Powder metallurgy – basics & applications

Powder metallurgy – science of producing metal powders and making finished /semifinished objects from mixed or alloyed powders with or without the addition of nonmetallic constituents

Steps in powder metallurgy: Powder production, Compaction, Sintering, & Secondary operations

Powder production:

Raw materials => Powder; Powders can be pure elements, pre-alloyed powders

Methods for making powders – Atomization: Produces powders of both ferrous and non-ferrous powders like stainless steel, superalloys, Ti alloy powders; Reduction of compounds: Production of iron, Cu, tungsten, molybdenum; Electrolysis: for making Cu, iron, silver powders

Powders along with additives are mixed using mixers

Lubricants are added prior to mixing to facilitate easy ejection of compact and to minimize wear of tools; Waxes, metallic stearates, graphite etc.

Powder characterization – size, flow, density, compressibility tests

Compaction: compaction is performed using dies machined to close tolerances

Dies are made of cemented carbide, die/tool steel; pressed using hydraulic or mechanical presses

The basic purpose of compaction is to obtain a green compact with sufficient strength to withstand further handling operations

The green compact is then taken for sintering

Hot extrusion, hot pressing, hot isostatic pressing => consolidation at high temperatures

Sintering: Performed at controlled atmosphere to bond atoms metallurgically; Bonding occurs by diffusion of atoms; done at 70% of abs. melting point of materials

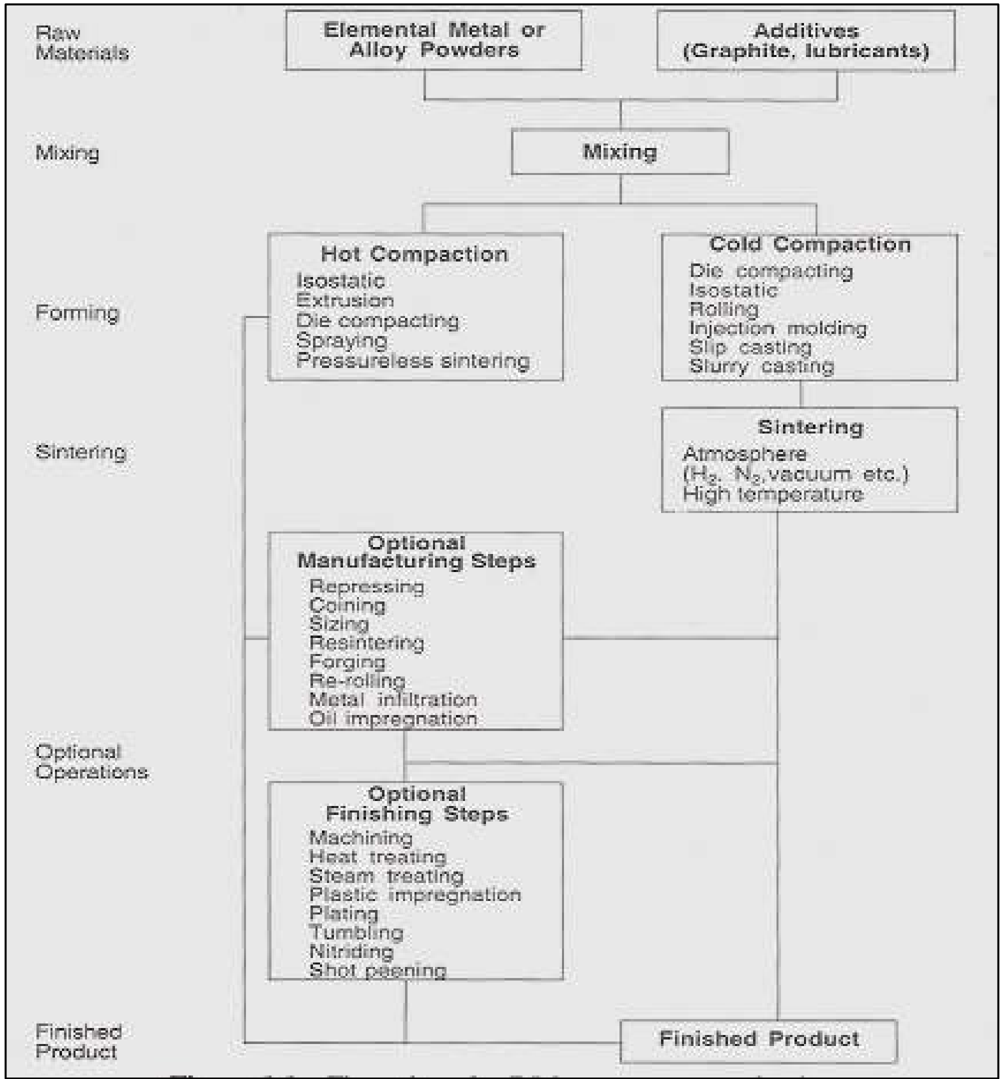
It serves to consolidate the mechanically bonded powders into a coherent body having desired on service behavior

Densification occurs during the process and improvement in physical and mechanical properties are seen

Furnaces – mesh belt furnaces (up to 1200C), walking beam, pusher type furnace, batch type furnaces are also used

Protective atmosphere: Nitrogen (widely used)

Secondary operations: Operations include repressing, grinding, plating can be done; They are used to ensure close dimensional tolerances, good surface finish, increase density, corrosion resistance etc.



Flow chart for making P/M components

Advantages & limitations

- Efficient material utilization
- Enables close dimensional tolerances – near net shape possible
- Good surface finish
- Manufacture of complex shapes possible
- Hard materials used to make components that are difficult to machine can be readily made – tungsten wires for incandescent lamps
- Environment friendly, energy efficient
- Suited for moderate to high volume component production
- Powders of uniform chemical composition => reflected in the finished part
- wide variety of materials => miscible, immiscible systems; refractory metals
- Parts with controlled porosity can be made
- High cost of powder material & tooling
- Less strong parts than wrought ones
- Less well known process

Production of powders

• Metal powders => Main constituent of a P/M product; final properties of the finished P/M part depends on size, shape, and surface area of powder particles

• Single powder production method is not sufficient for all applications

Powder production methods: 1. Mechanical methods, 2. Physical methods, 3. Chemical methods

1. Mechanical methods => cheapest of the powder production methods; These methods involve using mechanical forces such as compressive forces, shear or impact to facilitate particle size reduction of bulk materials; Eg.: Milling

Milling: During milling, impact, attrition, shear and compression forces are acted upon particles. During impact, striking of one powder particle against another occurs. Attrition refers to the production of wear debris due to the rubbing action between two particles. Shear refers to cutting of particles resulting in fracture. The particles are broken into fine particles by squeezing action in compression force type.

Main objective of milling: Particle size reduction (main purpose), Particle size growth, shape change, agglomeration (joining of particles together), solid state alloying, mechanical or solid state mixing, modification of material properties

Mechanism of milling: Changes in the morphology of powder particles during milling results in the following events.

