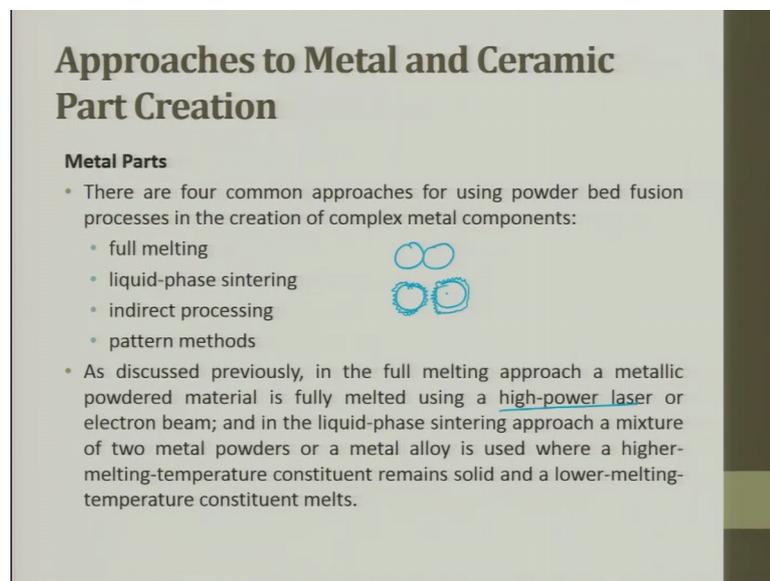


**Rapid Manufacturing**  
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**Lecture – 22**  
**Power based processes (Part 3 of 3)**

Welcome to the lecture on powder based processing.

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**Approaches to Metal and Ceramic Part Creation**

**Metal Parts**

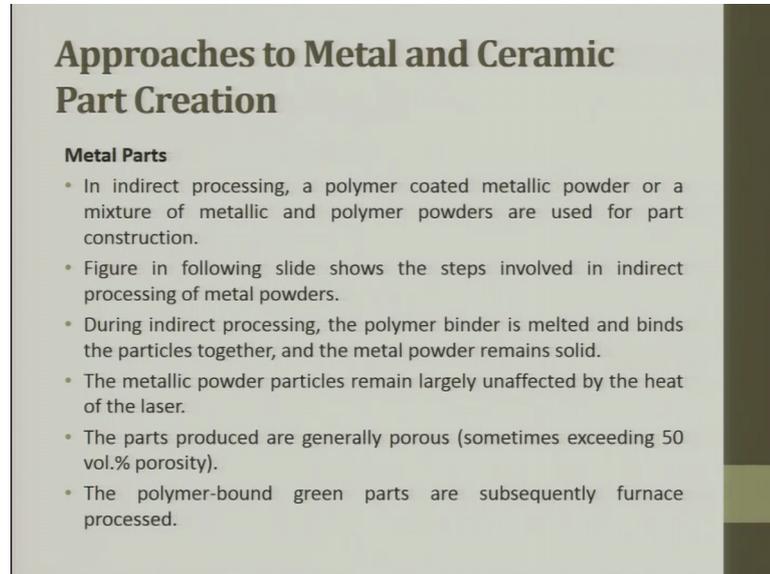
- There are four common approaches for using powder bed fusion processes in the creation of complex metal components:
  - full melting
  - liquid-phase sintering
  - indirect processing
  - pattern methods
- As discussed previously, in the full melting approach a metallic powdered material is fully melted using a high-power laser or electron beam; and in the liquid-phase sintering approach a mixture of two metal powders or a metal alloy is used where a higher-melting-temperature constituent remains solid and a lower-melting-temperature constituent melts.

Melting parts there are 4 common approaches for using powder bed fusion process in the creation of the complex metal component, fully melt, liquid phase sintering, indirect processing, pattern methods. So, full melting is you try to take 2 powders you fully melt those powders, liquid phase sintering is you have 2 powders where in between these powders on top you are coating with another metal which has a lower melting point and this can give you a better consolidation, then indirect processing and pattern methods we will see in details.

As discussed previously, in the full melting approach a melting powder material is fully melt using high power laser or electron beam and in liquid phase sintering approach a mixture of 2 metal powders or metal alloy is used where a higher melting temperature

constituent remains solid and the lower melting that is what I said lower melting constituent melts and it helps in sticking with each other.

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**Approaches to Metal and Ceramic Part Creation**

**Metal Parts**

- In indirect processing, a polymer coated metallic powder or a mixture of metallic and polymer powders are used for part construction.
- Figure in following slide shows the steps involved in indirect processing of metal powders.
- During indirect processing, the polymer binder is melted and binds the particles together, and the metal powder remains solid.
- The metallic powder particles remain largely unaffected by the heat of the laser.
- The parts produced are generally porous (sometimes exceeding 50 vol.% porosity).
- The polymer-bound green parts are subsequently furnace processed.

In indirect processing a polymer coated metallic powder or a mixture of metallic and a polymer powder are used for part construction. So, once only for the part construction after the part is constructed you burn the polymer. For the figure in the next slide we will see shows the step involved in processing of metal powder. During indirect processing the polymer binder is melted and binds the particle together and the metal powder remains solid that is indirect.

The metallic powder particles remind largely unaffected by the heat of the laser, the parts produced are generally porous and the polymer bounded green parts are subsequently furnace processed. So, what you do is you try to get a shape out of the polymer binder and you also heat the polymer binder. So, that is polymer binders can stick to each other and then form a shape.

After it forms a shape what is required, then you take it a furnace blower or burn away all the binders. So, moment the binder is burned so, what is left with you, you can take that and go for next stage of post heating process to get the required output.

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**Approaches to Metal and Ceramic Part Creation**

**Metal Parts**

- Furnace processing occurs in two stages:
  - Debinding
  - Infiltration or consolidation.

So, the metal parts furnace processing occurs in 2 stage, one is debinding and infiltration or by consolidation.

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**Approaches to Metal and Ceramic Part Creation**

**Metal Parts**

- During debinding, the polymer binder is vaporized to remove it from the green part.
- Typically, the temperature is also raised to the extent that a small degree of necking (sintering) occurs between the metal particles.
- Subsequently, the remaining porosity is either filled by infiltration of a lower melting point metal to produce a fully dense metallic part, or by further sintering and densification to reduce the part porosity.
- Infiltration is easier to control, dimensionally, as the overall shrinkage is much less than during consolidation.
- However, infiltrated structures are always composite in nature whereas consolidated structures can be made up of a single material type.

*Handwritten notes:* metal particles → liquid infiltration.

During debinding, the polymer binder is vaporized to remove it from the green part. Typically, the temperature is also raised to the extent that a small degree of necking occurs between the metal particles.

Subsequently, the remaining porosity is either filled by infiltration of a lower melting point metal to produce a fully dense metallic part or by further centring and densification

to reduce the part porosity this is very very important. If you are happy with the porosity leave with it, if you are not happy you try to infiltrate material where is application, you make ceramic porous material and then inside the ceramic material through the pores you try to infiltrate metals; so, these metals which are infiltrated gives you lubrication ok. So, there we use this application exhaustively, infiltration is easier to control dimensionally as the overall shrinkage is much less than during consolidation.

However infiltrated structures are always composite in nature where as consolidated structures can be made by a single material type, infiltrated structures are always composite in nature. So, you will have a base structure for example, what are we talking about this is a base structure and here are the infiltrated materials these are liquid infiltrates or solid infiltration these are all the metal parts particles.

However, the infiltration structure are always composite in nature where as consolidated structure can be made by a single material too. So, you make particles and then you bind it after you bind you try to sinter it and still you have pores you infiltrate a liquid of the same material.

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### Approaches to Metal and Ceramic Part Creation



**Metal Parts**

- The last approach to metal part creation using PBF is the pattern approach.
- For the previous 3 approaches, metal powder is utilized in the PBF process; but in this final approach, the part created in the PBF process is a pattern used to create the metal part.
- The two most common ways PBF-created parts are utilized as patterns for metal part creation are as investment casting patterns or as sand-casting molds.
- In the case of investment casting, polystyrene or wax-based powders are used in the machine; and subsequently invested in ceramic during post-processing, and melted out during casting.
- In the case of sand-casting molds, mixtures of sand and a thermosetting binder are directly processed in the machine to form a sand-casting core, cavity or insert.

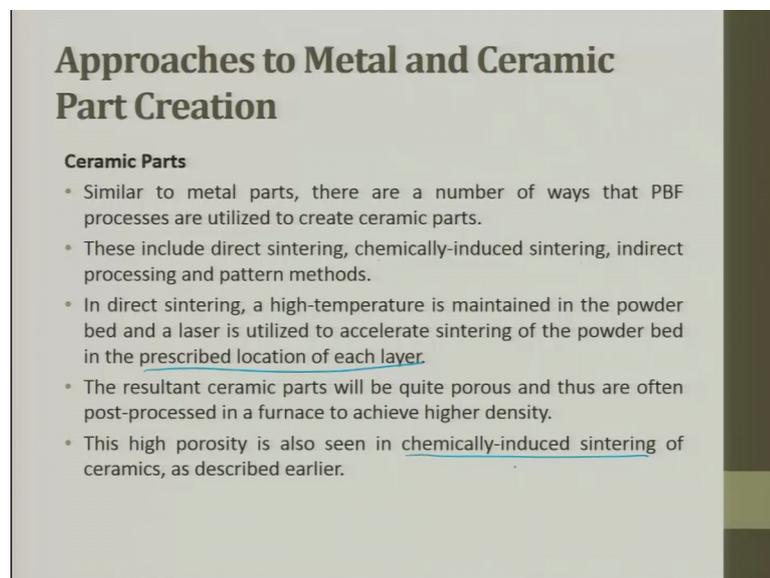
The last approach to metal part creation using powder bed fusion method is the pattern approach. For the previous 3 approaches metal powder is utilised in the powder bed process, but in this final approach the part created in the powder bed process is a pattern used to create metal parts pattern used to create metal parts. The two most common ways

of powder bed fusion created part are utilised as pattern for a metal part creation are as investment casting patterns or a sand casting patterns. So, basically what we do is in sand casting we try to make patterns this is mould this is sand ok.

