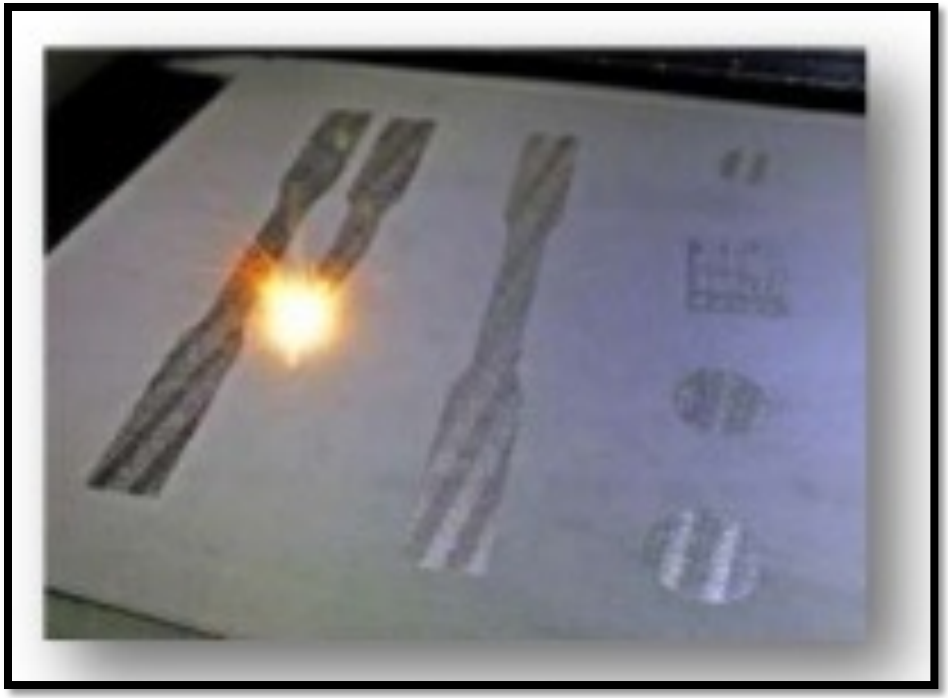
Chapter 6
Powder Bed Fusion



Contents

1. Introduction - Powder Bed Fusion

1. History of PBF

- First commercialized AM process
- Selective Laser Sintering was first commercialized PBF process
- Developed in University of Texas at Austin, USA
- Material: Plastic, Metal, Ceramic, and composite powders

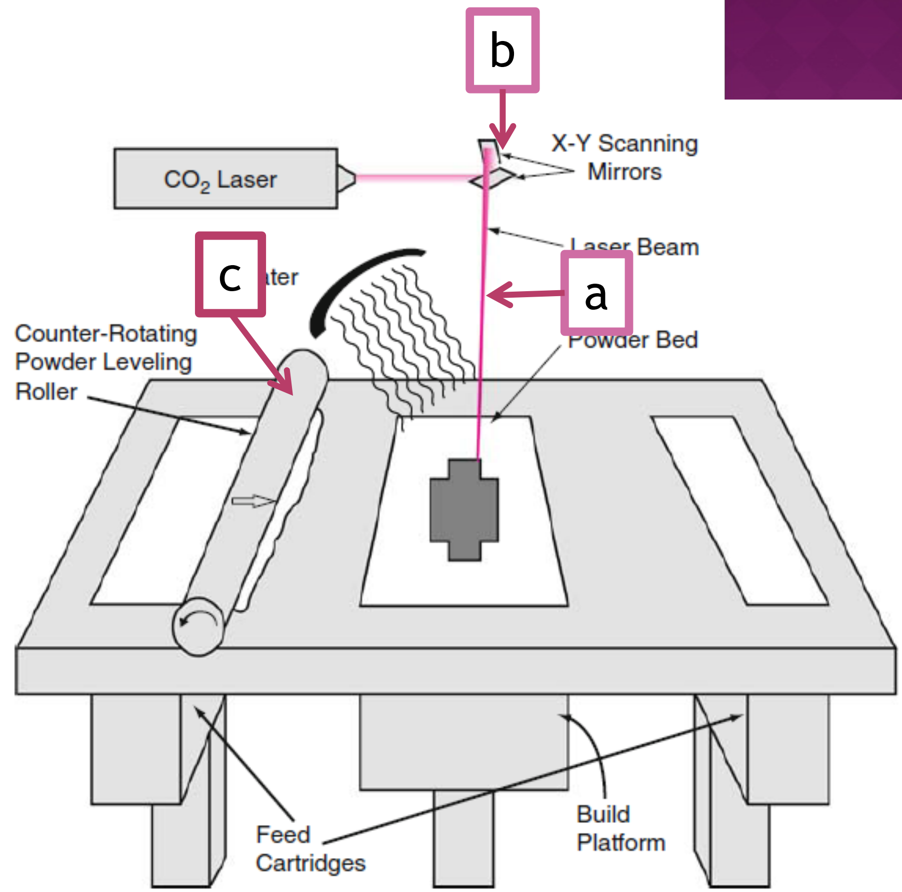


Fig. 5.1 Schematic of the Selective Laser Sintering process

2. General Process Set Up

a. Thermal Source – To fuse the powder particles
b. Method to control powder fusion to a prescribed region of each layer
c. Mechanisms for adding and smoothing powder layer

2. How PBF (SLS) Process works?

1. SLS fuses thin layers of powder which have been spread across the build area using a roller.
2. Laser is moved using galvanometers on required area
3. This happens layer-wise till part is printed.
4. Finally, part is removed from the bed, loose powder is cleaned-off and further finishing operations can be carried out.

