Metal Additive Manufacturing
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Lecture 07
Basic Processes (Part 1 of 2)

Welcome to the next lecture on Metal Additive Manufacturing. This lecture we will have two parts. So, we will try to cover basic processes, which are all involved in metal additive manufacturing.

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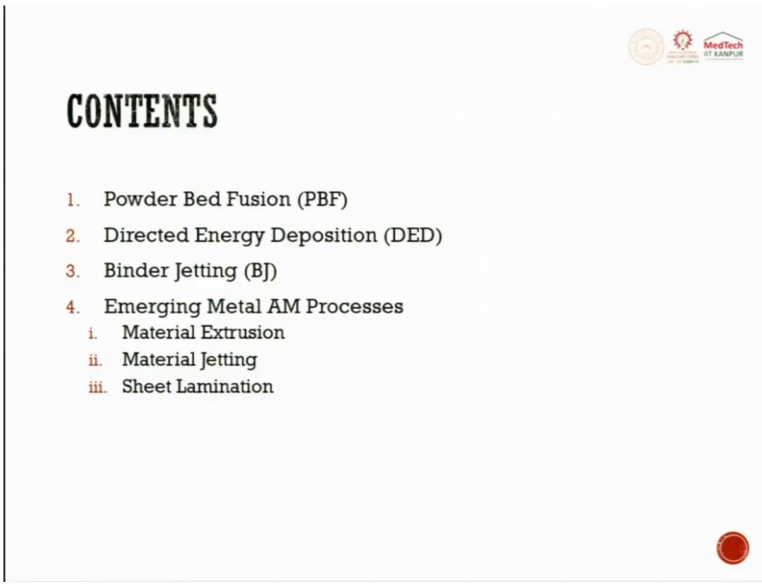

The content of this lectures are going to be powder bed fusion method we will try to discuss, then we will try to talk about direct energy deposition, which is DED or directed energy deposition, next one is going to be binder jetting, the last one is going to be emerging metal additive manufacturing process material extrusion, material jetting and sheet lamination. These processes are still emerging and it has not come up in a big way in the industry. The first three processes are very well established in lab scale and has moved to industries.

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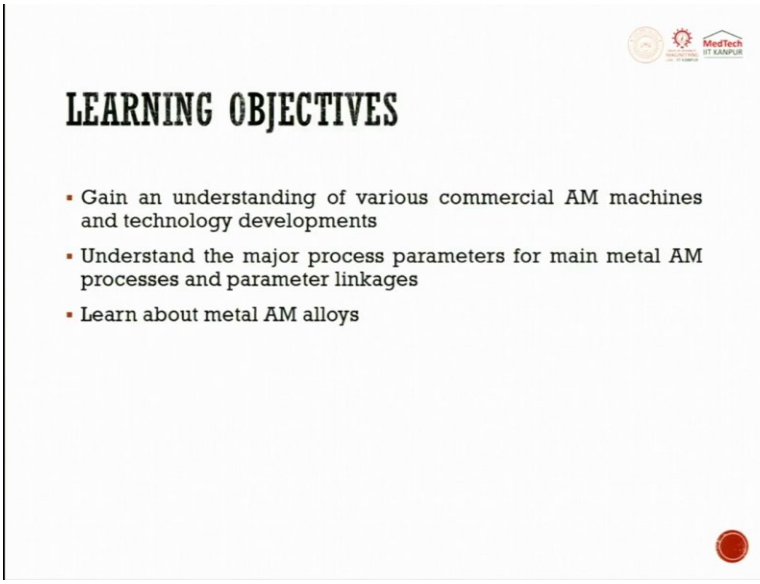

At the end of this lecture, what will be the learning objectives you have, you would have gained an understanding of various commercial AM machines and technology developments. Understand the major process parameters for main metal additive manufacturing process and parameter linkage. Last, you will learn about AM alloys.

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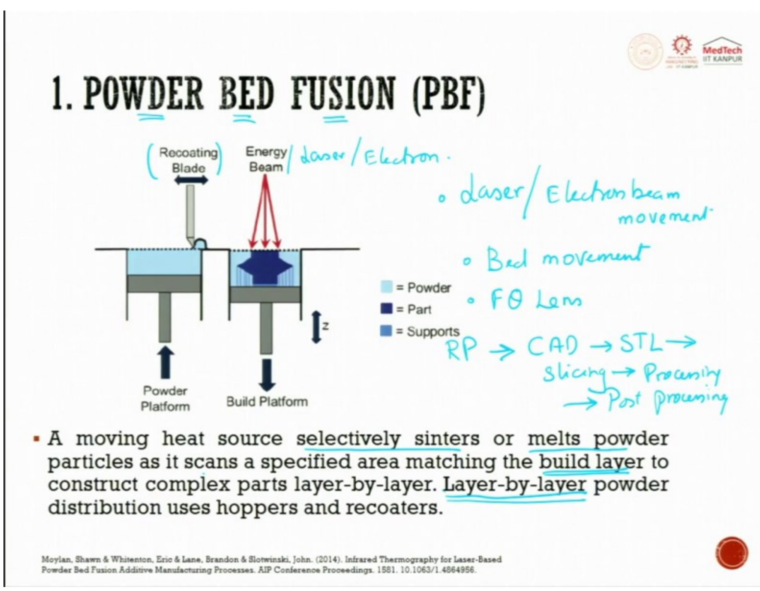

First let us try to understand powder bed fusion process. This is always shortly called as PBF process. So, here as the name suggests, you will have a powder, this powder will be placed in a bed and the placed powder will be fused together by using some heat source or it will be converted or you can call it as energy beam.

So, the energy beam which can be either laser or electron beam can be used to focus on the bed where you have powder and then the heat which tries to fuse the powder and then attach to each other. So, this is powder bed fusion method. A moving heat source selectively sinters, so that means to say the laser is not constant, the laser can move or the bed can move or the laser will be fixed, you pass it through your F theta lens where in which you try to have the coverage in one full plane.

So, you can have laser or electron beam movement, the next one is you can have bed movement and the third option what I said is you can have an F theta lens attached to the laser which can scan or which can flush over one full particular area. So, these are the energy beam sources depending upon the requirements, you can have these three options.

Now, what happens is this moving heat source or the moving bed source selectively sinters, sinter means you are not 100 percent melting the powder you are trying to join the powders along the boundary. So, selectively sinters or completely melt the metal powder so that you can have a better fusion and avoid voids or defects which are getting generated in the build part.

So, selectively sintered or melt the powder particles as it scans a specified area matching the build layer. So, if you go back in the steps which are involved in RP we were discussing CAD, CAD to tessellation, tessellation to slicing then afterwards it is processing and then you will try to have post processing. So, what will happen is the slicing will try to take care of the build layer.

