ME306 ADVANCED MANUFACTURING TECHNOLOGY

Course Objectives

1. To introduce machining principles and processes in the manufacturing of precision components and products that use conventional and nonconventional technologies.
2. To give basic understanding of the machining capabilities, limitations, and productivity of advanced manufacturing processes.
3. To describe how PLC's operate and how they control automated equipment and systems
4. To demonstrate tool path simulations with CNC powered equipment
5. To introduce CNC programming

MODULE 1

Introduction: Need and comparison between traditional, non-traditional and micro & nano machining process.
Powder Metallurgy: Need of P/M - Powder Production methods:- Atomization, electrolysis, Reduction of oxides, Carbonyls (Process parameters, characteristics of powder produced in each method).
Powder characteristics: properties of fine powder, size, size distribution, shape, compressibility, purity etc.
Mixing – Compaction:- techniques, pressure distribution, HIP & CIP.
Mechanism of sintering, driving force for pore shirking, solid and liquid phase sintering - Impregnation and Infiltration Advantages, disadvantages and specific applications of P/M.
Programmable Logic Controllers (PLC): need – relays - logic ladder program –timers, simple problems only.
Point to point, straight cut and contouring positioning - incremental and absolute systems – open loop and closed loop systems - control loops in contouring systems: principle of operation.

Machining is a broad term to describe removal of material from a workpiece.

- Machining categories: –

- Cutting involves single-point or multipoint cutting tools, each with a clearly defined geometry.

– Abrasive processes, such as grinding.

– Nontraditional machining, utilizing electrical, chemical, and optical sources of energy.

WHY NON TRADITIONAL MACHINING?....

- Situations where traditional machining processes are unsatisfactory or uneconomical:
  - Workpiece material is too hard, strong, or tough.
  - Workpiece is too flexible to resist cutting forces or too difficult to clamp.
  - Part shape is very complex with internal or external profiles or small holes.
  - Requirements for surface finish and tolerances are very high.
  - Temperature rise or residual stresses are undesirable or unacceptable.

Nontraditional Machining

- Ultrasonic Machining (USM)
- Water-Jet Machining & Abrasive-Jet Machining
- Chemical Machining
- Electrochemical Machining (ECM)
- Electrical-Discharge Machining (EDM)
- High-Energy-Beam Machining
  - *Laser-beam machining (LBM)*
  - *Electron-beam machining (EBM)*

Traditional vs. Nontraditional

- Primary source of energy

– *Traditional: mechanical.*

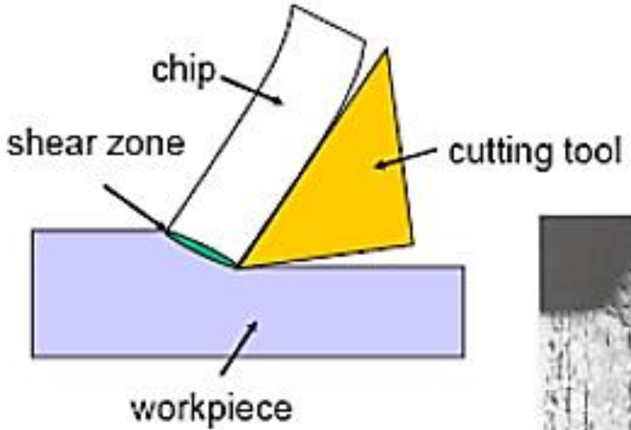
– *Nontraditional: electrical, chemical, optical*

- Primary method of material removal

– *Traditional: shearing*

– *Nontraditional: does not use shearing (e.g., abrasive water jet cutting uses erosion)*

Water jet machining



DIFFERENCES BETWEEN TRADITIONAL AND NON TRADITIONAL MACHINING PROCESSES

Sl No.	Conventional Process	Non Conventional Process
1	The cutting tool and work piece are always in physical contact with relative motion with each other, which results in friction and tool wear.	There is no physical contact between the tool and work piece, In some non traditional process tool wear exists.
2	Material removal rate is limited by mechanical properties of work material.	NTM can machine difficult to cut and hard to cut materials like titanium,ceramics,nimonics, SST,composites,semiconducting materials
3	Relative motion between the tool and work is typically rotary or reciprocating. Thus the shape of work is limited to circular or flat shapes. In spite of CNC systems, production of 3D surfaces is still a difficult task.	Many NTM are capable of producing complex 3D shapes and cavities
4	Machining of small cavities , slits , blind holes or through holes are difficult	Machining of small cavities, slits and Production of non-circular, micro sized, large aspect ratio, shall entry angle holes are easy using NTM

DIFFERENCES BETWEEN TRADITIONAL AND NON TRADITIONAL MACHINING PROCESSES

Conventional v/s Non Conventional

5	Use relative simple and inexpensive machinery and readily available cutting tools	Non traditional processes requires expensive tools and equipment as well as skilled labour, which increase the production cost significantly
6	Capital cost and maintenance cost is low	Capital cost and maintenance cost is high
7.	Traditional processes are well established and physics of process is well understood	Mechanics of Material removal of Some of NTM process are still under research
8	Conventional process mostly uses mechanical energy	Most NTM uses energy in direct form For example : laser, Electron beam in its direct forms are used in LBM and EBM respectively.
9	Surface finish and tolerances are limited by machining inaccuracies	High surface finish(up to 0.1 micron) and tolerances (25 Microns)can be achieved
10	High metal removal rate.	Low material removal rate.

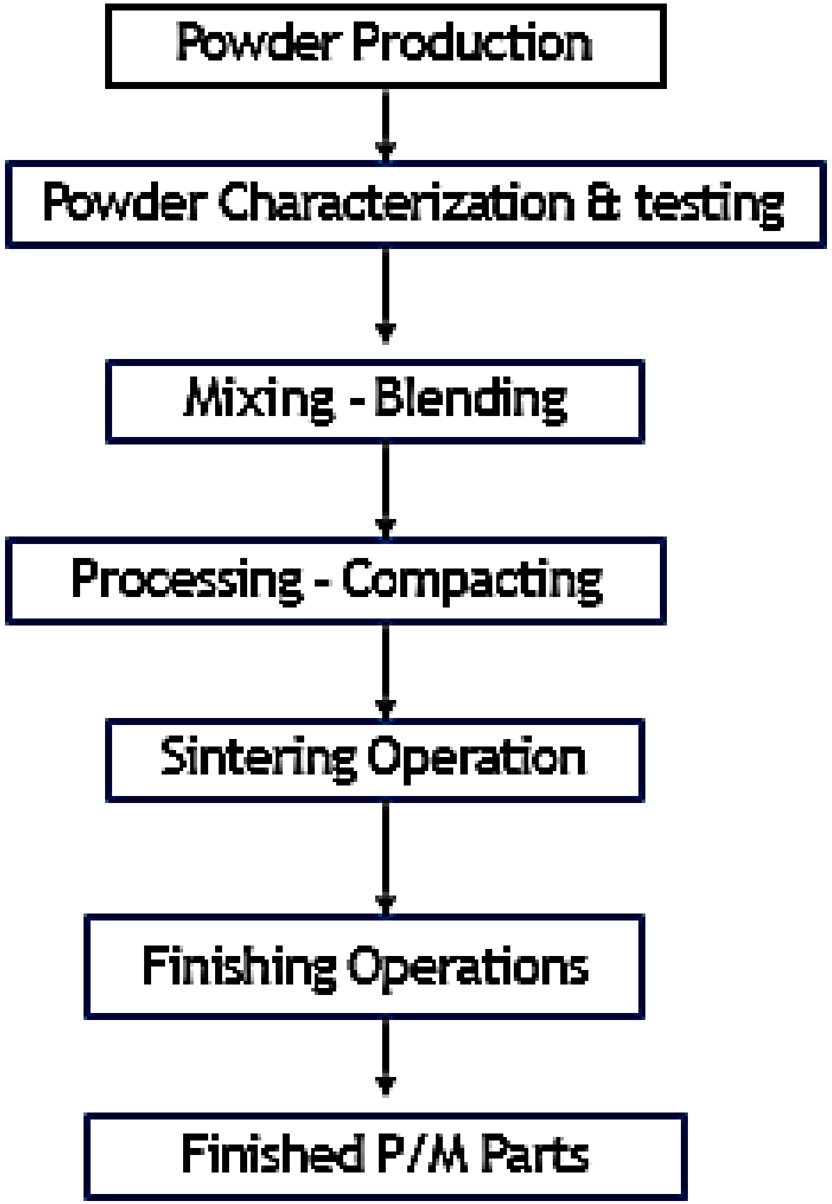
Definition of Powder Metallurgy

- Powder metallurgy may defined as, “the art and science of producing metal powders and utilizing them to make serviceable objects.”

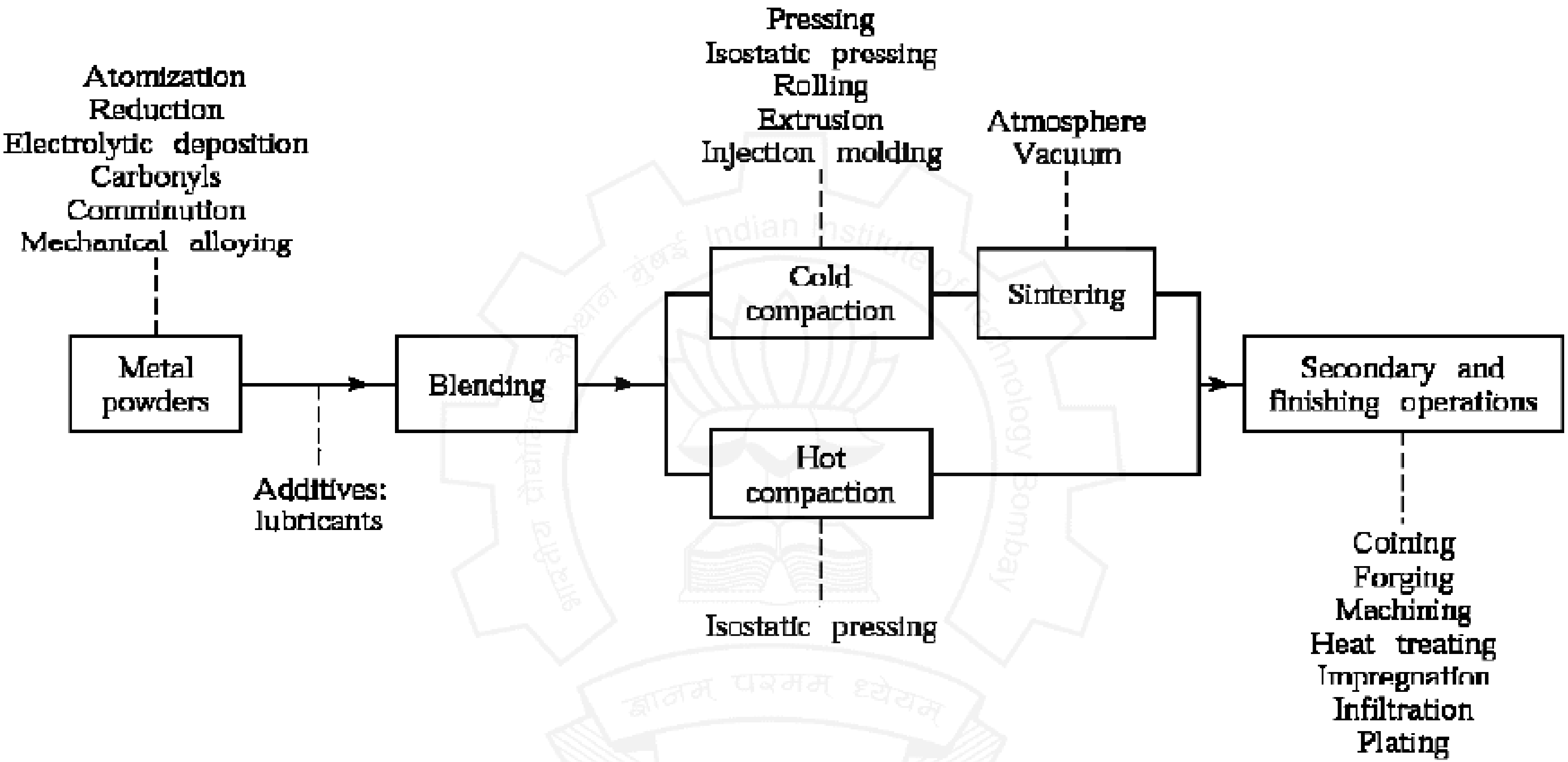
OR

- It may also be defined as “material processing technique used to consolidate particulate matter i.e. powders both metal and/or non-metals.”

Process of Powder Metallurgy:



POWDER METALLURGY STEPS



PRODUCTION OF METAL POWDERS

The selection of materials in powder metallurgy is determined by two factors.

i)The alloy required in the finished part.

ii)Physical characteristics needed in the powder.

Both of these factors are influenced by the process used for making powder.

i) There are numerous ways for powder production which can be categorized as follows.

1) **Mechanical methods of powder production:**

i) Chopping or Cutting

ii) Abrasion methods

iii) Machining methods

iv) Milling

v) Cold-stream Process.

2. Chemical methods of powder production:

i) Reduction of oxides

ii) Precipitation from solutions

iii) Thermal decomposition of compounds

iv) Hydride decomposition

v) Thermit reaction

vi) Electro- chemical methods

3. Physical methods of powder production:

i) Water atomization

ii) Gas atomization

iii) Special atomization methods

The choice of a specific technique for powder production depends on particle size, shape, microstructure and chemistry of powder and also on the cost of the process.

1. Chopping or Cutting:

- In this process, strands of hard steel wire, in diameter as small as 0.0313 inches are cut up into small pieces by means of a milling cutter.
- This technique is actually employed in the manufacturing of cut wire shots which are used for peening or shot cleaning.

Limitations:

It would, however, be difficult and costly to make powders by this method.

2. Rubbing or Abrasion Methods:

These are all sorts of ways in which a mass of metal might be attacked by some form of abrasion.

a) Rubbing of Two Surfaces:

When we rub two surfaces against each other, hard surface removes the material from the surface of soft material.

b) Filing:

Filing as a production method has been frequently employed, especially to alloy powders, when supplies from conventional sources have been unobtainable.

Such methods are also used for manufacture of coarse powders of dental alloys.

Filing can also be used to produce finer powder if its teeth are smaller.

* commercially not feasible.

c) Scratching:

If a hard pin is rubbed on some soft metal the powder flakes are produced.

