JOMO KENYATTA UNIVERSITY OF AGRICULTURE AND TECHNOLOGY

EMT 2540 Advanced Production Technology

Lecture Notes Compiled By: Ms Maurine N. Andanje

Students are reminded not to treat these lecture notes as a comprehensive and solely sufficient material for their studies since the purpose of the notes is not meant to be a substitute for regularly attending classes, reading relevant textbooks and recommended books. The notes are aimed at providing a quick reference and a brief guidance for the students.

May, 2021

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Course description

1. Powder metallurgy: Metal powders, pressing, sintering, pre-sintering, sizing and finishing. Properties of powder metallurgy products. Design of metal powder parts. Advantages and disadvantages of powder metallurgy.

2. Specialized machining processes: Electrochemical, electrodischarge, electrobeam, laser, chemical, ultrasonic, abrasive jet, plasma arc.

3. Welding and fabrication techniques: Forging, gas flame welding, resistance welding, other welding processes. Torch and arc cutting. Heat and design considerations in welding.

4. Jigs and fixtures.

5. Decorative and protective surface treatment.

6. Mass production tools and techniques; machining centers.

7. Practical exercises in powder metallurgy and specialized machining processes. Recent advances in production technology.

Course Textbooks

1. DeGarmo E.P. and Black J.T. (1996) Materials and Processes in Manufacturing, Wiley, John and Sons, Inc.

2. Larry J, Harold V.J, (2002) Welding: Principles and Application, Delmar Publishers, Inc.

References

1. Chapman W. A. J. (1986) Workshop Technology - Part 3, Arnold International, Students Ed.

2. Hindustani Machine Tools (HMT), (1980) Production Technology Tata McGraw-Hill Pub. Co, Bangalore India

3. International Journal of Production Research.

Mode of Examination: Continuous assessment and written University examination shall contribute 30% and 70%, respectively of the total marks.

Chapter 1

Powder Metallurgy

Powder metallurgy is the name given to the process by which fine powdered materials are blended, pressed into a desired shape (compacted), and then heated (sintered) in a controlled atmosphere to bond the contacting surfaces of the particles and establish desired properties. This process is one of the four major methods of shaping metals (machining, hot and cold plastic deformation, casting, and powder metallurgy). The process, commonly designated as P/M, readily lends itself to the mass production of small, intricate parts of high precision, often eliminating the need for additional machining or finishing. There is little material waste, unusual materials or mixtures can be utilized, and controlled degrees of porosity or permeability can be produced. Major areas of application tend to be those for which the P/M process has strong economical advantage or where the desired properties and characteristics would be difficult to obtain by any other method. Because of its level of manufacturing maturity, powder metallurgy should actually be considered as a possible means of manufacture for any part where the geometry and production quantity are appropriate.

Parts manufactured by the P/M process have found widespread applications in the automotive industry, household appliances, recreational equipment, hand and power tools, hardware items, office equipment, industrial motors, and hydraulics. Areas of rapid growth include aerospace applications, advanced composites, electronic components, magnetic materials, metalworking tools, and a variety of biomedical and dental applications.

1.1 The Basic Process

The powder metallurgy process generally consists of the following basic steps:

(a) Powder manufacture

(b) Mixing or blending

(c) Compacting

(d) Presintering

(e) Sintering

(f) Hot Pressing

(g) Secondary operations

Compaction is generally performed at room temperature, and the elevated-temperature process of sintering is usually conducted at atmospheric pressure. Optional secondary processing often follows to obtain special properties or enhanced precision. Figure 1.1.1 presents a simplified block diagram of the conventional die-compaction P/M process.

