7.1 Powder Metallurgy

Powder metallurgy (PM) is a metal processing technology in which parts are produced from metallic powders.

In the usual PM production sequence, the powders are compressed into the desired shape and then heated to cause bonding of the particles into a hard, rigid mass. Compression, called pressing, is accomplished in a press-type machine using tools designed specifically for the part to be manufactured. The tooling, which typically consists of a die and one or more punches, can be expensive, and PM is therefore most appropriate for medium and high production.

The heating treatment, called sintering, is performed at a temperature below the melting point of the metal. Considerations that make powder metallurgy an important commercial technology include:

i. PM parts can be mass produced to net shape or near net shape, eliminating or reducing the need for subsequent processing.
ii. The PM process itself involves very little waste of material; about 97% of the starting powders are converted to product. This compares favorably with casting processes in which sprues, runners, and risers are wasted material in the production cycle.
iii. Owing to the nature of the starting material in PM, parts having a specified level of porosity can be made. This feature lends itself to the production of porous metal parts such as filters and oil-impregnated bearings and gears.
iv. Certain metals that are difficult to fabricate by other methods can be shaped by powder metallurgy. Tungsten is an example; tungsten filaments used in incandescent lamp bulbs are made using PM technology.
v. Certain metal alloy combinations and cermets can be formed by PM that cannot be produced by other methods.
vi. PM compares favorably with most casting processes in terms of dimensional control of the product. Tolerances of ± 0.13 mm (± 0.005 in) are held routinely.
vii. PM production methods can be automated for economical production.

There are limitations and disadvantages associated with PM processing. These include the following: (1) tooling and equipment costs are high, (2) metallic powders are expensive, and (3) there are difficulties with storing and handling metal powders (such as degradation of the metal over time, and fire hazards with particular metals). Also, (4) there are limitations on part geometry because metal powders do not readily flow laterally in the die during pressing, and allowances must be provided for ejection of the part from the die after pressing. In addition, (5) variations in material density throughout the part may be a problem in PM, especially for complex part geometries.

7.1.1 Geometric Features

The geometry of the individual powders can be defined by the following attributes: (1) particle size and distribution, (2) particle shape and internal structure, and (3) surface area.

7.2 Production of Metallic Powders

In general, producers of metallic powders are not the same companies as those that make PM parts. The powder producers are the suppliers; the plants that manufacture components out of powder metals are the customers. Virtually any metal can be made into powder form. There are three principal methods by which metallic powders are commercially produced, each of which involves energy input to increase the surface area of the metal. The methods are (1) atomization, (2) chemical, and (3) electrolytic. In addition, mechanical methods are occasionally used to reduce powder sizes; however, these methods are much more commonly associated with ceramic powder production.

7.2.1 Atomization

This method involves the conversion of molten metal into a spray of droplets that solidify into powders. It is the most versatile and popular method for producing metal powders today, applicable to almost all metals, alloys as well as pure metals. There are multiple ways of creating the molten metal spray, several of which are illustrated in Figure 7.1. Two of the methods shown are based on gas atomization, in which a high velocity gas stream (air or inert gas) is utilized to atomize the liquid metal. In Figure 7.1(a), the gas flows through an expansion nozzle, siphoning molten metal from the melt below and spraying it into a container. The droplets solidify into powder form. In a closely related method shown in Figure 7.1(b),molten metal flows by gravity through a nozzle and is immediately atomized by air jets. The resulting metal powders, which tend to be spherical, are collected in a chamber below.

The approach shown in Figure 7.1(c) is similar to (b), except that a high-velocity water stream is used instead of air. This is known as water atomization and is the most common of the atomization methods, particularly suited to metals that melt below 1600^{o}C (2900^{o}F). Cooling is more rapid, and the resulting powder shape is irregular rather than spherical. The disadvantage of using water is oxidation on the particle surface.

A recent innovation involves the use of synthetic oil rather than water to reduce oxidation. In both air and water atomization processes, particle size is controlled largely by the velocity of the fluid stream; particle size is inversely related to velocity.