Scratching is a technique actually used on a large scale for the preparation of coarse magnesium powders.

- scratching a slab of magnesium with hardened steel pins.
- a revolving metal drum to the surface of which is fixed a scratching belt.

d) Machining:

A machining process, using for example a lathe or a milling cutter in which something more than just scratching is involved, since the attacking tool actually digs under the surface of the metal and tears it off.

On lathe machine by applying small force we get fine chips.

A large amount of machining scrap is produced in machining operations. This scrap in the form of chips and turnings can be further reduced in size by grinding.

* small scale production.

Disadvantages:

- Lack of control on powder characteristics, including chemical contamination such as oxidation, oil and other metal impurities.
- The shape of the powder is irregular and coarse.

Advantages:

- For consuming scrap from another process, machining is a useful process.
- Presently the machined powder is used with high carbon steel and some dental amalgam powders.

COMMERCIAL METHODS

These are the methods used for high production rate. Best examples of mechanical production methods are **the Milling Process** and **Cold Stream Process.**

Milling:

The basic principle of milling process is the application of impact and shear forces between two materials, a hard and a soft, causing soft material to be ground into fine particles.

Milling techniques are suitable for brittle materials.

Two types of milling are;

i) Ball Milling

ii) Attrition Milling.

Objectives of milling include:

- ❖Particle size reduction (comminution or grinding)
- ❖Shape change (flaking)
- ❖Solid-state alloying (mechanical alloying)
- ❖Solid-state blending (incomplete alloying)
- ❖Modifying, changing, or altering properties of a material (density, flowability, or work hardening)
- ❖Mixing or blending of two or more materials or mixed phases

Ball Milling:

Ball milling is an old and relatively simple method for grinding large lumps of materials into smaller pieces and powder form.

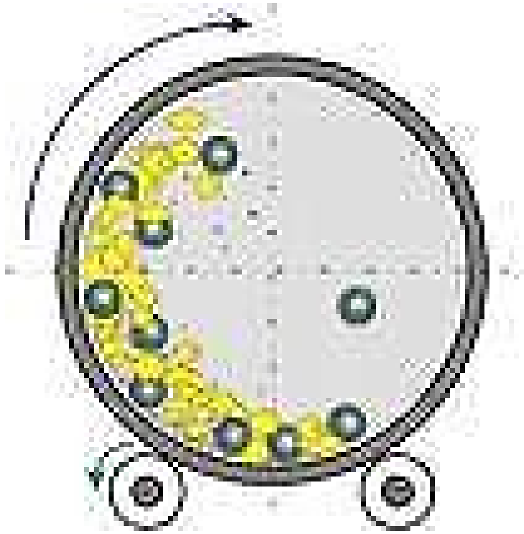
Principle of the process:

The principle is based on the **impact and shear forces**. Hard balls are used for mechanical comminution of brittle materials and producing powders.

Milling Unit:

The basic apparatus consists of the following;

- A ball mill or jar mill which mainly consists of a rotating drum lined from inside with a hard material.
- Hard balls, as a grinding medium, which continue to impact the material inside the drum as it rotates/rolls.



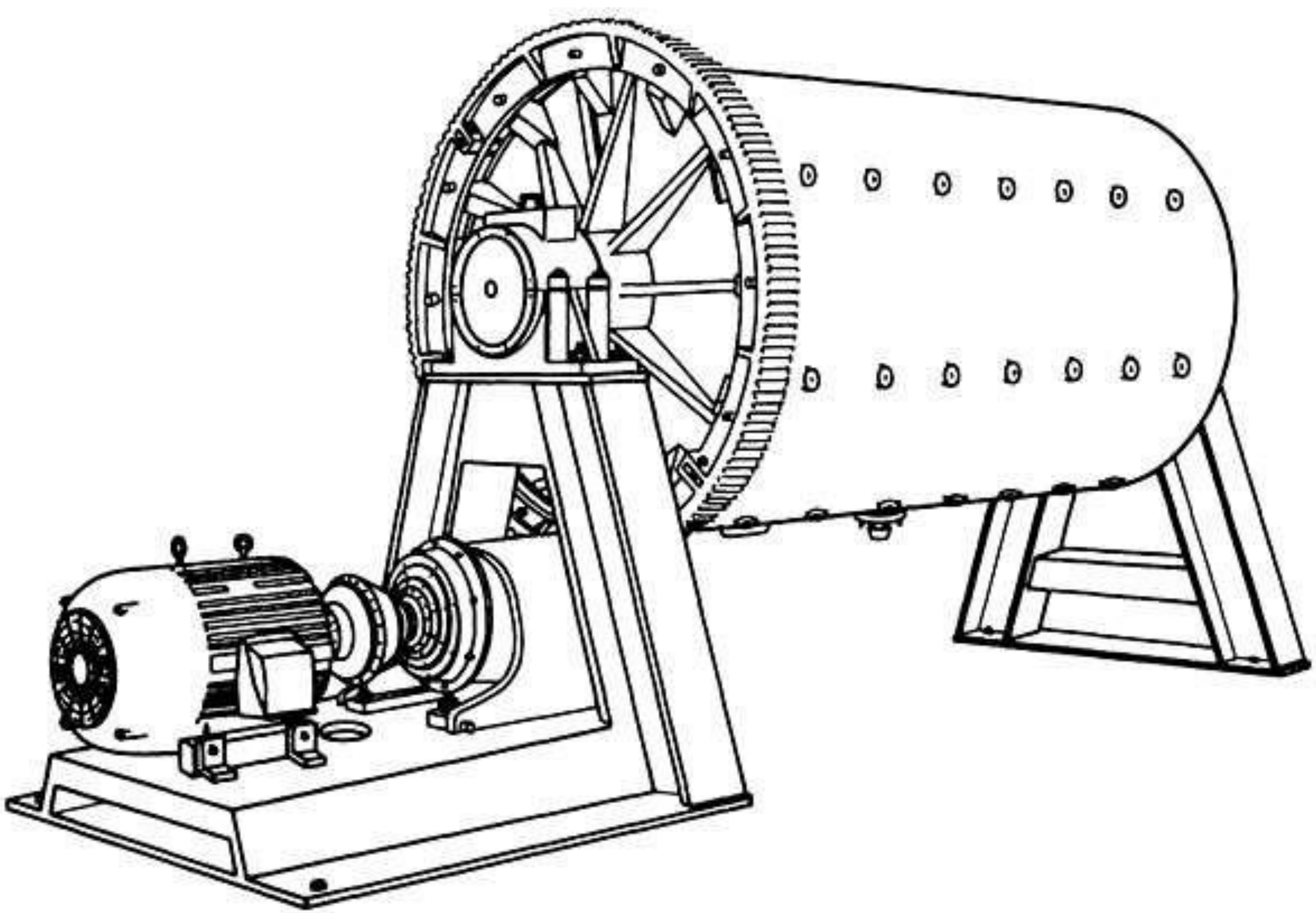


Figure: Tumbler mill used for milling metal powders

Important Parameters:

1. The most important parameter to consider is the speed of rotation of the drum. An optimum/critical speed is adjusted for maximum impact velocity.

 * Critical speed is the speed above which the ball will centrifuge.

- Very slow speed of rotation will not carry the balls to the top, these will roll back down the drum sides.
- Very fast speed (higher than critical speed) will not let the balls drop down as they will be carried around due to centrifugal forces. Thus, an optimum speed is required. This speed of rotation varies with the inverse square root of the drum diameter.

2. The material of grinding media and its size and density.

- The size and density of the milling medium is selected according to the deformation and fracture resistance for metals.
- For hard and brittle materials large and dense media is used. Whereas, small balls are used for finer grinding.
- As a general rule, the balls should be small and their surface should be a little rough. The material of the balls and lining of the drum should be same as that of the material being ground.

3.The rate of milling of a powder is a function of quantity in the total space between the balls.

4.Lubricants and surface active agents are used to nullify the welding forces which causes agglomeration.

Grinding Mechanism:

During milling the following forces cause fracture of material into powder.

Impact Forces: These are caused by instantaneous striking of one object on the other. (Impact is the instantaneous striking of one object by another. Both objects may be moving or one may be stationary).

Shear Forces: These are caused as one material slides/rubs against the other.

Limitations:

- Rubbing action causes contamination of powder since balls may also get rubbed.
- Working hardening of metal powder is caused during milling.
- There is a possibility of excessive oxidation of final powder.
- Quality of powder is poor.
- Particle welding and agglomeration may take place.

COLD STREAM PROCESS

- This process is based on impact phenomenon caused by impingement of high velocity particles against a cemented carbide plate.

- The unit consists of:

- A feed container;
- A compressor capable of producing a high velocity stream of air (56 m^3/min.) operating at 7 MPa (1000 psi);
- A target plate, made of cemented tungsten carbide, for producing impact;
- A classifying chamber lined with WC while the supersonic nozzle and target generally are made of cemented tungsten carbide.

Mechanism of the Process:

The material to be powdered is fed in the chamber and from there falls in front of high velocity stream of air.

This air causes the impingement of material against target plate, where material due to impaction is shattered into powder form. This powder is sucked and is classified in the classifying chamber. Oversize is recycled and fine powder is removed from discharge area.

* Rapidly expanding gases leaving the nozzle create a strong cooling effect through adiabatic expansion. This effect is greater than the heat produced by pulverization.

CHEMICAL METHODS

- Almost all metallic elements can be produced in the form of powders by suitable chemical reactions or decomposition.

Mostly chemical methods are based on the decomposition of a compound into the elemental form with heating or with the help of some catalyst.

In most cases such processes involve at least two reactants.

(i) a compound of the metal

(ii) a reducing agent

REDUCTION OF METAL OXIDES

Manufacturing of metal powder by reduction of oxides is extensively employed, particularly for Fe, Cu, W and Mo.

Advantages:

- A variety of reducing agents can be used and process can be economical when carbon is used.
- Close control over particle size
- Porous powders can be produced which have good compressive properties.
- Adoptability either to very small or large manufacturing units and either batch or continuous processes.

Limitations:

- Process may be costly if reducing agents are gases.
- Large volumes of reducing gas may be required, and circumstances where this is economically available may be limited; in some cases, however, costs may be reduced by recirculation of the gas.
- The purity of the finished product usually depends entirely upon the purity of the raw material, and economic or technical considerations may set a limitation to that which can be attained.
- Alloy powders cannot be produced.

Production of Iron Powder

by Reduction of Iron Oxide:

(Direct Reduction Process)

Iron powders are commercially used for a large number of applications such as fabrication of structural parts, welding rods, flame cutting, food enrichment and electronic and magnetic applications.

The classical technique for production of iron powder is the reduction of iron oxide.

Theory of the process:

It is the oldest process of production of iron powder by using carbon as the reducing agent.

In this process pure magnetite (Fe_3O_4) is used. Coke breeze is the carbon source used to reduce iron oxide. Some limestone is also used to react with the sulphur present in the coke. The mixture of coke and limestone (85% + 15%) is dried in a rotary kiln and crushed to uniform size.

The ore and coke-limestone mixture is charged into ceramic tubes (Silicon Carbide) with care so that ore and reduction mixture are in contact with each other but not intermixed. It can be achieved by using concentric charging tubes with in the ceramic tube.

Within the hot zone, several chemical reactions occur and metallic iron is formed in the form of sponge cake.

The main reaction is;

$$MO + R \longrightarrow M + RO$$

If magnetite ore is used, then the following reactions will take place:

$$Fe_3O_4 + 3CO \longrightarrow FeO + 3CO_2$$

$$FeO + CO \longrightarrow Fe + CO_2$$

$$C + \frac{1}{2} O_2 \longrightarrow CO$$

Decomposition of the limestone generates carbon dioxide, which oxidizes the carbon in the coke to form carbon monoxide. The ferrous iron oxide is further reduced by the carbon monoxide to metallic iron.

Desulphurization occurs in parallel with reduction by reaction between gas and sulphides present in the ore resulting in gaseous sulphide compounds which in turn react with lime to form calcium sulphide.

The sponge cake is removed from ceramic tubes and dropped into a tooth crusher where this is broken into pieces.

After these pieces are ground to desired particle size. During grinding the powder particles are considerably work hardened. The powder is annealed at 800 - 870 ^{o}C in the atmosphere of dissociated ammonia.

The powder is loosely sintered, but requires only light grinding and screening to produce a finished product.

THE CARBONYL PROCESS

- The only method for the manufacture of metal powder by the pyrolysis of a gaseous compound which has been used industrially on a substantial scale is the carbonyl iron or nickel process.
- When iron and nickel ores react under high pressure (70 – 300 atm.) with carbon monoxide, iron pentacarbonyl [$Fe(CO)_5$] or nickel tetracarbonyl [$Ni(CO)_4$] is formed, respectively.
- Both compounds are liquids at room temperature.
- $Fe(CO)_5$ evaporates at 103 ^oC and $Ni(CO)_4$ at 43 ^oC.

