



## **Powder Metallurgy**

Powder metallurgy has been defined as the art and science of producing fine metal powder (i.e. raw materials) and objects finished or semi-finished-shaped from individual, mixed or alloyed metal powders with or without the inclusion of non- metallic constituent. It is that branch of metal working process, which in its simplest form, consists of preparing and mixing of metal powders, compacting and simultaneous or subsequent heating, (or sintering) at elevated temperature in a furnace under a protective atmosphere (non- oxidizing atmosphere or vacuum) with or without fusion of a low melting-point constituent only so as to develop metallic or metal-like bodies with satisfactory strength, density and without losing the essential shape imported during compacting.

## **Modern Development**

Numerous developments of powder metallurgy techniques took place during the closing years of World War II and were applied to the production of electric contact materials consisting of tungsten as a hard refractory metal by the impregnation of porous part with oil, termed as self lubricating bearings, metal filters; copper graphite brushes for electric motors and dynamos; powdered iron cores for electric circuits; and lastly small component for various types of machinery.

Several methods of powder compaction such as continuous rolling, slip casting, hot pressing, etc were developed but the oldest and simplest method of die compaction is still of high repute and remains unchallenged. The presses which were originally in the range of a few tens of tons have increased their capacity to thousands of tons today and the trend is now for

an ever increasing size of powder metallurgy parts. The mechanical properties of sintered steels have increased from 15-20 Kg/ mm<sup>2</sup> tensile strength and low elongation value to over 50 Kg/mm<sup>2</sup> as tensile strength and a considerable elongation.

Larger sizes of sintering furnaces with increasing productivity have been developed and the use of indirect sintering of large tungsten and molybdenum ingots is now made possible. The use of vacuum sintering furnaces for certain applications is another outstanding development.

## **Manufacture of Gears**

The manufacture of gear made of steel casting by the conventional method of casting and machining consists of:

1. Casting the steel into blanks
2. Drilling the holes
3. Turning to internal and external diameter
4. Machining the keyway, teeth, and finishing

The main shortcomings of this method are high labour consumption, considerable loss of metal in the form of chips, and relatively low strength of teeth due to cutting of metal.

The manufacture of gear by powder metallurgy method consists of:

1. Reduction of iron oxide
2. Milling of the reduced metal
3. Compacting
4. Sintering

Very accurate and precision machining of teeth or any other part of the gear, this result in considerable reduction of:

1. Labour consumption
2. The amount of equipment
3. Production time
4. The number of workers
5. Total manufacturing cost

Metal powder gears make less noise than solid and milled gears and due to self-lubricating properties its wear resistance and also a number of special properties are improved which enhance their operational qualities.

## **Advantages**

The powder metallurgy process has certain basic advantages over conventional melting and casting method of producing metals, alloys and finished articles. These advantages include:

1. Freedom to start with raw materials of high purity having characteristics of consistent uniformity
2. Maintaining this purity to the end use by the control of fabricating steps
3. Economy, greater accuracy,(i.e. closed dimensional tolerance in the finished part) and smooth surfaces
4. Cleaner and quieter operations and longer life
5. Lack of void, gas pockets, porosity or blow- holes, stringering of segregated particles and various inclusions common in castings
6. Control of grain size and relatively much uniform structure
7. Excellent reproducibility
8. Improved physical properties
9. Ability to offer complex shapes
10. Elimination of numerous machinery operations during finishing in the production of finished parts

11. Possibility of producing new materials, composition of metals and non-metals which are quite impossible to prepare by normal methods
12. Greater freedom of design in the case of production of machined part
13. No requirement of highly qualified or skilled personnel

## **Limitations**

Powder metallurgy has some serious drawbacks as given below which limit its application in narrow field:

1. It is difficult to secure exceptionally high purity powder with satisfactory quality, without which it is impossible to prepare the parts with optimum physical properties. Also, it is highly expensive to prepare such powders
2. It is unprofitable to manufacture articles in very small quantities because of the great expense of suitable tooling and equipment (for example, dies, punches, presses, sintering equipment) and high cost of powders.
3. Difficulties are experienced in obtaining alloy powders such as of steel, brass, bronze, etc, because of the non-availability of simpler methods.
4. Porous materials are liable to oxidize at the surface as well as throughout the whole body due to its porosity
5. P/M parts possess comparatively poor plastic properties (impact strength, plasticity, elongation, etc.) which limit their use in many applications.
6. High investment is needed in heavy presses for making large parts
7. There are also shape and size limitations of the article produced by P/M technique due to

- Absence of plastic flow in powder under pressure
- Friction of powder on the sides of die barrel and punch
- Mechanical limitations of dies and tools

## **Applications**

The importance of P/M in the development of modern technology is so much that the P/M part is said to be ubiquitous