Several methods are based on centrifugal atomization. In one approach, the rotating disk method shown in Figure 7.1(d), the liquid metal stream pours onto a rapidly rotating disk that sprays the metal in all directions to produce powders.

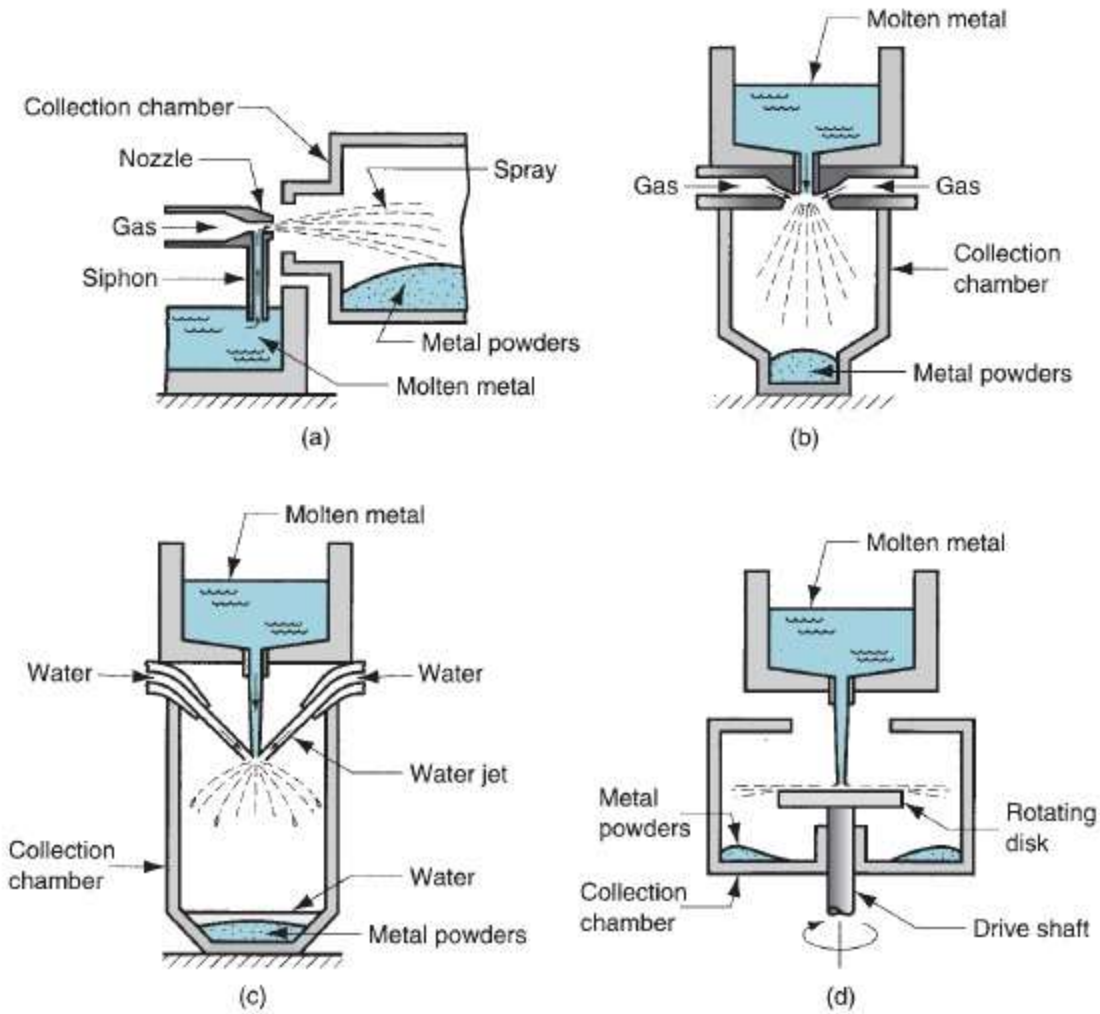

FIGURE 7.1: Several atomization methods for producing metallic powders: (a) and (b) two gas atomization methods; (c) water atomization; and (d) centrifugal atomization by the rotating disk method.