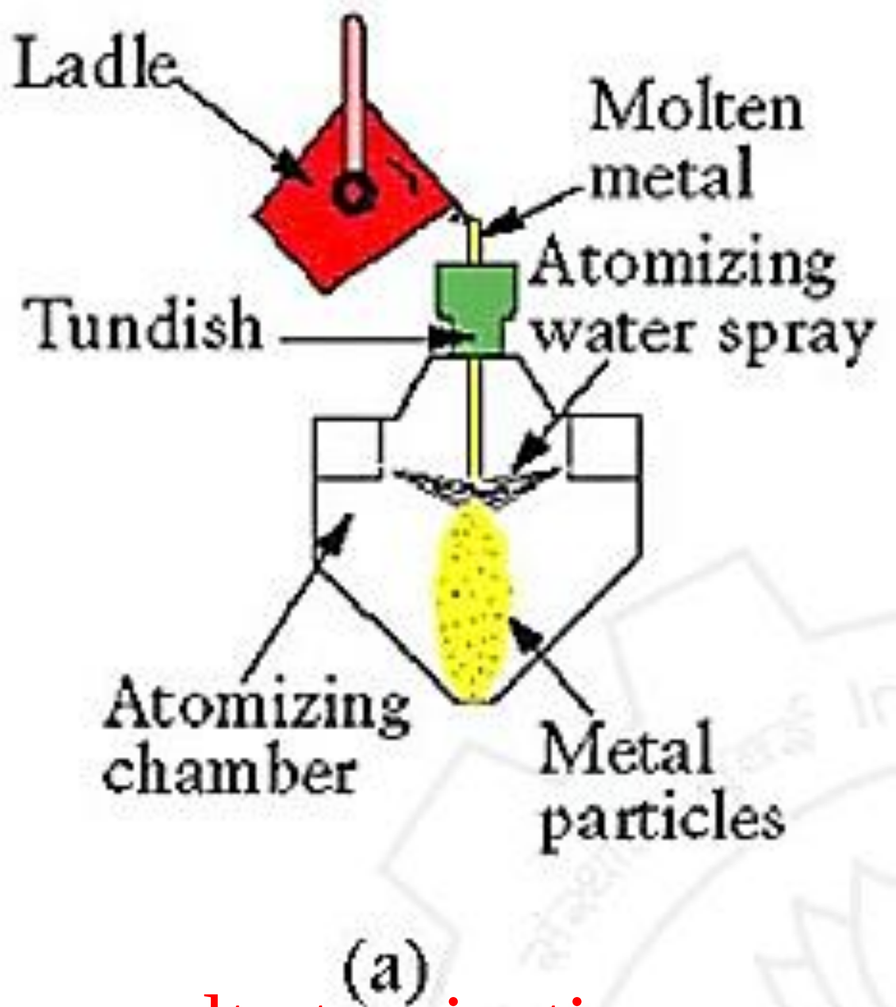
Precipitate Formation:

This step of the process is carried out according to the following scheme:

- The liquid carbonyles are stored under pressure in tanks submerged in water.
- The distilled and filtered liquids are conveyed to steam heating cylinders, where they are vaporized.
- The vapors of liquid are sent to decomposers. The decomposers are jacketed and heated, giving an internal temperature of 200 – 250 ^{o}C. These cylinders are 9 – 10 feet high with an internal dia of 3 feet, with conical bottoms.
- The incoming stream of vapors meets a tangential stream of ammonia gas. CO is removed here and precipitates of metals are formed which are then sieved, dried and may be milled to break up the agglomerates.
- The CO gas arising from the decomposition is recovered and re-used.

- Carbonyl iron powder is used for the production of magnetic powder cores for radio or television applications.
- In P/M it is used for the manufacture of soft magnetic materials and permanent magnets.
- Because of its high price and poor die filling properties, it is not suitable for the manufacture of sintered structural components.
- The carbonyl process is also well suited for the extraction of both metals from lean ores. The process can be controlled so as to yield a spherical metal powder.

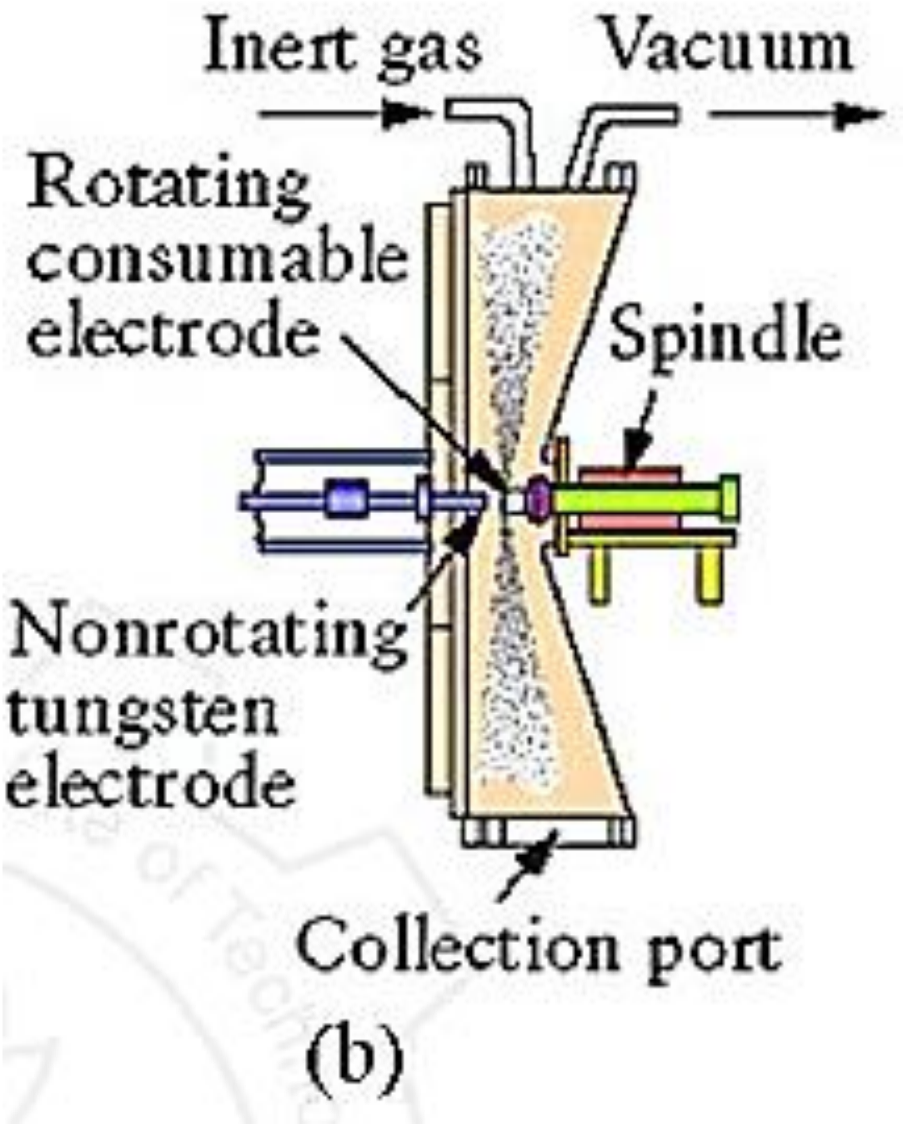
Powder Manufacture Techniques



melt atomization

Atomising Process

In this process the molten metal is forced through an orifice into a stream of high velocity air, steam or inert gas. This causes rapid cooling and disintegration into very fine powder particles and the use of this process is limited to metals with relatively low melting point.



atomization with a rotating consumable electrode

Electrolysis Process

In this process the conditions of electrode position are controlled in such a way that a soft spongy deposit is formed, which is subsequently pulverised to form the metallic powder. The particle size can be varied over a wide range by varying the electrolyte compositions and the electrical parameters.

➢ *Gaseous Reduction*

This process consists of grinding the metallic oxides to a fine state and subsequently, reducing it by hydrogen or carbon monoxide. This method is employed for metals such as iron, tungsten, copper, etc.

Granulation Process

This process consists in the formation of an oxide film in individual particles when a bath of metal is stirred in contact with air.

Mechanical Alloying

In this method, powders of two or more pure metals are mixed in a ball mill. Under the impact of the hard balls, the powders are repeatedly fractured and welded together by forming alloy under diffusion.

Characteristics of fine powder

1. Surface area
2. Density
   I. True density
   II. Apparent density
   III. Tap density
   IV. Green density
3. Flow rate
4. Green strength
5. Green spring
6. Compressibility and compression ratio

7. Particle shape

- depends on powder production method

8. Particle size

-dia of spherical particles

-Av. Dia of non spherical particles

divided into 3 classes

1. sieve
2. sub sieve
3. sub micron

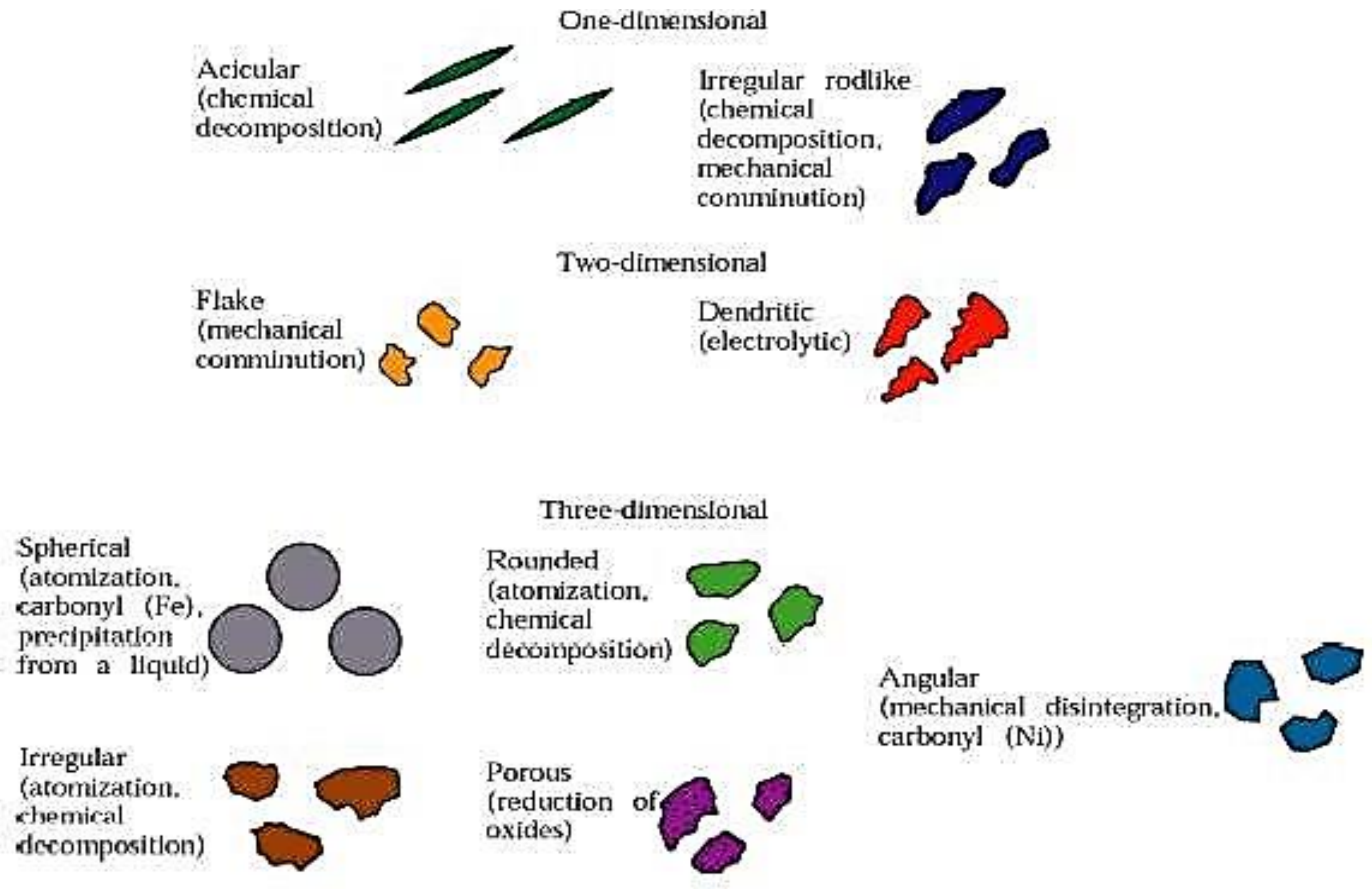
9. Particle size distribution

shape factor= surface area/ Volume

Aspect ratio = largest dim/ smallest dim

- ✓ **Apparent density** of a powder sometimes called packing density or loading weight is defined as the mass per unit. Volume of loose or unpacked powder.
- ✓ **Tap density** 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.
- ✓ **Flow rate** characteristic of powders measures, the ability of a powders to be transferred.
- ✓ **Green strength** of a powder is defined as the mechanic strength of a green compact required to with stand.
- ✓ **Green spring** property of the green compact, associated with the difference between the size of the compact and the tools employed prepare it, is usually termed green spring because the compact expand both radially and longitudinally on ejection from the tool.

Characteristics of fine powder



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

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;

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

b) Grinding

c) Powder classification & screening

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.

Mixing methods

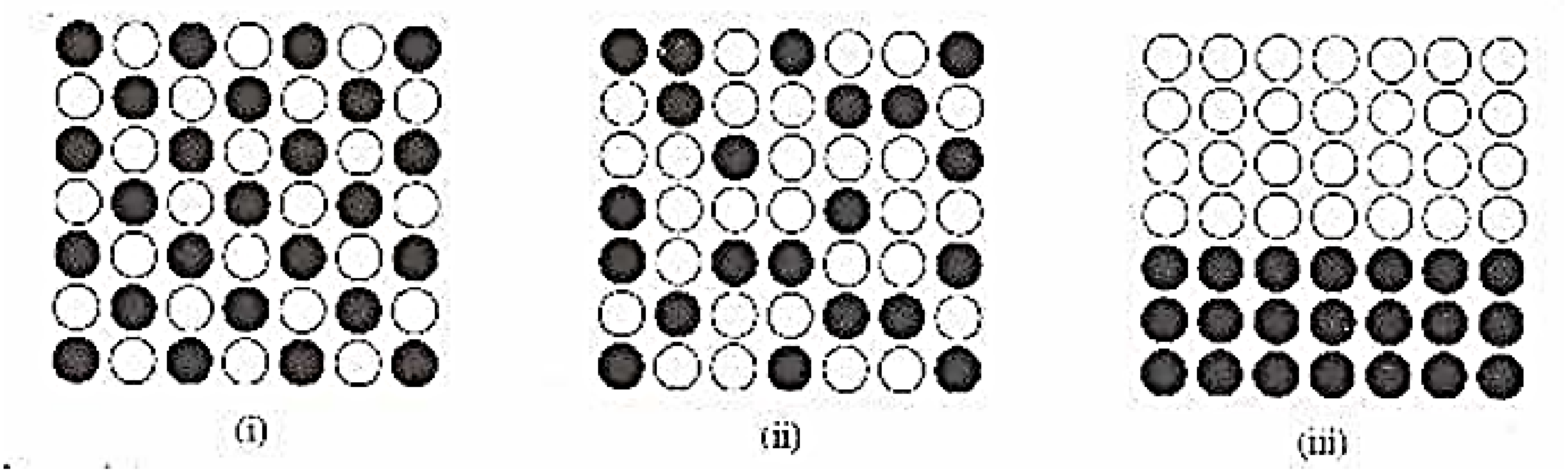
(i) convective mixing: transfer of one group of particles from one location to another,

(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) (ii) random mixed, &
iii) (iii) totally un-mixed.



uniform mixing   random mixed   un-mixed.

