

Composites and Powder Metallurgy

Chapter 12

Powder Metallurgy

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Introduction

- **Powder Metallurgy** (PM): is a metal processing technology in which parts are produced from metallic powders.
 - **Powder**: a finely divided particulate solid.
 - 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.
 - Due to tooling high cost, PM is appropriate for medium and high production.
 - The heating treatment, called **sintering**, is performed at a temperature below the melting point of the metal.

Introduction

- PM is an important commercial technology, due to:
 - PM parts can be mass produced to *net shape* or *near net shape*.
 - Very little waste of material; about 97% of the starting powders are converted to product.
 - Parts having a specified level of porosity can be made; e.g. porous metal parts, such as filters, and oil-impregnated bearings and gears.
 - Certain metals that are difficult to fabricate by other methods can be shaped by powder metallurgy. Tungsten is an example; tungsten filaments used in lamp bulbs are made using PM technology.
 - High tolerances ± 0.13 mm, and process can be automated.

Introduction

- Limitations of PM include:
 - Tooling and equipment costs are high.
 - Metallic powders are expensive.
 - There are difficulties with storing and handling metal powders (such as degradation of the metal over time, and fire hazards with particular metals).
 - 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.
 - Variations in material density throughout the part may be a problem in PM, especially for complex part geometries.

Introduction

- Although parts as large as 22 kg can be produced, most PM components are less than 2.2 kg.
- Metals for PM are alloys of Fe & Al (largest tonnage). Other PM metals include Cu, Ni, Mo & W.

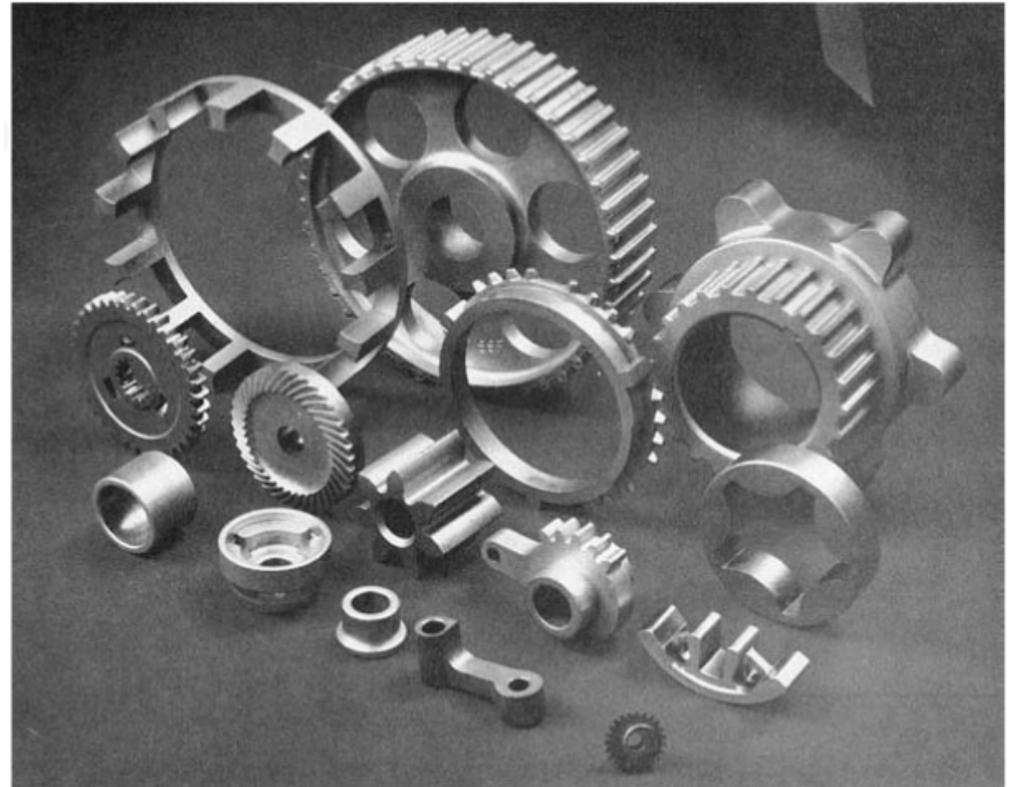


Fig. 16-1 A collection of powder metallurgy parts. (Courtesy of Dorst America, Inc.).

Characterization of Engineering Powders

Geometric Features

- Geometry of the individual powders can be defined by the following attributes:
 - *Particle Size and Distribution.*
 - *Particle Shape and Internal Structure.*
 - *Surface Area.*

Characterization of Engineering Powders

Geometric Features

- **Particle Size and Distribution:** particle size refers to the dimensions of the individual powders.
 - If the particle shape is spherical, a single dimension is adequate. For other shapes, two or more dimensions are needed.
 - **Mesh count:** most common method to obtain particle size data, and is used to refer to the number of openings per linear inch of screen.
 - A mesh count of 200 means there are 200 openings per linear inch. As the mesh is square, the count is the same in both directions, and the total number of openings / inch² is $200^2 = 40,000$. The higher the mesh count, the smaller the particle size.

Characterization of Engineering Powders

Geometric Features

– ***Particle Size and Distribution.***

- ***Classification*** in mesh count: the procedure of separating the powders by size, done in a series of screens of progressively smaller mesh size as follows:

[1] The powders are placed on a screen of a certain mesh count and vibrated so that particles small enough to fit through the openings pass through to the next screen below.

[2] The second screen empties into a third, and so forth, so that the particles are sorted according to size.

[3] A certain powder size might be called size 230 through 200, indicating that the powders have passed through the 200 mesh, but not 230.

Characterization of Engineering Powders

Geometric Features

– *Particle Size and Distribution.*

- The openings in the screen are less than the reciprocal of the mesh count because of the thickness of the wire in the screen:

$$PS = \frac{K}{MC} - t_w$$

where PS = particle size, mm; MC = mesh count, openings per linear inch (25.4 mm); and t_w = wire thickness of screen mesh, mm; and K = a constant whose value = 25.4 when the size units are millimeters.

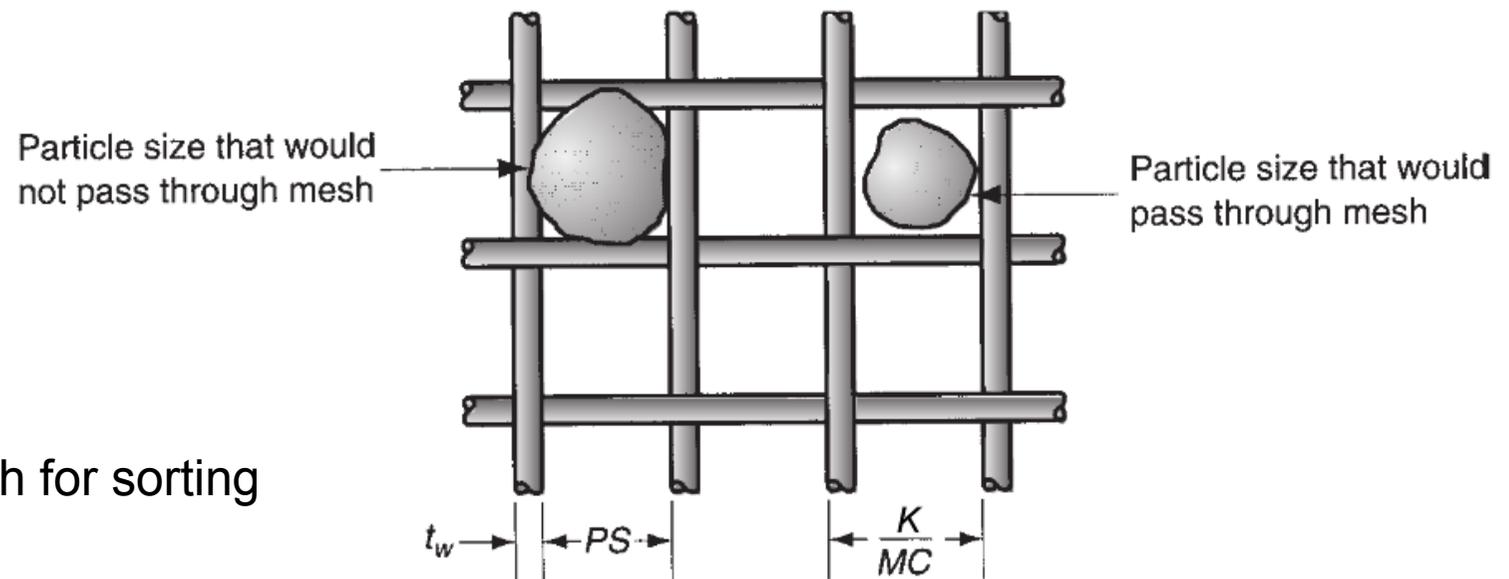


Fig. 16-2 Screen mesh for sorting particle sizes.

Characterization of Engineering Powders

Geometric Features

– *Particle Size and Distribution.*

- Variations occur in the powder sizes sorted by screening due to:
 - Differences in particle shapes.
 - The range of sizes between mesh count steps.
 - Variations in screen openings within a given mesh count.
 - Also, the screening method has a practical upper limit of $MC = 400$ (approximately), because of the difficulty in making such fine screens and because of agglomeration of the small powders.
 - Typical size used in PM range between 25 and 300 μm .

Characterization of Engineering Powders

Geometric Features

– **Particle Shape & Internal Structure:**

- **Particle Shape:** various particles may have different shapes.
 - **Aspect Ratio:** ratio of maximum dimension to minimum dimension for a given particle.
- **Internal Structure:** spaces between particles or within any individual particle. So two types as follows;
 - **Open Pores:** spaces between particles which a fluid can penetrate.
 - **Close Pores:** internal voids in the structure of an individual particle. Does not affect geometry, instead it affects the density.

