CHAPTER 1
POWDER METALLURGY PROCESSING

CHAPTER CONTENTS

1.1 OVERVIEW OF POWDER METALLURGY (PM)?

1.1.1 Definitions

PM is the art of producing commercial products from metallic powders by pressure. Heat, which may or may not be used, must be kept at a temperature below the melting point of the powder. Application of heat is called sintering and it results in bonding the fine particles together, thus improving the strength. Metal powders may be mixed with some other element powders for lubrication or binding purposes.

Metal powders are expensive, and machines and dies are expensive as well. PM is generally used for mass-production applications. The higher cost is often justified by the unusual properties obtained. Some products can not be made by other processes.

1.1.2 Applications

Powder Metallurgy (P/M) is a processing technology in which parts are produced by *compacting* and *sintering* metallic and/or nonmetallic powders. Therefore, P/M is a typical example of an additive manufacturing process. P/M parts can be mass produced to *net shape* or *near net shape*, eliminating or reducing the need for subsequent machining.

Although parts as large as 20 kg can be produced by P/M, most products are less than 2 kg. The largest tonnage of metals for P/M is steel and alloys of aluminum. Other P/M materials are copper, nickel, tungsten, ceramic materials, etc.

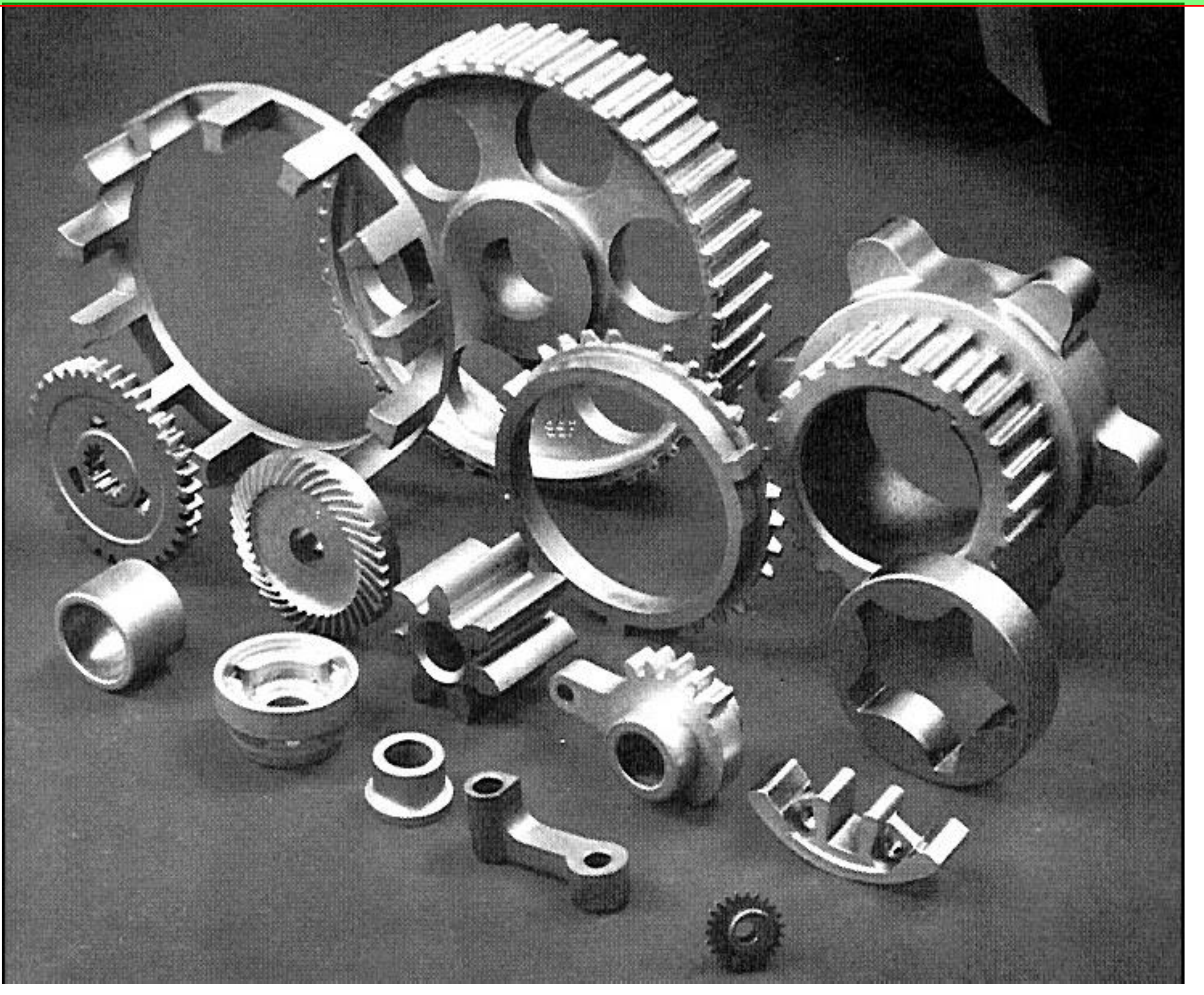


Fig. 1.1 A collection of powder metallurgy parts

1.1.3 Advantages of PM:

1. PM parts can be mass produced to net shape or near net shape, eliminating or reducing the need for subsequent processing.
2. The PM process itself involves very little waste of material; about 97% of the starting powders are converted to product. This compares favorably to casting processes in which sprues, runners, and risers are wasted material in production cycle.
3. 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.
4. Certain metals that are difficult to fabricate by other methods can be shaped by PM. Tungsten is an example; tungsten filaments used in incandescent lamp bulbs are made using PM technology.
5. Certain metal alloy combinations and cermets can be formed by PM that cannot be produced by other methods.
6. PM compares favorably to most casting processes in terms of dimensional control of the product. Tolerances of ±0.13 mm are held routinely.
7. PM production methods can be automated for economical production.

1.1.4 Disadvantages of PM:

1. High tooling and equipment costs,
2. The expensive metallic powders,
3. Difficulties with storing and handling metal powders,
4. 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.
5. Variations in material density throughout the part may be a problem in PM, especially for complex part geometries.

1.2 ENGINEERING POWDERS

1.2.1 Characteristics Of Metal Powders

1) Shape: The shape of powder particles is depended to its production method; spherical, dendritic, flat or angular.

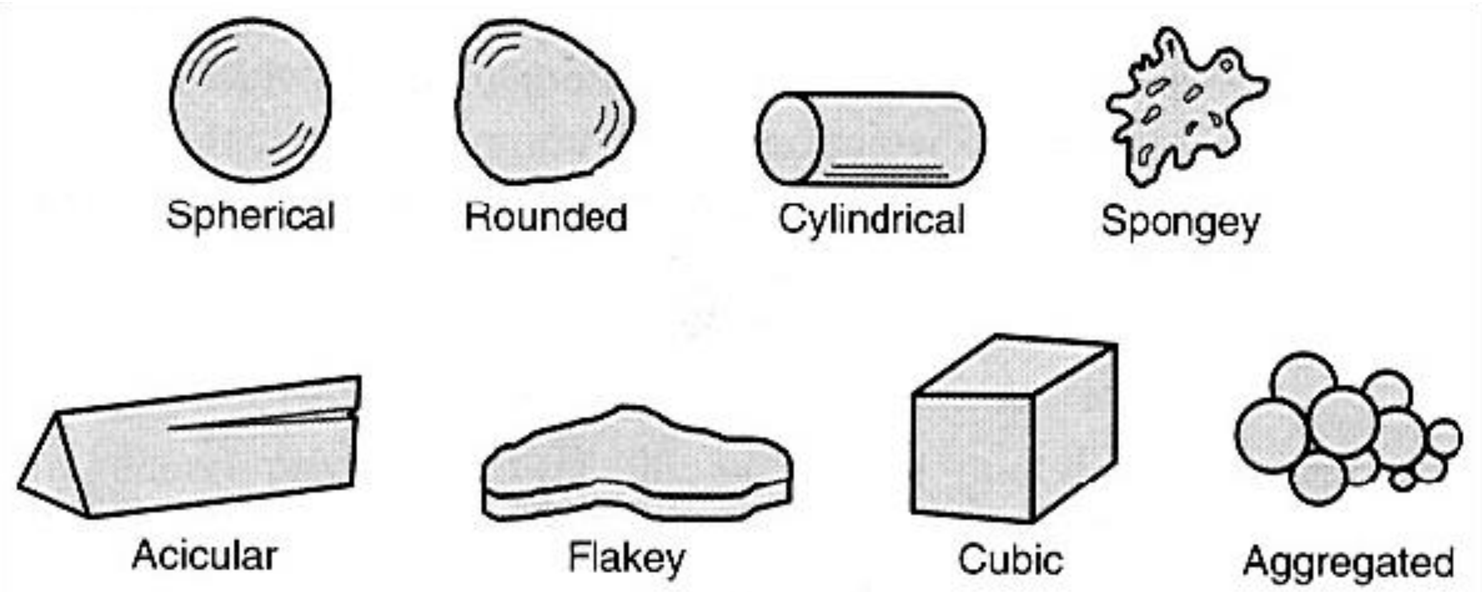


Fig. 1.2 Several of the possible (ideal) particle shape in powder metallurgy

2) Fineness: It is similar to sand size. Powders are sized with standard sieves ranging from 36-850 μm. Particle size distribution affects flowability and apparent density.

3) Flowability: It is the ability of a powder flow and fills a die cavity. It can be described as the rate of flow through fixed orifice.

4) Compressibility: It is the ratio of the volume of initial powder to the volume of the pressed compact. It varies considerably with the particle size distribution. Green strength (strength before sintering) of a compact is dependent on compressibility.

5) Apparent Density: It is the weight of powders occupying a certain volume, expressed as grams/cm^3.

6) Sintering Ability: Sintering is the bonding of particles by the application of heat. The temperature range should be smaller than melting temperature.

1.2.2 Powder Production

All metal powders, because of their individual physical and chemical characteristics, can not be manufactured in the same way. The procedure varies considerably, and so does the particles obtained from various processes.

1) Machining: It results in coarse particles and used principally in production of magnesium powders.
2) Milling: It uses various types of crushers, rotary mills, etc. Brittle materials may be reduced to irregular shapes of almost any fineness. The process is also used for pigment production from ductile materials. Generally oil is used as carrier medium.
3) Shotting: It is pouring molten metal through an orifice slowly and cooling by dropping into water. Spherical or pear-shaped particles are obtained. Size is too large for PM.
4) Electrolytic Deposition: It is common method for producing iron, silver, tantalum and several other metals. For producing iron powder, steel plates are placed as anodes in the electrolysis tanks. Stainless steel is used as cathode. Direct current passed through the circuit and iron powders are deposited on the cathode. In this condition they are brittle and must be annealed.

5) Direct Reduction: It reduces metal oxide mines to metal powder. Minerals are crushed to powder size and than under reducing atmospheres (H or C rich) reduced to metal powder. For producing iron powder, iron oxide (crushed) is fed into a rotating kiln along with crushed coke. It is heated up to 1050 °C. Carbon combines with oxygen and pure iron powder is obtained. It looks like a sponge, and called as “sponge iron”.

6) Atomization: A metal stream is atomized by a pressurized fluid. It is the most common metal powder production method. It is very much in use for production of alloy steel powders. Powder size and shape can be controlled by controlling metal flow rate and pressure of atomizing jets.