1. Microforging, 2. Fracture, 3. Agglomeration, 4. Deagglomeration

Microforging => Individual particles or group of particles are impacted repeatedly so that they flatten with very less change in mass

Fracture => Individual particles deform and cracks initiate and propagate resulting in fracture

Agglomeration => Mechanical interlocking due to atomic bonding or vande Waals forces

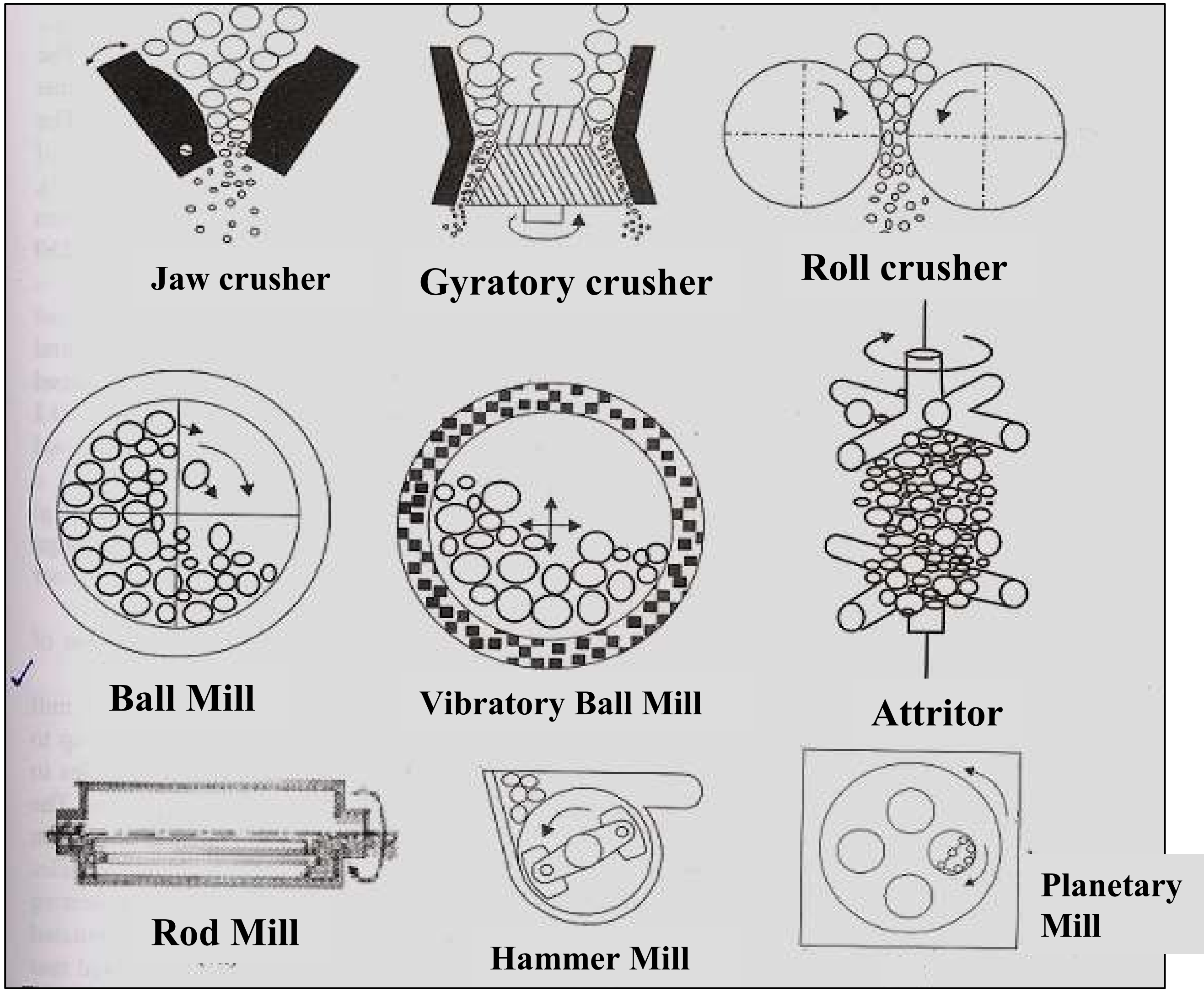
Deagglomeration => Breaking of agglomerates

The different powder characteristics influenced by milling are shape, size, texture, particle size distribution, crystalline size, chemical composition, hardness, density, flowability, compressibility, sinterability, sintered density

Milling equipment: The equipments are generally classified as crushers & mills

Crushing => for making ceramic materials such as oxides of metals; Grinding => for reactive metals such as titanium, zirconium, niobium, tantalum

Grinding: Different types of grinding equipments/methods are shown in the figure

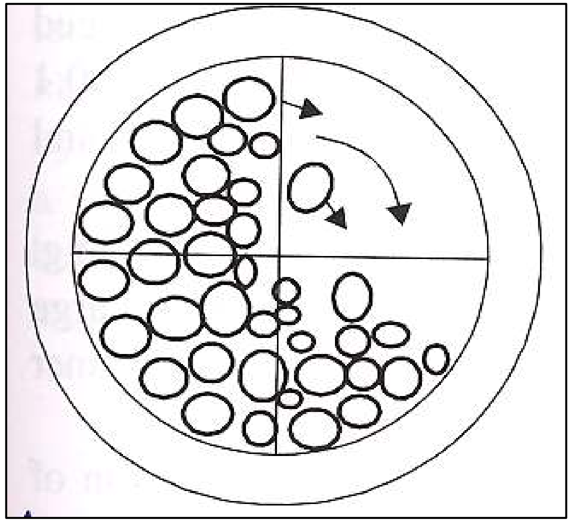


Ball mills

• This contains cylindrical vessel rotating horizontally along the axis. Length of the cylinder is more or less equal to diameter. The vessel is charged with the grinding media. The grinding media may be made of hardened steel, or tungsten carbide, ceramics like agate, porcelain, alumina, zirconia. During rolling of vessel, the grinding media & powder particles roll from some height. This process grinds the powder materials by impact/collision & attrition.

• Milling can be dry milling or wet milling. In dry milling, about 25 vol% of powder is added along with about 1 wt% of a lubricant such as stearic or oleic acid. For wet milling, 30-40 vol% of powder with 1 wt% of dispersing agent such as water, alcohol or hexane is employed.

• Optimum diameter of the mill for grinding powders is about 250 mm



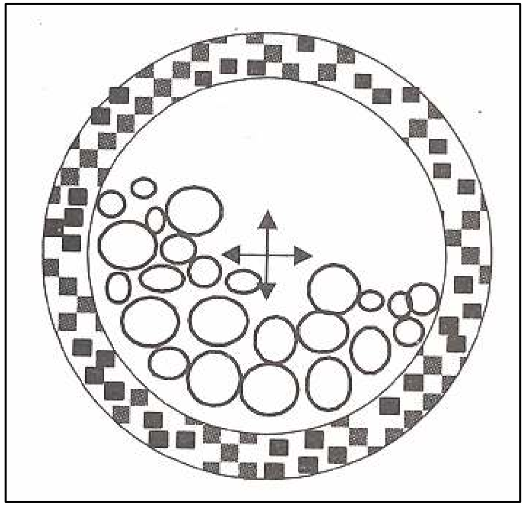
Ball Mill

Vibratory ball mill

• Finer powder particles need longer periods for grinding

• In this case, vibratory ball mill is better => here high amount of energy is imparted to the particles and milling is accelerated by vibrating the container

• This mill contains an electric motor connected to the shaft of the drum by an elastic coupling. The drum is usually lined with wear resistant material. During operation, 80% of the container is filled with grinding bodies and the starting material. Here vibratory motion is obtained by an eccentric shaft that is mounted on a frame inside the mill. The rotation of eccentric shaft causes the drum of the vibrating mill to oscillate.