7.2.2 Other Production Methods

Other metal powder production methods include various chemical reduction processes, precipitation methods, and electrolysis.

Chemical reduction includes a variety of chemical reactions by which metallic compounds are reduced to elemental metal powders. A common process involves liberation of metals from their oxides by use of reducing agents such as hydrogen or carbon monoxide.

The reducing agent is made to combine with the oxygen in the compound to free the metallic element. This approach is used to produce powders of iron, tungsten, and copper.

Another chemical process for iron powders involves the decomposition of iron pentacarbonyl

(Fe(Co)5) to produce spherical particles of high purity. Powders produced by this method are illustrated in the photomicrograph of Figure 7.2. Other chemical processes include precipitation of metallic elements from salts dissolved in water. Powders of copper, nickel, and cobalt can be produced by this approach.

In electrolysis, an electrolytic cell is set up in which the source of the desired metal is the anode. The anode is slowly dissolved under an applied voltage, transported through the electrolyte, and deposited on the cathode. The deposit is removed, washed, and dried to yield a metallic powder of very high purity. The technique is used for producing powders of beryllium, copper, iron, silver, tantalum, and titanium.

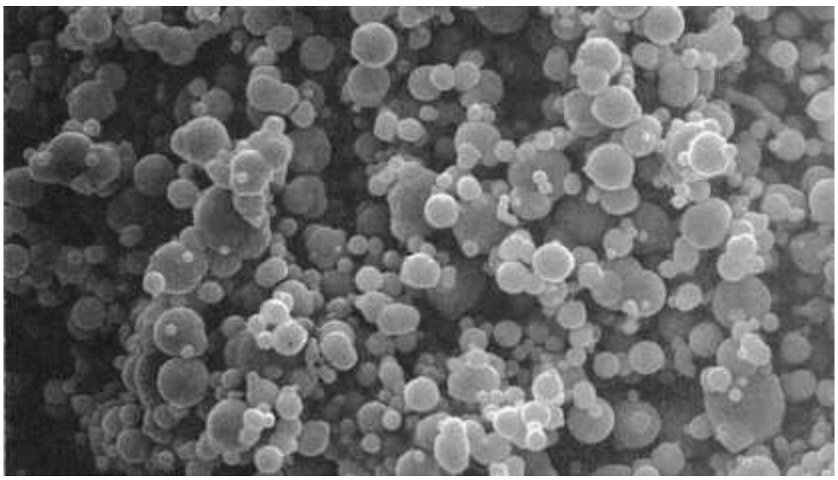

FIGURE 7.2: Iron powders produced by decomposition of iron pentacarbonyl

7.3 Conventional Pressing and Sintering

After the metallic powders have been produced, the conventional PM sequence consists of three steps:

(1) blending and mixing of the powders;

(2) compaction, in which the powders are pressed into the desired part shape; and

(3) sintering, which involves heating to a temperature below the melting point to cause solid-state bonding of the particles and strengthening of the part. The three steps, sometimes referred to as primary operations in PM, are portrayed in Figure 7.3. In addition, secondary operations are sometimes performed to improve dimensional accuracy, increase density, and for other reasons.

7.3.1 Blending and Mixing of the Powders

To achieve successful results in compaction and sintering, the metallic powders must be thoroughly homogenized beforehand. The terms blending and mixing are both used in this context. Blending refers to when powders of the same chemical composition but possibly different particle sizes are intermingled.

Blending and mixing are accomplished by mechanical means. Four alternatives are illustrated in Figure 7.3: (a) rotation in a drum; (b) rotation in a double-cone container; (c) agitation in a screw mixer; and (d) stirring in a blade mixer. There is more science to these devices than one would suspect. Best results seem to occur when the container is between 20% and 40% full. The containers are usually designed with internal baffles or other ways of preventing free-fall during blending of powders of different sizes, because variations in settling rates between sizes result in segregation—just the opposite of what is wanted in blending. Vibration of the powder is undesirable, because it also causes segregation.