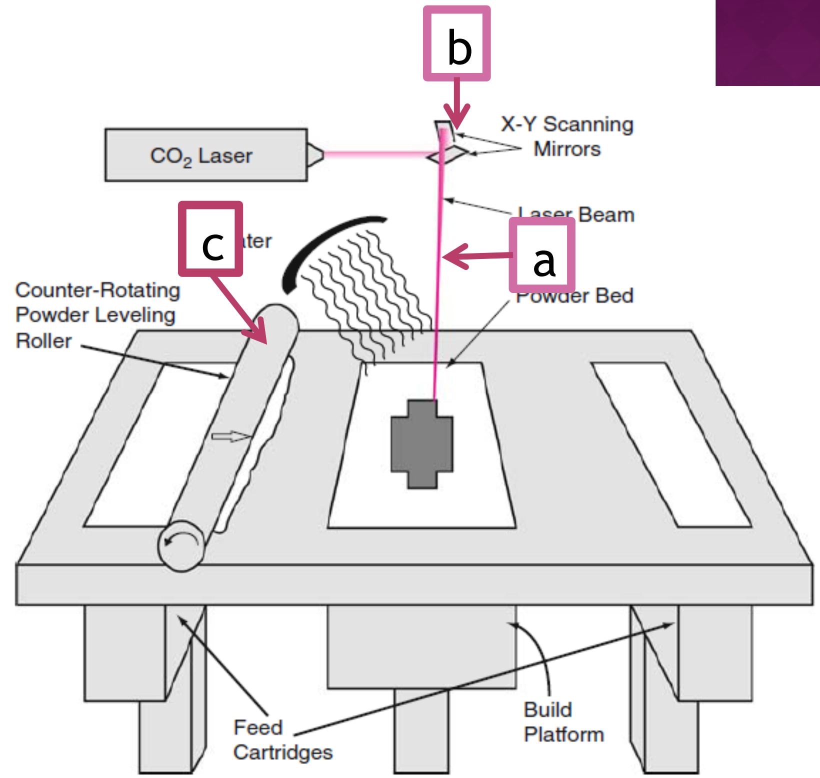


Fig. 5.1 Schematic of the Selective Laser Sintering process

- **Inside Condition of the chamber:** chamber is filled with nitrogen gas to minimize oxidation and degradation of the powdered material.
- **Chamber temperature:** at an elevated temperature just below the melting point and/or glass transition temperature of the powdered material.
- **Infrared heaters:** To pre-heat the powder prior to spreading over the build area and to prevent the warping.

3. Types of PBF

- **Four different types of mechanism**

1. Solid-state sintering
2. Chemically-induced binding
3. Liquid-phase sintering, and
4. Full melting

1. Solid-State Sintering

Sintering

- Sintering == It indicates the fusion of powder particles without melting (i.e., in their "solid state") at elevated temperatures
- Temperature == Between one half of the absolute melting temperature and the melting temperature.
- Driving Force == The minimization of total free energy, Es, of the powder particles

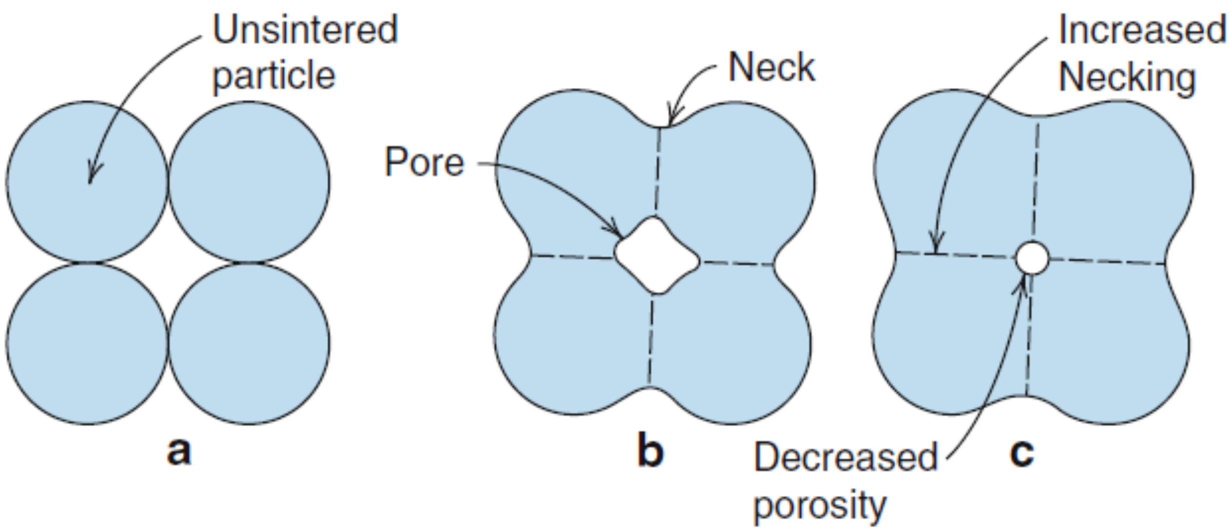


Fig. 5.2 Solid-State Sintering. (**a**) Closely packed particles prior to sintering. (**b**) Particles agglomerate at temperatures above one half of the absolute melting temperature, as they seek to minimize free energy by decreasing surface area. (**c**) As sintering progresses, neck size increases and pore size decreases

- Effect of surface area on sintering

$$\boxed{E_s = \gamma_s \times S_A}$$

E_s: Surface Energy
S_A: Surface area
γ_s: the surface energy per unit area for a particular material, atmosphere, and temperature)

- As fusion occurs, total surface area decreases and this surface energy also decreases.
- To achieve very low porosity levels, long sintering times or high sintering temperatures are required.