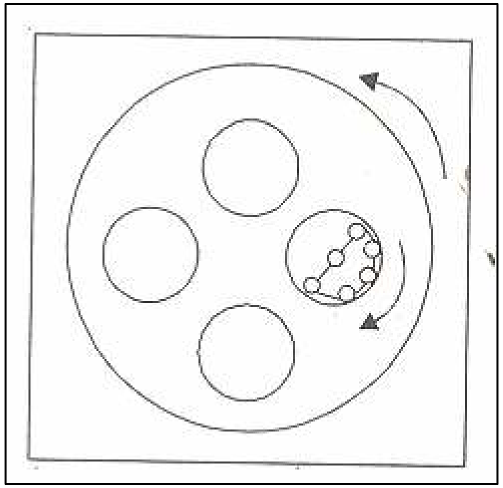
Vibratory Ball Mill

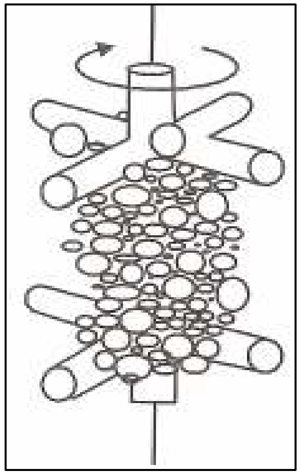
• In general, vibration frequency is equal to 1500 to 3000 oscillations/min. The amplitude of oscillations is 2 to 3 mm. The grinding bodies is made of steel or carbide balls, that are 10-20 mm in diameter. The mass of the balls is 8-10 times the charged particles. Final particle size is of the order of 5-100 microns

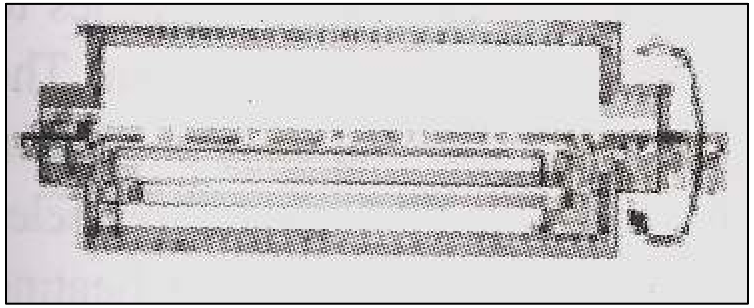
Attrition mill: IN this case, the charge is ground to fine size by the action of a vertical shaft with side arms attached to it. The ball to charge ratio may be 5:1, 10:1, 15:1. This method is more efficient in achieving fine particle size.

Rod mills: Horizontal rods are used instead of balls to grind. Granularity of the discharge material is 40-10 mm. The mill speed varies from 12 to 30 rpm.

Planetary mill: High energy mill widely used for producing metal, alloy, and composite powders.

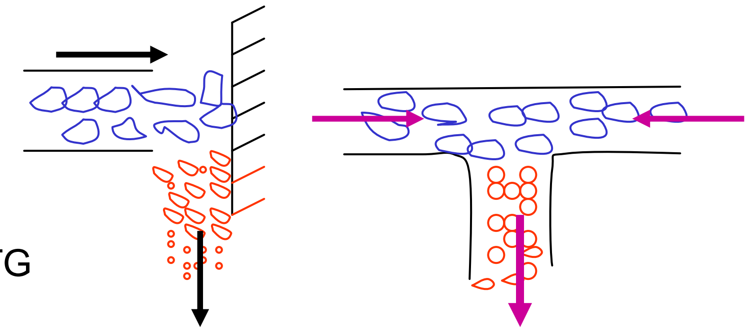






Fluid energy grinding or Jet milling:

The basic principle of fluid energy mill is to induce particles to collide against each other at high velocity, causing them to fracture into fine particles.



• Multiple collisions enhance the reduction process and therefore, multiple jet arrangements are normally incorporated in the mill design. The fluid used is either air about 0.7 MPa or stream at 2 MPa. In the case of volatile materials, protective atmosphere of nitrogen and carbon-di-oxide is used.

• The pressurized fluid is introduced into the grinding zone through specially designed nozzles which convert the applied pressure to kinetic energy. Also materials to be powdered are introduced simultaneously into the turbulent zone.

• The velocity of fluid coming out from the nozzles is directly proportional to the square root of the absolute temperature of the fluid entering the nozzle. Hence it is preferable to raise the temperature of fluid to the maximum possible level without affecting the feed material.

• If further powdering is required, large size particles are separated from the rest centrifugal forces and re-circulated into the turbulent zone for size reduction. Fine particles are taken to the exit by viscous drag of the exhaust gases to be carried away for collection.

• This Jet milling process can create powders of average particle size less than 5 μm

Machining: Mg, Be, Ag, solder, dental alloy are specifically made by machining; Turning and chips thus formed during machining are subsequently crushed or ground into powders

Shotting: Fine stream of molten metal is poured through a vibratory screen into air or protective gas medium. When the molten metals falls through screen, it disintegrates and solidifies as spherical particles. These particles get oxidized. The particles thus obtained depends on pore size of screen, temperature, gas used, frequency of vibration. Metal produced by the method are Cu, Brass, Al, Zn, Sn, Pb, Ni. *(this method is like making Boondhi)*

Graining: Same as shotting except that the falling material through sieve is collected in water; Powders of cadmium, Bismuth, antimony are produced.

2. Physical methods

Electrolytic deposition

• In this method, the processing conditions are so chosen that metals of high purity are precipitated from aqueous solution on the cathode of an electrolytic cell. This method is mainly used for producing copper, iron powders. This method is also used for producing zinc, tin, nickel, cadmium, antimony, silver, lead, beryllium powders.