So, matching the build layer to construct a complex parts layer by layer, this layer by layer powder distribution uses hoppers or recoaters. So, now, what I am trying to say is, if you want to maintain this layer thickness, then you try to use this recoating blade. So, a hump will be spread, the powder bed is pushed up, so, the powder gets accumulated on the top, you use recoating blade to move the powder into the bed where it is getting build.

So, this is called as a build platform, this is called as the powder platform and then this is called as z, the height. So, powder bed fusion means using a powder to build the object layer by layer by the process of sintering or melting to get the final part. So, here you have to have a build the platform and then you should have a powder platform.

So, today what is happening is instead of one powder platform, you can have n powder platform, for example, in one you fill up with stainless steel alloy powder, then you can have copper, then you can have something else. You can have 6 or 7 powder platforms and that will be a recoating blade, which tries to move and then put all the things on build platform.

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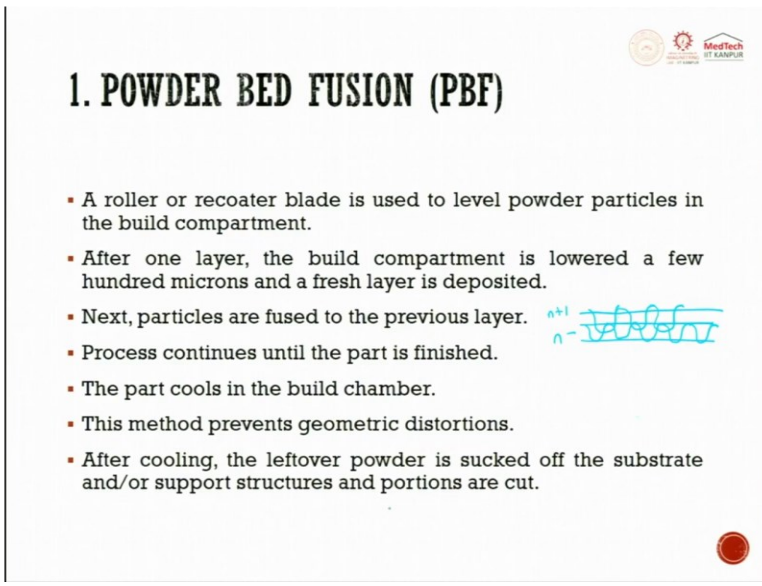

So, if you see the process your roller or your recoater blade is used to level the powder particles in the build compartment. So, the powder platform pushes the powder so by a layer, it will be slightly higher than a layer. You cannot exactly maintain a layer, it will be slightly higher than a layer then what happens is the recoater blade maintains the height and then it sweeps through the powder platform and then moves to a build platform.

The roller or the recoater blade is used to level powder particles in the build compartment. After one layer, the build compartment is lowered of few 100 microns and a fresh layer is deposited. So, as and when the melting happens, this gets sunk down by one layer, this gets pushed up by one layer so slightly higher than a layer. So, next, the particles are fused to the previous layer.

So, you will have one layer and the other layer, and when the laser hits, this is how you have Gaussian distribution of heat which is happening in that layer. So, when the next layer comes, the next layer will be like this, the heat will also try to stitch in with the bottom layer so that it does not try to provide any defects.

So, the particles are fused to the previous layer, this is the n layer this is the n+1 layer, previous layer and the process continues until the part is finished. The part is cooled in the build chamber and this method prevents geometric distortion. And after cooling, the leftover powder is sucked off the substrate and or the support structure and a portion are cut. So, support structures are cut and the leftover powders are sucked so that you get the final part.

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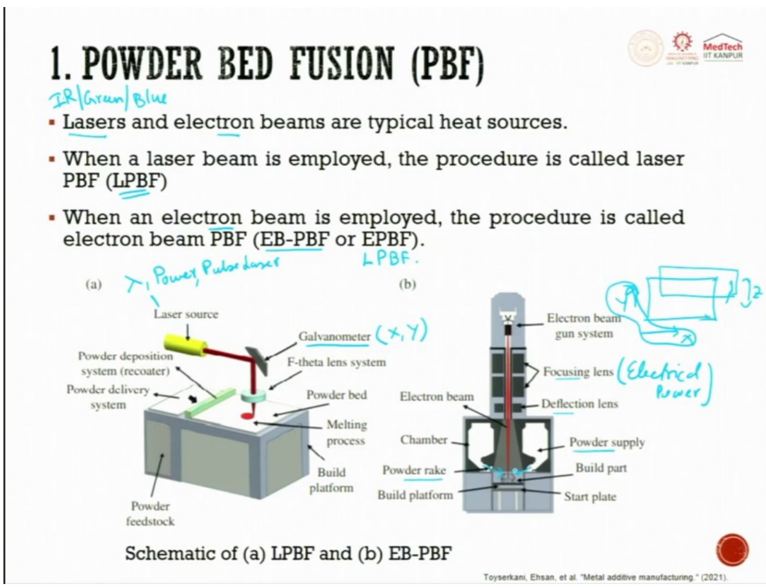

So, as I told you, you can either use a laser or an electron beam, when we talk about the laser, you can use varying wavelengths or different wavelength lasers can be thought of which can be IR, it can be green, it can be blue, depending upon the alloying condition. So, here the absorption property of the laser with the alloy material comes into importance and you decide the laser and the power such that you try to get the best out of the process.

The laser and the electron beam are the typical heat source. Today, people have even started using plasma but plasma does not give you the highest accuracy. So, people are happy with laser as well as electron beam. When a laser beam is employed, the procedure is called as laser powder bed fusion technique. So, this is in short called as LTBF.

When an electron beam is employed, so, the procedure is called as electron beam powder bed fusion or it is called as EB-PBF or EPBF. So, it is LPBF or EPBF. So, if you see the schematic diagram between the two processes, you will see a laser source there. I have already told you the λ, the power and if you want to have continuous you can use it, otherwise you can also use pulsed laser for doing the printing process.

So, the laser beam tries to hit at the galvanometer, this galvanometer is trying to take the information of x and y, in one plane x and y. So, if you take a layer, you will have y axis, you will have x axis and if you try to build it another layer, so, this is called the z axis. So, in galvao we always try to protect or we will try to take the information for x and y.

So, a galvanometer is used where in which the laser hits the mirror and the mirror tries to sweep and try to transfer the x, y data to through the F theta lens to a powder bed. So, F theta lens has a property such that anywhere in that plane, they have the same uniform distribution of laser such that it does not bring in any variation in one layer while fusing.