Characterization of Engineering Powders

Geometric Features

– *Particle Shape & Internal Structure:*



Spherical



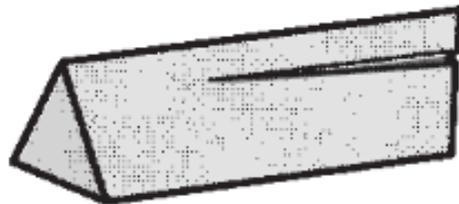
Rounded



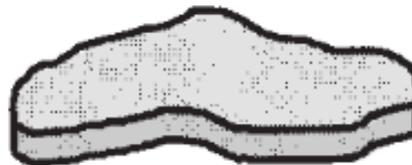
Cylindrical



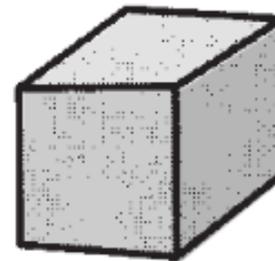
Spongey



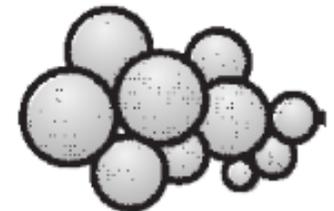
Acicular



Flakey



Cubic



Aggregated

Fig. 16-3 Several of the possible (ideal) shapes in PM.

Characterization of Engineering Powders

Geometric Features

- **Surface Area:** assuming the particle is a sphere:

$$\begin{array}{l} A = \pi D^2 \\ V = \frac{\pi D^3}{6} \end{array} \Rightarrow \frac{A}{V} = \frac{6}{D} \quad \text{where } D = \text{diameter of the spherical particle, mm.}$$

- **Surface Area:** in general, the area-to-volume ratio can be expressed for any particle shape—spherical or nonspherical—as follows:

$$\frac{A}{V} = \frac{K_s}{D} \quad \text{where } K_s = \text{shape factor; } D = \text{diameter of a sphere of equivalent volume as the nonspherical particle, mm. For a sphere } K_s = 6 \text{ and larger for other shapes.}$$

Characterization of Engineering Powders

Geometric Features

– *Surface Area.*

- If K_s is high and D is small, surface area for the same weight is high.
 - This means greater area for surface oxidation to occur.
 - Also, small size leads to more agglomeration of the particles, which is disadvantageous in automatic feeding of the powders.
 - It is better to use smaller particle size as they provide more uniform shrinkage and better mechanical properties in the final PM product.

Characterization of Engineering Powders

Other Features

- Other features of engineering powders include:
 - *Interparticle Friction and Flow Characteristics.*
 - *Packing, Density and Porosity.*
 - *Chemistry and Surface Films.*

Characterization of Engineering Powders

Other Features

– *Interparticle Friction and Flow Characteristics:*

- The higher the friction between the particles, the less its ability to flow and be packed tightly.
- ***Angle of response***: a common measure of interparticle friction, which is the angle formed by a pile of powders as they are poured from a narrow funnel.
- The larger the angle and smaller the particle size, the greater the friction.
- Spherical particles result in lower interparticle friction.
- The better the flow characteristics, the easier the filling of the die and the pressing process.

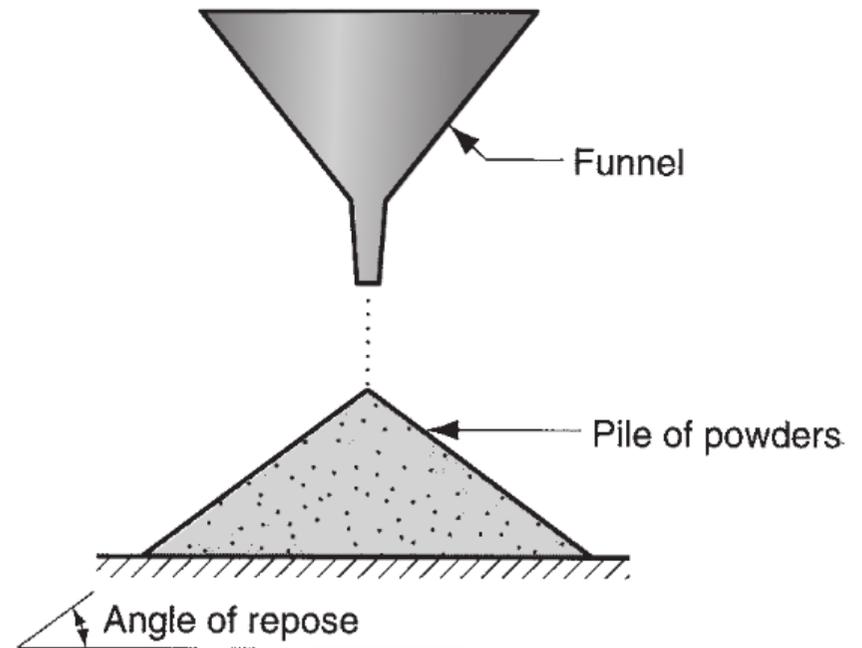
Characterization of Engineering Powders

Other Features

– *Interparticle Friction and Flow Characteristics:*

- A common measure of flow is the time required for a certain amount of powder to flow through a standard-sized funnel.
- Smaller flow times indicate easier flow and lower interparticle friction.

Fig. 16-4 Interparticle friction as indicated by the angle of repose of a pile of powders poured from a narrow funnel. Larger angles indicate greater interparticle friction.



Characterization of Engineering Powders

Other Features

– **Packing, Density & Porosity**: packing depend on:

[1] **True density**: the density of the true volume of the material. This is the density when the powders are melted into a solid mass.

[2] **Bulk density**: the density of the powders in the loose state after pouring, which includes the effect of pores between particles. Because of the pores, bulk density is less than true density.

- **Packing factor** (PF): bulk density divided by true density (~0.5 – 0.7).
- PF depends on particle shape and the distribution of particle sizes.
- Various sizes have higher PF, as small particles would fill gaps between bigger ones.
- PF can also be increased by vibrating the powders, to settle tightly.
- External pressure would also increase the PF.

Characterization of Engineering Powders

Other Features

- ***Packing, Density & Porosity***: porosity represents an alternative way of considering the packing characteristics of a powder.
 - ***Porosity***: the ratio of the volume of the pores (empty spaces) in the powder to the bulk volume.
 - Porosity + Packing factor = 1.
 - The issue is complicated by the possible existence of closed pores in some of the particles.
 - If these internal pore volumes are included in the above porosity, then the equation is exact.

Characterization of Engineering Powders

Other Features

– **Chemistry & Surface Films:**

- **Chemistry** identification: important to characterize the powder.
 - Metallic powders are classified as either **elemental**, consisting of a pure metal, or **pre-alloyed**, wherein each particle is an alloy.
- **Surface Films:** are problematic in powder metallurgy because of the large area per unit weight of metal when dealing with powders.
 - Example on films: oxides, silica, adsorbed organic materials, and moisture which must be removed before shape processing.

Production of Metallic Powders

1. Atomization

- **Atomization**: the conversion of molten metal into a spray of droplets that solidify into powders.
- Most common and applicable to all metals. Several methods:
 - **Gas atomization**: a high velocity gas stream (air or inert gas) is utilized to atomize the liquid metal.
 - **Water atomization**: similar to gas atomization except that high-velocity water stream is used instead of gas. (disadvantage: oxidation problem).
 - **Centrifugal atomization**: liquid metal stream pours onto a rapidly rotating disk that sprays the metal in all directions to produce powders.

Production of Metallic Powders

1. Atomization

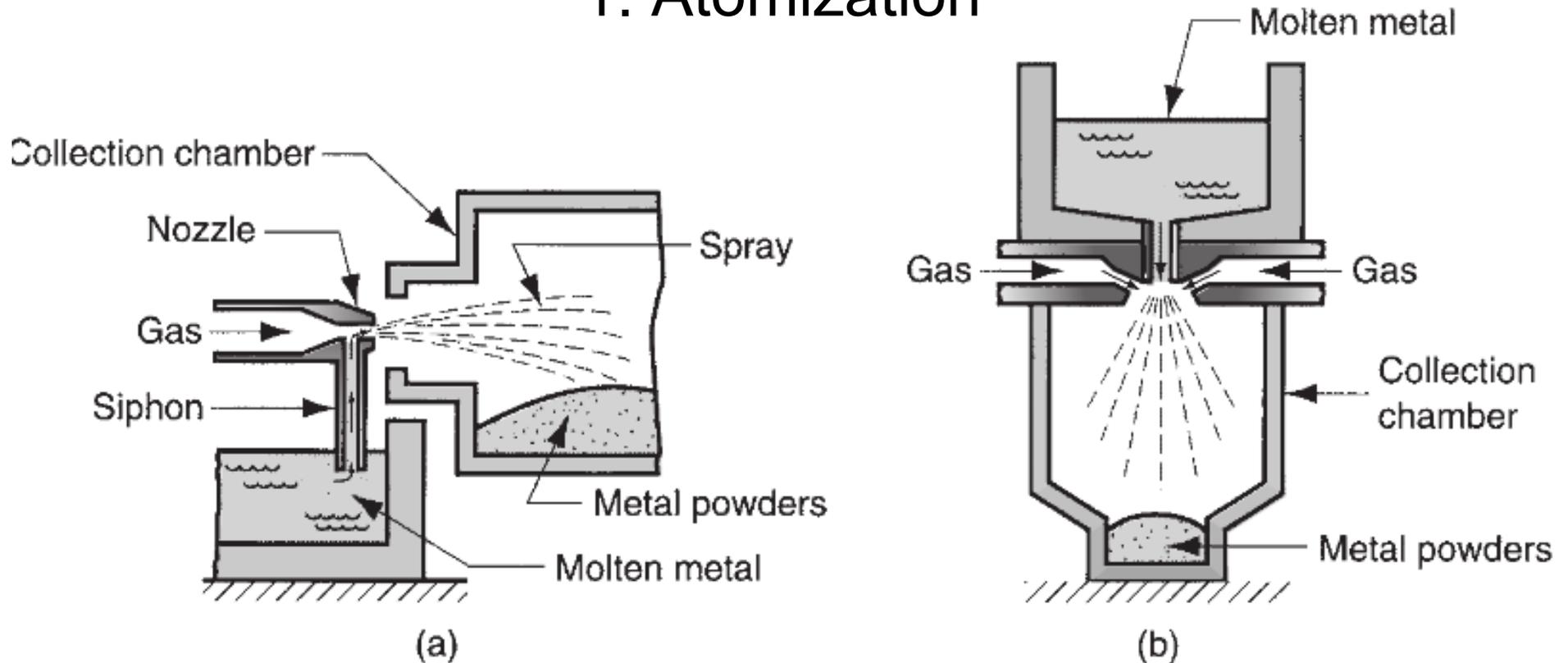


Fig. 16-5 Several atomization methods for producing metallic powders: (a) and (b) two gas atomization methods.

