Chapter 17

Processing of Metal Powders

QUALITATIVE PROBLEMS

17.15 Why is there density variation in the compacting of powders? How is it reduced?

The main reason for density variation in compacting of powders (Section 17.3 on p. 490) is associated with mechanical locking and friction among the particles; this leads to variations in pressure depending on distance from the punch and from the container walls (see Fig. 17.11 on p. 493). The variation can be reduced by having double-acting presses, lowering the frictional resistance of the punch and die surfaces, or by adding lubricants that reduce inter-particle friction among the powders.

17.16 What is the magnitude of the stresses and forces involved in powder compaction?

Compaction pressures depend, among others, on the powder metal and are given in Table 17.1 on p. 493. The students should compare this values with the strength of sold metals, such as those given in Table 2.2 on p. 67 and various other tables in the text (see also Table 40.1 on p. 1240). Although the forces required in most P/M parts production are usually less than 100 tons, press capacities generally range from 200 to 300 tons, and can be higher. Comparing the pressures with the yield strengths, one can note that the pressures are roughly on the same order.

17.17 Give the reasons why powder-injection molding is an important process.

Powder-injection molding (p. 497) has become an important process because of its versatility and economics. Complex shapes can be obtained at high production rates using powder metals that are blended with a polymer or wax (see PIM in Fig. 17.14 on p. 495). Also, the parts can be produced with high density to net or near-net shape.

17.18 How does the equipment used for powder compaction vary from those used in other metalworking operations?

As described in Section 17.3.1 on p. 493, several types of presses are used for P/M compaction, depending on various factors. For ease of operation, these presses are vertical and highly automated. Metalworking operations also utilize similar equipment, including horizontal presses, as described in sections of chapters on processes such as forging and cold extrusion (see, for example, Sections 14.8 on p. 390 and 15.6 on p. 414). Abrasive resistance is a major factor in P/M die and punch material selection; consequently, the dies in all these operations are made of similar and sometimes identical materials. Processes such as isostatic pressing utilize flexible molds, which is not the case in forging and extrusion. An important difference is that in P/M, it can be advantageous to have a multi-action press so that compaction densities are more uniform (see Fig. 17.11d on p. 493). The students are encouraged to make further comments.

17.19 Why do mechanical and physical properties depend on the density of P/M parts?

The mechanical properties, especially strength, ductility, and elastic modulus, depend on density (see also bottom of p. 491). Not only is there less material in a given volume for less dense P/M parts, but voids are stress concentrations, and the less dense material will have more and larger voids. Physical properties, such as electrical and thermal conductivity, are also adversely affected because (since air is a poor conductor) the less dense the P/M part is, the less material is available to conduct electricity or heat, as shown in Fig. 17.10 on p. 492. (See also answer to Problem 10.22.)

17.20 What are the effects of the different shapes and sizes of metal particles in P/M processing?

The shape, size, size distribution, porosity, chemical purity, and bulk and surface characteristics of metal particles (see Fig. 17.3 on p. 485) are all important because, as expected, they have significant effects on permeability and flow characteristics during compaction and in subsequent sintering operations. It is beneficial to have angular shapes with approximately equally sized particles to aid in bonding.

17.21 Describe the relative advantages and limitations of cold and hot isostatic pressing.

Cold isostatic pressing (CIP) and hot isostatic pressing (HIP) both have the advantages of producing compacts with effectively uniform grain structure and density, thereby making shapes with uniform strength and toughness (see Section 17.3.2 on p. 494). The main advantage of HIP is its ability to produce compacts with essentially 100% density, good metallurgical bonding of powders, and very good mechanical properties; however, the process is relatively expensive and is therefore used mainly for aerospace applications.

17.22 Are the requirements for punch and die materials in powder metallurgy different from those for forging and extrusion? Explain.

In processes such as forging and extrusion and P/M compaction, abrasive wear resistance (see Section 33.5 on p. 1046) is a major factor in die and punch material selection. For that reason, the dies on these operations utilize similar and sometimes identical materials. Processes such as isostatic pressing utilize flexible molds, which is not used in forging and extrusion. (See also answer to Problem 17.18.)

17.23 We have stated that P/M can be competitive with processes such as casting and forging. Explain why this is so, giving ranges of applications.