So, you pass through the F theta lens and this light is trying to hit at the powder bed and in the powder bed it undergoes a sintering or a melting process and then the object is getting build on a build platform and the powder is feedstock. So, this is called as the recoater blade, the previous diagram was looking as though it is a 2D you can think of a 3D, it has like a sweeping blade or if you can take an analogy of a wiper in the car.

So, it is almost like that. So, it is powder deposition system recoater. So, it tries to push and powder delivery system is where you try to have all these things. So, this process is called as laser powder bed fusion technique. When we try to talk about the electron beam on the other side, you will have the powder rack feeding from here and you can have powder supply.

So, this is powder supply, this is powder rack, so you can have several, it tries to fall on the build platform. So, this is the build platform. And you can see here the material flows from here to here. And then, you have an E beam which tries to hit at the work piece to develop the work piece while doing so, like F theta lens.

You also have focusing lens which are all working using electrical power say for example, you try to have electrical coil, which tries to focus the electron beam to one spot, if you want to deviate again you will have deflection lenses, so that that tries to hit at the surface and you try to develop it. So, you will have F theta lens here you will have focusing lens and deflection lens which tries to focus on the work piece or on the powder to get the output. So, this is how the construction of your powder bed fusion procedure or a technique works.

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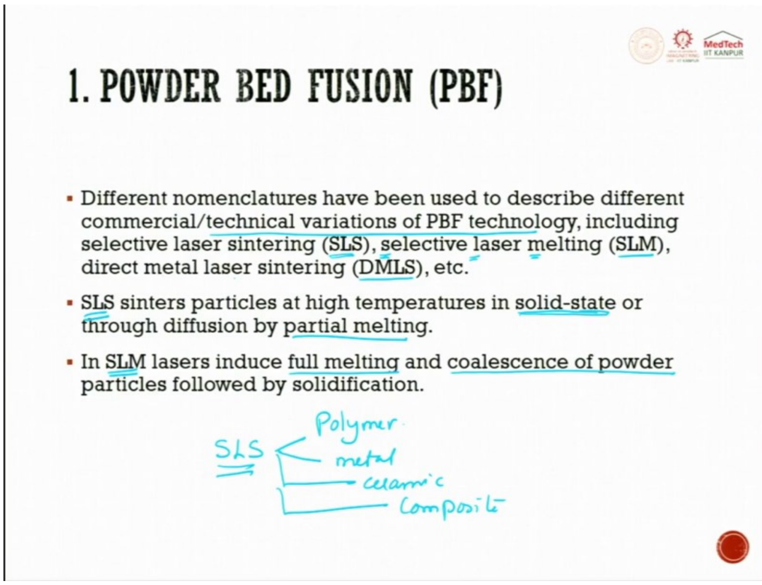

So, different nomenclatures have been used to describe different commercial technical variations of powder bed fusion technology, which includes selective laser sintering which is SLS process. SLS process can be used for polymer, it can be used for metal, it can be used for ceramic, it can be used for composite also. So, SLS process can be used for polymers, again in polymers, you can try to have a blend of polymers.

So, polymers SLS process, you can have SLM process which is selective laser melting, Selective Laser Melting (SLM process), and you can also have Direct Metal Laser Sintering (DMLS process), these are all the different technical variations of powder bed technology. SLS sinters particle at high temperatures in solid state or through diffusion by partial melting, at very high temperatures solid state.

When we talk about SLM process, laser induces full melting and coalescence of powder particles followed by solidification. So, here like in casting you will have full melting and coalescence of powder particles followed by solidification. That is the difference between SLS process and

SLM process. So, SLS is the sinter particles at high temperature in solid state or through diffusion by partial melting here it is full melting.

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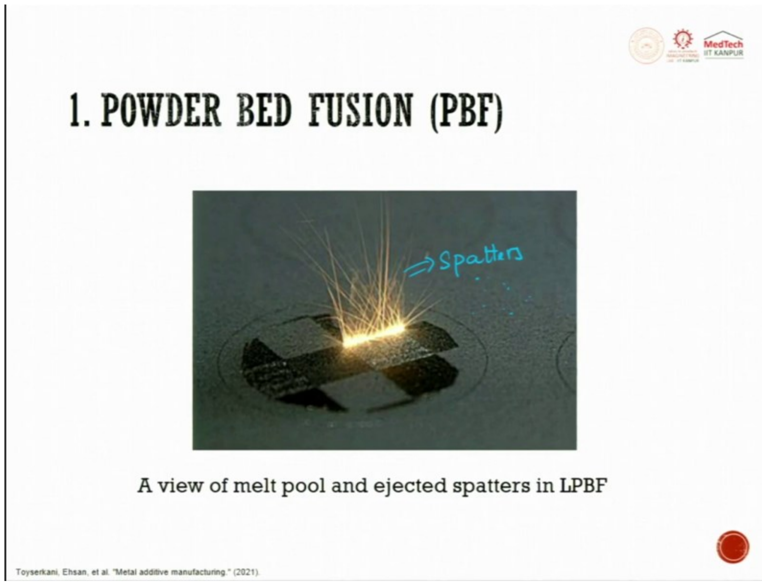

So, this is how the powder bed fusion technique looks like. A view of the melt pool and ejected spatters in laser powder bed fusion. If you see the laser hits, and these are the spatters. So, these spatters are like our flower crackers, which is like a flower pot, it will just try to sprinkle the melt metal outside the laser focus here. So, that is what is a melt pool ejected spatters, these ejected spatters are melt powders which are very small in size and they are dispersed all around the build part.

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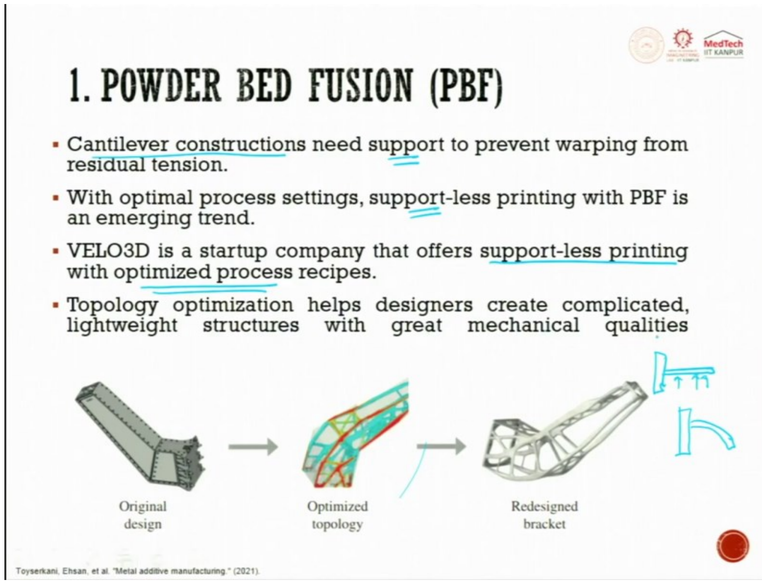

So, cantilever constructions need support to prevent warping from residual tension. So, these are some of the techniques or which you have to follow while constructing cantilever constructions. So, when we try to do cantilever constructions, we always try to support the cantilever.