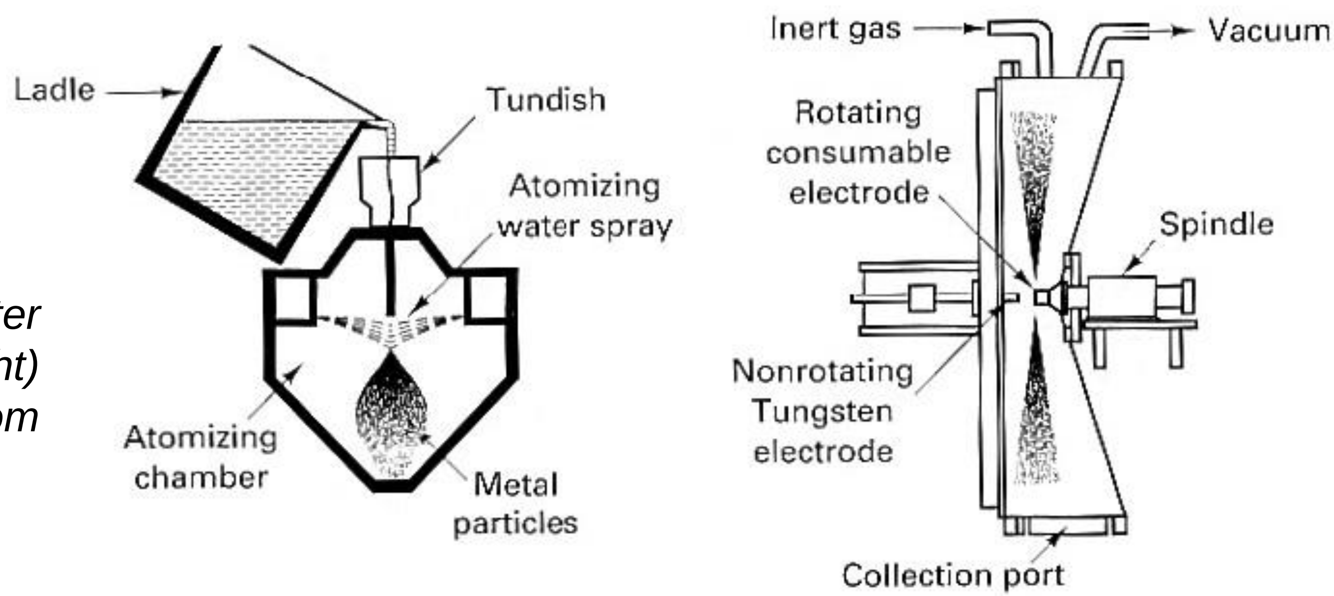


Fig. 1. 3 (Left) Water atomization; and (Right) Centrifugal atomization from a consumable electrode

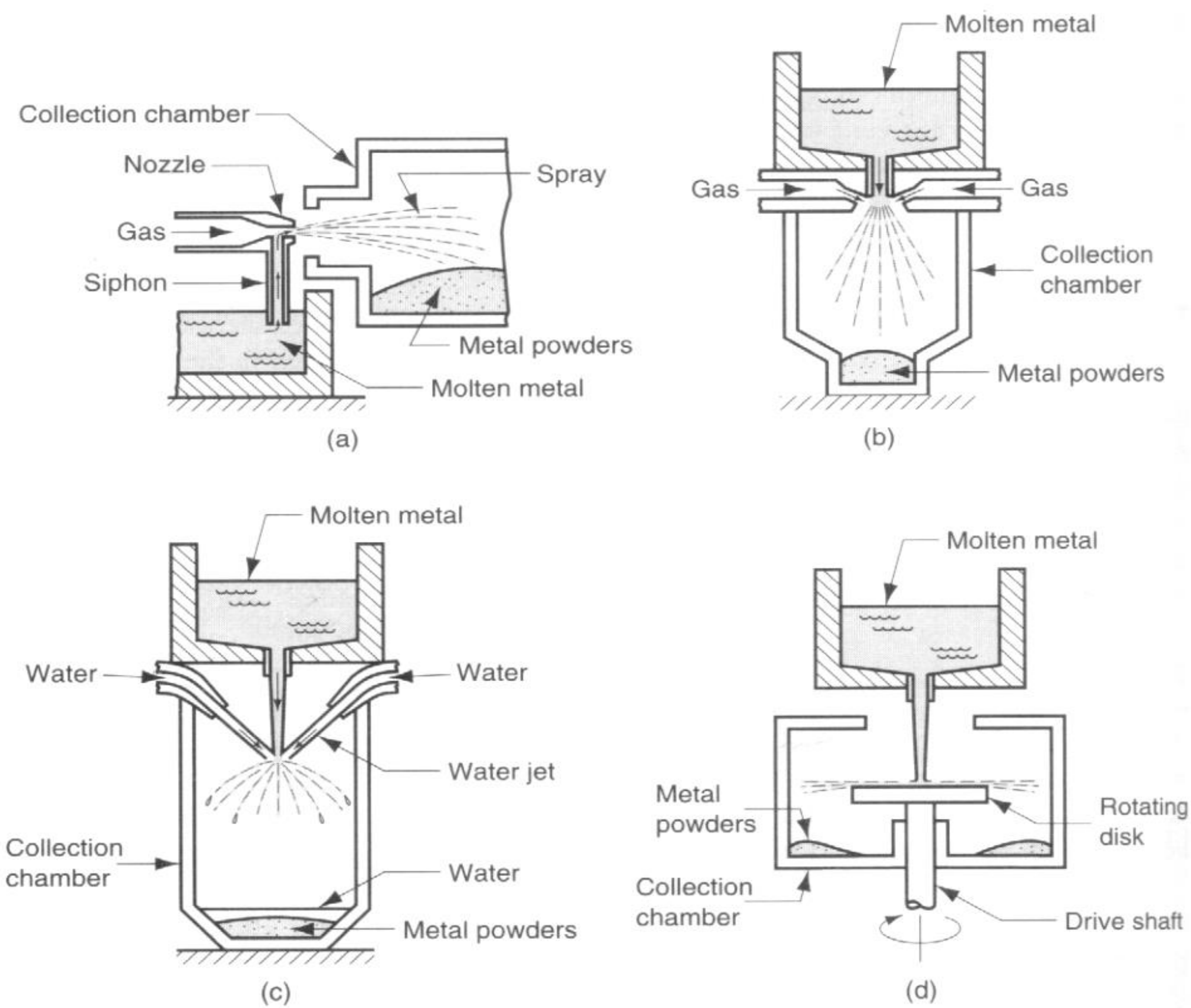


Fig. 1.4 Several atomization methods for producing metallic powders: (a) and (b) gas atomization methods; (c) water atomization; and (d) centrifugal atomization.

1.3 POWDER METALLURGY PROCESS

1.3.1 *Overview*

After the metallic powders have been produced and classified, the conventional P/M process sequence consists of three major steps: (1) *blending* and *mixing* of powders, (2) *compaction*, and (3) *sintering*, and a number of optional and finishing secondary operations.

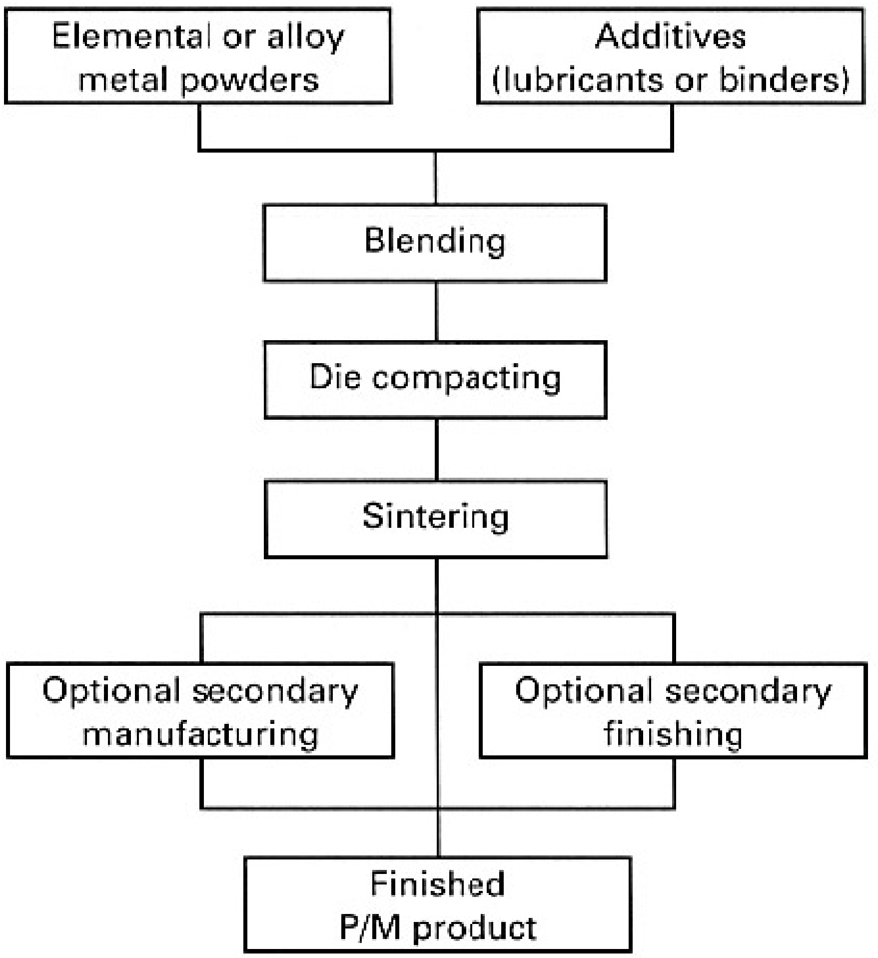


Fig. 1.5 Simplified flowchart illustrating the sequence of operations in powder metallurgy process

The condition of powders during the three primary P/M operations is shown in the figure:

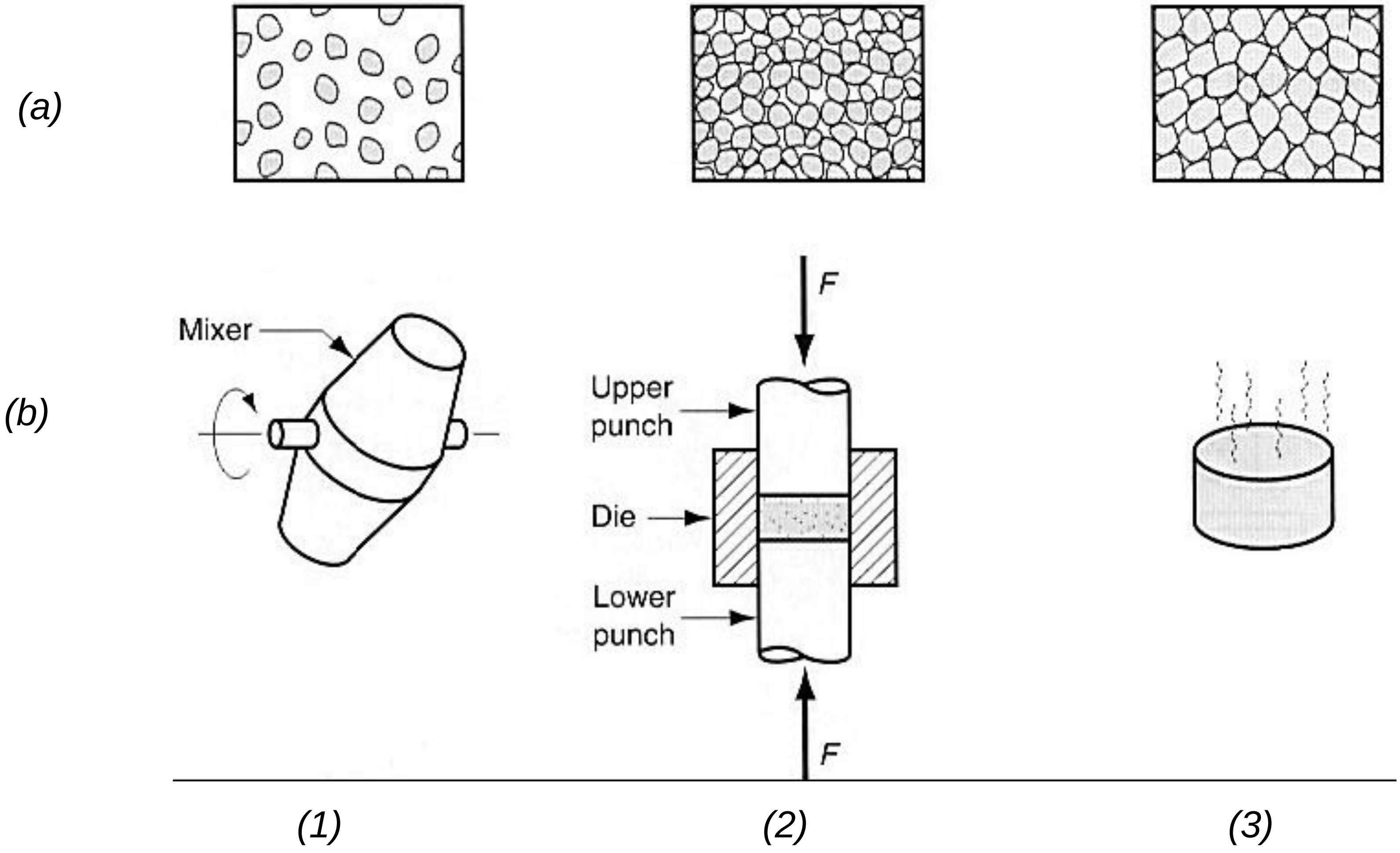


Fig. 1.6 The conventional P/M process sequence: (1) blending, (2) compacting, and (3) sintering; (a) shows the condition of powders, and (b) shows the schematics of operation