By the student. Powder metallurgy has become economically competitive with other operations for several reasons. One is the major advantage of producing net or near-net shapes, thus eliminating costly and time-consuming finishing operations. Also, scrap is reduced or eliminated (see Table 40.6 on p. 1250). Functionally, P/M parts are advantageous because of their lubricant-entrapment characteristics, thus reducing the need for external lubricantion in some applications. The high initial cost associated with tooling applies equally to forging, so this can be considered a common drawback to both operations.

17.24 Explain the reasons for the shapes of the curves shown in Fig. 17.10 and for their relative positions on the charts.

The end points of the curves in Fig. 17.10a on p. 492 are not surprising because at low compaction pressures, the density of the P/M parts is low, and at high compacting pressures it approaches the theoretical density (i.e., that of the bulk material). Note that the concavity of the curves is downward, because to increase the density further, smaller and smaller voids must be filled which require much higher pressures. Thus, it is easier to shrink larger cavities in the material than smaller ones. The reasons for the beneficial aspects of density increases (Fig. 17.10b) have been discussed in the answer to Problem 17.19.

17.25 Should green compacts be brought up to the sintering temperature slowly or rapidly? Explain your reasoning.

Rapid heating can cause excessive thermal stresses in the part being sintered and can lead to distortion or cracking; on the other hand, it reduces cycle times. Slow heating has the advantage of allowing heating and diffusion to occur more uniformly.

17.26 Because they undergo special processing, metal powders are more expensive than the same metals in bulk form, especially powders used in powder-injection molding. How is the additional cost justified in powder-metallurgy parts?

By the student. The additional cost can easily be justified because of the numerous advantages inherent in P/M production (see also p. 508). For example, P/M parts can be produced at net or near-net shapes, thus reducing or eliminating finishing operations. Powder metallurgy allows the production of relatively complex shapes from exotic alloys which would otherwise be difficult to manufacture by other means. Also, the self-lubricating capability of sintered metal powders makes P/M parts attractive for bushings, gears, races, and cams; the ability to make alloys with compositions that cannot be cast is attractive for particular applications, especially in the electronics industry. Compaction of powders has certain advantages over other forming operations, such as forging, because by controlling porosity (hence their density) makes them advantageous in applications where weight is critical. (See Chapter 40 for various cost considerations.)

17.27 In Fig. 17.11e, we note that the pressure is not uniform across the diameter of the compact at a particular distance from the punch. What is the reason for this variation?

The nonuniformity of the pressure in the figure (on p. 493) is due to the frictional resistance at the die walls and within the powder particles throughout the compact. The pressure will drop away from the punch because these effects are cumulative, and are similar to the pressure drop in a water-pumping system.

17.28 Why do the compacting pressure and the sintering temperature depend on the type of powder metal?

The compacting pressure depends on the type of metal because interparticular adhesion must take place to develop (minimal) strength in the greenware stage. The compacting pressure is dependant on the powder metal because the softer the material, the larger the contact areas for a given pressure. In sintering, diffusion and vapor and liquid phase transport are dependent on the melting temperature of th material.

17.29 Comment on the shapes and the ranges of the curves of process capabilities in Fig. 17.14.

By the student. There are many acceptable answers, such as the recognition that few parts are very large and very complex, so that these processes serve the vast number of applications. Also, the relative popularity of P/M is explained by its noted flexibility compared to other processes.

QUANTITATIVE PROBLEMS

17.30 Estimate the maximum tonnage required to compact a brass slug 2.5 in. in diameter. Would the height of the slug make any difference in your answer? Explain your reasoning.

As we can see in Table 17.2 on p. 499, the compacting pressure for brass can be as high as 700 MPa = 100 ksi. Thus the force required can be as high as

$$F = (100 \text{ ksi})(A) = (100 \text{ ksi})(\pi/4)(2.5 \text{ in.})^2 = 491 \text{ kip} = 245 \text{ tons}$$

As can be seen in Fig. 17.11e on p. 493, the higher the slug the greater is the pressure drop. This situation can be alleviated by using double punches. Also, note that we have used the highest pressure listed in the table.

17.31 Refer to Fig. 17.10a; what should be the volume of loose, fine iron powder in order to make a solid cylindrical compact 25 mm in diameter and 15 mm high?