- 1. Refractory Metals:** Component made of tungsten, molybdenum and tantalum by powder metallurgy are widely used in the electric light bulbs, fluorescent lamps, radio valves, oscillator valves, mercury arc rectifiers and x-ray tubes in the form of filament, cathode, anode, screen and control grids.
- 2. Refractory carbides:** Refractory carbide made by P/M has caused a major breakthrough in modern industries dealing with machine construction (for example, various parts of lathes, curve, drilling and threaded guides, etc)
- 3. Automotive Applications:** In the developed countries, it is the motor industry which relies heaviest upon powder metallurgical components.( for example, in USA motor uses 100P/M parts per 1000 while the UK motor industry uses 48 P/M parts per 1000)
- 4. Aerospace Applications:** Metal powders are playing an important role in rocket, missiles, satellites and space vehicles.
- 5. Atomic Energy Applications:** P/M has played a significant role in the development of nuclear power reactors. Composite materials are applied in various fuel elements and control rod systems (for example, the distribution of uranium oxide throughout the stainless steel matrix).



## **Characteristics and Testing of powders**

The processes of manufacturing P/M articles economically depend largely on the physical and chemical characteristics of the initial metal powders. The characteristics of metal powders depend upon the method used in producing these metal powders. There are various methods of manufacturing metal powders and consequently there is a wide range in their characteristics. A choice regarding the suitability of manufacturing techniques of metal powders can be made only after considering the required finished product for a specific job.

The main purpose of powder testing is to ensure that the powder is suitable for subsequent processing. A sample of metal powder is always selected for the determination of its characteristics and control of these characteristics is necessary for maintaining the (required) uniformity in different powder lots.

The basic characteristics of a metal powder are:

1. Chemical composition and purity
2. Particle size and its distribution
3. Particle shape
4. Particle porosity
5. Particle microstructure

The other characteristics which are dependent entirely or to a large extent on the above primary properties of metal powders:

1. Specific surface
2. Apparent density
3. Tap density

4. Flow rate
5. Compacting
6. Sintering

Primary properties such as the particle size distribution and the important secondary properties such as apparent density and flow rate are most widely used in specification and control routine.

Other properties such as permeability regarding liquids and gases, magnetic properties, electrical and thermal conductivity, etc. are also of importance for special applications of P/M parts.

## **Sampling**

For carrying out testing of numerous properties of metal powders, samples are required either in bulk as in sieving or in minute quantities as in analysis photo-sedimentation, coulter counter, etc. in all these cases, the samples used must be truly representative of the entire batch; and unless the true sample is obtained, the testing is meaningless.

There are four sampling procedures for metal powders which have been used by technologists:

### **1. Coning and quartering method**

Involves pouring of the original quantity of powder on to a sheet of aluminum with a polished surface in the form of a cone, splitting up into four equal segments with a thin sheet of polished brass and repeating this procedure until a suitable quantity for testing is obtained.

### **2. Chute riffler method**

This method consists of a V- shaped trough with a series of chutes at the bottom, which alternately directs powders to two

receptive trays placed on either side of the trough thereby rendering two identical samples.

### **3. Spinning riffler process**

This method consists of a closed ring of containers spinning under the steady stream of powder feed so that each container collects a series of small portions of the powder as it passes several times beneath the powder feed. This method is highly efficient and should be used whenever possible.

### **4. The scoop sampling**

This method consists in inserting a scoop into a thoroughly mixed powder in a container and withdrawing the scoopful of powder as a sample.

## **Chemical composition**

The chemical composition of powders is the outstanding characteristic. It usually reveals the type and percentage of impurity and determines the particle hardness and compressibility. The term impurity refers to some elements or compounds which has an undesirable effect. Impurities influence not only the mechanical properties of the powder compacts, but also their chemical, electrical and magnetic properties. It may also exert a decisive effect on pressing, sintering, and other post-sintering operation which are essential for the production of finished product from powders.

Insoluble oxides such as alumina, silica in appreciable amounts give rise to serious troubles such as abrasion of die and poor mechanical properties due to non-uniform sintering. The gaseous impurities may improve the sintering under some circumstances while in others it shows

harmful effects. These impurities also affect the density of the green compact because of increasing the side wall friction.

The chemical composition of a powder is determined by the well established standard techniques of chemical analysis. Oxygen content is determined either by wet analysis or by "loss of weight in hydrogen". Some oxides may not be reduced at all or there may be error due to incomplete reduction of oxides. Therefore, it is desirable for both processing and optimum properties of the final product to have low oxygen content.

The effective way to reduce the oxygen content is the annealing of powders by which the hydrogen loss value becomes almost halved. It is not possible to reduce certain oxides such as silica (and silicates), alumina, titania, chromium trioxides, etc. by hydrogen under the conditions of such a test and therefore these must be determined by other methods. Oxides such as silica (and silicates) are insoluble in mineral acids and hence may be determined by dissolving the metal, and filtering, washing, igniting and weighing of the residue.

## **Particle size**

The particle size has a great importance in P/M because it affects most of the properties such as

- mould strength,
- density of compact,
- porosity,
- expulsion of trapped (occluded) gases,
- dimensional stability,
- agglomerations
- Flow and mixing characteristics.