This is a pattern which is created by this process, investment casting also we can do we can try to take this out of polymer pattern out of polymer then what we do is we give a ceramic coating on top of it heat the ceramic. So, the polymer which is inside melts and dies of or it is into liquid you pour it of now what you have is a shell a ceramic shell the ceramic shell can be used as a pattern and then you can start making oh lot of applications, in you can use polymer, you can wax also.

In the case of investment casting polystyrene or wax based powders are used in the machine and subsequently invested in the ceramic during post processing and melted out during casting. In the case of sand casting mold this is a sand casting mold, the mixture of the sand and thermosetting binders are directly processed in the machine to form a sand casting core, cavity or insert.

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**Approaches to Metal and Ceramic Part Creation**

**Ceramic Parts**

- Similar to metal parts, there are a number of ways that PBF processes are utilized to create ceramic parts.
- These include direct sintering, chemically-induced sintering, indirect processing and pattern methods.
- In direct sintering, a high-temperature is maintained in the powder bed and a laser is utilized to accelerate sintering of the powder bed in the prescribed location of each layer.
- The resultant ceramic parts will be quite porous and thus are often post-processed in a furnace to achieve higher density.
- This high porosity is also seen in chemically-induced sintering of ceramics, as described earlier.

Ceramic parts like metal parts ceramic parts also can be created the only difference between metal and ceramic is metal lower melting point as compared to that of a ceramic. There are a number of ways that powder bed fusion processes are utilised to create ceramic parts. These include direct sintering, chemically induced sintering, indirect processing and pattern methods, like in metals here also you will have pattern

methods. In direct sintering a temperature is maintained in the powder bed when the laser is utilised to accelerate sintering of the powder bed in the prescribed location to form each layer. The resultant ceramic part will be quite porous and thus are often post processed in the furnace to achieve higher density. This porosity is also seen in chemically - induced sintering of ceramics.

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## Approaches to Metal and Ceramic Part Creation

### Ceramic Parts

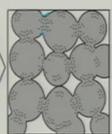
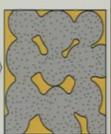
- Indirect processing of ceramic powders is identical to indirect processing of metal powders (following Figure).
- After debinding, the ceramic brown part is consolidated to reduce porosity or is infiltrated.
- In the case of infiltration, when metal powders are used as the infiltrant then a ceramic/metal composite structure can be formed.
- In some cases, such as when creating SiC structures, a polymer binder can be selected, which leaves behind a significant amount of carbon residue within the brown part.
- Infiltration with molten Si will result in a reaction between the molten Si and the remaining carbon to produce more SiC, thus increasing the overall SiC content and reducing the fraction of metal Si in the final part.

The indirect processing of ceramic powder is identical to indirect processing of metal powder, what was the indirect way.

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## Approaches to Metal and Ceramic Part Creation

Fig. Indirect processing of metal and ceramic powders using PBF

Loose Powder	Green Part	Brown Part	Finished Part
			
Metal or ceramic particles mixed with polymer binders.	Melting and resolidification of polymer binders enable complex parts to be formed without thermally affecting the metal or ceramic powders.	Polymer vaporization and particle sintering at elevated temperatures results in a porous, sintered component.	Infiltration with a lower-melting-temperature metal results in a dense, finished component.

Gibson, D.W. Rosen, and B. Stucker, Additive Manufacturing Technologies, 2010

This is what it is so, you will have your loose powder. So, in the loose powder you can see metal or ceramic particles mixed with a polymer binder these are polymer binders. So, the powder bed fusion process happens so this is consolidated and you try to make a green part. So, you just melt the polymers. So, the polymer stitches or ties the ceramic or the metal particles and then what you do is you take it your furnace heat it, when you try to furnace heat it all this polymer goes away and some amount of necking happens, necking happens between the two particles metal or ceramic depending upon the temperature.

And then what you do is, you try to take it to further processing furnace processing you see a better consolidation happening and here where ever there was a whole vacant spot you have in filtered through some material. So, that is as required for example, copper can be done, aluminium can be done, lead can be done, for your requirements for lubrication effect. Metals and ceramic particles binded with the polymer are seen here, next melting and resolidification of polymer binder enabling the complex part to be formed without thermally affecting the metal or the ceramic powder so, the particle is (Refer Time: 09:21).

Then the polymer vaporization and particle sintering at elevated temperature happens resulting in the porous sinter component. Then you infiltrate with lower melting point metal resulting in the density finishing component. So, this is the flow for indirect processing of metals and ceramics.

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## Approaches to Metal and Ceramic Part Creation

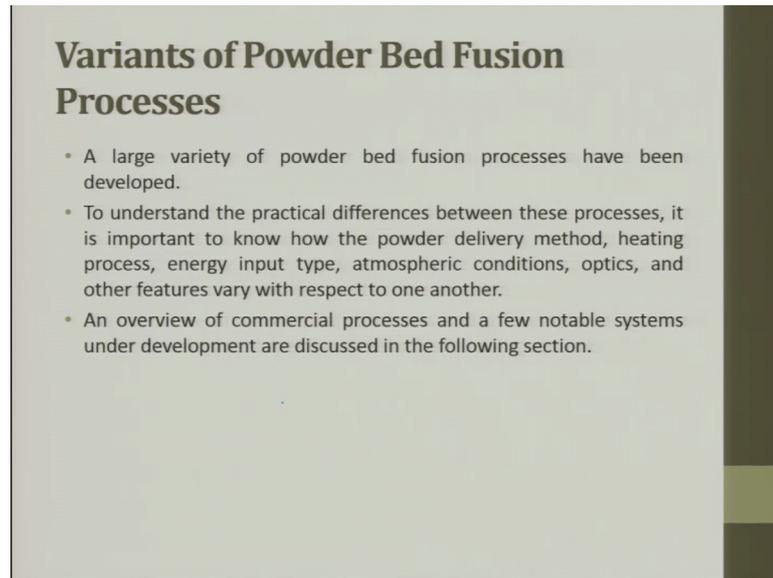
### Ceramic Parts

- Indirect processing of ceramic powders is identical to indirect processing of metal powders (following Figure).
- After debinding, the ceramic brown part is consolidated to reduce porosity or is infiltrated. *Pressure +*
- In the case of infiltration, when metal powders are used as the infiltrant then a ceramic/metal composite structure can be formed. *Pressure -*
- In some cases, such as when creating SiC structures, a polymer binder can be selected, which leaves behind a significant amount of carbon residue within the brown part.
- Infiltration with molten Si will result in a reaction between the molten Si and the remaining carbon to produce more SiC, thus increasing the overall SiC content and reducing the fraction of metal Si in the final part.

After the debinding the ceramic brown part is consolidated to reduce the porosity and is infiltrated. In the case of infiltration with this can be done by two pressure, it can be done by positive pressure or it can be done by negative pressure that is vacuum can be applied you suck and then allow the material to flow or you pressurize the liquid material to flow.

When metal powders are used as the infiltrant then a ceramic metal composite structure can be formed. In such a case such as when creating SiC structure, a polymer binder can be selected, which leaves behind the significant amount of carbon residue within the brown part. Infiltration with molten silicon will result in the reaction between the molten silicon and the carbon to produce SiC this is how people producer sic parts, Si molten sic and carbon thus increasing the overall sic content and reducing the fraction of Si in the final part.

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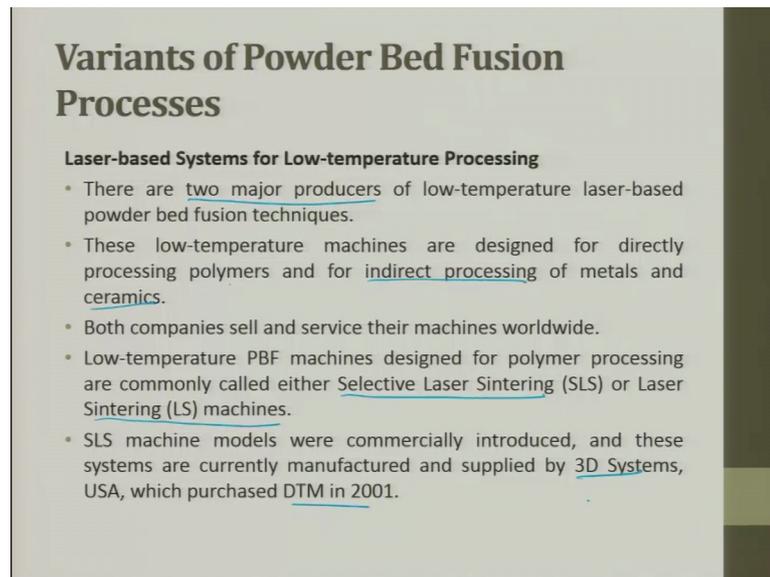
**Variants of Powder Bed Fusion Processes**

- A large variety of powder bed fusion processes have been developed.
- To understand the practical differences between these processes, it is important to know how the powder delivery method, heating process, energy input type, atmospheric conditions, optics, and other features vary with respect to one another.
- An overview of commercial processes and a few notable systems under development are discussed in the following section.

