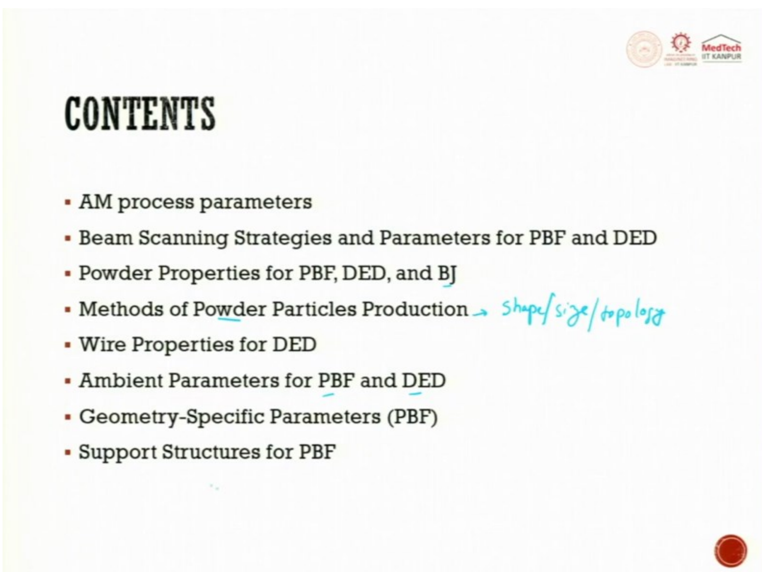
Metal Additive Manufacturing
Prof. Janakranjan Ramkumar
Prof. Amandeep Singh Oberoi
Department of Mechanical Engineering and Design
Indian Institute of Technology Kanpur
Lecture 16
Process Parameters

Welcome to the next lecture in Metal Additive Manufacturing. In the past, we have seen in depth knowledge about basics of laser, basics of electron beam, electron machine setup, laser machine setup and we also have seen wire feed parameters. Now, in this lecture we will start focusing more on powder bed fusion method, what are all the different process parameters for a machine, to run a machine, you will have several inputs to be given. What is the influence of these inputs with respect to the output, so that is what we try to see the process parameters.

(Refer Slide Time: 01:07)

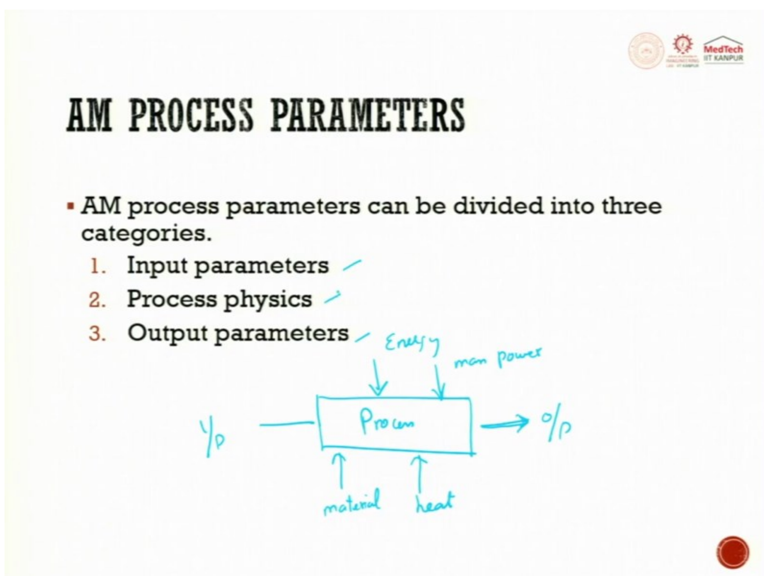


In this lecture, we will be trying to cover in additive manufacturing what are all the different process parameters which are used, let it be laser, let it be electron beam, let it be wire. So the next is beam scanning strategies. You have a beam, it is electron beam or laser beam. So this beam has to build a layer. So in a layer you also have a thickness. So moment there is a thickness then you have to have strategies of fabricating or to create the pattern. So those things are called as beam scanning strategies.

And then, you will have parameters for powder bed fusion and directed energy deposition. Next, we will try to see powder properties for powder bed fusion method directed energy deposition and binder jetting. Then methods of powder particle production, this is also very important because this directly influences the shape and the size and also the topology of the powder particles.

Why is this very important? Because this is going to influence your flowability. The next one is wire properties for directed energy deposition, then ambient parameters which are required for both the process, then we will try to see geometric and specific parameters, then finally, we will start looking into supporting structures for powder bed fusion method.

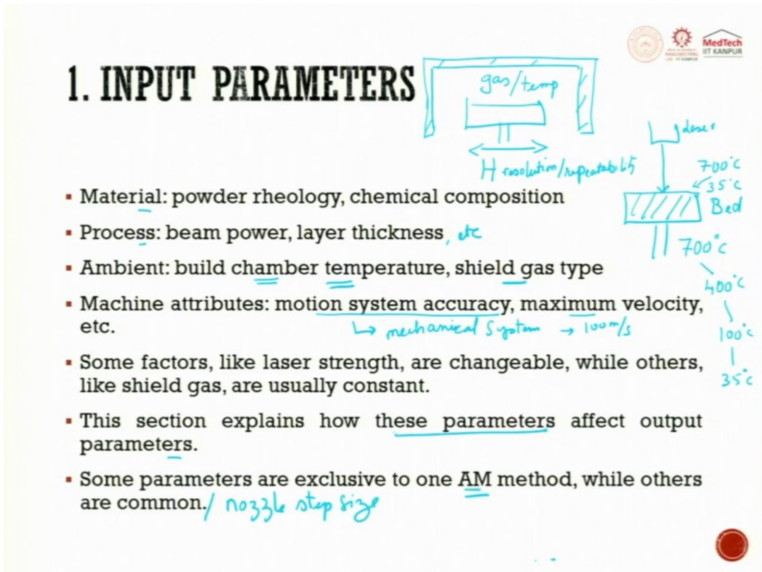
(Refer Slide Time: 02:57)



When we take any process, you will have input and then you will have a output. In the process you might have energy, you might have manpower, you might have materials, whatever it is, all these things, you might have heat energy, all these things are applied in the process, and finally what you get out is the output.

So any process will have an input parameter, output parameter and the process physics. So additive manufacturing also has the same. In additive manufacturing, the process parameters can be divided into three categories, input parameters, output parameters and process physics which is involved in it.

(Refer Slide Time: 03:55)



What is the physics? Here sintering and melting are the physics. What are the input parameters? Input parameters can be material. So when we talk about material, powder rheology, powder size, powder shape, powder topography, chemical composition, its electrical structures, all these things play a very important role.

When we talk about process, there are several, but we have taken only significant. One is beam power, the other one is layer thickness, there are many more, but these two, just for your understanding. Beam power varies, it is a continuous laser, it will be talked in kilo joule, when we talk about pulsed laser we talk in mega joules or we talk in kilowatts, megawatts, gigawatts etc. when it is pulsed laser. Layer thickness we vary from 50μ-100μ.

Next is ambient build chamber temperature. See, this is a very important thing. When you have a bed where in which you are trying to expose laser, this is a bed where the part is getting made, so you have a laser which tries to hit at the surface. So now the temperature at this point will go maybe to 700^0C. And then the next thing what it comes is from 700^0C it comes to room temperature which is 35^0C. So you see here, there is a big gradient which happens from 700 to 35 which is around about 650 degrees reduction which happens in a short instant of time.

In order to get out of this gradient, why? Because this gradient will try to induce thermal residual stresses. These thermal residual stresses will lead or may lead to crack formation. In order to avoid this, what we do is we try to have from 700 ^{0}C, we try to take it to 400 ^{0}C, 400 to 100 ^{0}C, 100 to 35 ^{0}C. So here, this is called the smooth gradation happening from the higher temperature to room temperature. So here, if we want to do it, we would try to have a build chamber where there is a temperature control.

So how do you do it? You have a build platform and this build platform will be placed inside a container. In this container, you will try to see you have a gas or something else which tries to make the temperature slightly higher than the room temperature. And slowly, you can try to bring it down.

The next one is a gas, because when we try to do many of the metals, melt or sinter, it always has a habit of getting diffused with oxygen. So oxides get formed very easily, in some cases carbides get formed very easily. So in that case what we do is we fill this with gas and try to prevent them from oxidization or carburization. So then the ambient, these two are the input parameters. Machine attribute, motion system accuracy. At what accuracy does this motion happen? What is the minimum resolution it can do?

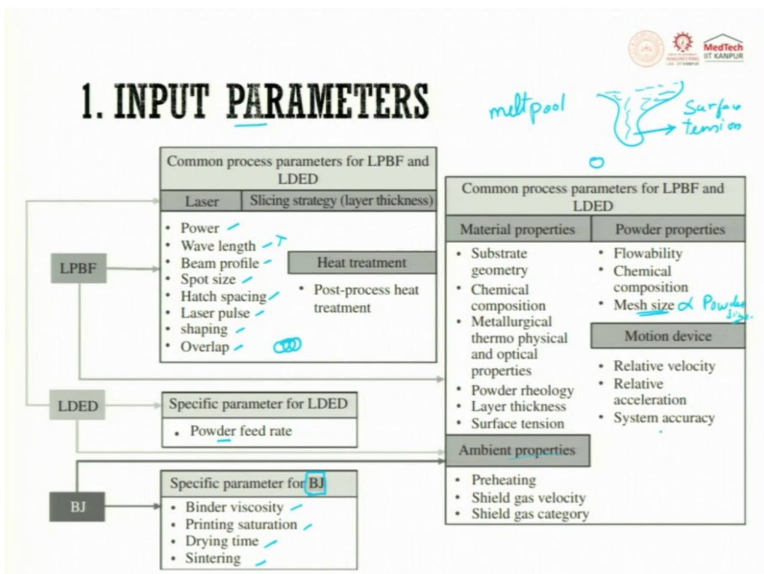
So this is resolution. Minimum resolution, the least count, which it can move, that is called as minimum resolution. And then it also talks about repeatability. Repeatability is the other important parameter. When I move left or right, how is it moving? This motion system accuracy also tries to dictate the machine built, the drives what you use, the bells what you use. So if there is a loosening, then you will always have inaccuracies while moving.

Next, the maximum velocity with which it can move. So these two, etcetera I have written, these two are one of the major parameters. We also saw in this, there is a limitation for a mechanical system. For example, it is very hard for you to go more than 100 m/s in mechanical system, generally I am speaking, you can have exceptions, but it is very difficult for you to touch even 100 m/s. Generally, the, the mechanical systems operate somewhere between 5-10 m/s.

Next one is the maximum velocity with which it can move. Some other factors like the laser strength are changeable while others like shielded gas are usually constant. So some other factors you see, the shielding gas once, you purge it with argon, it is neutral gas, but whereas the laser strength, for example, you can keep changing the power from 200 mJ-300 mJ, 300 to 700 mJ, 1 pulse to 10 pulse, all these things are possible in the laser strength.

So this section, we will also try to explain how these parameters affect the output parameter. Some parameters are exclusive to only AM process, while the others are common. So what is there for AM common features is the nozzle step size movement.

(Refer Slide Time: 09:54)



So these are the various input parameters for different processes. Let us take laser powder bed fusion. When we talk about laser, you have power of the laser, wavelength, that is λ, you have blue laser, green laser, red laser then you have beam profile. We saw the beam profile. So it can be TEM_{00} mode, then Gaussian distribution mode, cowboy hat pattern mode, spot size is the least diameter, the smallest diameter which it can take.

Hatch spacing, we will see more in details in the coming slide. Then, laser pulse, what is the hertz we are using, shape of the laser, TEM_{00} mode, overlapping. These are the parameters of laser which is used, laser power, wavelength, beam profile, spot size, hatch spacing, laser pulse, then shaping, and then overlapping.