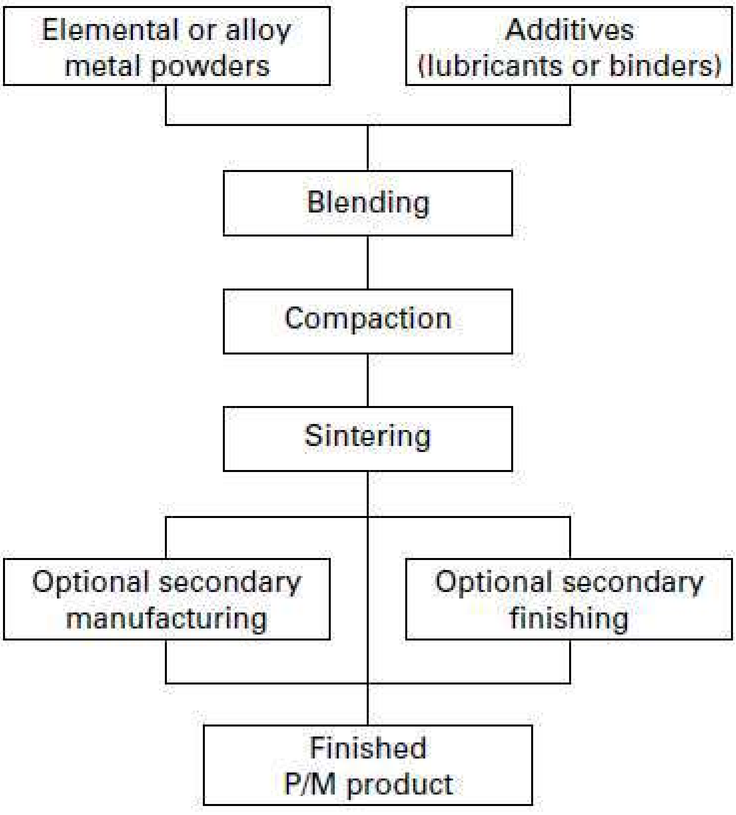

Figure 1.1.1: The basic powder metallurgy process

1.2 Powder Manufacture

A number of different metals and their alloys are used in P/M (e.g., iron, alloy steel, stainless steel, copper, tin, lead). The properties of powder metallurgy products are highly dependent on the characteristics of the starting powders. Some important properties and characteristics include *chemistry and purity, particle size, size distribution, particle shape, and the surface texture* of the particles. Several processes can be used to produce powdered material, with each imparting distinct properties and characteristics to the powder and hence to the final product. The particle size of the metal powder should be in the range of 10 to 100 microns. The three most important methods of producing metal powders are:

(a) atomization

(b) chemical methods

(c) electrolytic processes

1.2.1 Atomization

Over 80% of all commercial powder is produced by some form of melt *atomization*, where liquid material is fragmented into small droplets that cool and solidify into particles.

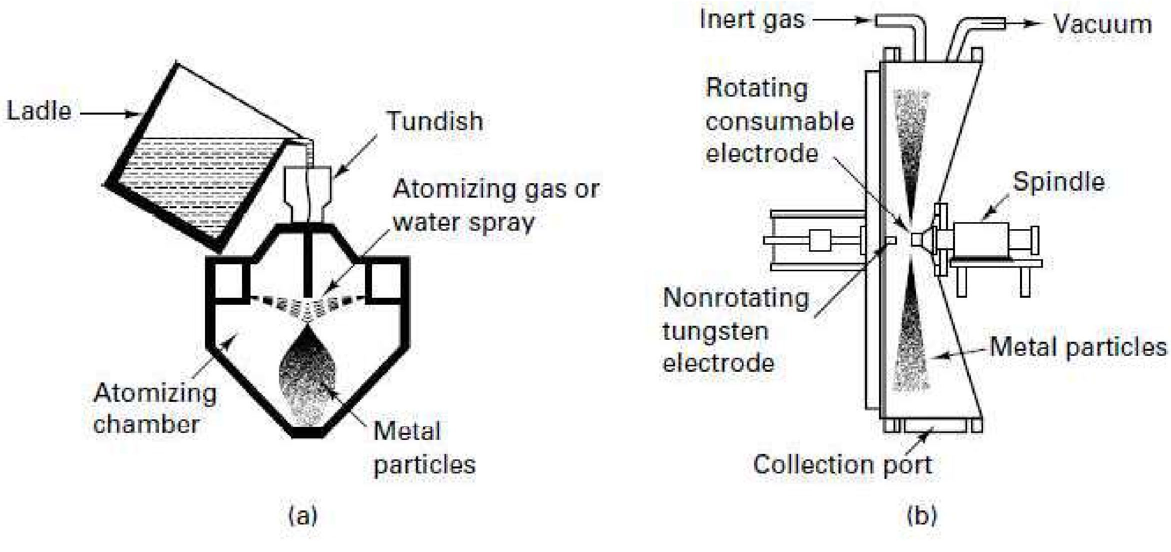

Figure 1.2.1: (a) melt atomization (b) atomization from a rotating consumable electrode.