Heat treatment of powders

i) Improving the purity of powder

Reduction of surface oxides from powders by annealing in hydrogen or other reducing atmosphere

ii) Improving the powder softness

iii) Modification of powder characteristics

Powder Compaction

The principle goal of the *compaction process* is to apply pressurize and bond the particles to form a cohesion among the powder particles. This is usually termed as the *green strength*.

Compaction of metal powders

Compaction is an important step in powder processing as it enables the forming of loose metal powders into required shapes with sufficient strength to withstand till sintering is completed

Powder compaction methods

1. Methods without application of pressure –

i) loose powder sintering in mould,
ii) vibratory compaction,
iii) slip casting,
iv) slurry casting,
v) injection moulding

2. Methods with applied pressure –

i) cold die compaction (single action pressing, double action pressing, floating die pressing),
ii) isostatic pressing,
iii) powder rolling,
iv) powder extrusion,
v) explosive compaction

Pressureless compaction techniques

1. loose powder sintering in mould

In this method, the metal powder is vibrated mechanically into the mould, which is the negative impression of the product and heated to sintering temperature.

Applications

Highly porous filter materials made of bronze, stainless steel, and monel, porous nickel membrane for use as electrodes in alkaline storage batteries and fuel cells are typical examples

II) Slip cassting

A slip is a suspension of metal or ceramic powder (finer than 5 µm) in water or other soluble liquid which is pored into a mould, dried and further sintered.

- Steps in slip casting:

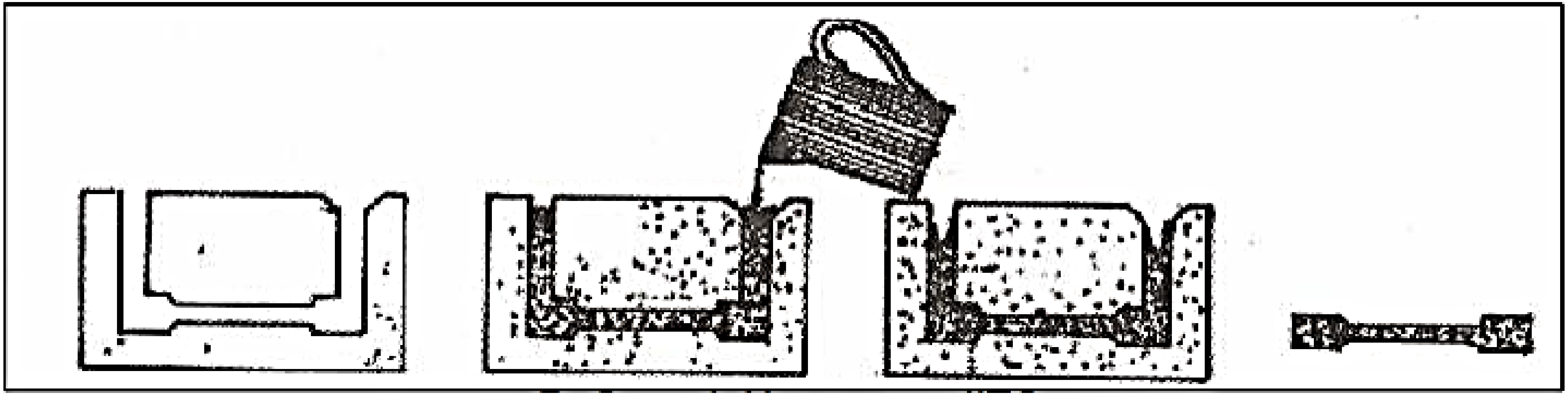
i) Preparing assembled plaster mould,
ii) filling the mould,
iii) absorption of water from the slip into the porous mould,
iv) removal of part from the mould,
v) trimming of finished parts from the mould

- Sometimes mould release agents like oil, graphite can be used.
- Hollow and multiple parts can be produced

Slip is usually made of,

1) a dispersion agent to stabilize the powder against colloidal forces,
2) a solvent to control the slip viscosity and facilitate casting,
3) a binder for giving green strength to the cast shape,
4) plasticizer to modify the properties of the binder

Applications: tubes, boats, crucibles, cones, turbine blades, rocket guidance fins; Also products with excellent surface finish like basins, water closets.



Assembled mould **Filling mould** **Absorption of water from slip** **Part removal**

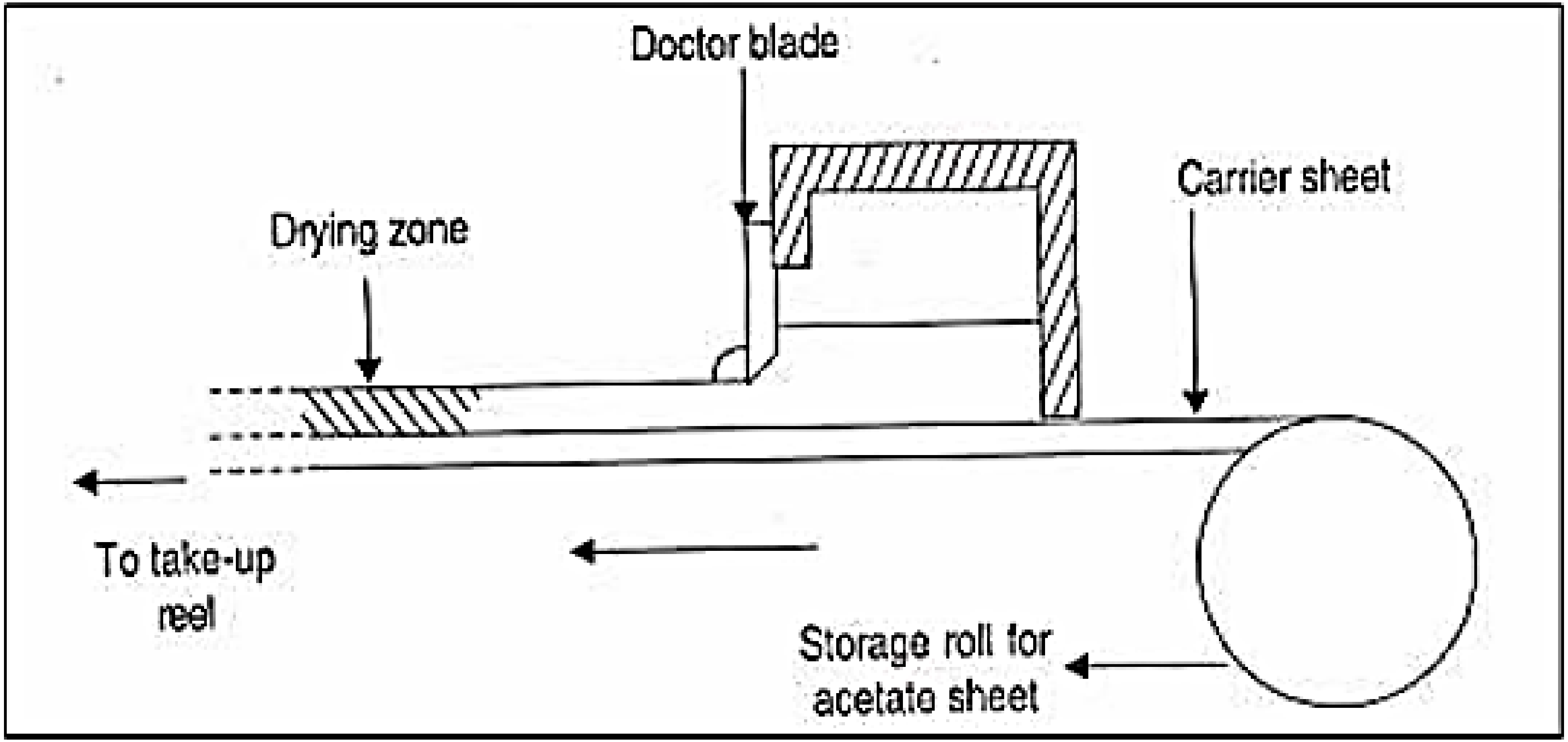
III) Slurry casting:

This process is similar to slip casting except that a slurry of metal powders with suitable liquids, various additives, and binders is poured into a mould and dried.

IV) Tape casting (doctor blade casting)

Process involves preparing a dispersion of metal or ceramic powder in a suitable solvent with the addition of dispersion agent (to improve the dispersion of the particles). Then a binder is added and fed to a reservoir. Whole mixture is fed on to a moving carrier film from the bottom of the reservoir.

This process can be used for making very thin tapes between 50 to 1000 µm thickness (stainless steel belt instead of carrier sheet). This method is used for making electronic substrates, dielectrics for capacitors and piezoelectric actuators.



Schematic of tape casting

V) Vibratory compaction:

Vibratory compaction uses vibration energy to compact the powder mass. During this process, smaller voids can be filled with particles of still smaller size and this sequence is carried out till a high packing density of powder is achieved even before consolidation.

- Important variables in vibratory compaction:

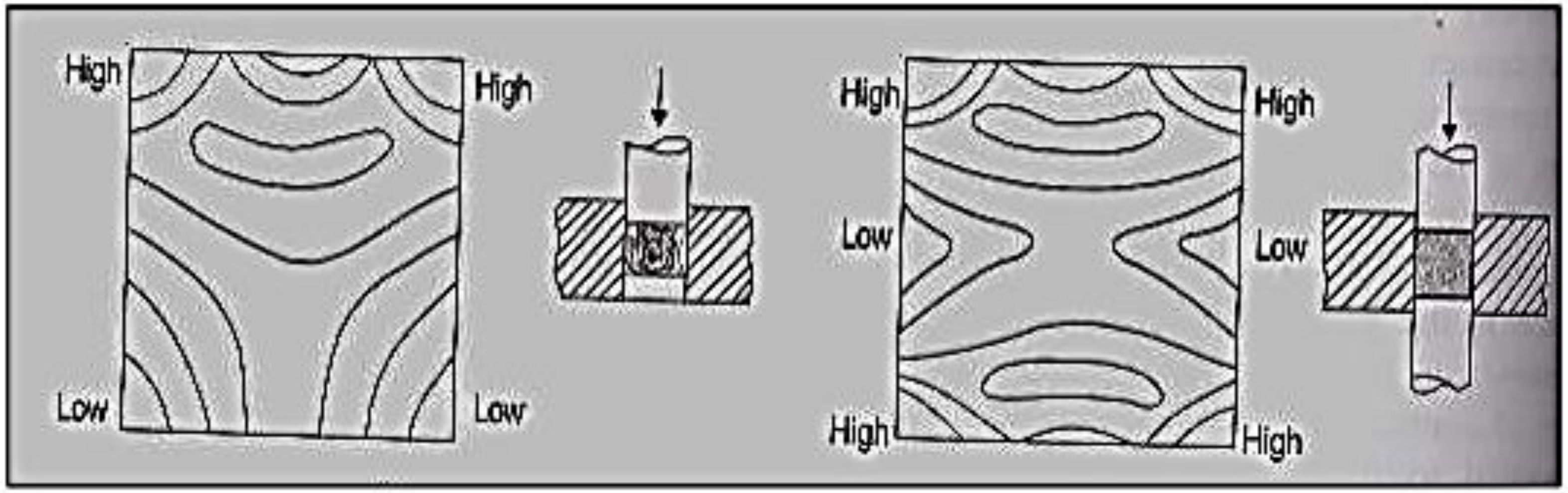
- 1. inertia of system: larger the system, more the energy required for packing
- 2. friction force between particles: more friction results in need of more KE for compaction
- 3. particle size distribution: more frequency required if more large particles are present. Vibration cycle is important and not period of vibration.

Pressure compaction techniques

Die compaction:

In this process, loose powder is shaped in a die using a mechanical or hydraulic press giving rise to densification. The mechanisms of densification depend on the material and structural characteristics of powder particles.