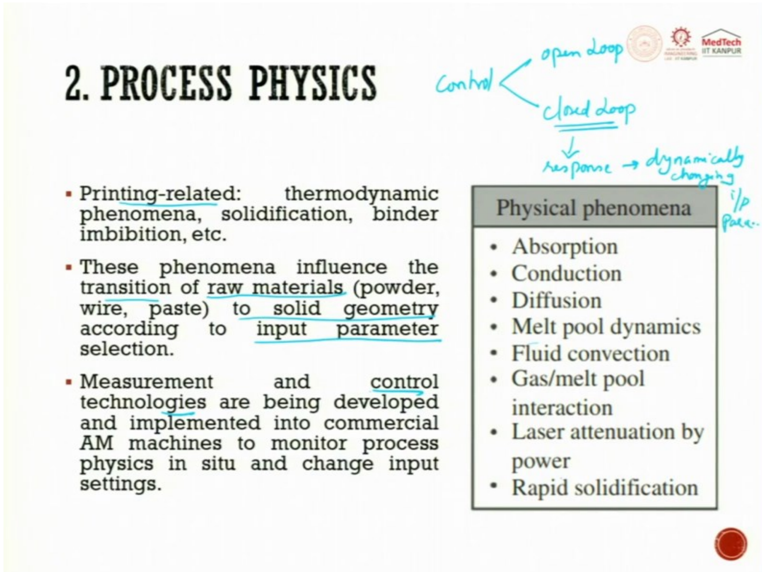
When we talk about heat treatment here, post process heat treatment to remove the residual stresses, we use this heat treatment process. When we look at laser directed energy deposition, the specific parameter apart from all these things will be powder feed rate. When we look at binder jet process you will have binder viscosity, printing saturation, drying time and sintering time. This is common with binder jetting process.

Some of the common parameters for laser powder bed fusion and laser directed energy deposition, these are the material properties, these are the ambient properties, these are the powder properties and motion. When we look at the material property, substrate geometry, metal powder geometry, chemical composition, metallurgical, thermophysical, optical properties, then we have electronic structures, then powder rheology, layer thickness and surface tension.

Surface tension is in the melt pool. What is melt pool? This is a portion where the powder is melt. So that is called as a melt pool. So in melt pool, what dictates is the surface tension, because the surface tension will always try to roll it. Viscosity plays a very important role. Temperature plays a very important role. So these are all some of the material properties. When we look at ambient properties, preheating, gas shield velocity, and shielding gas category.

Now, we talk about powder processing, flowability, chemical composition, mesh size. Mesh size is directly proportional to the powder size. Motion devices, relative motion, relative accelerations and system accuracy. These are some of the common parameters which are used.

(Refer Slide Time: 12:52)



Process physics. Before getting into the process physics, these are some of the physical phenomena which generally dictate the laser process. Adsorption, conduction, diffusion, melt pool dynamics, fluid convection, gas metal pool interaction, laser attenuation by power, rapid solidification, these are all the physical phenomenas which try to dominantly play when we use laser or electron beam for additive manufacturing.

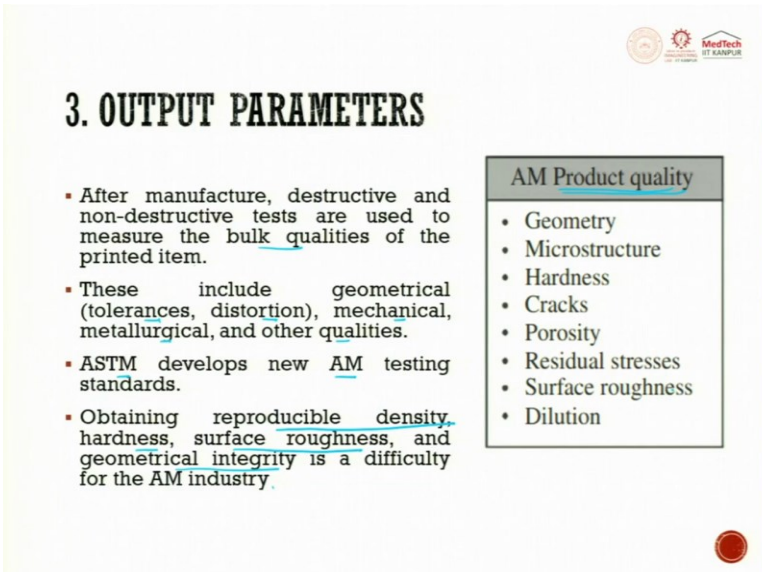
So, here conductivity is very important, diffusion is also very important. Then fluid convection, Marangoni convection we study. So when there is a hot zone, cold zone, there is a vortex created, current created. So gas melt pool interaction and laser attenuation by power.

When we are talking about printing related thermodynamic phenomena, solidification, binder in vibration, etc. are some of the printing related matters. These phenomenas influence the transition of raw material to solid geometry according to input parameters selection. So this is very important, transition of raw materials to solid geometry depending upon the input parameters.

The measurement and control technologies are being developed and implemented into commercial AM machines to monitor process physics in situ and change input settings. So the control technologies. So that is what we say we were discussing all about. Controls, there are two types, open loop and the other one is called as closed loop.

So when you are trying to develop technologies for a closed loop system implement into commercial AM machines to monitor process physics in situ and change the input parameters. Here, what is happening? Depending upon the response, dynamically changing input parameters. So this is very important.

(Refer Slide Time: 15:24)



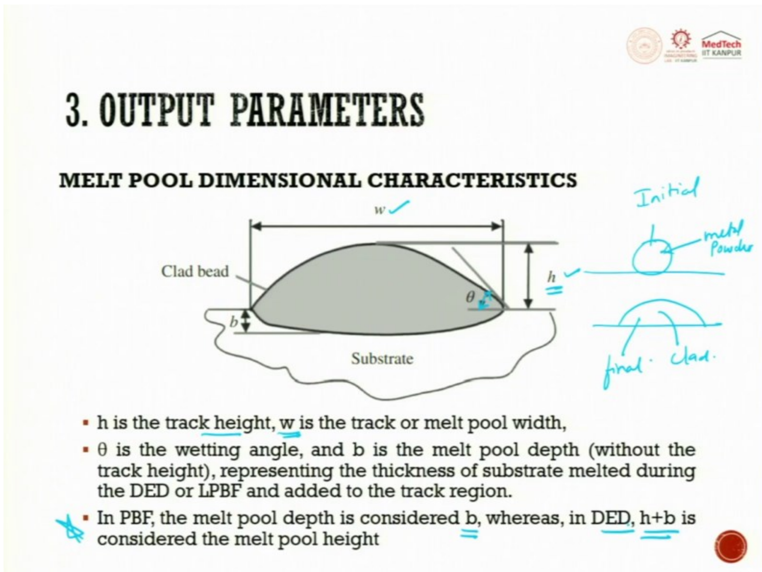
So what are the output parameters? After manufacturing, we try to do destructive and non destructive tests to measure the bulk qualities of the printed item. This include tolerance, distortion, mechanical, metallurgical and other qualities. Several ASTM standards are getting developed. Even now, ASTM standards for additive manufacturing are in a very, very prematured way.

Now, there is lot of development happening and standards are getting established. Over a period of time, yes, this will be done. Like ASTM, you have many other standards which I have discussed in the past. Obtaining reproducibility, density, hardness, surface roughness, geometrical integrity is a difficulty for the additive manufactured industry.

Swap training, reproducible density, hardness, surface roughness, and geometric integrity is difficult for additive manufacturing industry. Additive manufacturing product quantities are geometry, microstructure, these are all output, product qualities, microstructure, hardness, cracks, porosity, residual stresses, roughness and dilution. All these things are product qualities which are output parameters of additive manufacturing.

Geometry, it talks about tolerances, microstructure, hardness and toughness, ductility, all these things are together. Cracks, porosities which come before because of improper material flow. Residual stresses, surface roughness and dilution. What is dilution, we will see that.

(Refer Slide Time: 17:15)

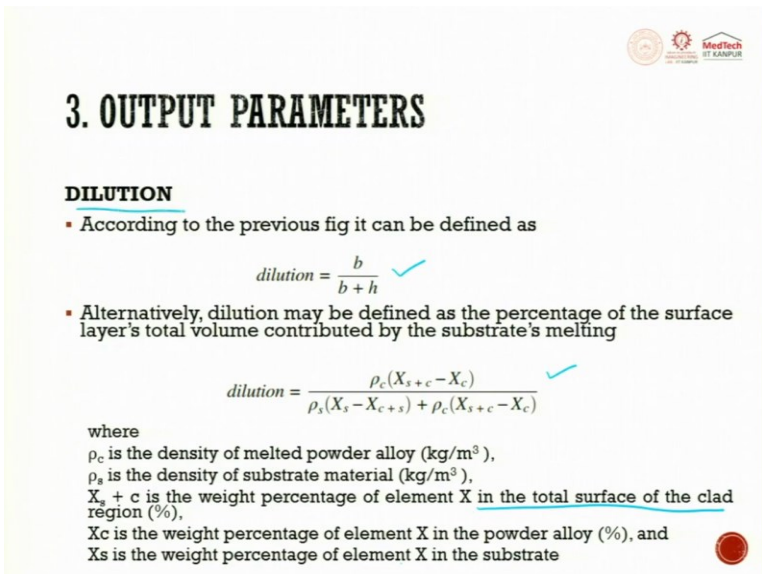


Before that we will try to see melt pool dimensional characteristics. This is the substrate and, on the substrate, there are particles. These particles are laser hit or electron beam hit. So now you see that there is a clad bead which is getting formed, so which was like this, now it is forming like this. This was initial, this is the final, and this is your metal powder, this is your clad. So metal powder is now getting, when it is hit, it is getting a melt pool and this is getting a layered clad bead. So this is called as clad bead.

So, whatever is the h is a track height, w is a track or the melt pool width. This is melt pool width, this is track height h, and w. θ is the wetting angle. So, this wetting angle dictates how the fluid, the hot metal, molten material how it can flow easily and how it can smear itself easily to the substrate. So θ is the wetting angle and b is the melt pool depth, representing the thickness of the substrate melted during the DED process or laser powder bed fusion process and added to the track region.

So this is wettability, this is the bead depth. The powder bed fusion, the melt pool depth is considered to be b, whereas in DED, h+b is considered to be the melt pool. This is a very, important point. If at all I ask a problem in the examination, you will have to keep that in mind. The powder bed fusion, the melt pool diameter depth is considered as b, whereas it is h+b in DED. Why so? You please think about it and then let us discuss during the discussion hour.

(Refer Slide Time: 19:44)



The other output parameter is going to be dilution. So according to the previous figure which is given,

$$dilution = \frac{b}{b+h}$$

Alternatively, dilution may be defined as a percentage of the surface layer's total volume contributed by the substrate's melting. So this can be written like this also.

$$dilution = \frac{\rho_c(X_{s+c} - X_c)}{\rho_s(X_s - X_{c+s}) + \rho_c(X_{s+c} - X_c)}$$

where

ρ_c is the density of melted powder alloy (kg/m^3),

ρ_s is the density of substrate material (kg/m^3),

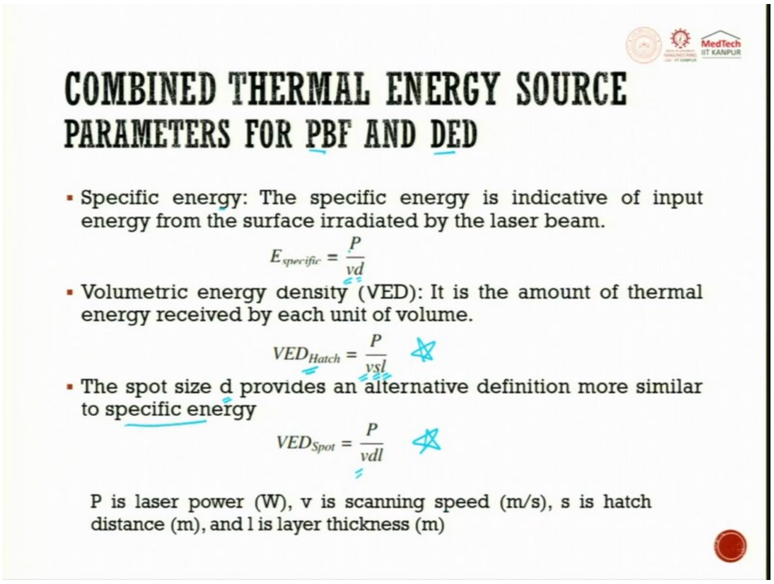
X_s + c is the weight percentage of element X in the total surface of the clad region (%),

Xc is the weight percentage of element X in the powder alloy (%), and

Xs is the weight percentage of element X in the substrate.

So we can use this formula or this formula to find out what is dilution.

(Refer Slide Time: 20:38)



Combining the thermal energy source parameters for PBF and DED. These are some of the parameters. Specific energy, the specific energy is indicative of input energy from the surface irradiated by the laser beam.

$$E_{specific} = \frac{P}{vd}$$

v is the scanning speed, and d is the spot dia. This is specific energy.