1.3.2 *Blending and mixing*

Blending: mixing powder of the same chemical composition but different sizes
Mixing: combining powders of different chemistries
Blending and mixing are accomplished by mechanical means:

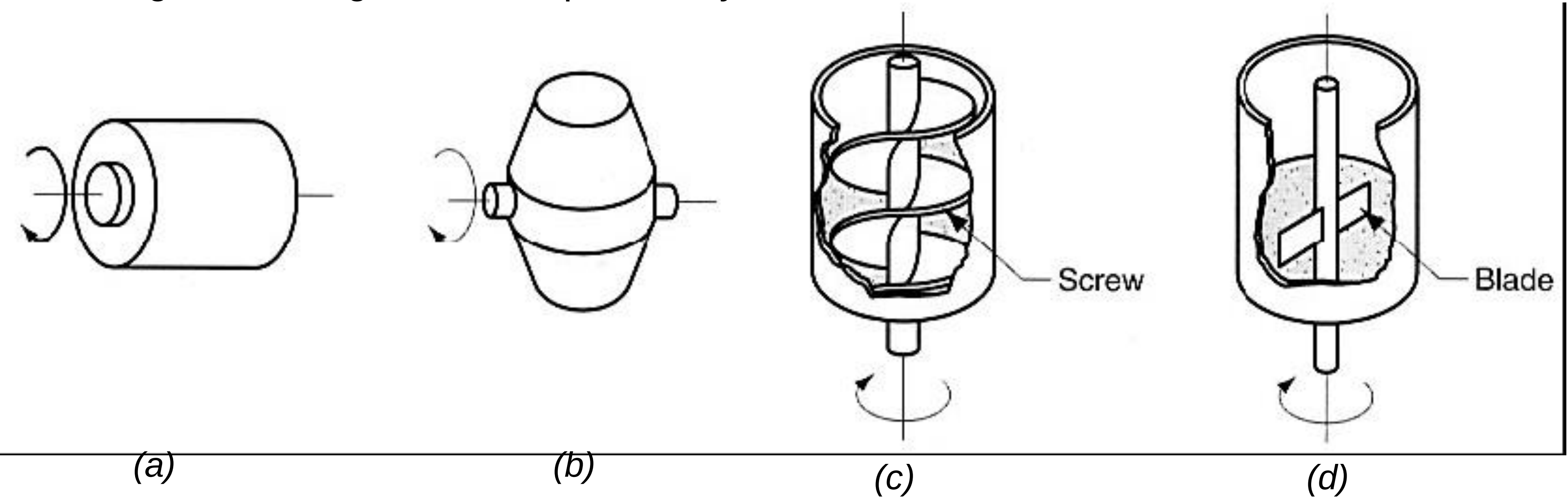


Fig. 1.7 Several blending and mixing devices: (a) rotating drum, (b) rotating double cone, (c) screw mixer, (d) blade mixer

Except for powders, some other ingredients are usually added:

- *Lubricants*: to reduce the particles-die friction
- *Binders*: to achieve enough strength before sintering
- *Deflocculants*: to improve the flow characteristics during feeding

1.3.3 *Compaction*

Blended powers are pressed in dies under high pressure to form them into the required shape. The work part after compaction is called a *green compact* or simply a *green*, the word green meaning not yet fully processed.

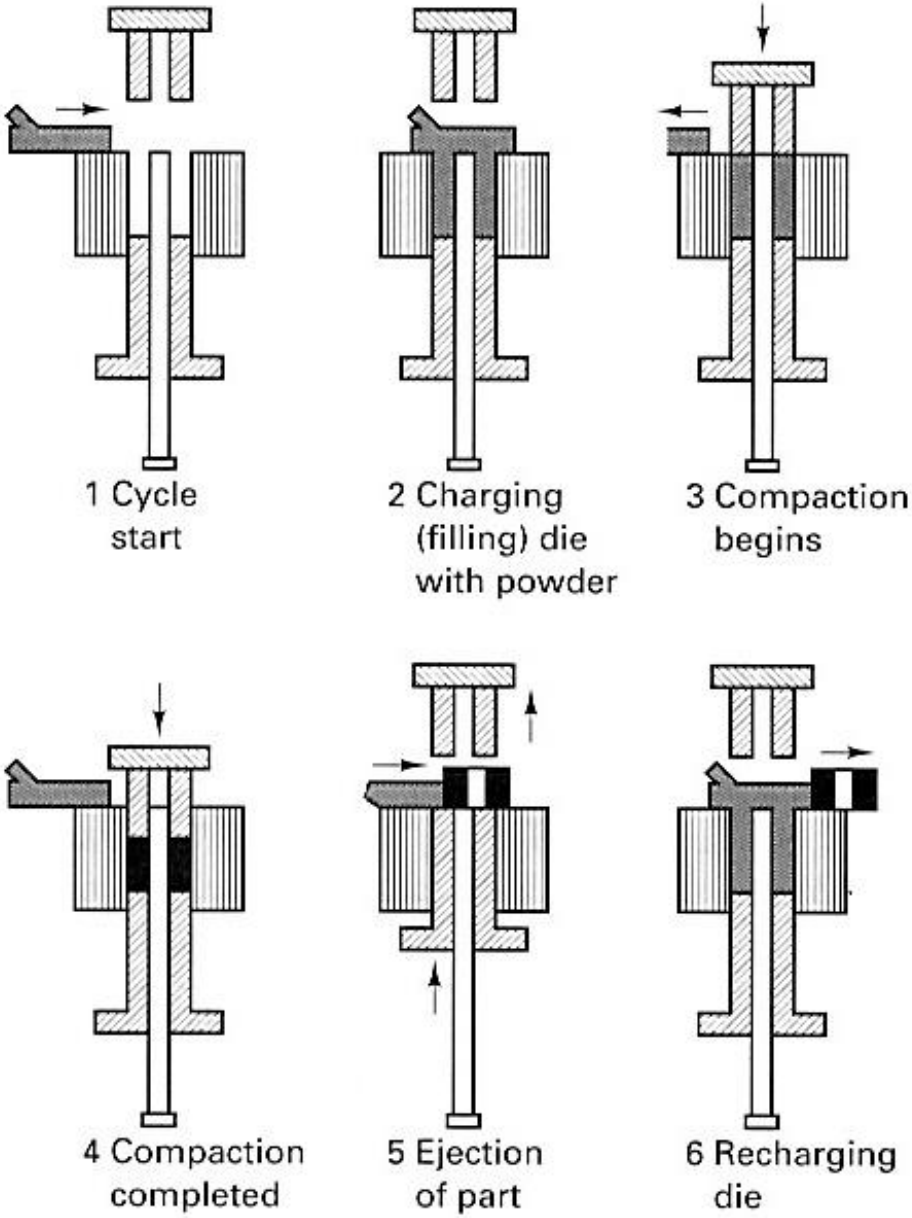
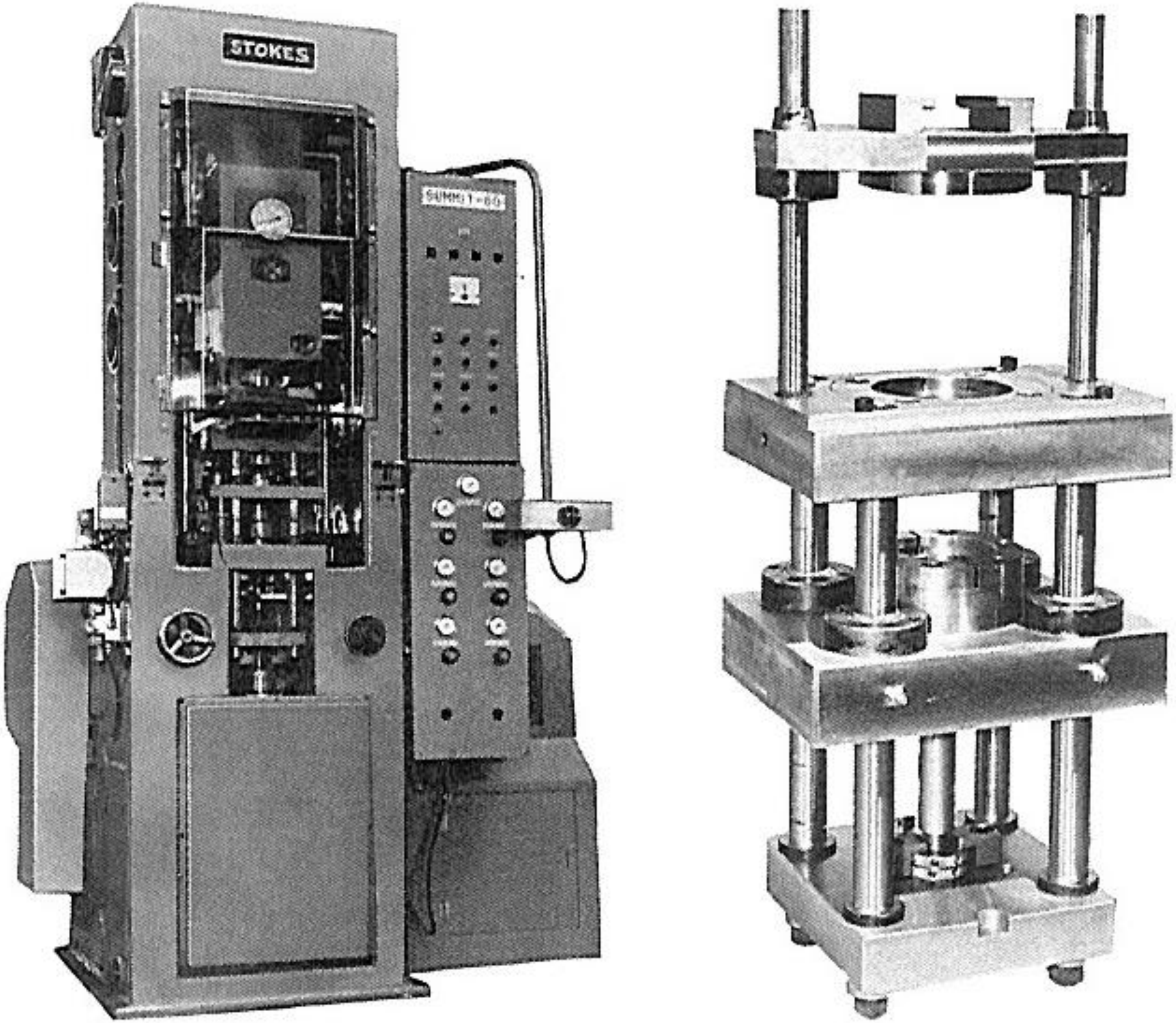


Fig. 1. 8 Typical steps in compaction

Fig. 1.9 Typical press for the compaction of metallic powders. The removable die set (right) allows the machine to be producing parts with one die set while another is being fitted to produce a second part



Powders are mixed with different sizes for better compressibility. Then they are blended with lubricants. Common lubricants are stearic acid, zinc stearate and powder graphite. Then, they are compacted to shape under pressures ranging from 20 to 1400 MPa.