Particle size is expressed by the diameter for spherical shaped particles and by the average diameter for non- spherical particles.

Average diameter is defined in different ways according to the method employed for size distribution.

- When the method involves sizing, the particle size is measured as the opening of a standard screen which just retains or passes the particle.
- When determined by micro count method, the diameter is measured by averaging several dimensions.
- According to the sedimentation method the particle size is defined as the diameter of the spherical particle having the same specific gravity and settling velocity as the non-spherical particle under test.
- The average diameter in the case of large particle size can be determined by counting and weighing as the cube root of the volume.

In practical P/M metal powders are divided into three distinct classes:

1. Sieve
2. Sub-sieve
3. Sub-micron (or ultrafine)

The screen with the opening of finest standard mesh-sieve for production purposes is the 325 mesh screen having the aperture of 44 micron. Sub-sieve particles are smaller than the aperture of such a screen but greater than  $1\mu$ . This class of powder is used for the production of refractory metals, hard carbides and magnetic cores. As the name suggests, the sub-micron powder particle size is smaller than  $1\mu$  and is used for the manufacture of dispersion strengthened high temperature alloy, bearing and micro porous components, magnetic materials, nuclear reactor fuels.

Sieve size powders are used for most ordinary mass production because of their good flow ability and lack of further processing requirement such as granulation.

Majority of metal powders employed in powder metallurgy industry vary in size from 4 to 200 microns. Powders of sub-micron size have been developed and used for the production of many powder metallurgical parts particularly dispersion strengthened materials, etc. Metal powder particle sizes in the range of 0.01 to 1 micron are employed for the production of these alloys but their (powders) use poses many problems. For example, apparent density is very low, flow rate is poor, inter particle friction is high, they agglomerate readily, they tend to be pyrophoric, they oxidize quickly with the atmosphere and difficulty reduce without bonding together and they alter their characteristics during their storage. The advantages include:

- Very fine grain sizes possible in the dispersed phase and the good dispersion itself
- Fine powders sinter easily at lower temperatures and in shorter times than are required by the coarse powders.
- Sintering is invariably accompanied by very high shrinkages which cause the dimensional control of parts more difficult.

## **Particle Size Measurement Technique**

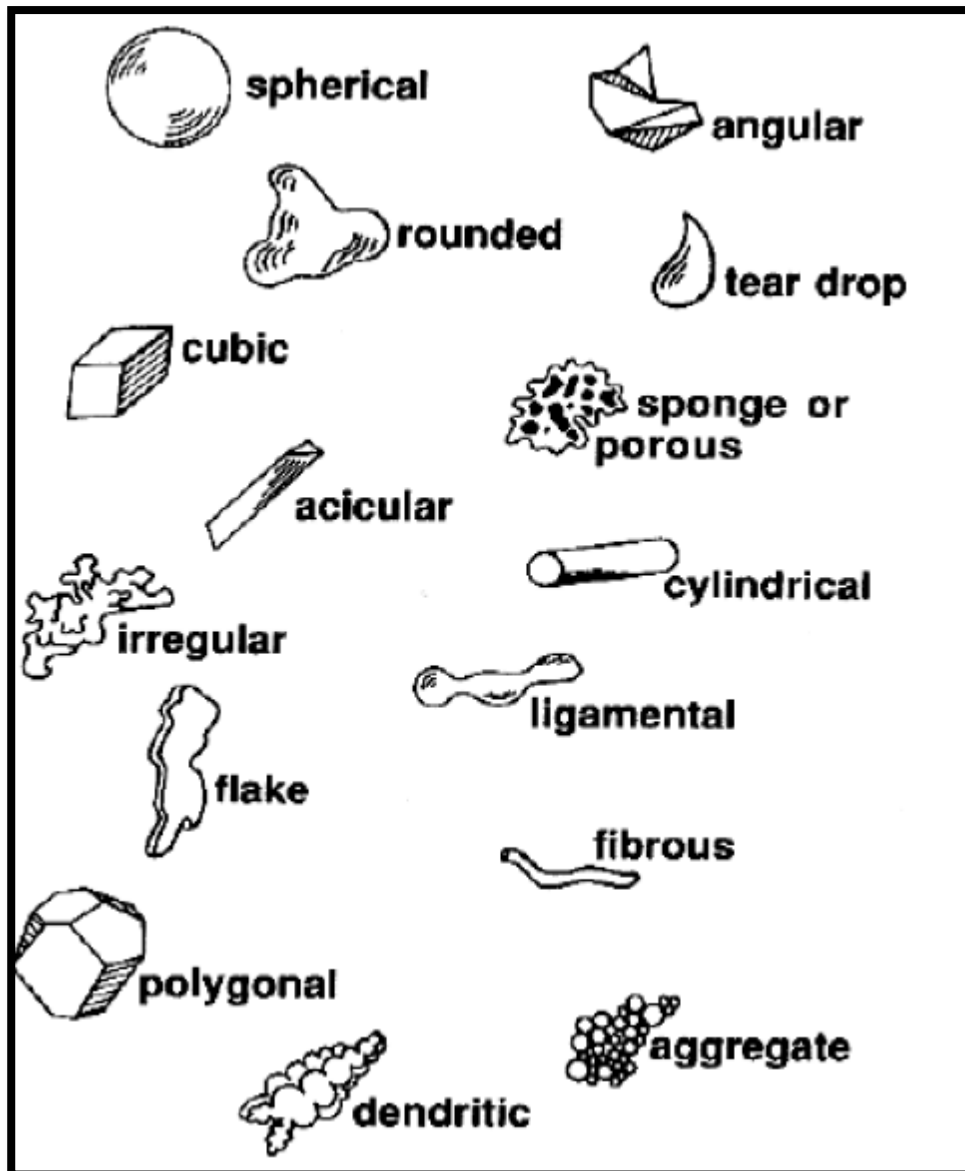
There are numerous techniques of particle size measurement. The more common techniques employed in P/M and their ranges of applicability are given in table below.