Other ingredients are usually added to the metallic powders during the blending and/or mixing step. These additives include (1) lubricants, such as stearates of zinc and aluminum, in small amounts to reduce friction between particles and at the die wall during compaction; (2) binders, which are required in some cases to achieve adequate strength in the pressed but unsintered parts; and (3) deflocculants, which inhibit agglomeration of powders for better flow characteristics during subsequent processing.

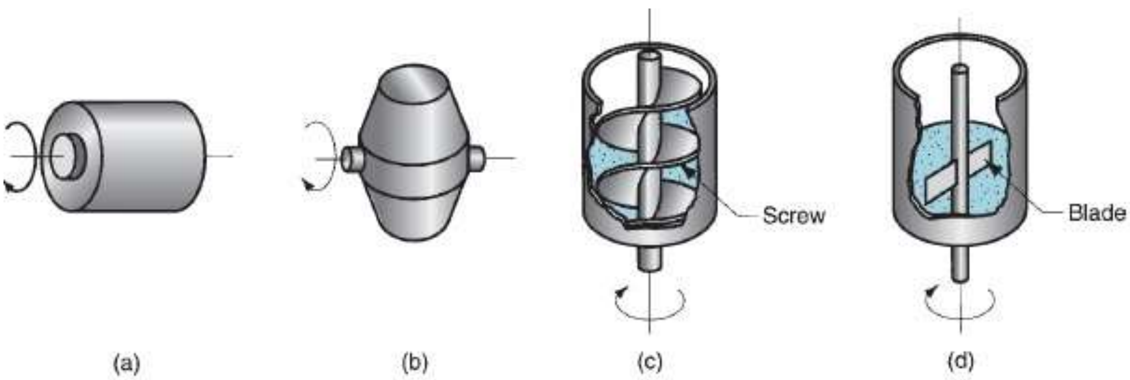

FIGURE 7.3: Several blending and mixing devices: (a) rotating drum, (b) rotating double-cone, (c) screw mixer, and (d) blade mixer.

7.3.2 Compaction

In compaction, high pressure is applied to the powders to form them into the required shape. The conventional compaction method is pressing, in which opposing punches squeeze the powders contained in a die. The steps in the pressing cycle are shown in Figure 7.4. The workpart after pressing is called a green compact, the word green meaning not yet fully processed. As a result of pressing, the density of the part, called the green density, is much greater than the starting bulk density. The green strength of the part when pressed is adequate for handling but far less than that achieved after sintering.

The applied pressure in compaction results initially in repacking of the powders into a more efficient arrangement, eliminating ‘‘bridges’’ formed during filling, reducing pore space, and increasing the number of contacting points between particles. As pressure increases, the particles are plastically deformed, causing inter-particle contact area to increase and additional particles to make contact.

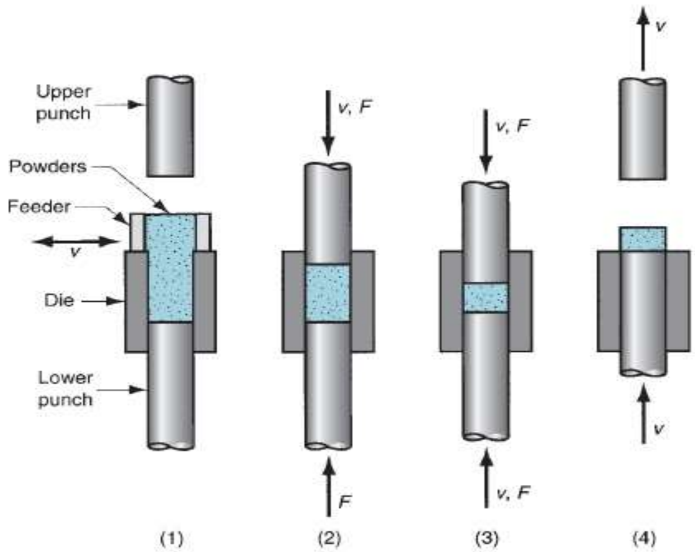

FIGURE 7.4: Pressing, the conventional method of compacting metal powders in PM: (1) filling the die cavity with powder, done by automatic feed in production, (2) initial, and (3) final positions of upper and lower punches during compaction, and (4) ejection of part.