Fig. 1.10 Pressing, the conventional method of compacting metal powders in PM

1.3.4 Pressure and density distributions after compaction

As a result of compaction, the density of the part, called the green density is much greater than the starting material density, but is not uniform in the green. The density and therefore mechanical properties vary across the part volume and depend on pressure in compaction:

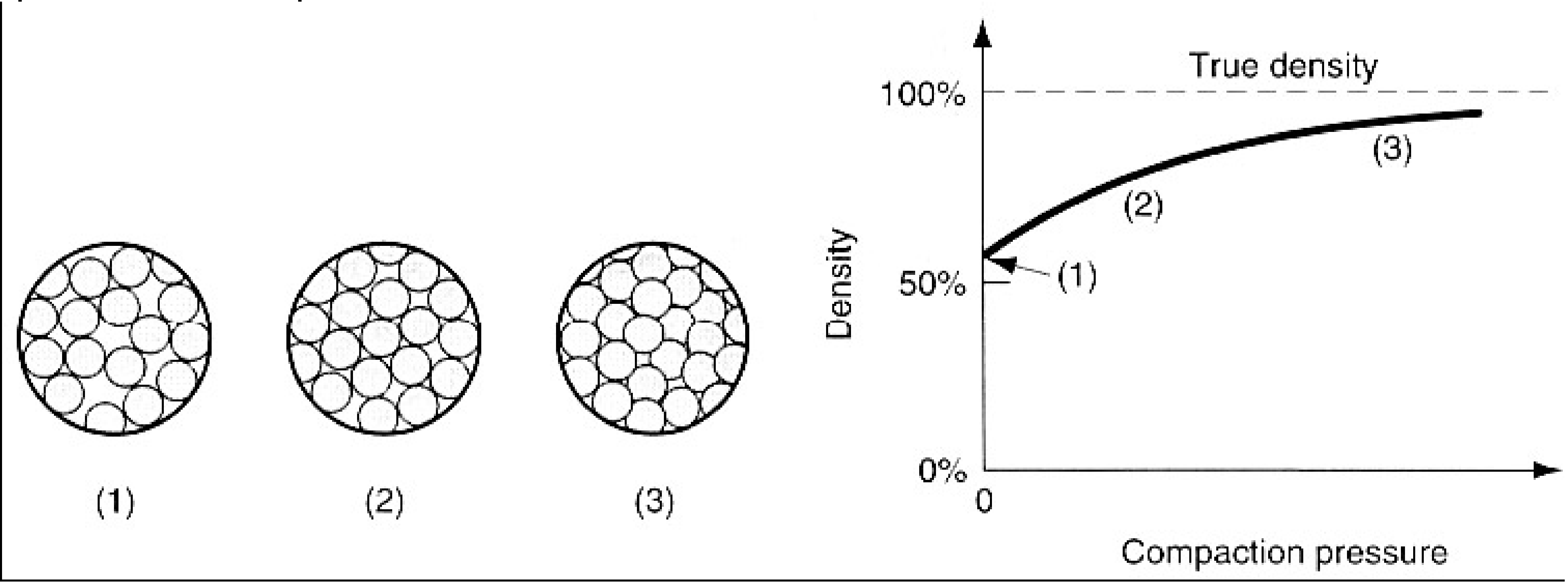


Fig. 1.11 Effect of applied pressure during compaction: (1) initial loose powders after filling, (2) repacking, and (3) deformation of particles.

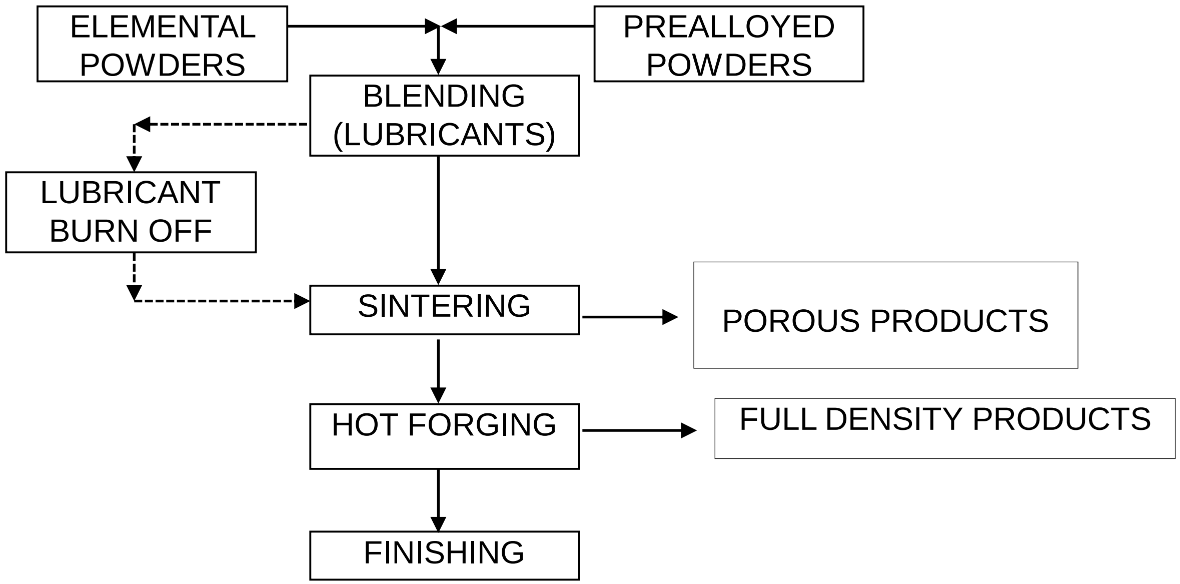


Fig. 1.12 PM Processing Flow-Chart

The die cavity must be very smooth and must have a slight draft to facilitate removal of the part. Wall friction prevents much of the pressure from being transmitted to the powder. So, double acting punches are more affective. Compacted part is called “green compact” and has little strength. Final strength is obtained by sintering.

There are different ways to improve the density distribution:

Application of double acting press and two moving punches in conventional compaction

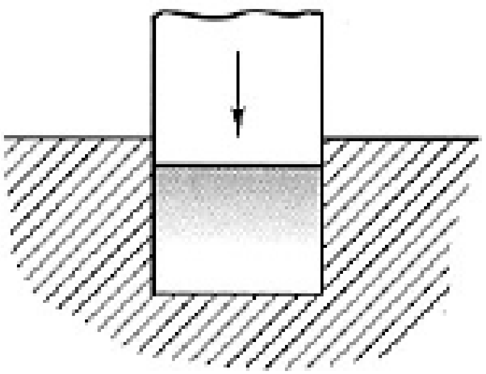


Fig. 1.13 Compaction with a single punch, showing the resultant non-uniform density

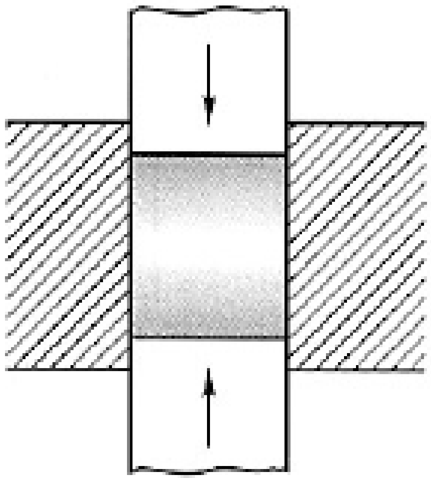


Fig. 1.14 Density distribution obtained with a double acting press and two moving punches

Pressure is applied from all directions against the powder, which is placed in a flexible mold:

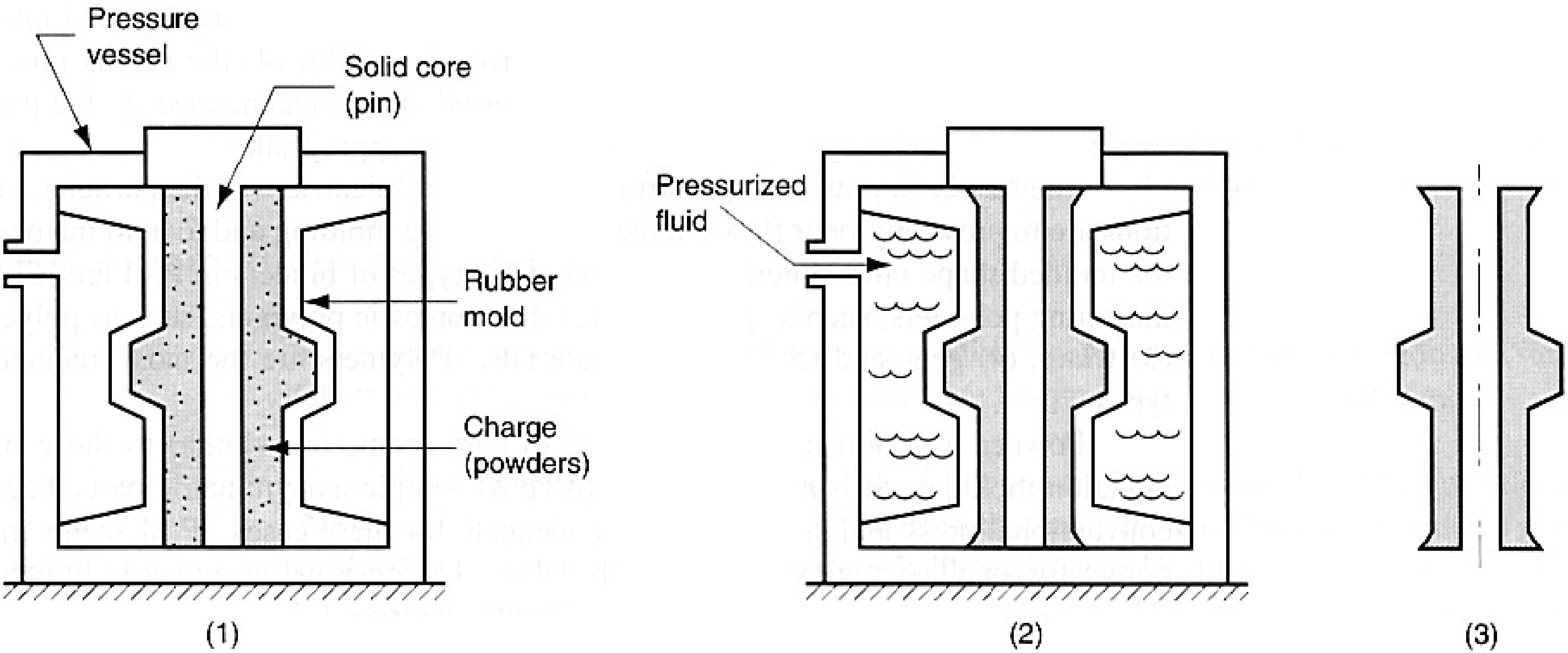


Fig. 1.15 Cold isostatic pressing: (1) powders are placed in the flexible mold; (2) hydrostatic pressure is applied against the mold to compact the powders; and (3) pressure is reduced and the part is removed.

1.3.5 Sintering

The operation of heating a green compact to an elevated temperature is known as sintering. Solid powders are welded together and generally solid state diffusion takes place. There is shrinkage during sintering, so results in densification. Temperature is generally below the melting point of powders. But, one of the elements might melt, “Liquid phase sintering”, commonly used in cemented carbide tool production. Sintering temperature is about 1100° C for steels with times about 20-40 minutes. To prevent reduction or oxidation of the powders, sintering furnaces are atmosphere controlled. Sintering of steel is done under dissociated ammonia (nitrogen rich).