• Copper powder => Solution containing copper sulphate and sulphuric acid; crude copper as anode

• Reaction: at anode: $Cu \rightarrow Cu^+ + e^-$; at cathode: $Cu^+ + e^- \rightarrow Cu$

• Iron powder => anode is low carbon steel; cathode is stainless steel. The iron powder deposits are subsequently pulverized by milling in hammer mill. The milled powders are annealed in hydrogen atmosphere to make them soft

• Mg powder => electrodeposition from a purified magnesium sulphate electrolyte using insoluble lead anodes and stainless steel cathodes

• Powders of thorium, tantalum, vanadium => fused salt electrolysis is carried out at a temperature below melting point of the metal. Here deposition will occur in the form of small crystals with dendritic shape

In this method, final deposition occurs in three ways,

1. A hard brittle layer of pure metal which is subsequently milled to obtain powder (eg. iron powder)
2. A soft, spongy substance which is loosely adherent and easily removed by scrubbing
3. A direct powder deposit from the electrolyte that collects at the bottom of the cell

Factors promoting powder deposits are, high current density, low metal concentration, pH of the bath, low temperature, high viscosity, circulation of electrolyte to avoid of convection

Advantages:

Powders of high purity with excellent sinterability

Wide range of powder quality can be produced by altering bath composition

Disadvantages:

Time consuming process; Pollution of work place because of toxic chemicals;

Waste disposal is another issue; Cost involved in oxidation of powders and hence they should be washed thoroughly

Atomization

This uses high pressure fluid jets to break up a molten metal stream into very fine droplets, which then solidify into fine particles

High quality powders of Al, brass, iron, stainless steel, tool steel, superalloys are produced commercially

Types: water atomization, gas atomization, soluble gas or vacuum atomization, centrifugal atomization, rotating disk atomization, ultrarapid solidification process, ultrasonic atomization

Mechanism of atomization:

In conventional (gas or water) atomization, a liquid metal is produced by pouring molten metal through a tundish with a nozzle at its base. The stream of liquid is then broken into droplets by the impingement of high pressure gas or water. This disintegration of liquid stream is shown in fig. This has five stages

i) Formation of wavy surface of the liquid due to small disturbances

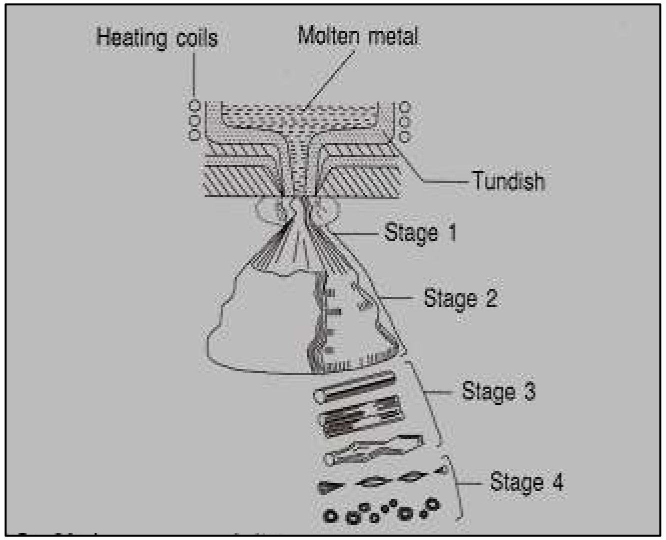
ii) Wave fragmentation and ligament formation

iii) Disintegration of ligament into fine droplets

iv) Further breakdown of fragments into fine particles

v) Collision and coalescence of particles

atomization



• The interaction between jets and liquid metal stream begins with the creation of small disturbances at liquid surfaces, which grow into shearing forces that fragment the liquid into ligaments. The broken ligaments are further made to fine particles because of high energy in impacting jet.

• Lower surface tension of molten metal, high cooling rate => formation of irregular surface => like in water atomization

• High surface tension, low cooling rates => spherical shape formation => like in inert gas atomization

• The liquid metal stream velocity, $v = A\,[2g\,(P_i - P_g)\rho]^{0.5}$

where P_i – injection pressure of the liquid, P_g – pressure of atomizing medium, ρ – density of the liquid

Types of atomization

Atomization of molten metal can be done in different ways depending upon the factors like economy and required powder characteristics. At present, water or gas atomizing medium can be used to disintegrate a molten metal stream. The various types of atomization techniques used are,

1. Water atomization: High pressure water jets are used to bring about the disintegration of molten metal stream. Water jets are used mainly because of their higher viscosity and quenching ability. This is an inexpensive process and can be used for small or large scale production. But water should not chemically react with metals or alloys used.

2. Gas atomization: Here instead of water, high velocity argon, nitrogen and helium gas jets are used. The molten metal is disintegrated and collected as atomized powder in a water bath. Fluidized bed cooling is used when certain powder characteristics are required.

3. Vacuum atomization: In this method, when a molten metal supersaturated with a gas under pressure is suddenly exposed into vacuum, the gas coming from metal solution expands, causing atomization of the metal stream. This process gives very high purity powder. Usually hydrogen is used as gas. Hydrogen and argon mixture can also be used.

4. Centrifugal atomization: In this method, one end of the metal bar is heated and melted by bringing it into contact with a non-consumable tungsten electrode, while rotating it longitudinally at very high speeds. The centrifugal force created causes the metal drops to be thrown off outwards. This will then be solidified as spherical shaped particles inside an evacuated chamber. Titanium powder can be made using this technique

5. Rotating disk atomization: Impinging of a stream of molten metal on to the surface of rapidly spinning disk. This causes mechanical atomization of metal stream and causes the droplets to be thrown off the edges of the disk. The particles are spherical in shape and their size decreases with increasing disk speed.

6. Ultrarapid solidification processes: A solidification rate of 1000C/s is achieved in this process. This results in enhanced chemical homogeneity, formation of metastable crystalline phases, amorphous materials.

Atomization Unit

Melting and superheating facility: Standard melting furnaces can be used for producing the liquid metal. This is usually done by air melting, inert gas or vacuum induction melting. Complex alloys that are susceptible to contamination are melted in vacuum induction furnaces. The metal is transferred to a tundish, which serves as reservoir for molten metal.

Atomization chamber: An atomization nozzle system is necessary. The nozzle that controls the size and shape of the metal stream if fixed at the bottom of the atomizing chamber. In order to avoid oxidation of powders, the tank is purged with inert gas like nitrogen.

Powder collection tank: The powders are collected in tank. It could be dry collection or wet collection. In dry collection, the powder particles solidify before reaching the bottom of the tank. In wet collection, powder particles collected in the bottom of the water tank. The tank has to be cooled extremely if used for large scale production.

During operation, the atomization unit is kept evacuated to 10^{-3} mm of Hg, tested for leak and filled with argon gas.

Atomizing nozzles

• Function is to control the flow and the pattern of atomizing medium to provide for efficient disintegration of powders

• For a given nozzle design, the average particle size is controlled by the pressure of the atomizing medium and also by the apex angle between the axes of the gas jets