Next is volumetric energy density, VED. Volumetric energy density, VED is nothing but it is the amount of thermal energy received by each unit volume is called as VED, Volumetric energy density. So VED Hatch can be expressed as:

$$VED_{Hatch} = \frac{P}{vsl}$$

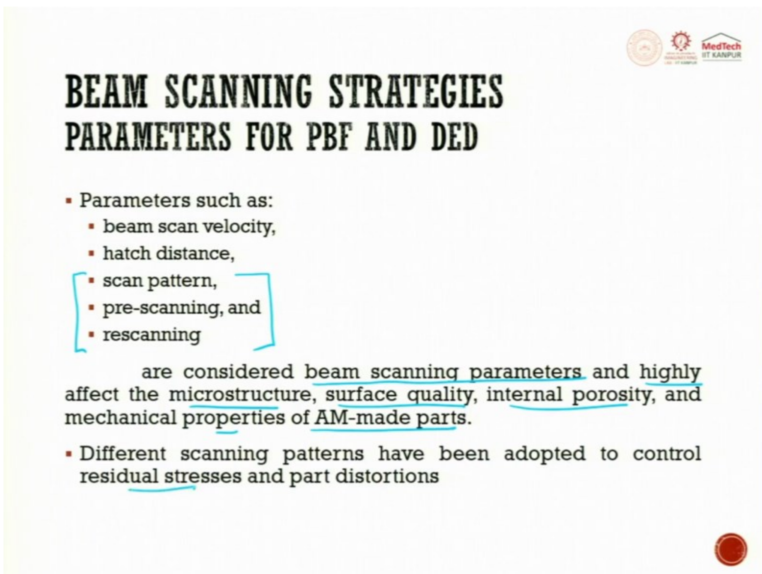
s is the hatching distance, l is the layer thickness, v is the scanning speed. So with this, we will try to get the volumetric energy density.

So in melt pool, we always look at volumetric energy density. In specific energy, in grinding and all, we look at specific energy.

$$VED_{Spot} = \frac{P}{vdl}$$

l is the layer thickness, d is nothing but the spot diameter, v is the scanning speed. With this, we will try to get the, the alternative to specific energy.

(Refer Slide Time: 22:39)

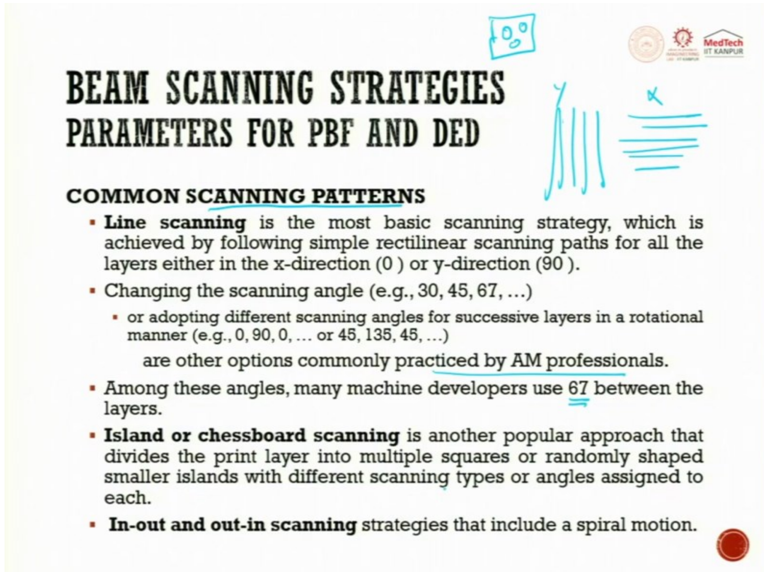


Beam scanning strategies is the next important parameter. So beam scan velocity, hatch distance, scan pattern, pre-scanning and rescanning are the other things which are important. So these three are very important. Scanning patterns, pre-scanning patterns, and rescanning patterns. Let us see that.

So all these things parameters are considered as beam scanning parameters and highly affect the microstructure, surface quality, internal porosity and mechanical properties of AM made parts. All these things are very important. Beam scanning parameter influences, highly affects the microstructure surface quality, internal porosity and mechanical properties.

So all these things are very important. Highly affect the microstructure, scan surface qualities, internal porosities. Different scanning patterns have been adopted to control residual stress and part distortion. So first let us understand what are the different scanning patterns or strategies.

(Refer Slide Time: 23:56)



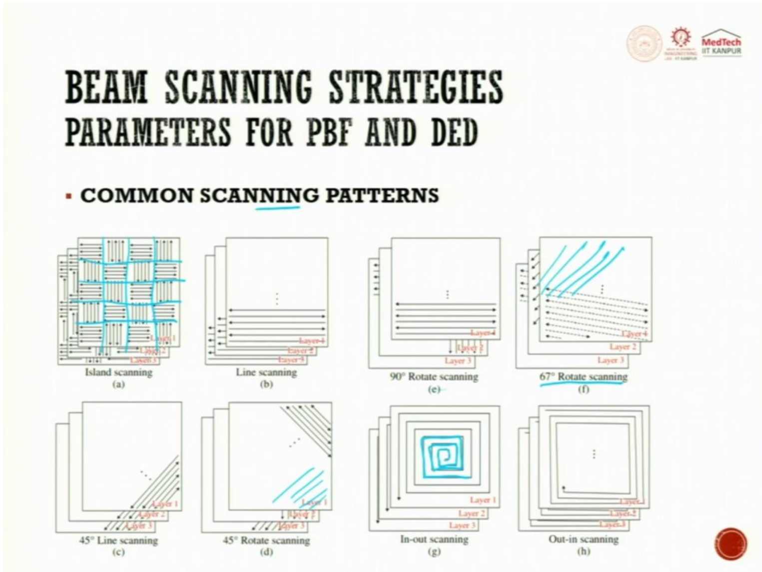
Line scanning is the most basic scanning strategy which is achieved by following simple rectilinear scanning path for all the layers either in the x-direction or in the y-direction, x-direction or in the y-direction, whatever it is. X-direction, this is x, and this is y. Changing the scanning angle from 30 to 45 to 67 etc. are also possible.

For adopting different scanning angles for successive layers in a rotational manner 0, 90, 0, 45, 135, 45, etc. are other options commonly practiced by additive manufacturing professionals. Amongst these angles, many machine developers use 67 between the layers, 6 to 7 between the layers.

The island or chessboard scanning is another popular approach that divides the print area into multiple squares or randomly shaped smaller islands with different scanning types or angles assigned to each other. So it is, see inside a paper, you are trying to make some part.

So this is called as island scanning, which is another popular approach that divides the print area into multiple squares or randomly shaped smaller islands with different scanning types or angles assigned to each other in and out in scanning strategies that include a spiral motion.

(Refer Slide Time: 25:47)



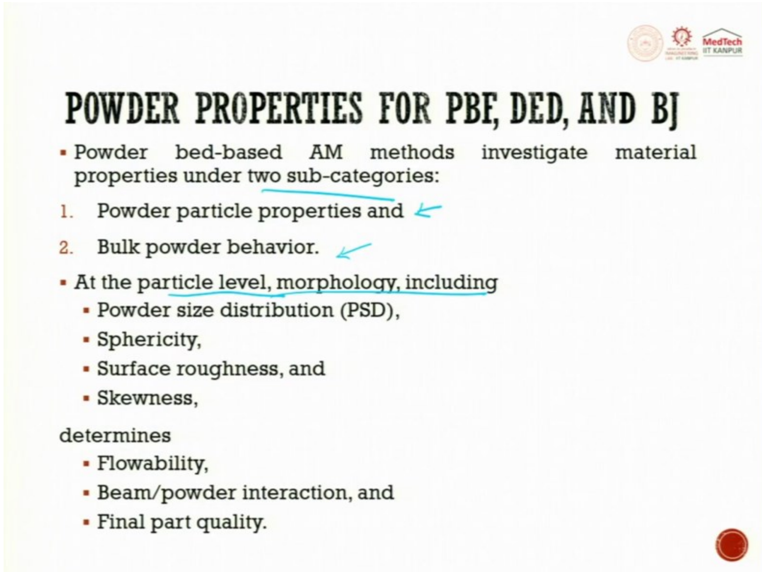
So these are all some of the common strategic patterns which are used. You can see here, islands of scanning. So you can see very clearly, I will just draw a checkerboard here. You see here it is just like a chessboard. Or here, in this you see here how are the different patterns done. So this is called as island scanning.

These are called as line scanning. These are, lines are rotated at 90 degrees, you will see. The first one is like this and the next one is, which is on the top, is like this. So it is rotated scanning. Then, it is 67 rotational scanning. First time, it is doing like this, next time, it will go like this. This is 65.

You also have something called as 45^0 line scanning. Then you have 45^0 rotation scanning. So you first start like this, you rotate and you go like this. Next time it will go like this. Next is In-out. In-out is, from the in, you start going out. This is also a strategic scanning pattern.

Then it is out to in. So what we do is we start from outside and then we go towards in. So these are some of the scan patterns which are exhaustively used today. So you have island scanning, line scanning, 90 degrees rotate scanning, 67 rotate scanning, 45 line scanning, 45 rotation scanning, in to out scanning and out to in scanning.

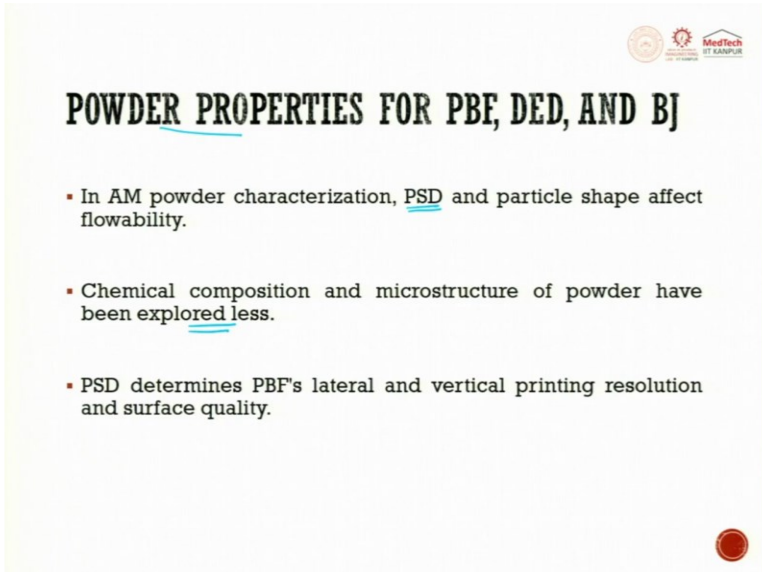
(Refer Slide Time: 27:26)



When we look at the powder properties for our powder bed fusion, directed energy deposition and binder jet, the powder bed based additive manufacturing methods investigate material property under two categories. One is powder particle properties, the other one is bulk powder behavior. So it falls into any one of these two categories. At the particular level, morphology includes powder size distribution, sphericity, surface roughness and skewness.

These are all called as particle level or morphology included. Particle size distribution, sphericity, surface roughness and skewness, these are all at particle level. Determinants level, flowability, beam power interaction, final part quality, these are all determinants which are coming out. So there are two categories which the investigation can happen, one is powder particle properties, the other one is bulk properties.

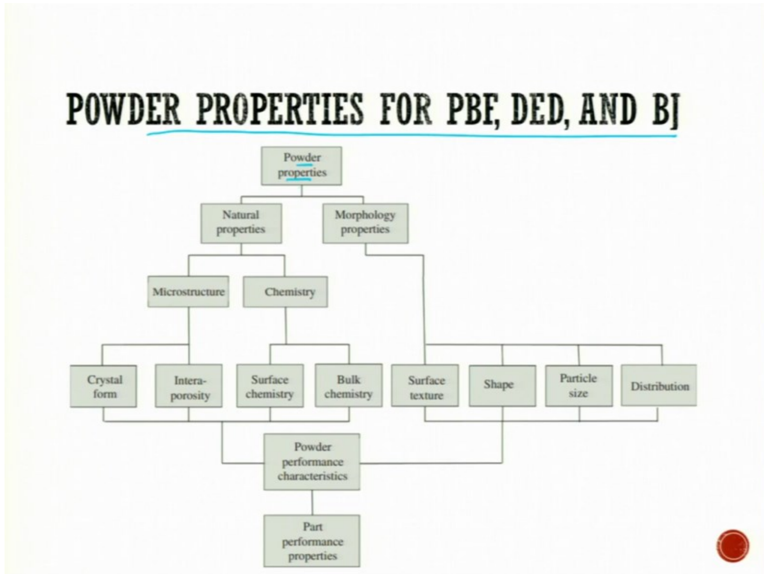
(Refer Slide Time: 28:32)



What are the powder properties? In additive manufacturing, powder characterization PSD and particle shape affect flowability. These two are very important. Particle size distribution. PSD and the particle shape effect affects the flowability. Chemical composition and microstructure of the powder have been explored less.