Figure 1.2.1 illustrates two methods for producing metal powders: melt atomization and atomization from a rotating consumable electrode. Part (a) illustrates *gas atomization*, where jets of high-pressure gas (usually nitrogen, argon, or helium) strike a stream of liquid metal as it emerges from an orifice. Pressurized liquid (usually water) can replace the pressurized gas, converting the process to *liquid atomization* or *water atomization*. In part (b), an electric arc impinges on a rapidly rotating electrode. Centrifugal force causes the molten droplets to fly from the surface of the electrode and freeze in flight. Particle size is very uniform and can be varied by changing the speed of rotation.

Oxidation of the metal powder can be prevented by maintaining an inert atmosphere. This method is generally used for metals with low melting points such as: Zn, Pb, Sn, Al and Mg.

1.2.2 Chemical Methods

Chemical methods such as reduction, decomposition and condensation are used to produce metal powders.

a. **Reduction**

Chemical reduction is a process in which metal powders are formed by chemical reaction between metal oxides and reducing agents (e.g., hydrogen or carbon monoxide). Hydrogen or carbon monoxide reacts with oxygen in the metal oxide, producing pure metal. This method is used for metals with high melting points

Example: W, Mo powders are prepared by this method.

Tungsten powder is produced by the reduction of WO_3

$WO_3 + 3\ H_3 \rightarrow W + 3\ H_2O$

b. **Decomposition**

This method is specially used to produce metals from carbonyls. In this process, the gaseous metal carbonyls are decomposed thermally to get the corresponding metals. The powder so produced is spherical:

Example: Carbonyls of Ni & Fe i.e. $Ni(CO)_4$, $Fe(CO)_5$

$Ni(CO)_4 \rightarrow Ni + 4CO$

c. **Condensation**

In this process, a metal rod is vapourised by heating it to very high temperatures and the vapours are condensed.

Example:

Zn, Mg, Cd powders can be prepared by this method.

1.2.3 Electrolytic Process

The *electrolytic process* that is utilized to precipitate metal powders begins in the electrolytic cell where the source of desired metal is the anode. As the anode is dissolved, the desired metal is deposited on the cathode. After this step is complete, the metal deposit is removed from the cathode and is washed and dried.

Other methods of powder manufacture include:

- *Pulverization* or *grinding* of brittle materials (comminution).
- *Precipitation from solution.*
- *Shooting*

1.2.4 Mechanical Pulverization (or) Comminution

Mechanical pulverization is done using a mechanical pulverizer such as counter rotating blades or rapidly moving hammers. Due to the mechanical forces, it disintegrates the metal particles into fine powder. Pulverization is usually followed by ball milling. Brittle metals and alloys can be powdered by this method to a size of 0.001mm. Example of powders that can be produced by this method are: Mg, Zn, Pb.

In each process, the powders may be ground further to a desired fineness, usually in a ball mill. Metal powders are screened, and larger particles are returned for further crushing or grinding. The powders are classified according to particle size and shape in addition to other considerations such as chemical composition, impurity, density, and metallurgical condition of the grains. Particle diameters range from about 0.002 in. to less than 0.000 1 in. Test sieves are used to determine particle size. This method of testing has been standardized throughout the industry.

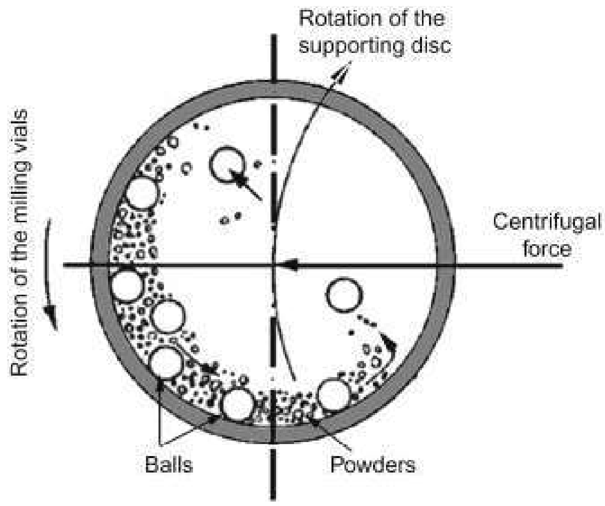

Figure 1.2.2: Ball milling process

Powders are often blended by tumbling or mixing. Lubricants (e.g., graphite) are added to improve flowability of material during feeding and pressing cycles. Deflocculants are also added to inhibit clumping and to improve powder flow during feeding.

