temperature in a purified hydrogen atmosphere—broadly a measure of the oxygen content of the sample, when applied to materials containing only such oxides as are reducible with hydrogen and no hydride forming material.

Hydrogen-Reduced Powder-Powder produced by the hydrogen reduction of a metal oxide.

Impregnation-A process of filling the pores of a sintered compact with a nonmetallic material such as oil, wax or resin.

Infiltration-A process of filling the pores of a sintered, or unsintered, P/M compact with a metal or alloy of lower melting point.

Interconnected Porosity-A network of contiguous pores in and extending to the surface of a sintered compact. Usually applied to P/M materials where the interconnected porosity is determined by impregnating the specimens with oil.

Irregular Powder-Particles lacking symmetry.

K-factor-The strength constant in the formula for radial crushing strength of a plain sleeve specimen of sintered metal. See Radial Crushing Strength.

Lamination-A rupture in the pressed compact caused by the mass slippage of a part of the compact. Synonymous with Pressing Crack and Slip Crack.

Leafing-Formation of a continuous film of metal through surface tension; the higher the surface tension, the more rapid and complete is the leafing.

Liquid Phase Sintering-Sintering of a P/M compact, or loose powder aggregate under conditions where a liquid phase, is present during part of the sintering cycle.

Loading-The filling of the die cavity with powder.

Lower Punch-The member of the compacting tool set or die that determines the volume of powder fill and forms the bottom of the part being produced. Secondary or subdivided lower punches may be necessary to facilitate filling, forming and ejecting of multiple-level parts.

Lubricating-Mixing with, or incorporating in, a powder, some agent to facilitate pressing and ejecting the compact from the die body; applying a lubricant to the die walls and punch surfaces.

Matrix Metal-The continuous phase of a polyphase alloy or mechanical mixture; the physically continuous metallic constituent in which separate particles of another constituent are embedded.

Maximum Pore Size-See Absolute Pore Size.

Mechanical Component-A shaped body pressed from metal powder and sintered wherein self-lubrication is not a primary property. A part but not an oil-impregnated bearing. See Powder Metallurgy Part.

Mesh-The sieve number of the finest screen through which substantially all of the particles of a given sample will pass. The number of screen openings per linear inch of screen.

Metal Filter-A metal structure having controlled interconnected porosity produced to meet filtration or permeability requirements.

Metal Powder-Discrete particles of elemental metals or alloys normally within the size range of 0.1 to 1000 microns.

Milling-The mechanical treatment of metal powder, or metal powder mixtures, as in a ball mill, to alter the size or shape of the individual particles, or to coat one component of the mixture with another.

Minus Sieve-The portion of a powder sample which passes through a standard sieve of specified number. See Plus Sieve.

Mixing-The thorough intermingling of powders of two or more materials.

Mold-See Die.

Molding-The pressing of powder to form a compact.

Needles-Elongated rod-like particles.

Nodular Powder-Irregular particles having knotted, rounded, or similar shapes.

Oversize Powder-Particles coarser than the maximum permitted by a given particle size specification.

Packing Material-Any material in which compacts are embedded during the presintering or sintering operation.

Particle Size-The controlling lineal dimension of an individual particle as determined by analysis with sieves or other suitable means.

Particle Size Distribution-The percentage by weight, or by number, of each fraction into which a powder sample has been classified with respect to sieve number or microns. (Preferred usage: "Particle size distribution by weight" or "particle size distribution by frequency.")

Permeability-A property measured as the rate of passage of a liquid or gas through a compact; measured under specified conditions.

Plates-Flat particles of metal powder having considerable thickness.

Plus Sieve-The portion of a powder sample retained on a standard sieve of specified number. See Minus Sieve.

P/M-The acronym representing powder metallurgy. Used as P/M Part, P/M Product, P/M Process, etc.

P/M Part-A shaped object that has been formed from metal powders and bonded by heating below the melting point of the major constituent. A structural or mechanical component, bearing or bushing, made by the powder metallurgy process.

Polishing-An operation in which flake powder and a small quantity of lubricant are rotated in a cylinder to cause the particles to rub against each other, thus smoothing the surfaces. The lubricant imparts leafing qualities to the powder.

Pore-Forming Material-A substance included in a powder mixture which volatizes during sintering and thereby produces a desired kind and degree of porosity in the finished compact.

Porosity-The amount of pores (voids) expressed as a percentage of the total volume of the powder metallurgy part.