This is, not many people are working in this area. It is a good area, so chemical composition and micro structural of the powder have been explored less. The particle size distribution determines particle bed fusion lateral and vertical printing resolutions and surface quality.

(Refer Slide Time: 29:14)



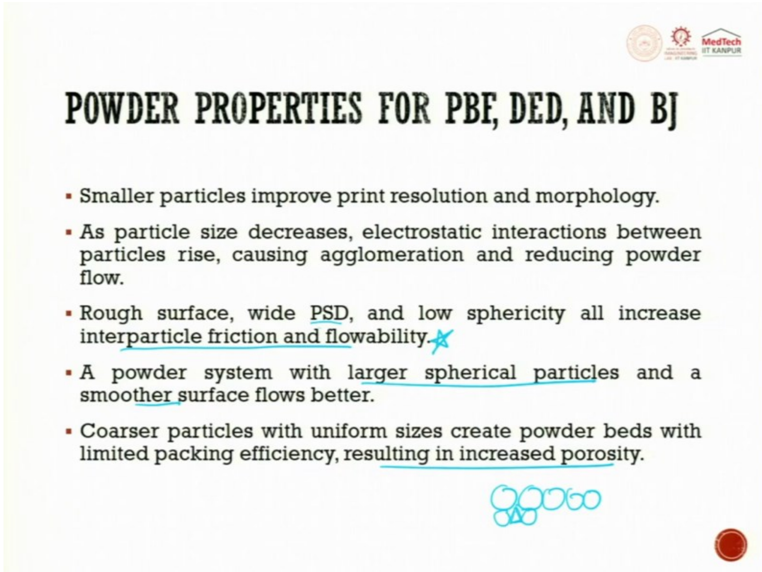
So if you look at the powder properties for powder bed fusion and DED and binder jet, so you will see powder properties, you will have natural properties, you will have morphological properties. Natural properties, you will have micro structural properties, you will have chemistry. Then in the microstructural properties, you will have internal porosities, crystal formation.

In the chemistry, you will have surface chemistry, bulk chemistry. And then you will try to have powder performance characteristics and then you will try to have part performance properties. So these are something which is all done in the powder properties. So powder properties you can natural, natural in turn is microstructural and chemistry, microstructure will have crystal form and intra porosity, you will try to see.

Chemistry, surface chemistry and bulk chemistry, so then you will see powder performance characteristics. From there, you will try to see part performance properties. When we go for morphological properties, it is surface structures, shape, particle size and distribution. All these people play a very, very important role.

This graph or this table, this slide talks to you fully, fully about the different types of properties which a powder should possess while doing powder bed fusion, directed energy deposition and binder jetting.

(Refer Slide Time: 30:41)



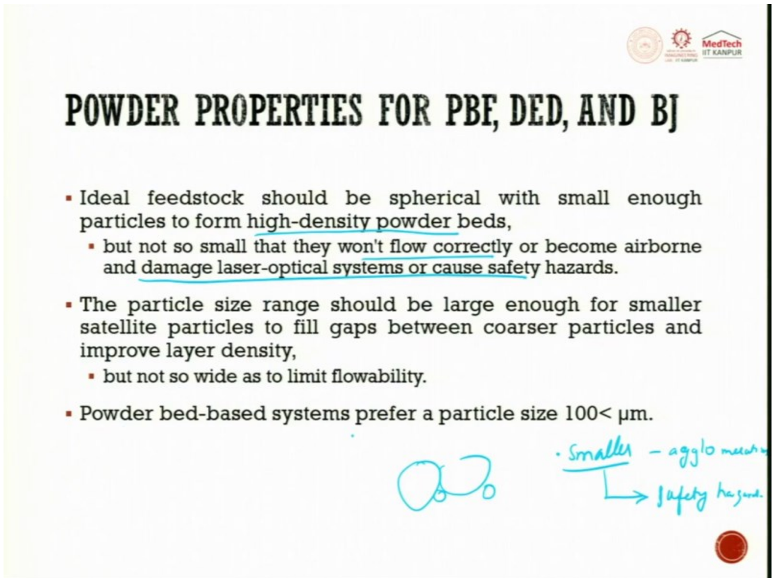
Smaller particles improve print resolution and morphology. As particle size decreases, electrostatic interaction between the particle rises, causing agglomeration and reducing the powder flow. Rough surfaces and wide particle size distribution and low sphericity all increase inter particle friction and flowability. This is very important.

What properties dictate surface roughness, particle size distribution and low sphericity, all increase inter particle friction and flowability. So the material will not easily flow and it does not get fall on the bed or while recorder is moved, it does not get spread properly. A powder system with larger spherical particles and, yes, smoother surface flows better.

Larger spherical particles and a smoother surface, so low sphericity, that is not good. And then, then it also talks about roughness and wide particle size distribution. Coarser particles with uniform size create powder bed with limited packing efficiency resulting in increased porosity.

So if it is all circular, all circular, so then what will happen you will have lot of space between this person and the next person. So the particle size, this is what it is, the coarse particles with uniform size create powder beds with limited packing efficiency resulting in increasing increased porosity.

(Refer Slide Time: 32:25)

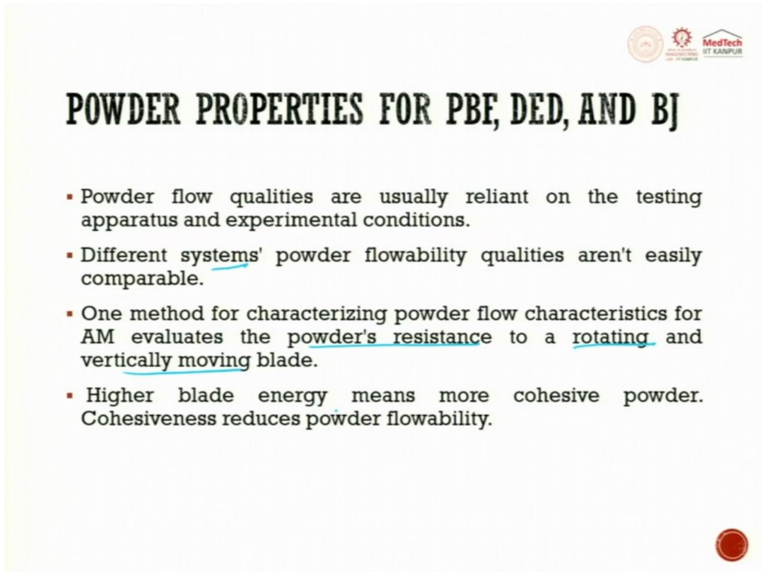


Ideal feedstock should be spherical with small enough particles to form high density powder bed. So what they try to say is you have larger powders, along with the larger powders you also try to have some amount of smaller powders. So this will try to go lock in the necessary positions and try to create high density powder bed but, not so small that they would not flow correctly or even air bound and damage laser optic system or cause safety hazard.

So when we are going smaller and smaller and smaller, you have two things. One is agglomeration, A-G-, agglomeration, the other one is going to be safety hazard. So, but not so small that they do not flow correctly or become air bound and damage laser optic system. So you should try to choose a powder slightly larger. It should not be extremely large, you get a coarser output, if it is extremely small then it will try to disperse and it will try to sit in the laser optics and damage it.

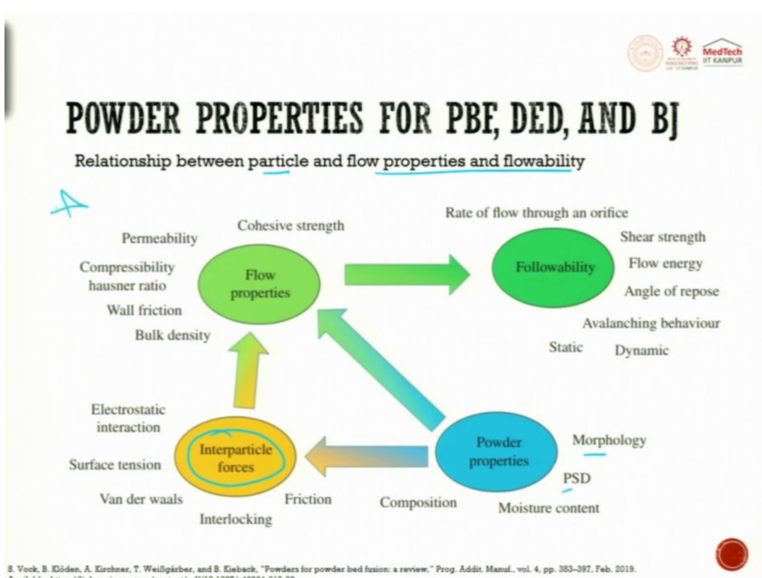
The particle size range should be large enough for smaller satellite particles to fill the gap between the coarse particles and improve the layer density, this is what I said. But not so wide as the, as that it limits flowability. The powder bed based system prefers a particle size of 100 microns.

(Refer Slide Time: 33:59)



Powder flow qualities are usually reliant on the testing apparatus and experimental conditions. Different systems powder flowability qualities are not easily comparable. Different systems are not easily comparable. One method of characterizing powder flow characteristics for AM evaluates the powders resistance to rotating and vertical moving table, powder resisting to, to a rotation or vertical moving blade. Higher blade energy means more cohesive power. Cohesiveness reduces the powder flowability.

(Refer Slide Time: 34:41)



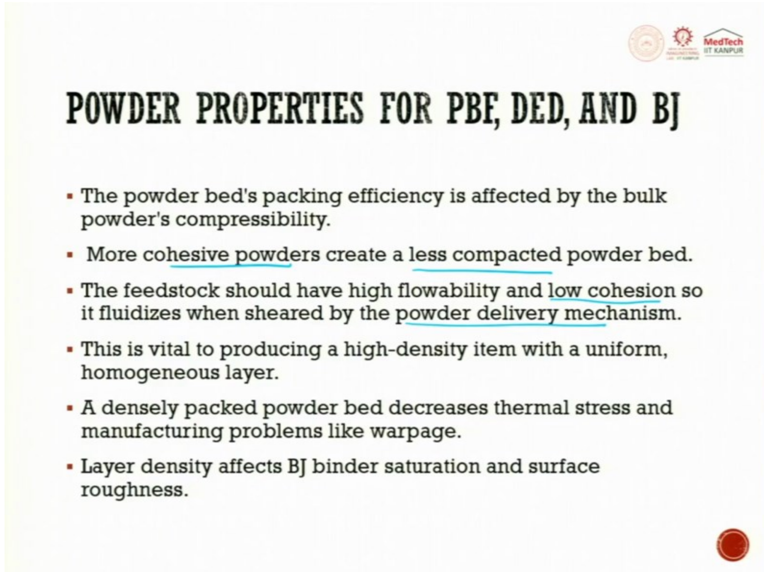
So if you try to take a relationship diagram between the particle and the flow properties and the flowability, you can see here flow properties, interparticle force, powder properties and flowability. So if you see here, flow properties goes to flowability. Rate of flow through an orifice, shear strength, flow energy, angle of response, all the three are important.

Avalanching behavior, static and dynamic is also part of flowability. When we talk about powder property, it talks about morphology and it talks about particle size distribution. Moisture content composition, so, are also very important. When we talk about interparticle force, it is interlocking, friction, Van der waals force, surface tension, electrostatic interaction. So all these properties fall under the interparticle force.

Electrostatic interaction, surface tension, Van der waals force. Van der waals force or Van der waals are very weak joints which are the interlocking and friction. From here, when we talk about flow properties, we talk about cohesive strength, permeability, compressibility, the Hausner ratio, wall friction and bulk density. So these are some of the flow property related things.

So you can see here, flow properties are related with powder properties, interparticle force, these two lead to flow properties. From the flow properties, it leads to flowability. So this is a very, very important table, which, or a figure, which it is very useful for you to analyze when you try to produce a part.