Compressed metal powder is heated in a controlled-atmosphere furnace to a temperature below its melting point, but high enough to allow bounding of the particles:

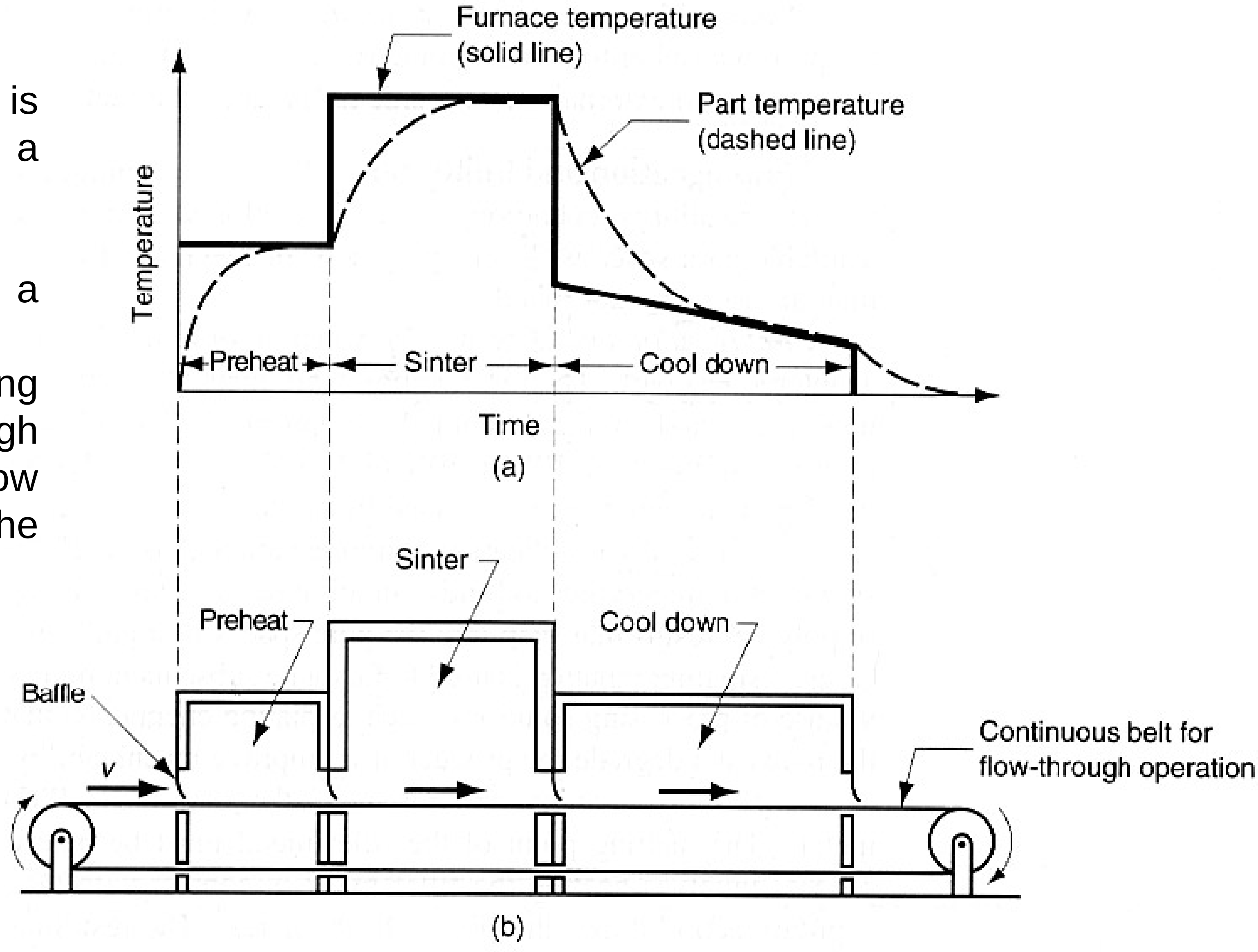


Fig. 1.16 (a) Typical heat treatment cycle in sintering; and (b) schematic cross-section of a continuous sintering furnace

The primary driving force for sintering is not the fusion of material, but formation and growth of bonds between the particles, as illustrated in a series of sketches showing on a microscopic scale the changes that occur during sintering of metallic powders.

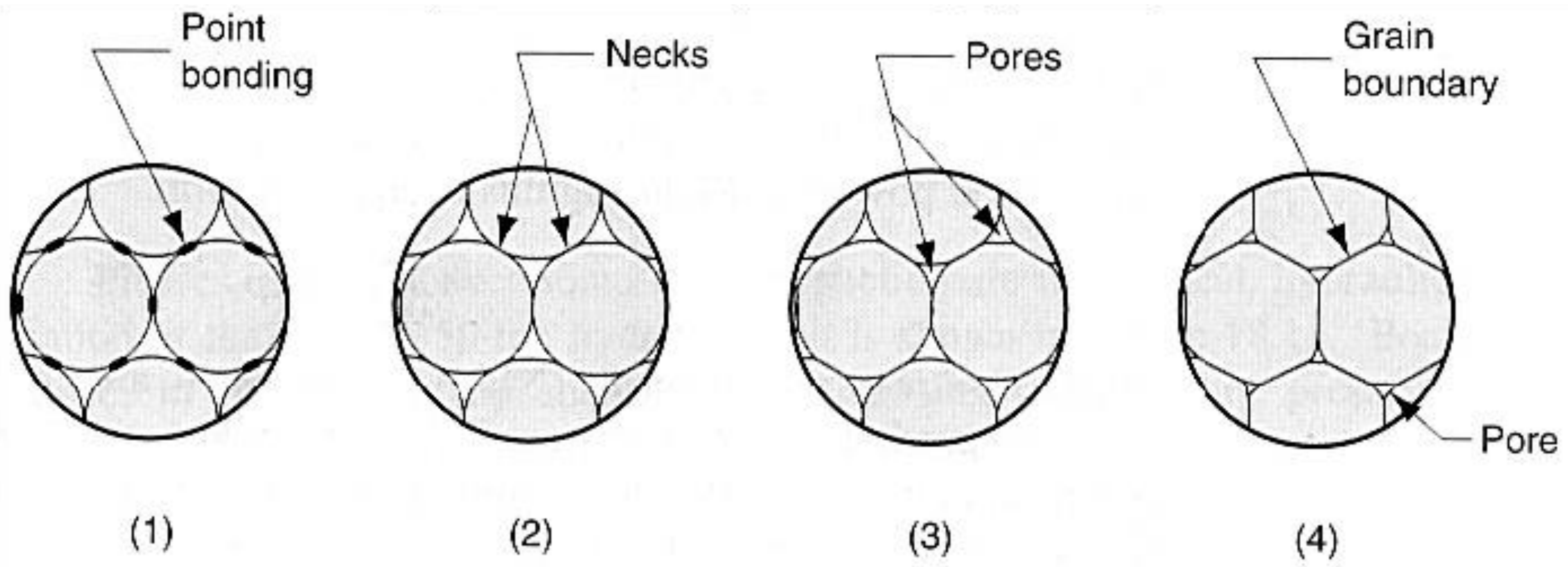


Fig. 1.17 Sintering on a microscopic scale: (1) particle bounding is initiated at contact points; (2) contact points grow into "necks"; (3) the pores between particles are reduced in size; and; (4)grain boundaries develop between particles in place of the necked regions.

1.3.6 *Finishing operations*

A number of secondary and finishing operations can be applied after sintering, some of them are:

Hot Forging

Porous sintered products have limited mechanical properties. By hot forging full density products can be produced which have equivalent mechanical properties to cast-rolled products.

- *Sizing*: cold pressing to improve dimensional accuracy
- *Coining*: cold pressing to press details into surface
- *Impregnation*: oil fills the pores of the part
- *Infiltration*: pores are filled with a molten metal
- *Heat treating, plating, painting*

1.4 APPLICATIONS

PM parts are continuously increasing in number. They are generally smaller than 1 kg in weight.

1) Metallic Filters: Metallic filter have greater strength than ceramic filter. Metallic filters can have up to 80% porosity.

2) Cemented Carbides: WC is mixed with Co powder, pressed to shape and than liquid phase sintered. They are commonly used as cutting tool material and metal deformation die material (wire drawing, rolling)

3) Gears and Pump Rotors: They are produced from iron powder mixed with graphite. They have porosity about 20%. After sintering pores are infiltrated with oil for quiet operation.

4) Porous Bearings: Most bearings are made copper, tin, and graphite powders. After sintering they are sized and impregnated with oil. These are called “self lubricated bearings” and they do not need lubrication during working.

5) Magnets: Excellent small magnets are called “ferrites” and they are very much superior to cast magnets.

6) Contact Parts: They must have wear resistance, refractoriness and at the same time must have good electrical conductivity. Combinations as W-Cu, W-Co, W-Ag have been developed.

1.4.1 Manufacturing Of Cemented Carbides

The cemented carbides used in making cutting tools and drawing dies consists of the carbides of tungsten (W), titanium (Ti), tantalum (Ta), Molybdenum (Mo) bounded with ductile cobalt (Co) or nickel (Ni).

Tungsten oxide → reduced by H_2 → Tungsten → grinding → tungsten powders →

Mix with carbon → heat (1500 ^{0}C) 2 hrs → mix with Co + paraffin wax → compact →

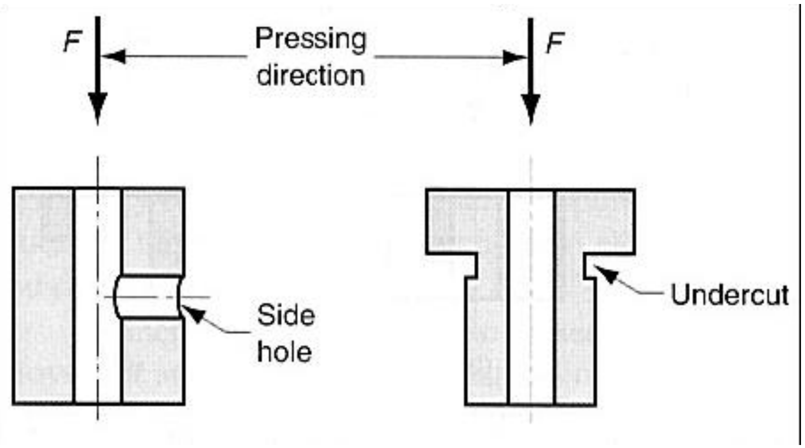
Sintering (850-1000 ^{0}C) → final sintering (1350-1550 ^{0}C)90 min → WC tool

Fig. 1.18 Flowchart of producing WC tool by PM Processing

1.5 DESIGN CONSIDERATIONS IN POWDER METALLURGY

The next design requirements are essential for P/M parts:

- The shape of the parts must be as simple as possible.
- PM parts should be made with the widest tolerances. The PM process is capable of achieving tolerances of bigger than 0.1 mm.
- Hole and grooves must be parallel to the direction of ejection:



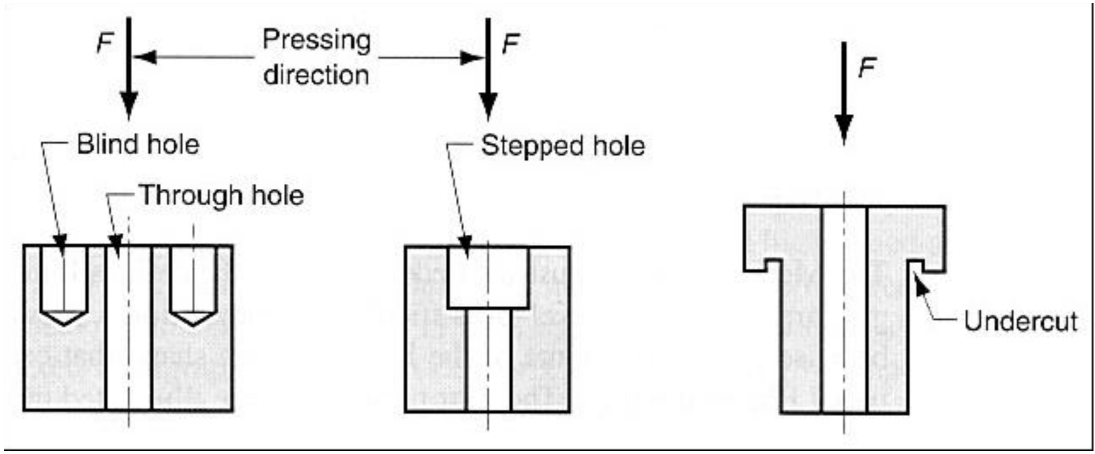


Fig. 1.19 Not recommended Part injection is impossible

Fig. 1.20 Permissible part features in P/M parts

Sharp corners, radii, thin section must be avoided. Minimum wall thickness is 1.5 mm. Corners radii and chamfers are still possible, but certain rules should be observed:

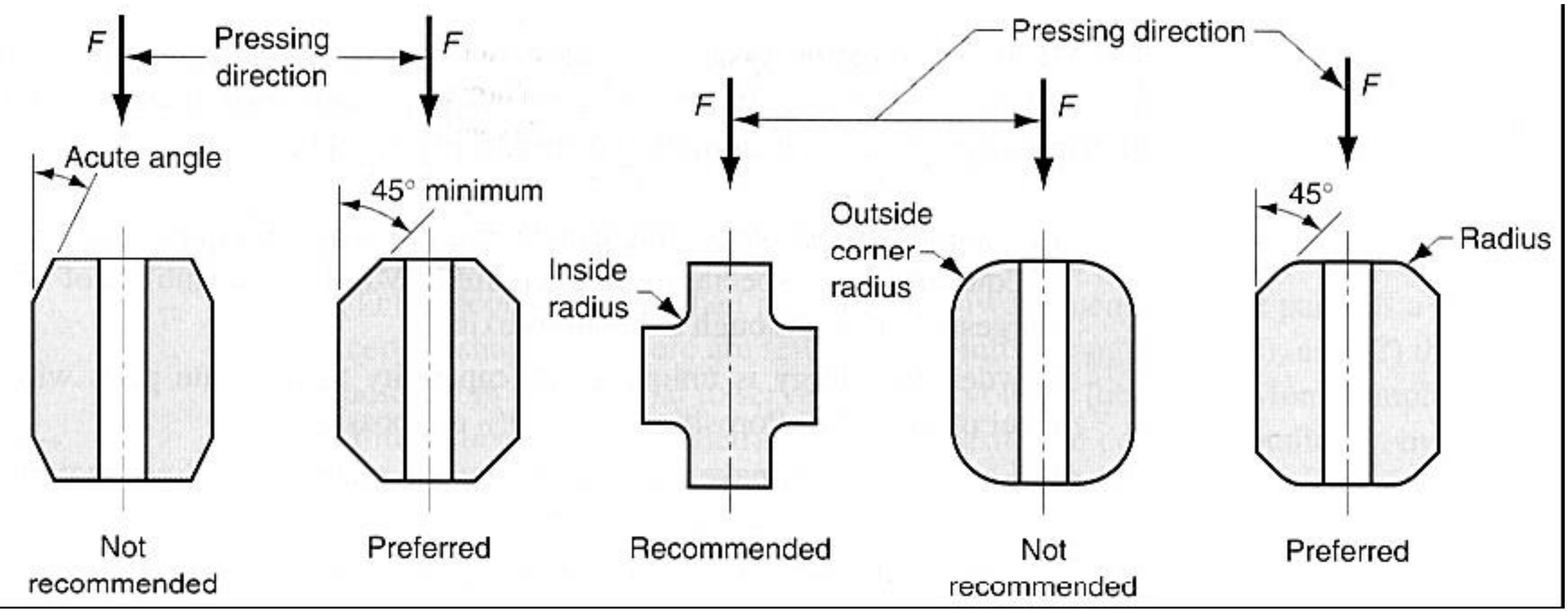


Fig. 1.21 Rules for chamfers and corner radii in P/M parts

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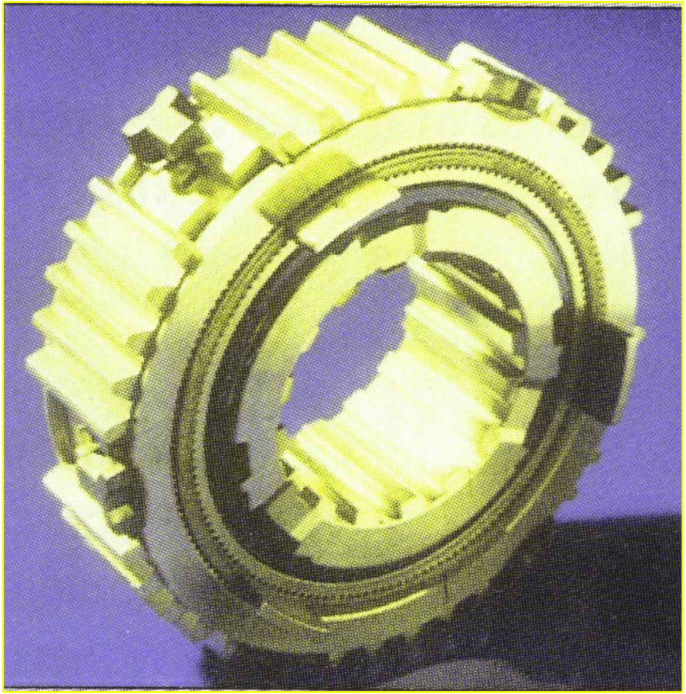
POWDER-BASED MANUFACTURING

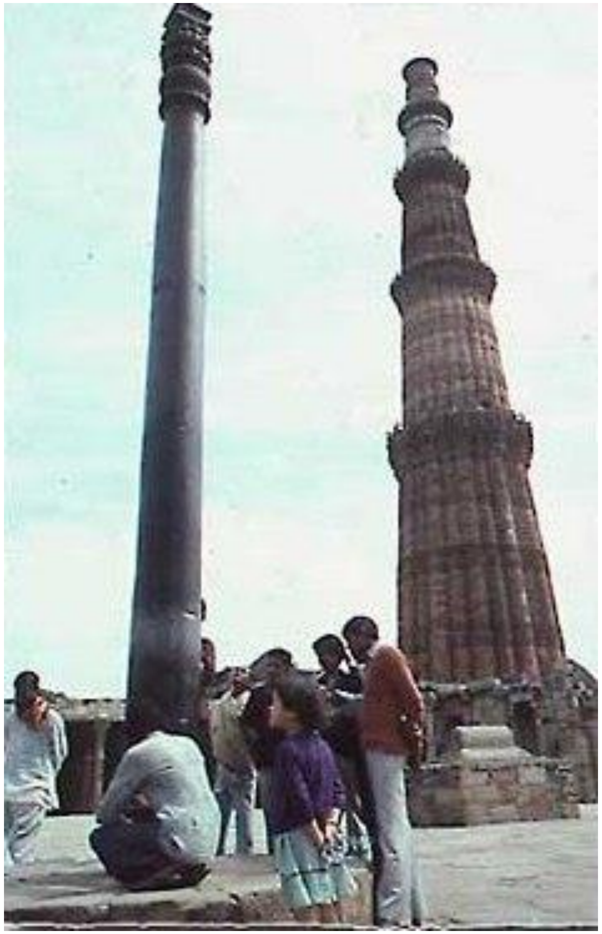


Steel gear produced using Powder Metallurgy
Close dimensional tolerance and high strength and wear resistance

HISTORY

Ancient Egyptians

Silver, copper, lead coins



Delhi Pillar (6.5 tons) erected 300AD in INDIA,

http://www.corrosion-doctors.org/Landmarks/Pillar.htm

The ability to produce net shape engineering components using *powders*

SANDCASTLES

http://www.acclaimstockphotography.com/_gallery/_pages/0027-0407-1609-1023.html

POWDER METALLURGY

- POWDER PRODUCTION
- POWDER CHARACTERIZATION
- POWDER MIXING
- COMPACTION
- HIGH-TEMPERATURE CONSOLIDATION
- FINISHING OPERATIONS

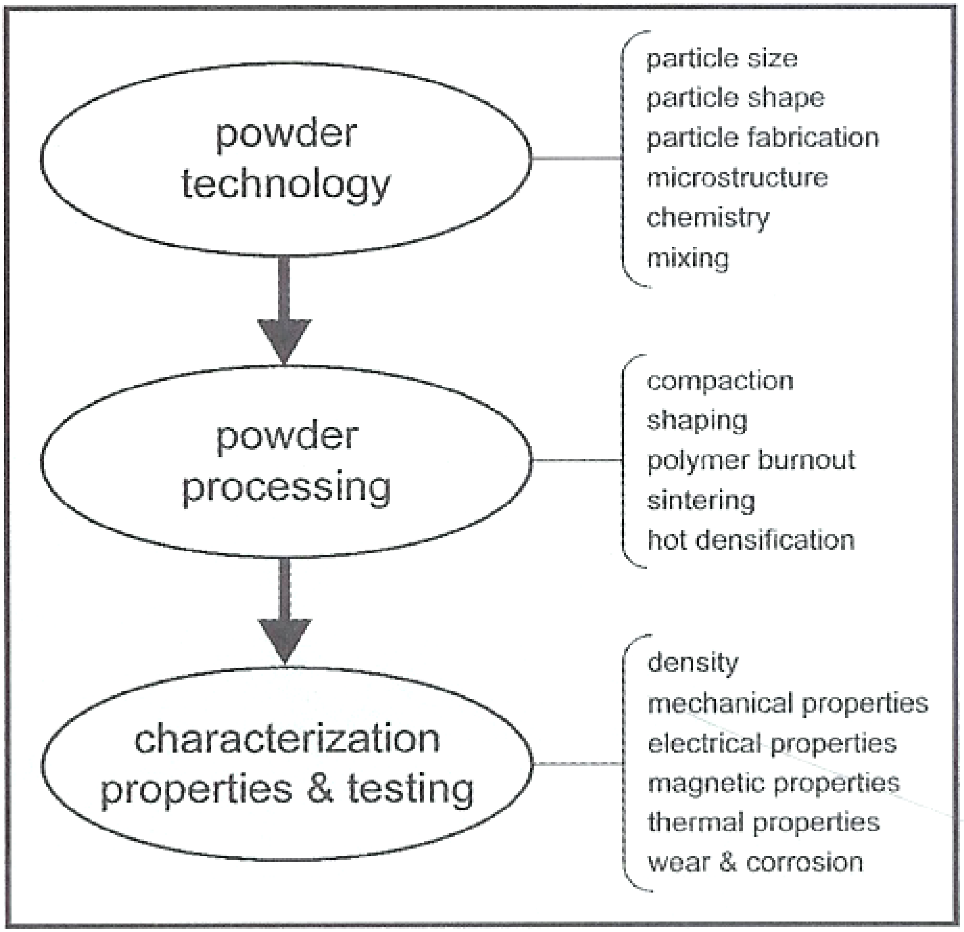


Figure 1.2. *The conceptual flow in P/M² processing from the powder through the consolidation steps to the final product. Example concerns are given for each of the three main steps.*

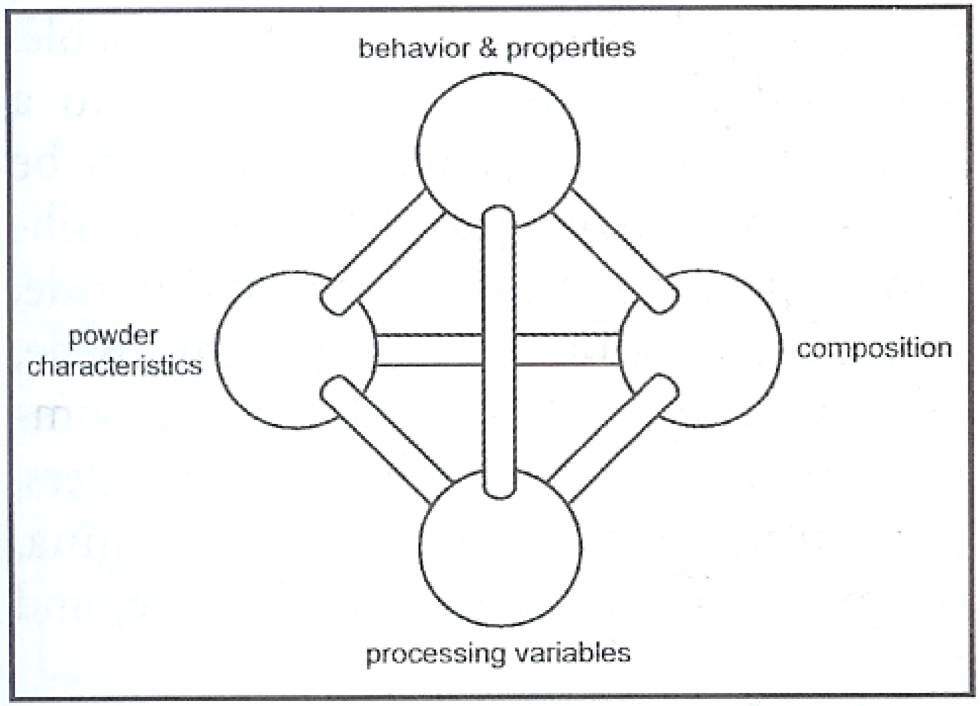


Figure 1.3. A tetrahedron illustrating the interdependence between several aspects of P/M², including the composition, powder characteristics, processing variables, and final product performance.