So, the variant of powder bed fusion processes a large variant of powder bed fusion process have been developed today, what we have seen is only few successful processes, but people have come up with variants depending upon their requirements.

To understand the practical difference between these processes, it is important to know how the powder delivery method, heating process, energy input type, atmospheric conditions, optics and other features vary with respect to one another. An overview of commercial process and a few notable systems under development are discussed in this section.

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## Variants of Powder Bed Fusion Processes

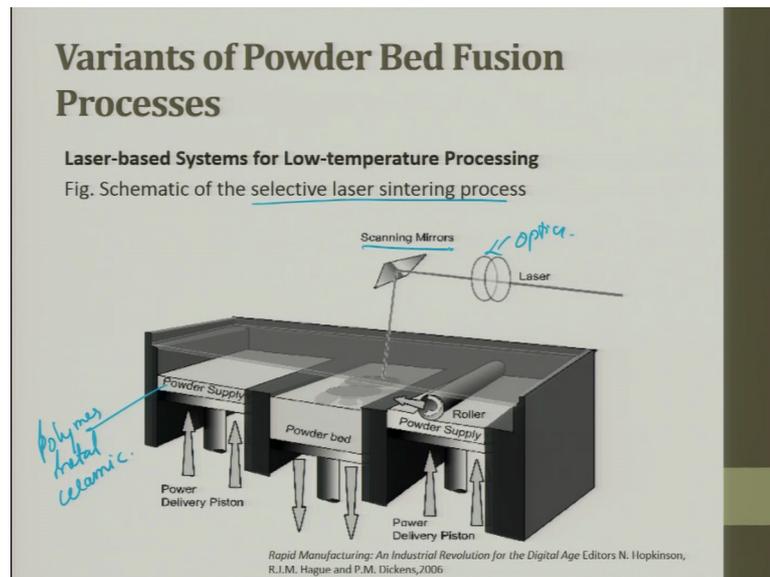
### Laser-based Systems for Low-temperature Processing

- There are two major producers of low-temperature laser-based powder bed fusion techniques.
- These low-temperature machines are designed for directly processing polymers and for indirect processing of metals and ceramics.
- Both companies sell and service their machines worldwide.
- Low-temperature PBF machines designed for polymer processing are commonly called either Selective Laser Sintering (SLS) or Laser Sintering (LS) machines.
- SLS machine models were commercially introduced, and these systems are currently manufactured and supplied by 3D Systems, USA, which purchased DTM in 2001.

Laser based system for low temperature processing, there are 2 major producers for low temperature laser bed powder bed fusion technique. These low temperature machines are designed for directly processing polymer and for indirectly processing of metals and ceramics. Both these companies sell and service their machines worldwide.

Low temperature powder bed washing machines designed for polymer processing are commonly called as selective laser sintering machines or laser sintering machines. The SLS machines machine model were commercially introduced and these systems are currently manufactured and supplied by 3 D system, USA which purchased DTM in 2001. This industry is fastly changing and companies buy companies, company sell companies so, there is not a single owner for a long time like in automobile we have few joints. So, in 3 D in rapid manufacturing or in rapid prototyping we do not have a single joint they by establish a technology sell it then establish another company so, this keeps going.

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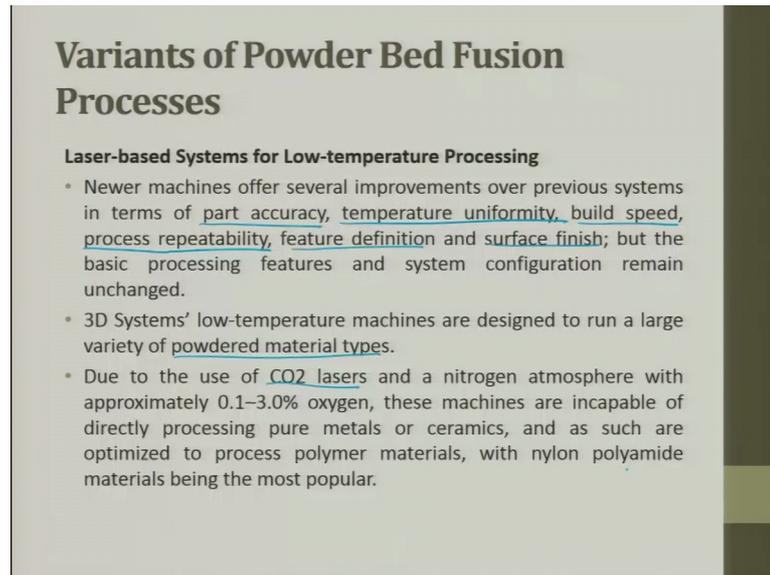


So, 3 D system purchased DTM in 2001 so, this is a tip this is the schematic diagram for laser sintering process selective laser sintering process. So, you have a powder bed so in this bed you have you can have a polymer metal or a ceramic powder can be there. So, this powder will be is there so this powder is now moved into a powder bed.

So, this powder bed is otherwise called as a table, thus the powder bed moves up that table moves down. So, the roller which roles from one side to the other side tries to the tries to take the required quantity of a single layer of powder and spread it on top of a table and then this roller goes to the other extreme end.

In the next time when the single layer information of sintering is over the bed pulls it down by a single layer this powdered delivery piston goes up by a single layer the roller takes the material from this extreme end and moves to the table and then goes to this experiment so, this extreme end. So, now, what you have is layer by layer by layer information you have and that is how it is done. So, here you have laser this is the optics which is attached with the laser this is a scanning mirror; so, it gives you 2 D layer information so to for producing.

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## Variants of Powder Bed Fusion Processes

### Laser-based Systems for Low-temperature Processing

- Newer machines offer several improvements over previous systems in terms of part accuracy, temperature uniformity, build speed, process repeatability, feature definition and surface finish; but the basic processing features and system configuration remain unchanged.
- 3D Systems' low-temperature machines are designed to run a large variety of powdered material types.
- Due to the use of CO<sub>2</sub> lasers and a nitrogen atmosphere with approximately 0.1–3.0% oxygen, these machines are incapable of directly processing pure metals or ceramics, and as such are optimized to process polymer materials, with nylon polyamide materials being the most popular.

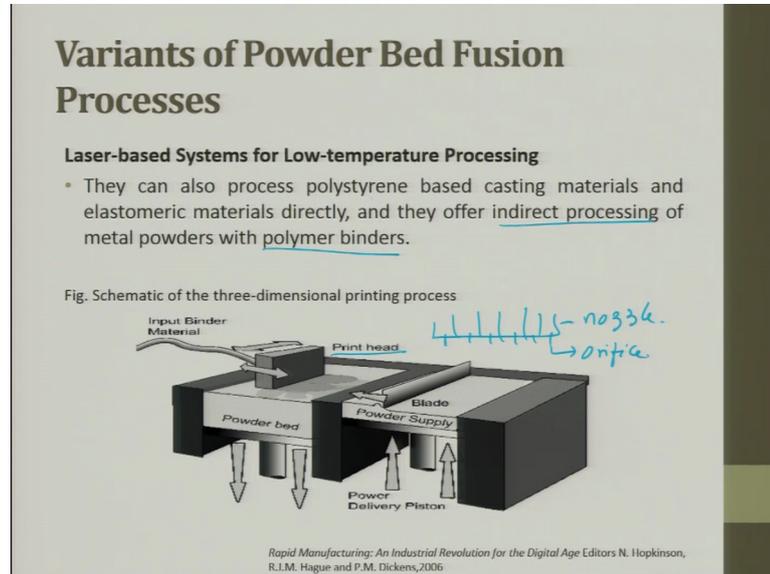
The newer machines offer several improvements over previous machines in terms of part accuracy, temperature uniformity, building speed, repeatability, feature definition and surface finish. And by the way you should also understand that is a heater placed around the powder bed here in the centre portion there is a heating; it will not take you to a very high temperature and then on the delivery piston here also you will maintain or the entire system will be maintained at a inside a small furnace at a lower temperature not melting temperature.

In order to make sure no contamination happens with respect to the free atmosphere the water molecules will should not be there and it should not react. So, they do it or they put it inside a furnace and project with argon gas. So, the laser acute the laser resolutions are improved the powder size has been has the powder size is been reduced, then uniformity in powder size is done, then led to the scanning speeds are become high, then the repeatability the drive mechanisms have improved. So, these are certain things which are kept on we going on in the SLS process so that now you get better features the 3 D system low temperature machines are designed to run a large variety of powder material type.

Due to the use of CO<sub>2</sub> laser and nitrogen atmosphere with approximately 0.1 to 3 percent oxygen, these machines are incapable of directly processing pure metals and

ceramics and acids are optimised to process polymer materials with nylon polyamide material being the most popular one.