Method of Analysis	Approximate useful particle size range (microns)
<b>1. Sieving Analysis</b>	
• Sieving using mechanical shaking	44-840
• Micromesh sieve	5-44
<b>2. Microscopic analysis</b>	
• Light Microscopy	0.1-100
• Electron Microscopy	0.001-10
<b>3. Sedimentation Method</b>	
• Sedimentation and decantation Method	2-50
• Pipette Method	2-50
• Gravitational	1-50
• Turbidimetry	0.05-50
• centrifugal	0.05-10
<b>4. Elutriation Method</b>	
• Elutriation	5-100
• Roller Air Analyzer	5-40
<b>5. Permeability Method</b>	
• Permeability	0.5-100
• Fisher Sub-sieve sizer	0.2-50
<b>6. Adsorption Method</b>	
• Adsorption (gases)	0.002-20
<b>7. Electrolytic Resistivity Method</b>	
• Coulter counter	0.3-300

## **Particle Shape**

There are various shapes of metal powders such as:

1. Spherical (carbonyl iron, condensed zinc, lead, atomization, precipitation from aqueous solution by gases)
2. Rounded or droplets ( atomized copper, zinc, aluminum, tin, chemical decomposition)
3. Angular (mechanically disintegrated Sb, cast iron, stainless steel obtained by intergranular corrosion)
4. Acicular (chemical decomposition)
5. Dendritic ( electrolytic silver, copper, iron powders)
6. Flakes (ball milled copper, aluminum, and stamped metals)
7. Porous (reduction of oxides)
8. Irregular (atomization, reduction, chemical decomposition)
9. Fragmented



Particle shape has a pronounced effect on the packing of a powder and has an influence on its compacting and sintering properties and the mechanical strength of the sintered product thus; **irregularly** shaped particles have reduced apparent density and flow rate, good pressing and sintering properties, while **spherical particles** have maximum apparent density and flow rate but reduced pressing properties and good sintering characteristics. In the same way, **dendritic** powders result in reduced apparent density and poor flow rate.

Optical or electron microscopic examination is the usual and direct method of evaluating the particle shape. It is customary to express it also by shape factor which is the ratio of the length of particle to its breadth or surface area to particle size. Presence of cracks or grain boundaries in the individual particles increases considerably the shape factor.

## **Particle Microstructure**

In general, the metal powder is mixed with Bakelite powder in the proportion of 1:8, mounted in the mounting press, polished with slight pressure at every stage, etched in a suitable etchant, washed with hot water and alcohol and dried in hot air blast and examined under microscope. Another method involves the mixing of a small amount of metal powder in an epoxy- filled metal cylinder which, after the resin hardens, is remounted in a longitudinal direction and the section ground and polished. The metallographic examination of these powders will reveal not only various phases, inclusions, impurities, fissures, and internal porosity, but also the particle size, relative size distribution and particle shape.



## **Specific Surface**

The specific surface of a powder is defined as the total surface area per unit weight ( $\text{cm}^2/\text{gm}$ ). It depends on size, shape, density and surface conditions of the particle.

The compacting and sintering properties are considerably influenced by contact between the metal particles. High specific surface not only results in high sintering rate, but also causes entrapment of air and bridging effects thereby causing the compact to crack rather before or during sintering. Coarser powders with smaller contact areas have an inferior sintering characteristic and, therefore, mechanically weak.

## **Apparent Density**

The apparent density of a powder is defined as the mass per unit volume of loose or unpacked powder. Thus it includes internal pores but excludes external pores. It is governed by chemical composition, particle shape, size, size distribution, method of manufacture of metal powders as well as shape and surface conditions which can vary from 20-50% of the theoretical density.