- Smaller particles experience a greater driving force for necking and consolidation,
- Thus, smaller particles sinter more rapidly and initiate sintering at lower temperature than larger particles

Understanding from AM point of view

- For AM, the shorter the time it takes to form a layer, the more economically competitive the process becomes.
- Thus, the heat source which induces fusion should move rapidly and/or induce fusion quickly to increase build rates.
- Since the time it takes for fusion by sintering is typically much longer than for fusion by melting, **few** AM processes use sintering as a primary fusion mechanism.

2. Chemically Induced Sintering

Basic Principle

- **Definition:** It involves thermally activated chemical reactions

1. Between two types of powder or
2. Between powders and atmospheric gases to form a by-product which binds the powders together

- In this case, **raw materials** which exothermically react to form the desired byproduct are premixed and heated using a **laser**. By adding **chemical reaction energy to the laser energy**, high-melting-temperature structures can be created at relatively low laser energies.

- **Material:** High-temperature structural ceramic and/or intermetallic precursor materials

- **Example of case 2:**

1. Laser processing of SiC in the presence of oxygen: composite of SiC and SiO2;
2. Laser processing of ZrB2 in the presence of oxygen: a composite of ZrB2 and ZrO2
3. Laser processing of Al in the presence of N2: the Al and AlN particles

- **Post-Processing:** post-process infiltration or high-temperature furnace sintering to reduce the porosity

- **Limitation: Cost and time required are high**

3. Liquid phase Sintering and Partial Melting

Basic Principle

- Here, a portion of constituents within a collection of powder particles become molten, while other portions remain solid.
- The molten constituents act as the glue which binds the solid particles together.
- High-temperature particles can be bound together without needing to melt or sinter those particles directly.
- For example: cemented carbide cutting tools – Co (Binder) + WC (Structural material)

Two types

1. Distinct Binder and Structural Materials
2. Indistinct Binder and Structural Materials

1. Distinct Binder and Structural Materials

- There is a clear distinction between the binding material and the structural material.
- They can be combined in three different ways.

(a) Separate particles

- Here, well-mixed combination of binder and structural powder particles is used.
- Binder particles are smaller than structural material.
- Efficient packing in the powder bed and less shrinkage and lower porosity after binding.
- **Ex:** Steel powder with the polymer, metal-metal Mixtures, metal-ceramic mixtures, etc.

(b) Composite particle

- Particles contain both the binder and structural material within each powder particle.
- Materials agglomeration done using – grinding of cast, extruded or molded mixtures into a powder
- This gives higher density green parts and typically have better surface finish after processing than separate particles.
- **Ex:** mixtures of polymer binders with higher melting point polymer, metal or ceramic structural materials.
- Metal binders with higher melting point metal or ceramic structural materials.
- Glass-filled nylon

(c) Coated particle

- Better than above two types.
- Advantages; including better absorption of laser energy, more effective binding of the structural particles, and better flow properties.

2. Indistinct Binder and Structural Materials

- Here, no distinct binder or structural materials are present.
- Here smaller powder particles and the outer regions of larger powder particles are get melted without melting the entire structure.
- It is similar to the partial melting of alloy.

4. Fully Melting

Basic Principle

- Here, the entire region of material subjected to impinging heat energy is melted to a depth exceeding the layer thickness.
- Thermal energy of subsequent scans of a laser or electron beam (is typically sufficient to re-melt a portion of the previously solidified solid structure;
- And thus, this type of full melting is very effective at creating well-bonded, high-density structures from engineering metals and polymers.
- **For example:** Polymer: PA, Nylon, etc.

  Metal: Ti, Stainless Steel, CoCr
- **Types of fully Melting:** Based on the binding mechanism used:

1. Selective Laser Sintering
2. Selective Laser Melting
3. Direct Metal Laser Sintering
4. Laser Cusing
5. Electron Beam Melting, etc.

4. Powder Handling

We will learn

1. Powder Handling Challenges
2. Powder Handling Systems
3. Powder Recycling

1. Powder handling Challenges

- Several different systems for powder delivery in PBF processes have been developed.
- Fig. is showing hopper based powder delivery system.