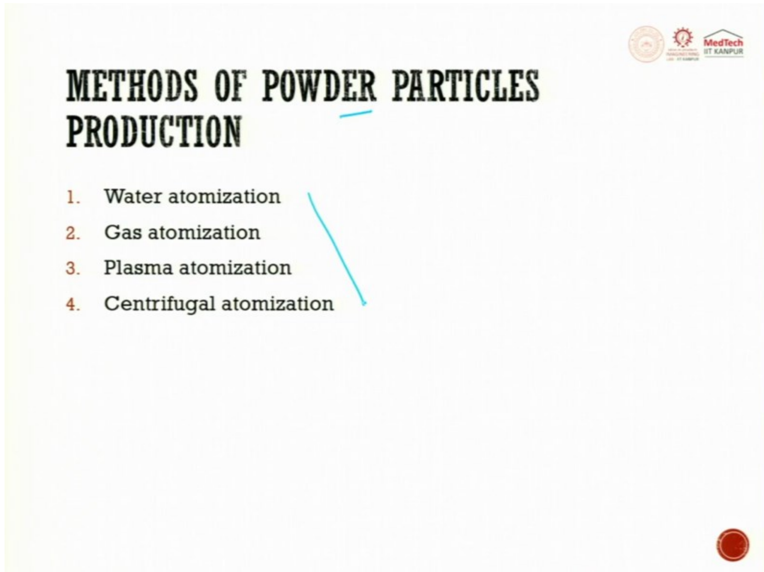
(Refer Slide Time: 36:31)



The powder bed packing efficiency is affected by the bulk powder compressibility. More cohesive powder creates less compaction, more cohesive powder, same, similar powders, it creates less compaction because there will be a space in between them. The feed stock should have high flowability and low cohesion. So it fluidizes when sheared by a powder bed mechanism.

Feedstock should have high flow ability and low cohesiveness. Cohesion is sticking. So they, so if it fluidizes when sheared by the powder. This is a vital to producing a high density item. This is vital to producing a high density item with a uniform homogeneous layer. Densely packed powder bed decreases thermal stresses and manufacturing problems like warpage. Layer density affects binder jet saturation and time.

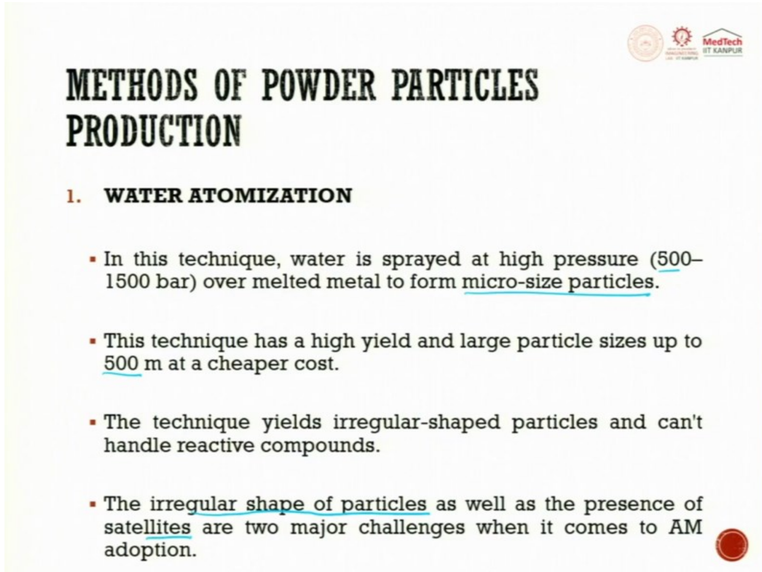
(Refer Slide Time: 37:29)



The next important thing we figure out is, as far as flowability is concerned, is the powder, how is it getting produced. So here, we will try to see the four different types of ways in which powders are created. Generally, the powder creation process is called as atomization.

Atomization means anything we are trying to split and then produce into small, small, small atoms or small, small, small volumes. So water atomization, gas atomization, plasma atomization and centrifugal atomization are the four methods through which the laser powders are manufactured.

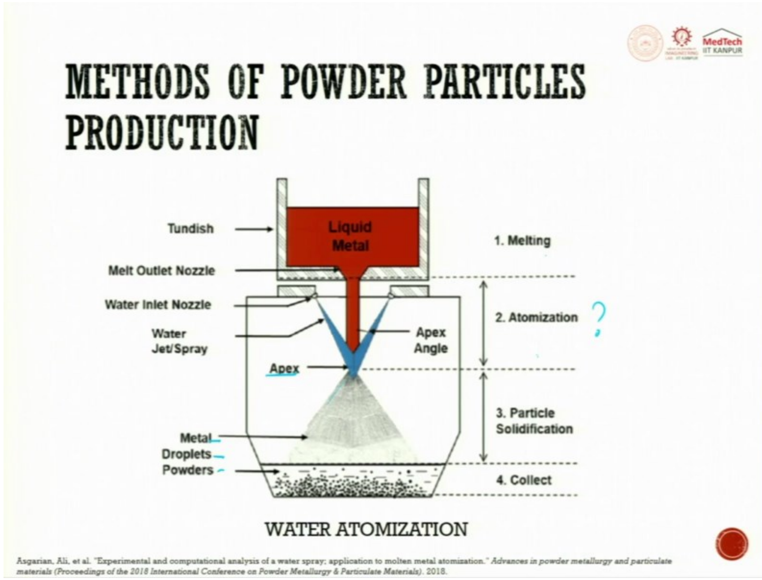
(Refer Slide Time: 38:08)



So water atomization, in this technique, the water is sprayed at a pressure of 500 to 1,500 bar over melted material to form micro sized particles. The technique has a high yield, and a large particle size up to 500 m at a cheaper cost can be made. The technique yields irregular shape particles and cannot be handle reactive components, this technique.

The irregularity shape of the particles as well as the presence of satellites are two major challenges when it comes to AM. Irregular shapes of a particle and then presence of satellite, two things are very important which makes a challenge for this additive manufacturing.

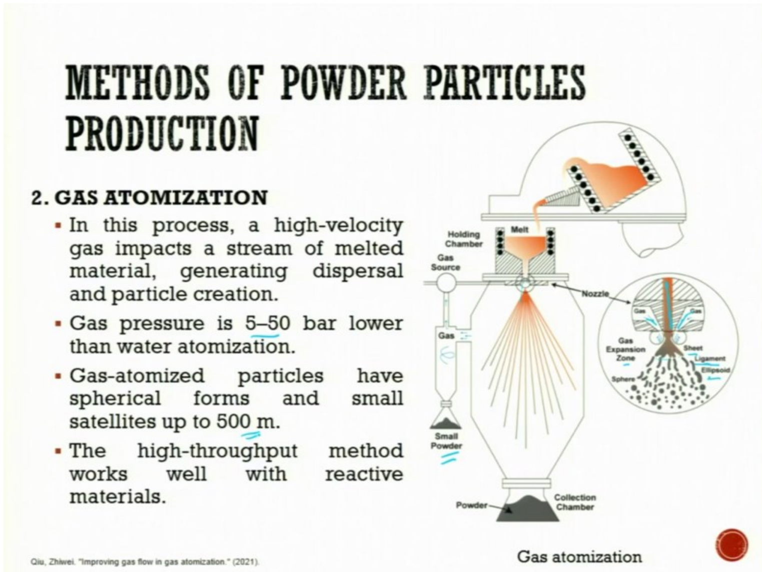
(Refer Slide Time: 38:56)



So this is how the water method is, water method is you have liquid metal coming, and then you will, you have a water inlet nozzle which sprays. So here also, it sprays. When it tries to spray on this, it instantly, there is an apex which is formed, and that, after that instant, it is all getting atomized. So you get a metal droplet powder which sperms and then it falls on top of it.

So here, it is a very, very easy process. At this process top, there is a melting which is happening. Then in the second stage, it is atomization happening. And in the third stage, it is particle solidification and forming. And the fourth stage is the collection stage. The challenge is here, so atomization, so though it looks like pictorially very easy, but to produce this it needs lot of skill efforts. So melting, atomization, particle solidification and collection.

(Refer Slide Time: 39:47)

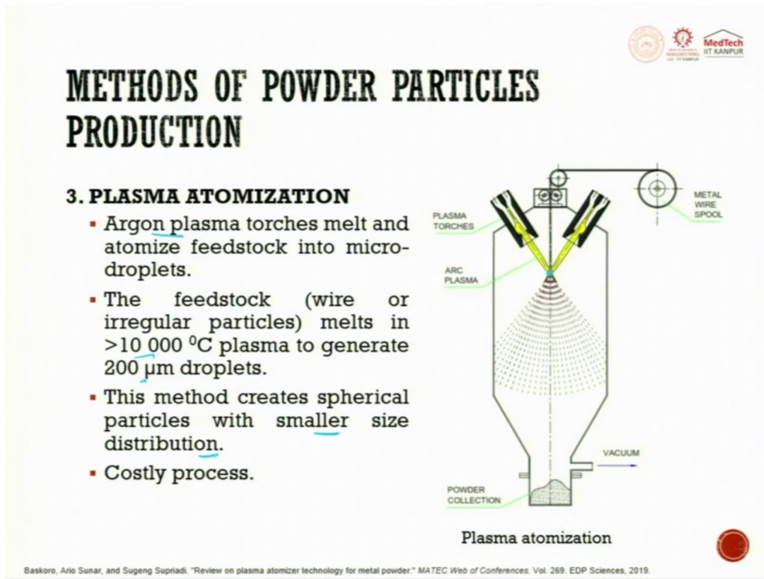


The next one is gas atomization. Gas atomization is very similar to that of your water. So you have a melt, so through this melt you will have a gas source which hits. So from here, all these things which are spraying here, these gases, so they will all try to spray in between the liquid, so it will try to settle down. And here, it will try to have lot of metal powders which are getting generated.

So the gas, whatever is there, we pump into the gas and this gas when it gets exhausted, it tries to come inside the gas and then it gets, you get to filter small powders and then the rest of the gas is released. So when we look at here, you see here there is a gas which is coming, there is a gas which is coming and here, there is a liquid metal which is getting poured.

So when it is poured, it tries to form a several droplet of particles. So gas expansion zone, so you have a sheet, ligament and then ellipsoid. So all these things are seen here. So here in this process, high velocity gas impacts a stream of melted material, generating dispersal and particle creation. The gas pressure generally uses from 5 to 50 bar. The gas atomization particles have a spherical form and small satellites up to 500 microns can be there. The higher throughput method works well in the reaction type.

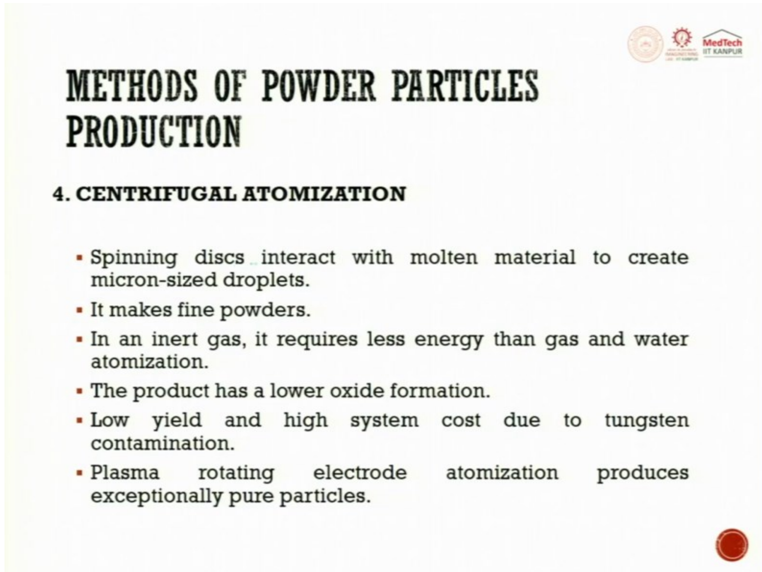
(Refer Slide Time: 41:17)



So the next one is going to be plasma. So you have a plasma torch, you have a plasma torch, melt wire spool is sent and then when the, both the plasma meet at this point, it tries to melt and then whatever comes out is, is the output of this melting. It gets shattered and you try to get small particles.