So, if you want to build such high hanging structures, we always have to do supporting so that this fellow does not bend like this. So, that is what cantilever construction needs support to prevent warping from residual tension, while optimal process setting supportless printing with PBF is an emerging trend.

So, what we are trying to say is now if you try to plan the process parameters that is the heat which is getting induced during the building, if you can try to have that optimization done, then you can try to eliminate support structures. So, why is it very important? Because, one- support structures take money, two- support structures has to be removed, third- for support structure also, location placing with respect to building up the object is also a challenge.

So, now when we try to remove these support structures, so then you are assured of getting a good quality output. So, VELO3D is a startup company that offers supportless printing with optimized process recipe. So, optimization of the process is very important to build a sound quality output. Topology optimization, this is the original design, this is the topology optimized design and this is the redesign of the bracket such that you have reduced material and you have enhanced the strength. Topology optimization helps designers create complicated lightweight structures with great medical qualities.

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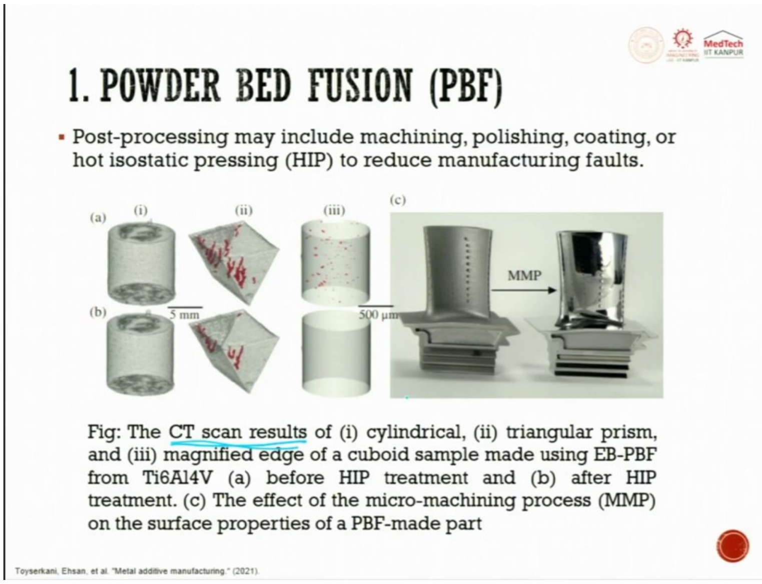

Post processing may include machining, polishing, coating or hydro isotatic pressing, to reduce manufacturing faults. So, in powder bed fusion, as I told you previously, the steps involved in CAD are CAD, STL, slicing, processing and post processing. Now, we are trying to look at post processing, post processing may include machining, polishing, coating or hydro isostatic pressing to reduce the manufacturing faults.

So, in order to find out the pores, which are getting developed inside the object, many a times we use CT scan technique to find out the internal defects. So, one is cylindrical triangular pieces and magnetic edge of a cuboidal sample made using electron beam powder bed fusion of Ti6AlV4 is shown here, this is before hipping and the next one is after hipping.

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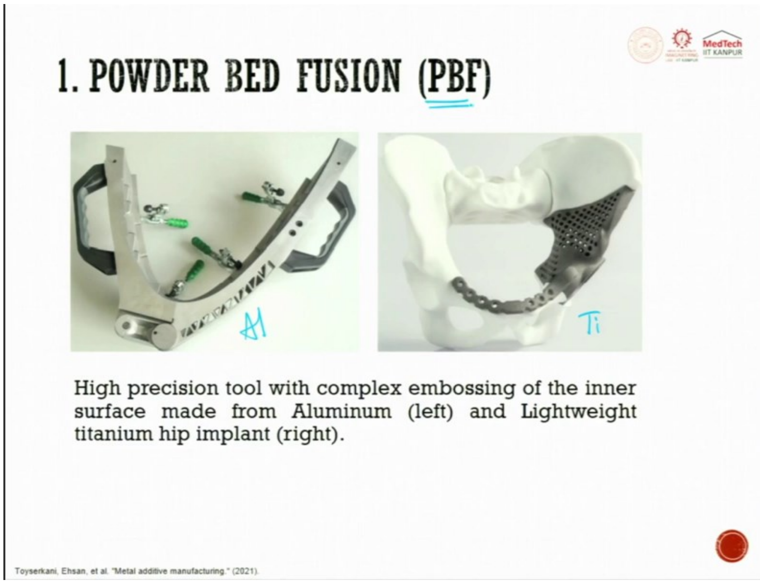

So, high precision tool with complex embossing of the inner surface made from aluminum and lightweight from titanium are shown here, which is all build by powder bed fusion method.

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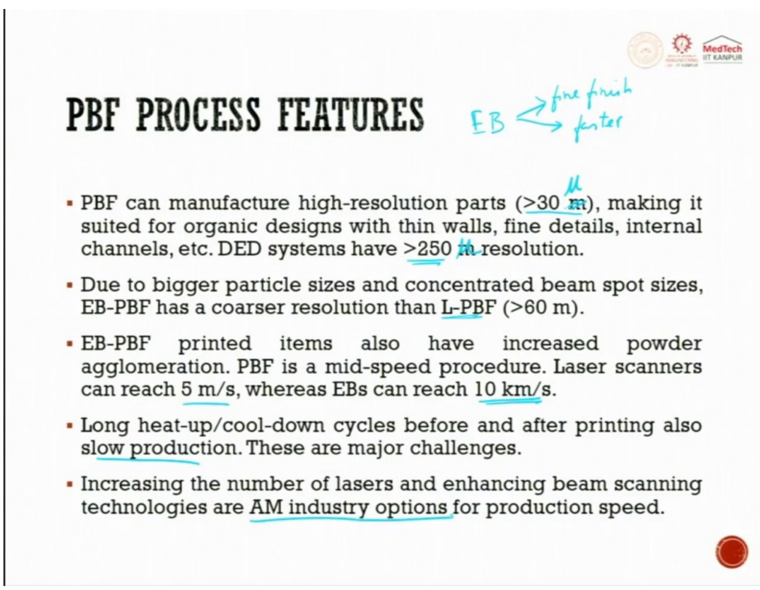

So, what are all the process features of powder bed fusion? Powder bed fusion can manufacture high resolution parts of less than 30µ. Making it suited for organic design with thin walls, fine details, internal channels, etc. The DED system which we will see next has a resolution of 250µ.