Note: particle shape is spherical and size is controlled by the velocity of the fluid stream; inverse proportion.

Production of Metallic Powders

1. Atomization

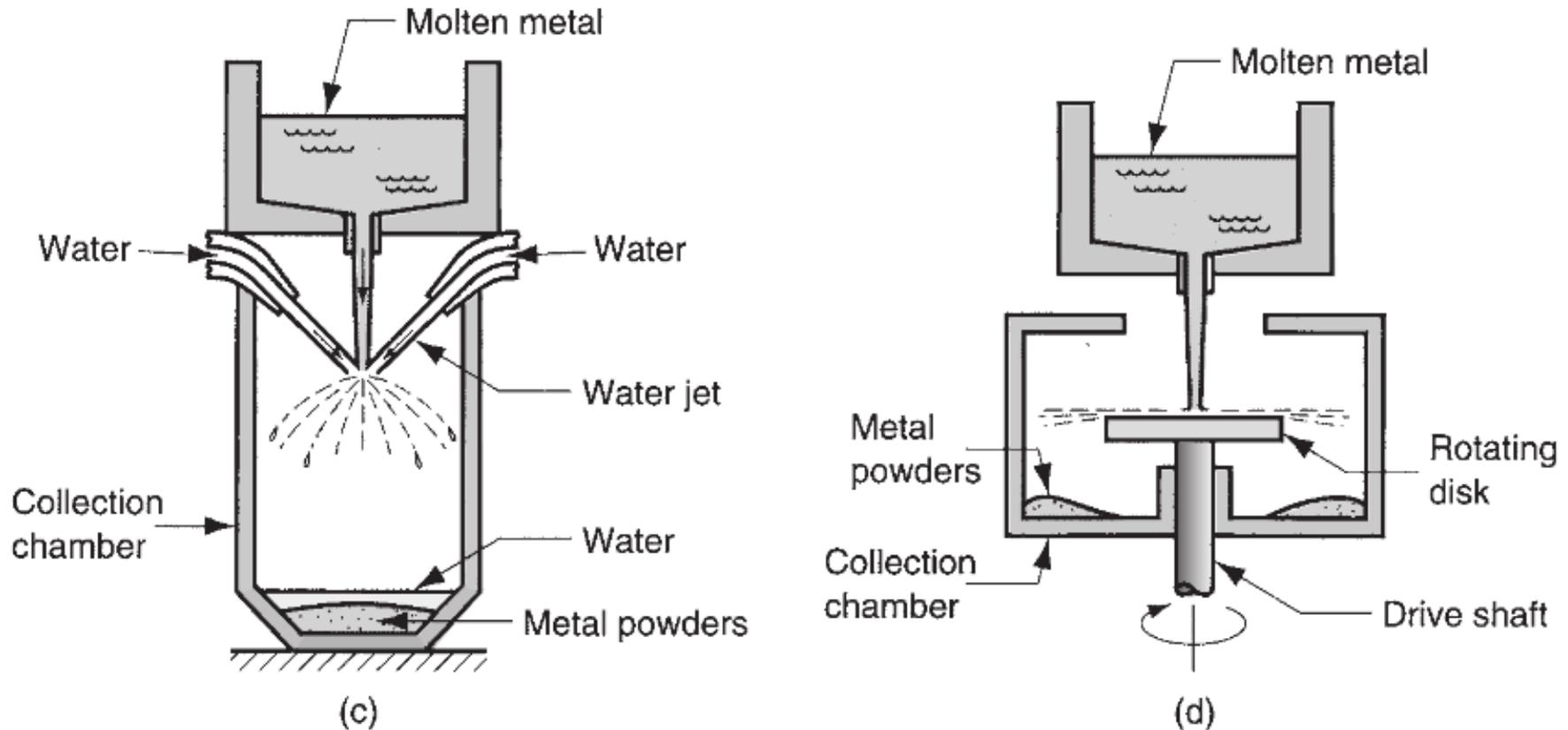


Fig. 16-5 Several atomization methods for producing metallic powders: (c) water atomization; and (d) centrifugal atomization by the rotating disk method.

Note: particle shape in (c) is irregular and size is also controlled by the velocity of the fluid stream; inverse proportion.

Production of Metallic Powders

1. Atomization

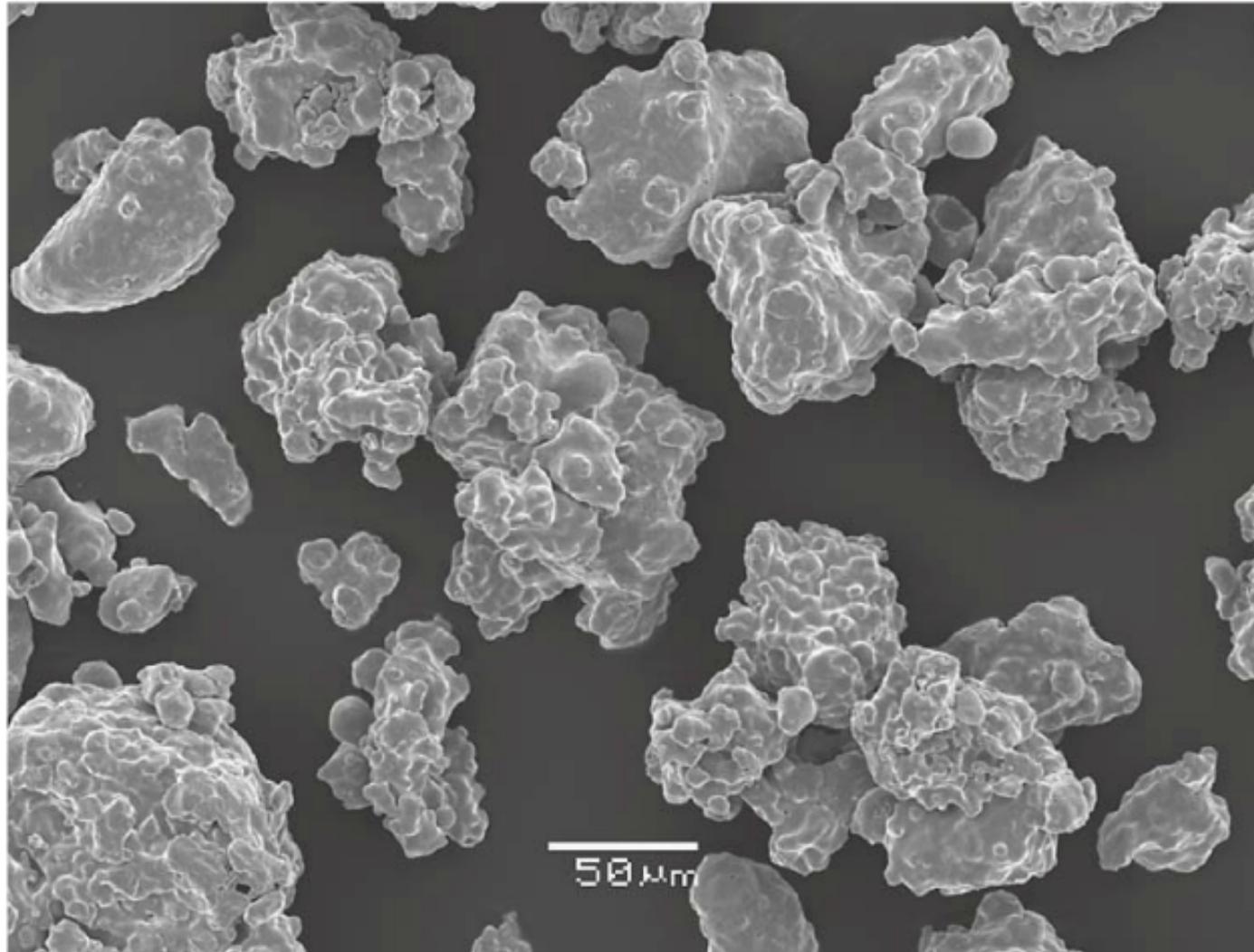


Fig. 16-6 Iron powders produced by water atomization; particle sizes vary. (Photo ₂₄ courtesy of T. F. Murphy and Hoeganaes Corporation.)

Production of Metallic Powders

2. Other Production Methods

- **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.
 - Used to produce powders of Fe, W & Cu.
- Another chemical process for iron powders involves the decomposition of iron pentacarbonyl [Fe(CO)₅] to produce spherical particles of high purity.
- Another method involves **precipitation** of metallic elements from salts dissolved in water; e.g. powders of Cu, Ni, and Co.

Conventional Pressing & Sintering

- After the metallic powders have been produced, the conventional PM sequence consists of three steps:
 - **Blending** and **Mixing** of the powders.
 - **Compaction**: the powders are pressed into the desired part shape.
 - **Sintering**: heating to a temperature below the melting point to cause solid-state bonding of the particles and strengthening of the part.
- These steps are referred to as **primary processes**.
- **Secondary processes**: performed to improve dimensional accuracy, increase density, etc.