Porous Metal-A metal structure having controlled interconnected porosity. See Metal Filter.

Powder Flow Meter-An instrument for measuring the rate of flow of a powder according to a specified procedure.

Powder Lubricant-An agent mixed with or incorporated in a powder to facilitate the pressing and ejecting of the compact.

Powder Metallurgy-The arts of producing metal powders and of the utilization of metal powders for the production of massive materials and shaped objects.

Powder Metallurgy Part-See P/M Part.

Powder Rolling-The progressive compacting of metal powders by the use of a rolling mill. Synonymous with Roll Compacting.

Pre-alloyed Powder-An alloy in powder form in which each particle is of the same composition.

Preforming-The initial pressing of a metal powder to form a compact which is subjected to a subsequent pressing operation other than coining or sizing. Also, the preliminary shaping of a refractory metal compact after presintering and before the final sintering.

Premix-A uniform intermingling of powders of two or more materials performed by the powder producer (not to be confused with pre-blending-See Blending).

Presintering-The heating of a compact at a temperature below the normal final sintering temperature, usually to increase the ease of handling or shaping the compact, or to remove a lubricant or binder prior to sintering.

Pressed Bar-A compact in the form of a bar; a green compact.

Pressed Density-The weight per unit volume of an unsintered compact. Synonymous with Green Density.

Pressing Crack-See Lamination.

Puffed Compact-A compact expanded by internal gas pressure.

Pulverization-The reduction in particle size of metal powder by mechanical means; a specific type of Disintegration.

Punch-Part of a die or compacting tool set which is used to transmit pressure to the powder in the die cavity. See Upper Punch and Lower Punch.

Radial Crushing Strength-The relative capacity, of a plain sieve specimen made by powder metallurgy, to resist fracture induced by a force applied between flat parallel plates in a direction perpendicular to the axis of the specimen.

Rate-of-Oil-Flow-The rate at which a specified oil will pass through a sintered porous compact under specified test conditions.

Reduced Metal Powder-Metal powder produced, without melting, by the chemical reduction of metal oxides or other compounds.

Repressing-The application of pressure to a previously pressed and sintered compact, usually for the purpose of improving some physical property.

Roll Compacting-See Powder Rolling.

Rolled Compact-A compact made by passing metal powder continuously through a rolling mill so as to form relatively long sheets of pressed material.

Rotary Press-A machine fitted with a rotating table carrying multiple dies in which a material is pressed.

Screen Analysis-See Sieve Analysis.

Segment Die-A die made of parts which can be separated for the ready removal of the compact. Synonymous with Split Die.

Shrinkage-A decrease in dimensions of a compact which may occur during sintering (converse of Growth).

Sieve Analysis-Particle size distribution; usually expressed as the weight percentage retained upon each of a series of standard sieves of decreasing size and the percentage passed by the sieve of finest size. Synonymous with Screen Analysis.

Sieve Classification-The separation of powder into particle size ranges by the use of a series of graded sieves.

Sieve Fraction-That portion of a powder sample which passes through a standard sieve of specified number and is retained by some finer sieve of specified number.

Sintering-Bonding of particles in a mass of metal powder by molecular (or atomic) attraction in the solid state, through the application of heat, causing strengthening of the powder mass and normally resulting in densification and recrystallization due to material transport. Sintering (Noun)-See P/M Part.

Sizing-A final pressing of a sintered compact to secure desired size.

Slip Casting-A method of forming metal shapes by pouring a stabilized water suspension of metal powders into the shaped cavity of a fluid-absorbing mold, diffusing the liquid into the mold wall, removing the casting from the mold and sintering.

Slip Crack-See Lamination.

Specific Surface-The surface area of one gram of powder, usually expressed in square centimeters.

Spherical Powder-Globular shaped particles.

Split Die-See Segment Die.

Spongy-A porous condition in metal powder particles usually observed in reduced oxides.

Stoking-See Continuous Sintering.

Stripper Punch-A punch, which in addition to forming the top or bottom of the die cavity, later moves further into the die to eject the compact.

Subsieve Fraction-Particles all of which will pass through a 44 micron (No. 325) standard sieve.

Superfines-The portion of a powder composed of particles which are smaller than a specified size, currently less than 10 microns.

Sweating-See Exudation.

Tap Density-The apparent density of a powder obtained when the receptacle is tapped or vibrated during loading under specified conditions.

