15 POWDER METALLURGY

Review Questions

15.1 Name some of the reasons for the commercial importance of powder metallurgy.

Answer. PM is important because (1) parts can be made to net or near net shape, (2) parts can be made with a controlled level of porosity, (3) certain metals difficult to process by other methods can be processed by PM, and (4) PM allows the formulation of unusual alloys not easily obtained by traditional alloying methods.

15.2 What are some of the disadvantages of PM methods?

Answer. Disadvantages include (1) high tooling costs, (2) metal powders are expensive, (3) difficulties in storing and handling metallic powders, (4) certain limitations on part geometry imposed by the uniaxial press methods, and (5) variations in density in a PM component can be troublesome.

15.3 In the screening of powders for sizing, what is meant by the term *mesh count*?

Answer. The mesh count of the screen is the number of openings per linear inch.

15.4 What is the difference between open pores and closed pores in metallic powders?

Answer. Open pores are air spaces between particles, while closed pores are voids internal to a particle.

15.5 What is meant by the term *aspect ratio* for a metallic particle?

Answer. The aspect ratio of a particle is the ratio of the maximum dimension to the minimum dimension of the given particle.

15.6 How would one measure the angle of repose for a given amount of metallic powder?

Answer. One measure would be to let the powders flow through a small funnel and measure the angle taken by the resulting pile of powders relative to the horizontal.

15.7 Define *bulk density* and *true density* for metallic powders.

Answer. Bulk density refers to the weight per volume of the powders in the loose state, while true density is the weight per volume of the true volume of metal in the powders (the volume that would result if the powders were melted).

15.8 What are the principal methods used to produce metallic powders?

Answer. The powder production methods are (1) atomization - the conversion of molten metal into droplets which solidify into powders; (2) chemical reduction - reducing metallic oxides by use of reducing agents which combine with the oxygen to free the metals in the form of powders; and (3) electrolysis - use of an electrolytic cell to deposit particles of the metal onto the cathode in the cell.

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

Answer. The steps are (1) blending and/or mixing, (2) pressing, and (3) sintering.

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

Answer. Blending means combining particles of the same chemistry but different sizes, while mixing refers to the combining of metal powders of different chemistries.

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

Answer. The additives include (1) lubricants, (2) binders, and (3) deflocculants.

15.12 What is meant by the term *green compact*?

Answer. The green compact is the pressed but not yet sintered PM part.

15.13 Describe what happens to the individual particles during compaction.

Answer. Starting with the initial powder arrangement, the particles are first repacked into a more efficient arrangement, followed by deformation of the particles as pressure is increased.

15.14 What are the three steps in the sintering cycle in PM?

Answer. The three steps in the cycle are (1) preheat, in which lubricants and binders are burned off, (2) sintering, and (3) cool down.

15.15 What are some of the reasons why a controlled atmosphere furnace is desirable in sintering?

Answer. Some of the purposes of a controlled atmosphere furnace are (1) to protect against oxidation, (2) to provide a reducing atmosphere to remove existing oxides, (3) to provide a carburizing atmosphere, and (4) to remove lubricants and binders from pressing.

15.16 What is the difference between impregnation and infiltration in powder metallurgy?

Answer. Impregnation is when oil or other fluid is permeated into the pores of a sintered PM part. Infiltration is when a molten metal (other than the PM metal) is permeated into the pores of a sintered part.

15.17 What is the difference between powder injection molding and metal injection molding?

Answer. Metal injection molding is a subset of powder injection molding, in which the powders are metallic. The more general term includes powders of ceramic.

15.18 How is isostatic pressing distinguished from conventional pressing and sintering in PM?

Answer. Isostatic pressing applies hydrostatic pressure to all sides of the mold, whereas conventional pressing is uniaxial.

15.19 Describe liquid phase sintering.

Answer. Liquid phase sintering occurs when two metals of different melting temperatures are sintered at a temperature between their melting points. Accordingly, one metal melts, thoroughly wetting the solid particles and creating a strong bonding between the metals upon solidification.

