SNS COLLEGE OF TECHNOLOGY

Department of Mechanical Engineering

19MEE307 Additive Manufacturing

UNIT III PHOTO POLYMERIZATION AND POWDER BED FUSION PROCESSES

Theory:

Photo polymerization: **SLA-Photo curable materials** – **Process - Advantages and Applications**. **Powder Bed Fusion**: **SLS-Process description** – **powder fusion mechanism** – **Process Parameters** – Typical Materials and Application. Electron Beam Melting.

Prof.Dr.MSUBRAMANIAN

Vat polymerization process

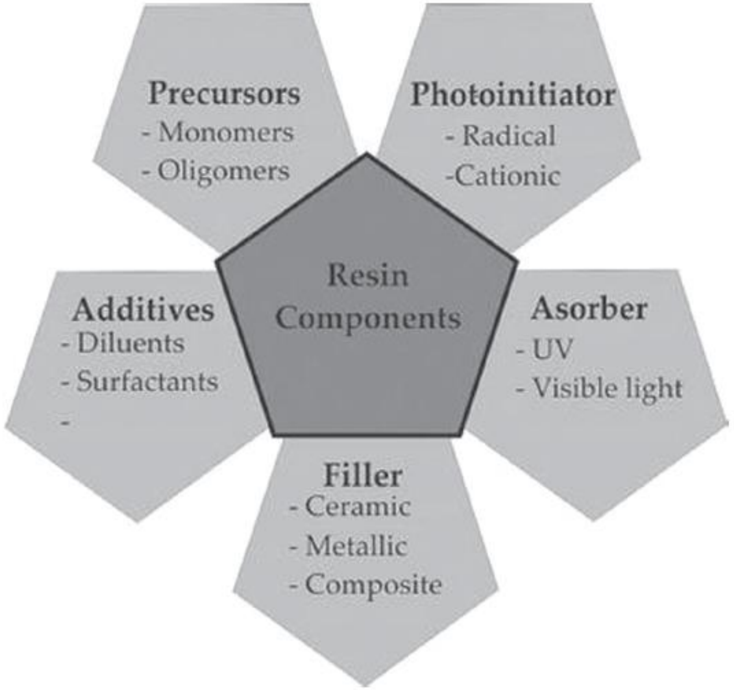
Vat photopolymerization is an additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization”

SLA was first used for plastic part creation. However, with the passage of time this technique has proven its versatility in fabrication of a variety of intricate and customized parts. The SLA process is capable of making parts from metals, ceramics, plastics, composites and so on.

AM processes using vat photopolymerization in terms of various material related aspects including: precursors, photoinitiators, absorbers, filled resins, additives and post-processing; details of the photopolymerization process; process modelling aspects; variants and classification of the vat photopolymerization process, including free and constrained surface approach, Laser-SLA, digital light processing SLA process (DLP-SLA), liquid crystal display stereolithography (LCD-SLA)

Materials

Vat photopolymerization processes use plastics as well as polymeric materials, especially UV-curable photopolymeric resins. An example of resins used with these processes is the Visijet range (3D systems). There are various integral parts of any photocurable SLA resin which include precursor, hoto initiator, additives, absorber and filler as shown in Figure



Resin Components in SLA.

Precursors

These are liquid molecules that link mutually or polymerize when exposed to light for obtaining solid three-dimensional network. Monomers, oligomers, prepolymers, etc. can be utilized based upon specific requirements. Acrylate-based resins which are based upon radical photopolymerization possess high reactivities and are available in different types based upon the number of reactive groups or oligomer types for specific requirements of mechanical and thermal resistances.

Photoinitiators

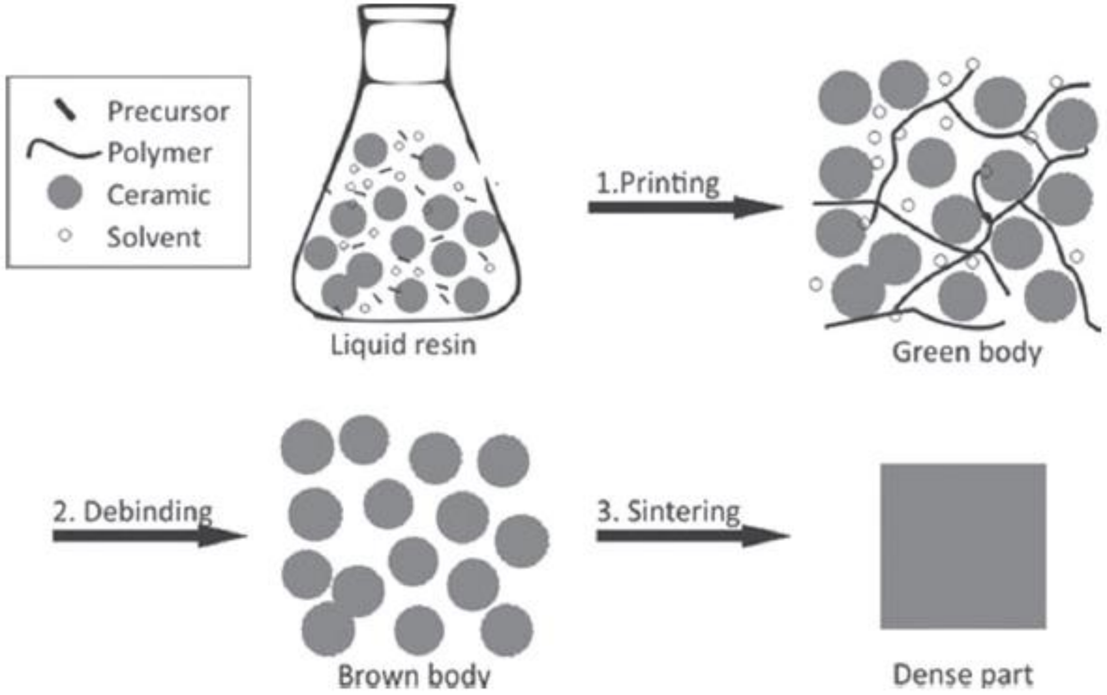
Photoinitiators (PIs) are reactive to light. Irradiation of PIs with lights of the
right wavelength leads to their excitation and thus initiation of the curing reaction. Correct choice of PI is therefore important and also depends on precursor type. It also effects a number of important SLA characteristics including kinetics, cross-linking density, mechanical characteristics, etc. to name a few.

Absorbers

Absorbers limit light penetration beyond the desired cure depths. Benzotriazole derivative is a common UV absorber. A precise control is very important for intricate geometries with overcuts otherwise feature loss will result

Filled Resins

Resins are filled with powders to fabricate metal/ceramic parts. After filling resins with powders, the parts are printed using the standard vat photopolymerization technique, debinded for removal of organic resin parts via pyrolysis and sintered using heat treatment to obtain final dense parts. This process is shown in Figure



Typical Steps in Fabrication of Dense SLA Ceramic Parts Using Filled Resins.

Shrinkage coefficients of different metals need to be taken into account for specific geometrical requirements. To minimize shrinkage, high filler amounts are required. It should be kept in mind that size of particle should be smaller than layer height. If the size of particles approaches the wavelength of incident light, then scattering phenomenon becomes important and needs to be effectively dealt with in obtaining final cure depth and accuracy.

If nano-sized particles are added, then the properties of parts obtained can be further improved.

Additives

Many additives are added to counteract the negative effects of high-volume fraction of solid loading that can change resin flow behavior, affect coating mechanism, increase requirement of mechanical forces for lifting platform and so on. Rheological additives as well as stabilizers are added which can enhance solid loading, their shelf life as well as stability. The particles agglomerate and sediment during the process, which can be prevented by using oligomeric surfactants, oleic acid (long chain acid) or phosphine oxides to obtain homogeneity in ceramic/metal powder distribution.

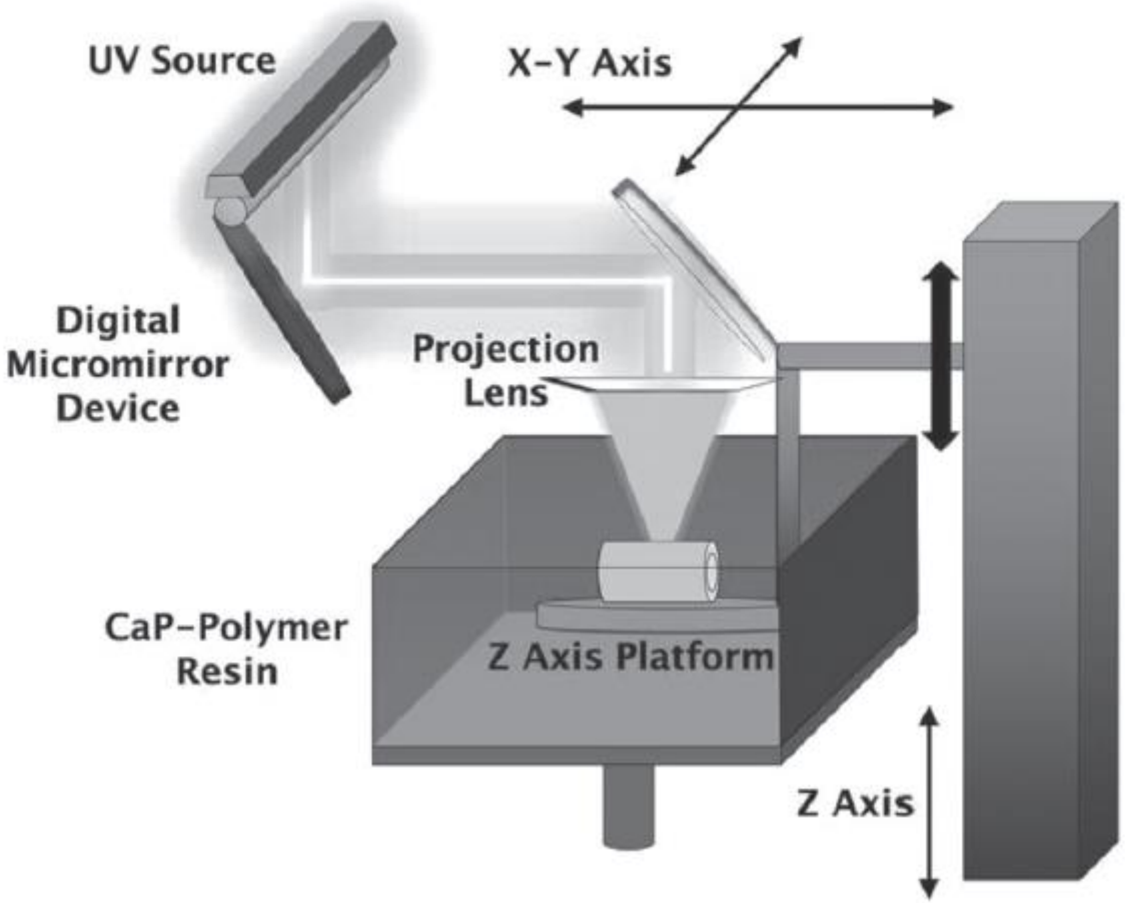
Post-Processing

When the part is removed from the build platform, support structures are eliminated from it. This involves cleaning in solvents, drying of structures and then sanding. The parts are then cured in a UV chamber to obtain enhanced mechanical characteristics. Debinding and sintering are considered as post-processing steps in the case of filled resins.