### Relation between Various Types of Powder and Apparent Density

Types of Powder	Apparent Density
Electrolytic or atomized powders	High
Reduction of oxides or Chemical precipitation	Low
Spherical	Maximum
Dendritic	Reduced
Irregular	Lower
Flake	Very poor
Coarse	Good
Fine	Poor
Uniform sized powder	Lower
Mixed sized Powder	Optimum

The main factor is not the particle size but the particle size distribution for altering the apparent density. Thus the uniform and identical particles occupy a constant fraction of the available space but various sized particles increase the density to an optimum extent. An increase in apparent density is obtained with additions of fine particles and results from the ability of fines to fill the inter particle voids. Because of their more brittle behavior, oxides present on the surface result in the lowering of strength and altering the apparent density of the metal powder.

## **Tap Density**

Tap density (or load factor) is the apparent density of the powder after it has been mechanically shaken down or tapped until the level of the powder no longer falls. It appears to be widely used for storage, packing or transport of commercial powders and also a control test on mixed powder.

## **Flow Rate**

The flow rate is a very important characteristic of powders which measures the ability of a powder to be transferred. It is defined as the rate at which a metal powder will flow under gravity from a container through an orifice both having the specific shape and finish. The powder filling of die must be rapid and uniform without bridge formation for obtaining a rapid rate of production, consistent compacts and economy. On the other hand poor flow properties of the powder result in the slow and uneconomical feeding of the die cavity and the possibility during pressing of uneven filling of the die cavity. It is affected only by particle size, size distribution and shape, but also by absorbed air or gas, moisture, lubricant, coefficient of inter particle friction, etc. in general, fine or dendritic, irregular, coarse and spherical powders have poor, reduced, good and maximum flow rates respectively. Flow rate increases with decreased particle irregularity and increased particle size, specific gravity, and apparent density. It can also be increased by tapping or vibrating.

The standard apparatus, known as **Hall Flowmeter**, is generally used for the determination of flow rate. It consists of a standard and accurately machined conical funnel made of brass with smooth finish having an internal angle of 60°. The orifice situated at the bottom of the funnel is either 1/8" for ferrous powders or 1/10" in diameter for non-ferrous powders. The time required to flow the weighed sample of powder

(usually 50 gm) from the funnel into a cup held at a fixed distance below the orifice is a measure of flow rate, which is expressed in seconds or gm/minute in case a non- standard weight of the sample is employed.

There is such a close relationship between apparent density and flow properties that is very difficult to vary one without altering the other. Flow rate, apparent density, and tap density are essential processing factors since they affect the transporting and pressing of powders.

### **Pressing Properties**

These are represented by the term compressibility and compactibility. Compressibility is one of the most important characteristics of a metal powder since it affects the densification process. It is a measure of the powder's ability to deform under applied pressure and is represented by the pressure/ density (or pressure/ porosity) relationship. It is defined as the ratio of:

- a. The green density of the compact to the apparent density of the powder
- b. The height of the un compacted powder in the die to the height of the pressed compact
- c. The volume of powder poured into the die to the volume of the pressed compact

This ratio is usually termed "compression ratio". The maximum compression ratio is given by the relation:

$$\text{Maximum compression ratio} = \frac{\text{Ultimate (or true) density of bulk material}}{\text{Apparent density}}$$

Though the compression ratio can be varied from about (2 – 8), in most practical applications, it approaches a value of about 3. Higher values of

compression ratio require greater die depths and produce severe complications due to the introduction of friction between the powder and the die walls and internal friction of the powder. Thus a low compression ratio is preferred because of the reduction of:

- i. Die depths
- ii. Breakage and wear of tooling
- iii. Press movement and thereby it is possible to achieve higher production rate.

Compactibility is indicated by the pressure/green strength relationship. Compactability of powder is defined as the minimum pressure required producing a compact of given "green strength"

Both these terms are dependent on particle size, shape, porosity or density and hardness, surface properties, chemical composition and previous history (e.g. hardening, annealing treatment, etc) of the powder.

### **Green Density**

In general, green density has been found to increase with:

- i. Increase of compaction pressure
- ii. Increase of particle size or apparent density
- iii. Decrease of particle hardness and strength
- iv. Decrease of compaction speed

Improvements in green density may also be affected by employing smooth and regularly shaped annealed particles with high particle densities (possessing no internal or interconnected porosity).

Some experimental results illustrating the dependence of green density are given in table:

metal	Particle size	Compaction pressure	Green density
Cu	2 $\mu$	30	6.94
	44-74 $\mu$	30	7.65
Fe	100%-325 mesh	30	6.15
	22%-325 mesh	30	6.54
316 stainless steel	100%-325 mesh	50	6.32
	100%- 325 mesh	50	6.42

### **Green Strength**

The strength of the green compacts is primarily dependent on the consolidation pressure and a rise mainly from cold welding and mechanical interlocking neighboring particles and particle shearing. Particle shape and structure have a great effect upon green strength. Thus, it can be improved by using soft irregular shaped particles with clean surfaces.

### **Green Spring**

Another property of the green compact, associated with the difference between the size of the compact and the tools employed to prepare it, is usually termed green "spring" because the compacts expand both radially and longitudinally on ejection from the tools. During compacting, plastic deformation of the powder particles causes work hardening and an increase in the elastic limit.