• Higher apex angle lead to smaller particle size

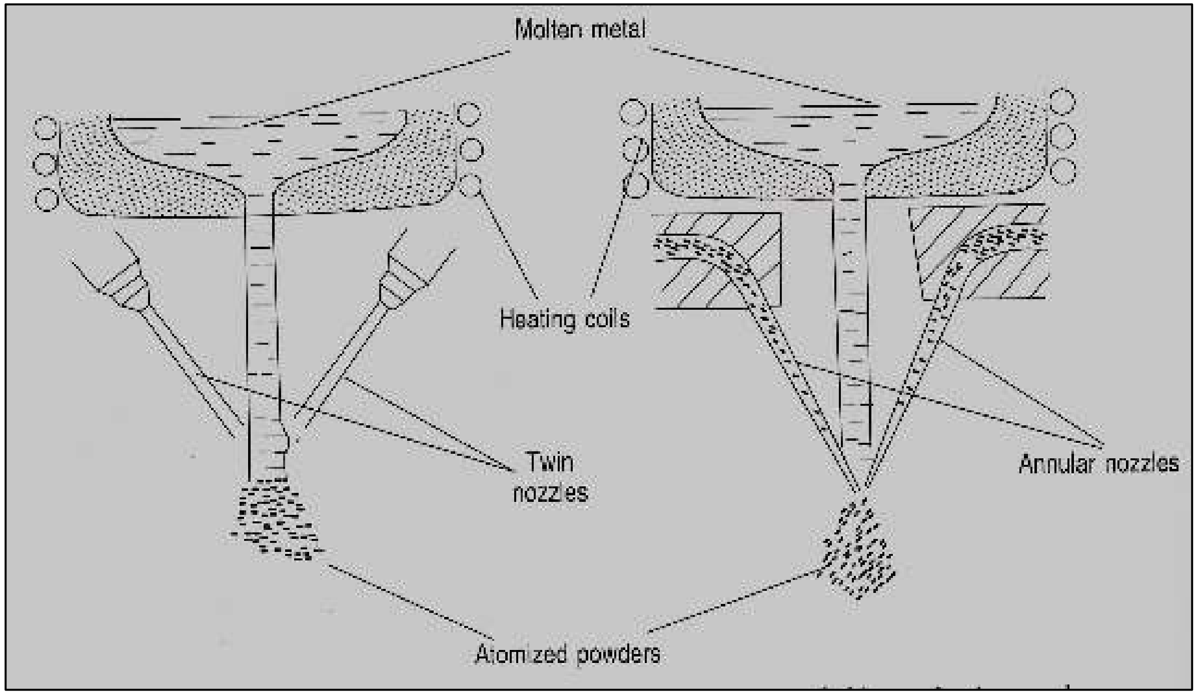
• Apex angle for water atomization is smaller than for gas atomization

• Nozzle design: i) annular type, ii) discrete jet type;

i) free falling, ii) confined design

• In free falling, molten metal comes in contact with atomizing medium after some distance. Here free falling of metal is seen. This is mainly used in water atomization.

• In confined design used with annular nozzle, atomization occurs at the exit of the nozzle. Gas atomization is used generally for this. This has higher efficiency than free falling type. One has to be cautious that "freeze up" of metal in the nozzle has to be avoided.



Atomic nozzle configuration, a) twin jet nozzle, b) annular jet nozzle

Atomizing mediums

- The selection of the atomizing jet medium is based mainly on the reactivity of the metal and the cost of the medium
- Air and water are inexpensive, but are reactive in nature
- Inert gases like Ni, Ar, He can be used but are expensive and hence have to be recycled
- Pumping of cold gas along with the atomizing jet => this will increase the solidification rate
- recently, **synthetic oils are used instead of gas or water** => **this yields high cooling rate & lower oxygen content** compared to water atomized powders
- **Oil atomization** is suitable for high carbon steel, high speed steels, bearing steals, steel containing high quantities of carbide forming elements like Cr, Molybdenum
- This method is not good for powders of low carbon steels

S. No.	Characteristics of the medium	Gases: N_2	Ar	He
1.	% in dry air	78.10	0.93	5.3×10^{-4}
2.	Production	Fractional distillation of air	Same as N_2	Fractional distillation from natural gas
3.	Physical properties			
	(a) Density at 70°C (lb/ft^3)	1.1613×10^{-3}	1.6563×10^{-3}	1.64×10^{-4}
	(b) Thermal conductivity in BTU/hr ft °F $\times 10^{-2}$	14.85	10.15	86.18
4.	Reactivity	Reacts with Al, Ti, Cr, Ta at high temperature	Inert to all metals	Inert to all metals
5.	Cost	Least expensive	Expensive	Most expensive
6.	Applications	Various alloys including tool steels and hard facing powder manufacture	Superalloy powder that contains elements which react with N_2	Al and Mg powders

Gases used for atomization

Important atomization processes

Inert gas atomization

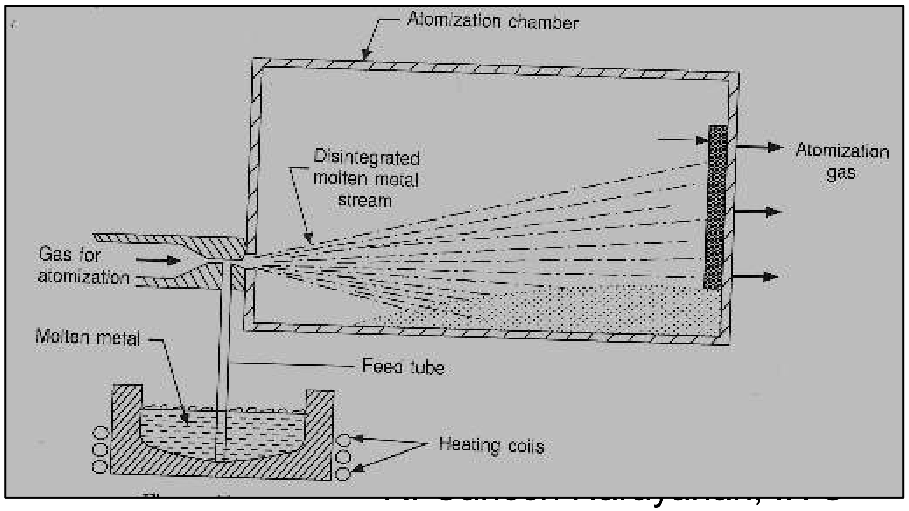
- Production of high grade metal powders with spherical shape, high bulk density, flowability along with low oxygen content and high purity

- Eg. Ni based super alloys

- **Controlling parameters:** (1) viscosity, surface tension, temperature, flow rate of molten metal; (2) flow rate, velocity, viscosity of atomizing medium; (3) jet angle, jet distance of the atomizing system; (4) nature of quenching media

- The flight path for Ni based super alloy powders of diameter '*d*' is,

$$L = 1806 \sqrt{d^3} / (6.12/d) + 12.5; \; L \text{ – Critical flight path in meters}$$



Schematic of horizontal gas atomization

Water atomization

- Water jet is used instead of inert gas

- Fit for high volume and low cost production

- Powders of average size from 150 micron to 400 micron; cooling rates from 10^3 to 10^5 K/s. Rapid extraction of heat results in irregular particle shape => less time to spheroidize in comparison to gas atomization