15.20 What are the two basic classes of metal powders as far as chemistry is concerned?

Answer. The two classes are (1) elemental powders - powders of pure metal such as iron or copper, and (2) pre-alloyed powders - powders of alloys such as stainless steel or brass.

15.21 Why is PM technology so well suited to the production of gears and bearings?

Answer. Because (1) the geometries of these parts lend themselves to conventional PM pressing, which consists of pressing in one direction, and (2) the porosity allows impregnation of the PM parts with lubricants.

Problems

Answers to problems labeled **(A)** are listed in an Appendix at the back of the book.

Characterization of Engineering Powders

15.1 **(A)** (SI/USCS units) A screen with 325 mesh count has wires with a diameter of 0.035 mm. Determine (a) the maximum particle size that will pass through the wire mesh and (b) the proportion of open space in the screen.

Solution: (a) By Equation (15.1), particle size $PS = 25.4/MC - t_w = 25.4/325 - 0.035$
$= 0.078 - 0.035 =$ **0.043 mm**

(b) There are $325 \times 325 = 105{,}625$ openings in one square inch of the mesh. From part (a), each opening is 0.043 mm on a side, thus each opening is $(0.043)^2 = 0.001849$ mm^2. The total open area in one square inch of mesh = $105{,}625(0.001849 \text{ mm}^2) = 195.3$ mm^2. This is total open space. One in$^2 = (25.4)^2 = 645.16$ mm^2. Therefore, the percent open space in one square inch of mesh 195.3/645.16 = 0.3027= **30.27%**.

15.2 (USCS units) A screen with 200 mesh count has wires with a diameter of 0.0021 in. Determine (a) the maximum particle size that will pass through the wire mesh and (b) the proportion of open space in the screen.

Solution: (a) By Equation (15.1), particle size $PS = 1/MC - t_w = 1/200 - 0.0021$
$= 0.0050 - 0.0021 =$ **0.0029 in**

(b) There are $200 \times 200 = 40{,}000$ openings in one square inch of the mesh. From part (a), each opening is 0.0029 inch on a side, thus each opening is $(0.0029)^2 = 0.00000841$ in^2. The total open area in one square inch of mesh = $40{,}000(0.00000841 \text{ in}^2) = 0.3364$ in^2. This is total open space. Therefore, the percent open space in one square inch of mesh = **33.64%**.

15.3 What is the aspect ratio of a cubic particle shape?

Solution: The aspect ratio is the ratio of the maximum dimension to the minimum dimension of the particle shape. The minimum dimension is the edge of any face of the cube; call it L. The maximum dimension is the cube diagonal, which is given by $(L^2 + L^2 + L^2)^{0.5} = (3\,L^2)^{0.5} = (3)^{0.5}\,L = 1.732\,L$. Thus, the **aspect ratio = 1.732:1.**

15.4 Determine the shape factors for particles of the following ideal shapes: (a) sphere, (b) cubic, (c) cylindrical with length-to-diameter ratio of 1:1, and (d) cylindrical with length-to-diameter ratio of 2:1.

Solution: (a) Sphere: $A = \pi D^2$ and $V = \pi D^3/6$
$K_s = AD/V = (\pi D^2)D/(\pi D^3/6) = 6\pi D^3/\pi D^3 = 6.0$

(b) Cube: Let L = edge of one face. For a cube, $A = 6L^2$ and $V = L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = L^3$
$D^3 = 6L^3/\pi = 1.90986\,L^3$
$D = (1.90986\,L^3)^{0.333} = 1.2407\,L$