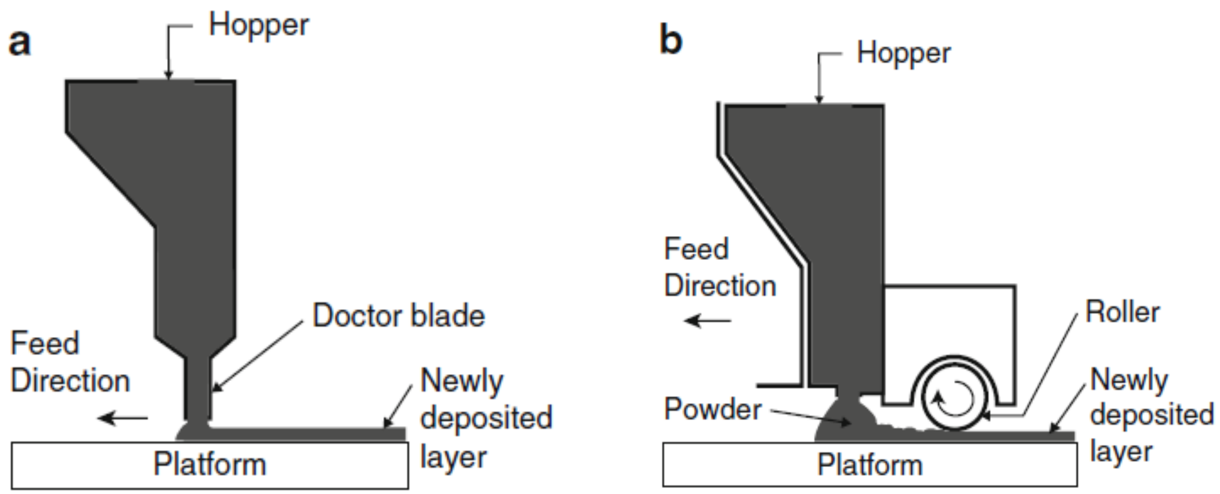


Fig. 5.6 Examples of hopper-based powder delivery systems [3]

✓ **Any powder delivery system for powder bed fusion must meet at least four characteristics.**

1. The powder must be spread to form a smooth, thin, repeatable layer of powder.
2. The powder spreading must not create excessive shear forces that disturb the previously processed layers.
3. The correct volume of powder must be transported from the powder reservoir to the build platform;
4. It must have a powder reservoir of sufficient volume to enable the process to build to the maximum build height without a need to pause the machine to refill the powder reservoir.

✓ **Any powder delivery system must be able to deal with these universal characteristics of powder feeding:**

- Inter-particle friction and electrostatic forces: powder size == decrease; friction == increase
- Surface energy and reactiveness: powder size == decrease; reactiveness == increase
- Airborne and float

2. Powder handling Systems

Counter-rotating roller: 1st Approach to optimizing these powder handling issues

- The two feed cartridges represent the powder reservoir.
- The correct amount of powder for each layer is provided by accurately incrementing the **feed cartridge** **up** and the **build platform** **down** by the layer thickness.
- The counter-rotating roller, over the build platform, deposits the powder.
- The shear forces on the previously processed layers created by this counter-rotating roller are small,
- And thus the previously processed layers are relatively undisturbed.

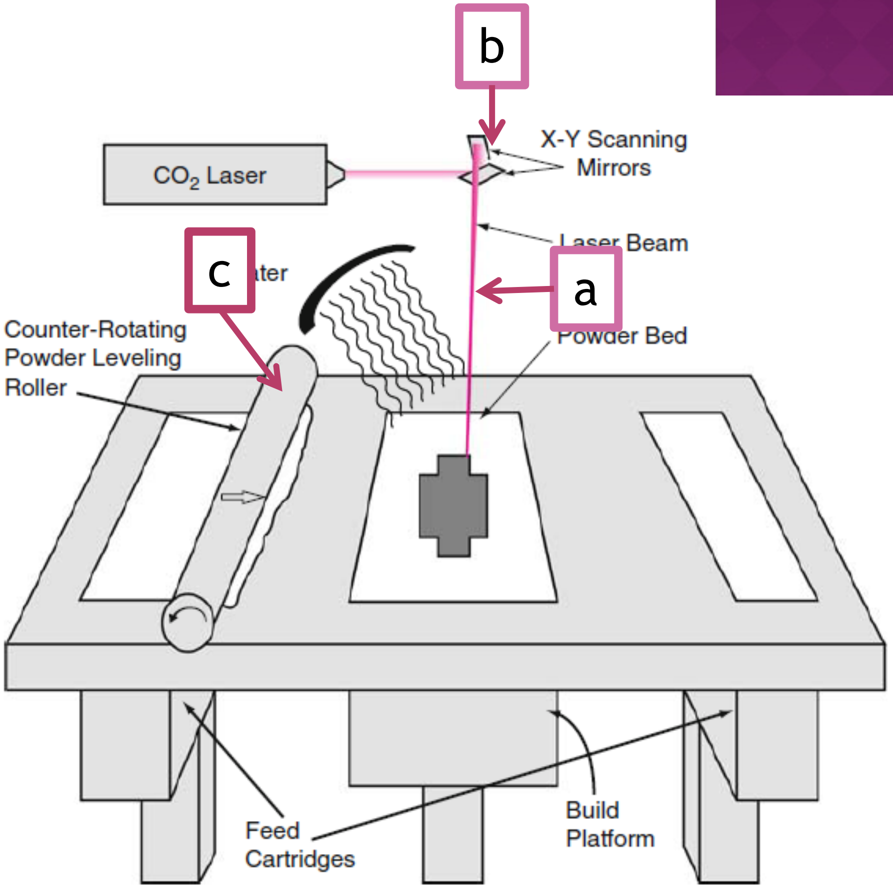
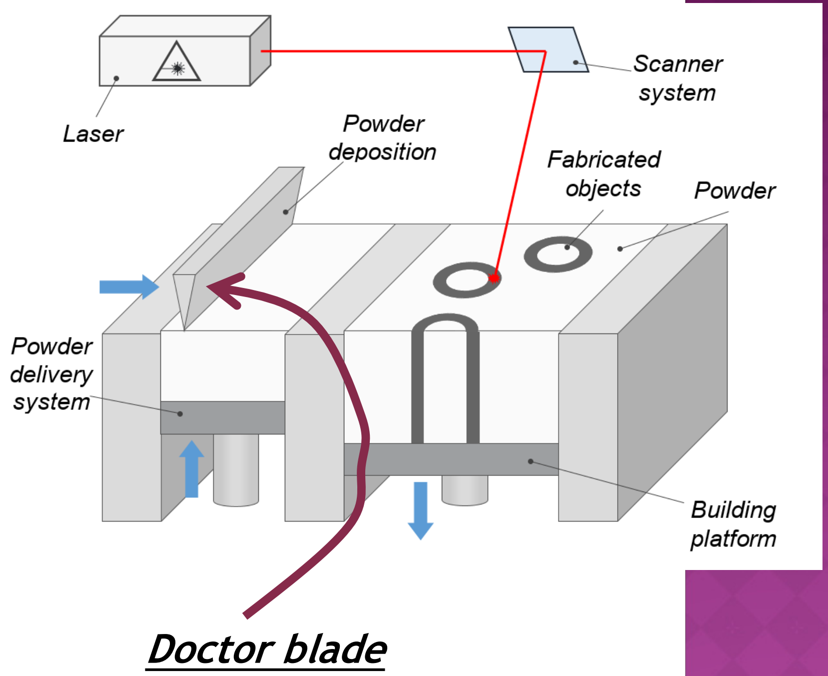