Presses used in conventional PM compaction are mechanical, hydraulic, or a combination of the two. Because of differences in part complexity and associated pressing requirements, presses can be distinguished as (1) pressing from one direction, referred to as single-action presses; or (2) pressing from two directions, any of several types including opposed ram, double-action, and multiple action. Current available press technology can provide up to 10 separate action controls to produce parts of significant geometric complexity. The capacity of a press for PM production is generally given in tons or kN or MN.

The required force for pressing depends on the projected area of the PM part (area in the horizontal plane for a vertical press) multiplied by the pressure needed to compact the given metal powders. Reducing this to equation form

$F = A_p p_c$

where F = required force, N (lb); A_p = projected area of the part, mm^2 (in^2); and p_c = compaction pressure required for the given powder material, MPa (lb/in^2). Compaction pressures typically range from 70 MPa (10,000 lb/in^2) for aluminum powders to 700 MPa (100,000 lb/in^2) for iron and steel powders.

7.3.3 Sintering

After pressing, the green compact lacks strength and hardness; it is easily crumbled under low stresses. ***Sinterin***g is a heat treatment operation performed on the compact to bond its metallic particles, thereby increasing strength and hardness. The treatment is usually carried out at temperatures between 0.7 and 0.9 of the metal's melting point (absolute scale). The terms solid-state sintering or solid-phase sintering are sometimes used for this conventional sintering because the metal remains unmelted at these treatment temperatures.

It is generally agreed among researchers that the primary driving force for sintering is reduction of surface energy. The green compact consists of many distinct particles, each with its own individual surface, and so the total surface area contained in the compact is very high. Under the influence of heat, the surface area is reduced through the formation and growth of bonds between the particles, with associated reduction in surface energy. The finer the initial powder size, the higher the total surface area, and the greater the driving force behind the process.

7.3.4 Secondary Operations

PM secondary operations include densification, sizing, impregnation, infiltration, heat treatment, and finishing.

Densification and Sizing: A number of secondary operations are performed to increase density, improve accuracy, or accomplish additional shaping of the sintered part.

Repressing is a pressing operation in which the part is squeezed in a closed die to increase density and improve physical properties. Sizing is the pressing of a sintered part to improve dimensional accuracy. Coining is a pressworking operation on a sintered part to press details into its surface.

Some PM parts require machining after sintering. Machining is rarely done to size the part, but rather to create geometric features that cannot be achieved by pressing, such as internal and external threads, side holes, and other details.

Impregnation and Infiltration: Porosity is a unique and inherent characteristic of powder metallurgy technology. It can be exploited to create special products by filling the available pore space with oils, polymers, or metals that have lower melting temperatures than the base powder metal.

Impregnation is the term used when oil or other fluid is permeated into the pores of a sintered PM part. The most common products of this process are oil-impregnated bearings, gears, and similar machinery components. Self-lubricating bearings, usually made of bronze or iron with10% to 30% oil by volume, are widely used in the automotive industry. The treatment is accomplished by immersing the sintered parts in a bath of hot oil.

An alternative application of impregnation involves PM parts that must be made pressure tight or impervious to fluids. In this case, the parts are impregnated with various types of polymer resins that seep into the pore spaces in liquid form and then solidify. In some cases, resin impregnation is used to facilitate subsequent processing, for example, to permit the use of processing solutions (such as plating chemicals) that would otherwise soak into the pores and degrade the product, or to improve machinability of the PM workpart.