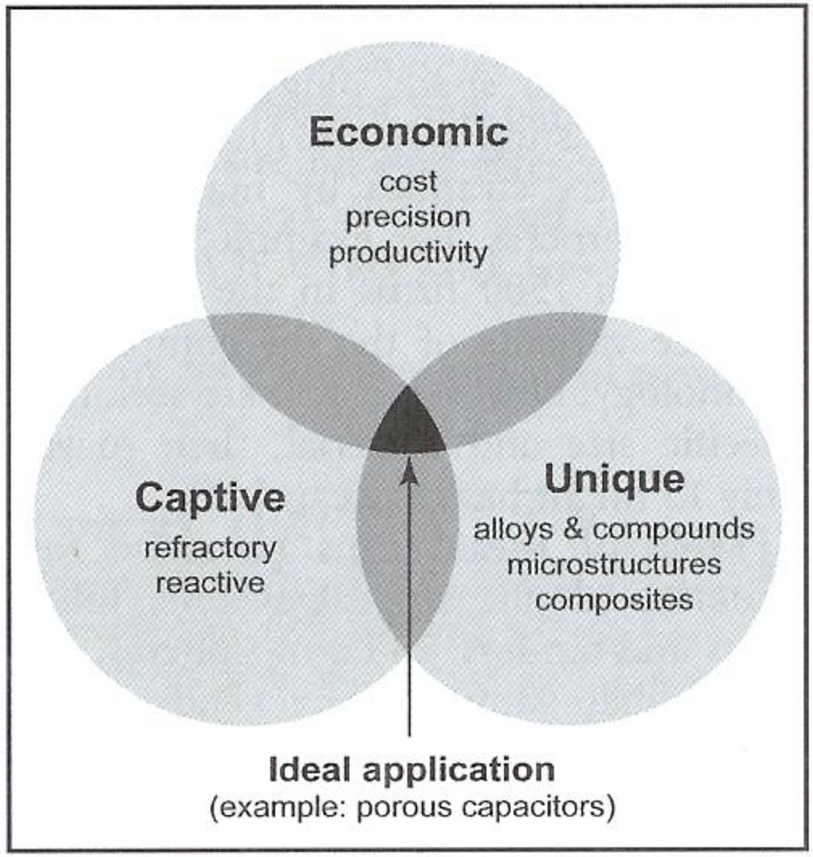


Figure 1.5. *The three main reasons for using powder techniques are shown in the form of a Venn diagram. The intersection of the circles represents an ideal area for applying P/M² techniques, such as for the fabrication of electronic capacitors.*

TABLE 16.1. Some Market Statistics Relevant to P/M[2]

Consumption of some important powders (in thousands of metric tons per year)

advanced ceramics	800
alumina	10,000
aluminum	100
bauxite	100,000
calcium carbonate	46,000
cobalt	39
copper	42
iron and steel	7,300
iron oxide	300
metal-matrix composites	5
molybdenum	4
nickel	25
nickel-base superalloys	10
silica	100,000
stainless steel	9
tantalum	1
tin	3
tungsten	50
tungsten carbide	20
zirconia	20

Production of some important P/M[2] products

700 million floor and wall tiles are fabricated globally each year
more than 500 billion capacitors are fabricated globally each year
sintered electronic ceramics amounts to $5.7 billion per year in the USA
sintered structural ceramics amounts to $515 million per year in the USA
refractory bricks and shapes amount to $2.4 billion per year in the USA
magnets and ferrite cores amount to $150 million per year in the USA
technical ceramic powders amount to $1 billion in sales per year in the USA
metal powder fabrication amounts to $1.7 billion in sales per year in the USA
thermal management materials is $3.3 billion in sales per year globally
metal matrix composites is $1.6 billion per year globally
sintered structural metal parts is $5 billion globally
sintered tungsten carbide components is $11 billion globally

APPLICATIONS

application	example uses
abrasives	metal polishing wheels, grinding media
agriculture	seed coatings, lawn and garden equipment
aerospace	jet engines, heat shields, rocket nozzles
automotive	valve inserts, bushings, gears, connecting rods
chemicals	colorants, filters, catalysts
coatings	paint, hard facings, thermal spray barriers
construction	asphalt roofing, caulking
electrical	contacts, wire clamps, brazes, connectors
electronic	heat sinks, inks, microelectronic packages
hardware	locks, wrenches, cutting tools
heat treating	furnaces, thermocouples, conveyor trays
industrial	sound adsorption, cutting tools, diamond bonds
joining	solders, electrodes, weld filler
lubrication	greases, abradable seals
magnetic	relays, magnets, cores
manufacturing	dies, tools, bearings, hardfacing
medical/dental	hip implants, amalgams, forceps
metallurgical	metal recovery, alloying
nuclear	shielding, filters, reflectors
office equipment	copiers, cams, gears, photocopy process carrier
ordnance	fuses, ammunition, penetrators
personal	vitamins, cosmetics, soaps, ballpoint pens
petrochemical	catalysts, drilling bits
plastics	tools, dies, fillers, cements, wear surfaces
printing	inks, coatings, laminates
pyrotechnics	explosives, flares, fuel, colorants

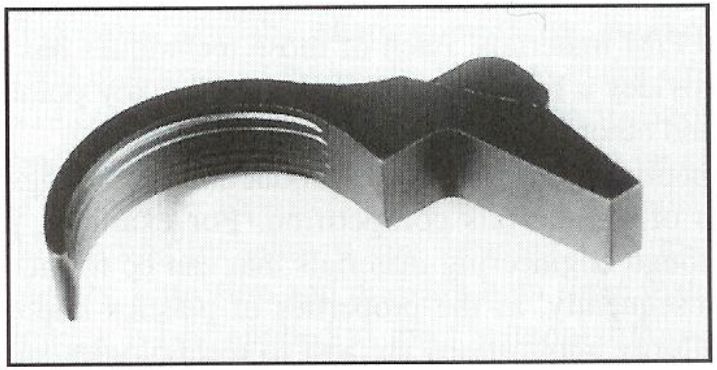


Figure 11.1. A photograph of a steel trigger used on a sporting firearm. The trigger was pressed from water atomized iron powder and subjected to repressing after sintering (photo courtesy of L. Baum).

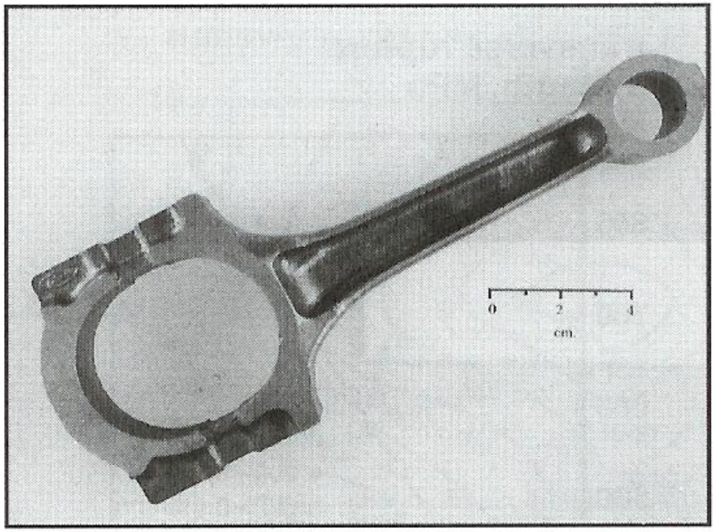


Figure 11.5. A photograph of a hot forged P/M automotive connecting rod manufactured from a Fe-2Cu-0.8C alloy (component courtesy of Exotic Metals and photo courtesy L. Emerson).

Porous Application

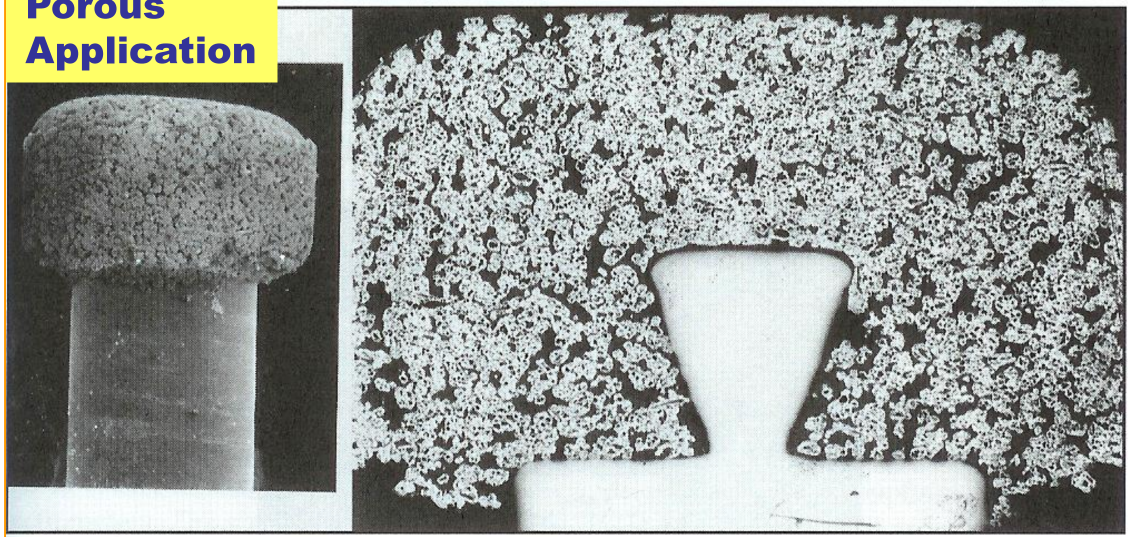


Figure 11.6. Two photographs of a heart pacemaker electrode. The left shows the porous platinum P/M tip and the right is a metallographic cross-section (photos courtesy of B. H. Rabin).

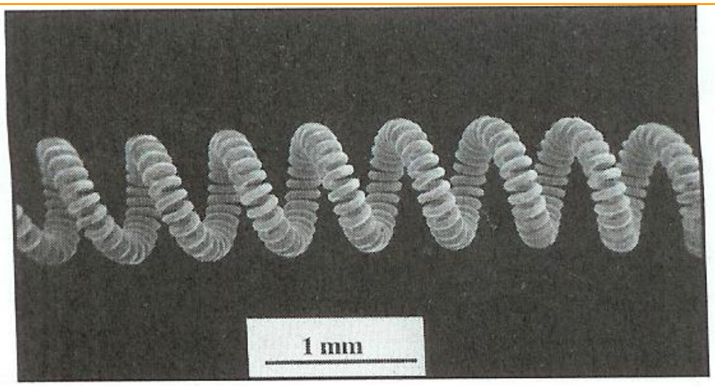


Figure 11.7. A tungsten lamp filament, for which the original material was made by P/M techniques. The filament is one of the oldest uses for the P/M process (photo courtesy of R. Iacocca).