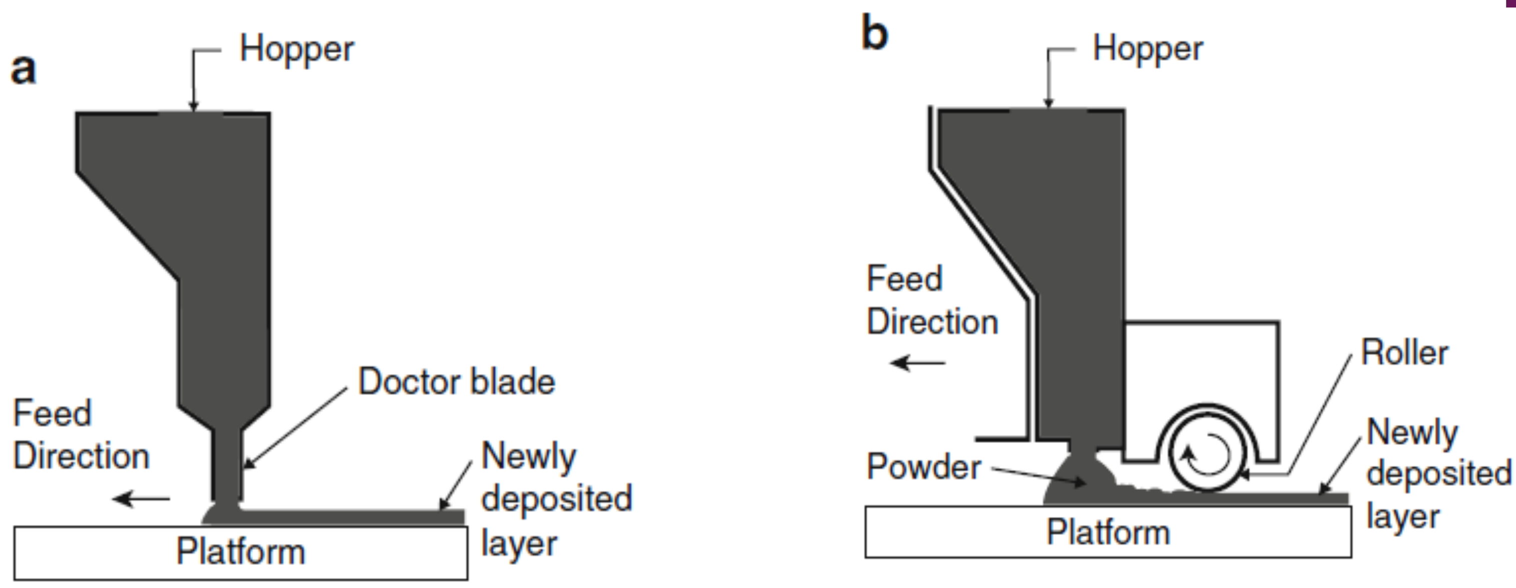
Fig. 5.1 Schematic of the Selective Laser Sintering process

Doctor Blade: 2nd Approach to optimizing these powder handling issues

- A doctor blade is simply a thin piece of metal that is used to scrape material across the surface of a powder bed.
- The shear forces applied to the previously deposited layer are greater than for a counter-rotating roller.
- This increased shear can be reduced if the doctor blade is ultrasonically vibrated, thus partly fluidizing the powder



Hopper Feeding System: 3rd Approach to optimizing these powder handling issues



- A hopper system delivers powder to the powder bed from above rather than beneath.
- The hopper is then used to deposit powder in front of a roller or doctor blade.
- Ultrasonic vibration can be utilized with any of these approaches to help fluidize the powders.