Conventional Pressing & Sintering

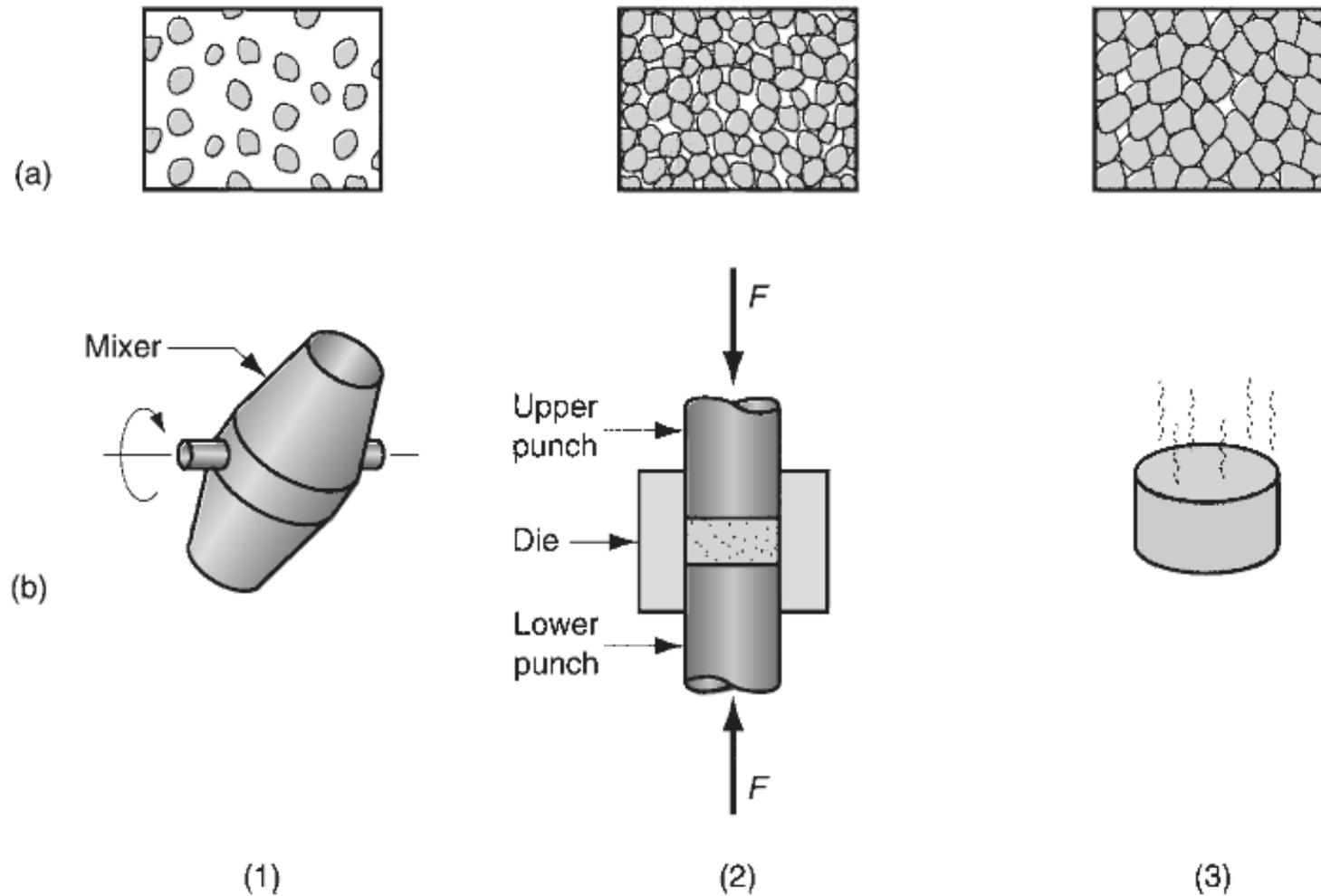


Fig. 16-7 The conventional powder metallurgy production sequence: (1) blending, (2) compacting, and (3) sintering; (a) shows the condition of the particles while (b) shows the operation and/or work part during the sequence.

Conventional Pressing & Sintering

Blending & Mixing of the Powders

- **Blending** and **Mixing** of the powders: thorough homogenization of the metallic powders.
 - **Blending**: when powders of the same chemical composition but possibly different particle sizes are intermingled to reduce porosity.
 - **Mixing**: powders of different chemistries being combined (PM adv).

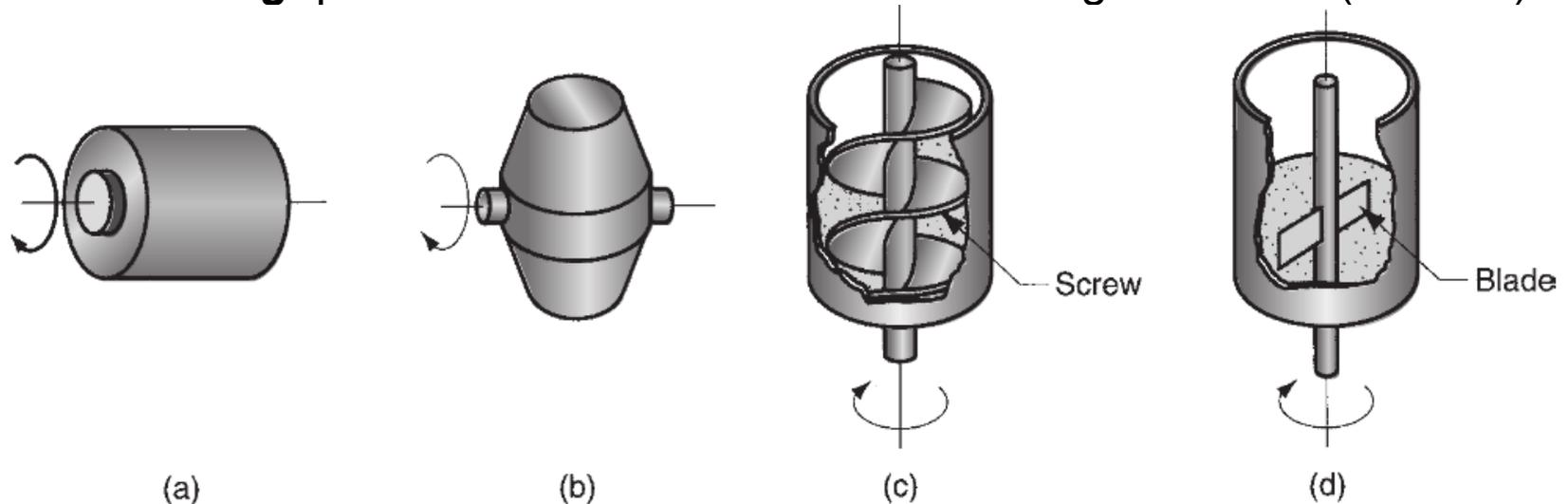


Fig. 16-8 Several blending and mixing devices: (a) rotating drum, (b) rotating double-cone, (c) screw mixer, and (d) blade mixer.

Conventional Pressing & Sintering

Blending & Mixing of the Powders

– **Blending** and **Mixing**:

- Best results when the container is 20% to 40% full.
- Free fall during mixing results in segregation. Hence, containers are designed with internal baffles to prevent this from happening.
- Vibration is also undesirable, since will also lead to segregation.
- **Lubricants** to reduce friction, **binders** that increase the strength in the pressed but unsintered part, and **deflocculants** that inhibit agglomeration for better flow of particles are ingredients usually added to the powders during blending and/or mixing step.

Conventional Pressing & Sintering Compaction

- **Compaction**: high pressure is applied to the powders to form them into the required shape.
 - **Pressing**: conventional compaction method in which opposing punches squeeze the powders contained in a die.
 - **Green compact**: the workpart after pressing (green indicates not fully processed part).
 - Accordingly, green density is higher than bulk density.
 - Green strength is adequate for handling the pressed part but far less than that achieved after sintering.

Conventional Pressing & Sintering Compaction

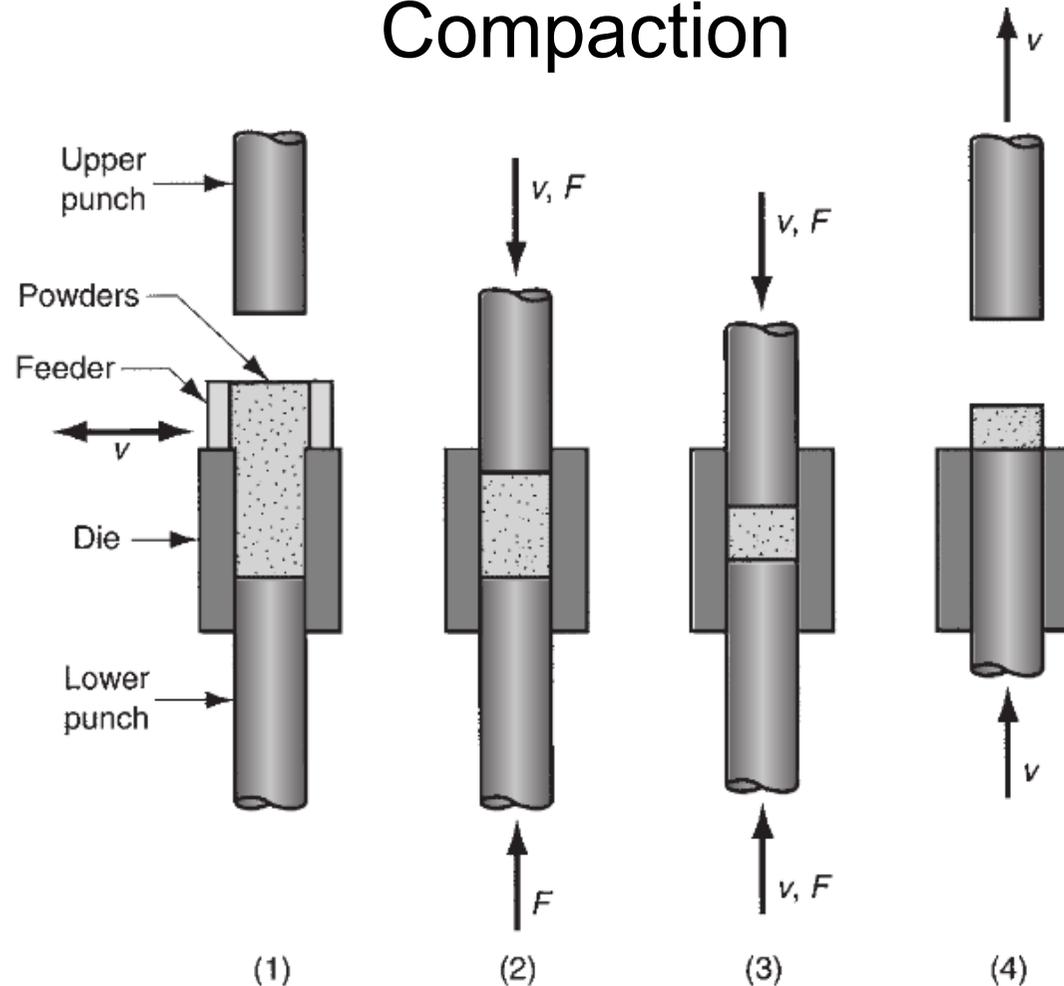


Fig. 16-9 Pressing, the conventional method of compacting metal powders in PM: (1) filling the die cavity with powder, done by automatic feed in production, (2) initial, and (3) final positions of upper and lower punches during compaction, and (4) ejection of part.