As the compact leaves the die, there is elastic recovery of the residual stresses and when it exceeds the green strength of the compact, cracking will occur on ejection. For the manufacture of parts with close

dimensional tolerance, it is necessary to determine the extent of green spring. In general, the green spring upon ejection amounts to 0.2% on the diameter and 0.5% on the length. It depends on the powder material, compacting pressure, elastic recovery of the tools and design of the dies.

## **Properties of the Sintered Compact**

### **1. Dimensional change during sintering**

Dimensional change is always occurring when a green compact is given a sintering operation. It is of special importance in the carbide industry where this change is of the order of 25%. It is determined by taking the measurement of dimensions of a standard specimen before and after sintering under standard conditions. It is customary to express the shrinkage (or growth) as a percentage of sintered length (particularly in the carbide industry).

$$\text{Shrinkage (or growth) \%} = \frac{\text{Change in length}}{\text{Sintered length}} \times 100$$

or it is defined as the percentage of unsintered length

$$\text{Shrinkage (or growth) \%} = \frac{\text{Change in length}}{\text{unsintered length}} \times 100$$

A rectangular specimen or hollow cylindrical specimen is used for performing a test on dimensional directions as this change may differ considerably in the two directions.

### **2. Sintered Density.**

The methods used for determination of sintered density are similar to those which have already been described for the determination of green density. The property facilitates rendering of information on porosity of the finished product. The mechanical properties, in general, increase with the decrease in porosity of the sintered compact.

### **3. Porosity**

The presence of porosity has a much greater influence on the elongation, and impact and fatigue strength and a rapid increase in these values is obtained with the density approaching the theoretical. Porosity acts as a stress raiser and sintered component does not indicate truly elastic behavior, rather it appears to function in a similar manner as graphite in cast iron. It is interesting to note here that the fatigue ratio of sintered alloys and of cast iron is about 0.4, as compared to the values of 0.5, for wrought steel.

It is very difficult to produce P/M parts without any porosity remaining after sintering. The total porosity present in the sintered part may be calculated from the following relationship.

$$P = \frac{P_v}{P_s}$$

Where P is the fractional porosity,  $P_v$  the density of the sintered and  $P_s$  the density of the solid materials.

### **4. Mechanical Properties of Sintered Parts**

It is customary to obtain the required mechanical properties of the finished part by using either one or a combination of the following processes:

- a. Double pressing and sintering
- b. Coining
- c. Infiltration
- d. Alloying
- e. Heat treatment

The radial crushing strength test is widely used particularly in the sintered bearing industry. In this test the specimen is compressed between two flat surfaces in the direction normal to the longitudinal axis of the specimen.

The point at which drop in loading observed because of the first crack determines the crushing which can be expressed by means of the following formula:

$$W = KLT^2 / (D-T)$$

Where W is the radial crushing strength (Ibs), K the strength constant (Ibs/in<sup>2</sup>), L, T and D the length, wall thickness and outside diameter of the cylinder respectively, all expressed in inches. The value of K varies between about 17500 and 40000 Ibs/in<sup>2</sup> depending upon the density and composition of the porous part.



## **Powder Manufacture**

Practically any material can be made into a powder by using one or more of these methods. The particular method chosen depends upon the types of raw materials readily available, the desired properties and structure, type of application, the intended market of the final product, the economics of the whole powder production process and the limitations of the special types of P/ M processes.

### **a. Mechanical Processes**

Powder preparation by mechanical disintegration is widely employed in P/M. this is, however a time-taking process rendering low yields. There are six methods of mechanical combination of metals and alloys, as indicated above. The first three apply to solid materials and are accomplished at room temperature. These powders should be annealed to remove the effect of cold work prior to compacting and sintering. A drawback common all methods of mechanical comminuting of metal and alloys into powders is the extraordinarily low productivity thereby causing expensive powder production. The last three require higher temperature and are carried out by disintegration of liquid metals or alloys.

#### **1. Machining:-**

This method is employed to produce filings, turnings, scratching, chips, etc, which are subsequently pulverized by crushing and milling. Since relatively coarse and bulky powders entirely free from fine particles are obtained by this method, it is particularly suitable in a very few special cases; such as the production of magnesium powders for pyrotechnic

application where the explosiveness and malleability of the powder would prohibit the use of other methods: beryllium powders, silver solders, and dental alloys (containing up to 70 % silver among its constituents). The powder particles produced are of irregular shape. This method is highly expensive and, therefore, has a limited application. This is especially employed where cost is not excessive in relation to the cost of the metals themselves or where the choice of the method is considered a necessity as in the case of Mg.