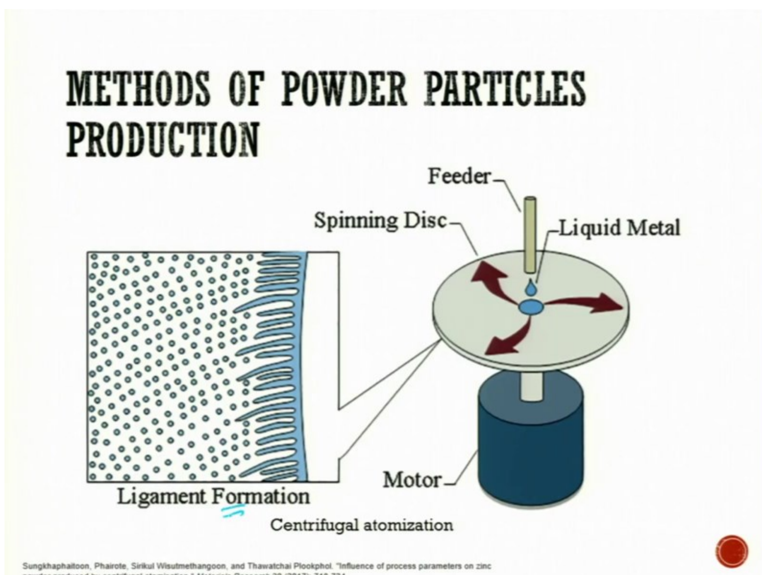
So plasma atomization, Argon plasma torch melts and atomize the feedstock into micro droplets. The feedstock melts at a temperature of $10,000^0$C and more, and generates 200 µm droplets. This method creates spherical particles with smaller size distribution is generated by plasma.

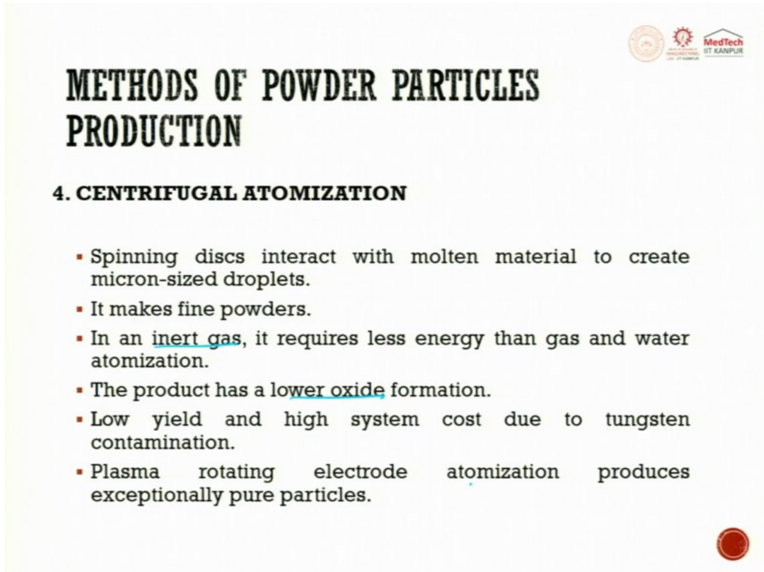
(Refer Slide Time: 41:58)



Centrifugal automation this is the last automation. So spinning disc interacts with the molten metal to create a micron size particle.

(Refer Slide Time: 42:08)

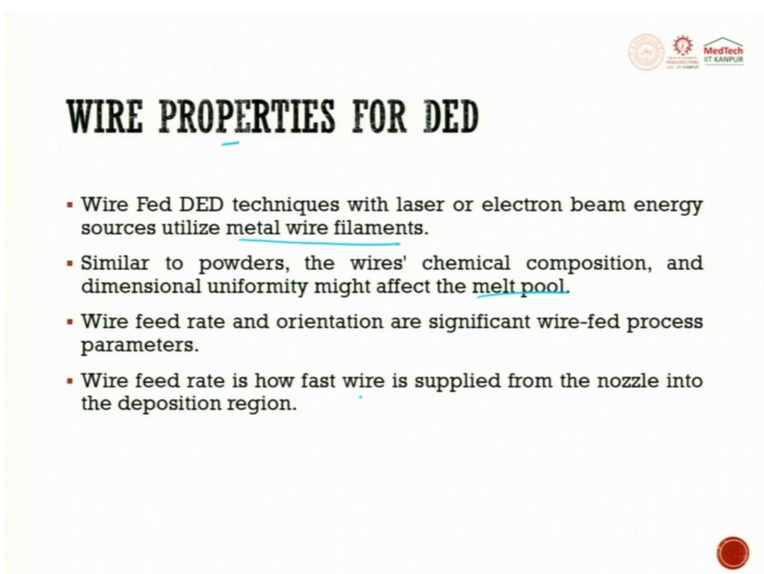




Spinning, so a droplet is drawn, so the spinning disc rotates, so the droplet goes to different places and it tries to create the powder. So spinning disc interacts with molten material to create molten size droplet. It makes fine powders, inert gas it requires less energy than gas or water, in inert gas.

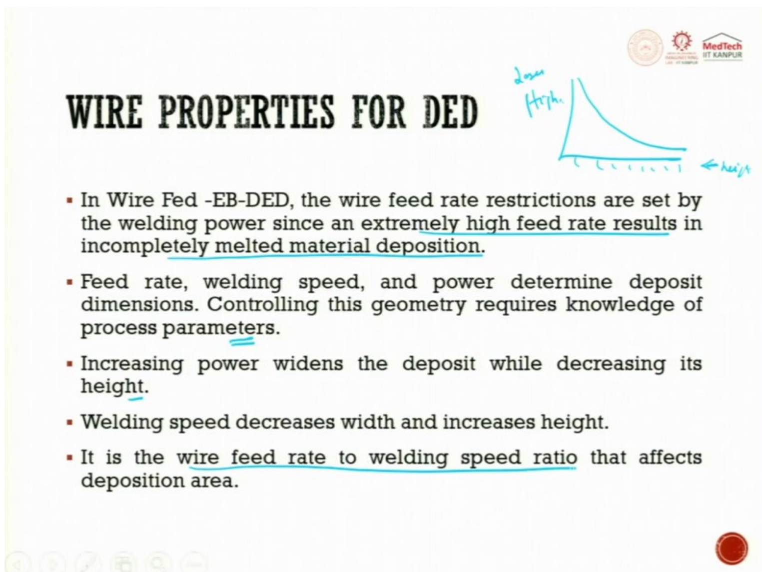
The product has a lower oxidation formation, the lower yield and high system cost due to tungsten contamination is there. And then plasma rotating electrode atomization produces exceptionally pure particles. So these are the ligament formation which is there.

(Refer Slide Time: 42:52)



Now the last part of this lecture, wire properties for DED. Wire Fed DED technique with laser or electron beam energy source utilizes metal wire filament. Similar to the powder, the wire chemical composition and the dimensional uniformity might affect the melt pool. The wire feed rate and the orientation are significant wire fed process parameters. Wire feed rate is how fast the wire is supplied through the nozzle into the deposition region.

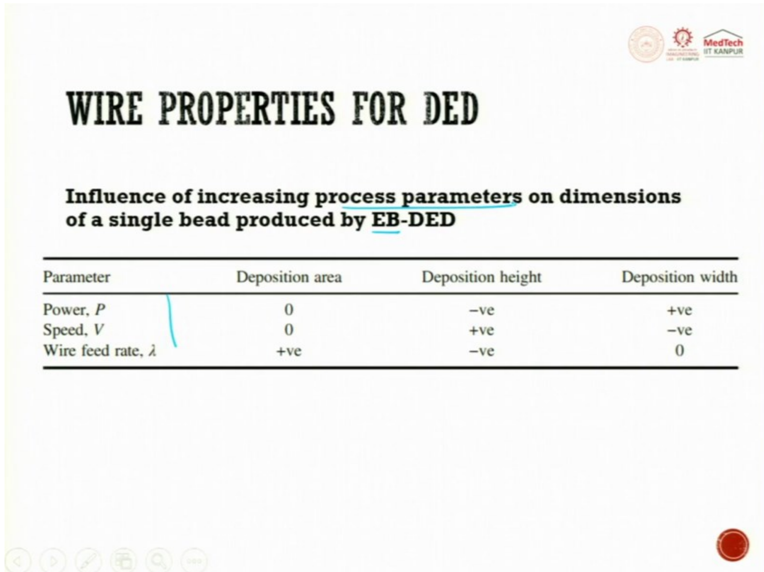
(Refer Slide Time: 43:30)



The wire fed electron beam directed energy deposition, the wire feed rate restrictions are set by the welding power since an extremely high feed rate results in incomplete pre melted material deposition. Very high speeds, incomplete melted metal deposition. Feed rate, weld speed, powder determination, deposition, dimension, cooling, this geometry requires a knowledge on process parameters.

Increasing the power widens the deposition while decreasing the height. When it is large energy, so when the power is high laser power, so then what happens the height, so you take this as height, so it will go something like this. So increasing the power widens the deposition while decreases the height. So the welding speed decreases width as well as increases length. It is the wire fed rate to welding speed ratio that decides or dictates the deposition area.

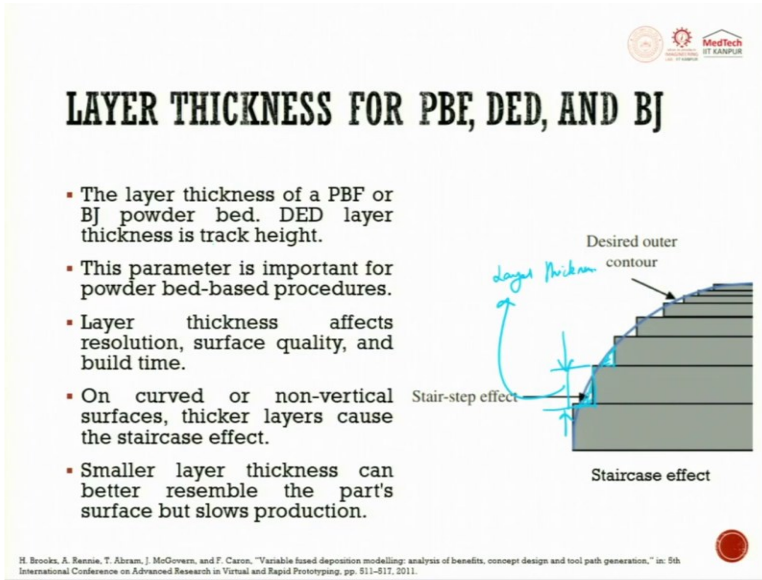
(Refer Slide Time: 44:48)



So here are the influence of increasing process parameters on dimension of a single bead produced by electron beam directed energy deposition. Power deposition area is 0, so deposition height is negative. And then the deposition width is positive. Speed. The deposition area is 0, so that means to say it is neutral. Then it is positive, means deposition height is more and then the deposition width is less.

When you talk about wire feed rate lambda, deposition rate is positive and the deposition height is negative and then the deposition width is 0. So here, it tries to compare the process parameters on dimensions of a single bead produced by EM.

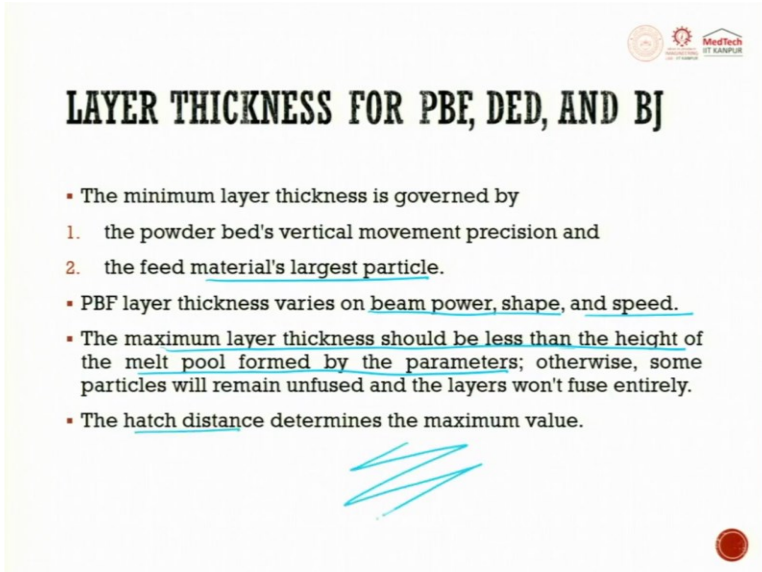
(Refer Slide Time: 45:35)



The layer thickness which have been all that I am talking about, this is called as the layer thickness. And this one is called as the staircase effect. Layer thickness of powder bed fusion or binder jet powder bed is the DED layer thickness is track height. This parameter is important for powder bed fusion procedures.