Conventional Pressing & Sintering Compaction

– ***Compaction:***

- 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 interparticle contact area to increase and additional particles to make contact. This is accompanied by a further reduction in pore volume.

Conventional Pressing & Sintering Compaction

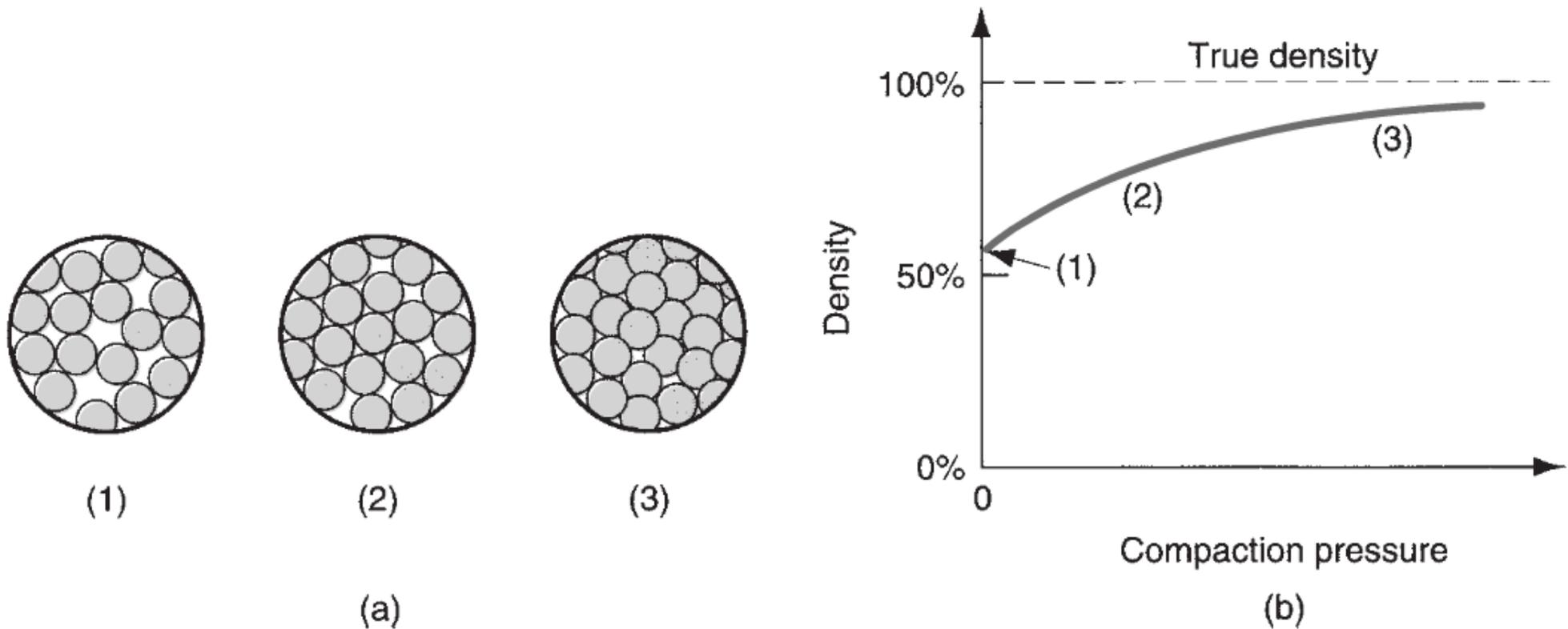


Fig. 16-10 (a) Effect of applied pressure during compaction: (1) initial loose powders after filling, (2) repacking, and (3) deformation of particles; and (b) density of the powders as a function of pressure. The sequence here corresponds to steps 1, 2, and 3 in Figure 16.9.

Conventional Pressing & Sintering Compaction

– **Compaction:**

- Several types of presses used for compaction.
- Could be hydraulic, mechanical or a combination of both.
- The required force for pressing depends on the projected area of the PM part multiplied by the pressure needed to compact the given metal powders.

$$F = A_p p_c$$

where F = required force, N; A_p = projected area of the part, mm²; and p_c = compaction pressure required for the given powder material, MPa. Compaction pressures typically range from 70 MPa for aluminum powders to 700 MPa for iron and steel powders.

Conventional Pressing & Sintering

Sintering

- **Sintering** (of green compact): a heat treatment operation performed on the compact to bond its metallic particles, thereby increasing strength and hardness.
 - Usually carried out at temperatures between 0.7 and 0.9 of the metal's melting point (metal remains in solid state).
 - The primary driving force for sintering is reduction of surface energy.
 - 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.

Conventional Pressing & Sintering

Sintering

– **Sintering:**

Note: diffusion is the principle mechanism in sintering.

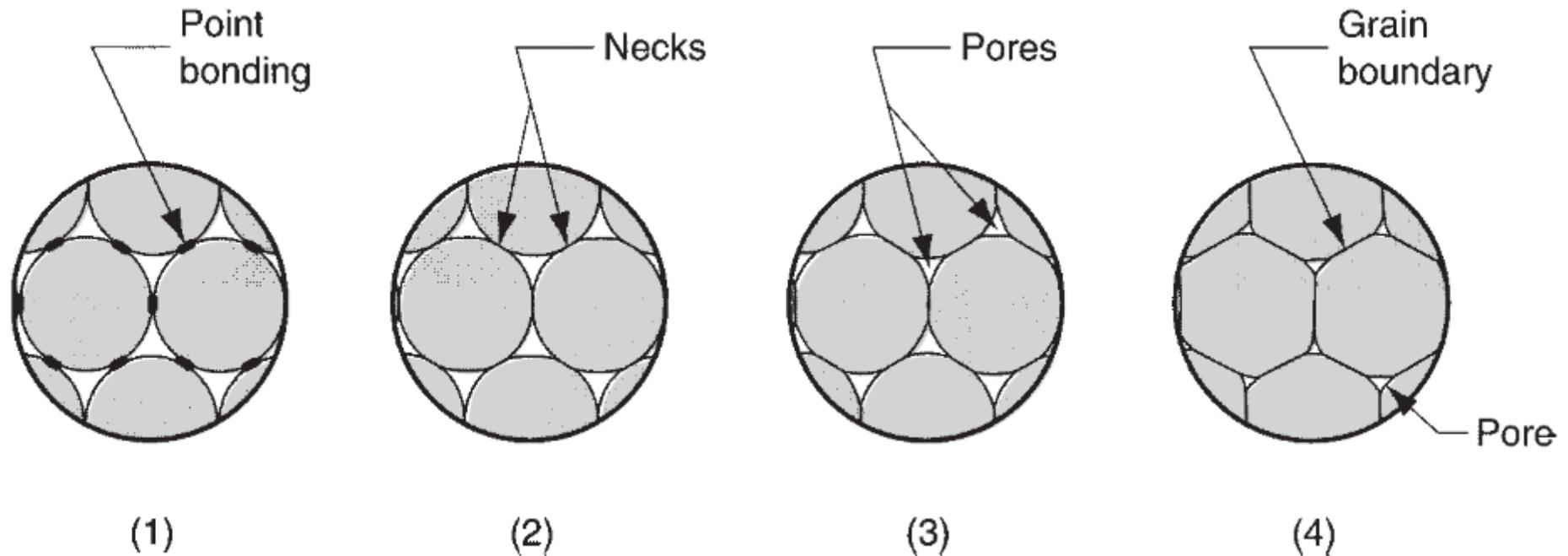


Fig. 16-11 Sintering on a microscopic scale: (1) particle bonding is initiated at contact points; (2) contact points grow into “necks”; (3) the pores between particles are reduced in size; and (4) grain boundaries develop between particles in place of the necked regions.

Conventional Pressing & Sintering

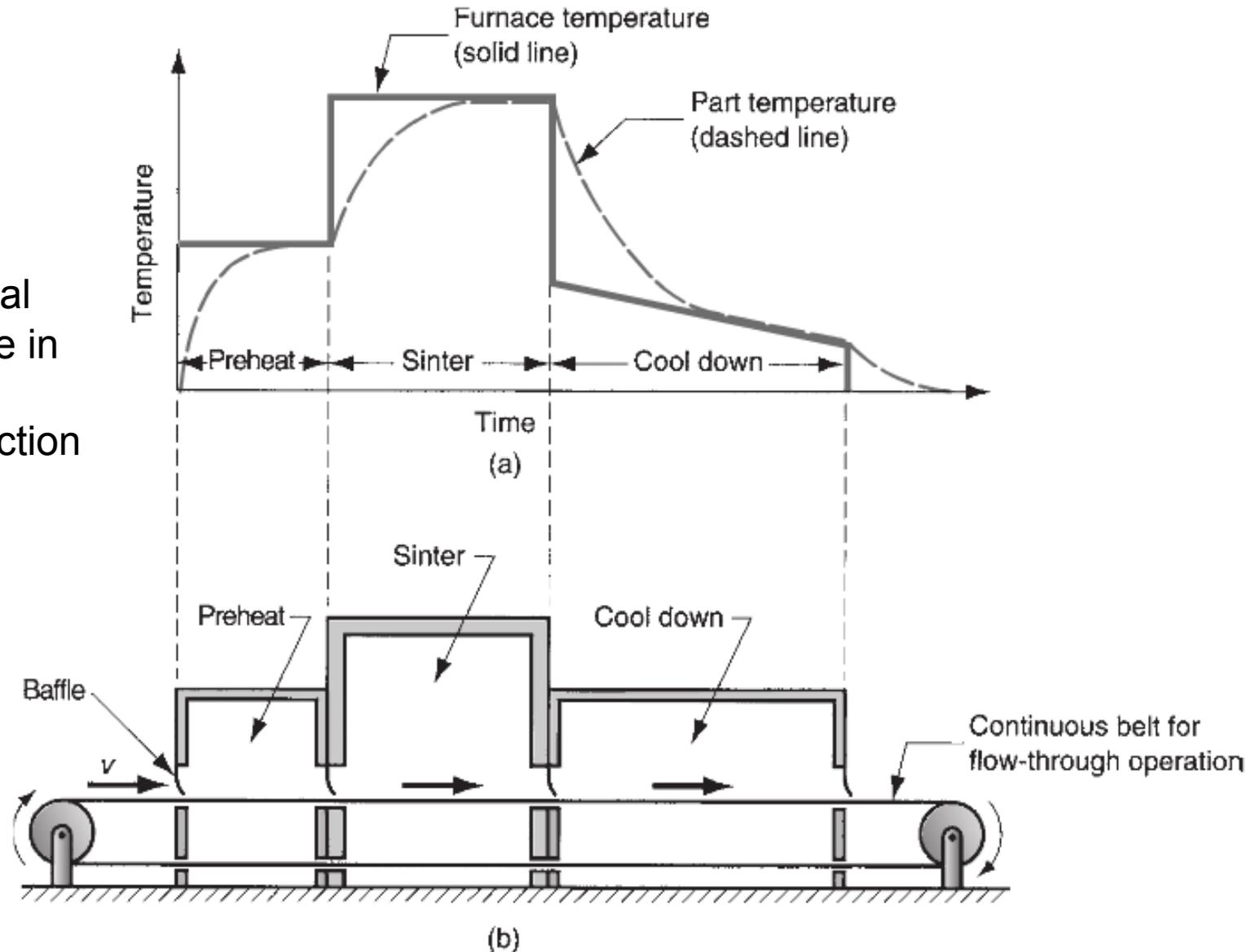
Sintering

– *Sintering.*

- Heat treatment consists of three steps, accomplished in three chambers in continuous furnaces: (1) preheat, in which lubricants and binders are burned off; (2) sinter; and (3) cool down.
- The atmosphere in the process is controlled; it includes:
 - Protection from oxidation.
 - Providing a reducing atmosphere to remove existing oxides.
 - Providing a carburizing atmosphere.
 - Assisting in removing lubricants and binders used in pressing.