$K_s = AD/V = (6L^2)(1.2407\ L)/L^3 =$ **7.444**

(c) Cylinder with $L/D = 1.0$. For this cylinder shape, $L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi L^2 + \pi L^2 = 1.5\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi L^3$.
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 0.25\pi L^3$
$D^3 = 6(0.25\pi L^3)/\pi = 1.5L^3$
$D = (1.5\ L^3)^{0.333} = 1.1447$ L
$K_s = AD/V = (1.5\pi L^2)(1.1447\ L)/0.25\pi L^3 =$ **6.868**

(d) Cylinder with $L/D = 2.0$. For this cylinder shape, $0.5L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi(0.5L)^2 + \pi(0.5L)L = 0.125\pi L^2 + 0.5\pi L^2 = 0.625\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi(0.5L)^2\ L = 0.0625\pi L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 0.0625\pi L^3$
$D^3 = 6(0.0625\pi L^3)/\pi = 0.375L^3$
$D = (0.375\ L^3)^{0.333} = 0.721\ L$
$K_s = AD/V = (0.625\pi L^2)(0.721\ L)/0.0625\pi L^3 =$ **7.211**

15.5 **(A)** Determine the shape factors for particles that are disk-shaped flakes with thickness-to-diameter ratios of (a) 1:10 and (b) 1:20.

Solution: (a) Disk with $t/D = L/D = 1/10 = 0.10$. For this shape, $10L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi(10L)^2 + \pi(10L)L = 50\pi L^2 + 10\pi L^2 = 60\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi(10L)^2\ L = 25\pi L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 25\pi L^3$
$D^3 = 6(25\pi L^3)/\ \pi = 150L^3$
$D = (150\ L^3)^{1/3} = 5.313\ L$
$K_s = AD/V = (60\pi L^2)(5.313\ L)/25\pi L^3 =$ **12.75**

(b) Disk with $L/D = 0.05$. For this shape, $20L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi(20L)^2 + \pi(20L)L = 200\pi L^2 + 20\pi L^2 = 220\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi(20L)^2\ L = 314.16\pi L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 314.16\pi L^3$
$D^3 = 6(314.16\pi L^3)/\ \pi = 1884.96\ L^3$
$D = (1884.96\ L^3)^{1/3} = 12.353\ L$
$K_s = AD/V = (220\pi L^2)(12.353\ L)/314.16\pi L^3 =$ **8.65**

15.6 (USCS units) A pile of iron powder weighs 2 lb. The particles are spherical in shape and all have the same diameter of 0.002 in. (a) Determine the total surface area of all the particles in the pile. (b) If the packing factor = 0.6, determine the volume taken by the pile. *Note*: The density of iron = 0.284 lb/in^3.

Solution: (a) For a spherical particle of $D = 0.002$ in, $V = \pi D^3/6 = \pi(0.002)^3/6$
$= 0.00000000418 = 4.18 \times 10^{-9}$ in^3/particle
Weight per particle $W = \rho V = 0.284(4.18 \times 10^{-9}$ in$^3) = 1.19 \times 10^{-9}$ lb/particle
Number of particles in 2 lb $= 2.0/(1.19 \times 10^{-9}) = 1.681 \times 10^9$

$A = \pi D^2 = \pi(0.002)^2 = 0.00001256$ in^2 = 12.56×10^{-6} in^2
Total surface area = $(1.681 \times 10^9)(12.56 \times 10^{-6})$ = $\mathbf{21.116 \times 10^3}$ **in**$^{\mathbf{2}}$

(b) With a packing factor of 0.6, the total volume taken up by the pile = (2.0/0.284)/0.6 = **11.74 in**$^{\mathbf{3}}$

15.7 (USCS units) Solve the previous problem, except that the diameter of the particles is 0.004 in. Assume the same packing factor.