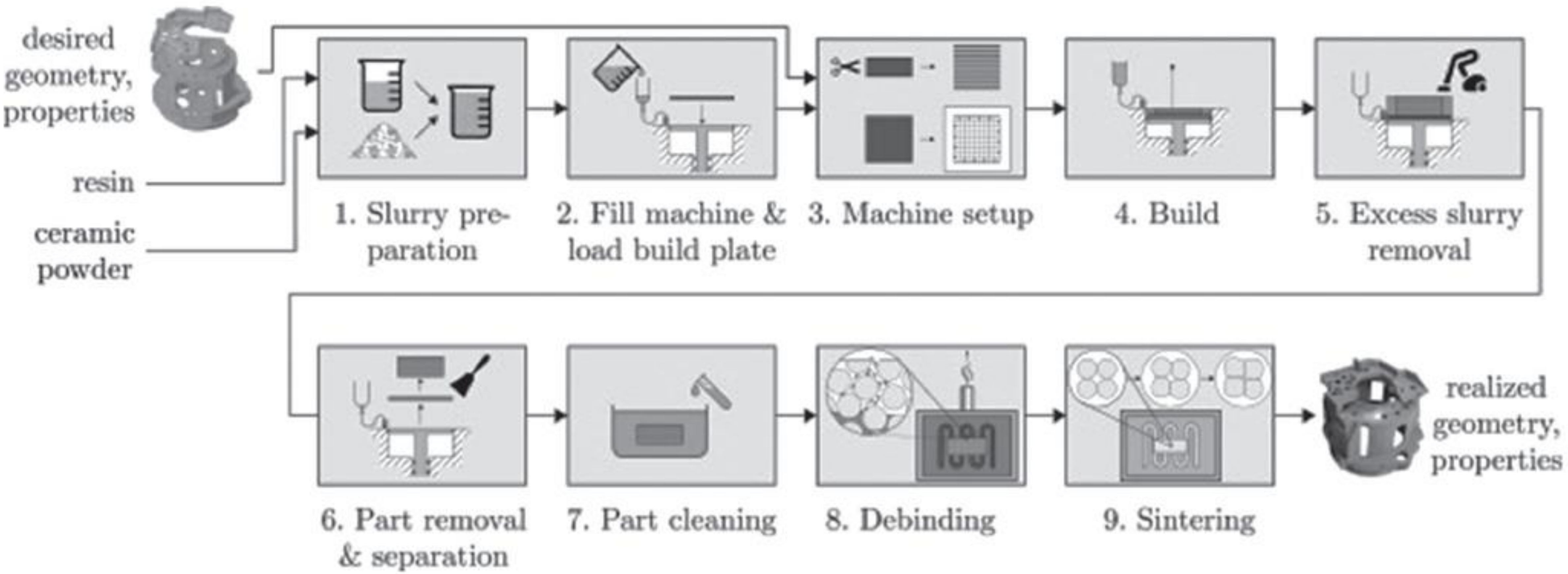
Photopolymerization Process

These systems utilize a vat of liquid photopolymer resin. Layers are obtained by curing or hardening this resin using ultraviolet (UV light) adjusted through motor-controlled mirrors according to a predefined scan strategy.

A photo initiator (PI) molecule is responsive to incident light in a fashion that it initiates a localized chemical photopolymerization reaction and hence curing. The platform holding the vat lowers each time a new layer is required to be cured. This process of layered artefact creation is common to all SLA processes.



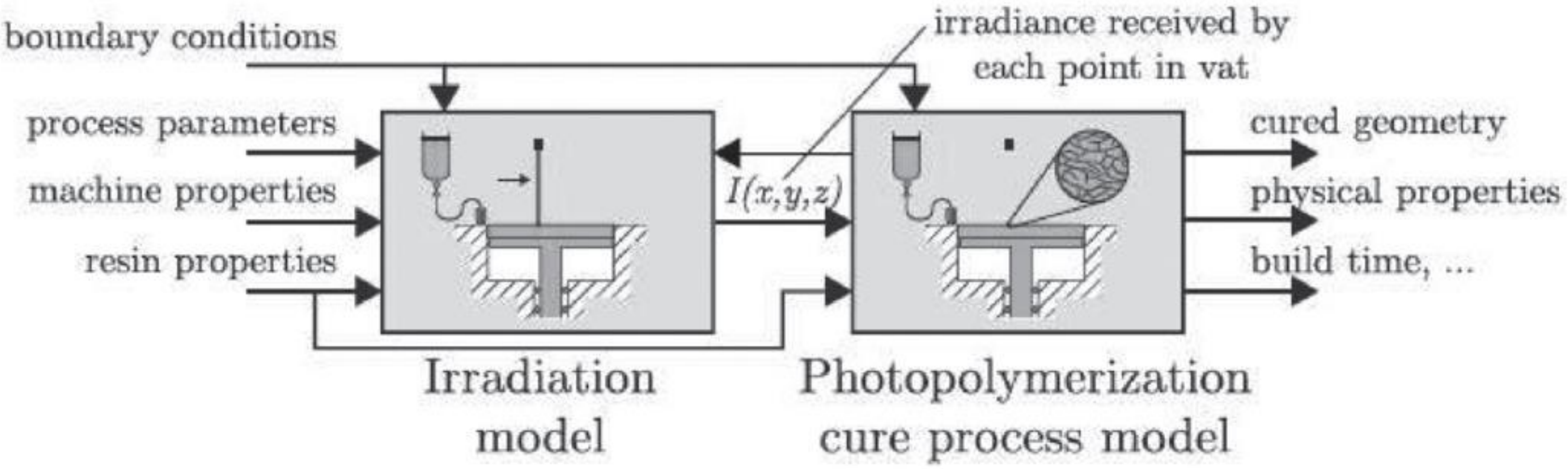
Schematic of Vat Photopolymerization



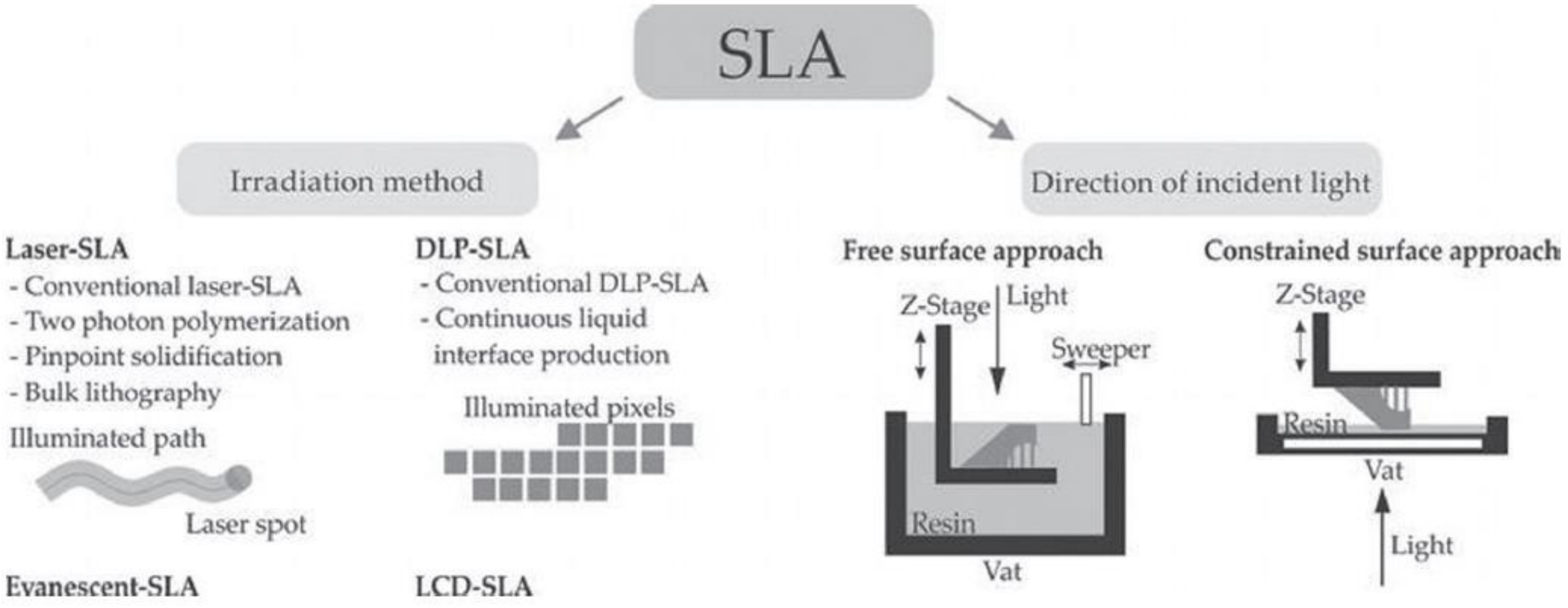
Vat Photopolymerization Process Chain

The main steps of the vat photopolymerization process are defined below:

1. Lowering of build platform from resin vat top by one-layer thickness
2. Curing of resin by UV light and subsequent lowering of platform to accommodate next layer
3. Smoothening of resin to provide base for next layer
4. Draining of resin from vat
5. Removal of part
6. Removal of support
7. Post-curing.



Block Diagram for Process Modelling of Photopolymerization Model.

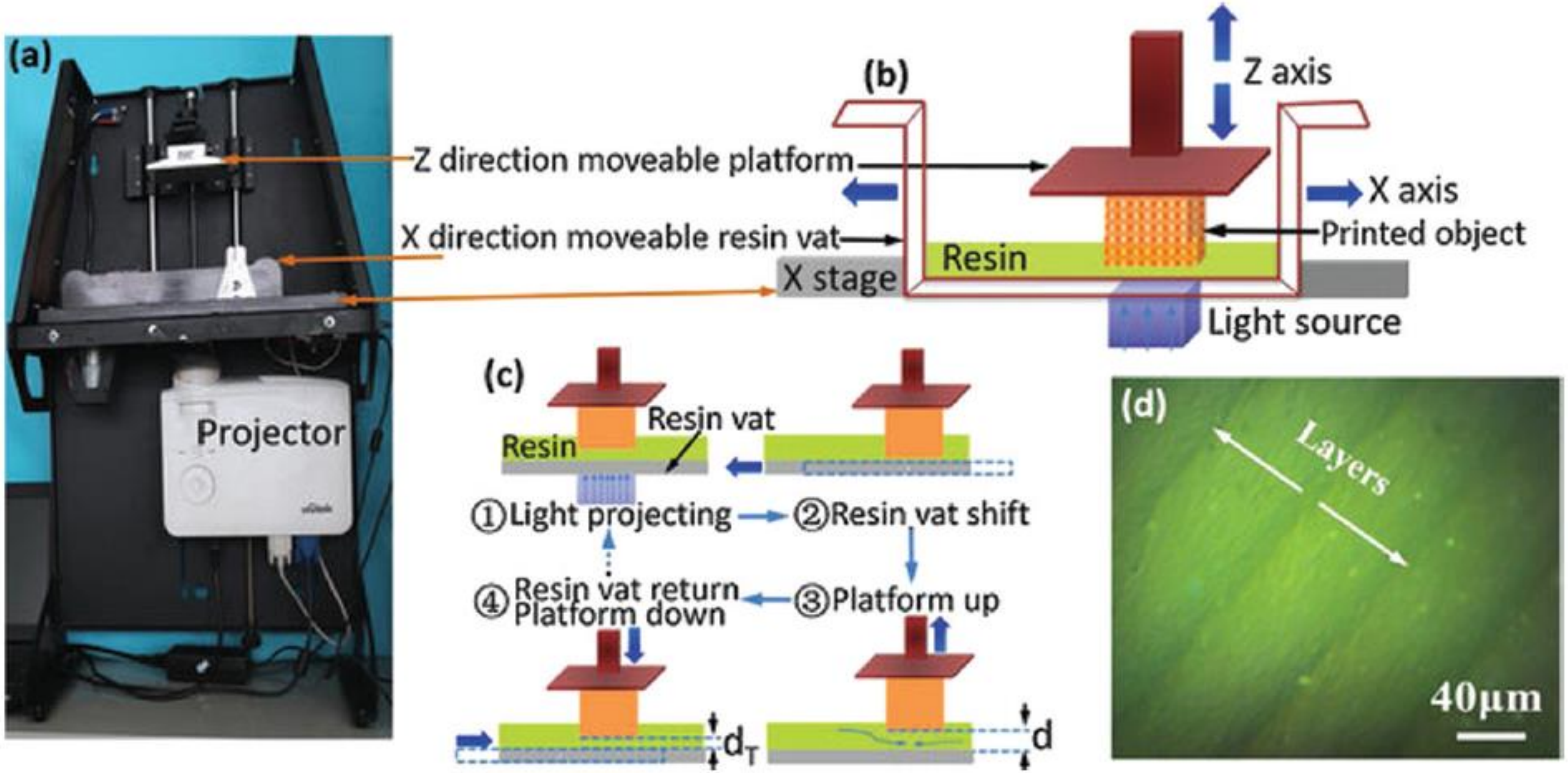


Basis of Classification of SLA Process.