Conventional Pressing & Sintering

Fig. 16-12 (a) Typical heat treatment cycle in sintering; and (b) schematic cross section of a continuous sintering furnace.



Conventional Pressing & Sintering

TABLE • 12.1 Typical sintering temperatures and times for selected powder metals.

Metal	Sintering Temperatures	
	°C	Typical Time
Brass	850	25 min
Bronze	820	15 min
Copper	850	25 min
Iron	1100	30 min
Stainless steel	1200	45 min
Tungsten	2300	480 min

Table. 16-1 (a) Typical sintering temperatures.

Conventional Pressing & Sintering

Secondary Operations

- ***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***: the term used when oil or other fluid is permeated into the pores of a sintered PM part. Self-lubricating bearings, usually made of bronze or iron with 10% 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.

Conventional Pressing & Sintering Secondary Operations

- ***Impregnation and Infiltration.***
 - ***Infiltration:*** an operation in which the pores of the PM part are filled with a molten metal.
 - Melting point of the filler metal must be below that of the PM part.
 - 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 has a more uniform density, as well as improved toughness and strength.
 - An application of the process is copper infiltration of iron PM parts.

Conventional Pressing & Sintering Secondary Operations

- ***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; e.g., salt baths are not used for heating PM parts.
 - Plating and coating operations are applied to sintered parts for appearance purposes and corrosion resistance.
 - Common platings for PM parts include Cu, Ni, Cr, Zn, and Cd.

Alternative Pressing & Sintering Techniques

Isostatic Pressing

- **Isostatic Pressing:** pressure is applied from all directions (rather than uniaxially as in conventional pressing) against the powders that are contained in a flexible mold; hydraulic pressure is used to achieve compaction.
 - Uniaxial pressing imposes limitations on part geometry, since metallic powders do not easily flow in directions perpendicular to the applied pressure.
 - Uniaxial pressing also leads to density variations in the compact after pressing.
 - Isostatic pressing takes two alternative forms: (1) **cold isostatic pressing** and (2) **hot isostatic pressing**.

Alternative Pressing & Sintering Techniques

Isostatic Pressing

- ***Cold Isostatic Pressing*** (CIP): compaction performed at room temperature.
 - The mold, made of rubber is oversized to compensate for shrinkage.
 - Water or oil is used to provide the hydrostatic pressure against the mold inside the chamber.
 - Advantages: more uniform density, less expensive tooling, and greater applicability to shorter production runs.
 - Limitations: good dimensional accuracy is difficult to achieve in isostatic pressing. So, subsequent finish shaping operations are often required to obtain the required dimensions, either before or after sintering.

Alternative Pressing & Sintering Techniques

Isostatic Pressing

- ***Cold Isostatic Pressing (CIP).***

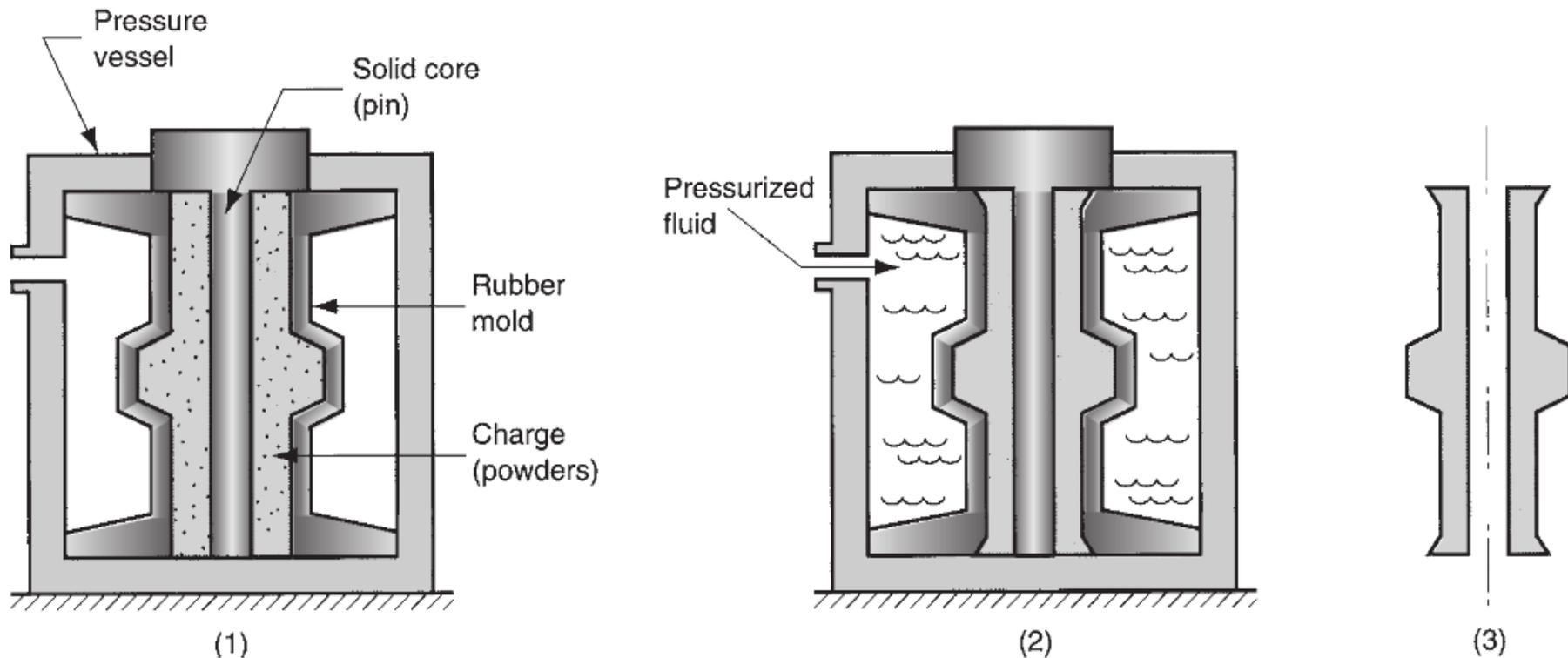


Fig. 16-13 (a) Cold isostatic pressing: (1) powders are placed in the flexible mold; (2) hydrostatic pressure is applied against the mold to compact the powders; and (3) pressure is reduced, and the part is removed.

Alternative Pressing & Sintering Techniques

Isostatic Pressing

- **Hot Isostatic Pressing (HIP)**: carried out at high temps & pressures, using a gas such as Ar or He as the compression medium.
 - The mold in which the powders are contained is made of sheet metal to withstand the high temperatures.
 - Advantages: accomplishes pressing and sintering in one step. Parts made by HIP have high density (porosity near zero), via interparticle bonding, and good mechanical strength.
 - Limitations: relatively expensive process and its applications seem to be concentrated in the aerospace industry.

Alternative Pressing & Sintering Techniques

Powder Injection Molding

- ***Metal Injecting Molding*** (MIM): steps include:
 - Metallic powders are mixed with an appropriate binder (carrier for metallic particles, usually a polymer. It enhances flow characteristics and holds the powders in the molded shape until sintering).
 - Granular pellets are formed from the mixture.
 - The pellets are heated to molding temperature, injected into a mold cavity, and the part is cooled and removed from the mold.
 - The part is processed to remove the binder using any of several thermal or solvent techniques.
 - The part is sintered.
 - Secondary operations are performed as appropriate.
 - Suited to small complex parts of high value.

Alternative Pressing & Sintering Techniques

Powder Rolling, Extrusion & Forging

- **Powder Rolling:** metallic powders are compacted between rolls into a green strip that is fed directly into a sintering furnace. It is then cold rolled and resintered.