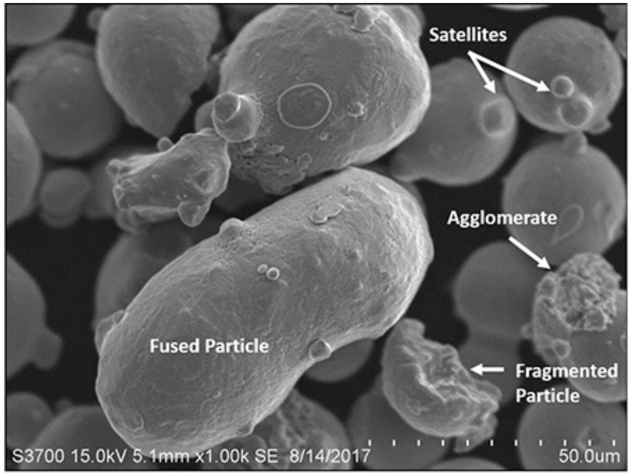
Hopper Feeding System: for Multi material PBF

- In the case of multi-material powder bed processing, the only effective method is to use multiple hoppers with separate materials.
- In a multi-hopper system, the material type can be changed layer-by-layer.
- However, all PBF technologies uses a single material powder feeding system.

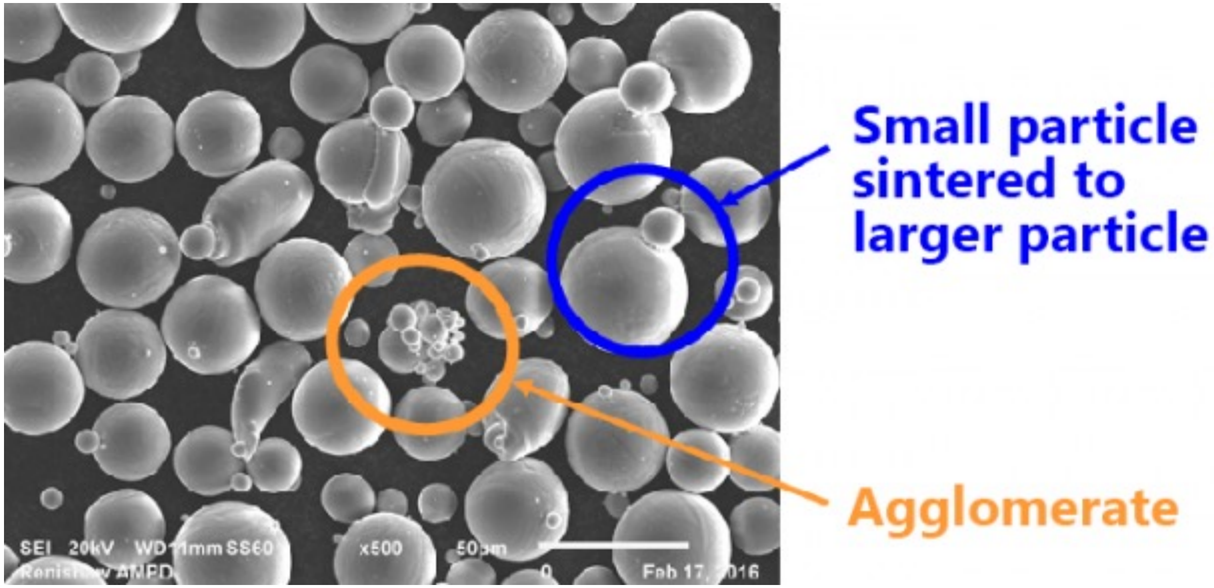
3. Powder Recycling

- For some materials these changes are small, and thus are considered highly recyclable or infinitely recyclable.

- In other materials these changes are dramatic, and thus a highly controlled recycling methodology must be used to maintain consistent part properties between builds.



- For example: PBF SLS: for Nylon Polyamide: both the effective particle size and molecular weight change during processing.
- Solution: 1/3 unused powder + 1/3 overflow/feed powder + 1/3 build platform powder



- <u>**Particle sorting method:**</u> **a vibratory screen-based sifting device or an air classifier** == they mix the powders together more effectively and help break up agglomerates == thus enabling a larger fraction of material to be recycled.