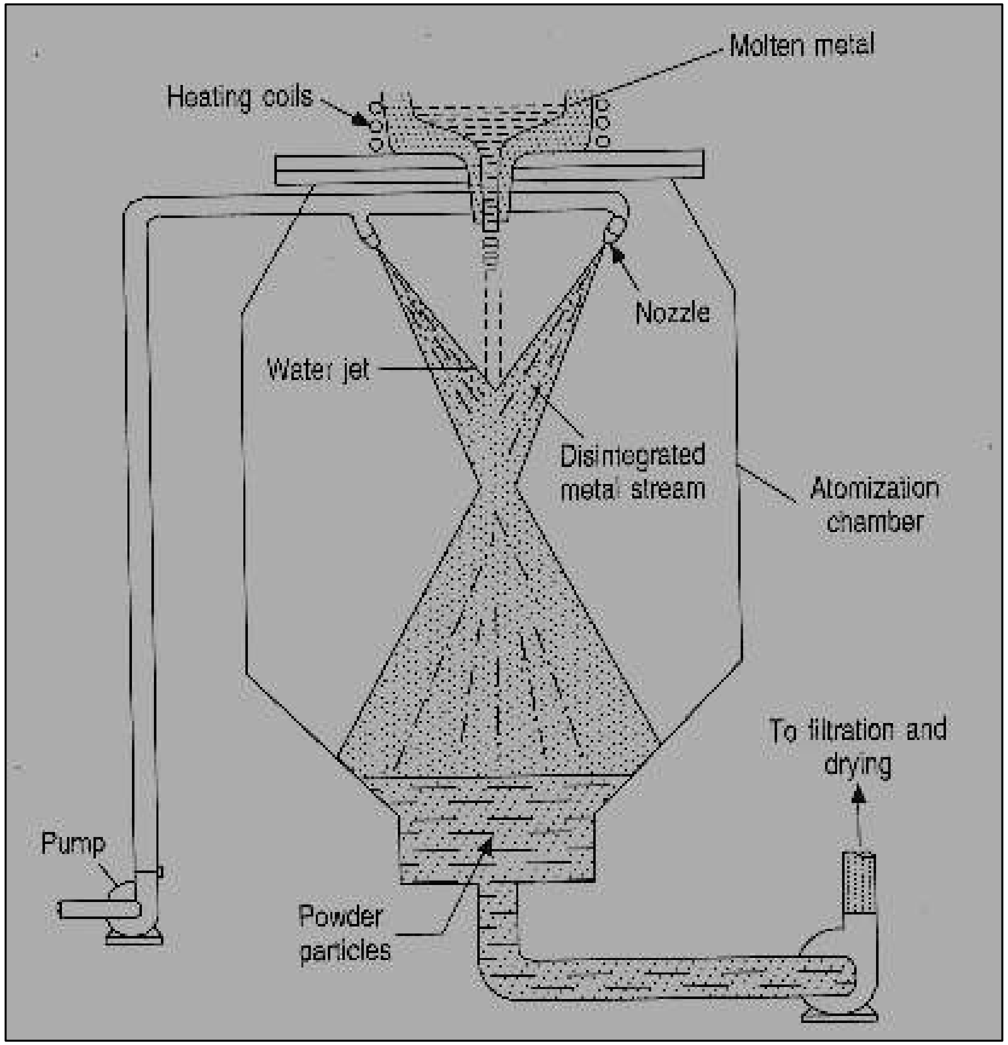
- Water pressure of 70 MPa for fine powders in 10 micron range

- **important parameters:**

1. Water pressure: Increase water pressure => size decrease => increased impact

2. water jet thickness: increase thickness => finer particles => volume of atomizing medium increases

3. Angle of water impingement with molten metal & distance of jet travel



Schematic of water atomization

Atomization process parameters

1. Effect of pressure of metal head: $r = a + b\sqrt{h}$; r – rate of atomization
2. Effect of atomizing medium pressure: $r = a\sqrt{p} + b$; Increase in air pressure increases the fineness of powder up to a limit, after which no increase is seen
3. Molten metal temperature: As temperature increases, both surface tension and viscosity decrease; so available energy can efficiently disintegrate the metal stream producing fine powders than at lower temperature; Temperature effect on particle shape is dependent on particle temperature at the instant of formation and time interval between formation of the particle and its solidification; Temperature increase will reduce surface tension and hence formation of spherical particle is minimal; however spherical particles can still be formed if the disintegrated particles remain as liquid for longer times.
4. Orifice area: negligible effect
5. Molten metal properties:

   Iron and Cu powder => fine spherical size; Pb, Sn => irregular shape powder; Al powders => irregular shape even at high surface tension (oxidation effect)

Summary of various powder production methods

Sl. no.	Method	Purity	Particle characteristics		Compressibility	Apparent density	Green strength
			Shape	Mesh			
1	Atomization	Relatively good	Irregular to smooth, rounded dense particles	Coarse shots to 325 mesh	Low to high	Generally high (spherical powder)	Generally low
2	Gaseous reduction of solids	Medium	Irregular, spongy	100 mesh and finer	Medium	Low to medium	High to medium
3	Gaseous reduction of solutions	High	Irregular, spongy	100 mesh and finer	Medium	Low to medium	High
4	Reduction with carbon	Medium	Irregular, spongy	All meshes from mesh size 8 downwards	Medium	Medium	Medium to high
5	Electrolytic deposition	High	Irregular, dendritic	All mesh sizes	High (pure and ductile)	Medium to high	Medium
6	Carbonyl method	High	Spherical	Usually in low micron ranges	Medium	Medium to high (spherical)	Low
7	Grinding	Medium	Flaky and dense	All mesh sizes	Medium	Medium to low (flakes powders A.D. low)	Low (flaky particles 2D)

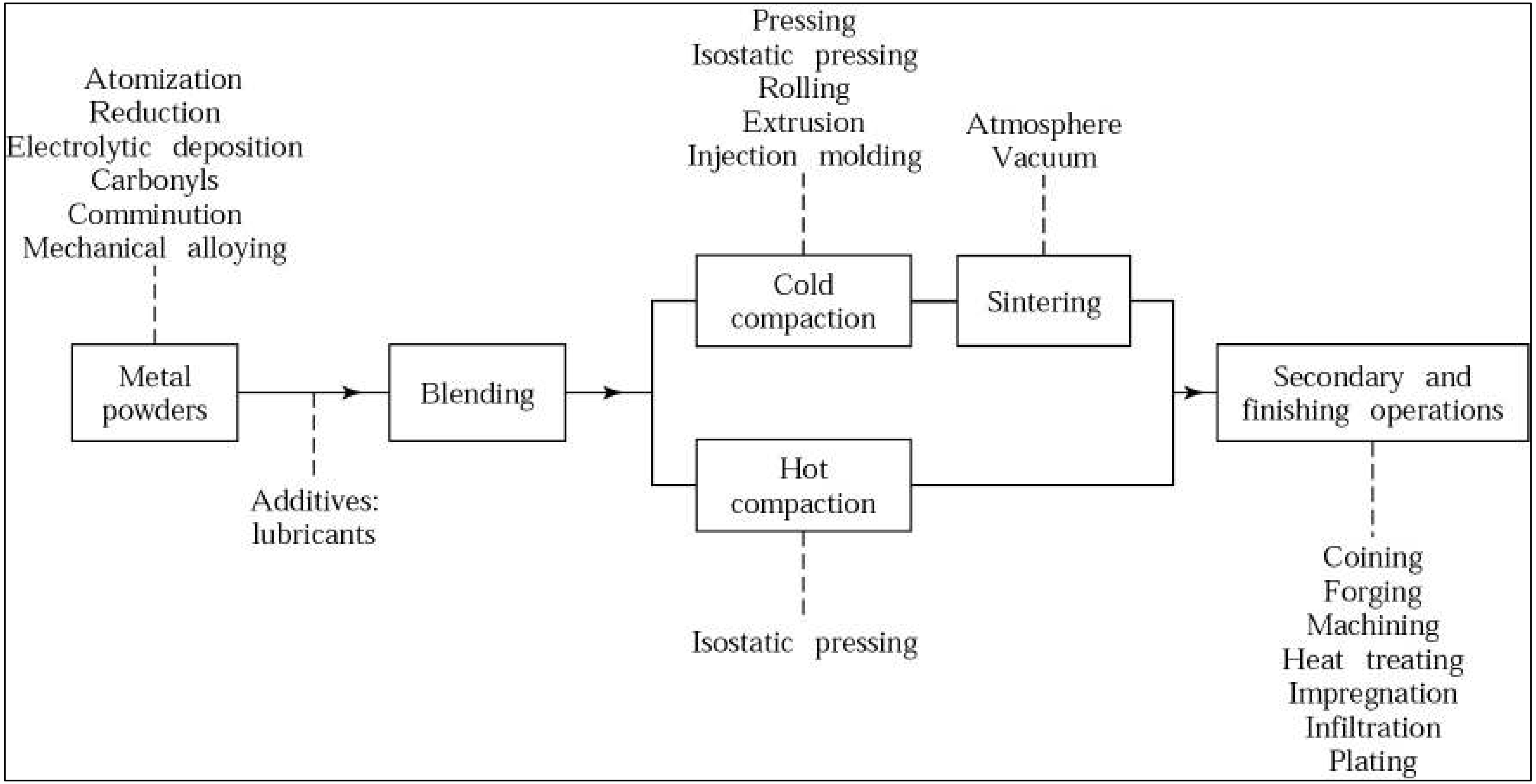
Characteristics of different atomization processes