The volume of the cylindrical compact is $V = \pi[(25)^2/4]15 = 7360 \text{ mm}^3$. Loose, fine iron powder has a density of 1.40 g/cm^3 (see Fig. 17.10a on p. 492). Density of iron is 7.86 g/cm^3 (see Table 3.1 on p. 103). Therefore, the weight of iron used is

$$W = \rho V = (7.86 \text{ g/cm}^3)(7360 \text{ mm}^3)(10^{-3} \text{ cm}^3/\text{mm}^3) = 57.8 \text{ g}$$

Therefore, the initial volume is

$$V = W/\rho = 57.8/1.40 = 41.3 \text{ cm}^3$$

17.32 Determine the shape factors for (a) a cylinder with dimensional ratios of 1:1:1 and (b) a flake with ratios of 1:10:10.

(a) The volume of this cylinder is

$$V = (\pi/4)(1)^2(1) = \pi/4$$

The equivalent diameter for a sphere of the same volume is

$$D = (6V/\pi)^{1/3} = 1.14$$

The surface area is

$$A = (\pi)(1)(1) + (2)(\pi/4)(1)^2 = 3\pi/2$$

Therefore, $A/V = (3\pi/2)/(\pi/4) = 6$. Hence the shape factor SF is $(1.14)(6) = 6.84$.

(b) The volume of the flakelike particle is $V = (10)(10)(1) = 100$. Note that this is in arbitrary units. The equivalent diameter for a sphere is

$$D = (6V/\pi)^{1/3} = 5.75$$

The surface area A of the particle is

$$A = (2)(10)(10) + (4)(10)(1) = 240$$

Therefore, $A/V = 240/100 = 2.4$. Thus the shape factor SF is $(5.75)(2.4) = 13.8$.

17.33 Estimate the number of particles in a 400-g sample of iron powder, if the particle size is 75 μm.

The density of iron is 7.86 g/cm^3. The particle diameter D is 75 μm = 0.0075 cm. The volume of each spherical particle is

$$V = (4/3)(\pi)(D/2)^3 = (\pi/6)(5.27 \times 10^{-8}) \text{ cm}^3$$

Thus its mass is $(5.27)(\pi/6)(10^{-8}) = 2.75 \times 10^{-8}$ g. Therefore, the number of particles N in the 300-g sample is

$$N = 400/2.75 \times 10^{-8} = 1.45 \times 10^{10}$$

17.34 Assume that the surface of a copper particle is covered by an oxide layer 0.1 mm in thickness. What is the volume (and the percentage of volume) occupied by this layer, if the copper particle itself is 60 μm in diameter?

Because $60 \gg 0.1$, the volume of the oxide layer can be estimated as

$$V = 4\pi r^2 t = (4\pi)(30)^2(0.1) = 1130 \mu\text{m}^3$$

17.35 Survey the technical literature to obtain data on shrinkage during the sintering of P/M parts. Comment on your observations.

By the student. Excellent sources are powder metallurgy source books and general reference materials. Shrinkage values obtained will have a large range, depending on particle morphology and compaction approaches.

17.36 Plot the total surface area of a 100-gram sample of aluminum, as a function of the natural log of particle size.

The density of aluminum is 2.7 g/cm^3 (see Table 3.1 on p. 103). The mass of each particle is:

$$m = \rho V = \left(2.7 \text{ g/cm}^3\right)\left(\frac{\pi}{6}D^3\right)$$

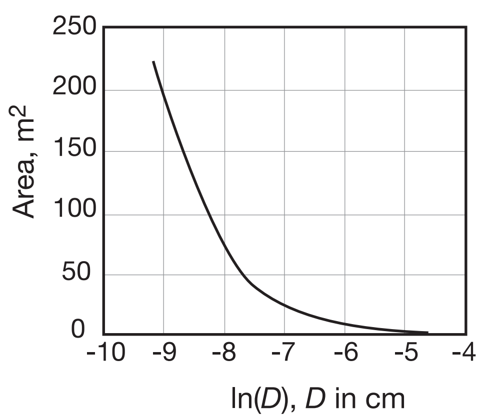
So the number of particles is given by

$$N = \frac{100 \text{ g}}{m} = \frac{100 \text{ g}}{\left(2.7 \text{ g/cm}^3\right)\left(\frac{\pi}{6}D^3\right)} = \left(70.7 \text{ cm}^3\right)\left(D^{-3}\right)$$

The total surface area of these particles is

$$A = N\pi D^2 = \left(70.7 \text{ cm}^3\right)\left(D^{-3}\right)\pi D^2 = \left(222 \text{ cm}^3\right)D^{-1}$$

where D is in centimeters (μm $\times$ 10,000). The desired plot is then shown below.