1.3 Mixing and Blending

Mixing and blending of metal powders in desired proportions is done in order to get uniform and very good results especially when an alloy is to be manufactured. Lubricants and volatilizing agents are also added to give a desired amount of porosity and lubricity. The time of mixing may vary from a few minutes to several days depending upon the results desired. Overmixing should be avoided in many cases, since it may decrease particle size and work-harden the particles.

1.4 Powder Compaction

Powder compaction is the process of converting loose powder into the desired shape. Most compacting is done by cold pressing, but there are some specific applications, for which compacts are not pressed. The main purpose of compacting process is the forming of metal powders into compacts of desired shapes with sufficient strength to withstand ejection from the tools and handling it without breakage and damage.

1.4.1 Classification of compacting

Various methods of powder compaction are grouped into two types:

1. **Pressure shaping techniques**

   Pressure shaping techniques involves conversion of metal powder into desired article under pressure before sintering. It includes:

   i. Die compaction

   ii. Isostatic pressing

   iii. Powder extrusion

   iv. Powder forging

   v. High energy rate forming

   vi. Vibratory compaction

   vii. Continuous compaction

2. **Pressure-less shaping techniques** Pressure-less shaping techniques are those in which metal powder is converted into desired article without applying any external pressure. This technique includes:

   i. Slip casting

   ii. Gravity compaction

   iii. Continuous pressureless compaction

i. **Die compaction**

   About Die

   Dies are usually made of ground, hardened steels. The dies consists of two parts lower punch and upper punch. The lower punch is provided with shaping hole, in which metal powder is introduced.

   Process

   The metal powder is introduced into the cavity of the die. Required pressure is given by movement of upper and lower punches towards each other. After that, the green compact is ejected from the lower punch, see Figure 1.4.1. The pressures commonly employed range from 19 - 50 tons / sq. inch. It may be obtained by either mechanical or hydraulic presses.

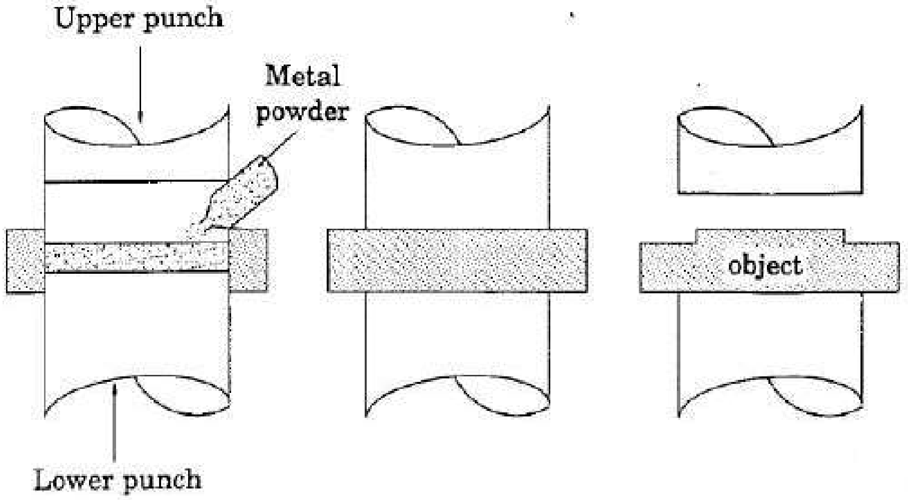

Figure 1.4.1: Shaping Dye

a. **Mechanical presses**

Mechanical presses are available with pressure ratings of 10 - 50 tons and speeds of 6 - 150 strokes/min. The important features of which are high speed production rates, flexibility in design, simplicity, economy in operation, relatively low investment and maintenance costs.

b. **Hydraulic presses**

Hydraulic presses are available with ratings upto 5,000 tons, but slower stroke speeds generally less than 20 strokes/min. These presses are used for higher pressure, more complicated metal parts.

ii. **Isostatic Pressing** Isostatic pressing is the consolidation of powdered metal contained in a tightly sealed flexible mould. The mould is then kept into shaped bodies in which a uniform pressure is applied simultaneously and equally in all directions thereby achieving uniform density and strength.

a. **Hydrostatic Pressing** If the pressure transmitting medium is liquid such as water, water-soluble oil mixture, glycerine or various hydraulic oils, the process is referred to as "hydrostatic pressing".

b. **Isostatic Pressing** If the pressing media used are gases, powders, rubber or plastics, the process is referred to as "isostatic pressing".