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The other one is where in which you use a binder which is kept in a printer head and then this binder instead of a laser the laser is replaced by a binder head this binder the binder head or the sorry the next advanced version is removing the laser and then replacing with the print head so, this print head will have a nozzle.

This will be several nozzles and through this nozzles every nozzle you will have orifices. So, these are nozzle these are orifice through this orifice the binder material falls down and this binder material drops on the location where ever you have to join the particles and then you get an output. So, these are they can also process polystyrene based casting materials and elastomeric materials directly and they often offer indirect processing of metal powders with polymer binders, this is an advanced next variant of SLS process.

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## Variants of Powder Bed Fusion Processes

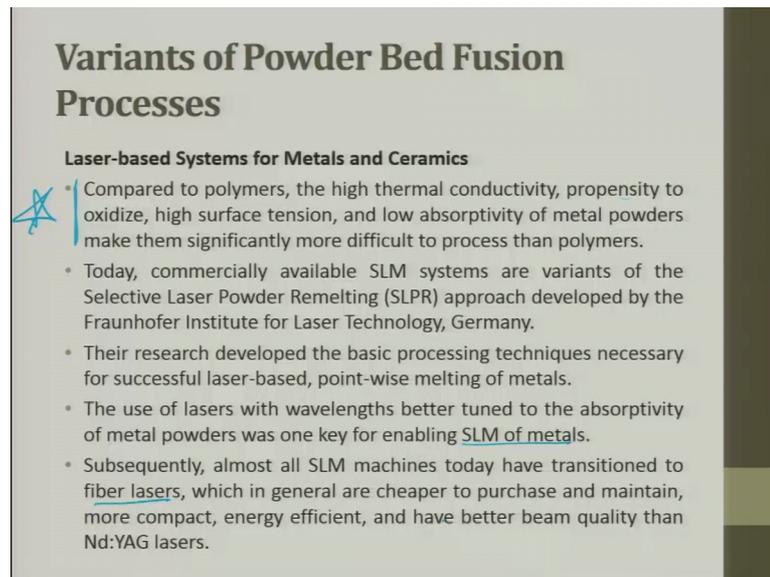
### Laser-based Systems for Metals and Ceramics

- There are four companies which make commercially available laser-based systems for direct melting and sintering of metal and ceramic powders: [EOS GmbH](#) (Germany), [MTT Technologies Ltd](#) (UK), [Concept Laser GmbH](#) (Germany), and [Phenix System](#) (France).
- Not all of these companies sell and service machines worldwide.
- For instance, all four companies sell machines in Europe, whereas EOS and MTT (through a partnership with 3D Systems) actively sell systems in the United States.
- The most commonly used terminology to describe this category of technologies is [Selective Laser Melting \(SLM\)](#); however the terms [Laser Cusing](#) and [Direct Metal Laser Sintering](#) are also used by certain manufacturers, as mentioned in the following section.
- For this discussion, we will use SLM to refer to the technologies in general and not to any particular variant.

There are 4 big companies which make commercial available laser based systems for direct melting and sintering of metal and ceramic powders EOS Germany, MTT UK, Concept Laser Germany and Phenix System France. So, all the 4 are a big player even now they are available in the market, they do a wonderful job all the 4 they are competitive to each other, not all of these companies sell and service machine worldwide for instances all 4 companies sell machines in Europe whereas, EOS and MTT actively sell systems in the United States so, they also have a fixed market they go through it.

In India you can get all the 4 through a agent right, the most commonly used terminology to describe this category of technology is selective laser melting; however, the term laser in the laser cusing and direct metal laser sintering are also used by certain manufacturer as mentioned in the following sections. For this discussion we use SLM to refer to the technologies in general and not to any particular variant.

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## Variants of Powder Bed Fusion Processes

### Laser-based Systems for Metals and Ceramics

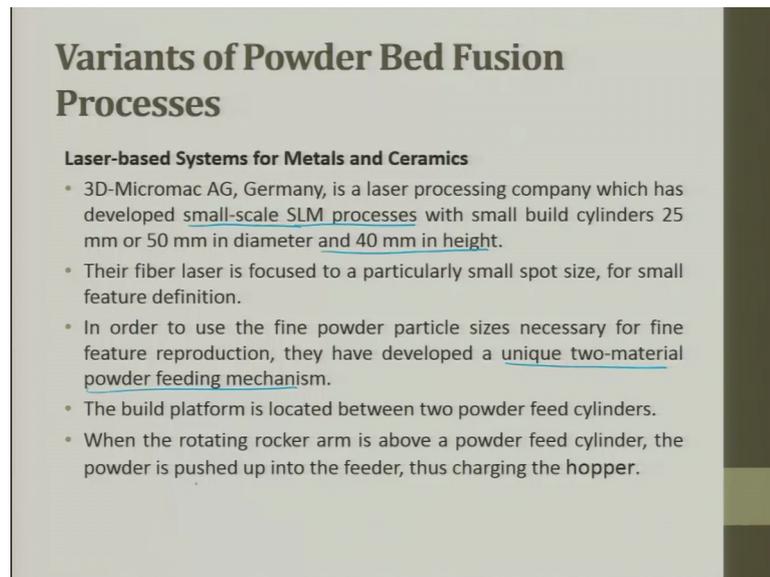
- Compared to polymers, the high thermal conductivity, propensity to oxidize, high surface tension, and low absorptivity of metal powders make them significantly more difficult to process than polymers.
- Today, commercially available SLM systems are variants of the Selective Laser Powder Remelting (SLPR) approach developed by the Fraunhofer Institute for Laser Technology, Germany.
- Their research developed the basic processing techniques necessary for successful laser-based, point-wise melting of metals.
- The use of lasers with wavelengths better tuned to the absorptivity of metal powders was one key for enabling SLM of metals.
- Subsequently, almost all SLM machines today have transitioned to fiber lasers, which in general are cheaper to purchase and maintain, more compact, energy efficient, and have better beam quality than Nd:YAG lasers.

Compared to polymers the high temperature conductivity, the propensity to oxidise surface at a high surface tension, low absorptivity of the metal powders make them significantly more difficult to process than polymers. These are important properties which have to be noted. Today commercially available SLM so the same laser cannot be used the interaction time cannot be the same.

Today commercially available SLM systems are variant of the selective laser powder remelting approach developed by Fraunhofer Institute of Germany. Their research developed the basic processing technique necessary for successful based point wise melting of the metal powder. The use of laser with wavelength better tuned to the absorptivity of the metal powder was one key for enhancing SLM process for example, there is a red laser, green laser, blue laser, the response of the red laser, blue laser and green laser are completely different.

So, depending upon the requirement they choose the laser and in terms of when we talk about laser material interaction it is the absorptivity property which plays a important role. Subsequently almost all SLM machines today have transitioned to fibre laser, with in general are cheaper to purchase and maintain more compact energy efficient and have better beam quality than Nd-YAG laser.

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## Variants of Powder Bed Fusion Processes

### Laser-based Systems for Metals and Ceramics

- 3D-Micromac AG, Germany, is a laser processing company which has developed small-scale SLM processes with small build cylinders 25 mm or 50 mm in diameter and 40 mm in height.
- Their fiber laser is focused to a particularly small spot size, for small feature definition.
- In order to use the fine powder particle sizes necessary for fine feature reproduction, they have developed a unique two-material powder feeding mechanism.
- The build platform is located between two powder feed cylinders.
- When the rotating rocker arm is above a powder feed cylinder, the powder is pushed up into the feeder, thus charging the hopper.

3 D Micromac AG Germany is the is a laser processing company which has developed small small scale SLM processes with small built cylinders of 25 millimetre and 50 millimetre in diameter and a height of 40 millimetre in height.

So, today when we are looking at bio implants when we are looking at micro fluidic channels, when we are looking at electronics, when we are looking at MEMS application where directly you want to produce from the from the start from the building block we use this technique for making the final part. In fact, there are certain complex geometries which are used complex geometry parts which are used as your implants which is too difficult for you to generate to subtract 2 process, but the additive process develops it within no time and again you can also have functionally graded material there.

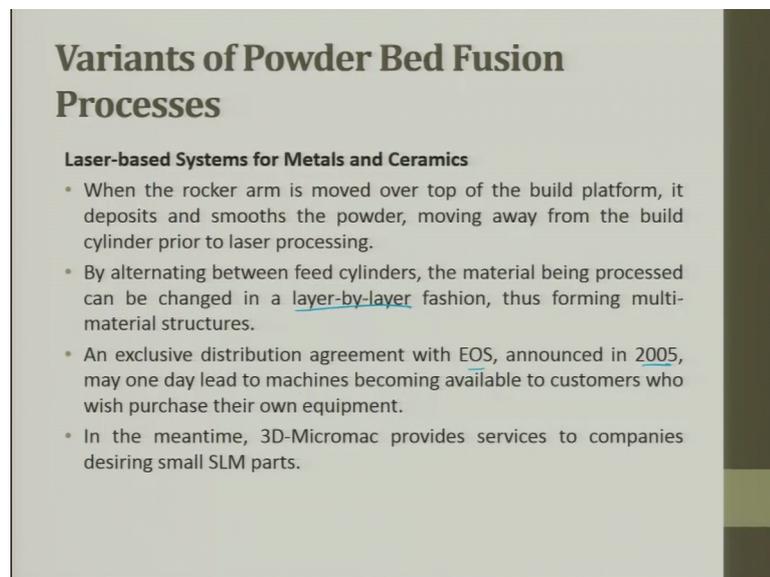
So, this makes the implant very sensitive to even small deflect small deflections or change in pressure. So, for your implants SLM process is the only process used for making metal based or parts for those applications. So, here it is rapid manufacturing and as I told you earlier when we try to do one layer in a single layer you can initiate an array of metal parts together. So, maybe in one one one short like if you have 30 centimetre cross 30 centimetre table and if your component size is hardly 2 centimetre ok.