Due to bigger particle size and concentrated beam spot size, E beam has a coarser resolution than electron bed fusion method. So, nowadays the process has improved. An electron beam also tries to give the same accuracy in fact better finish as compared to that of laser powder bed fusion method. Electron beam powder bed fusion printed items also have increased powder agglomeration. The powder bed fusion is a mid speed procedure.

Laser scanners can reach 5m/s whereas in electron beam it can go up to 10 km/s. So, what is the inference? Electron beam nowadays is fine finish and it is faster in building, it can go 10km/s. Long heat up/cool down cycles before and after printing also slows production. These are the major challenges.

So, if you heat up or if you cooled down slowly, then what happens is it tries to take a long time for printing. The non-productivity time goes high that is what we are trying to say. Increasing the number of lasers and enhancing beam scanning technologies are additive manufacturing industry options for production speed.

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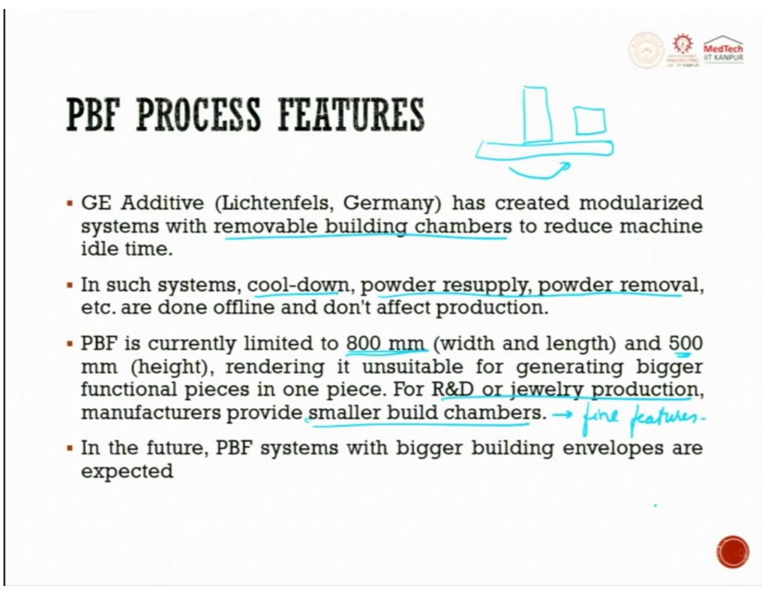

GE has created modularized system with removable building chambers to reduce the machine ideal time, so removable build chambers. So, one it will print and then it will switch, and then you can try to remove from the build one and then the next one gets set. So, GE additive has created modularized system with removable building chamber.

In such system, cooling down and powder resupply, powder removal, etc. are done offline and does not affect the production. So, it is basically something like this, you will have a table so in that table here you build the pot so then you can just swap it. This fellow comes outside and this fellow goes inside. So, now what will happen, you can start doing cooling down, powder resupply, powder removal all these things can be taken into control.

Powder bed fusion is currently limited to 800 mm, there are a few exceptions today, and the 500 mm height rendering is unsuitable for generating bigger functional pieces in one piece. So, that means to say a large area cannot be printed. So, you try to print small pieces and then you try to assemble them to get the final output.

For R&D or jewelry production, manufacturers provides smaller build chambers for jewelry industry, we always look for smaller building chambers because here you will have fine features to be printed. In future, powder bed fusion system with bigger building envelopes are expected to be created.

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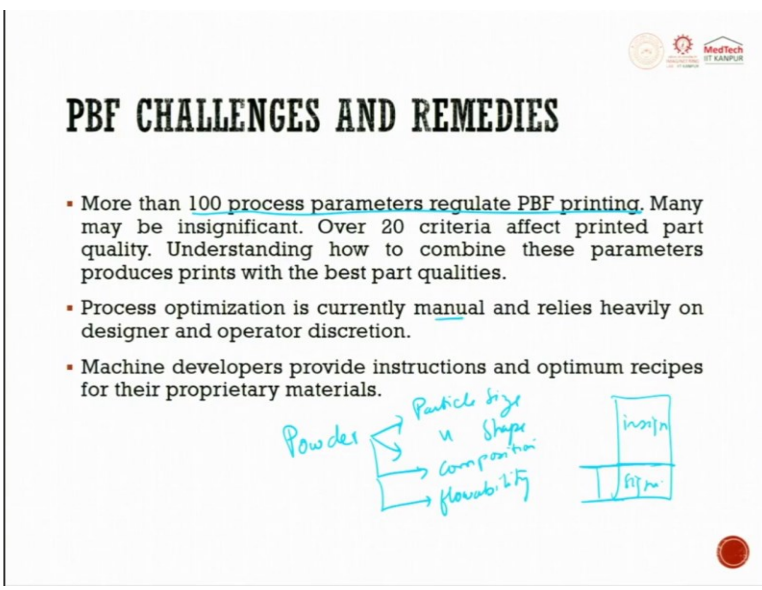

More than 100 process parameter regulates the PBF process like powder, particle size, particle shape, then we try to talk about composition, so you have then flow ability, etc. you see like that 100 process parameters are to be regulated to get powder bed fusion printing process or a powder bed fusion printing product. Many may be insignificant out of this 100.

So, you might have these are all insignificant and you will have significant. So, you focus always on the significant. So, over 20 criteria affect printing parts quality. Understand how to combine these parameters produces prints with the best part quality. The process optimization is even now, you have very green area and it is currently given in the manuals and relies heavily on the designer and the operator's discretion. Many developers provide instructions and optimum recipes for producing a good quality output.