Single ended compaction

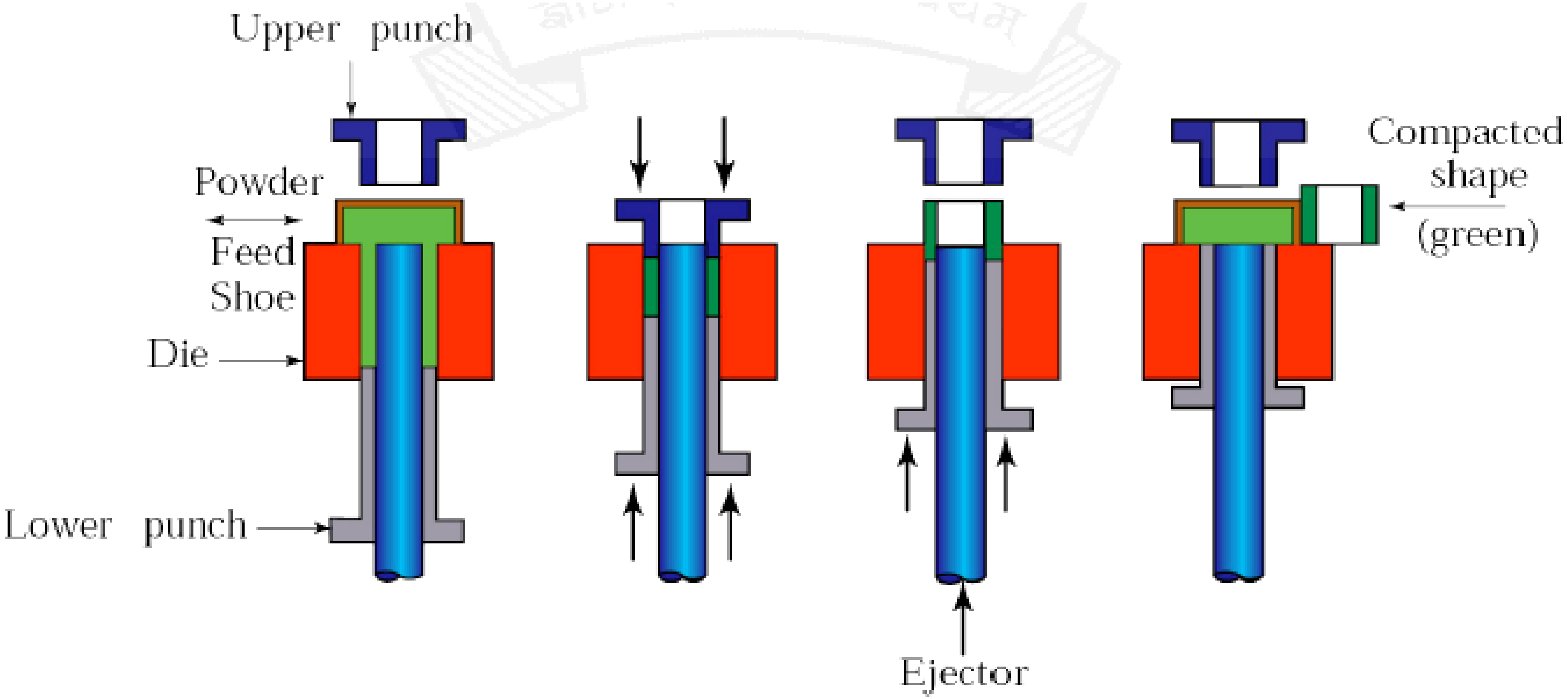


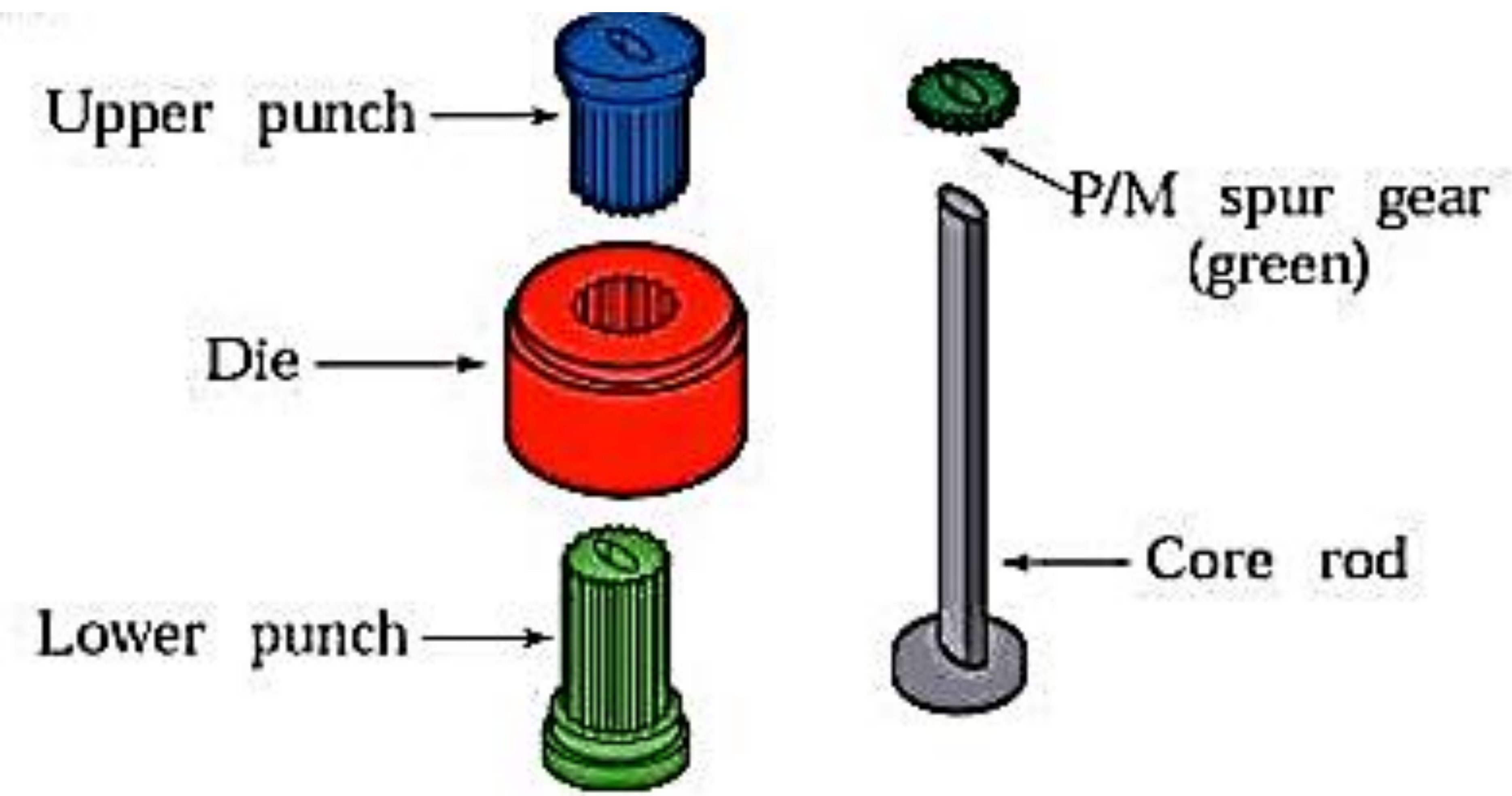
Double ended compaction

The *compaction* exercise imparts the following effects.

1. Reduces voids between the power particles and enhance the density of the consolidated powder,
2. Produces adhesion and bonding of the powder particles to improve green strength in the consolidated powder particles,
3. Facilitates plastic deformation of the powder particles to conform to the final desired shape of the part,
4. Enhances the contact area among the powder particles and facilitates the subsequent sintering process.

Compaction of metal powder to form a bushing





Upper punch
Die
Lower punch
P/M spur gear
(green)
Core rod

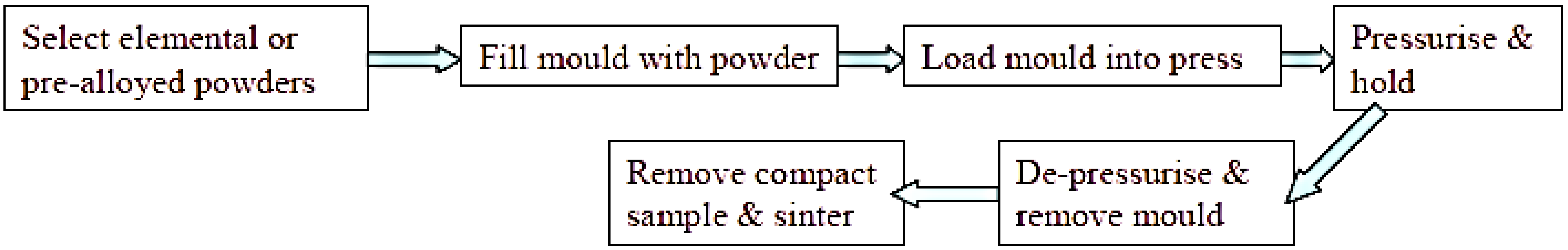
Cold isostatic compaction (CIP)

- CIP is a compaction process in which isostatic fluid pressure is applied to a powder mass at room temperature to compact it into desired shape.
- Powder parts can be compacted up to 80-90 % of their theoretical densities.
- Water or oil can be used as pressuring medium.

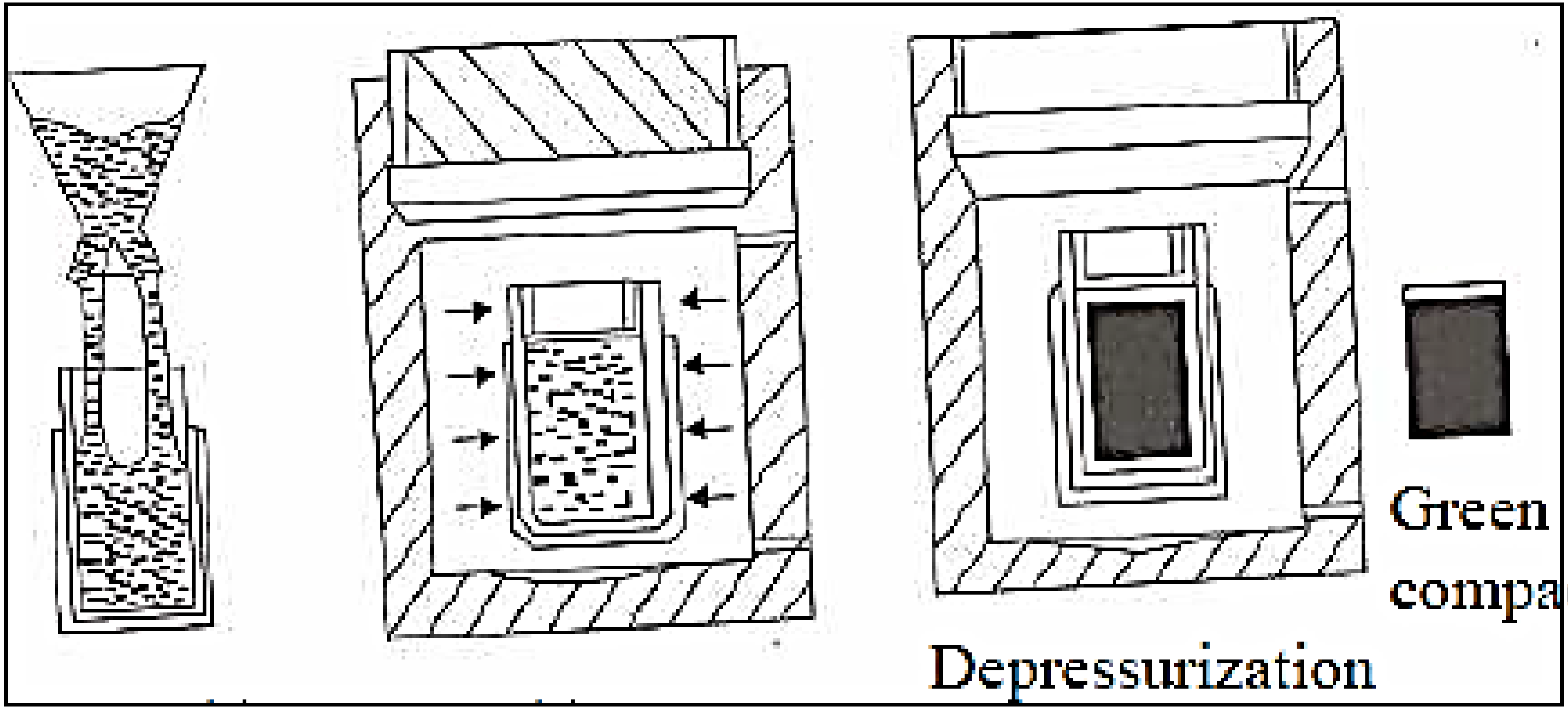
Process details: High density near-net shape green parts, long thin walled cylinders, parts with undercuts can be readily fabricated.

In this process, pressure is applied simultaneously and equally in all directions using a fluid to an elastomeric fluid with powder at room temperature.

Sintered CIP component can reach up to 97 % of theoretical density.

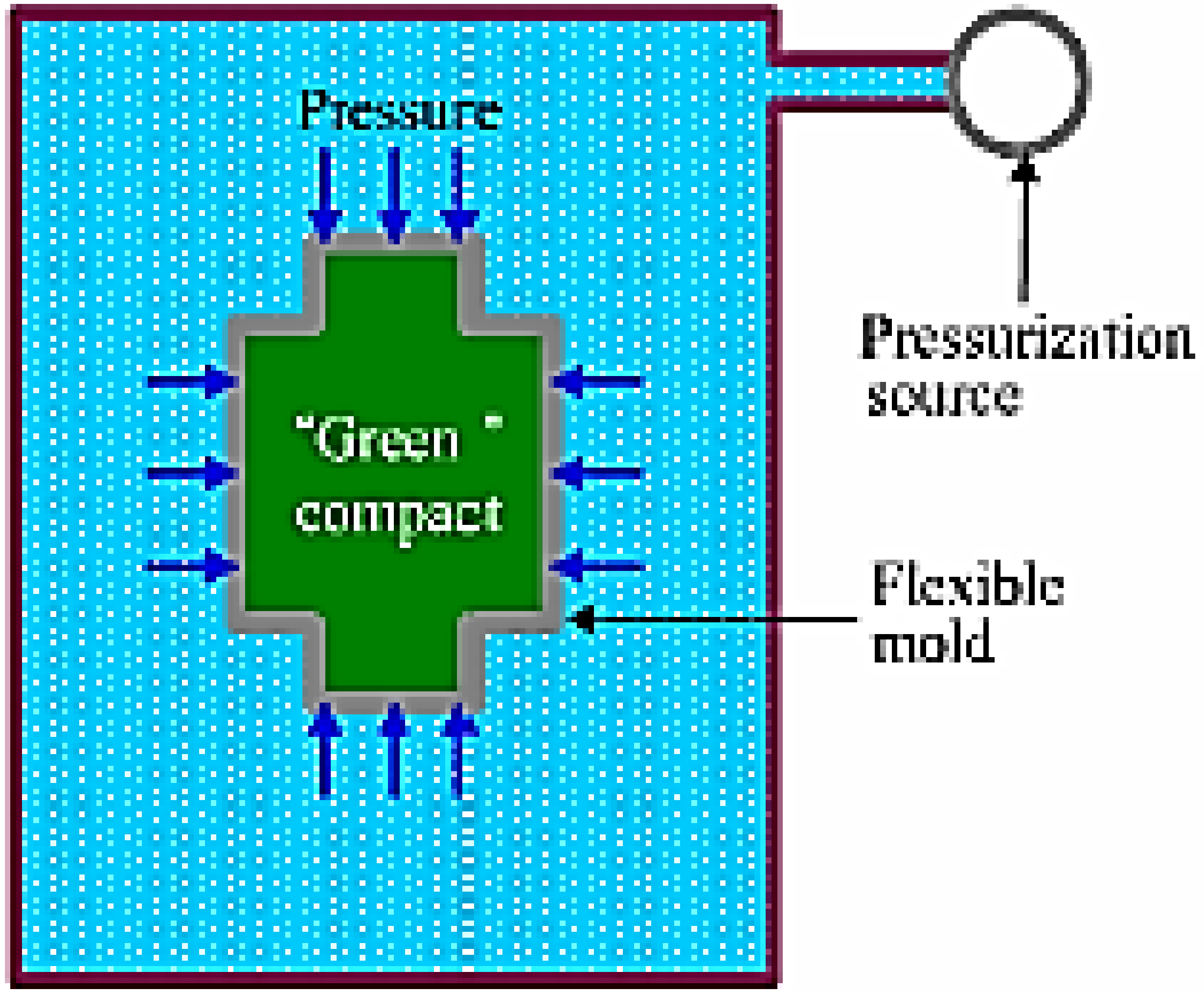


STEPS INVOLVED IN CIP



Mould filling Mould pressurization

Cold isostatic pressing



Types of cold isostatic pressing

Wet bag process: In this, the mould is directly in contact with the fluid. This reduces the productivity, since the bag has to be removed every time before refilling. Tooling costs are reduced in this.