So, now, what will happen you can make 25 or 30 parts layer by layer by layer it can be done at when you finish one part. You will also get 30 parts an array of parts are made

this is the new technology where people are using towards rapid manufacturing you plan properly use rapid prototyping techniques for manufacturing live applications.

The fibre laser is focused to a particular small spot for small featured definitions. In order to use the fine powder particle size necessary for fine feature reproduction they have developed a unique 2 material powder feeding mechanism. A build platform is located between the 2 powder feed cylinders, when the rotating rocker arm is above the powder feed cylinder the powder is pushed into the feeder thus charging the hopper.

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**Variants of Powder Bed Fusion Processes**

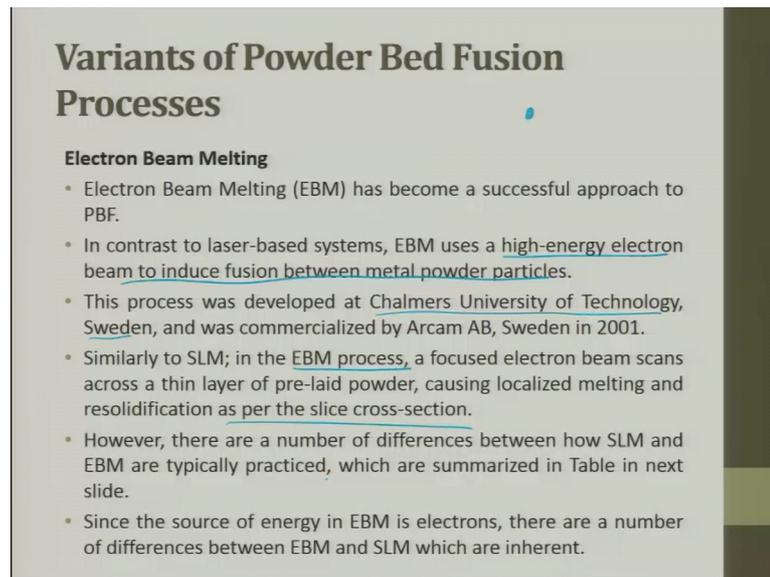
**Laser-based Systems for Metals and Ceramics**

- When the rocker arm is moved over top of the build platform, it deposits and smooths the powder, moving away from the build cylinder prior to laser processing.
- By alternating between feed cylinders, the material being processed can be changed in a layer-by-layer fashion, thus forming multi-material structures.
- An exclusive distribution agreement with EOS, announced in 2005, may one day lead to machines becoming available to customers who wish purchase their own equipment.
- In the meantime, 3D-Micromac provides services to companies desiring small SLM parts.

When the rocker arm is moved over top of the building platform it deposits and smoothens the powder, moving away from the building cylinder prior to the laser processing. By altering by altering between the feed cylinder the material being processed can be changed in a layer by layer fashion thus forming multilayer structures. An exclusive distribution arrangement of ESO announced in 2005, may one day lead to machines becoming available to consumers who wish to purchase their own equipments.

So, like desktop printing we will have desktop 3 D printing machines where in which they can use laser because the lasers are also becoming economical. Initially which was a solid state laser now it has become a fibre laser fibre laser are economical of course, when you go for higher powers it has lot of other technical challenges, but nowadays the fibre lasers are becoming very economical.

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## Variants of Powder Bed Fusion Processes

### Electron Beam Melting

- Electron Beam Melting (EBM) has become a successful approach to PBF.
- In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles.
- This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden in 2001.
- Similarly to SLM; in the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification as per the slice cross-section.
- However, there are a number of differences between how SLM and EBM are typically practiced, which are summarized in Table in next slide.
- Since the source of energy in EBM is electrons, there are a number of differences between EBM and SLM which are inherent.

Replacing laser with electron beam is a new trend why because you want to have a precise control of sintering. So, electron beam melting has become a successful approach in powder bed fusion. In contrast to laser bed systems electron beam uses high energy electron beam to induce fusion between the metal powder particles.

This process was developed in Chalmers university of technology in Sweden so now, today it is available in the market. Similar to SLM the EBM process a focused laser beam scans across a thin layer of pre laid powder causing localized melting and resolidification as per the slice cross section. So, it is a pixel of information one spot. However, there are a number of difference between how SLM and EBM are typically practiced which are summarised in the table I will show you the table next.

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### Variants of Powder Bed Fusion Processes

#### Electron Beam Melting

Table. Differences between EBM and SLM

Characteristic	Electron beam melting	Selective laser melting
Thermal source	Electron beam	Laser
Atmosphere	Vacuum ✓	Inert gas ✓
Scanning	Deflection coils ✓	Galvanometers ✓
Energy absorption	Conductivity-limited	Absorptivity-limited ← optics
Powder pre-heating	Use electron beam	Use infrared heaters
Scan speeds	Very fast, magnetically-driven	Limited by galvanometer inertia
Energy costs	Moderate	High
Surface finish	Moderate to poor	Excellent to moderate
Feature resolution	Moderate	Excellent
Materials	Metals (conductors)	Polymers, metals and ceramics

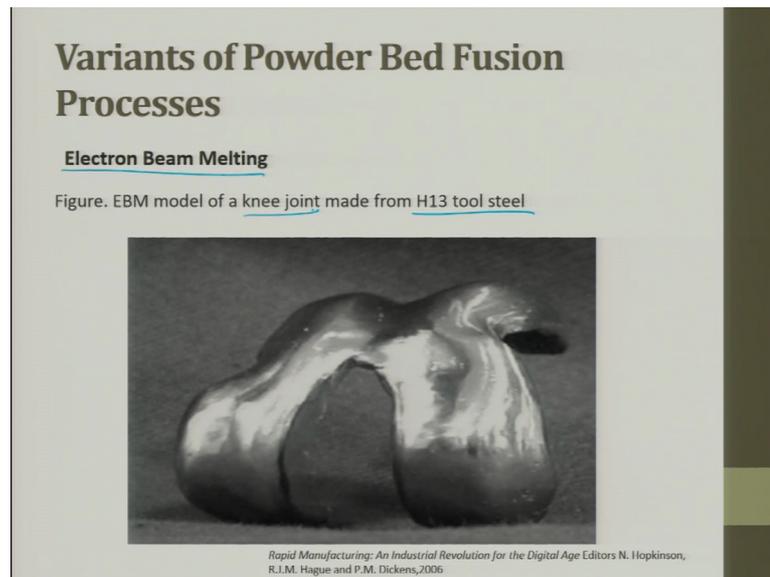
Gibson, D.W. Rosen, and B. Stucker, Additive Manufacturing Technologies, 2010

So, these are the summarizing thing thermal source, electron beam, laser beam, atmosphere, you have vacuum, you have inert gas, scanning, it is deflection coil. So, here we use in EBM we use a deflection coil.

Here we use a galvo, because the galvo is used to give the information on xy plane, then and then energy absorption is conductive here it is absorptive these 2 properties are completely different this is a optic based property. Then pre preheating, use electron beam can be done, infrared can be used to avoid the contamination from the free atmosphere getting, next scanning speed very fast it is limited electron because the laser can be the coil is used deflection coil is used so, it can scan at very high speeds.

The energy cost is moderate, it is very high, surface finish is moderate to poor, it is excellent to moderate, the feature resolution is moderate in electron beam excellent and selective laser melting materials it can be used for metals it can be used for any metals and non metals.

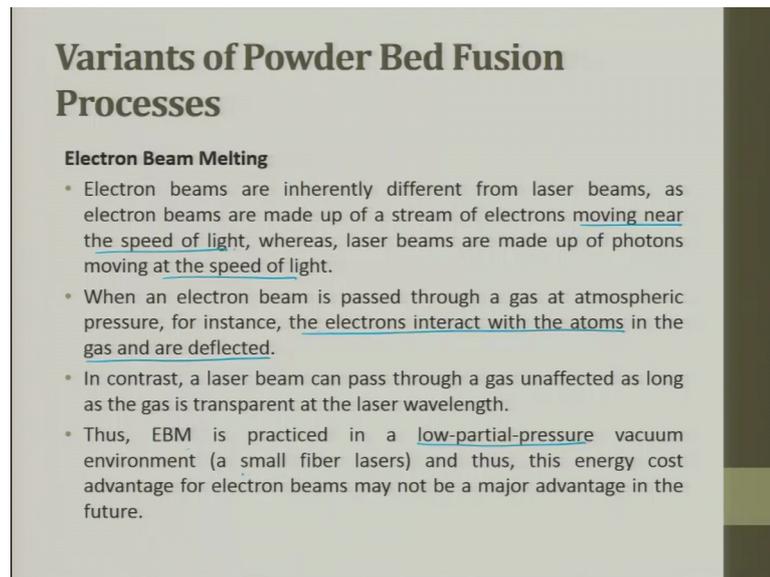
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This is a typical part which is a knee joint which is made using H 13 tool steel by using electron beam melting you see a wonderful surface finish today it has become a mandatory it has become an integral part of the knee surgery see the interesting part is when we start working on this knee joints we realise many things. When I also worked we realised many things, no 2 patients will have almost the same knee joint because your body to mass index is different and your loading part time is different on the knee.