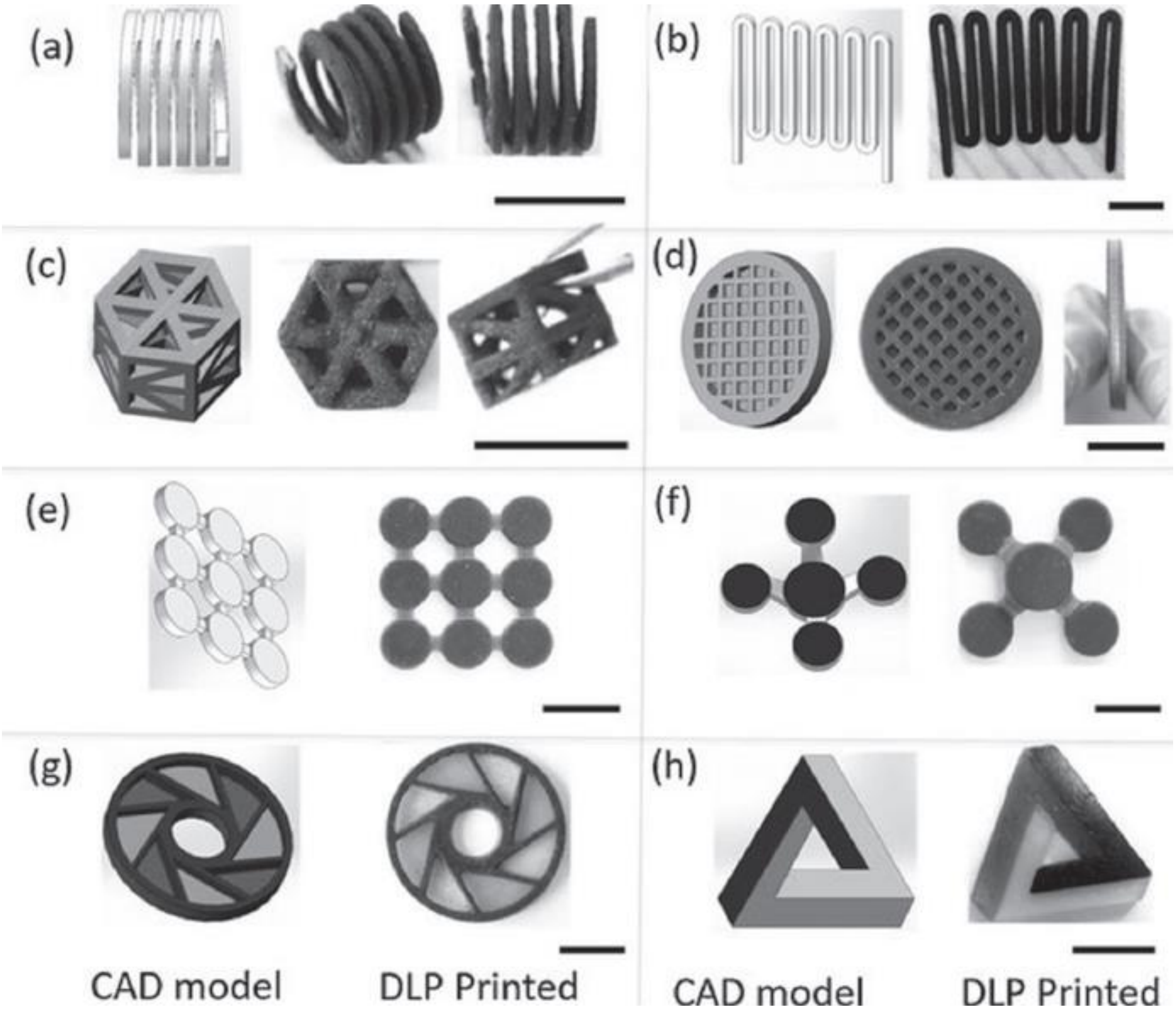
Various vat photopolymerization processes include continuous liquid interface production (CLIP), scan, spin and selectively photocure technology (3SP), solid ground curing (SGC), stereolithography (SL), stereolithography apparatus (SLA), two-photon polymerization (2PP), etc. However, owing to SLA processes being pioneers in their category, vat photopolymerization techniques are used synonymously with SLA processes.

Digital light processing (DLP).

If a LCD photomask is utilized for irradiation then the process is called LCD-SLA.



DLP-SLA Printer:



Different Components Made by DLP SLA Route, Scale Bar of Parts is Kept at 10 millimetres.

AM techniques utilizing **powder bed fusion processes** including materials; powder fusion mechanism; process parameters and modelling; powder handling; powder fusion techniques, including solid state sintering, chemical sintering, complete melting, liquid phase sintering/partial melting, indirect processing, pattern method and direct sintering; powder bed fusion process variants including low temperature laser-based processing, metal and ceramic laser-based systems, electron beam melting (EBM) and line- and layer-wise systems; and strengths and weaknesses of PBF-based AM techniques.

Materials

PBFs can fabricate components from any material that can undergo melting and re-solidification.

However, a special class of materials are best compatible with these PBFs. These mainly include:

- Thermoplastic materials, owing to low melting point, thermal conductivity, balling tendency

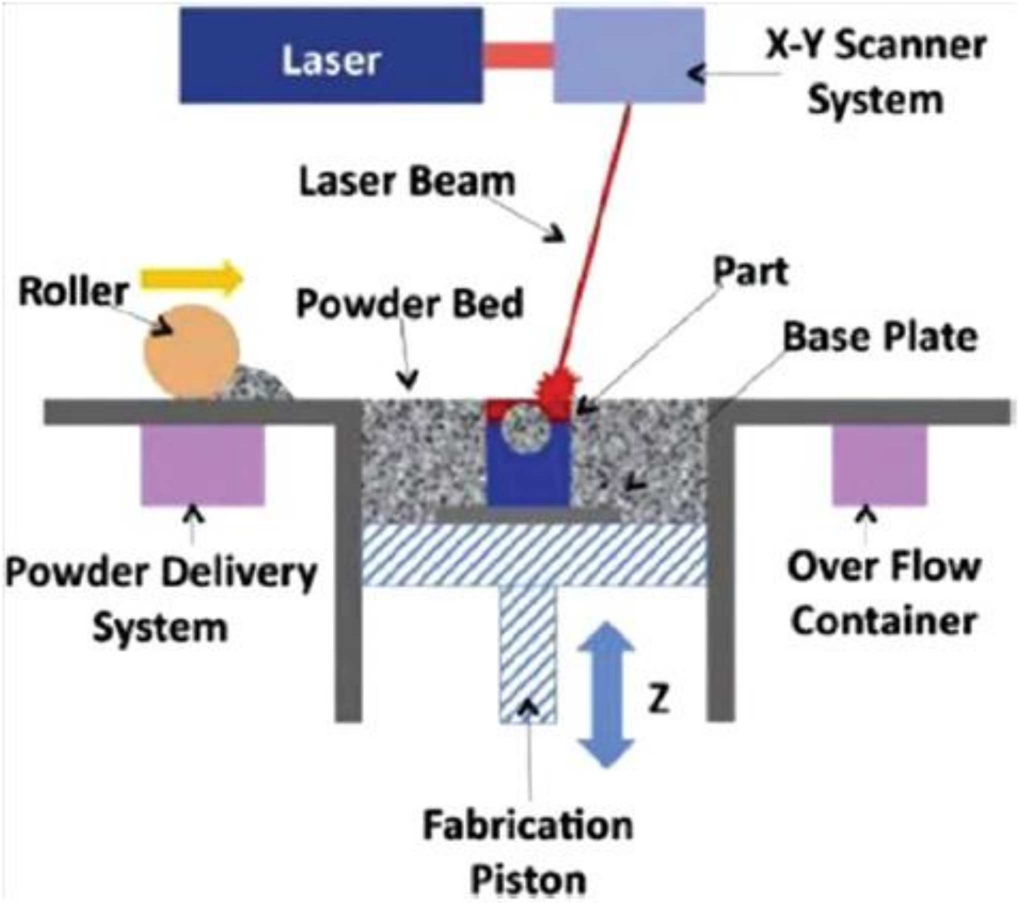
- Polyamide (PA) for plastic components of functional parts
- Glass-filled PAs to make parts extra strong and rigid with reduced ductility
- Polystyrene-based materials with lesser residual ash content in investment casting
- Amorphous polymer materials which tend to create porous structures
- Crystalline materials for high density, better surface as well as mechanical traits, but their shrinkage, curling and distortion exceeds that found in their amorphous counterparts
- Elastomeric thermoplastic polymers for high flexibility
- Biocompatible materials for specific uses
- Numerous proprietary metals, for example, RapidSteel, RapidSteel 2.0 by DTM Corp., LaserForm ST-100
- Metal alloys such as Ti–6Al–4V, steel alloys, CoCrMo, Inconel, etc.

PBF processes use a distinct method to fabricate metallic and ceramic parts. In case of metal parts, there are four main approaches, which include: (1) liquid phase sintering; (2) full melting; (3) indirect processing and (4) pattern methods. In case of ceramic components, there are four main processing approaches, including: (1) direct sintering; (2) chemical induced sintering; (3) indirect processing and (4) pattern methods.

Powder Fusion Mechanism

A few traits are common to each PBF process. These include:

1. A thermal source which enables powdered particles to fuse
2. A control mechanism to control fusion to a specified area of every layer
3. Mode of addition of subsequent layer
4. Mode to smoothen each layer before addition of next layer. Understanding the mechanism of the SLS process, which is the basis of almost all PBF techniques, is an important part of comprehending the mechanism of PBF processes and is considered a baseline for comparison.



Powder Bed Fusion Schematic

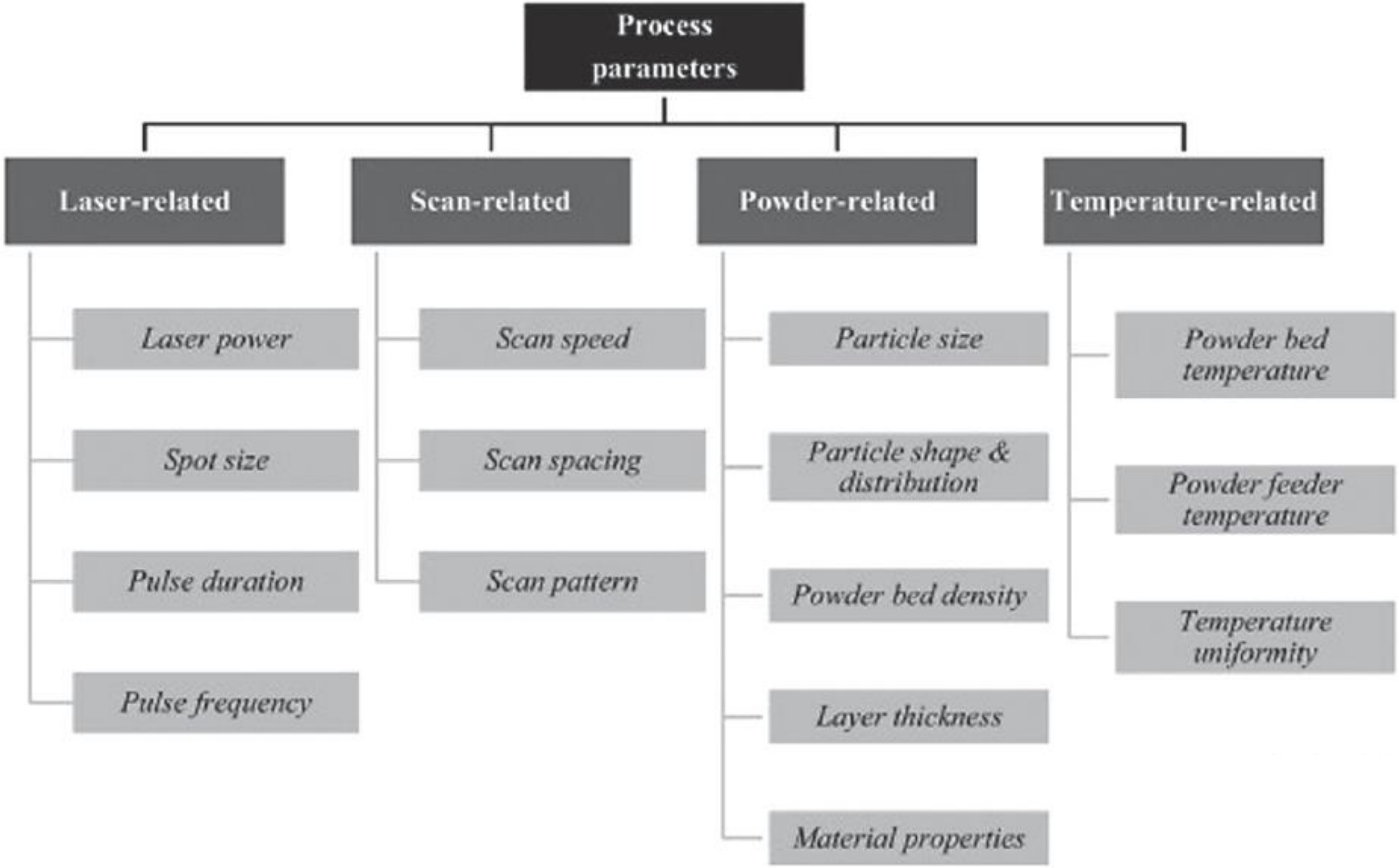
PBFs are obtained by changing the mode of fusion of powdered material. Four variable ways to obtain fusion can be: (1) sintering in solid state; (2) sintering in liquid state; (3) chemical binding; and (4) complete melting.