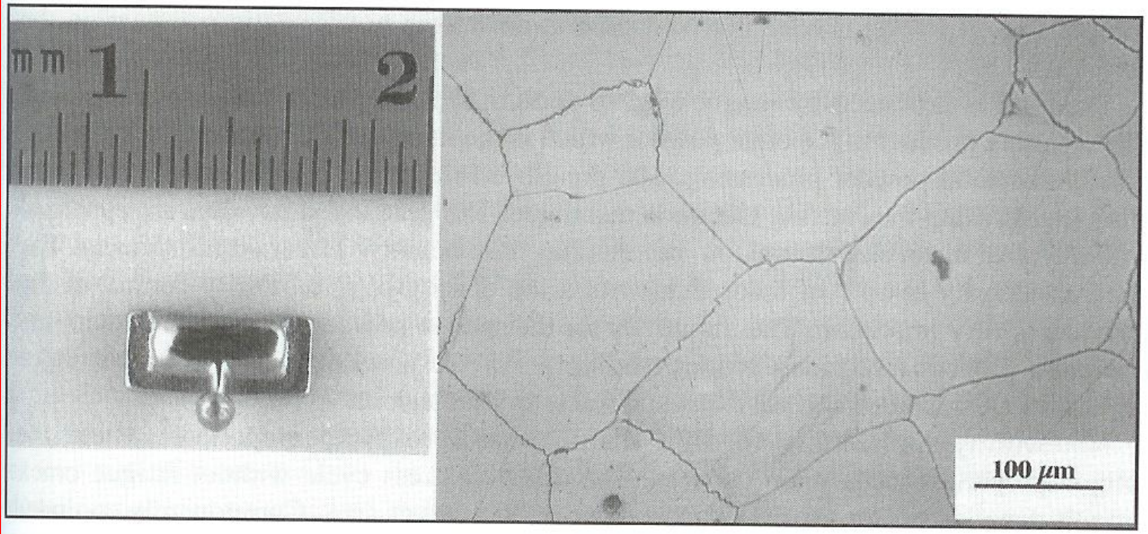


Figure 11.12. The left picture shows an orthodontic bracket made by powder injection molding a small stainless steel powder which is subsequently sintered to nearly full density as evident in the microstructure shown on the right (photo courtesy of C. M. Kipphut).

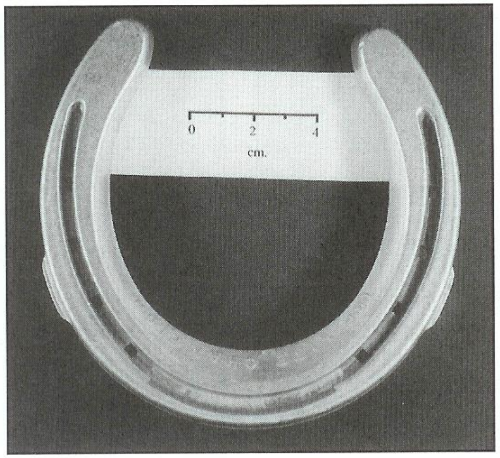


Figure 11.15. An endurance racing horseshoe made from an aluminum alloy containing 20 vol.% SiC. The horseshoe was hot formed from a billet which was made by cold isostatic compaction of mixed powders that were subsequently vacuum sintered (component courtesy of T. Haynes and photo courtesy of L. Emerson).

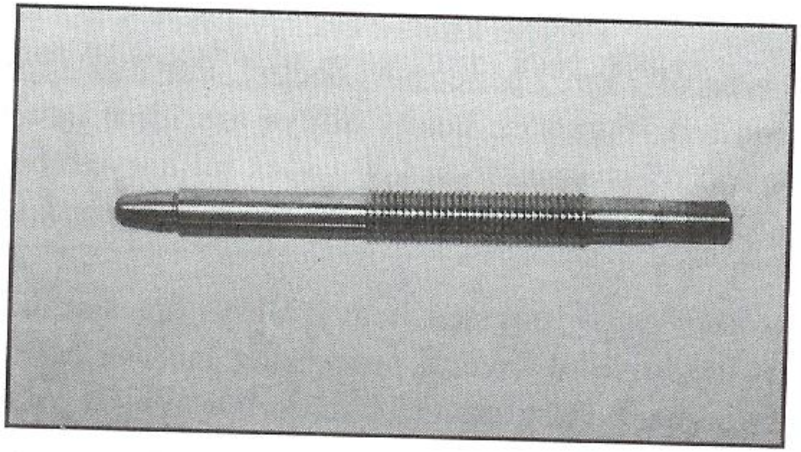


Figure 11.18. A photograph of a long rod kinetic energy penetrator designed to defeat armor. The penetrator was manufactured from a liquid phase sintered tungsten heavy alloy with post-sintering swaging to increase strength (photo courtesy of S. Caldwell).

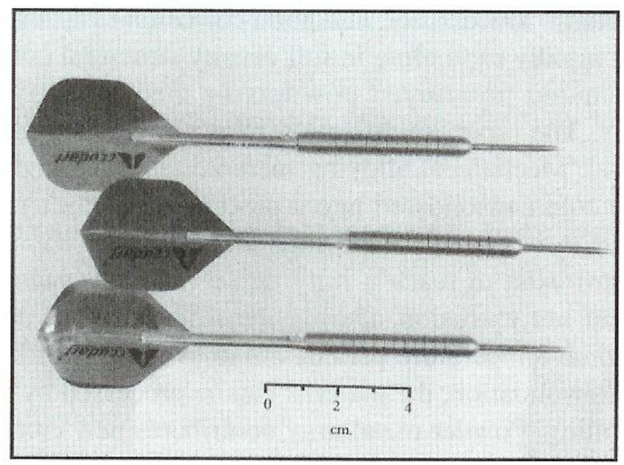
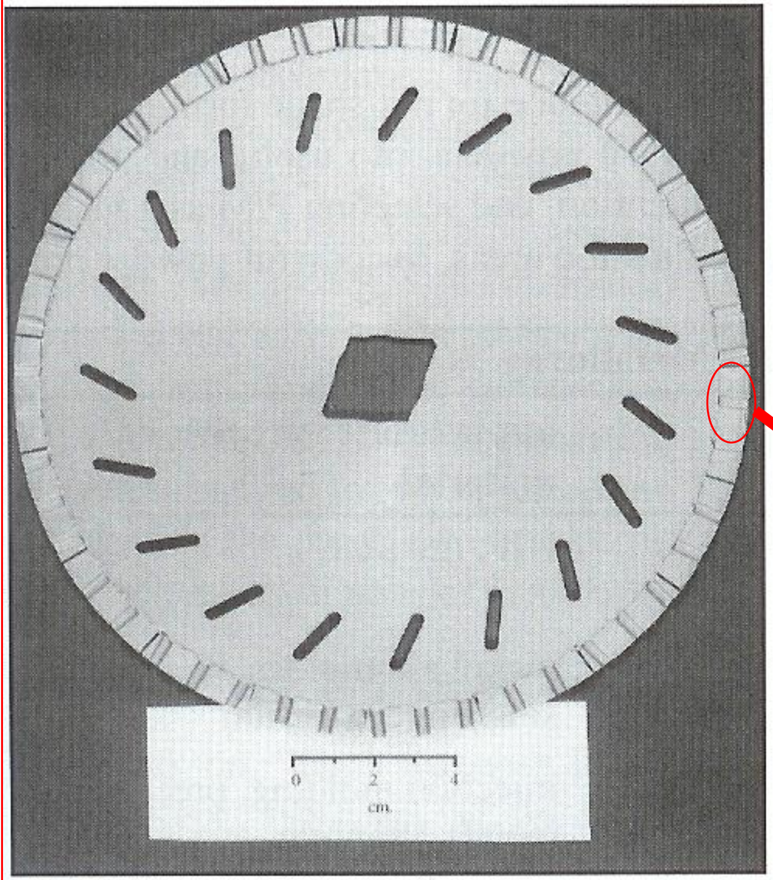


Figure 11.19. A picture of the body of high performance darts in which strategic balancing is achieved with a tungsten heavy alloy shank, formed by liquid phase sintering (component courtesy of R. Kurtz and photo courtesy of L. Emerson).



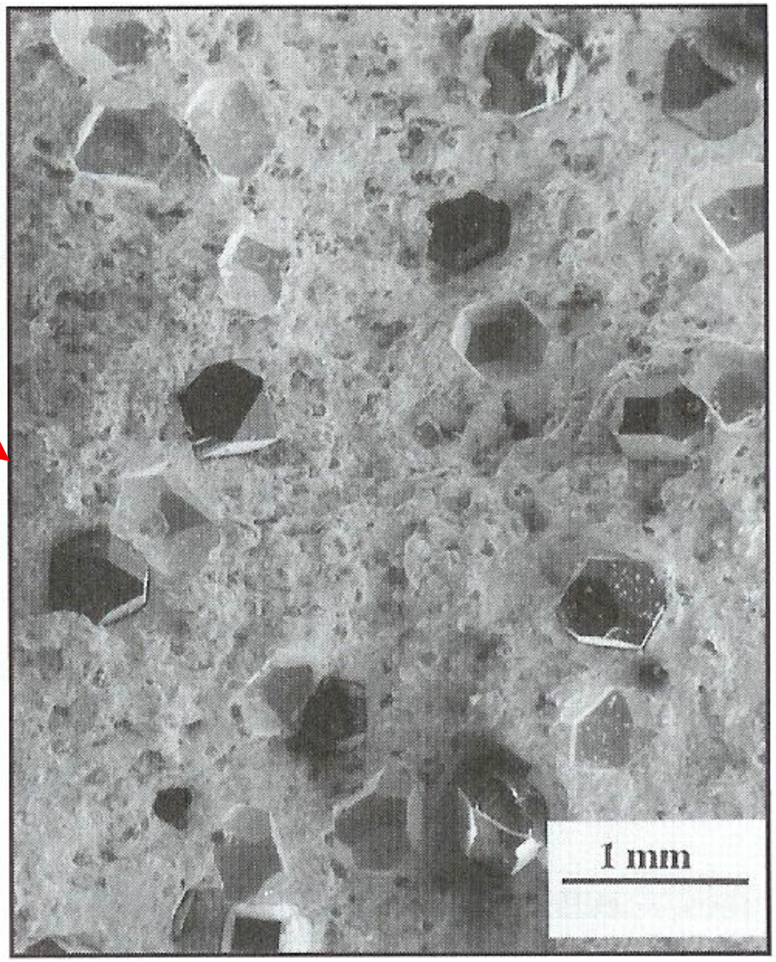


Figure 11.24. A diamond impregnated saw blade fabricated by hot pressing mixed cobalt powder and diamonds. Such a blade is used to cut masonry and brick materials. The micrograph on the right shows a fracture surface of the cutting tip with the polygonal diamonds imbedded in the fractured cobalt matrix (photos courtesy of R. Iacocca and L. Emerson).

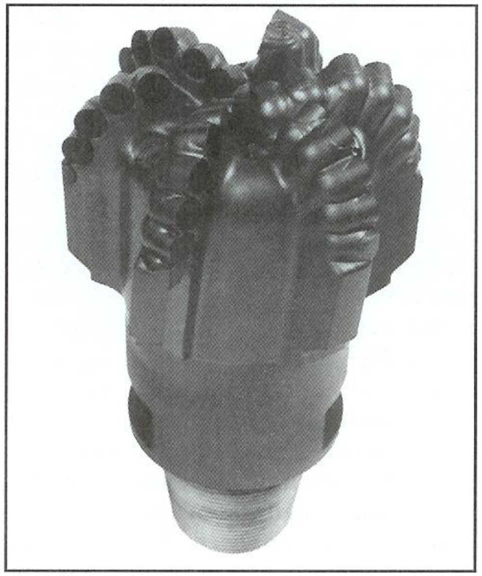


Figure 16.13. An example of a high performance cutting tool used for oil and gas exploration. This 222 mm (8.75 in) diameter body is formed from WC and infiltrated prior to the addition of the polycrystalline diamond cutters, which are diamond sinter bonded to WC-Co substrates. This heavy P/M^2 product has only a few pieces buried in the body that are not produced from powders (photograph courtesy of Anthony Griffo).

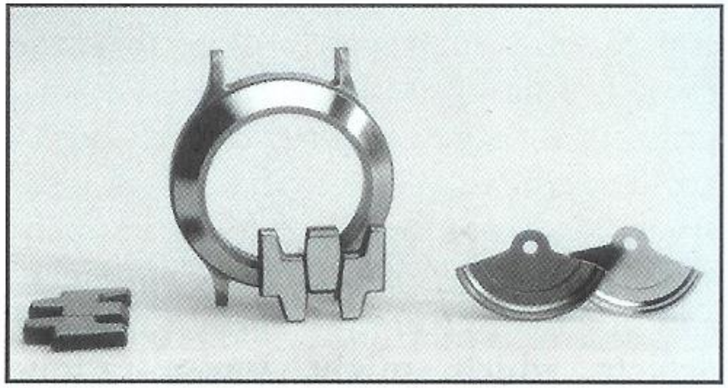


Figure 16.11. Watch band links, case and winding weights made using P/M^2 (photograph courtesy of Kay Leong Lim).

THE END