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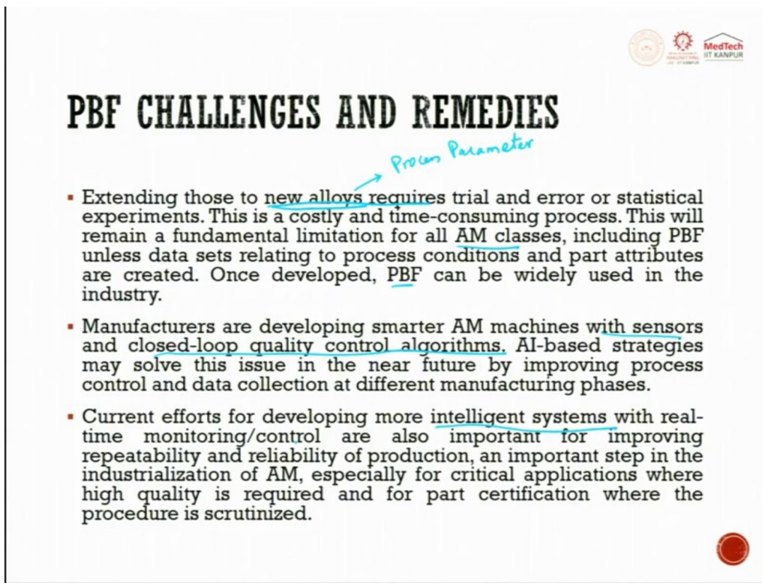

What are all the challenges and remedies? Extending those to new alloys, so new alloy is a challenge because we are not able to produce powders in the required composition and required quantity in an economical price. So, extending those new alloys require trial and error or statistical experimentation. Then this alloy is leading to process parameters, this is a major challenge.

Because you do have to do experiments, it is costly and time-consuming process. This will remain a fundamental limitation of AM classes including powder bed fusion, unless we have a huge data set for the process condition. Of course, today deep learning, machine learning, 5G technologies are coming up they will produce more and more data, with these data we can try to understand the process and develop high quality products to meet the customer requirements.

Once developed PBF can be widely used in industry. Manufacturers are developing smarter AM machines with sensors and closed loop quality control algorithm. So, sensors what we are trying to do is we are trying to see temperature sensor, fume sensor, then we are trying to integrate cameras, so all these things are sensors, and the closed loop quality control algorithms are being used today, like in CNC here also we are trying to do closed loop algorithms. AI based strategies may solve this issue in the near future. Current efforts for developing more intelligent systems with real time monitoring and controlling are being used today.

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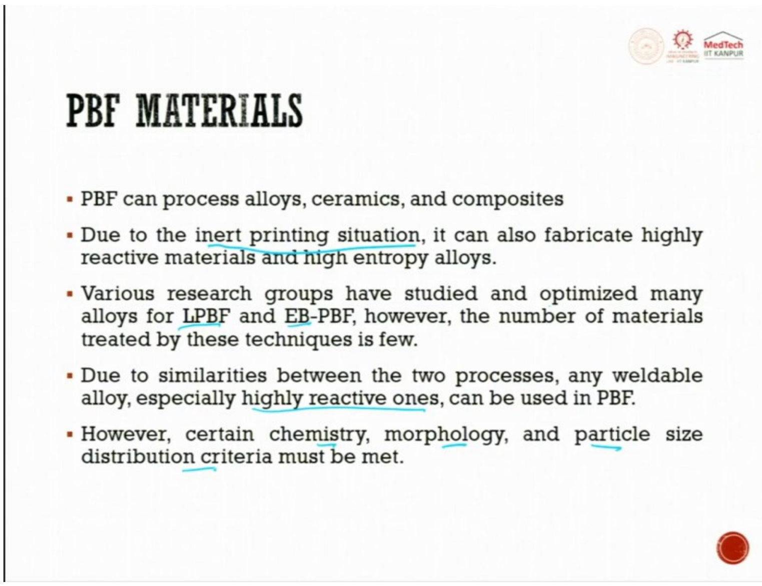

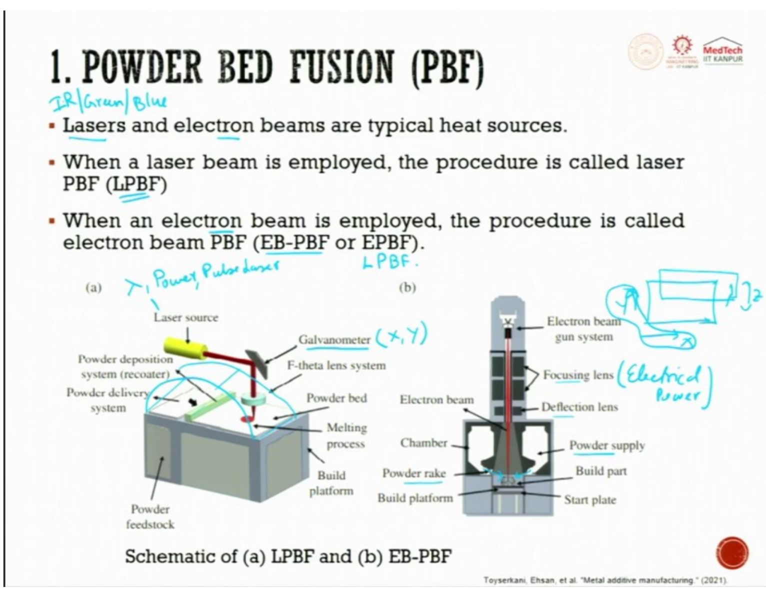

The PFD materials, PFB can process alloys, ceramic, composites, polymers. Due to the inert printing situation, it can also fabricate highly reactive materials and high entropy alloys. So, what are we trying to say is when we are trying to do all these processes, we are trying to do this processes in free air. Instead of that, if we try to cover this entire machine, such that the gas tries to prevent the reaction of the alloy with the atmosphere. So, it will be very good. So, it tries to avoid so that is what I said due to inert printing situation it can also fabricate highly reactive materials and high entropy alloys. Various research groups have studied the optimization of many alloys for LBPF and E-PBF.

However, still a number of materials which are used is very few and there is lot of scope for improvement. Due to similarities between the process, any weldable alloy, especially highly reactive ones can be used in powder bed fusion. Certain chemistry, morphology, particle size, distribution criteria must be met to produce the good quality output.

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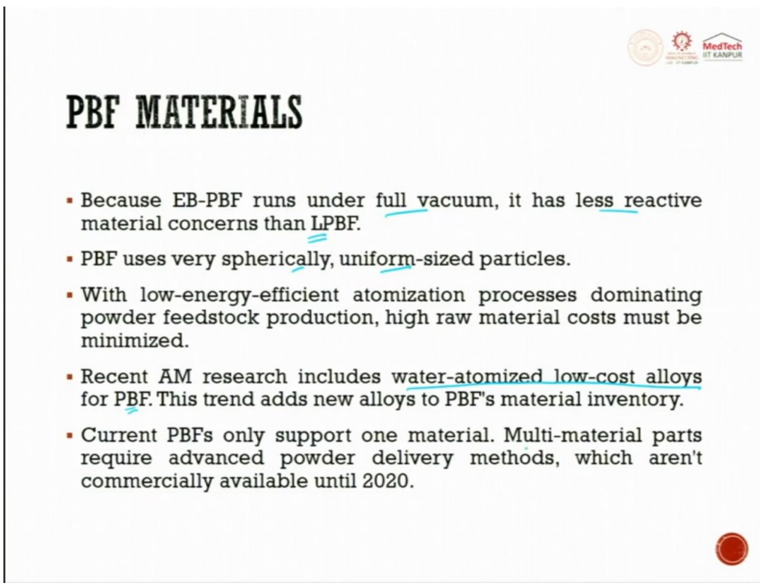

Because electron beam powder bed fusion runs fully in vacuum, it is less reactive than the laser, laser powder bed fusion technique. Powder bed fusion technique uses very spherically uniformed size particles. With low energy efficiency optimization process dominating powder feedstock production, high raw material cost must be minimized. Even today the raw material is expensive.