So, in that case the knee joint is not constant for everybody. So, you have to first scan your knee understand the negative counterpart from the MRI information try to make a polymer model look at your knee joint once you have understood everything then trace the same caed model go to electron beam or use SLM process try to make your part. So, this part is custom made for you many a times you will you can see that doctors are involved in doing a a knee implant operation for 7 hours and 9 hours, the majority of the time is towards mass customisation how do we custom make this to the patient.

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## Variants of Powder Bed Fusion Processes

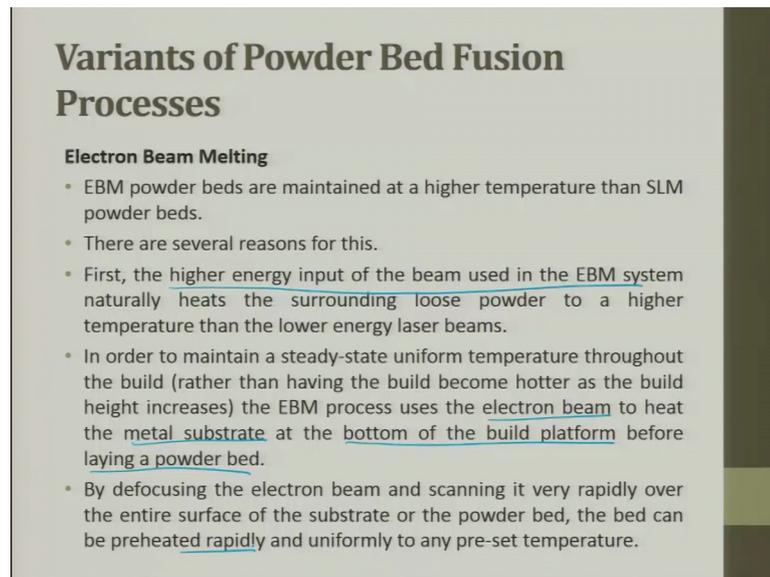
### Electron Beam Melting

- Electron beams are inherently different from laser beams, as electron beams are made up of a stream of electrons moving near the speed of light, whereas, laser beams are made up of photons moving at the speed of light.
- When an electron beam is passed through a gas at atmospheric pressure, for instance, the electrons interact with the atoms in the gas and are deflected.
- In contrast, a laser beam can pass through a gas unaffected as long as the gas is transparent at the laser wavelength.
- Thus, EBM is practiced in a low-partial-pressure vacuum environment (a small fiber lasers) and thus, this energy cost advantage for electron beams may not be a major advantage in the future.

The electron beam are inherently different from laser beam as electron beam are made up of stream of electrons moving near the speed of light, where as laser beam are made of photons moving at the speed of light so, moving near the speed of light here speed of light. When the electron beam is passing through a gas at atmospheric pressure, for instant the electron interacts with the atom and gas and gets deflected.

So, you need a vacuum chamber to be attached in the machine. In contrast the laser beam can pass through a gas unaffected as long as a gas is transparent to the particular wavelength. Thus electron beam is practised in low partial vacuum environment where as the fibre laser is used in any atmosphere.

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## Variants of Powder Bed Fusion Processes

### Electron Beam Melting

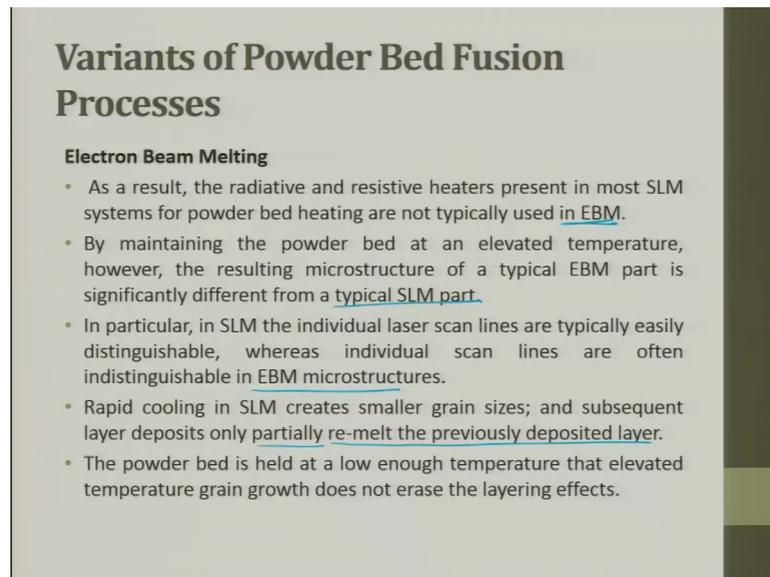
- EBM powder beds are maintained at a higher temperature than SLM powder beds.
- There are several reasons for this.
- First, the higher energy input of the beam used in the EBM system naturally heats the surrounding loose powder to a higher temperature than the lower energy laser beams.
- In order to maintain a steady-state uniform temperature throughout the build (rather than having the build become hotter as the build height increases) the EBM process uses the electron beam to heat the metal substrate at the bottom of the build platform before laying a powder bed.
- By defocusing the electron beam and scanning it very rapidly over the entire surface of the substrate or the powder bed, the bed can be preheated rapidly and uniformly to any pre-set temperature.

Provided the laser should be allowed to pass through, the electron powder beds are maintained at higher temperatures than SLM process first there are several reasons. The first is the higher energy input of the beam used in electron beam system naturally heats the surrounding loose powders to a higher temperature than the lower energy laser beam very important.

So that means, to say you will have a spreading of your spot, in order to maintain a steady state uniform temperature throughout the build the EBM process uses an electron beam to heat the metal substrate at the bottom of the build platform before laying the powder. It heats the electron beam metal substrate at the bottom of the build platform is heated before the powder is laid.

By defocusing the electron beam and scanning it very rapidly over a entire surface of the substrate or the powder bed the bed is preheated rapidly and uniformly to have a pre-set temperature. Suppose the temperature is too low you apply so much of heat conduction phenomena comes because of this conduction phenomena there is a the resolution is lost.

(Refer Slide Time: 28:04)



## Variants of Powder Bed Fusion Processes

### Electron Beam Melting

- As a result, the radiative and resistive heaters present in most SLM systems for powder bed heating are not typically used in [EBM](#).
- By maintaining the powder bed at an elevated temperature, however, the resulting microstructure of a typical EBM part is significantly different from a [typical SLM part](#).
- In particular, in SLM the individual laser scan lines are typically easily distinguishable, whereas individual scan lines are often indistinguishable in [EBM microstructures](#).
- Rapid cooling in SLM creates smaller grain sizes; and subsequent layer deposits only partially [re-melt the previously deposited layer](#).
- The powder bed is held at a low enough temperature that elevated temperature grain growth does not erase the layering effects.

As a result the radiative and resistive heating present in most SLM systems for powder bed heating are not typically used in EBM it is not the resistive heating or infrared heating. By maintaining the powder bed at elevated temperature; however, the resulting microstructure of a typical EBM part is significantly different from that of SLM completely different if you see the microstructure it will be completely different EBM gives a very good output.

In particular SLM the individual laser scan lines are typically easily distinguishable whereas, in individual scan lines are often indistinguishable in EB micro structuring. So, this is a very very important advantage it of using you get a very smooth surface the finishing the post processing becomes very easy as far as electron beam is concerned. Rapid cooling in SLM creates small grain size and subsequently subsequent layer deposit only partially re melt the previously deposited layer. The powder bed is held at low enough temperature that elevated temperature grain growth does not erase the layering effect.

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## Variants of Powder Bed Fusion Processes

### Electron Beam Melting

In EBM, the higher temperature of the powder bed, and the larger and more diffuse heat input result in a contiguous grain pattern that is more representative of a cast microstructure, with less porosity than an SLM microstructure.

*very advanced & def*

In electron beam the higher temperature of the powder bed and the larger and more diffused heat input results in continuous grain pattern are the resulting in contiguous grain pattern that is more representative of casting microstructure with little porosity than SLM process, electron beam is very advanced and defect free because spot size heating controlled grain structure you get the best output.

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## Variants of Powder Bed Fusion Processes

### Line-wise and Layer-wise PBF Processes

- PBF processes have proven to be the most flexible general approach to RM.
- The large variety of materials, manufacturers and applications that are available surpass those of any other approach.
- However, the use of expensive laser or electron beams, the fact that these beams can only process one "point" of material at any instant in time, and the overall cost of the systems means that there is considerable room for improvement.
- As a result, a number of organizations are developing ways to fuse lines or layers of material at a time.
- Although these processes currently use too low of temperature to process metals directly, the potential for polymer processing in a line-wise or layer-wise manner could dramatically increase the build-rate of PBF processes, thus making them more cost-competitive.