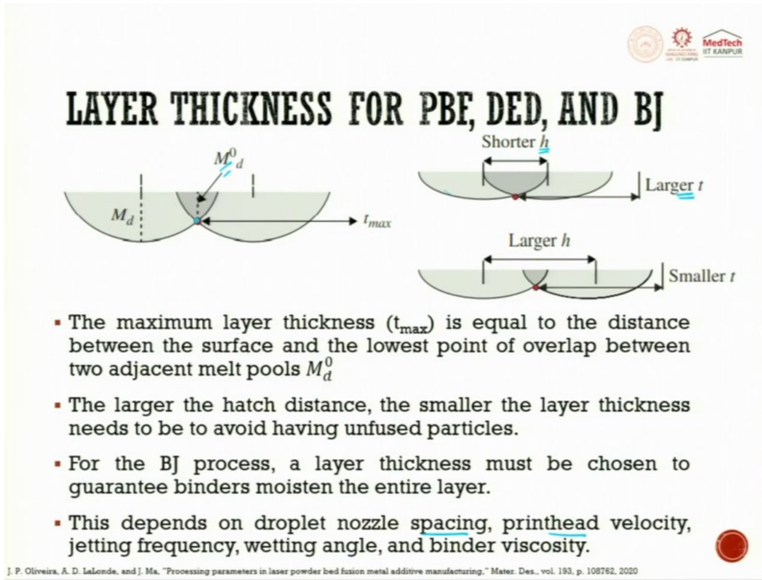
Layer thickness affects the resolution, surface quality and the build time. On curved or nonvertical surfaces, layer thickness causes a staircase effect. So the small layer thickness can better resemble the parts surface but slow production.

(Refer Slide Time: 46:28)



The minimum layer thickness is governed by powder bed vertical movement precision and the freed materials largest particles. The powder bed fusion layer thickness varies on beam power, shape and speed. The maximum layer thickness should be less than the height of the melt pool formed by the parameter. Otherwise, some particles will remain unfused and the layer would not fuse entirely. The hatch distance determines the maximum value, hatch distance. What is hatch distance? This is what is the hatch distance.

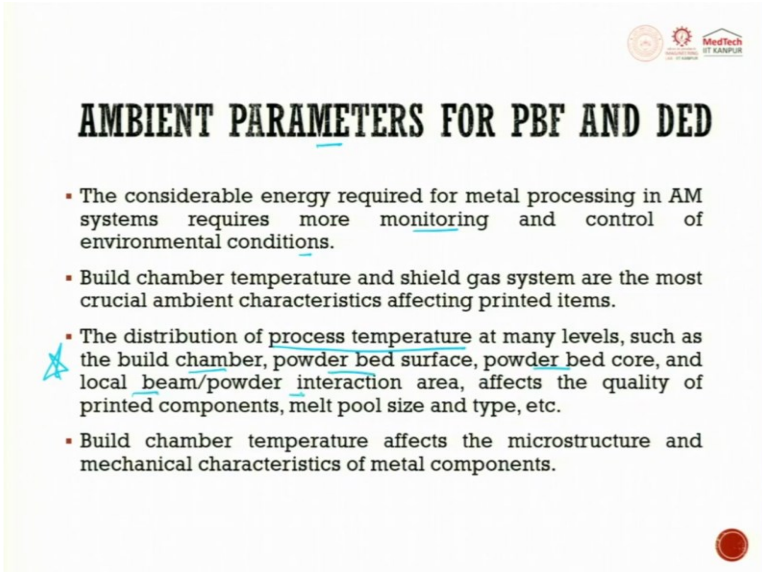
(Refer Slide Time: 47:03)



So this is the one bead, this is the another bead. So in between, you have a meeting point. So that is called as a M_o. So you have shorter, you have longer. So here, when you do shorter h, shorter layer, so you got you shorter layer head, you try to have a layer t. So the maximum layer thickness t_{max} is equal to the distance between the surface and the lowest point of overlap between the two adjacent melt pools which is called as M^o_d.

The maximum layer thickness t_{max} is equal to the distance between the surface and the lowest point and the lowest point of the overlap between the two adjacent melt pools. The larger the hatch distance, the smaller is the layer thickness needs to be avoid having unfused particles. For the binder jet process, a layer thickness must be chosen to guarantee binder moisten the entire layer. This depends on the droplet nozzle spacing, print head velocity, jetting frequency, wetting angle and binder viscosity.

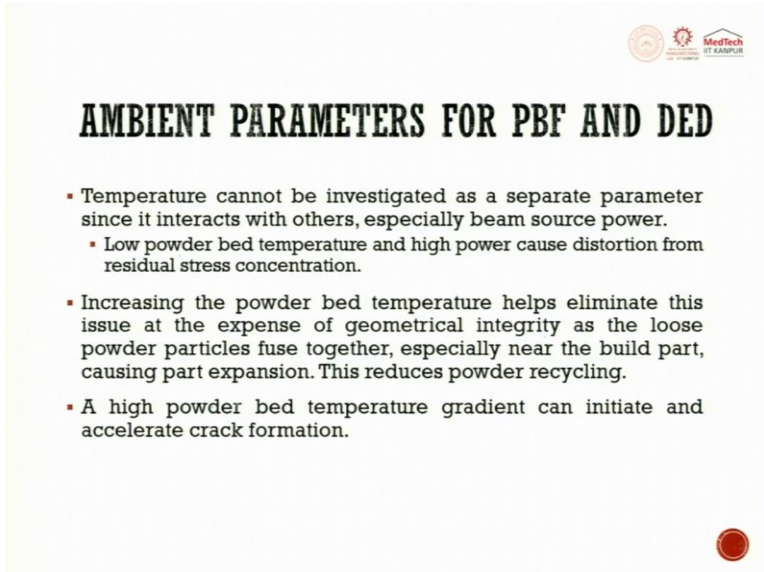
(Refer Slide Time: 48:18)



So the ambient parameters for powder bed fusion and directed energy deposition. Considerable energy required for the metal processing in AM system requires more monitoring and control of the environmental condition, build chamber temperature and shielding gas are most important crucial ambient characteristics.

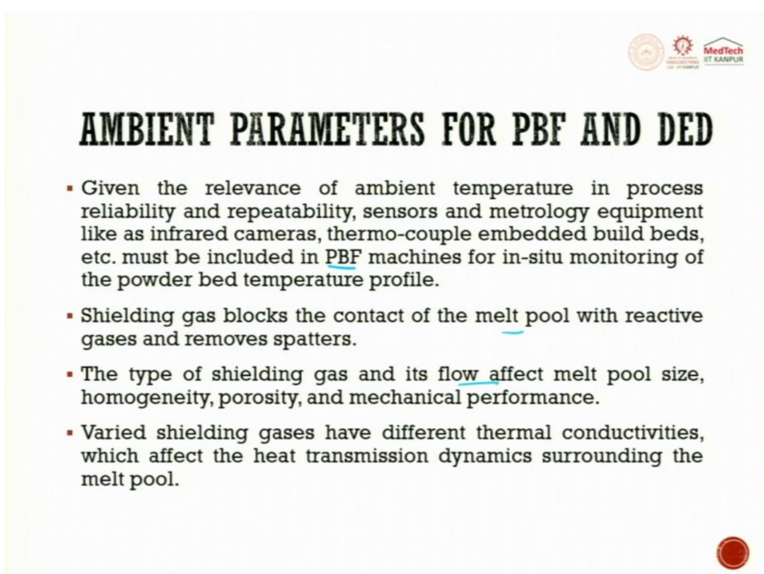
The distribution of process temperature at many levels, such as building chamber, powder bed surface, powder bed core and local beam, powder interaction area affects the quality and the printed component, melt pool size and type etcetera. This is a very important point. Process temperature at many levels such as build temperature, provided this and this, affects the quality of the printed component, melt pool size and the type. Build chamber temperature affects the microstructure and the mechanical characteristics.

(Refer Slide Time: 49:22)



The temperature cannot be investigated as a separate parameter since its interaction with others, especially the beam source power. Lower powder bed temperature and higher power causes distortion from the residual stress concentration. Increasing the powder bed temperature helps eliminate this issue at the expense of geometric integrity as well as loose powder particles fused together, especially near the build area causing a part expansion.

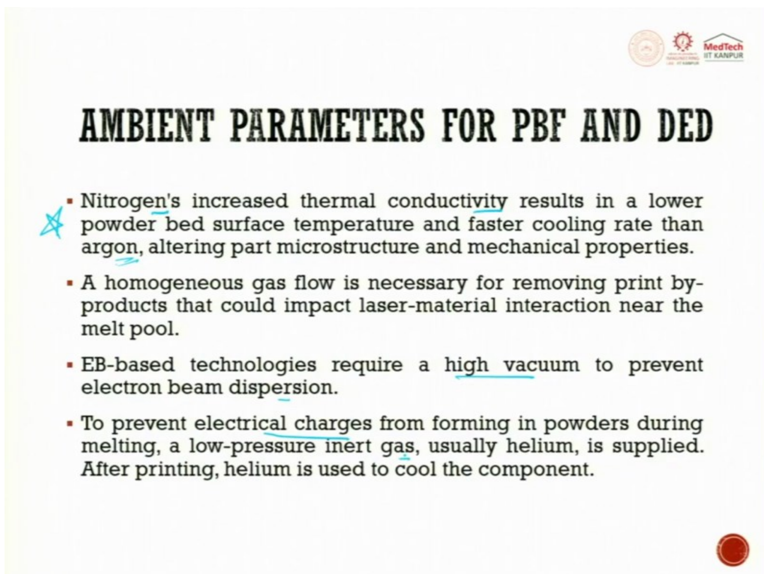
(Refer Slide Time: 49:51)



Given the relevance of ambient temperature in the process, reliability and repeatability and methodology equipment like as infrared camera thermocouple, embedded built heat beds etcetera must be included in the powder bed fusion. Shielding gas blocks the contact of the melting pool that reacts with the open gas.

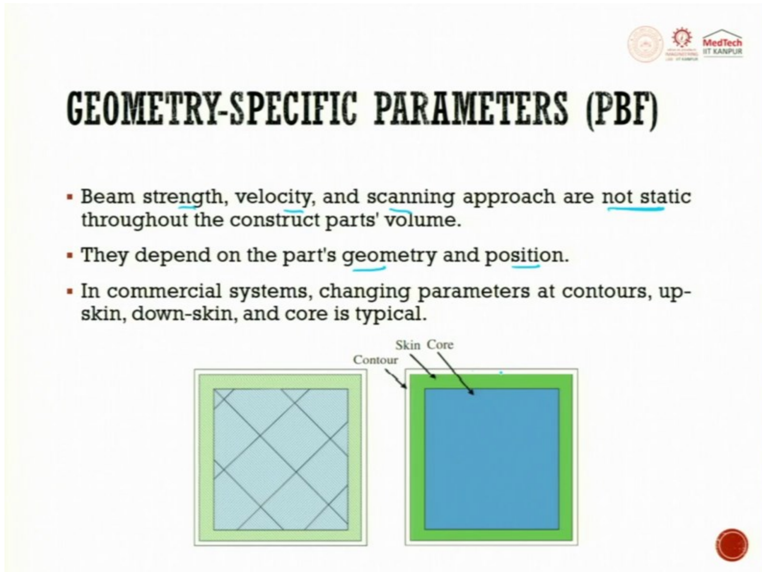
The types of shielding gas and the flow affects the melt pool size. Varied shielding gas have different thermal conductivities which affects the heat transmission dynamics surrounding the melt pool.