Recently AM research includes water optimized low cost alloy for PBF. So, producing high purity, low cost powders are becoming a challenge. This trend adds new alloys to powder bed fusion material inventory. Currently powder bed fusion only support one type of material, multi material parts require advanced powder delivery system.

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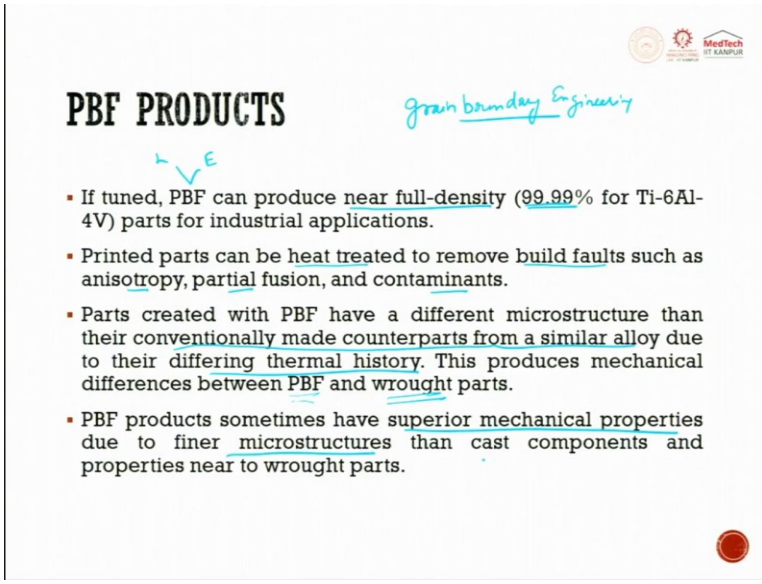

If tuned PBF can produce nearly fully dense 99.99 percentage for Ti-6Al-V4 for parts industry today. So, again here you can use laser or electron. Printed parts can be heat treated to remove the build fault such as anisotropy, partial fusion and contamination. So, this is another thing, post processing process of heat treatment. So, the part created by powder bed fusion have a different microstructure than the conventional made counterpart from the similar alloys.

So, now you are tailoring the microstructure. So, there is something called as grain boundary engineering. So, now in this which tries to dictate the strength and the performance of the produced part, here what we are trying to do is after producing the microstructure will be completely different because they follow different thermal histories. Because of this varying thermal history is repeated heating, they produce a different microstructure as compared to that of the conventional one.

This produces mechanical difference in the powder bed and the wrought iron. This makes the powder bed fusion parts attractive as compared to that of a conventional one. BBF products sometimes have superior mechanical properties due to finer microstructure than cast iron components.

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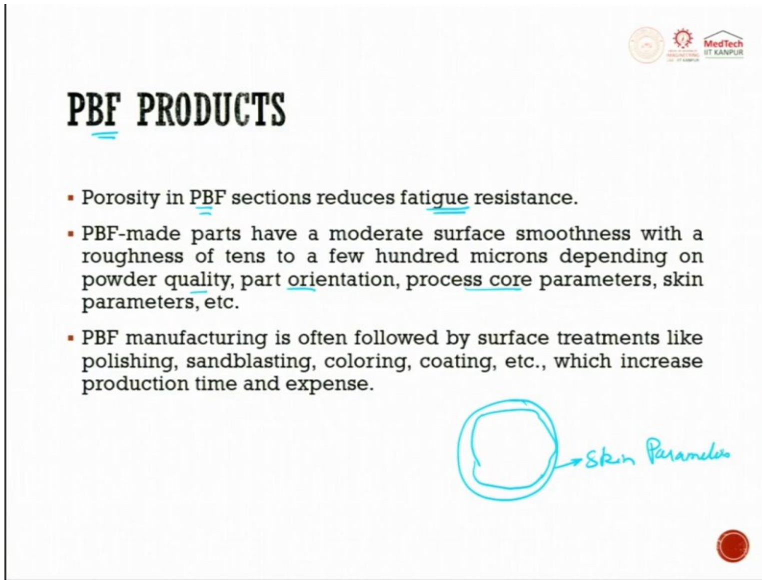

Porosity which produces in PBF reduces the fatigue life. So, the fatigue resistance is reduced. PBF made parts have your moderate surface smoothness with roughness of 10s of few 100-μ depending on the powder bed quality, part orientation, process core parameters, skin parameters, etc.

So, process core parameters are laser parameters, skin parameters are the skin or the layer whatever it is used. The PBF manufacturing is often followed by surface treatment like polishing, sandblasting, etc. which increases the output quality. So, with that we have finished going through powder bed fusion. So, here you will try to talk about the skin parameters.

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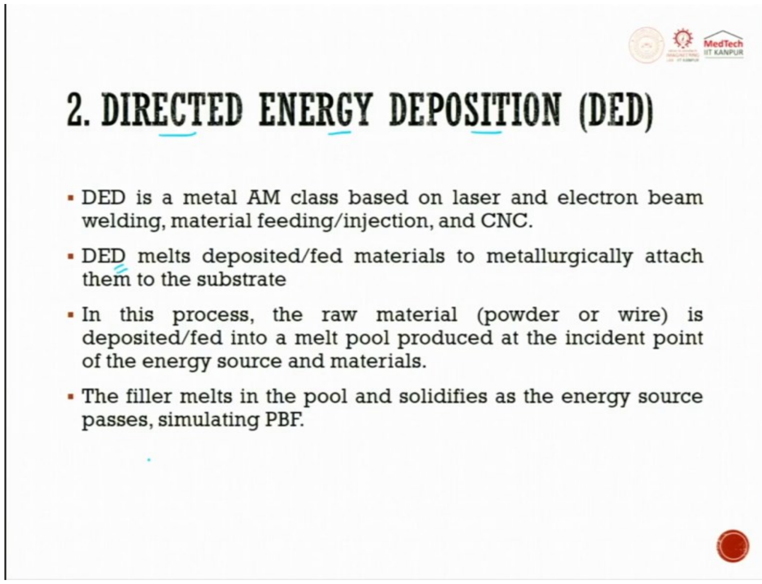

Next, let us see the process called as Directed Energy Deposition, DED. DED is a metal additive manufacturing class based on laser and electron beam welding, material feeding, injection and CNC machine. Here, the DED melts deposited/ fed material to metallurgically attach them to the substrate.