Process of Isostatic Pressing

The powder is loaded in a shaped flexible mould (rubber) for the production of the desired shape and tightly sealed against leakage. The flexible mould is then placed in a pressure chamber where pressure is applied. The component shape is determined by the flexible mould and density is controlled by the amount of pressure used in the process.

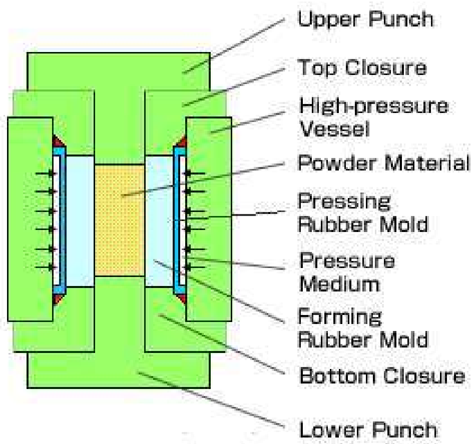

Figure 1.4.2: Isostatic pressing layout

The pressure required is generated either by a high pressure pump or by direct compression. Pressure is then released and the article is taken out from the pressure chamber after opening it. Figure 1.4.2 shows a layout of the isostatic pressing.

iii. **Powder Forging**

Forging is the working or forming of powder metal into a required shape by pressing.

Classification of forging process

Forging process can be classified into two types:

a. Hot forging or Hot working

b. Cold forging or Cold working

a **Hot forging**

If the temperature of the metal is increased to a certain degree in a protective atmosphere, new refined (recrystallised) grains are formed. The process of formation of these new refined grains is called recrystallisation. The temperature at which this process is completed is called recrystallisation temperature. The mechanical working of metal powder above the recrystallisation temperature is called "hot forging". After hot forging, the component is withdrawn from the die and is either quenched or cooled in protective atmosphere to minimise oxidation.

b **Cold forging**

The mechanical working of metal powders below the recrystallisation temperature is called "cold forging".

Example: Powder extrusion

iv. **Powder Extrusion**

The process consists of extruding the mixture of powder and materials at high pressures through the appropriate die. It is recommended to use pre-pressed mixture in order to attain the desired density. The extruded parts are then sintered.

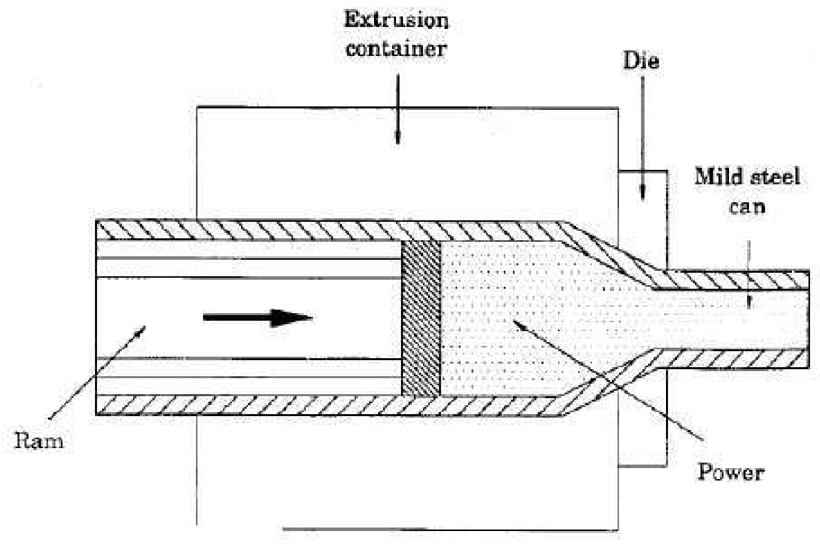

Figure 1.4.3: Powder extrusion

Figure 1.4.3 shows the operation of the powder extrusion process where the powder is placed in some kind of metal container. The sealed container is heated or evacuated and then extruded. After extrusion, the container material is then removed either mechanically or chemically.