Process Parameters and Modelling

There are four main categories of process parameters with reference to PBF processes which are categorized as: (1) laser; (2) scan related; (3) powder; and (4) temperature related parameters.

Laser Sintering Process Parameters

Parameter	Description
Laser power	Applied power of laser as it scans area of each layer
Scan speed	Velocity at which laser beam travels as it traverses a scan vector
Scan spacing	Distance between parallel laser scans
Scan count	Number of times laser beam traverses a scan vector per layer
Scan strategy	Pattern of laser as it scans over a layer, in combination with the laser parameters used in each specific area
Layer thickness	Distance build platform lowers for spreading of new layer of powder
Build temperature	Temperature of process chamber and/or part bed



Principal Processing Parameters Involved in Selective Laser Melting Process.

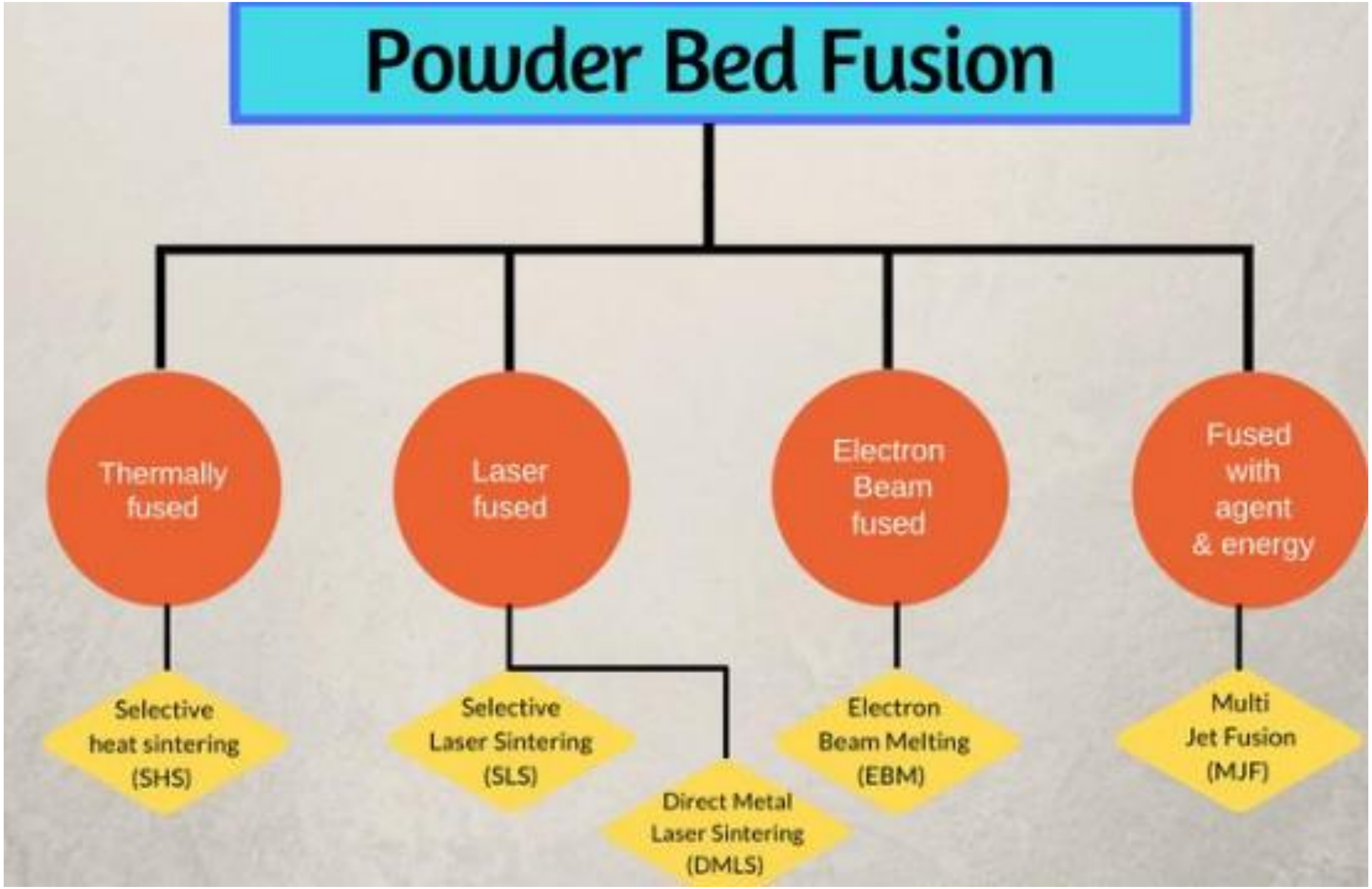
What is Powder Bed Fusion?

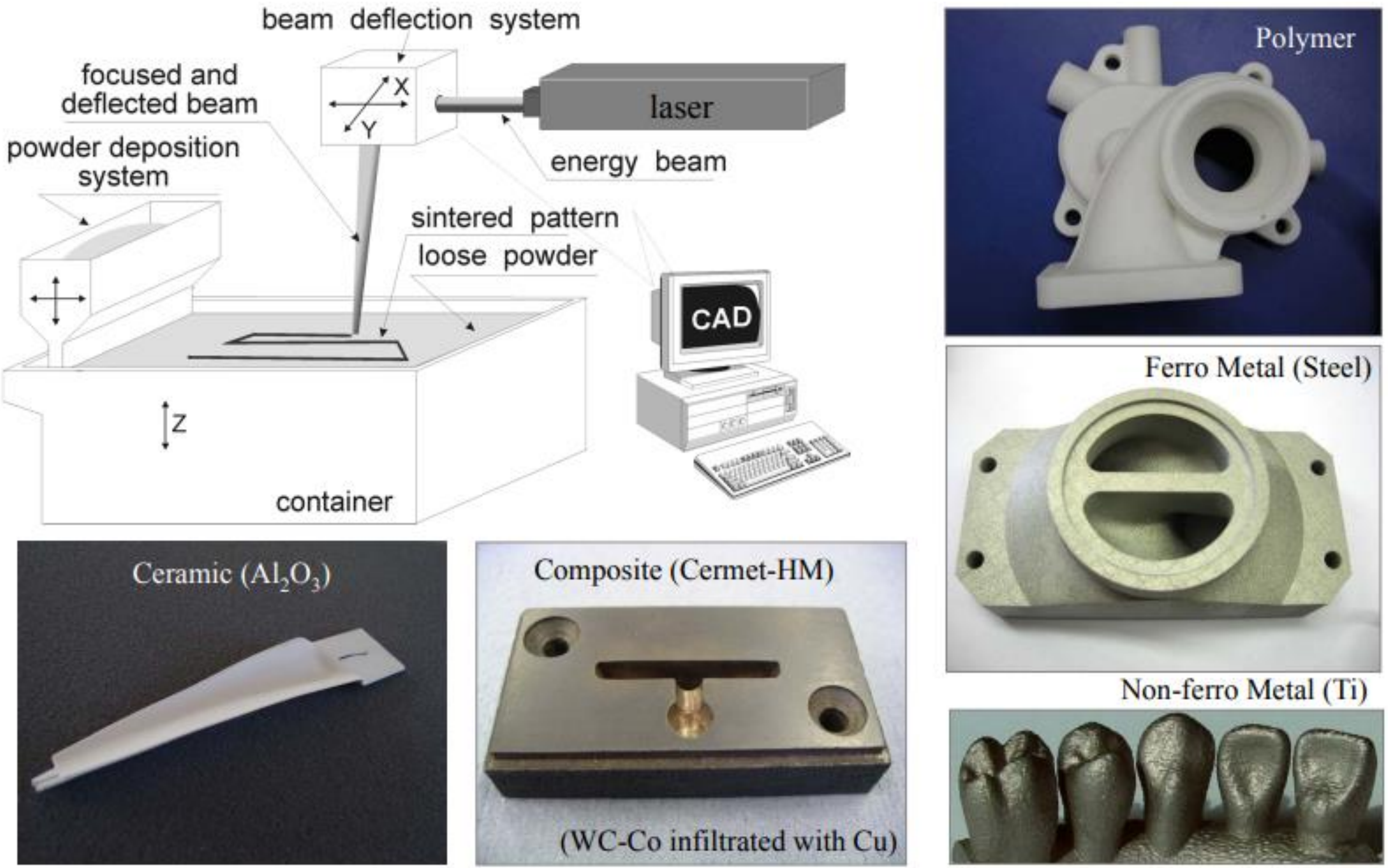
Powder bed fusion is one of seven **Additive Manufacturing** techniques, in which either laser, heat or electron beam is used to melt and fuse the material together to form a three-dimensional object.

Types of Powder bed fusion

Both metal and plastic parts can be made using this technique and it can be classified into the following four groups by the energy source it uses to melt the material.

- Laser Fused
- Electron Beam fused
- Fused with agent and energy
- Thermally fused


Powder Bed Fusion
Thermally fused
Laser fused
Electron Beam fused
Fused with agent & energy
Selective heat sintering (SHS)
Selective Laser Sintering (SLS)
Direct Metal Laser Sintering (DMLS)
Electron Beam Melting (EBM)
Multi Jet Fusion (MJF)

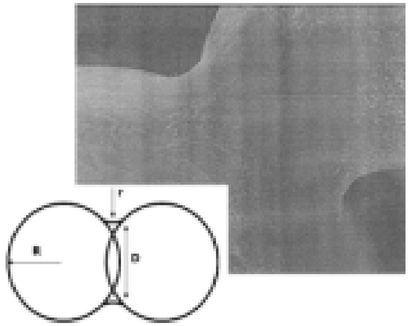

beam deflection system
focused and deflected beam
X
Y
laser
energy beam
powder deposition system
sintered pattern
loose powder
CAD
Z
container
Polymer
Ferro Metal (Steel)
Non-ferro Metal (Ti)
Ceramic (Al_2O_3)
Composite (Cermet-HM)
(WC-Co infiltrated with Cu)

Classification of binding mechanisms

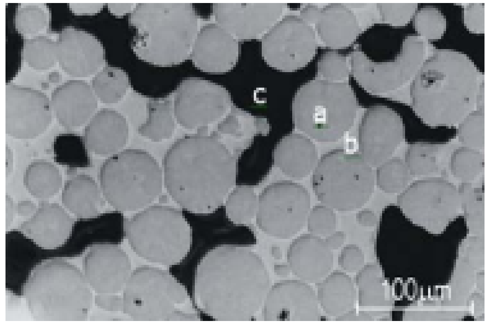
Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**