Infiltration is an operation in which the pores of the PM part are filled with a molten metal. The melting point of the filler metal must be below that of the PM part. The process involves heating the filler metal in contact with the sintered component so that capillary action draws the filler into the pores. The resulting structure is relatively nonporous, and the infiltrated part has a more uniform density, as well as improved toughness and strength.

7.3.5 Heat Treatment and Finishing

Powder metal components can be heat treated and finished by most of the same processes used on parts produced by casting and other metalworking processes. Special care must be exercised in heat treatment because of porosity; for example, salt baths are not used for heating PM parts. Plating and coating operations are applied to sintered parts for appearance purposes and corrosion resistance. Again, precautions must be taken to avoid entrapment of chemical solutions in the pores; impregnation and infiltration are frequently used for this purpose. Common platings for PM parts include copper, nickel, chromium, zinc, and cadmium.

7.4 Materials and Products for Powder Metallurgy

The raw materials for PM processing are more expensive than for other metalworking because of the additional energy required to reduce the metal to powder form. Accordingly, PM is competitive only in a certain range of applications. In this section we identify the materials and products that seem most suited to powder metallurgy.

Powder Metallurgy Materials: From a chemistry standpoint, metal powders can be classified as either elemental or pre-alloyed. Elemental powders consist of a pure metal and are used in applications in which high purity is important. For example, pure iron might be used where its magnetic properties are important. The most common elemental powders are those of iron, aluminum, and copper.

Elemental powders are also mixed with other metal powders to produce special alloys that are difficult to formulate using conventional processing methods. Tool steels are an example; PM permits blending of ingredients that is difficult or impossible by traditional alloying techniques. Using mixtures of elemental powders to form an alloy provides a processing benefit, even where special alloys are not involved. Because the powders are pure metals, they are not as strong as pre-alloyed metals. Therefore, they deform more readily during pressing, so that density and green strength are higher than with pre-alloyed compacts.

In pre-alloyed powders, each particle is an alloy composed of the desired chemical composition. Pre-alloyed powders are used for alloys that cannot be formulated by mixing elemental powders; stainless steel is an important example. The most common pre-alloyed powders are certain copper alloys, stainless steel, and high-speed steel.

The commonly used elemental and pre-alloyed powdered metals, in approximate order of tonnage usage, are: (1) iron, by far the most widely used PM metal, frequently mixed with graphite to make steel parts, (2) aluminum, (3) copper and its alloys, (4) nickel, (5) stainless steel, (6) high-speed steel, and (7) other PM materials such as tungsten, molybdenum, titanium, tin, and precious metals.

Powder Metallurgy Products: A substantial advantage offered by PM technology is that parts can be made to near net shape or net shape; they require little or no additional shaping after PM processing. Some of the components commonly manufactured by powder metallurgy are gears, bearings, sprockets, fasteners, electrical contacts, cutting tools, and various machinery parts. When produced in large quantities, metal gears and bearings are particularly well suited to PM for two reasons: (1) the geometry is defined principally in two dimensions, so the part has a top surface of a certain shape, but there are no features along the sides; and (2) there is a need for porosity in the material to serve as a reservoir for lubricant. More complex parts with true three-dimensional geometries are also feasible in powder metallurgy, by adding secondary operations such as machining to complete the shape of the pressed and sintered part, and by observing certain design guidelines

PRACTICE QUESTIONS

7.1. Name some of the reasons for the commercial importance of powder metallurgy technology.

7.2. What are some of the disadvantages of PM methods?

7.3. Define bulk density and true density for metallic powders.

7.4. What are the principal methods used to produce metallic powders?

7.5. What are the three basic steps in the conventional powder metallurgy shaping process?

7.6. What is the technical difference between mixing and blending in powder metallurgy?

7.7. What are some of the ingredients usually added to the metallic powders during blending and/or mixing?

7.8. What is meant by the term green compact?

7.9. Describe what happens to the individual particles during compaction.

7.10. What are the three steps in the sintering cycle in PM?