v. **High-energy rate forming**

In this method, considerable work has been done on compacting parts using mechanical, explosive, spark-discharge and other high energy processes in order to produce high density parts. The machines used for the production of high energy parts are: Dynapak machine and Petro-forge machine.

vi. **Vibratory compaction**

Vibratory compaction involves the application of pressure and vibration simultaneously during pressing of a mass of powder within a rigid die. This method greatly enhances densification due to intensive mixing of particles and change in adjustment of their shapes. Both high frequency low-amplitude and low-frequency high-amplitude vibrations have been successfully applied for achieving the maximum densification.

vii. **Continuous compaction**

This method is applied primarily for simple shapes like rod, sheet, tube and plate. Roll compacting or powder rolling is the commonly used continuous compaction. Most of the commercial techniques involves flowing loose powder between a set of vertically oriented rolls as shown in Figure 1.4.4. In powder rolling, the rolls are set side by side so that the strip emerges vertically downwards as shown in Figure 1.4.4. When the channel rollers rotate, the powder is drawn into the gap between the rolls and is pressed into a strip. The continuous feeding of the powder produces the strip of infinite length. The strip is then sintered for a short time.

Pressure-less shaping techniques

i. **Slip casting**

Slip casting is commonly use for the production of ceramic articles, but only to a limited extent for metals. The slip for casting is first prepared by suspending a metal powder (finer than 5μ) in a liquid vehicle (suspending medium) and a small amount of suspension agent and binders. The slip is then placed in a mould which is made of fluid-absorbing material (like plaster of paris) to form the slip casting.

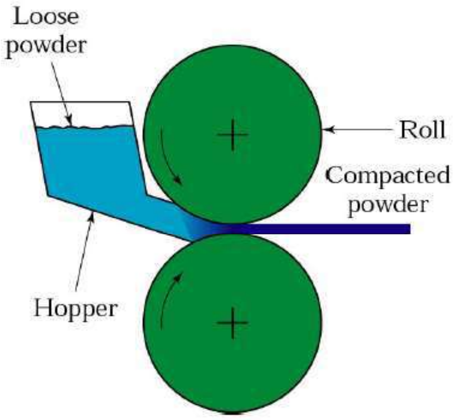

Figure 1.4.4: Roll compacting or powder rolling

The slip casting is then removed from the mould, dried and then sintered.

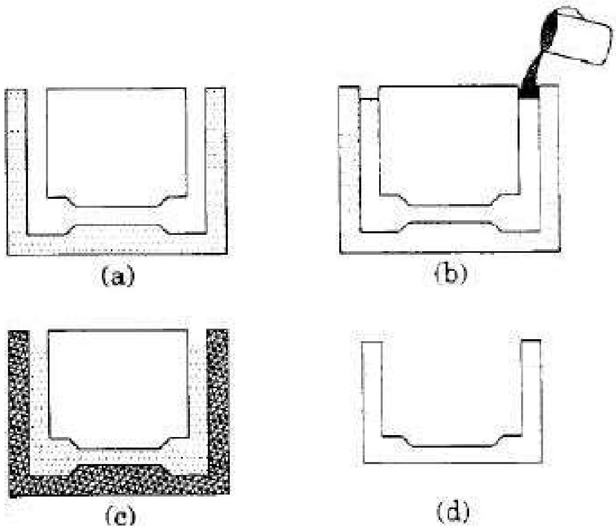

Figure 1.4.5: Principles of slip casting. (a.) Assembled mould (b.) Filling the mould (c.) Absorbing water from the slip (d.) Finished piece, removed from the mould and then trimmed

Figure 1.4.5 illustrates the principle stages of this method.

ii. **Gravity compaction**

The die is filled with loose powder and then heated to sintering temperature. The die is usually made of an inert material like graphite. Since pressure is not used during compacting, the parts produced are generally more porous. Commercially, this method is used for the production of P/M filters.

iii. **Continuous pressureless compaction**

In this process, the metal powder may be applied in the form of a slurry (similar to the slip in slip casting) to be coated on a metal screen or solid metal sheet for electrodes in nickel-cadmium rechargable batteries.