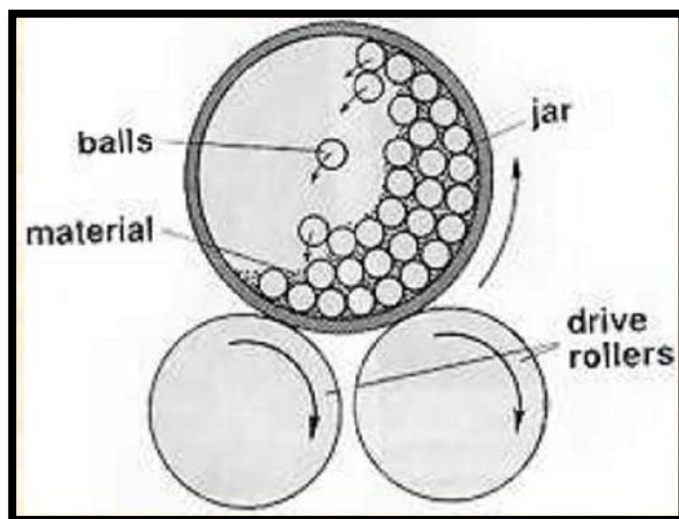
## **2. Crushing**

This method is mostly used for the disintegration of oxides (subsequently reduced to metal powders) and brittle materials. Any type of crushing equipment such as stamps, hammers, jaw crushers or gyratory crushers may be employed for crushing brittle materials. Various ferrous and non-ferrous alloys can be heat treated in order to obtain a sufficiently brittle material which can be easily crushed into powder form. Some metals particularly titanium, zirconium, vanadium, niobium, and tantalum when heated to moderate temperature in hydrogen atmosphere is converted to brittle hydrides. The powders produced by this method are of angular shapes which are subsequently comminuted by milling to attain the required fineness of the powder for processing by P/M technique.

## **3. Milling**

Milling is the most important and widely used method of producing powders of the required grade of fineness. Milling or grinding can be classified as comminution of brittle, friable, tough and hard materials and pulverization of malleable and ductile metals. It involves the application of impact force on the material being comminuted. The milling action is

carried out by the use of a wide variety of equipments such as ball mill, rod mill, impact mill, disk mill, eddy mill, vortex mill, etc.



Schematic diagram of simple ball mill

Figure above shows a schematic diagram of a simple ball mill. In the ball milling method, the material to be disintegrated is tumbled in the a container together with a large number of hard wear resistant solid balls which by hitting the materials, cause them to break down. The ball mills are of two types, rotary mill and vibratory mill. The latter produces equivalent grinding in a very short time as compared with the former type and more efficient grinding action takes place due to vibration with rotary motion. The powder so produced is also less contaminated because of smaller wear on balls and mills. The drums of rotary mills are usually made of stainless steel or steel lined with hard alloy plates. The balls are made of steel or hard alloy. Hard alloy balls contained in a drum lined with hard alloy plate are most frequently used since milling by other means will cause the contamination of the finished powder by iron (greater than 0.5 %) due to wear of the liners and balls. The fact that the

critical speed of rotation of the ball mill should be maintained is very important for the proper milling action of the balls. It should be neither slow nor very high. The milling action will be insignificant due to the movement of the balls only in the lower part of the drum in the former case. The milling action will not be carried out correctly in the latter case because the centrifugal force will result in the clinging of balls to the walls of the drum whereby the required tumbling action will not be achieved. The most intense grinding action is produced at the critical speed of rotation of the drum whereby the balls are lifted up to the top part of the drum and fall down on the material to be ground.

The milling action by **eddy mill** is based on a relatively new grinding principle which grinds through impact of the metal particles against each other. The eddy mill, consisting of two fans mounted at the opposite end of the entirely enclosed casing and rotating in opposite direction produces two high velocities but opposing gas-stream which carry the powder particles thus pulverizing them by collision. During the grinding operation, the metallic particles get heated, hardened and oxidized. In order to prevent oxidation and spontaneous combustion of the powder, the mill casing is furnished with a water jacket and inert or protective gas is continuously forced into the chamber.

The powders produced by this mill are characterized by the saucer-like shape of the particles which is particularly suitable for the manufacture of sintered products. It is useful for

- i. The production of extremely fine and very pure metal powder due to the complete elimination of contamination from either grinding balls or walls of the mill

- ii. Comminuting of malleable metals such as aluminum, iron, copper and final comminution of brittle metals previously disintegrated to coarse particle size by other methods
- iii. Modification of powder particle shape such as flake powder so that it may become suitable for sintering.

Another mill based on a similar principle is known as **Micronizer** in which high velocity (at the pressure of 100-500 Psi) jets of air or superheated steam in a particular direction is injected into the grinding chamber.

Pure powders free from contamination may be produced in **vortex mills** in which the particles of the materials to be ground are fractured by mutual collision. Such a mill consists of two or more very rapidly rotating propellers within a relatively small mill casing and gas flow systems which remove desired size fractions of powder particles. Its advantages include:

- i. Simple mechanism of the mill
- ii. Use of cheaper by product such as machine waste, etc, as the starting raw material
- iii. Suitability for mass as well as small scale production of powders

Milling may be carried out in either dry or wet medium. Wet grinding is widely employed for attaining the specified quality of the product because of acceleration of comminution or reduction of milling time and absence of oxidation in the liquid medium. Distilled water, alcohol, acetone, paraffin, and stearic acid are examples of the liquid media used in wet milling.