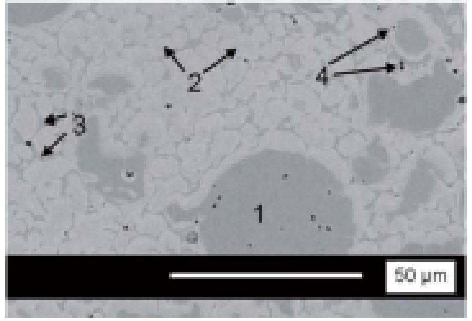
Solid State Sintering



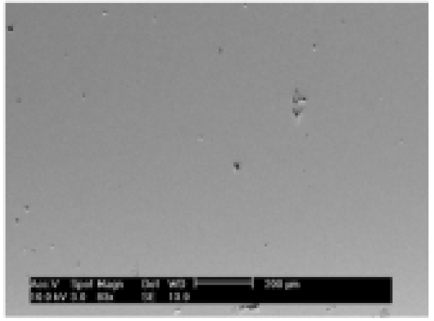
Liquid Phase Sintering



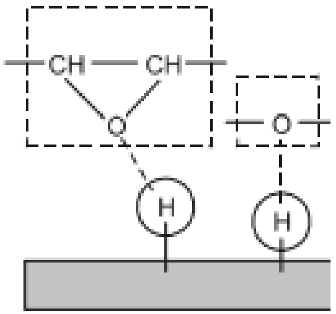
Partial Melting



Full Melting

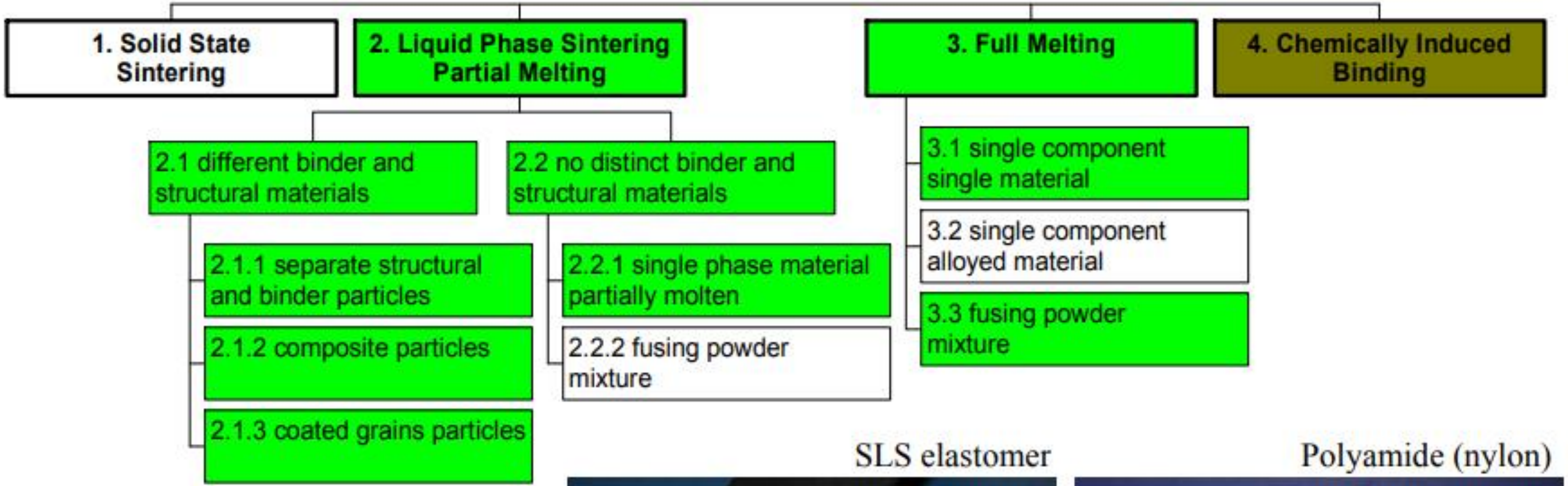


Chemical binding



Polymers

Binding mechanism classification



SLS elastomer

Polyamide (nylon)

Main binding mechanisms for metals

Metals

Binding mechanism classification

- 1. Solid State Sintering
- 2. Liquid Phase Sintering Partial Melting
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- 3. Full Melting
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- 4. Chemically Induced Binding

Steel

Titanium

Main binding mechanisms for ceramics

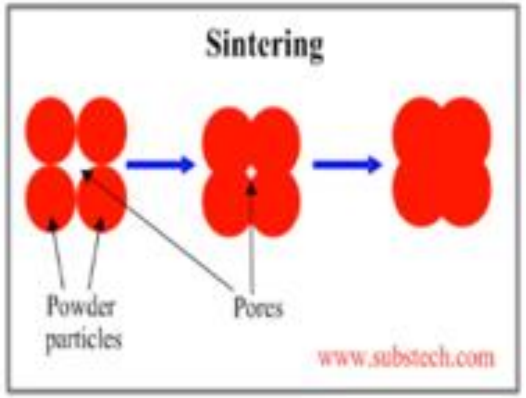
Ceramics

Binding mechanism classification

- **1. Solid State Sintering**
- **2. Liquid Phase Sintering Partial Melting**
  - 2.1 different binder and structural materials
    - 2.1.1 separate structural and binder particles
    - 2.1.2 composite particles
    - 2.1.3 coated grains particles
  - 2.2 no distinct binder and structural materials
    - 2.2.1 single phase material partially molten
    - 2.2.2 fusing powder mixture
- **3. Full Melting**
  - 3.1 single component single material
  - 3.2 single component alloyed material
  - 3.3 fusing powder mixture
- **4. Chemically Induced Binding**

Alumina

Introduction to PBF Process



Sintering combines materials by heat and pressure, without **melting** involved. **Melting** combines particles by heating them till they liquify and combine as one material.

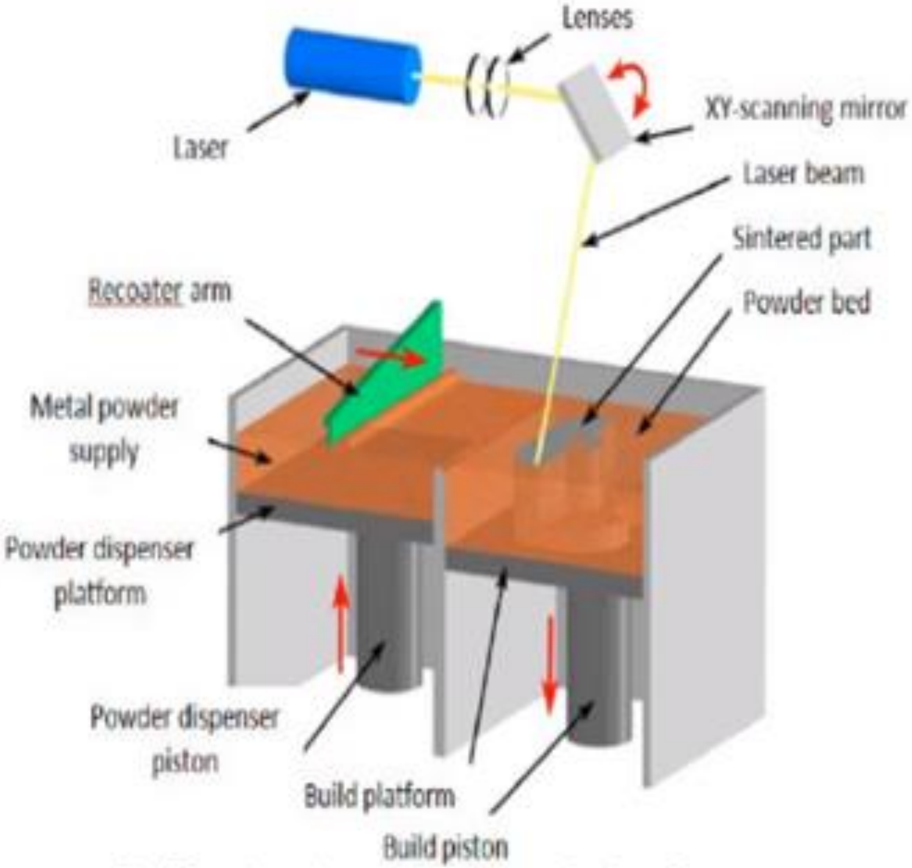


Fig. 3 Laser based powder bed fusion technology [1

Each layer of the required cross section is divided into number of segme called "islands", which are selected stochastically during scanning.

Most of these systems use one fiber laser of 200W to 1 KW capacity selectively fuse the powder bed layer.

The build chamber is provided with inert atmosphere of argon gas reactive materials and nitrogen gas for non-reactive materials.

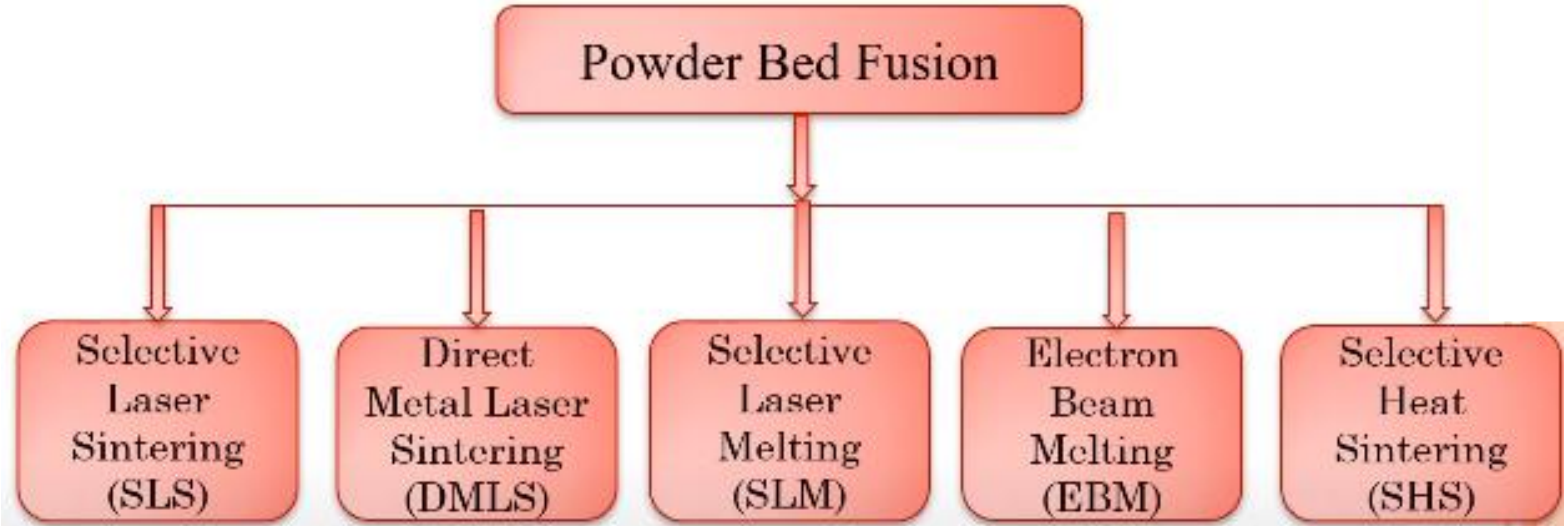
Power of laser source, scan speed, hatch distance between laser tracks a the thickness of powdered layer are the main processing parameters these processes .

Layer thickness of 20-100 μm can be used depending on the material.

All of these processes can manufacture fully dense metallic parts fr wide range of metal alloys like titanium alloys, inconel alloys, cob chrome, aluminium alloys, stainless steels and tool steels.

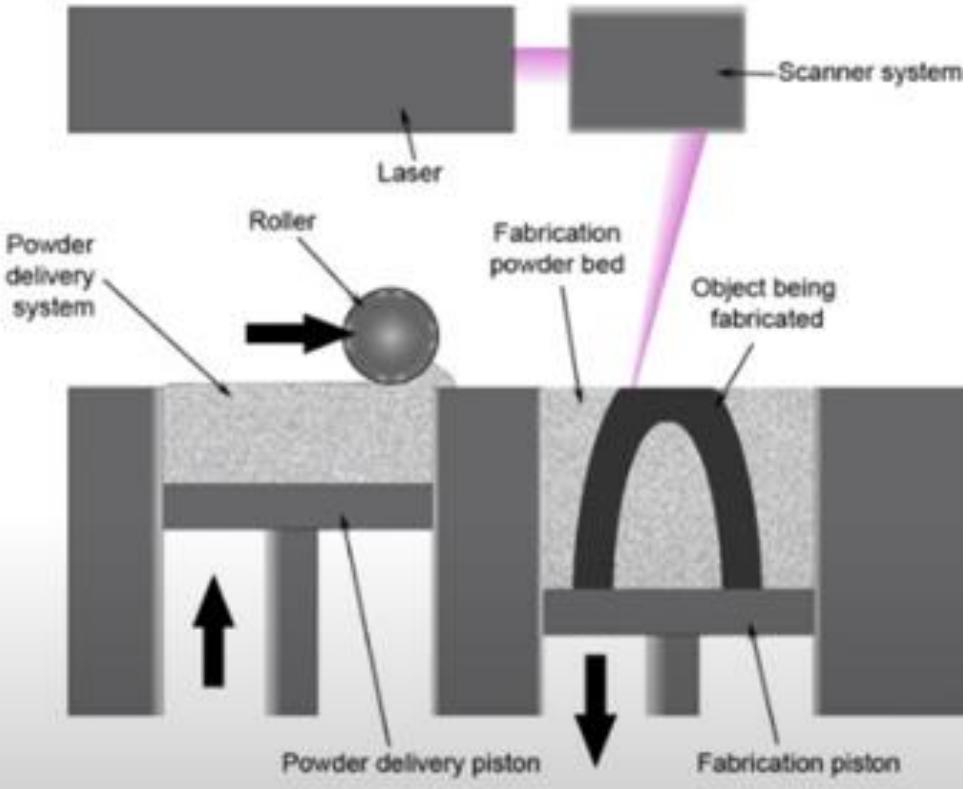
Most of the laser based PBF systems have low build rates of 5-20 cm3 and maximum part size that can be produced (build volume) is limited 250 x 250 x 325 mm3