1.5 Sintering

Sintering is defined as the heating of loose or compact aggregate of metal powders below the melting point of the base metal with or without the application of external pressure in order to transform it to a more dense material by inter particle bonding. Sintering process is concerned with:

i. the diffusion of particle to particle

ii. the formation of grain boundary, and

iii. the closing of voids present in the green briquettes

In general density, mechanical strength, ductility, electrical and thermal conductivity increases with increased amount of sintering.

1.5.1 Types of sintering

Sintering is done in two different methods:

i. Solid phase sintering

ii. Liquid phase sintering

1. Solid phase sintering

This is the most widely used method. The sintering temperature is usually 60 - 80 % of the melting temperature of the lowest melting point constituent. Sintering is generally carried out in a controlled atmosphere furnace or occasionally in a vacuum furnace to prevent or reduce surface oxidation. A dry hydrogen atmosphere is used in the sintering of refractory carbides and electrical contacts. Nitrogen and methan are also used. The increased strength developed in the powder compact during sintering is due to the disappearance of the individual particle boundaries through solid state diffusion and recrystallisation. The rate of diffusion depends on:

i. The size of the particle

ii. The percentage of each metal present

iii. The temperature

The sintering process may increase rapidly above the recrystallisation temperature with an increase in strength and density ordinarily. The density of the compact is increased by sintering and shrinkage will occur. Shrinkage is associated with increase in areas of contact of the particle and reduction of the size of holes in the compact. Slow heating or degassing can be used to minimise problems associated with expansion.

2. Liquid phase sintering

Liquid phase sintering is carried out at a temperature at which a liquid phase exists. The sintering temperature may be above the melting point of one of the alloy constituents or above the melting point of an alloy formed during sintering. In the former case, liquid exists during the entire sintering operation, but in the latter case liquid is initially formed but disappears prior to completion of sintering. The density, strength and other properties of sintered compacts are dependent upon a number of factors like compacting pressure, sintering temperature and time.

Advantages of LPS

i. It produces very good density, because all the pores are filled by the liquid due to liquid-solid interfacial tensions.

ii. The rate of diffusion through the liquid phase and therefore the rate of alloying is greatly increased.

iii. It produces a more desirable metallurgical structure producing excellent mechanical properties.

1.6 Hot Pressing

In this method, the powder is placed into a die pressure and temperature is applied simultaneously. Moulding and sintering takes place at the same time, resulting into higher densities and greater productions.

Advantage

The advantage of hot pressing as compared with cold compacting and sintering are a reduction in gas content and shrinkage effects, along with higher strength, density, hardness and elongation.

Disadvantages

i. Hot pressing cannot be used for the production of very hard cemented-carbide parts.

ii. High cost of dies to withstand pressure at elevated temperatures.

1.7 Secondary Operations / Finishing

Powder metallurgy products are often ready to use when they emerge from the sintering furnace. Many P/M products, however, utilize one or more secondary operations to provide enhanced precision, improved properties, or special characteristics. Some finishing operations include:

(i) Sizing

(ii) Coining

(iii) Infiltration

(iv) Impregnation

(v) Heat treatment

1.7.1 Sizing

Sizing, which is a post-sintering operation, is used to correct size, distortion and other dimensional defects and improves surface finish and wear properties of the sized surface without producing large deformation and an appreciable increase in density. This is carried out by forcing the sintered components in a die of smaller dimensions, which plastically deforms and smoothens the faces in contact with the die.

1.7.2 Coining

The coining operation is carried out after sintering, produces the same results as the sizing operation and in addition, it improves density, hardness and strength and decreases the elongation of the part.

1.7.3 Infiltration

It involves preparing a porous metallic body or skeleton metal with high melting point and subsequently filling the pore of the skeleton with a molten metal (infiltrant) having lower melting point. In practice, this is done by immersing the porous skeleton metal in the molten infiltrant metal.

1.7.4 Impregnation

It is a process of completely filling or closing the voids and interconnected porosities in a P/M component. This is done for a variety of purposes such as lubrication, pressure tightness, plating, protection against corrosion.

1.7.5 Heat treatment

It involves heating and cooling a solid metal in such a way as to obtain desired conditions or properties like increased toughness, hardness, fatigue, strength, wear resistance. Heat treatment processes include carburizing and nitriding.