The main disadvantages of milling are

- i. work hardening
- ii. excessive oxidation of the final powder
- iii. particle welding and agglomeration

The milling process is widely employed for carbide metal mixture and cermet materials to perform blending and particle size reduction.

#### **4. Shotting**

The method consists essentially in pouring a fine stream of molten metal through a vibrating screen into air or neutral atmosphere. In this way, molten metal stream is disintegrated into a large number of droplets which solidify as spherical particles during its free fall. All metal and alloys can be shotted; the size and character of the resultant shot depending on the temperature of molten metal and gas, diameter of the holes and frequency of vibration in case of vibrating screen. One drawback of this process is the formation of high oxide content which can be minimized with the use of inert gas.

The metal powders occasionally produced by this method for preliminary breakdown are those of copper, brass, aluminium, tin, zinc, gold, silver, lead, nickel, etc.

#### **5. Graining**

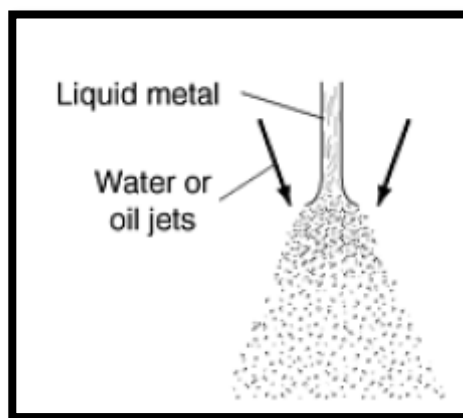
Graining involves the same procedure as the shotting the only difference being that the solidification is allowed to take place in water. In similar manner, other pulverization methods are used for the production of very fine powders. Frequently cadmium, zinc, tin, bismuth, antimony, and lead alloys are pulverized by this method.

## 6. Atomization

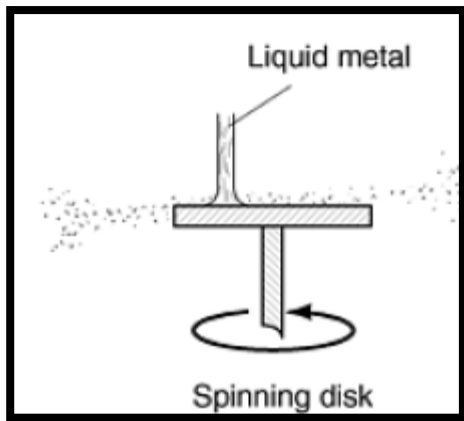
Basically atomization consists of mechanically disintegrating a stream of molten metal into the fine particles by means of a jet of compressed air, inert gases or water. The method has gained greater use because of the following advantages and benefits:

1. Virtually any material that can be melted can be made into powder by this technique
2. Relative ease of preparing higher purity metals, and pre-alloyed powder directly from the melt
3. Similar and uniform composition of atomized powder
4. Control of particle size, size distribution, shape and structure are made possible by the control of atomization processing parameters; i.e. liquid metal superheat or the atomization stream
5. Lower capital or investment cost
6. High productivity. For example, it is now possible to atomize 10 tons of molten steel within 30 minutes.

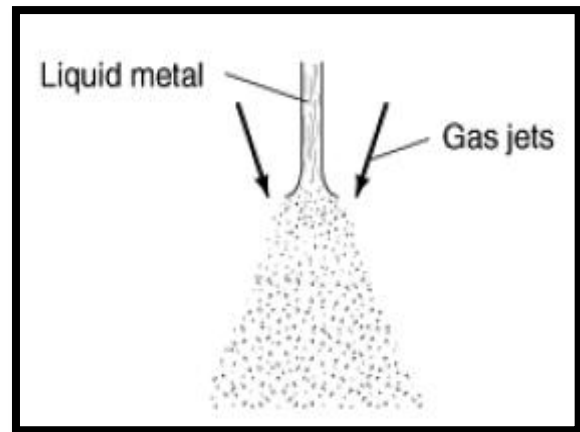
This is the main process for preparing aluminium, zinc, lead, pure iron, and low alloy steel powders, noble metals and more recently, high temperature alloys and special alloy powders (e.g., superalloys)



Water Atomization process



Centrifugal Atomization process



Gas Atomization process

### **7. Cold Stream Process**

Cold stream process relies upon the brittleness of certain metals and alloys at low temperatures. The starting materials is coarse particles (often obtained by grinding or atomization) of the required composition. This is conveyed in a high velocity, high-pressure air stream through a vertical nozzle and strikes on a target in an evacuated blast chamber. At the nozzle, the pressure drop occurs at once from about (7 atmospheres to 1 atmospheric) and this results in a very quick temperature drop to sub-zero. The brittle raw material shatters against the target into an irregular shaped powder having very little surface contamination and excellent pressing characteristics. The resulting powder is separated into suitable size fraction using a classifier. This process has been used to produce tungsten, tantalum, tungsten carbide, and tool steel powders.