TYPES OF PBF PROCESS



SELECTIVE LASER SINTERING (SLS)

1. A continuous layer of powder is deposited on the fabrication platform
2. A focused laser beam is used to fuse/sinter powder particles in a small volume within the layer
3. The laser beam is scanned to define a 2D slice of the object within the layer
4. The fabrication piston is lowered, the powder delivery piston is raised and a new layer is deposited
5. After removal from the machine, the unsintered dry powder is brushed off and recycled



Specifications of SLS

- Maximum build size - 700 mm x 380 mm x 560 mm
- Resolution in z - 0.005”
- Speed – Medium
- Cost - Medium
- Available materials - Powdered plastics (**nylon**), metals (steel, titanium, tungsten), ceramics (silicon carbide) and fiber-reinforced PMCs

Advantages, Disadvantages & Applications

- **Advantages**
  - Wide array of structural materials beyond polymers
  - Cheaper than EBM
  - One of two technologies that allow complex parts in metals

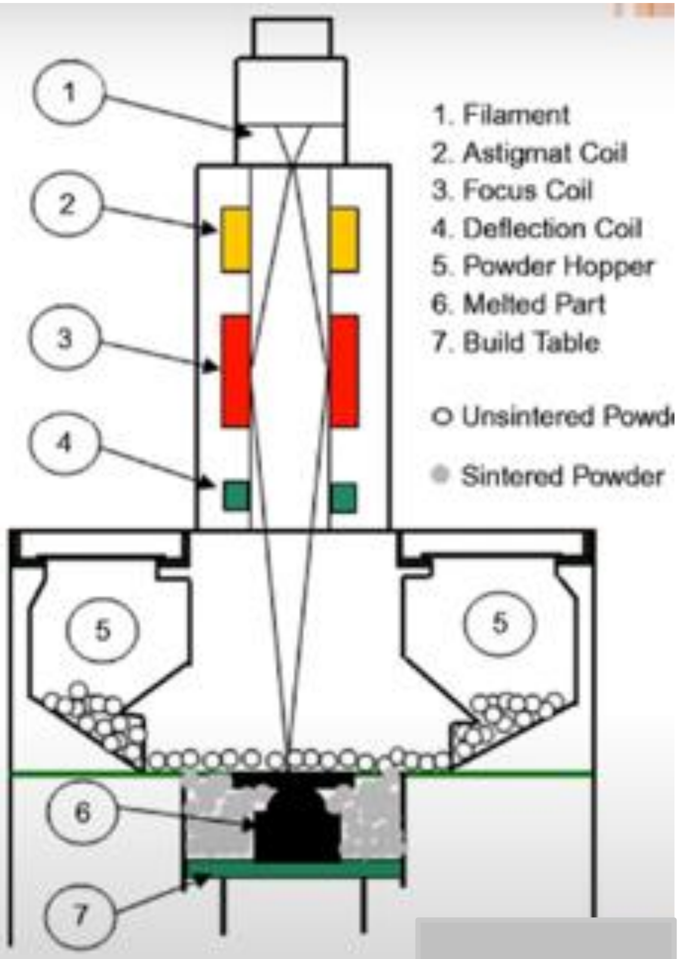
- **Disadvantages**
  - The quality of metal parts is not as high as with EBM

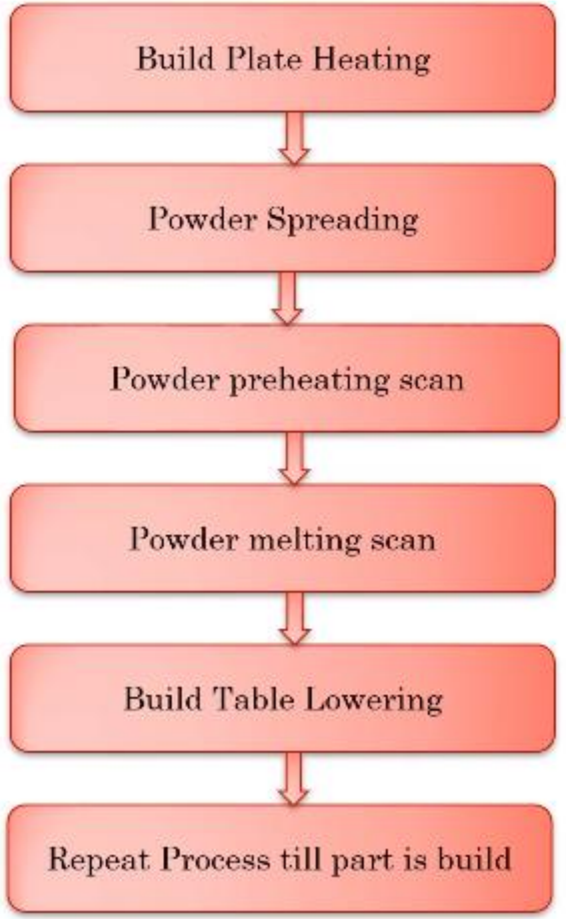
- **Applications**
  - Structural components

DIFFERENCE IN SLM, DMLS & SLS

- SLS – Sintering process donot fully melt the powder but heat it to the point that the powder can fuse together on a molecular level.
- SLM - This process fully melt the powder into a homogenous part.
- DMLS – Process is same as SLS only difference is material

- In EBM, a heated tungsten filament emits electrons at high speed which are then controlled by two magnetic fields, focus coil and deflection coil as shown in
- Focus coil acts as a magnetic lens and focuses the beam into desired diameter up to 0.1 mm whereas deflection coil deflects the focused beam at required point to scan the layer of powder bed .
- When high speed electrons hit the powder bed, their kinetic energy gets converted into thermal energy which melts the powder.
- In preheating stage, a high current beam with a high scanning speed is used to preheat the powder layer in multiple passes.




Build Plate Heating
Powder Spreading
Powder preheating scan
Powder melting scan
Build Table Lowering
Repeat Process till part is build

• SPECIFICATIONS

- Maximum build size - 200mm x 200mm x 350mm
- Resolution in (x,y) - +/- 0.2mm
- Resolution in z - 0.002" (0.05 mm)
- Speed - Medium
- Cost - High
- Available materials - Metals: titanium, tungsten, stainless steel, cobalt chrome, Ni-based superalloys.

Advantages, Disadvantages & Applications

Advantages

- Method of choice for high-quality metal parts
- Wide range of metals
- Fully dense parts with very homogeneous microstructures
- Vacuum operation allows building of highly reactive metals (e.g., Titanium)
- High temperature operation (700-1000C) results in structures free of internal stresses
- EBM allows even better microstructural control than many conventional processes

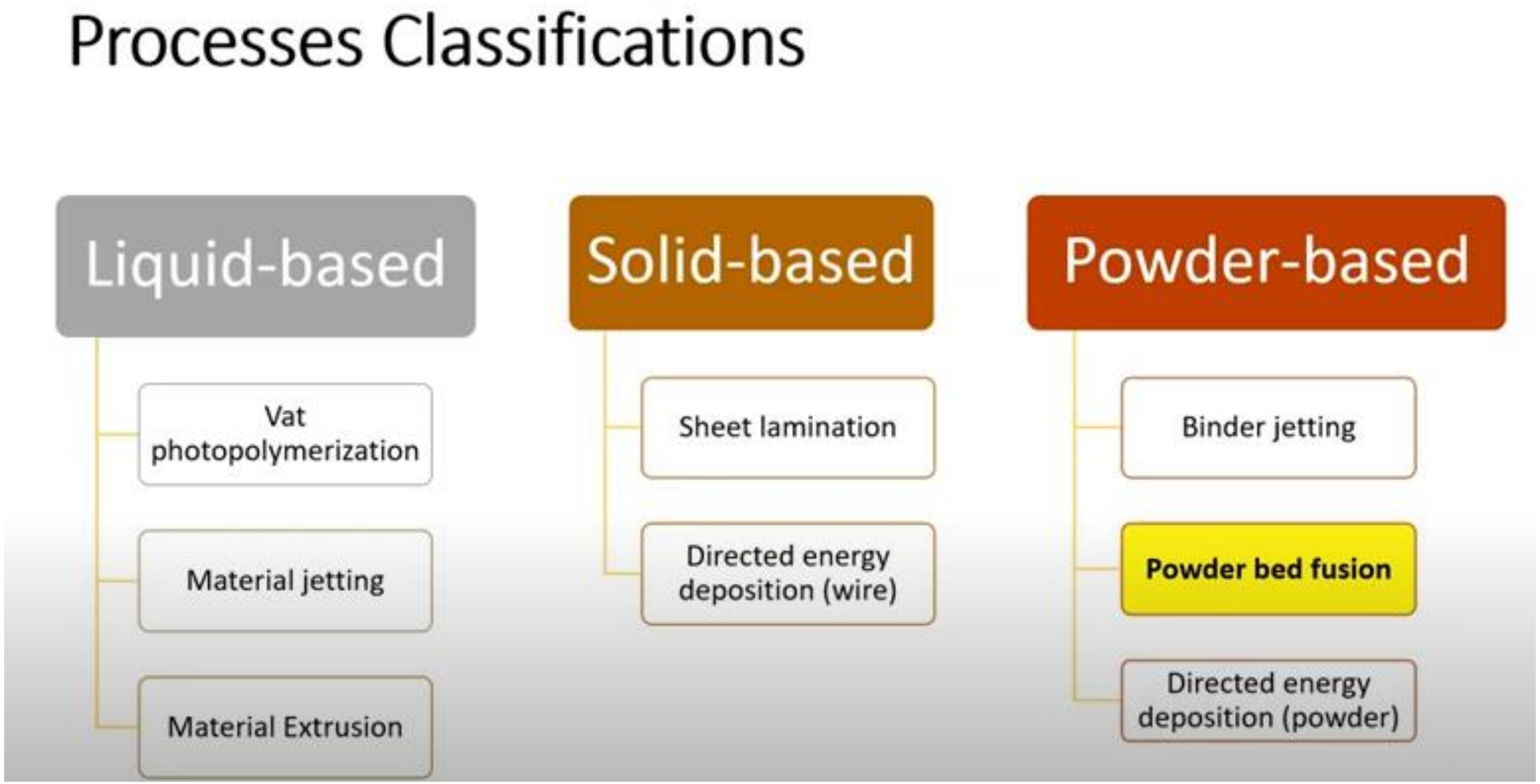
Disadvantages

- Extremely expensive (more than SLS)
- Conventional machining may be required to finish the goods (rough surface)
- Requires vacuum operation

Applications

- Structural components for aerospace (Ti6Al4V, gammaTiAl, Ni superalloys)
- Custom-made bio-implants (Ti6Al4V)

Powder Bed Fusion



Powder Bed Fusion

An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

Build Material:

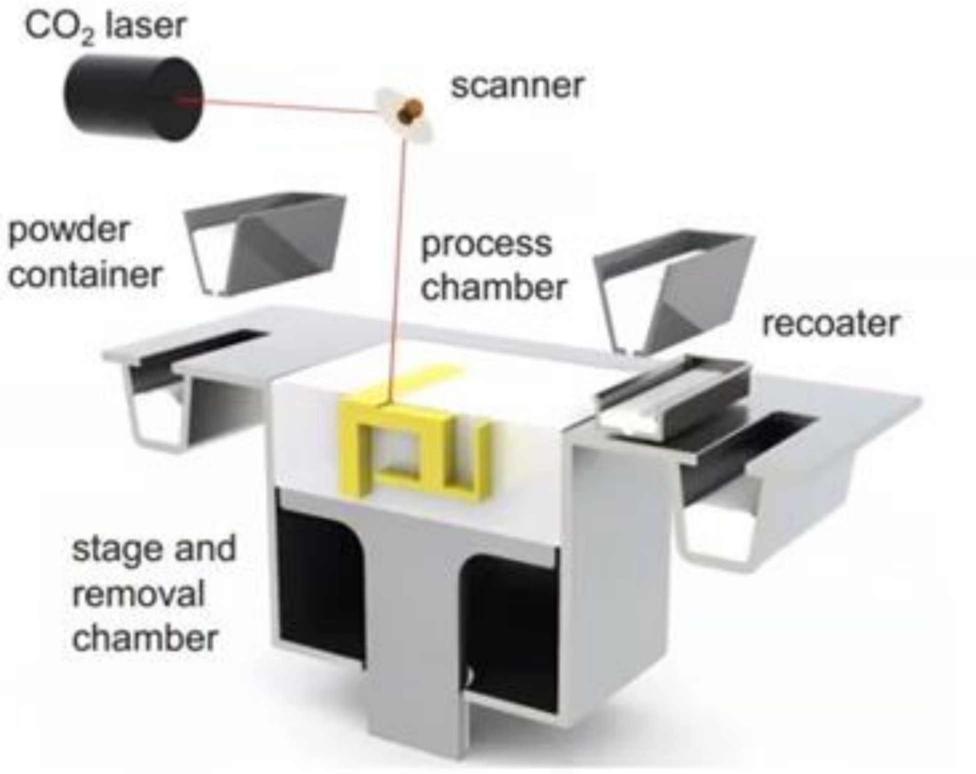
- Powder (polymer, metal, ceramic)

Material Distribution Method:

- Bed (roller, blade)

Binding Technique:

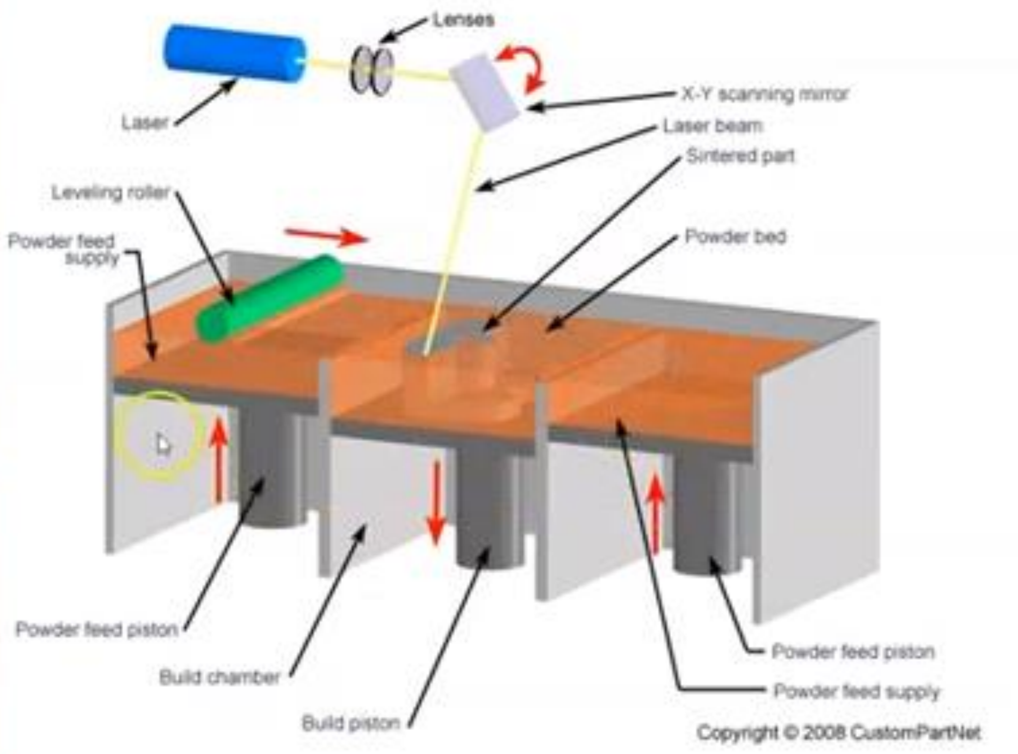
- Thermal energy (IR laser, electron beam)



Powder Bed Fusion

Basic Process:

1. A layer of material is spread over the build platform.
2. A laser fuses the first layer of the model.
3. A new layer of powder is spread across the previous layer using a roller.
4. Further layers are fused and added.
5. The process repeats until the entire model is created. Loose, unfused powder remains in position as support but is removed during post processing



Powder Bed Fusion

PBF Technologies	Materials	Major Industrial Manufacturers
SLS/LS – Selective Laser Sintering/Laser Sintering	Polyamides	EOS GmbH, 3D Systems
DMLS – Direct Metal Laser Sintering	Metals	EOS GmbH
DMP – Direct Metal Printing		3D Systems
SLM/LM – Selective Laser Melting/Laser Melting		SLM Solutions GmbH, Renishaw
LC - LaserCusing		Concept Laser GmbH
EBM – Electron Beam Melting		Arcam AB

Powder Bed Fusion

Basic Characteristics:

✓One or more thermal sources to induce fusion between powder particles
- Focused laser, electron beam

✓Method to control fusion to prescribed region on each layer.
- Galvanometer

✓Mechanism for adding and smoothing powder
- Roller and/or doctor blade (squeegee)

PBF Originally developed for plastics

✓Extended to metal and ceramic

Powder Bed Fusion

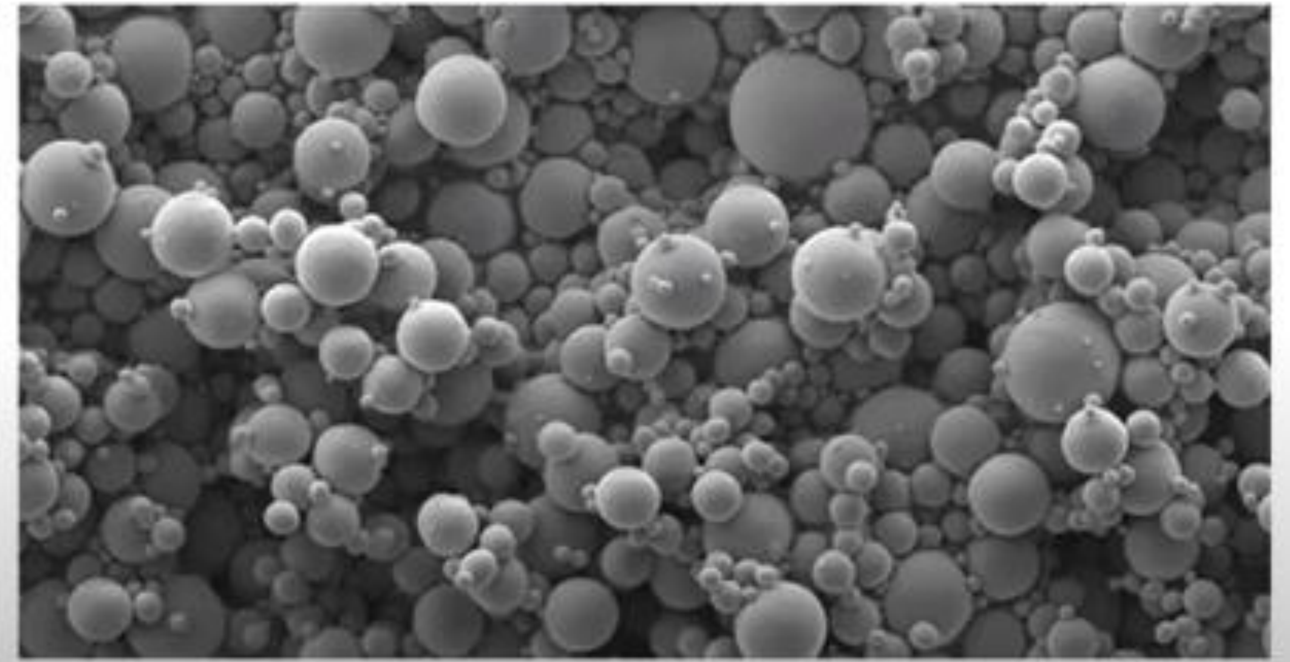
Strengths	Weaknesses
• Relatively inexpensive • Suitable for visual models & prototypes • Powder acts as support • Large range of materials • Parts can be stacked • Recycle materials	• Controlled environment • Slow speed (warm-up/cool down) • Size limitations • High power usage

Powder Bed Fusion Materials

*In the **powder bed fusion** process material in powdered form is melted together using a thermal energy source, typically a laser.*

Build materials:

- Polymer (thermoplastic)
- Metal
- Ceramics
- Composites



Powder Polymer Characteristics

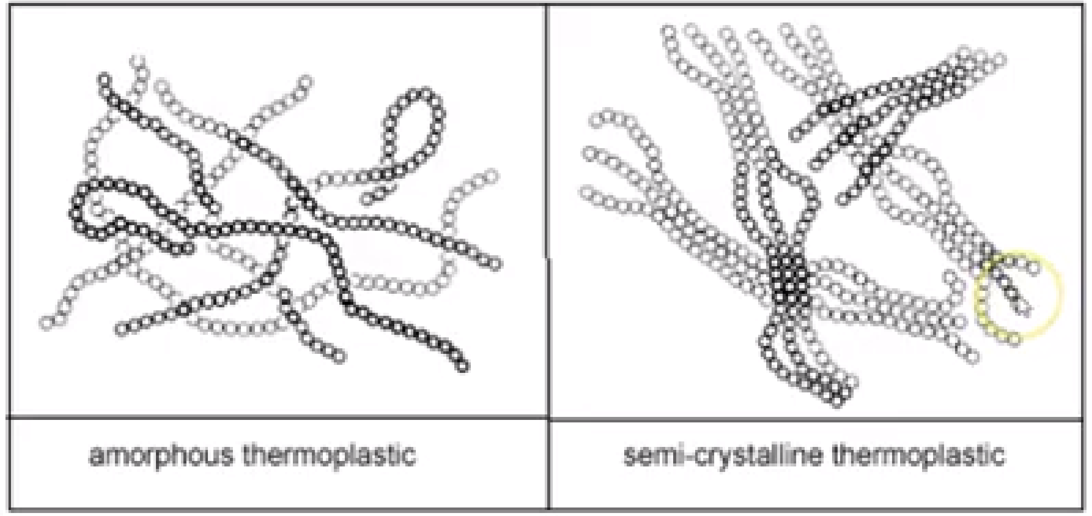
<u>Thermoplastics – ideal for PBF</u>

- Low melting temperature
- Low thermal conductivities
- Low tendency for "balling"
    - *sphereodisation of the liquid melt pool*
- *Limited recycling due to sintering of loose powder over time.*

Powder Polymer Characteristics

<u>Two types of thermoplastics used in PBF</u>

- Semi-crystalline
  - ✓Regions of orderly structure (crystallites)
  - ✓Distinct melting temperature
- Amorphous
  - ✓Random molecular structure
  - ✓Polymer chains intertwined
  - ✓Soften and melt at wide range of temperatures



Powder Polymer Characteristics

Polyamide (nylon)

- Most common polymer for PBF
- Semi-crystalline structure
- Distinct melting temperature
- Repeatable processing
    - *A given amount of laser energy will melt a certain amount of powder.*
- Cools quickly and uniformly
- Higher density (not porous)



Powder Metal Characteristics

- Wide range of metals available – *any metal that can be welded*
  - ✓Stainless steel
  - ✓Tool steel
  - ✓Cobalt chrome
  - ✓Titanium Ti64/Ti64ELI
  - ✓Aluminum
  - ✓Inconel
  - ✓Nickel alloy

- Includes precious metals – *gold, silver*
- Thermocoated binder coated metals – *polymer coated metal powders*

Powder Ceramic & Composite Characteristics

- Compounds consist of metal-oxides, carbides, and nitrides
  - ✓SiC
  - ✓Aluminum oxide
  - ✓Titanium oxide
- Composites
  - *Cermet – metal-ceramic composite*
  - *Glass-reinforced polymers*