(Refer Slide Time: 50:29)



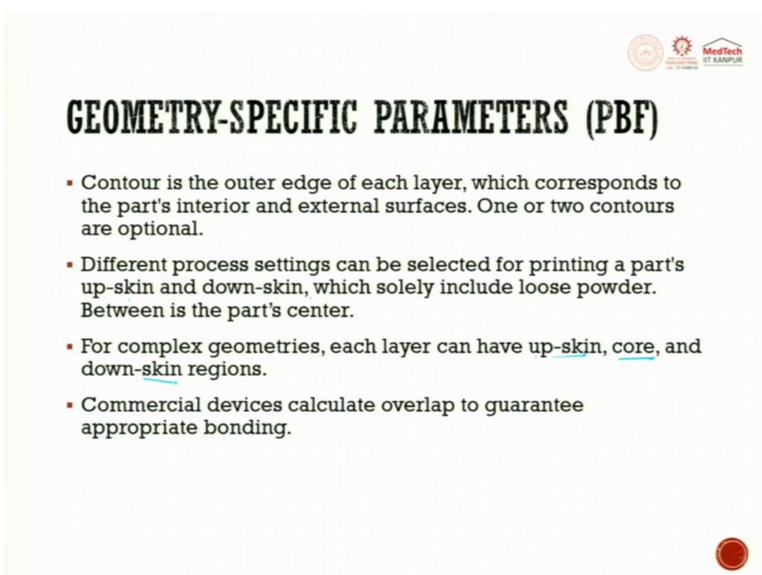
Nitrogen increases the thermal conductivity resulting in low powder bed surface temperature, faster cooling rate than argon, important. The homogeneous gas flow is necessary for removing print by product that could impact laser material interaction. Electron beam-based technologies require a high vacuum for the electron beam should not get dispensed. To prevent the electric charge forming in powder during the melting, a low pressure inert gas, especially helium, is supplied while doing electron beam.

(Refer Slide Time: 51:07)



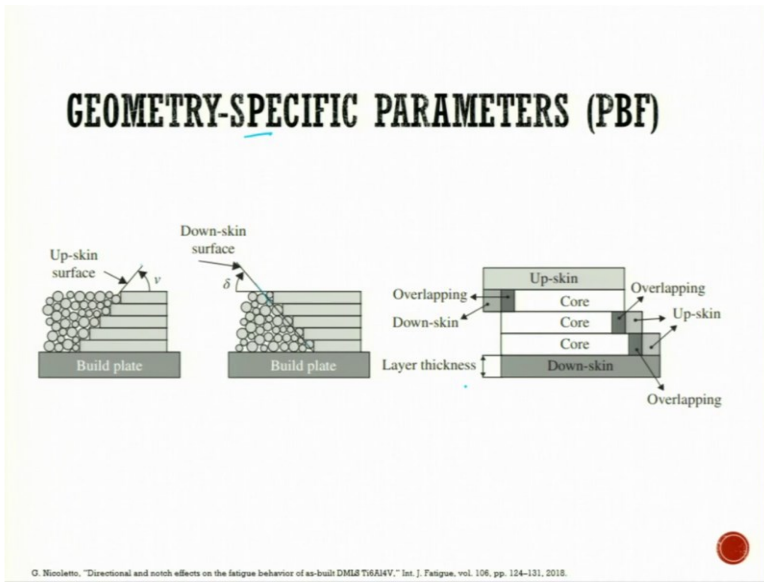
Beam strength, velocity, scanning approach are not static throughout the construction part volume, very important. It is not constant, not static. They depend upon the part geometry and position. The commercial systems change parameters at contours, up-skin, down-skin, so this is the skin core. Up-skin, down-skin and the core is also changed layer by layer when it start building.

(Refer Slide Time: 51:38)



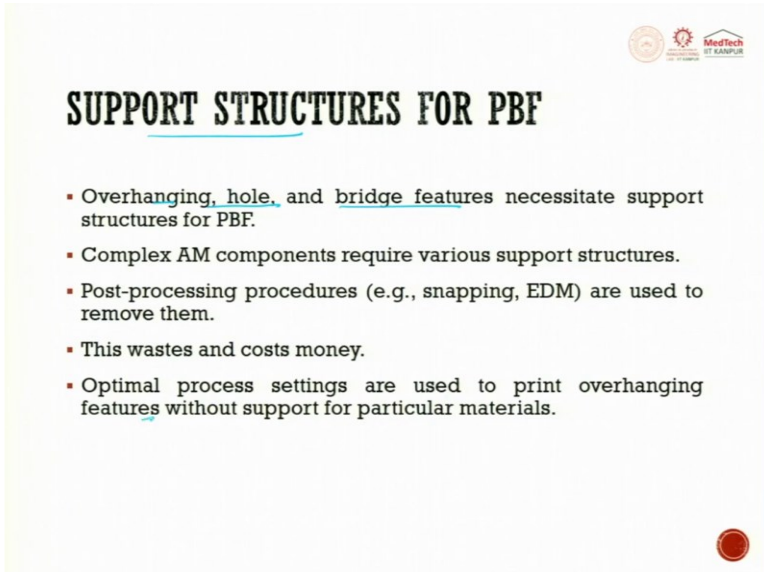
Contour is the outer edge of the layer which corresponds to the part interior and exterior surface. Different process setting can be selected for printing a part up-skin and down-skin which solely increases the loose powder. For complex geometries, each layer can have up-skin, core and down skin regions. What are up-skin, down-skin, these are all skin core. This is up-skin.

(Refer Slide Time: 52:07)



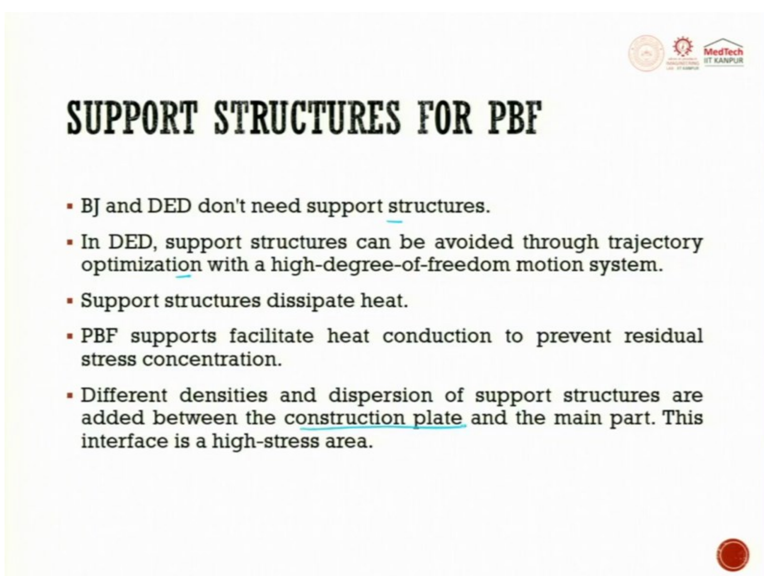
So when we talk about geometry-specific parameters, so you can see here build plate, up-skin, this is the up-skin surface. This is the down-skin surface. Up-skin surface, down-skin surface, build plate. So here you can see overlapping down-skin, up-skin and you have coarse. This is the layer thickness.

(Refer Slide Time: 52:31)



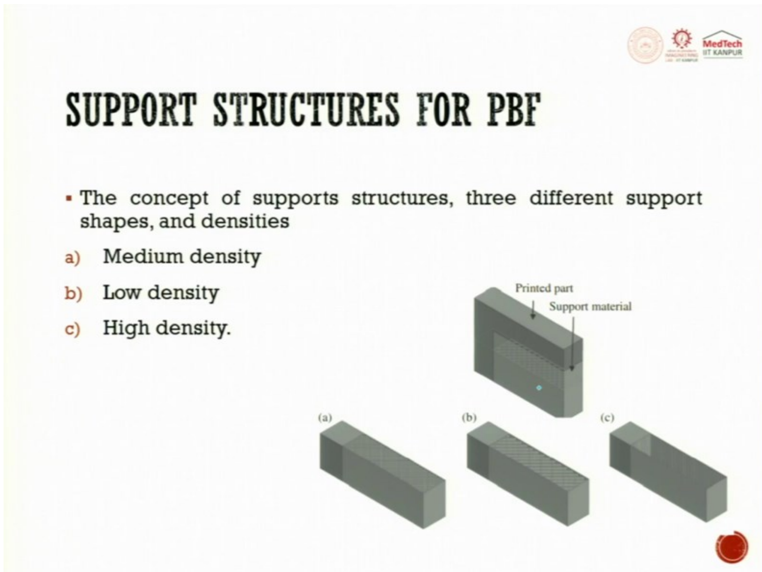
The last of this lecture support structures for PBF, overhanging whole bridge features necessitate support structure on powder bed fusion. Complex additive manufacturing components require various support structures. Post processing procedure are used to remove them, support structures which are built for overhanging holes and bridge features. This wastes and costs money. Optimum process settings are used to print overhang features without supports for particular material.

(Refer Slide Time: 53:07)



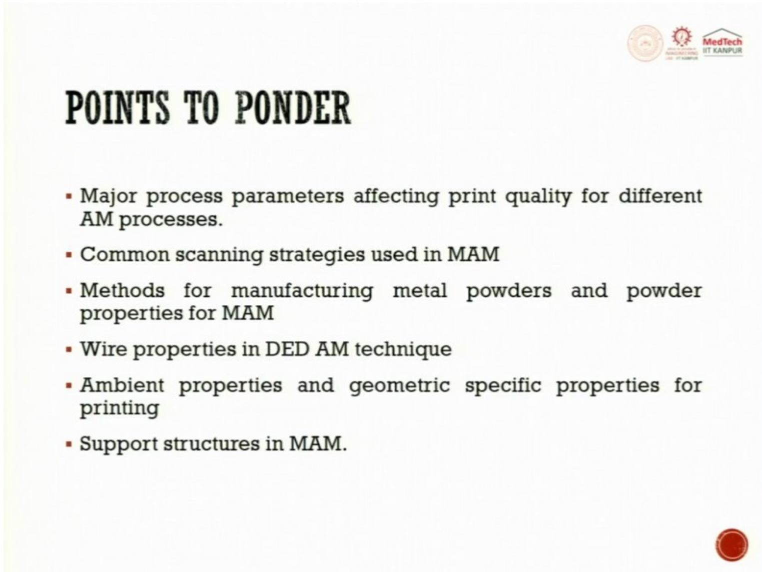
BJ and DED do not need support structures. In DED, support structures can be avoided through trajectory optimization. The support structures dissipate heat. The powder bed fusion supports facility, heat conduction to prevent residual stress concentration. Different densities and dispersion of support structures are added between the construction plate and the main part.

(Refer Slide Time: 53:36)



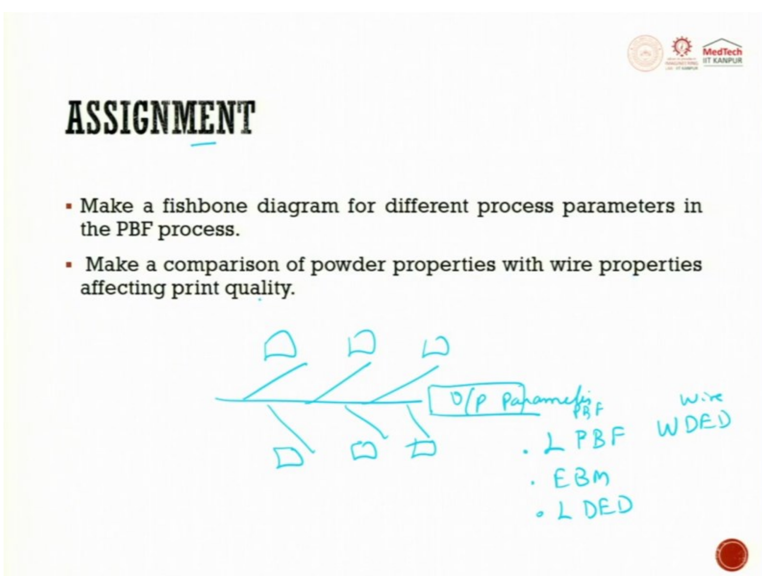
So these are all different support structures which are built. So a is medium dense, b is low dense, c is highly dense and this is a part, print part, there is a overhanging structure and this is a support structure.

(Refer Slide Time: 53:53)



So now points to ponder from this lecture. Major process parameters affecting print qualities for different additive manufacturing process has been discussed, common scanning strategies used in metal additive manufacturing is discussed. Methods for manufacturing metal powder and powder properties for MAM, wire properties in DED additive manufacturing technique, ambient properties and geometric specific properties for printing and support structures in MAM, all these things have been discussed in this chapter.

(Refer Slide Time: 54:28)



So, assignments. Can we make a fishbone diagram, this is a fishbone diagram, where you have output parameter, this can be anything, output parameter with several of these input parameters. You can have so you can refer to any book or literature. Try to develop a fishbone diagram for L PBF, EBM and L DED, then wire DED. So these are all powder based.

This is PBF, this is you can have it as wire based, extrusion based. So make a comparison of the powder properties with wire properties affecting the print quality. So take copper wire, take copper powder. Aluminum wire, aluminum powder. Take this and make a comparison so that you will try to understand more in details about metal powder and wire properties. Thank you very much.