Transverse Rupture Strength-The stress, calculated from the flexure formula, required to break a specimen as a simple beam supported near the ends and applying the load midway between the fixed center line of the supports.

Upper Punch-The member of the compacting tool set or die that closes the die and forms the top of the part being produced.

Warpage-Distortion which may occur in a compact during sintering.

APPENDIX C

METAL POWDER INDUSTRIES FEDERATION

P/M MATERIALS STANDARDS AND SPECIFICATIONS

MPIF Standard 35
Adopted 1961, Revised 1965, 1969, 1972, 1974

This Standard, prepared by the Metal Powder Industries Federation, is subject to periodic revision. Suggestions for revision should be addressed to the Metal Powder Industries Federation, Box 2054, Princeton New Jersey 08540. Users of standards are cautioned to secure the latest editions. Additional information must be approved by the Standards Board of the Metal Powder Industries Federation before it can be considered part of the Standard. Extra copies of MPIF Standards may be obtained from the Federation at the above address. A list of the other standards and prices will be sent on request.

Scope

MPIF Standard 35 is issued to provide the design and materials engineer with the information necessary for specifying those P/M materials which have been developed and accepted by the P/M parts manufacturing industry as standard and representative of their capabilities and commercial practices. It is reasonable to expect that any properly equipped and experienced P/M parts manufacturer could supply P/M materials that will meet this standard.

MPIF Standards are issued and adopted in the public interest. They are designed to eliminate misunderstandings between the manufacturer and the purchaser and to assist the purchaser in selecting and obtaining the proper material for his particular product. Existence of an MPIF Standard does not in any respect preclude any member or non-member from manufacturing or selling products not included in this Standard.

A Standard of the Metal Powder Industries Federation defines a product, process or procedure with reference to one or more of the following: nomenclature, composition, construction, physical properties, mechanical properties, dimension, tolerances, safety, operating characteristics, performance, quality, rating, testing, and the service for which designed.

The data provided herein represent typical mechanical properties achieved under conventional manufacturing procedures. Higher mechanical properties and other improvements in performance characteristics can be obtained by experienced P/M parts manufacturers through the use of more complex processing techniques or different starting materials.

By referring to the property and performance values specified in each of the P/M Materials Standards, it is possible for the user to designate the exact material he desires for a specific application. It should also be apparent that the range of properties available through powder metallurgy is constantly increasing and that there usually are several alternative approaches toward achieving identical properties and performance. The data given are realistic and can serve as an effective guideline in the proper application of the products of powder metallurgy.

Explanatory Notes

The following describe and explain the details of the P/M Materials Standards. An understanding of what is intended will aid the Standards user in the proper interpretation of the data furnished.

Material ...

A word description of the P/M material being specified.

Designation ...

A code designation of the P/M material being specified which is based on the P/M coding system adopted by the industry. The coding system offers a convenient means for designating the type of material, composition and density of a P/M part. It should be noted that those code designations shown in Standard 35 and revisions thereof apply only to P/M materials standardized by the Metal Powder Industries Federation.

Note: Materials not yet adopted as industry standards should not be classified under the MPIF coding system.

In the coding system the prefix letters denote the general type of material; for example, the letters "CT" = bronze.

Prefix Letter Code

A	Aluminum
Y	Antimony
B	Bismuth
D	Cadmium
E	Rare Earths
R	Chromium
C	Copper
F	Iron
FX	Infiltrated Steel (or Infiltrated Iron)
P	Lead
L	Lithium
G	Magnesium
M	Manganese
O	Molybdenum
N	Nickel
S	Silicon
SS	Stainless Steel
Q	Silver
H	Thorium
T	Tin
W	Tungsten
Z	Zinc
K	Zirconium

The four digits following the prefix refer to the composition of the material.

In nonferrous materials, the last two numbers in the four digit series designate the percentage of the major alloying constituent. If there are no minor constituents, two zeros are indicated for the first two digits. If a minor constituent is present, the first two numbers designate the percentage of the minor constituent. Additional minor constituents are indicated in the prefix letters only.

In ferrous materials, those major alloying elements (except carbon) which are shown as ranges are included in the prefix letter code. Other elements are excluded from the code but are represented in "Chemical Composition" (Line 1). The first two digits of the designation indicate the percentage of the major alloying constituent present.