1.8 Applications of Powder Metallurgy

- Porous product (any degree of porosity can be provided. Eg filters flow regulators and bearing parts).
- Bearings for automobiles eg engine main bearing.
- Oil pump gears
- Cemented carbides (for cutting tools, wire drawing dies & deep drawing dies)
- Refractory metal composites. (jet engine nose cone crucible etc.)
- Diamond impregnated tools (e.g. glass cutter grinding wheel dressers etc.)
- Electrical contact materials (e.g. circuit breakers, resistance-welding electrodes, contact switches, carbon bushes etc.)
- Magnetic materials (e.g. pole piece of generators, motors transformer cores, computer memories hard discs etc.)

- Tungsten filaments used in incandescence bulbs.

1.9 Advantages of Powder Metallurgy

Like all other manufacturing processes, powder metallurgy has distinct advantages and disadvantages that should be considered if the technique is to be employed economically and successfully. Among the important advantages are these:

1. *Elimination or reduction of machining.* The dimensional accuracy and surface finish of P/M products are such that subsequent machining operations can be totally eliminated for many applications. If unusual dimensional accuracy is required, simple coining or sizing operations can often give accuracies equivalent to those of most production machining. Reduced machining is especially attractive for difficult-to-machine materials.

2. *High production rates.* All steps in the P/M process are simple and readily automated. Labour requirements are low, and product uniformity and reproducibility are among the highest in manufacturing.

3. *Complex shapes* can be produced such as combination gears, cams, and internal keys. It is often possible to produce parts by powder metallurgy that cannot be economically machined or cast.

4. *Wide variations in compositions are possible.* Parts of very high purity can be produced. Metals and ceramics can be intimately mixed. Immiscible materials can be combined, and solubility limits can be exceeded. Compositions are available that are virtually impossible with any other process. In most cases the chemical homogeneity of the product exceeds that of all competing techniques.

5. *Wide variations in properties are available.* Products can range from low-density parts with controlled permeability to high-density parts with properties that equal or exceed those of equivalent wrought counterparts. Damping of noise and vibration can be tailored into a P/M product. Magnetic properties, wear properties, friction characteristics, and others can all be designed to match the needs of a specific application.

6. *Scrap is eliminated or reduced.* Powder metallurgy is the only common manufacturing process in which no material is wasted. In casting, machining, and press forming, the scrap can often exceed 50% of the starting material. This is particularly important where expensive materials are involved, and powder metallurgy may make it possible to use more costly materials without increasing the overall cost of the product. An example of such a product would be the rare earth magnets.

1.10 Disadvantages of Powder Metallurgy

1. *Inferior strength properties.* Because of the residual porosity, powder metallurgy parts generally have mechanical properties that are inferior to wrought or cast products of the same material. Their use may be limited when high stresses are involved. The required strength and fracture resistance, however, can often be obtained by using different materials or by employing alternate or secondary processing techniques that are unique to powder metallurgy.

2. *Relatively high tooling cost.* Because of the high pressures and severe abrasion involved in the process, the P/M dies must be made of expensive materials and be relatively massive. Because of the need for part-specific tooling, production quantities of less than 10,000 identical parts are normally not practical.

3. *High material cost.* On a unit weight basis, powdered metals are considerably more expensive than wrought or cast stock. However, the absence of scrap and the elimination of machining can often offset the higher cost of the starting material. In addition, powder metallurgy is usually employed for rather small parts where the material cost per part is not very great.

4. *Size and shape limitations.* The powder metallurgy process is simply not feasible for many shapes. Parts must be able to be ejected from the die. The thickness/diameter (or thickness/width) ratio is limited. Thin vertical sections are difficult, and the overall size must be within the capacity of available presses.

5. *Dimensions change during sintering.* While the actual amount depends on a variety of factors, including as-pressed density, sintering temperature, and sintering time, dimensional change can often be predicted and controlled.

6. *Density variations produce property variations.* Any non-uniform product density that is produced during compacting generally results in property variations throughout the part. For some products, these variations may be unacceptable.

7. *Health and safety hazards.* Many metals, such as aluminium, titanium, magnesium, and iron, are pyrophoric they can ignite or explode when in particle form with large surface/volume ratios. Fine particles can also remain airborne for long times and can be inhaled by workers. To minimize the health and safety hazards, the handling of metal powders frequently requires the use of inert atmospheres, dry boxes, and hoods, as well as special cleanliness of the working environment