Process	*Technique*	*Particle shape*	*Average particle size in (μm)*	*Cooling rate* (K/s)
Atomization	Water atomization	Irregular	75–200	10^2–10^4
	Ultrasonic gas atomization	Spherical	10–50	$\geq 10^6$
	Gas soluble	Spherical	20–150	10^2–10^4
Centrifugal	Rapid spinning cup	Variable	<50	10^4–10^6
Atomization	Rotating electrode	Spherical	150–250	10^4–10^6
Splat cooling	Electron beam splat quench	Splat	40–100	10^4–10^7

Powders produced by various atomization methods and applications

Sl. no.	*Atomizing method*	*Typical powders*	*Powder shape*	*Applications*
1.	Water atomization	Iron and alloys Stainless steel	Irregular	Mechanical pumps, welding rods, garden equipment Automotive and transport components Hardware, filters, parts for house hold appliances and business machines.
2.	Gas atomization	Aluminium base alloys	Spherical	Landing gear assembly in airliners, corrosion-resistant parts
3.	Centrifugal atomization (REP process)	Titanium base alloys Nickel base superalloys, low-carbon steel, cobalt-chromium alloys	Spherical	Aerospace applications. Photocopier applications Prosthetic devices for implants
4.	Vacuum atomization	Nickel base superalloy	Spherical	Gas turbine disks
5.	RSP (vacuum disk atomization)	Nickel base superalloys	Spherical	Aerospace engine parts
6.	Ultra-rapid solidification processes Ultrasonic atomization	Aluminum–lithium alloys Dispersion strengthened Al alloys (containing Fe, Co, Mo, Ce)	—	High-strength, low-weight applications Elevated temperature service parts

Making powder & subsequent processing



Powder treatment & Handling

In powder conditioning, the powders prepared by various methods are subjected to a variety of treatments to improve or modify their physical, chemical characteristics

Powder treatments

Powders manufactured for P/M applications can be classified into – elemental powders, and pre-alloyed powders

Elemental powders => powders of single metallic element; eg.: iron for magnetic applications

Pre-alloyed powders => more than one element; made by alloying elemental powders during manufacturing process itself; IN this case, all the particles have same nominal composition and each particle is equivalent to small ingot

Majority of powders undergo heat treatments prior to compaction like,

i) Drying to remove moisture, ii) grinding/crushing to obtain fine sizes, iii) particle size classification to obtain the desired particle size distribution, iv) annealing, v) mixing and blending of powders, vi) lubricant addition for powder compaction, vii) powder coating

a) Cleaning of powders:

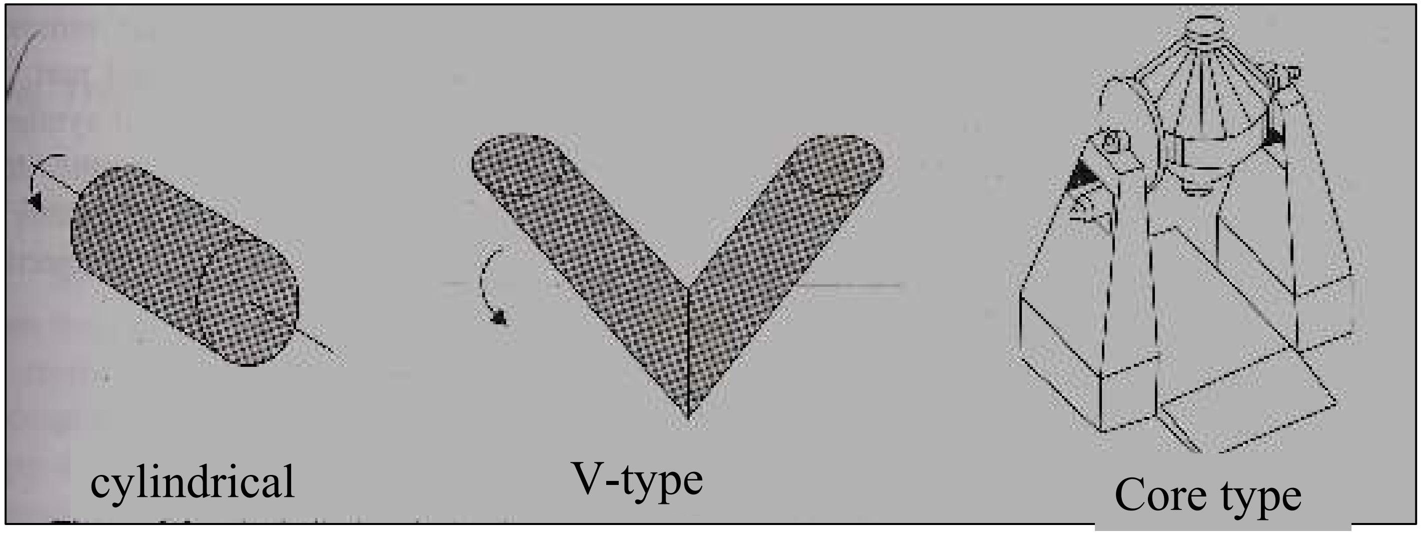
- Refers to the removal of contaminants, solid or gaseous, from the powder particles
- **Solid contaminants** => come from several sources like nozzles or crucible linings. They interfere during compaction and sintering preventing proper mechanical bonding
- Most of these contaminants are non-reactive, but they act as sites for crack nucleation and reduce the dynamic properties of the sintered part; Non-metallic solid impurities can be removed from superalloy powders by particle separators, electrostatic separation techniques
- **Gaseous impurities** like hydrogen and oxygen get into powders during processing, storage or handling if proper care is not taken. Finer the powders, contamination will be more because of large powder surface area.
- These gaseous impurities can form undesirable oxides during processing at relatively high temperature or gets trapped inside the material as pores, reducing the in situ performance of the P/M part; Degassing techniques like cold, hot static or dynamic degassing methods are used to remove adsorbed gases from the powders
- Lubricants added to the powders for better compaction has to be removed for desirable final P/M part