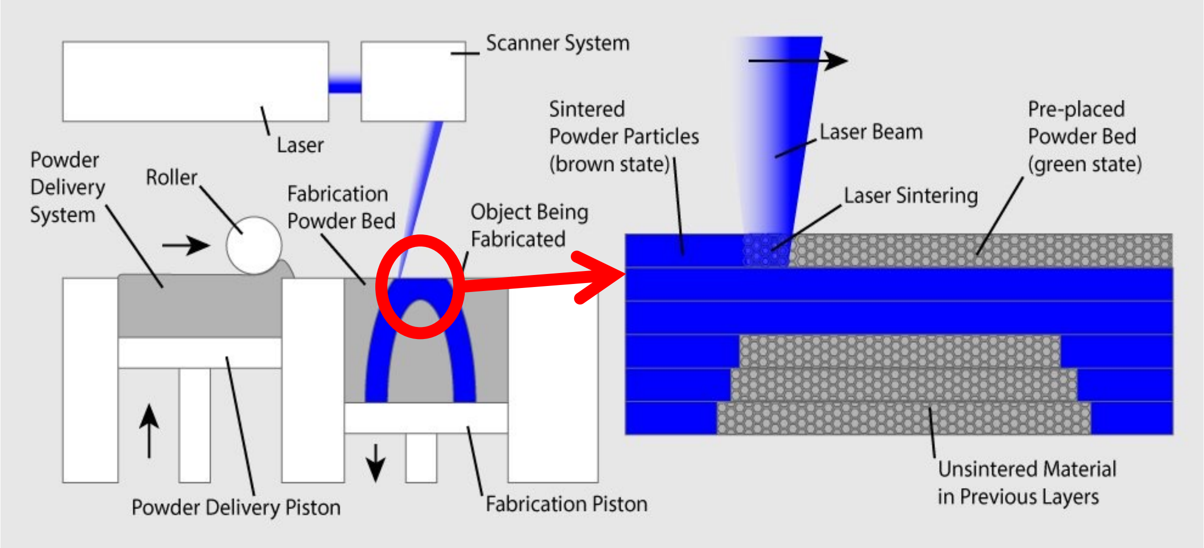
- it is critical that the material be well-mixed during recycling; otherwise, parts built from recycled powder will have different properties in different locations.

- In addition, repeated recycling over a long period of time may result in some powder becoming unusable.

5. Selective Laser Melting and Electron Beam Melting

5.1 Selective Laser Melting

- It uses a high power-density laser to melt and fuse metallic powders together.
- The SLM process has the ability to fully melt the metal material into a solid three-dimensional part.



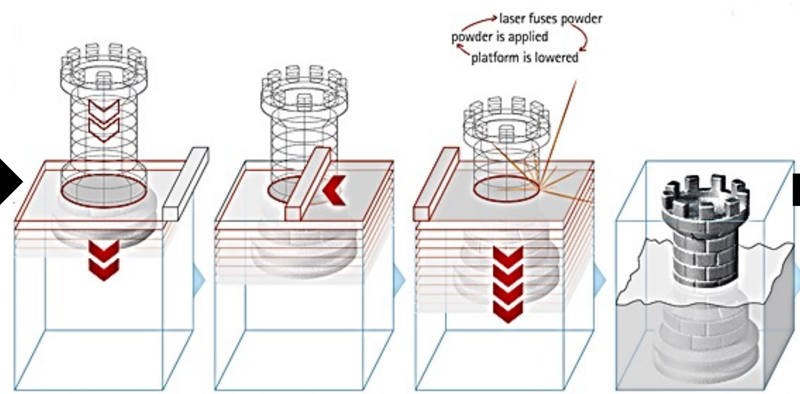
Schematic of selective laser melting

• General Principle for Selective Laser Melting

Step 1:
CAD Design → .STL File preparation → Slicing

3D geometry model

Step 2:
Manufacturing of part layer after layer



Building platform is lowered

The next layer of powder is applied

The process repeats itself until the part is complete

Loose powder is removed

Step 3:
Final Part

Completed part

Step 4:
Post-Processing

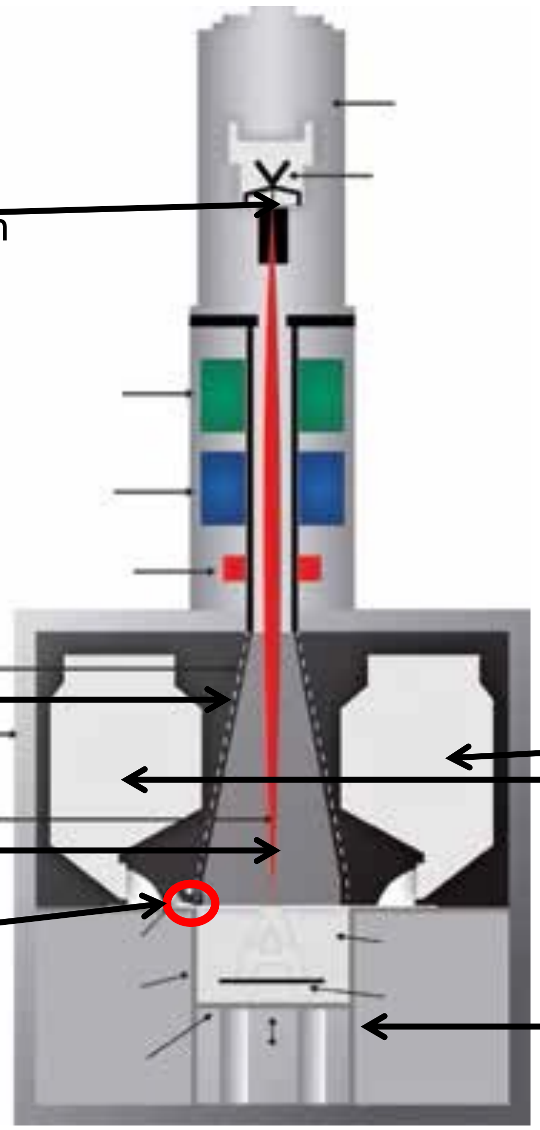
1. Heat Treatment (Stress Relieving/ Strengthening treatment/Customized treatment)

2. Hot Isostatic Pressing

3. Machining, Polishing, etc.

5.2 Electron Beam Melting

Electron Beam Gun:
- ✓ Single Crystal or Tungsten



Heat Shield:
- ✓ Helps to keep high process temperature (up to 1100 C)