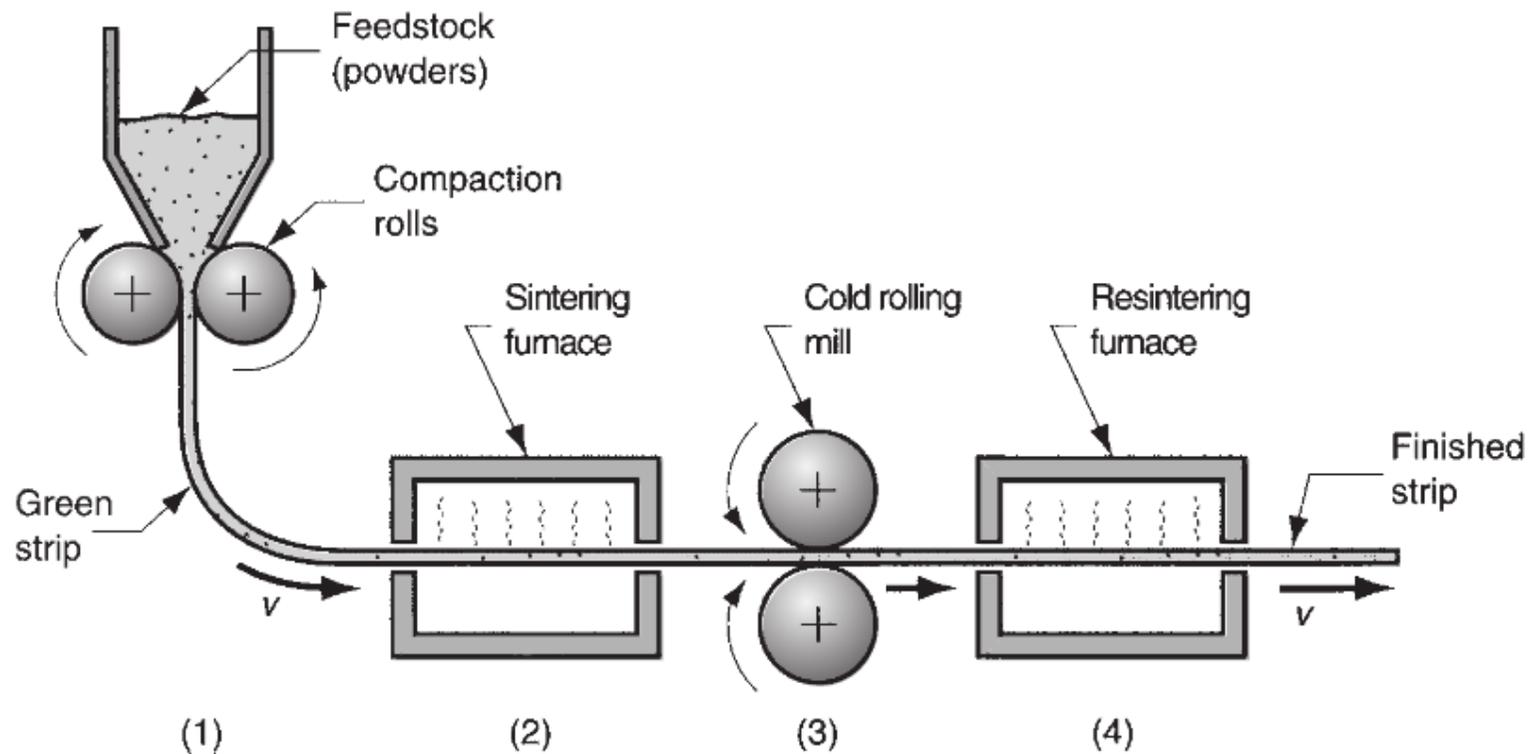


Fig. 16-14 Powder rolling: (1) powders are fed through compaction rolls to form a green strip; (2) sintering; (3) cold rolling; and (4) resintering.

Alternative Pressing & Sintering Techniques

Powder Rolling, Extrusion & Forging

- ***Powder Extrusion***: powders are placed in a vacuum-tight sheet metal can, heated, and extruded with the container.
- ***Powder Forging***: the starting work part is a powder metallurgy part preformed to proper size by pressing and sintering. Advantages:
 - Densification of the PM part,
 - Lower tooling costs and fewer forging “hits” (and therefore higher production rate) because the starting work part is preformed.
 - Reduced material waste.

Alternative Pressing & Sintering Techniques

Combined Pressing & Sintering

- **Hot Pressing:** setup in hot pressing is very similar to conventional PM pressing, except that heat is applied during compaction.
 - Advantages:
 - Resulting product is dense, strong, hard, and dimensionally accurate.
 - Limitations:
 - Selecting a suitable mold material that can withstand the high sintering temperatures.
 - Longer production cycle required to accomplish sintering.
 - Heating and maintaining atmospheric control in the process.
 - Applications: production of sintered carbide products using graphite molds.

Alternative Pressing & Sintering Techniques

Combined Pressing & Sintering

- **Spark Pressing:** approach that combines pressing and sintering but overcomes some of the problems in hot pressing.
 - Two steps:
 - Powder or a green compacted preform is placed in a die.
 - Upper and lower punches, which also serve as electrodes, compress the part and simultaneously apply a high-energy electrical current that burns off surface contaminants and sinters the powders, forming a dense, solid part in about 15 seconds.
 - Process applied to a variety of metals.

Alternative Pressing & Sintering Techniques

Liquid Phase Sintering

- **Liquid Phase Sintering:** used for systems involving a mixture of two powder metals, in which there is a difference in melting point between the metals.
 - Two powders are mixed, then heated to a temperature that is high enough to melt the lower-melting-point metal but not the other.
 - The melted metal thoroughly wets the solid particles, creating a dense structure with strong bonding between the metals upon solidification.
 - Resulting product is fully densified (no pores) and strong.
 - Examples of systems that involve liquid phase sintering include Fe–Cu, W–Cu, and Cu–Co.

Materials & Products for PM

PM Materials

- ***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.
 - Elemental powders are also mixed with other metal powders to produce special alloys that are difficult to formulate using conventional processing methods.
 - The most common elemental powders are those of Fe, Al, and Cu.
- ***Pre-alloyed Powders***: each particle is an alloy composed of the desired chemical composition.
 - Used for alloys that cannot be formulated by mixing elemental powders.
 - The most common pre-alloyed powders are certain copper alloys, stainless steel, and high-speed steel.

Materials & Products for PM

PM Products

- **Products:** some of the components commonly manufactured by powder metallurgy are gears, bearings, fasteners, electrical contacts, cutting tools, etc.
 - When produced in large quantities, metal gears and bearings are particularly well suited to PM for two reasons:
 - 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.
 - There is a need for porosity in the material to serve as a reservoir for lubricant.

Design Consideration in PM Parts Classification System

- Four classes of PM part designs by level of difficulty in conventional pressing:

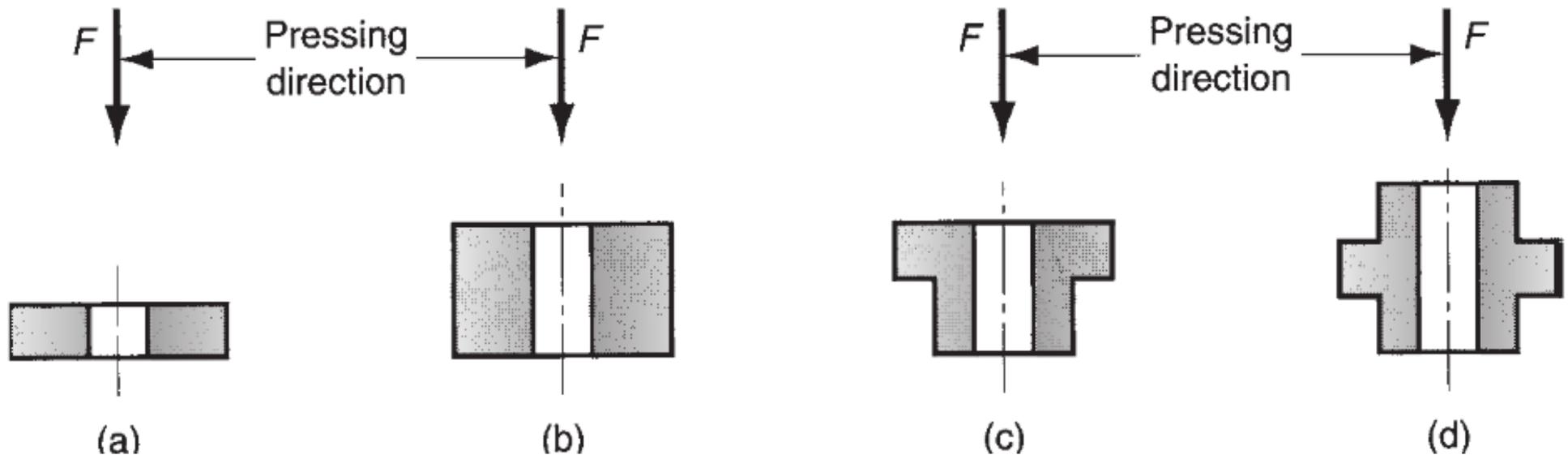


Fig. 16-15 Four classes of PM parts side view shown; cross section is circular (a) Class I—simple thin shapes that can be pressed from one direction; (b) Class II—simple but thicker shapes that require pressing from two directions; (c) Class III—two levels of thickness, pressed from two directions; and (d) Class IV—multiple levels of thickness, pressed from two directions, with separate controls for each level to achieve proper densification throughout the compact.

Design Consideration in PM

Design Guidelines for PM Parts

- Minimum quantity of 10,000 units is required to justify the process.
- Porosities up to 50% are possible.
- Justified for production of materials that would be difficult if not impossible to fabricate by other means.
- Part must have vertical or near vertical sides to permit ejection from the die after pressing.
- Screw threads cannot be fabricated by PM pressing.
- Wall thickness should be a minimum of 1.5 mm between holes or a hole and the outside part wall. Minimum recommended hole diameter is 1.5 mm.