The Seven Types of AM

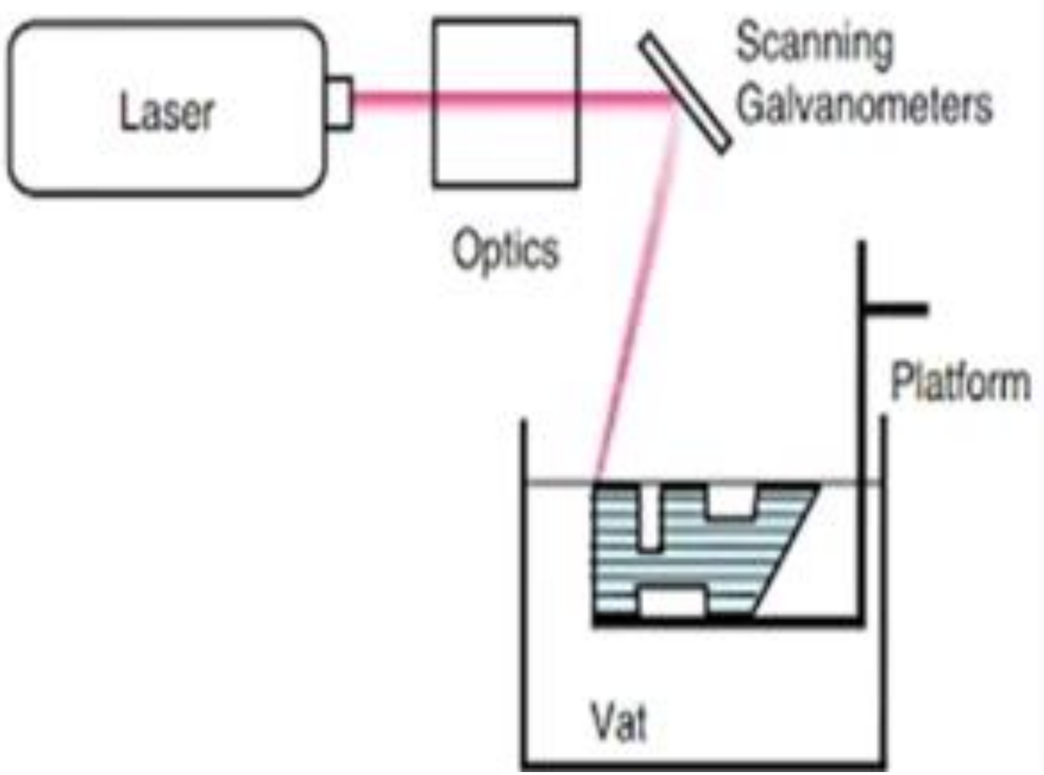
THE 7 TYPES OF ADDITIVE MANUFACTURING

According to ASTM F2792-12a

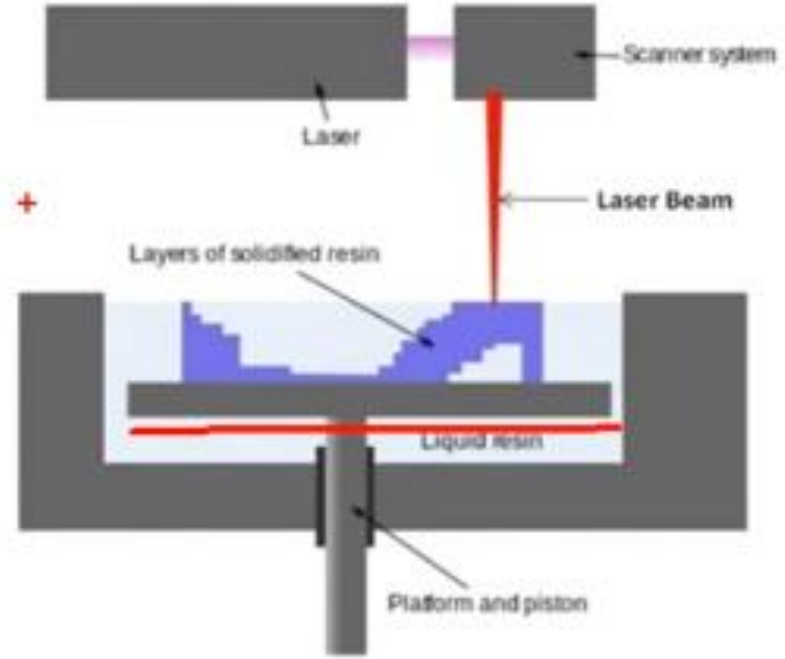
Material Extrusion	Binder Jetting	Material Jetting	Vat Photo-polymerization	Powder Bed Fusion	Directed Energy Deposition	Sheet Lamination
Typical Materials						
Thermoplastic Filament and Pellets Liquids and Slurries	Powdered: Plastic Metal Ceramics Glass Sand	Photopolymers Waxes Ceramics	UV-Curable Photopolymer Resin Additives: Ceramics Metals	Powdered: Plastics Metals Ceramics	Metal Wire and Powder, Could have Ceramic Additives	Paper Plastic Sheets Metal Foils and Tapes
Created and Designed by 3D Directions LLC						

PHOTOPOLYMERIZATION

- It is a 3-D printing technology whereby liquid plastic is exposed to a laser beam of ultraviolet light. During this exposure, the light converts the liquid into a solid.
- An ultraviolet (UV) light is used to cure or harden the resin wherever required, while the platform moves the object downwards after each layer is cured.



- Photopolymer is held in a large container with a movable platform
- UV light or laser beam is directed across the surface of the resin. The light source can be moved in X and Y axis
- When the light beam interacts with the resin, it gets hardened precisely where the light hits the surface
- Once the layer is completed, the platform lowers down in Z-axis, by a distance equal to layer thickness.
- The process continues until the entire object is completed

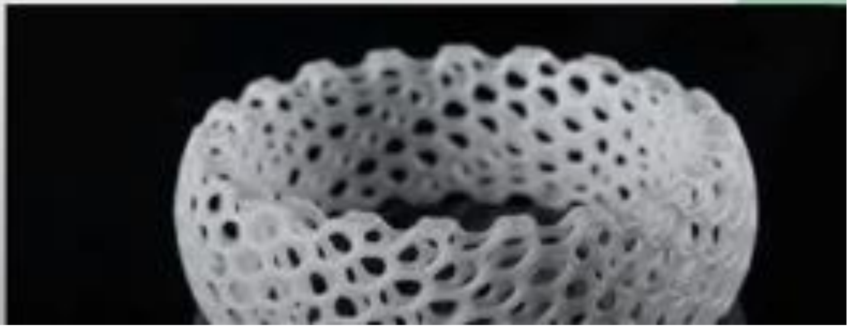


ADVANTAGES, DISADVANTAGES & APPLICATIONS

- High level of accuracy & excellent surface finish
- Relatively quick process
- Large build areas and large model weights can be accommodated

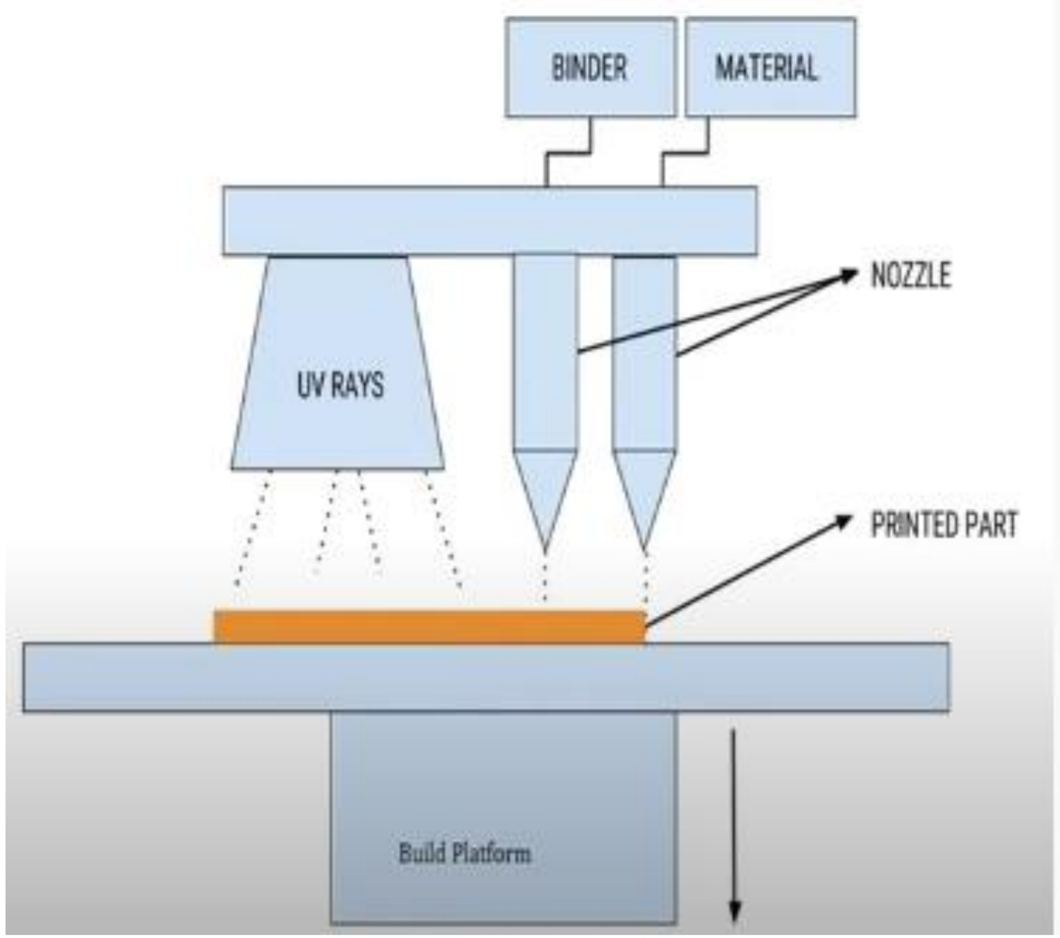
- Relatively expensive
- Post processing requires more time
- Requires support structure
- Post curing of parts is required

- Dentistry
- Hearing aids
- Surgical masks
- Bio medical engineering

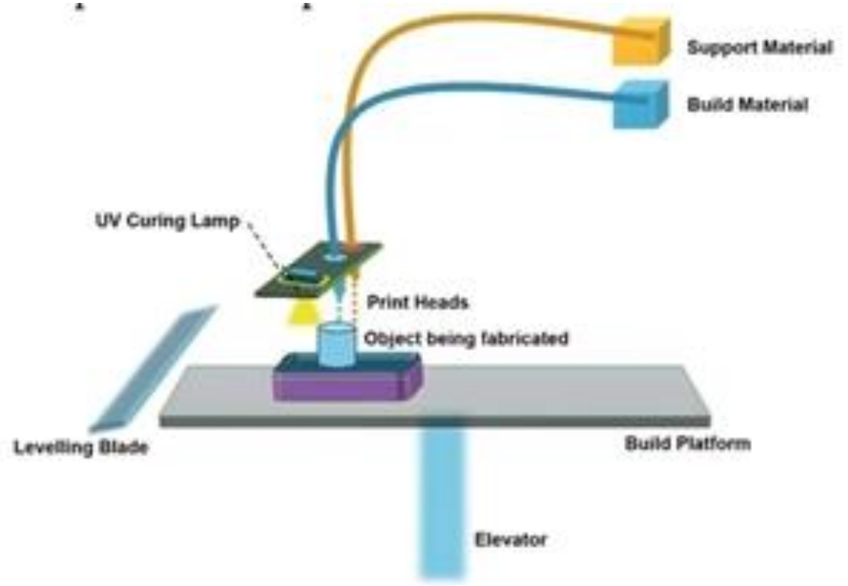


MATERIAL JETTING

- Material Jetting (MJ) is an additive manufacturing process that operates in a similar fashion to 2D printers.
- In material jetting, a print head moving horizontally (X-Y axis), dispenses droplets of a photosensitive material that solidifies under ultraviolet (UV) light, building a part layer-by-layer.
- The materials used in MJ are thermo-set photopolymers (acrylics)



- First, the liquid resin is heated to 30 - 60° C to achieve optimal viscosity for printing.
- Then the print head travels over the build platform and hundreds of tiny droplets of photopolymer are jetted/deposited to the desired locations.
- A UV light source that is attached to the print head cures the deposited material, solidifying it and creating the first layer of the part.
- After the layer is complete, the build platform moves downwards one layer height and the process repeats until the whole part is complete.



ADVANTAGES, DISADVANTAGES & APPLICATIONS

- Low wastage of material
- High accuracy of deposition of droplets
- The process allows multiple materials and colors under one process

- Materials are limited to polymers, plastics and waxes
- Parts produced have poor mechanical properties and are very brittle
- Requires support structure

- Dentistry
- Medical industry
- Jewellery

Ref: https://www.grantadesign.com/education/teachingresources/ongoing-development/additive-manufacturing/

Thank you