Fixed mould process: the mould is fixed in the pressure vessel and powders are filled. The tooling has internal channel into which fluid is pumped. This is an automated process in which the powder filling, compaction, depressurization and removal of green parts are done continuously. This involves higher tooling cost, but has higher production rate.

Advantages of CIP:

- Uniform, controlled, reproducible densification of powder;
- long, slender parts can be pressed;
- neat net shape forming;
- short production times;
- economy of operation for complex and large parts.

Applications:

Metallic filters made from bronze, brass, stainless steel, Inconel, Monel, Titanium, high speed tools, carbide tools.

Also ceramic parts such as sparks plugs and insulators are made by this method.

Hot isostatic pressing

- HIP is the application of pressure at elevated temperatures to obtain net or near net shape parts from metal, ceramic, cermet powders.

HIP unit consists of a pressure vessel, high temperature furnace, pressurizing system, controls and auxiliary systems (material handling, vacuum pumps, metering pumps).

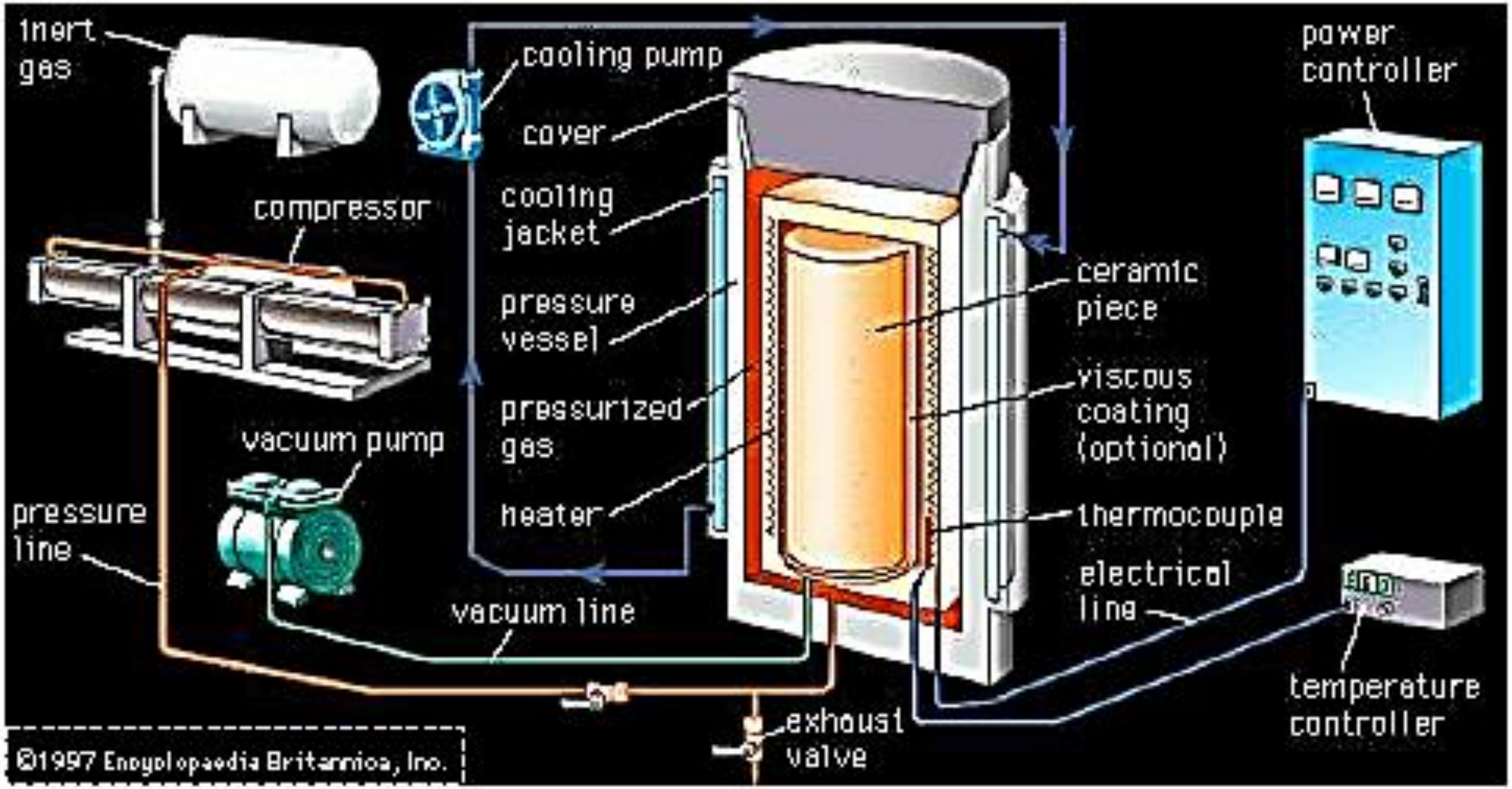
- The pressure vessel is made of low alloy steel.
- Its function is to heat the powders while applying uniform gas pressure on all the sides.
- Furnaces are of radiation or convection type heating furnaces with graphite or molybdenum heating elements. Nichrome is also used.
- Furnace heats the powder part, while pressurizing medium (a gas) is used to apply a high pressure during the process.

Generally, argon, nitrogen, helium or even air is used as pressurizing medium.

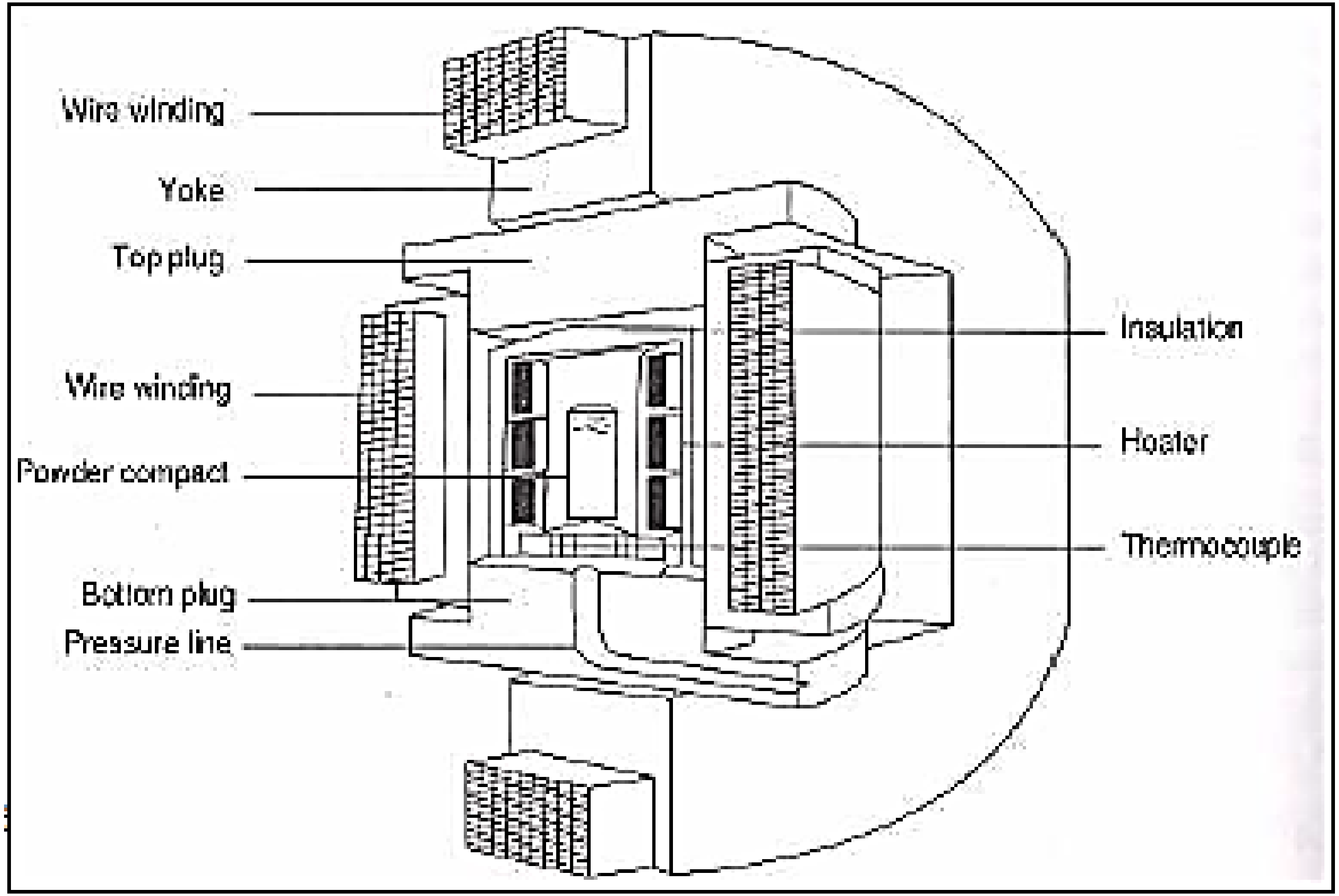
Ideal method for consolidation of powders of nickel and cobalt base super alloys, tool steels, maraging steels, titanium alloys, refractory metal powders, cermets.

It has got variety of applications including bonding of dissimilar materials, consolidation of plasma coatings, processing hard and soft magnetic materials etc.

HIP UNIT- used for ceramic material



Schematic of HIP UNIT (cross-section)



HIP presses are available in diameters up to 2m with pressures ranges from 40 to 300 MPa with temperature range from 500 to 2200 °C. The processing time can last up to 4 hours depending on the material and size of the part.

Commonly used heating elements:

Kanthal heating element – up to 1200 °C;

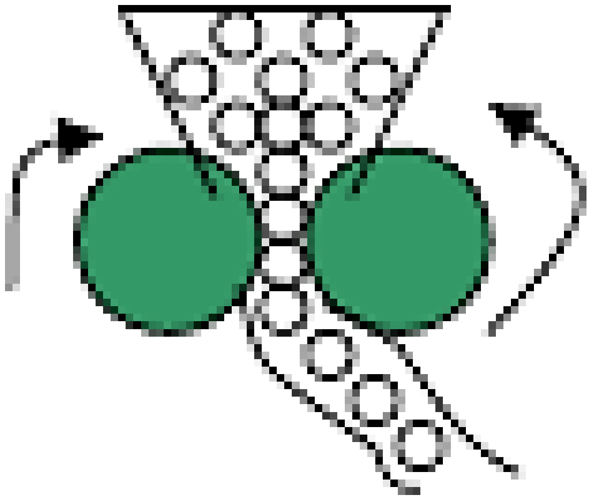
Molybdenum heating element – 1200 to 1700 °C;

Graphite heating element – 2000 to 2600 °C

Powder rolling

This process involves feeding of powders between rolls to produce a coherent and brittle green strip.
This green strip is then sintered & re-rolled to obtain a dense, finished product.

Steps: 1) preparation of green strip,
2) sintering,
3) densification of sintered strip,
4) final cold rolling and annealing

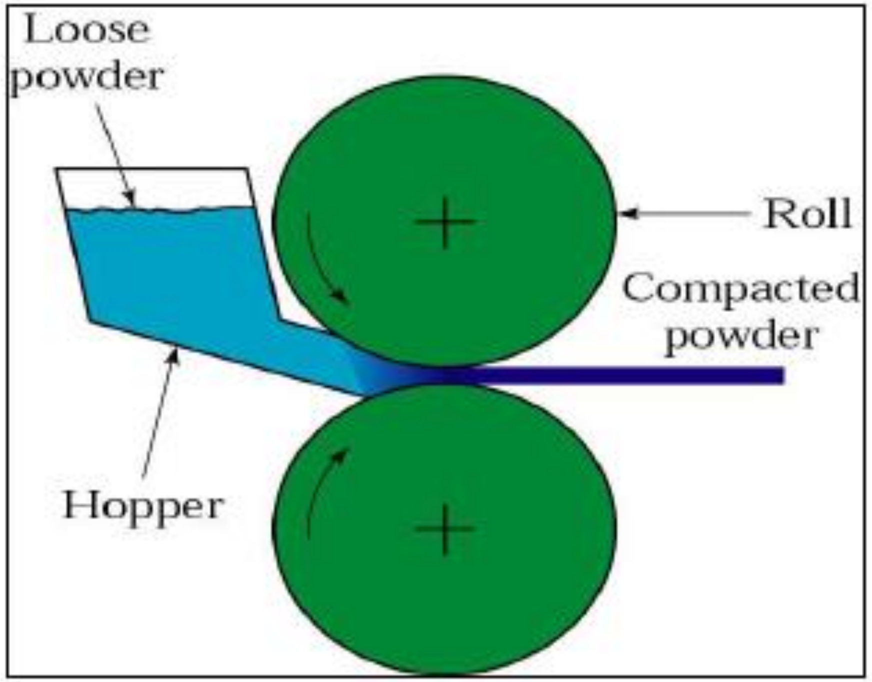


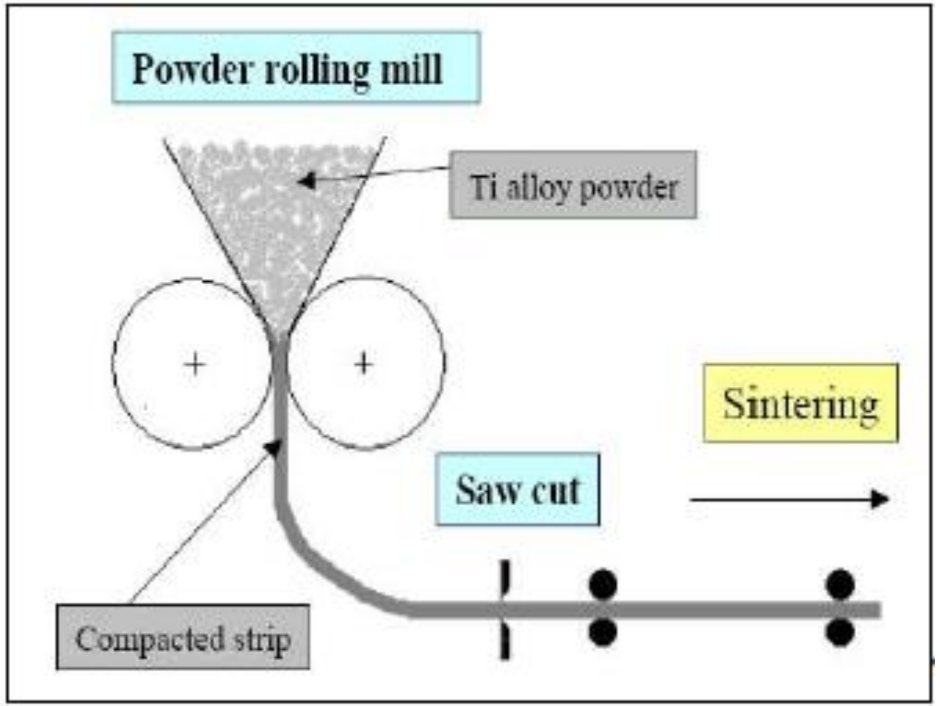
Parameters affecting powder rolling are roll gap, roll diameter, roll speed, powder characteristics;

Roll gap => large roll gap leads to decrease in green density; very small roll gap leads to edge cracking;
roll diameter => increase in density and strength with increase in roll dia. for a given strip thickness;
roll speed => Kept low, 0.3-0.5 m/s;
Powder => irregular powder with rough surfaces provide better strip density

Applications:

nickel strips for coinage,
nickel-iron strips for controlled expansion properties,
Cu-Ni-Sn alloys for electronic applications,
porous nickel strip for alkaline batteries and fuel cell applications.