Solution: (a) For a spherical particle of D = 0.004 in, $V = \pi D^3/6 = \pi(0.004)^3/6$
= 0.00000003351 = 33.51×10^{-9} in^3/particle
Weight per particle $W = \rho V = 0.284(33.51 \times 10^{-9}$ in$^3) = 9.516 \times 10^{-9}$ lb/particle
Number of particles in 2 lb = $2.0/(9.516 \times 10^{-9}) = 0.2102 \times 10^9$
$A = \pi D^2 = \pi(0.004)^2 = 0.00005027$ in^2 = 50.27×10^{-6} in^2
Total surface area = $(0.2102 \times 10^9)(50.27 \times 10^{-6})$ = $\mathbf{10.565 \times 10^3}$ **in**$^{\mathbf{2}}$

(b) With a packing factor of 0.6, the total volume taken up by the pile = (2.0/0.284)/0.6 = **11.74 in**$^{\mathbf{3}}$

15.8 (USCS units) A solid cube of copper with each side = 1.0 ft is converted into metallic powders of spherical shape by water atomization. What is the percentage increase in total surface area if the diameter of each particle is 0.004 in (assume that all particles are the same size)?

Solution: Area of initial cube $A = 6(1\text{ ft})^2 = 6\text{ ft}^2 = 864\text{ in}^2$
Volume of cube $V = (1\text{ ft})^3 = 1728\text{ in}^3$
Surface area of a spherical particle of D = 0.004 in is $A = \pi D^2 = \pi(0.004)^2$
= 50.265×10^{-6} in^3/particle
Volume of a spherical particle of D = 0.004 in is $V = \pi D^3/6 = \pi(0.004)^3/6$
= 33.51×10^{-9} in^3/particle
Number of particles in 1 ft^3 = $1728/33.51 \times 10^{-9} = 51.567 \times 10^9$
Total surface area = $(51.567 \times 10^9)(50.265 \times 10^{-6}\text{ in}^3) = 2{,}592 \times 10^3 = 2{,}592{,}000\text{ in}^2$
Percent increase = 100(2,592,000 – 864)/864 = **299,900%**

15.9 **(A)** (SI units) A solid cube of aluminum with each side = 1.0 m is converted into metallic powders of spherical shape by gas atomization. What is the percentage increase in total surface area if the diameter of each particle is 100 microns (assume that all particles are the same size)?

Solution: Area of starting cube $A = 6(1\text{ m})^2 = 6\text{ m}^2$
Volume of starting cube $V = (1\text{ m})^3 = 1\text{ m}^3$
$D = 100\ \mu\text{m} = 0.1\text{ mm} = 0.1 \times 10^{-3}\text{ m}$
Surface area of a sphere of $D = 0.1 \times 10^{-3}$ m is $A = \pi D^2 = \pi(0.1 \times 10^{-3})^2 = 3.142 \times 10^{-8}$ m^3/particle
Volume of a sphere of $D = 0.1 \times 10^{-3}$ m is $V = \pi D^3/6 = \pi(0.1 \times 10^{-3})^3/6 = 0.5236 \times 10^{-12}$ m^3/particle
Number of particles in 1 m^3 = $1.0/0.5236 \times 10^{-12} = 1.91 \times 10^{12}$
Total surface area = $(1.91 \times 10^{12})(\ 0.5236 \times 10^{-12}\text{ m}^3) = 5.9958 \times 10^4 = 59{,}958\text{ m}^2$
Percent increase = 100(59,958 – 6)/6 = **999,200%**

15.10 Given a large volume of metallic powders, all of which are perfectly spherical and having the same exact diameter, what is the maximum possible packing factor that the powders can take?

Solution: The maximum packing factor is achieved when the spherical particles are arranged as a face-centered cubic unit cell, similar to the atomic structure of FCC metals; see Figure 2.8(b). The unit cell of the FCC structure contains 8 spheres at the corners of the cube and 6 spheres on each face. The approach to find the packing factor consists of: (1) finding the volume of the spheres and portions thereof that are contained in the cell, and (2) finding the volume of the unit cell cube. The ratio of (1) over (2) is the packing factor.