Design Consideration in PM

Design Guidelines for PM Parts

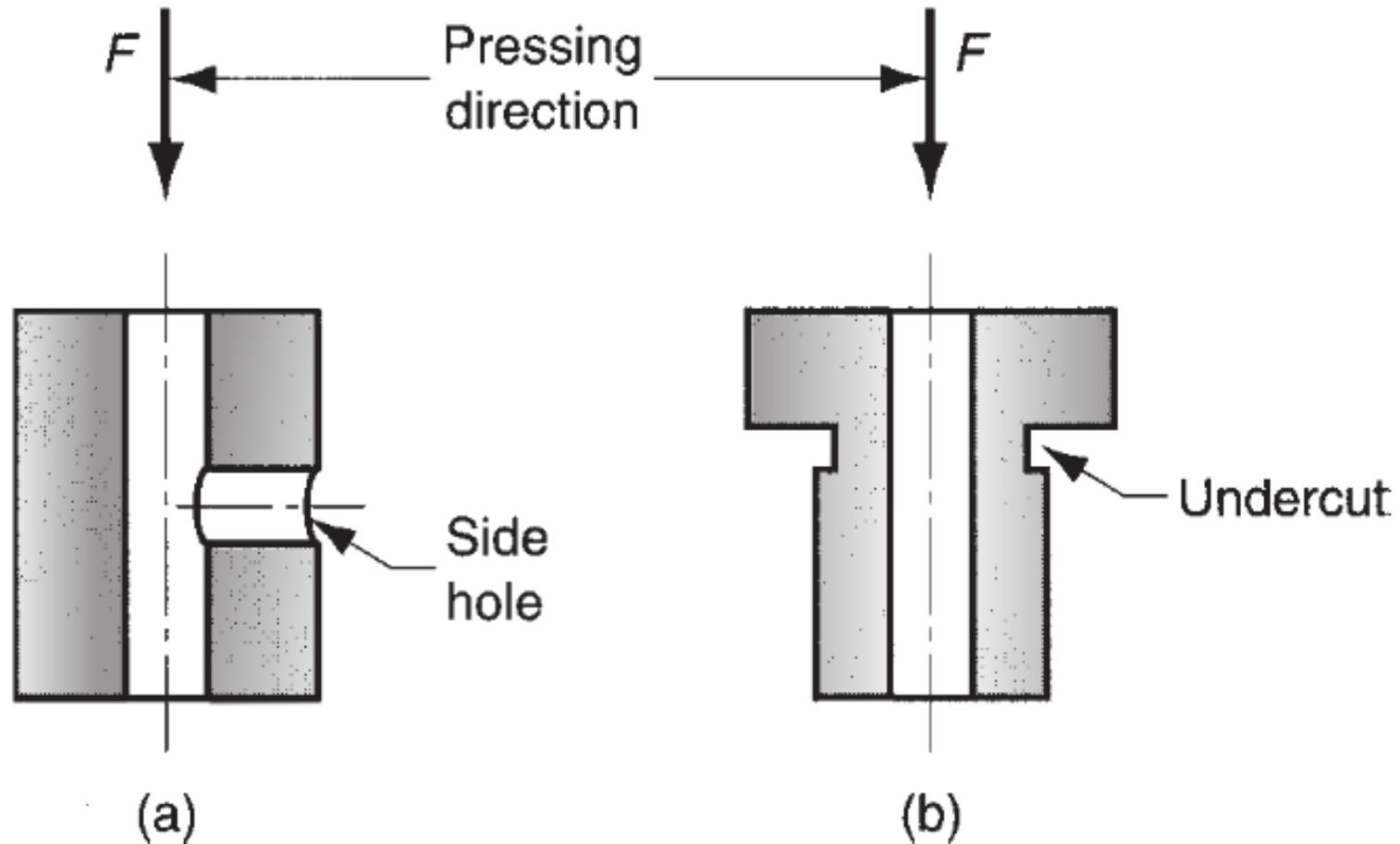


Fig. 16-16 Part features to be avoided in PM: (a) side holes and (b) side undercuts. Part ejection is impossible.

Design Consideration in PM

Design Guidelines for PM Parts

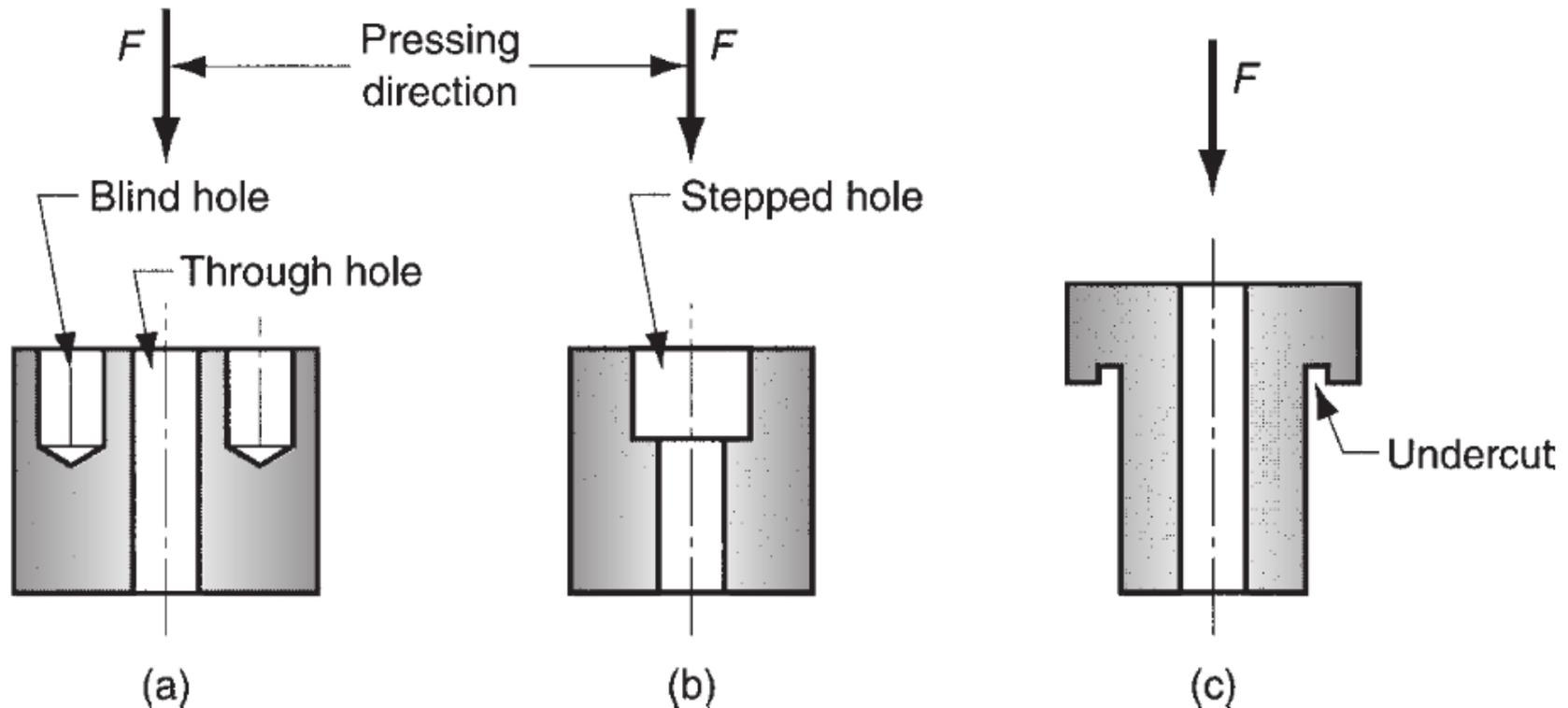


Fig. 16-17 Permissible part features in PM: (a) vertical hole, blind and through, (b) vertical stepped hole, and (c) undercut in vertical direction. These features allow part ejection.

Design Consideration in PM

Design Guidelines for PM Parts

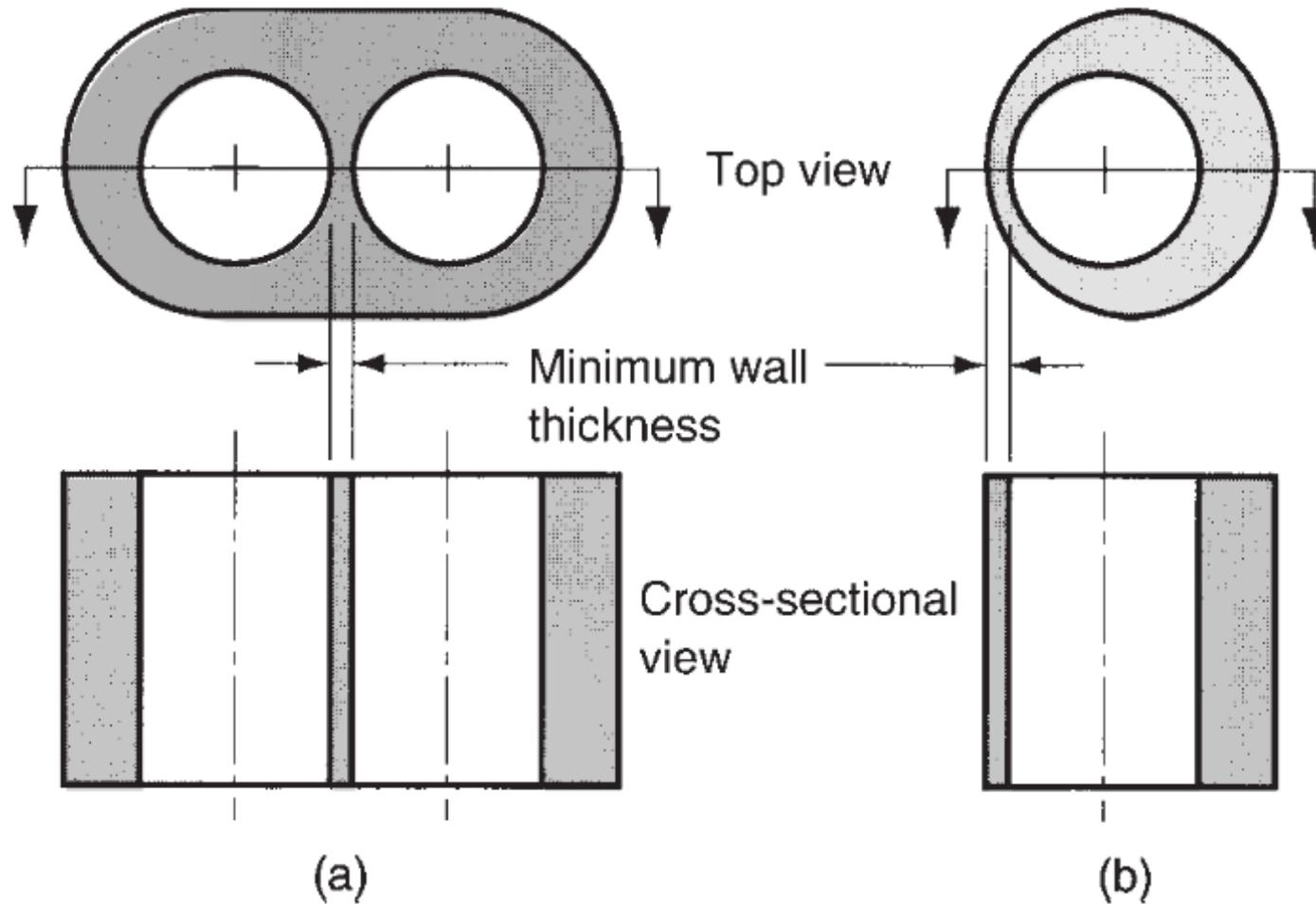


Fig. 16-18 Minimum recommended wall thickness (a) between holes or (b) between a hole and an outside wall should be 1.5 mm.