Line wise and layer wise powder bed process, the powder bed processes have proven to be the most flexible general approach of to rapid manufacturing. The large variety of the

material manufacture and applications that are available surpasses those of any other approach powder bed. However, the use of expensive laser or electron beams the fact that the beam can only process one “point” of the material at any instant of time the overall cost of the system means that there is a considerable room of improvement, why because the laser can go spot by spot EBM also can go spot by spot. So, now, instead of going spot by spot if I can put a small mask and allow light to fall. So, if the entire thing is done as one line in one shot with very high resolutions.

As a result number of organizations have developed ways to fuse lines or layers in the material at a time so, like photolithography, photolithography is what you have light just take an X ray, you have taken an X ray you have fixed the X ray on a on a flat transparent tube light box and the doctor looks at the X ray. So, it is almost the same the tube light is coming from the other side the x ray is a mass which is put on the top and the doctor is viewing from this site. So, if the light is allowed to pass through the mask and if that mask try the thus light tries to hit at the object that is nothing, but a powder bed.

So, then what you get is the entire layer information in one shot you can do point, line, layer or do line layer or do layer all the 3 options are possible. If you do point we use laser, we use binder, we used EB, when we use line it is an exposure we can do in one shot. So, you mix a polymer with a metal powder and the polymer is cured by a UV light possible ok. As a result a number of organisations are developing ways to fuse to fuse lines and layers of material at time.

All though these processes currently used to low of temperature to a process metal directly, the potential for polymer processing in a line wise or a layer wise manner could increase the build rate of PBF of powder bed process thus making them more cost effective.

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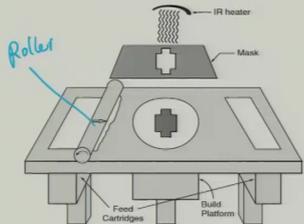
## Variants of Powder Bed Fusion Processes

### Line-wise and Layer-wise PBF Processes

- Three of these processes will be discussed below. All three utilize infrared energy to induce fusion in powder beds; the key differences lay in their approach to controlling which portions of the powder bed fuse and which remain unfused, as illustrated in Fig. below.

Fig. Three different approaches to line- and layer-wise powder bed fusion processing

- (a) mask-based sintering
- (b) printing of an absorptivity-enhancing agent in the part region
- (c) printing of a sintering inhibitor outside the part region



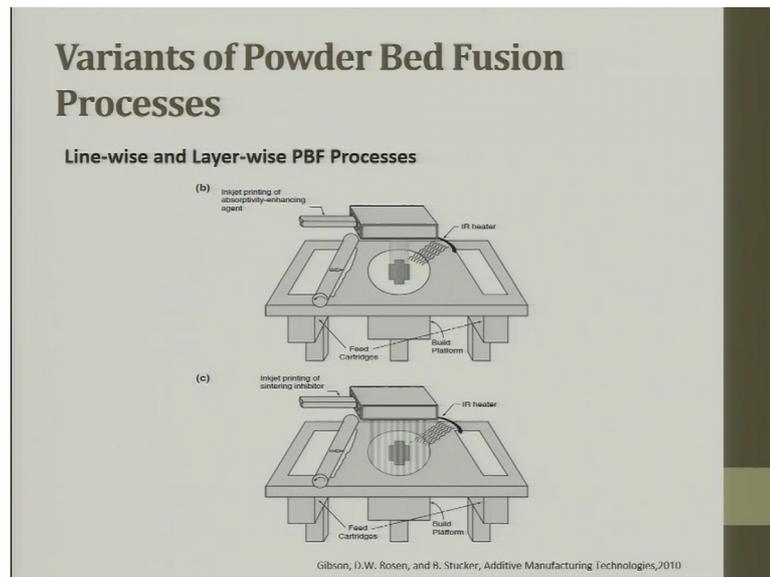
The diagram illustrates a cross-section of a powder bed fusion process. A roller is shown on the left, moving across a powder bed. Above the roller is a mask with a central cross-shaped opening. An IR heater is positioned above the mask. Below the powder bed is a build platform supported by feed cartridges. A blue handwritten label 'Roller' points to the roller. The diagram is labeled '(a)'.

Gibson, D.W. Rosen, and B. Stucker, Additive Manufacturing Technologies, 2010

So, you see here this is what is the example I give an infrared from the top you have a mask, then you have a bed, you have a this is a feeder cartridge from the feeder cartridge, this is a roller this rolls and add materials to the table and the table sinks. So, you get one layer of information on the mask layer is kept IR is exposed. So, you get one layer of information on the top, 3 of these processes will be discussed below all the 3 utilizes infrared to induce fusion in the polygon the powder bed heat.

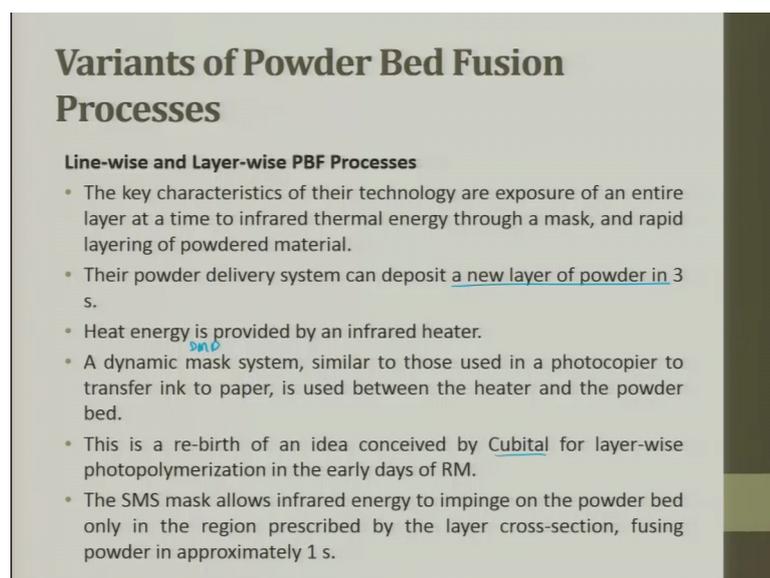
Basically you can have metal and polymer also there or you can use only polymer the key difference lay in their approach to control which portion of the powder bed fuses and which remain unfused as I have stated below. So, you can use a mask type you can use printing of an absorptivity enhanced agent in the part region and then printing of sintered in sintering inhibitor outside the part region.

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So, here it is inkjet so, here what the inkjet printing of absorptivity enhancing agent. So, here you just ink the jet is printed and then you use infrared so, this infrared is to create a layer. The third one is going to be inkjet printing of sintered inhabitants. So, you have an infrared you have a layer of information so, the centre portion along the outside portion is done the centre portion is not done.

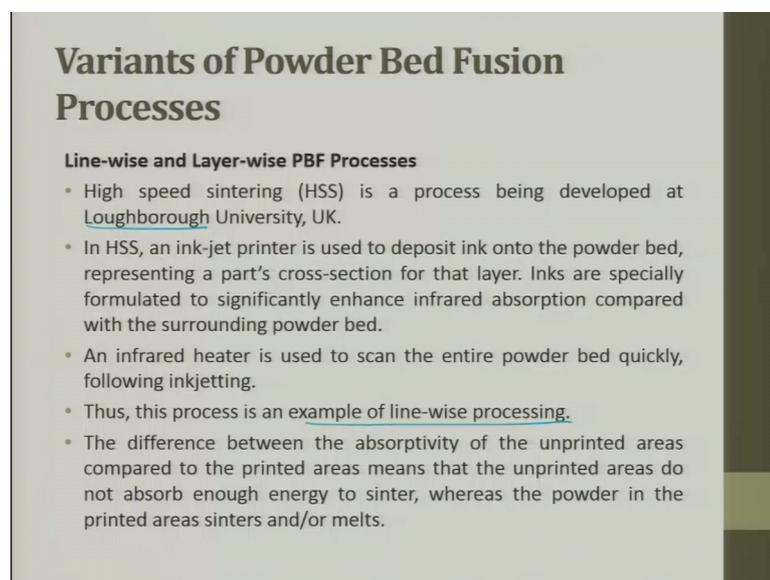
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So, the key characteristics of this technology are exposure of the entire layer at a time to infrared thermal energy through a mask and a rapid layer of powder making. Their

powder delivery system can deposit a new layer in 3 seconds. The heat energy is provided by a infrared heater. A dynamic mass system we can use DMD or you can just keep flipping like a movie olden days you have you had a film roll passed through continuously and you see a movie. So, in the same way dynamic mass systems similar to those used in a in a photocopier to transfer ink to paper is used between the heater and the powder. This ECR rebirth of an idea conceived by cubital of for layer photopolymerization in the early days. The SMS mask allows infrared energy to impinge on the powder bed in the region prescribed in the layer.