17.37 A coarse copper powder is compacted in a mechanical press at a pressure of 20 tons/in^2. During sintering, the green part shrinks an additional 8%. What is the final density?

From Figure 17.10 on p. 492, the copper density after compaction is around 7 g/cm^3. If the material shrinks an additional 7%, then the volume is $1/(0.93)^3$ times the original volume, so the density will be around 8.7g/cm^3.

17.38 A gear is to be manufactured from iron powders. It is desired that it have a final density 90% that of cast iron, and it is known that the shrinkage in sintering will be approximately 5%. For a gear that is 2.5 in. in diameter and has a 0.75 in. hub, what is the required press force?

From Table 3.1, the density of iron is 7.86g/cm^3. For the final part to have a final density of 90% of this value, the density after sintering must be 7.07g/cm^3. Since the part contracts 5% during sintering, the density before sintering must be 6.06g/cm^3. Referring to Figure 17.10 on p. 492, the required pressure for this density is around 20 tons/in^2. The projected area is $A = \pi/4(2.5^2 - 0.75^2) = 4.47$ in^2. The required force is then 89 tons, or roughly 90 tons.

17.39 Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is an outstanding, open-ended question that requires considerable focus and understanding from the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

17.40 Make sketches of P/M products in which density variations (see Fig. 17.11) would be desirable. Explain why, in terms of the functions of these parts.

Any kind of minimum-weight design application, such as aerospace and automotive, where lightly loaded areas can be reduced in weight by making the areas more porous. With bearing surfaces, a greater density at the surface is desirable, while a substrate need not be as dense.

17.41 Compare the design considerations for P/M products to those for (a) casting and (b) forging. Describe your observations.

The design considerations for P/M parts are similar to those for casting and forging. The similarities are due to the necessity of removing the parts from the dies or molds. Hence, tapers should be used whenever possible and internal cavities are difficult to manufacture. Large flat surfaces should be avoided, the section thickness should be uniform. Some of the design considerations are shown in Figs. 17.20-17.22 on pp. 505-507. There are many simularities with casting and forging part design, mainly because P/M parts need to be ejected just as forgings and the pattern for casting need to be ejected. However, there are some differences. For example, engraved or embossed lettering is difficult in P/M but can be done easily in casting. P/M parts should be easily ejectable; castings are more flexible in this regards.

17.42 Are there applications in which you, as a manufacturing engineer, would not recommend a P/M product? Explain.

P/M products have many advantages, but they do not completely attain the strength of forgings in a given part volume. Any application where a volume is restricted but strength needs to be maximized are poor applications for P/M parts. For example, bolts, rivets, architectural channels, and biomedical implants are poor P/M applications. Also, fatigue applications are not good applications for P/M parts, because cracks can propagate easier through the (porous) structure.

17.43 Describe in detail other methods of manufacturing the parts shown in Fig. 17.1.

By the student. These parts could be produced through forging, casting or machining processes.

17.44 How large is the grain size of metal powders that can be produced in atomization chambers? Conduct a literature search to determine the answer.