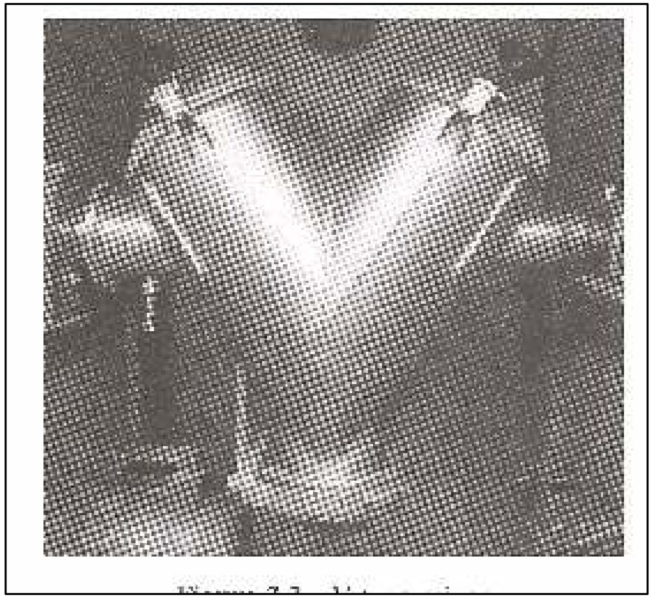
b) Grinding: similar to the mechanical methods seen earlier; Milling is widely used for reducing the aggregates of powder; Milling time, speed, type can be selected for getting required degree of grinding

c) Powder classification & screening: Powder size and shape, size distribution varied within specified range is required for better behavior of P/M parts; In this method, the desired particle size distributions with particle sizes within specific limits can be obtained; These variation depends on lot also.

d) Blending & mixing: *Blending* – Process in which powders of the same nominal composition but having different particle sizes are intermingled. This is done to (i) obtain a uniform distribution of particle sizes, i.e. powders consisting of different particle sizes are often blended to reduce porosity, (ii) for intermingling of lubricant with powders to modify metal to powder interaction during compaction

Mixing – process of combining powders of different chemistries such as elemental powder mixes (Cu-Sn) or metal-nonmetal powders. This may be done in dry or wet condition. Liquid medium like alcohol, acetone, benzene or distilled water are used as milling medium in wet milling. Ball mills or rod mills are employed for mixing hard metals such as carbides.



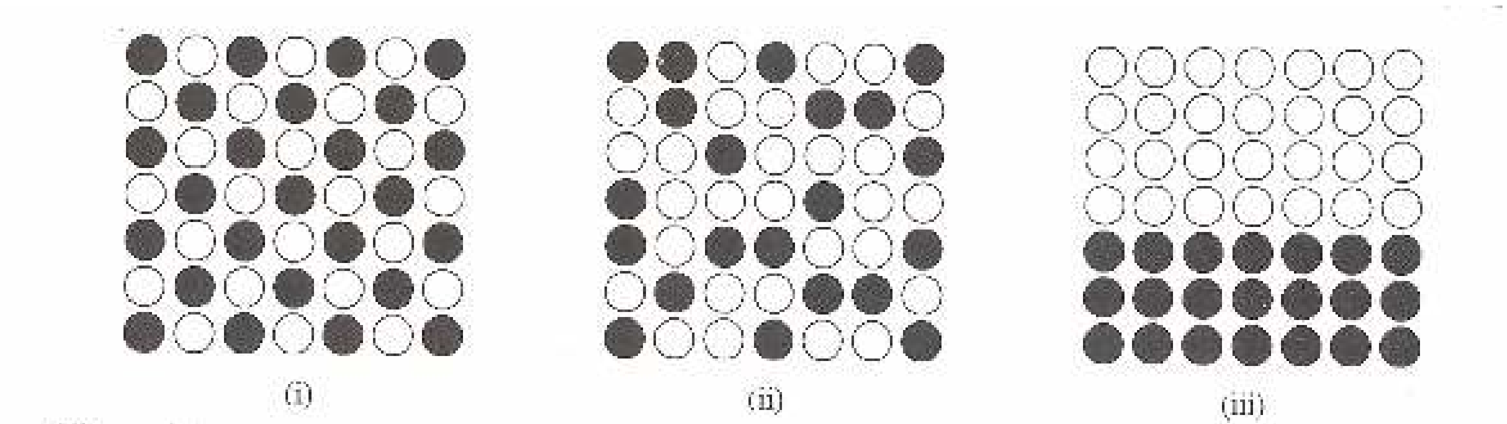


V-type mixer

Mixing methods

The various types of mixing methods are, (i) *convective mixing*: transfer of one group of particles from one location to another, (ii) *diffusive mixing*: movement of particles on to newly formed surface, (iii) *shear mixing*: deformation & formation of planes within the powders

Depending on the extent of mixing, mixing can be classified as (i) perfectly mixed or uniform mixing, (ii) random mixed, & (iii) totally un-mixed. The mixing should be stopped when random mixture is achieved. Overmixing leads to reduced flow characteristics of the mix.



uniform mixing   random mixed   un-mixed.

<u>Heat treatment of powders</u>

Heat treatment is generally carried out before mixing or blending the metal powders. Some of the important objectives are,

i) <u>Improving the purity of powder:</u> Reduction of surface oxides from powders by annealing in hydrogen or other reducing atmosphere. Dissolved gases like hydrogen and oxygen, other impurities are removed by annealing of powders. Lowering impurities like carbon results in lower hardness of the powder and hence lower compaction pressures & lower die wear during compaction. For eg., atomized powders having a combined carbon and oxygen content as high as 1% can be reduced after annealing to about 0.01% carbon and 0.2% oxygen. Heat treatment is done at protective atmosphere like hydrogen, vacuum.

ii) <u>Improving the powder softness:</u> Aim is to reduce the work hardening effect of powders that has be crushed to obtain fine powders; while many powders are made by milling, crushing or grinding of bulk materials. Powder particles are annealed under reducing atmosphere like hydrogen. The annealing temperature is kept low to avoid fusion of the particles.

iii) <u>Modification of powder characteristics</u>: The apparent density of the powders can be modified to a higher or lower value by changing the temperature of treatment.

Toxicity of powders

• Toxicity leads to undesirable health effects like eye, skin irritation, vomiting, respiratory problems, blood poisoning etc.

• powder like lead, nickel are highly toxic & Al, iron are less toxic

• Precautions: Use of protective gloves, respiratory masks, protective clothing etc.; use of well ventilated storage, workplace; careful handling, disposal of wastes

• flammability & reactivity data is required

• Health effects: Inhalation – disturbs the respiratory track; remedial measures include moving the person to fresh air. Artificial breathing is required if patient not breathing properly.

Skin, eyes – Brushing, washing skin and eyes with water and soap. Clean eyes with fresh water for 15 mts.