Powder Hoper:
- ✓ Powder will be stored

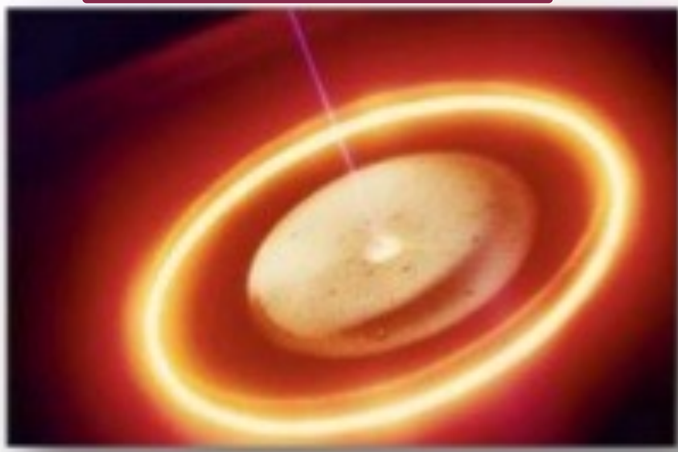
Electron Beam

Rake

Build Platform

Electron Beam Melting vs Selective Laser Melting

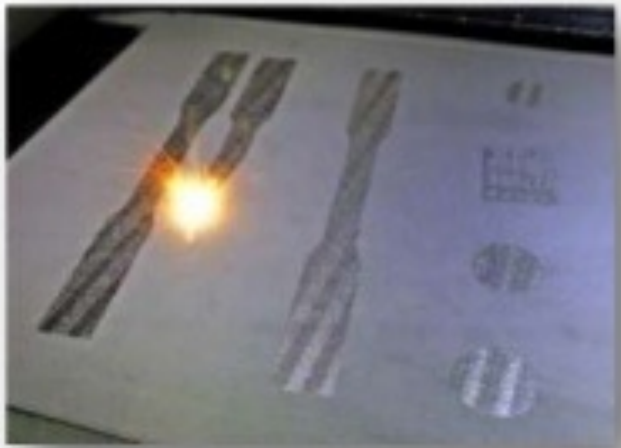
Electron Beam Melting



- ✓ Electron Beam, Vacuum, Process temperature: 680-720 °C
- ✓ <u>**Process Involves:**</u>

1. **Powder spreading on building platform**
2. **Sintering**
3. **Melting**
4. **Platform goes down**
5. **Process repeats from (1)**

Selective Laser Melting



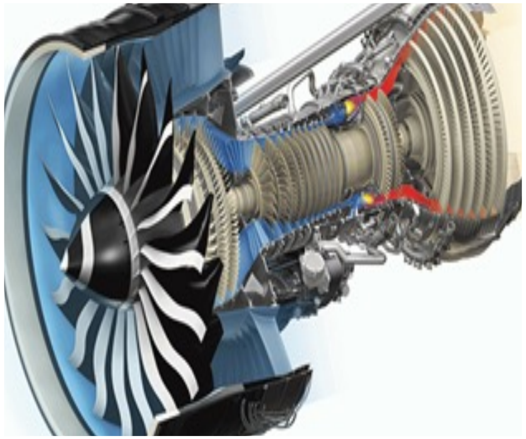
- ✓ Laser, Argon, Build temperature: 200 °C
- ✓ <u>**Process Involves:**</u>

1. **Powder spreading on building platform**
2. **Melting**
3. **Platform goes down**
4. **Process repeats from (1)**

6. Common Applications

1. Functional parts

- It offers a range of strong, functional materials.
- Because of this, SLS is often used for the production of parts that will be under load when placed in service.
- SLS allows for complex geometries that can be easily printed from well known materials like PA 12.



2. Low run part production

- SLS allows cost effective, low run production of function parts to provide feedback on the design and performance of parts.
- Because SLS always prints a full powder bin, multiple parts can be manufactured in a single build, offering viable economies of scale at certain build sizes ("smaller than a fist").

3. Complex ducting (hollow sections)

- It can create parts with hollow sections.
- SLS is ideally suited for the low run production of complex ducting and piping.
- By removing traditional design constraints, SLS is capable of printing parts that are optimized for application rather than manufacture.

7. Capabilities and Limitations

1. For Plastic: No support is required.

- The loose powder bed is a sufficient support material for polymer PBF.
- This saves significant time during part building and post-processing.
- As a result, internal cooling channels and other complex features that would be impossible to machine are possible.
- Additionally, the ability to nest polymer parts in 3-dimensions,
- Thus dramatically improving the productivity of these processes when compared with processes that require supports.

2. For Metal: Support is required.

- This means that post-processing of metal parts after AM can be expensive and time consuming.

3. Accuracy and surface finish:

- However, accuracy and surface finish are strongly influenced by the operating conditions and the powder particle size.
- Finer particle sizes produce smoother, more accurate parts but are difficult to spread and handle.

8. Conclusion

1. Polymer-based laser sintering is commonly used for prototyping and end-use applications in many industries

2. Metal-based processes, including laser and electron beam, are growing in popularity.

9. Questions and Discussion

1. What is PBF?
2. What are types of PBF?
3. SLM vs. EBM?
4. What are the powder handling systems?
5. PBF Machines available: name of the manufactures?

Thank You!