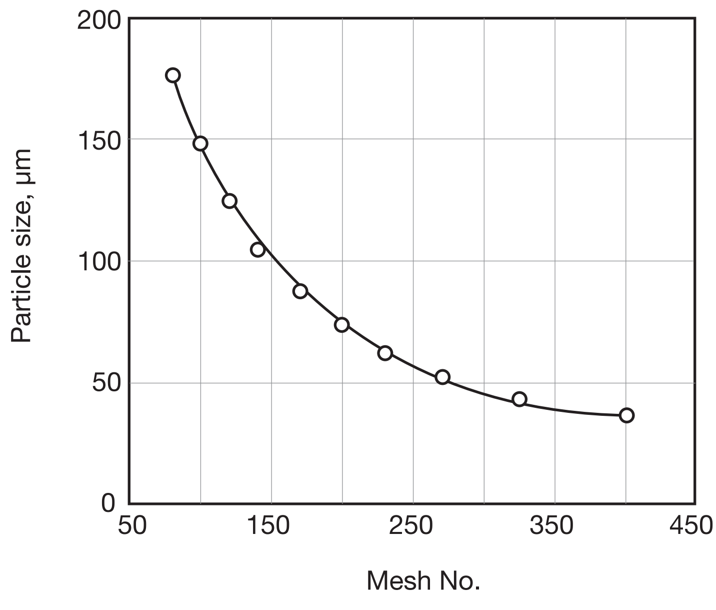
By the student. Perhaps the best illustration of the size limitation are the pellets used in shotgun shells, which are roughly 0.375 in. in diameter.

17.45 Plot the opening size versus the mesh size for screens used in powder-size sorting.

This requires a literature search to find how mesh sizes are defined. The following data is from the ASM reference text *Powder Metallurgy*:

Mesh No.	80	100	120	140	170	200	230	270	325	400
Particle size, μm	177	149	125	105	88	74	63	53	44	37

The desired plot is then very straightforward:



17.46 Use the Internet to locate suppliers of metal powders, and compare the cost of the powder to the cost of ingots for five different materials.

By the student. Ingot costs can vary depending on the size and the popularity of the material. This can be very challenging since the particular alloys may not be found in both powder and ingot forms.

17.47 It is known that in the design of P/M gears, the hub outside diameter should be as far as possible from the root of the gear. Explain why this is the case.

The reason for this is twofold. First of all, it is very difficult to get a good pressure in the cross section containing the root if the distance is small. Secondly, if the distance is small, it acts as a large stress concentration, which could cause part failure before sintering, especially during ejection.

17.48 Explain why powder-metal parts are commonly used for machine elements requiring good frictional and wear characteristics and for mass produced parts.

There are many acceptable answers to this question. Powder-metal parts are very commonly used for tribological machine elements like gears, bearings, races, and cams, because they can be impregnated with liquid lubricant. The main advantage to impregnating the P/M part with lubricant is that the component becomes self-lubricating. That is, when the temperature increases, the impregnated lubricant expands and percolates from the surface, thereby providing lubrication and wear ressistance. Mass produced parts are common because the high tooling costs of P/M and the additional processing steps of sintering makes P/M unattractive for low production runs.

17.49 It was stated that powder injection molding competes well with investment casting and small forgings for various materials, but not with zinc and aluminum die castings. Explain why.

MIM is commonly performed for metals with high melting temperatures. These metals are also very stiff in general, and would need very high compaction forces. MIM needs a fine enough powder that can be mixed with a polymer and injection molded, thus the material costs are high. On the other hand, the applications for magnesium and aluminum die castings are large-volume applications where cost is a concern. Examples are camera frames, fittings, toys, etc., and these applications are not well-suited for MIM as a result.

17.50 Describe how the information given in Fig. 17.14 would be helpful to you in designing P/M parts.

There are many possible answers to this question, and the answer depends on the experiences of the student. In general, the value is to consider a part and then judge its complexity. This allows one to quickly determine which powder metallurgy processes are suitable for that part. For example, if a part is a tube with a length of 0.5 m, then one would consider this to be simple; perhaps the complexity is 1.5 (it would be lower if the part were a cylinder instead of a tube). Clearly, one would not use compaction and sintering (P/F) because of the large size, and this would be a valuable conclusion. One would instead investigate CIP and HIP for this large part. Thus, Fig. 17.14 can quickly aid in identifying the best process for a part.

17.51 We have stated that in the process shown in Fig. 17.18, shapes produced are limited to axisymmetric parts. Do you think it would be possible to produce other shapes as well? Describe how you would modify the design of the setup to make those shapes, and explain the difficulties that may be encountered.

The spray deposition or Osprey process can be used to make parts that are assymetric, but it is in general not used to do so. First of all, it should be noted that sometimes a cylindrical billet is produced, and the billet is withdrawn in the same direction as the metal spray. If a die is used to define the shape, then an assymetric shape can be produced. Another option would be to perform shape rolling forms of powder rolling on the workpiece.