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**Variants of Powder Bed Fusion Processes**

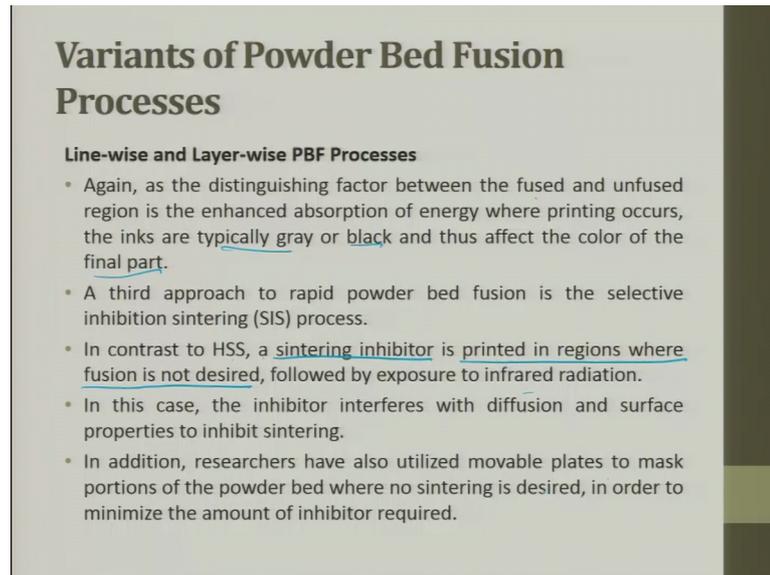
**Line-wise and Layer-wise PBF Processes**

- High speed sintering (HSS) is a process being developed at [Loughborough University, UK](#).
- In HSS, an ink-jet printer is used to deposit ink onto the powder bed, representing a part's cross-section for that layer. Inks are specially formulated to significantly enhance infrared absorption compared with the surrounding powder bed.
- An infrared heater is used to scan the entire powder bed quickly, following inkjetting.
- Thus, this process is an [example of line-wise processing](#).
- The difference between the absorptivity of the unprinted areas compared to the printed areas means that the unprinted areas do not absorb enough energy to sinter, whereas the powder in the printed areas sinters and/or melts.

The high speed sintering is process being developed at Loughborough University in UK, you see many of the variations are still in the research phase. The high speed sintering and inkjet printer is used to deposit ink onto the powder bed representing a parts cross section of the layer, inks are specially formulated to significantly enhance the infrared absorption compared with the surrounding layer. So, ink is spread you have an infrared so the ink cures the powder joints you get the part. The infrared heater is used to scan the entire powder bed quickly following the inkjetting.

Thus this process is an example of line wise processing. The difference between the absorptivity of the unprinted area compared to the printed area means that the unprinted area do not absorb enough energy to sinter whereas, the powder where the printed ink is there it absorbs.

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**Variants of Powder Bed Fusion Processes**

**Line-wise and Layer-wise PBF Processes**

- Again, as the distinguishing factor between the fused and unfused region is the enhanced absorption of energy where printing occurs, the inks are typically gray or black and thus affect the color of the final part.
- A third approach to rapid powder bed fusion is the selective inhibition sintering (SIS) process.
- In contrast to HSS, a sintering inhibitor is printed in regions where fusion is not desired, followed by exposure to infrared radiation.
- In this case, the inhibitor interferes with diffusion and surface properties to inhibit sintering.
- In addition, researchers have also utilized movable plates to mask portions of the powder bed where no sintering is desired, in order to minimize the amount of inhibitor required.

Again as distinguishing factor between the fused and unfused region is the enhanced absorption of the energy where printing occurs where the ink are typically grey or black and thus affecting the colour of the final part. The third approach you just drop ink there and the ink is cured fine.

The third approach to rapid powder bed fusion is the selective inhibition sintering process. In contrast to high speed sintering the sintering inhibition is printing is printed in a region where fusion is not desired followed by the exposure of the infrared. In this case the inhibitor interference with diffusion and the surface properties to inhibit sintering, yes sintering it is just a negative a sintering inhibitor is printed in the region where fusion is not desirable you put a negative to the previous process in this case the inhibitor interference interferes with diffusion and the surface properties to inhibit sintering. In addition researchers have also utilized movable plates to mask portion of the powder bed where no sintering is required in order to minimise the amount of inhibitor.

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## Variants of Powder Bed Fusion Processes

### Fused Metal Deposition Systems

- A number of processes have been developed that use the principle of blowing metal powders into a melt pool created by a laser (see Figure in next slide).
- Among the developers of these technologies were Sandia National Labs who used the expression laser engineered net shaping (LENS) and joint work between John Hopkins University, Penn State University and the MTS Systems Corporation.
- Different versions of the technology have been commercialised by numerous organisations including POM, Optomec and Aeromet.
- Generally these processes have relatively slow deposition rates and produce parts with poor surface finish, but they do offer the potential to process functionally graded materials (see Chapter 7) in high melt temperature metals including titanium.

The fused metal deposition system a number of processes have been developed that uses the principle of blowing metal powder into the melt pool created by the laser.

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## Variants of Powder Bed Fusion Processes

### Fused Metal Deposition Systems / LENS

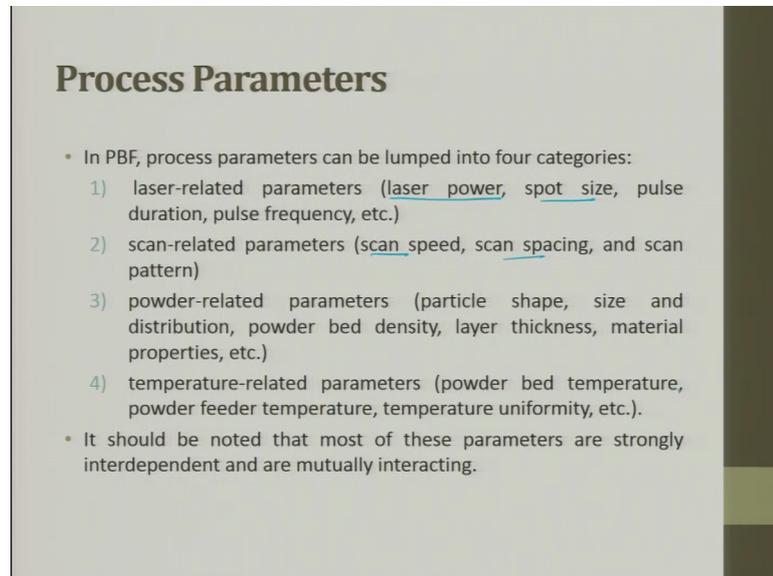
Schematic of fused metal deposition

*Rapid Manufacturing: An Industrial Revolution for the Digital Age* Editors N. Hopkinson, R.J.M. Hague and P.M. Dickens, 2006

So, look at it. So, you will have a laser which comes and hits then you have a powder metal supply with gaseous is done and here is a plate to hold this s feeding so that the particle are hitting at the surface and the gas is used. So, this process is called as fused metal deposition process or it is called as lens laser engineered net shaping. So, this was developed in John Hopkinson University. So, here what happens the laser moves the

plate where the 2 gases are there that also moves so, it is all coaxial you get it and then the carrier gas is also used to feed it.

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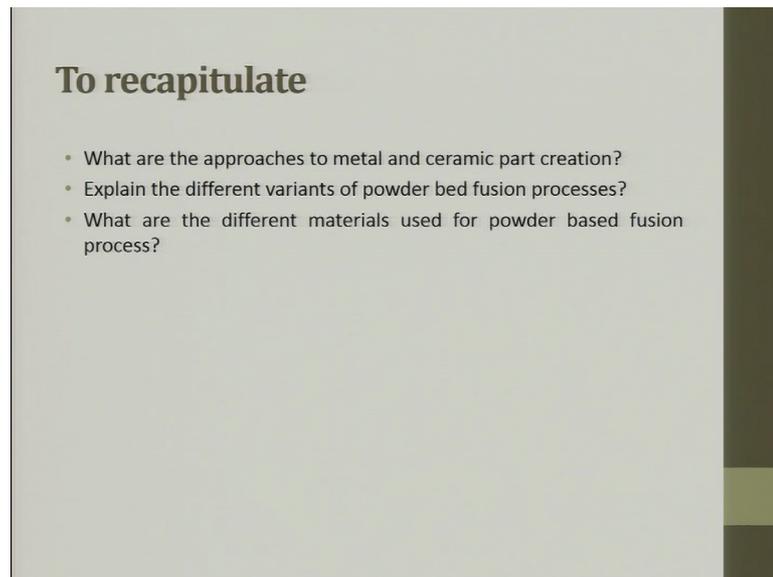


### Process Parameters

- In PBF, process parameters can be lumped into four categories:
  - 1) laser-related parameters (laser power, spot size, pulse duration, pulse frequency, etc.)
  - 2) scan-related parameters (scan speed, scan spacing, and scan pattern)
  - 3) powder-related parameters (particle shape, size and distribution, powder bed density, layer thickness, material properties, etc.)
  - 4) temperature-related parameters (powder bed temperature, powder feeder temperature, temperature uniformity, etc.).
- It should be noted that most of these parameters are strongly interdependent and are mutually interacting.

So, the process parameters are as far as laser is concerned laser power, spot, diameter, pulse duration, frequency, are very important. Scanning related properties are scanning speed, scanning space and scanning pattern is very important. Powder related particle size, particle shape, distribution, powder bed density, layer thickness and material property. Temperature related parameters are powder bed temperature, powder feeder temperature and temperature uniformity. These are some of the process parameters which are very important to be controlled.

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**To recapitulate**

- What are the approaches to metal and ceramic part creation?
- Explain the different variants of powder bed fusion processes?
- What are the different materials used for powder based fusion process?

To recapitulate in this lecture, what we covered was what are the approaches to metal and ceramic metal part creation; explain the different variants of powder bed fusion? So we saw a spot, then we saw a line then we saw a layer making, what are the different materials used for powder based fusion? These are certain things which we have gone through in this lecture.

Thank you very much.