12" wide Ti-6Al-4V strip

Sintering

Sintering refers to the heating of the compacted powder perform to a specific temperature (*below the melting temperature of the principle powder particles while well above the temperature that would allow diffusion between the neighbouring particles*).

Sintering facilitates the bonding action between the individual powder particles and increase in the strength of the final part. The heating process must be carried out in a controlled, inert or reducing atmosphere or in vacuum for very critical parts to prevent oxidation.

Bonding among the powder particles takes places in three ways:

(1)*melting of minor constituents in the powder particles*,

(2)*diffusion between the powder particles*, and

(3)*mechanical bonding*.

The *time*, *temperature* and *the furnace atmosphere* are the three critical factors that control the *sintering process*.

Types of sintering:

a) Solid state sintering
b) Liquid phase sintering
c) Activated sintering
d) Reaction sintering

Solid state sintering –

In this, densification occurs mainly because of atomic diffusion in solid state.

Liquid phase sintering – The densification in improved by employing a small amount of liquid phase (1-10% vol).

The liquid phase existing within the powders at the sintering temperature has some solubility for the solid. Sufficient amount of liquid is formed between the solid particles of the compact sample.

During sintering, the liquid phase crystallizes at the grain boundaries binding the grains. During this stage, there is a rapid rearrangement of solid particles leading to density increase.

In later stage, solid phase sintering occurs resulting in grain coarsening and densification rate slows down.

Used for sintering of systems like tungsten-copper and copper-tin. Also covalent compounds like silicon nitride, silicon carbide can be made, that are difficult to sinter.

Activated sintering – In this, an alloying element called ‘doping’ is added in small amount improves the densification by as much as 100 times than undoped compact samples.

Example is the doping of nickel in tungsten compacts

Reaction sintering – In this process, high temperature materials resulting from chemical reaction between the individual constituents, giving very good bonding.

Reaction sintering occurs when two or more components reacts chemically during sintering to create final part.

A typical example is the reaction between alumina and titania to form aluminium titanate at 1553 ***K*** *which then sinters to form a densified product.*

Stages in solid state sintering (3 stages)

1st stage:

Necks are formed at the contact points between the particles, which continue to grow.

During this rapid neck growth takes place. Also the pores are interconnected and the pore shapes are irregular.

2nd stage: In this stage, with sufficient neck growth, the pore channels become more cylindrical in nature. The curvature gradient is high for small neck size leading to faster sintering.

With sufficient time at the sintering temperature, the pore eventually becomes rounded. As the neck grows, the curvature gradient decreases and sintering also decreases.

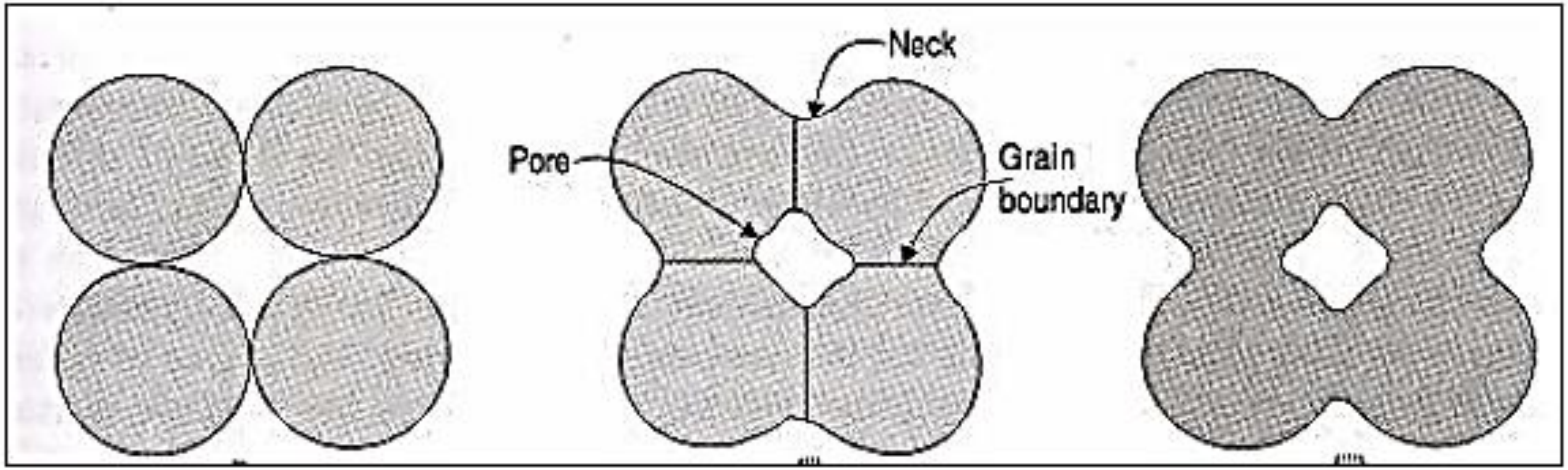
This means there is no change in pore volume but with change in pore shape => pores may become spherical and isolated.

With continued sintering, a network of pores and a skeleton of solid particle is formed.

The pores continue to form a connected phase throughout the compact.

3rd or final stage: In this stage, pore channel closure occurs and the pores become isolated and no longer interconnected.

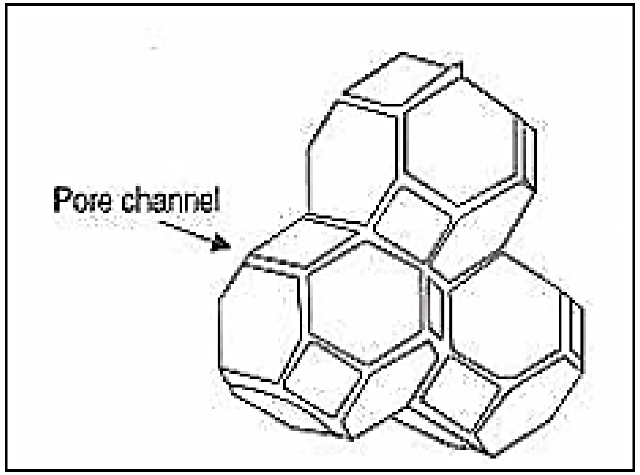
Porosity does not change and small pores remain even after long sintering times.



Particles in contact

Formation of necks, grain boundaries, pores

Final sintered geometry



Pore channel formation

Sintering theory

Sintering may involve,

1) single component system
2) multi-component system (involve more than one phase)

Single component system - self-diffusion is the major material transport mechanism and the driving force resulting from a chemical potential gradient due to surface tension and capillary forces between particles

Multi component system - inter-diffusion occurs with the concentration gradient being the major driving force for sintering in addition to self-diffusion caused by surface tension and capillary forces. IN this sintering, liquid phase formation and solid solution formation also occurs with densification.

First theory was proposed by Sauerwald in 1922

Adhesion and recrystallization - Adhesion occurs during heating due to atomic attraction and recrystallisation occurs at recrystallisation temperature (above 0.5 T_m).

In recrystallisation, microstructure changes, phase changes, grain growth, shrinkage occurs.

Solid state sintering process

Condition for sintering: Densification occurs during sintering and solid state sintering is carried out at temperatures where material transport due to diffusion is appreciable.
Surface diffusion is not sufficient, atomic diffusion is required.

This occurs by replacing high energy solid-vapour interfaces with the low energy solid-solid interface (particle-particle) of free energy.
This reduction in surface energy causes densification.

Initially free energy of solid-solid interface must be lower than free energy of solid vapour interface. The process of sintering will stop if the overall change in free energy of the system (dE) becomes zero

Driving force for sintering

- The main driving force is excess surface free energy in solid state sintering. The surface energy can be reduced by transporting material from different areas by various material transport mechanisms so as to eliminate pores.

- Material transport during solid state sintering occurs mainly by surface transport, grain boundary transportation.

This surface transport can be through adhesion, surface diffusion.

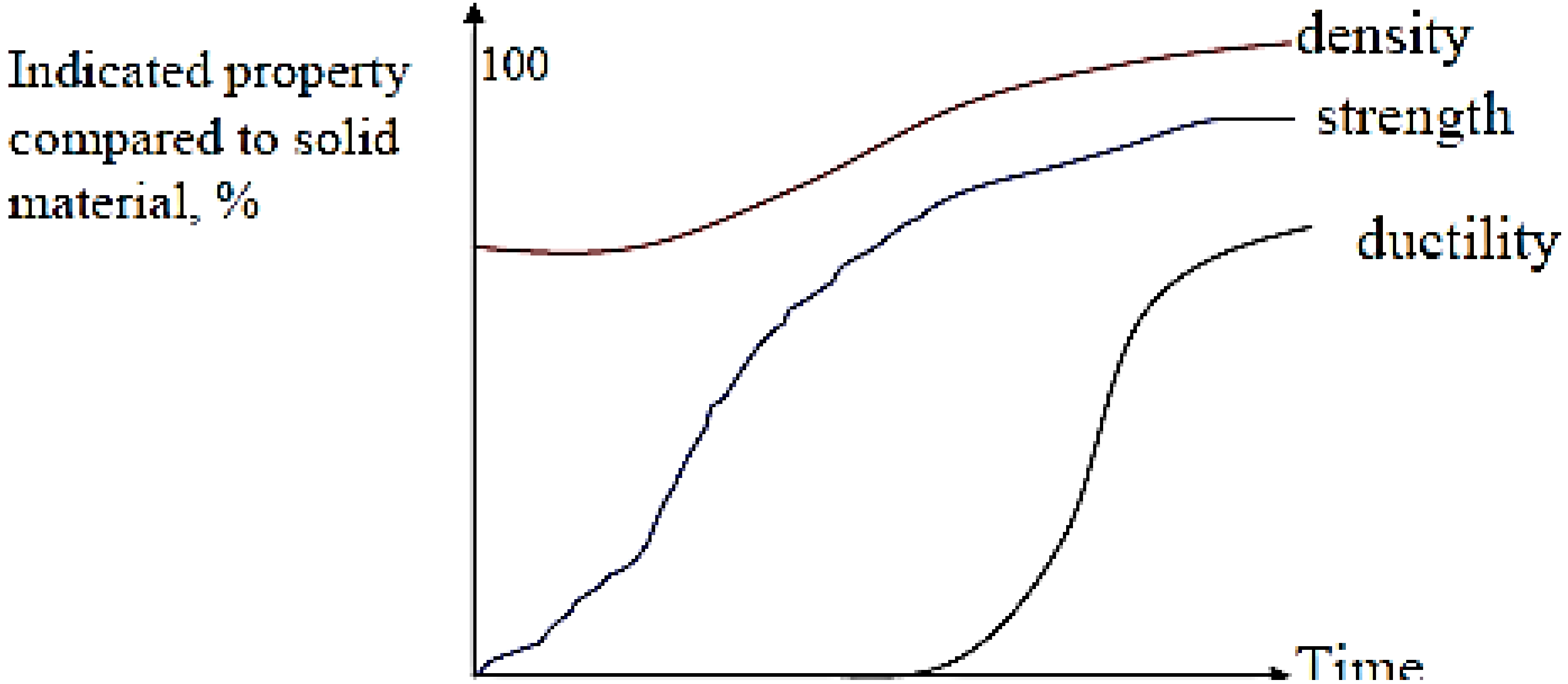
Many models available to describe sintering process – like viscous flow, plastic flow, grain boundary and volume diffusion models.

Property changes during sintering

- Densification is proportional to the shrinkage or the amount of pores removed in the case of single component system

- In multicomponent system, expansion rather than shrinkage will result in densification and hence densification can not be treated as equal to the amount of porosity removed.

- Densification results in mechanical property change like hardness, strength, toughness, physical properties like electrical, thermal conductivity, magnetic properties etc. Also change in composition is expected due to the formation of solid solution


Indicated property compared to solid material, %
100
density
strength
ductility
Time

Sintering atmosphere

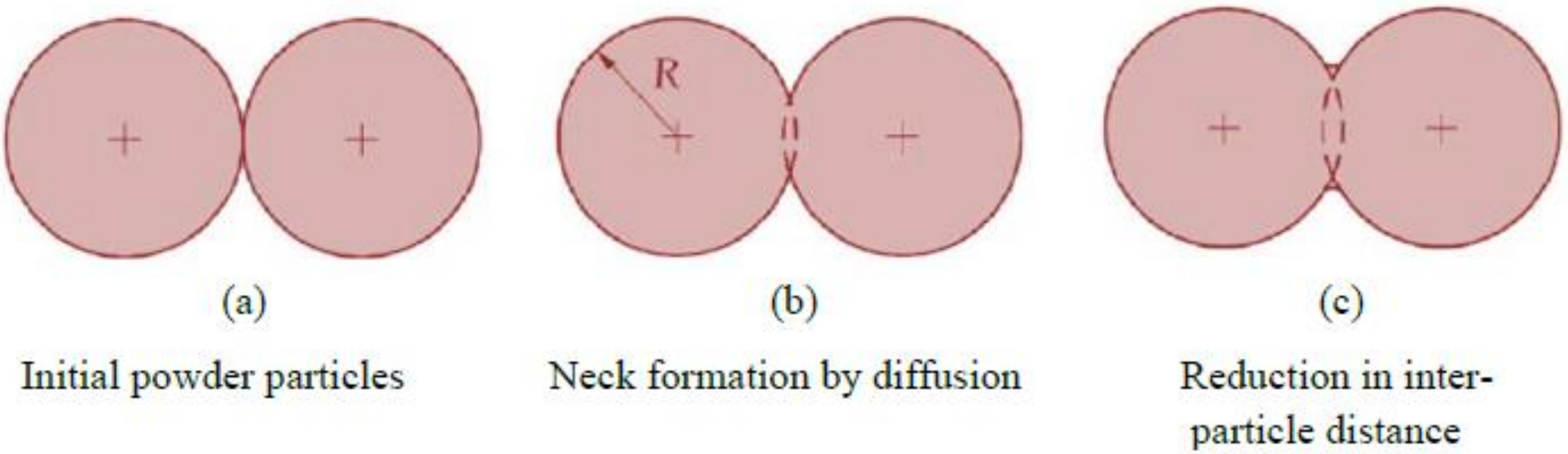
Functions of sintering atmosphere:

1. preventing undesirable reactions during sintering,
2. facilitate reduction of surface oxides,
3. facilitating the addition of other sintering and alloying elements which enhance the sintering rate and promote densification,
4. aiding the removal of lubricants,
5. composition control and adjusting the impurity levels.