(1) Volume of whole and/or partial spheres contained in the unit cell. The unit cell contains 6 half spheres in the faces of the cube and 8 one-eighth spheres in corners. The equivalent number of whole spheres = 6(.5) + 8(.125) = 4 spheres. Volume of 4 spheres = $4\pi D^3/6$ = 2.0944 D^3 where D = diameter of a sphere.

(2) Volume of the cube of one unit cell. Consider that the diagonal of any face of the unit cell contains one full diameter (the sphere in the center of the cube face) and two half diameters (the spheres at the corners of the face). Thus, the diagonal of the cube face = $2D$. Accordingly, the face is a square with each edge = $D\sqrt{2}$ = 1.414D. The volume of the unit cell is therefore $(1.414D)^3$ = 2.8284 D^3.

The maximum possible packing factor = 2.0944/2.8284 = **0.7405 = 74.05%**

Compaction and Design Considerations

15.11 In a certain pressing operation, the metallic powder fed into the open die has a packing factor of 0.5. The pressing operation reduces the powders to 70% of their starting volume. In the subsequent sintering operation, shrinkage amounts to 10% on a volume basis. Given that these are the only factors that affect the structure of the finished part, determine its final porosity.

Solution: Packing factor = bulk density / true density
Density = $(\text{specific volume})^{-1}$
Packing factor = true specific volume / bulk specific volume
Pressing reduces bulk specific volume to 0.70
Sintering further reduces the bulk specific volume to 0.90 of value after pressing.
Let true specific volume = 1.0
Thus for a packing factor of 0.5, bulk specific volume = 2.0.
Packing factor after pressing and sintering = $1.0/(2.0 \times 0.70 \times 0.90) = 1.0/1.26 = 0.794$
By Equation (18.6), porosity = $1 - 0.794$ = **0.206**

15.12 **(A)** (SI units) A bearing of simple geometry is to be pressed out of bronze powders, using a compacting pressure of 200 MPa. Outside diameter of the bearing = 35 mm, inside diameter = 20 mm, and length = 18 mm. What is the required press tonnage to perform this operation?

Solution: Projected area of part $A_p = 0.25\pi(D_o^2 - D_i^2) = 0.25\pi(35^2 - 20^2) = 648$ mm^2
$F = A_p p_c = 648(200) =$ **129,600 N**

15.13 (USCS units) The part shown in Figure P15.13 is to be pressed of iron powders using a compaction pressure of 75,000 lb/in^2. Dimensions are inches. Determine (a) the most appropriate pressing direction, (b) the required press tonnage to perform this operation, and (c) the final weight of the part if the porosity is 10%. Assume shrinkage during sintering can be neglected.

Solution: (a) Most appropriate pressing direction is parallel to the part axis.

(b) Press tonnage $F = A_p p_c$
Projected area of part $A_p = 0.25\pi(D_o^2 - D_i^2) = 0.25\pi(2.8^2 - 0.875^2) = 5.556$ in^2
$F = A_p p_c = 5.556(75{,}000) =$ **416,715 lb = 208 tons**

(c) $V = 0.25\pi(2.8^2 - 0.875^2)(0.5) + 0.25\pi(2.8^2 - 1.5^2)(1.25 - 0.5) = 0.25\pi(3.5372 + 4.1925)$
$= 6.071$ in^3
From Table 4.1, density of iron $\rho = 0.284$ lb/in^3.
At 10% porosity, part weight $W = 6.071(0.284)(0.90) =$ **1.55 lb**

15.14 (SI units) For each of the four part drawings in Figure P15.14, indicate which PM class the parts belong to, whether the part must be pressed from one or two directions and how many levels of press control will be required.

Solution: (a) Class II, two directions because of axial thickness, one level of press control.

(b) Class I, one direction because part is relatively thin, one level of press control.

(c) Class IV, two directions of pressing, three levels of press control required.

(d) Class IV, two directions of pressing, four or five levels of press control due to multiple steps in part design.