Carbon content in ferrous materials is designated by the last two numbers in the four digit series. The carbon content up to and including 0.3% will be considered as zero, higher contents will be indicated in ranges and coded as follows:

Carbon Ranges	Code Designation
0.0% - 0.3%	00
0.3% - 0.6%	05
0.6% - 1.0%	08

The percentage of carbon that is metallurgically combined is to be indicated in the coding system. Free carbon such as graphite in certain bearings is not to be included in the coding but may be referred to elsewhere in the Standard.

In the case of P/M Stainless Steels the four digit series shall be replaced with the appropriate designation adopted by the American Iron and Steel Institute, but the MPIF letter codes will still be used as part of the designation in this standard.

The **suffix letter** denotes the density range of the material. The range used is that in which the mean density lies.

Suffix Letter Codes for Density Range Classification

N	Less than 6.0 gms/cc
P	6.0 to less than 6.4 gms/cc
R	6.4 to less than 6.8 gms/cc
S	6.8 to less than 7.2 gms/cc
T	7.2 to less than 7.6 gms/cc
U	7.6 to less than 8.0 gms/cc
W	8.0 to less than 8.4 gms/cc

TYPICAL P/M MATERIAL CODE DESIGNATIONS

Nonferrous

Material	Compositions (by percent)	Code for Material & Composition
P/M Bronze	Cu-90, Sn-10	CT-0010
P/M Bronze (Leaded)	Cu-87, Sn-10, Pb-3	CTP-0310
P/M Nickel Silver	Cu-64, Zn-18, Ni-18	CZN-1818
P/M Nickel-Silver (Leaded)	Cu-64, Ni-18, Zn-16, Pb-2	CZNP-1618
P/M Brass (Leaded)	Cu-79, Zn-18, Pb-2	CZP-0218

Ferrous

Material	Composition (by percent)	Code for Material & Composition
P/M Iron	Fe-99, C-0.2	F-0000
P/M Steel	Fe-98, C-0.8	F-0008
P/M Copper Steel	Fe-96, Cu-2, C-0.8	FC-0208
P/M Iron-Copper	Fe-89, Cu-10, C-0.2	FC-1000
P/M Iron-Nickel	Fe-96, Ni-2, C-0.2	FN-0200
P/M Infiltrated Iron	Fe-78, Cu-20, C-0.2	FX-2000
P/M Infiltrated Steel	Fe-77, Cu-20, C-0.8	FX-2008
P/M Austenitic Stainless Steel	AISI 316	SS-316
P/M Martensitic Stainless Steel	AISI 410	SS-410

APPENDIX D

STANDARDS FOR METAL POWDERS AND COPPER-BASE P/M MATERIALS

	MPIF* Standard No.	ASTM** Standard
Determination of Bending Strength, Green Density, Hardness and Shrinkage of Compacted, Sintered Metal Powder Specimens	13	—
Standard Method of Test for Compressibility of Metal Powders	—	B331
Standard Method of Test for Apparent Density of Metal Powders	4	B212
Standard Method of Test for Apparent Density of Non-Free-Flowing Metal Powders	28	B417
Standard Method of Test for Flow Rate of Metal Powders	3	B213
Standard Method of Test for Green Strength of Compacted Metal Powder Specimens	15	B312
Standard Method of Test for Hydrogen Loss of Copper, Tungsten, and Iron Powders	2	E159
Standard Method of Test for Acid-Insoluble Content of Copper and Iron Powders	6	E194
Determination of Average Particle Size of Metal Powders by the Fisher Sub-sieve Sizer	32	—
Sampling Finished Lots of Metal Powder	1	—
Standard Method of Test for Sieve Analysis of Granular Metal Powders	5	B214
Standard Method for Sub-sieve Analysis of Granular Metal Powders by Air Classification	12	B293
Standard Methods of Tension Testing of Metallic Materials	10	E8
Test Methods for Bronze P/M Filter Powders	39	—

Material	Standard
P/M Bronze	CT-0010-N CT-0010-R CT-0010-S
P/M Brass (Leaded)	CZP-0218-T CZP-0218-U CZP-0218-W
P/M Nickel Silver	CZN-1818-U CZN-1818-W
P/M Nickel Silver (Leaded)	CZNP-1618-U CZNP-1618-W

*available from Metal Powder Industries Federation, P.O. Box 2054, Princeton, N.J. 08540.
**available in the Annual Book of ASTM Standards.