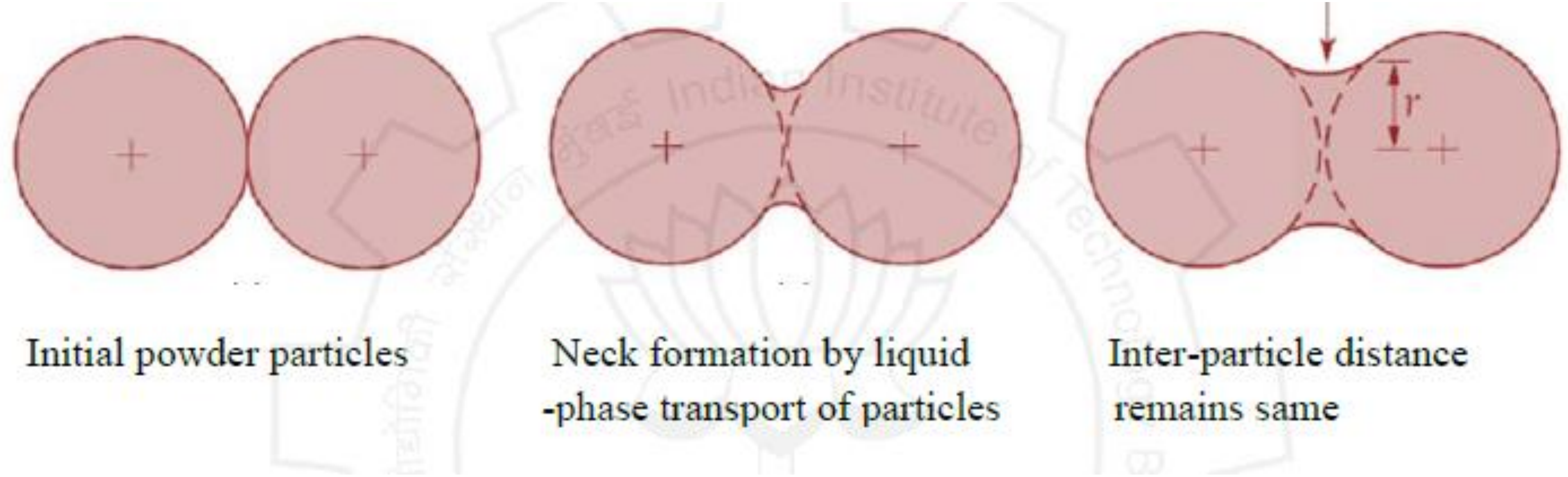
Eg. for sintering atmosphere: pure hydrogen, ammonia, reformed hydrocarbon gases, inert gases, vacuum, nitrogen based mixtures without carburizing addition, nitrogen based mixtures with carburizing addition

Type of transport	**Material transport mechanism**	**Driving force**
Vapour phase	Evaporation-condensation	Vapour pressure gradient between convex and concave regions
Sold state	Diffusion – surface diffusion Grain boundary diffusion, volume diffusion, viscous flow, plastic flow	Chemical potential Chemical potential Chemical potential
Liquid phase	Viscous flow	Surface tension

Schematic illustration of sintering of compact preform using solid-state diffusion between powder particles



Schematic illustration of sintering of compact preform using liquid-phase transport between powder particles



Mechanism in solid state sintering

1. Evaporation condensation,
2. diffusion (can be volume diffusion, grain boundary diffusion, surface diffusion),
3. viscous flow,
4. plastic flow

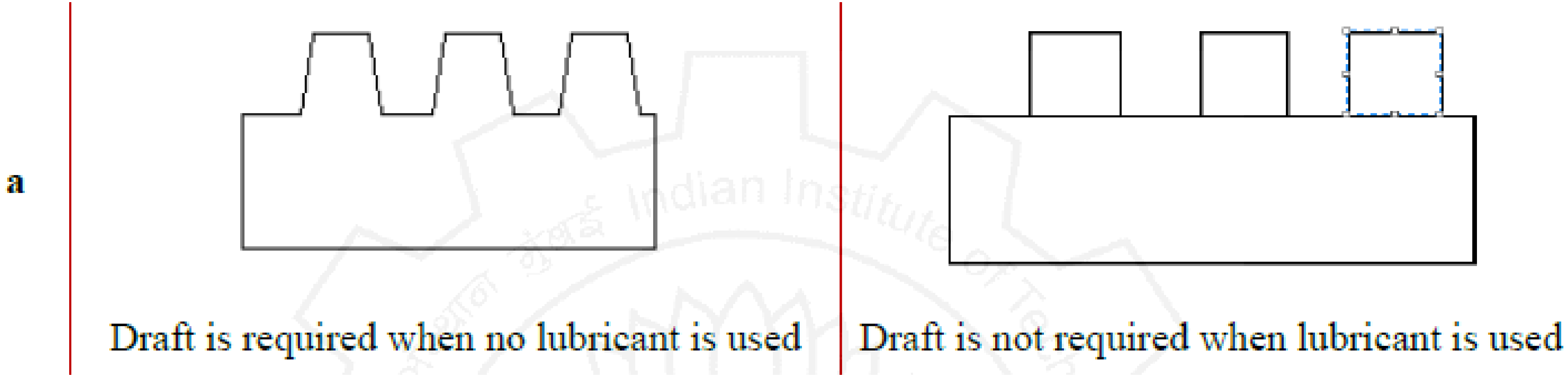
Finishing Operation

After sintering, some finishing operations such as *re-pressing* (*to impart dimensional accuracy*) and *machining* are carried out to further improve the quality of the final part.

Parts made through the powder metallurgy based processes are also subjected to other finishing operations such as heat treatment, machining and finishing depending on the requirements.

Design for Powder Metallurgy

Design must be such that the part can be ejected from the mould or die. Parts with straight wall are preferred. No draft should be required for the ejection of a part from a lubricated die



In designing the part, consideration should be given to the need for the powder particles to flow properly into all parts of the mould or die. Therefore, thin walls, narrow splines, or sharp corner should be avoided (should be thicker than 0.762 mm).

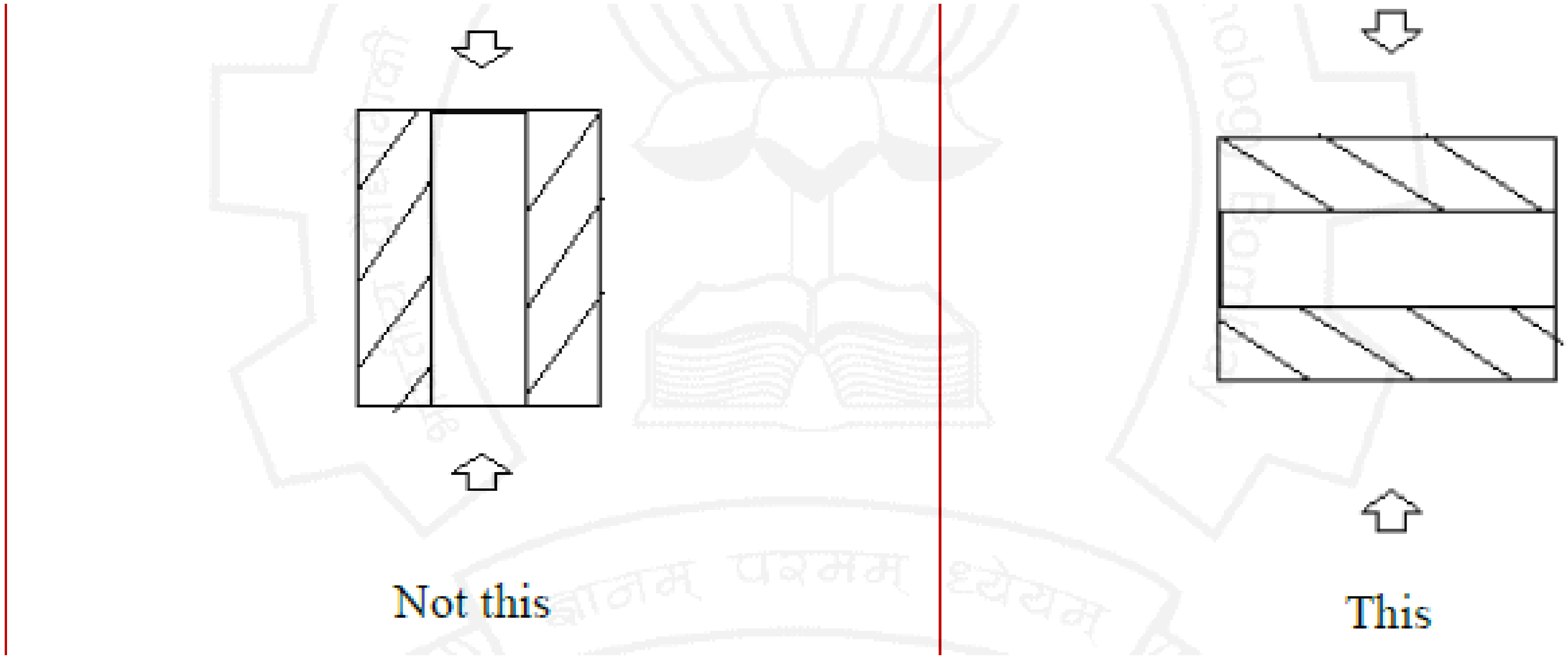
The shape of the part should permit the construction of strong tooling. Dies and punches should have no sharp edges. Reasonable clearance must be provided between the top and the bottom dies during pressing.

Since pressure is not transmitted uniformly through a deep bed of powder, the length of the part should not exceed about two and half times of the diameter.

Very close tolerance in the direction of compression should be avoided.

Shape of the parts should be kept as simple as possible and should contain with few levels and axial variation. Holes should not be designed in the direction of pressing

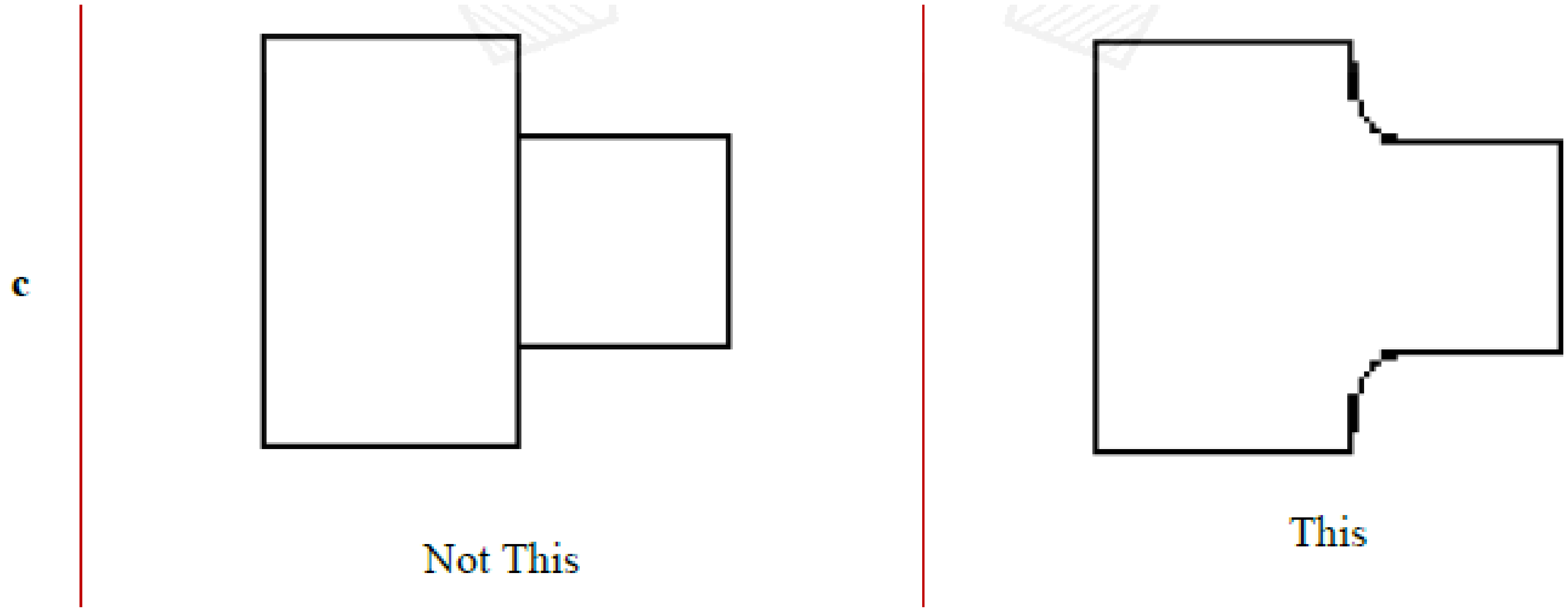
b



Provide sufficiently wide dimensional tolerance whenever possible. Wide tolerance means that the part can be made more economically with a longer tool life.

In designing flat section of high density, enough section thickness should be provided otherwise the punch may break under pressure.

Parts made through powder metallurgy may be bonded by assembling in the green condition and then sintering together to form a bond assembly.



As far as possible, abrupt changes in the section thickness should be avoided.