Predominantly DED can be used for repairing and refurbishing processes. In this process, the raw material is deposited/fed into a melt pool produced at the incident point of the energy source and materials. The filler melts in the pool and solidifies as the energy source passes simulating powder bed fusion.

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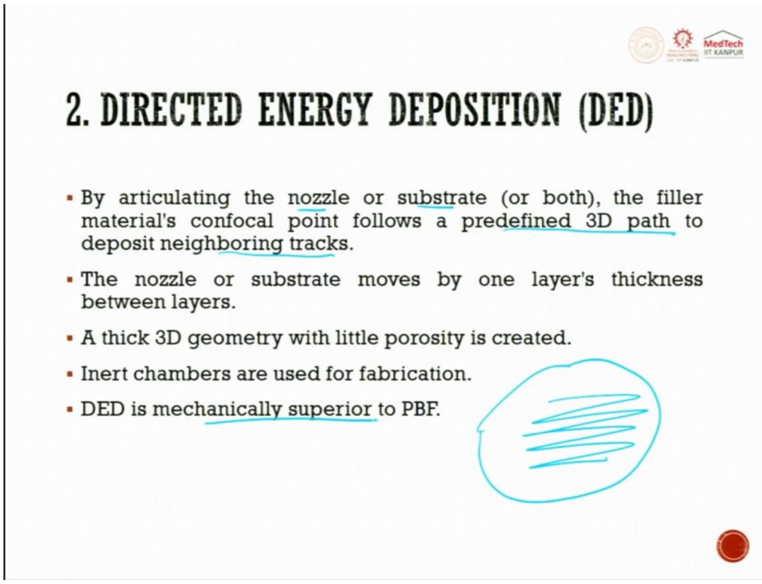

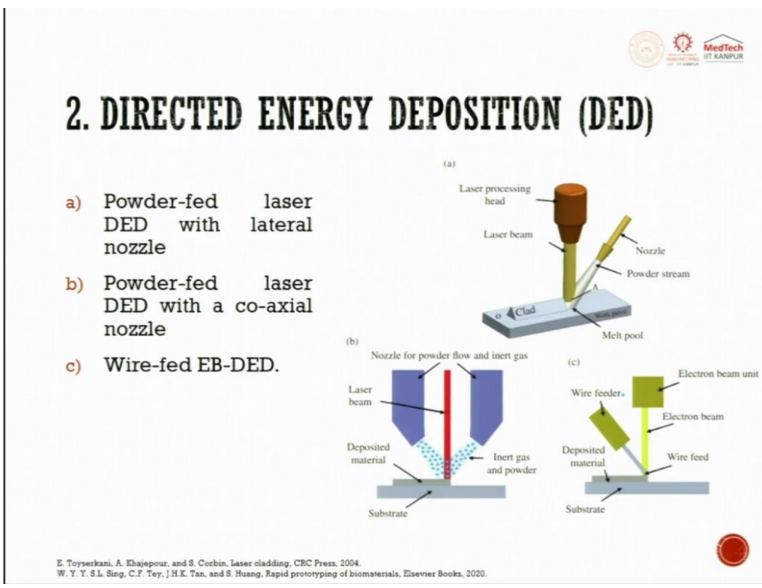

By articulating the nozzle or substance, here you will see that there will be a nozzle, and these nozzles will be articulated. So, by articulating the nozzle or substances the filler material confocal point follows a predefined 3D path to deposit neighboring track, predefined 3D path.

So, that means to say it will move in a zigzag pattern to make one layer, this zigzag pattern do it. The nozzle or the substrate moves by one-layer thickness between layer. Here, 3D geometry with little porosity is always created. Inert chambers are used for fabrication when you have reactive metal powders. DED is mechanically superior to powder bed fusion.

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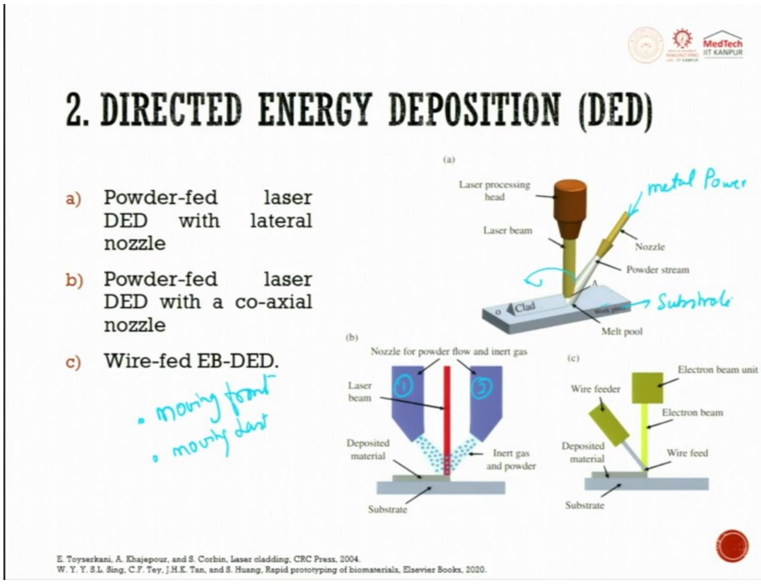

There are three techniques which are used, in generally three techniques which falls under Direct Energy Deposition, DED. One is powder fed laser DED with lateral nozzle. Next one is powder fed laser DED with coaxial nozzle. The third one is wire fed electron beam DED method.

So, this gets deposited on your substrate, this is a substrate. And when the powder deposits, the laser or the electron beam melts it and allows it to clad with the substrate. So, that process is called as powder bed laser DED with lateral nozzle. When we look at the other process where in which powder bed laser DED, a coaxial nozzle means you will have a nozzle for powder flow then you will have an inert gas.

So, these two try to dictate the flow deposition cooling and simultaneously when the laser moves it is able to deposit, so this is coaxial, one axial, second coaxial nozzle which deposits. One can have powder, we too can have two different powders, it can have one powder and it can have gas. So, depending upon your requirements it is there, if I do not want to work with powder, I would like to work with wire.

So, then you can have a wire feeder which feeds in deposition. You can have moving front or moving back, back or last. So, that means to say you can deposit powder and you can move forward or you can deposit the laser and move the nozzle here both are possible, but depending upon your requirements you can choose.

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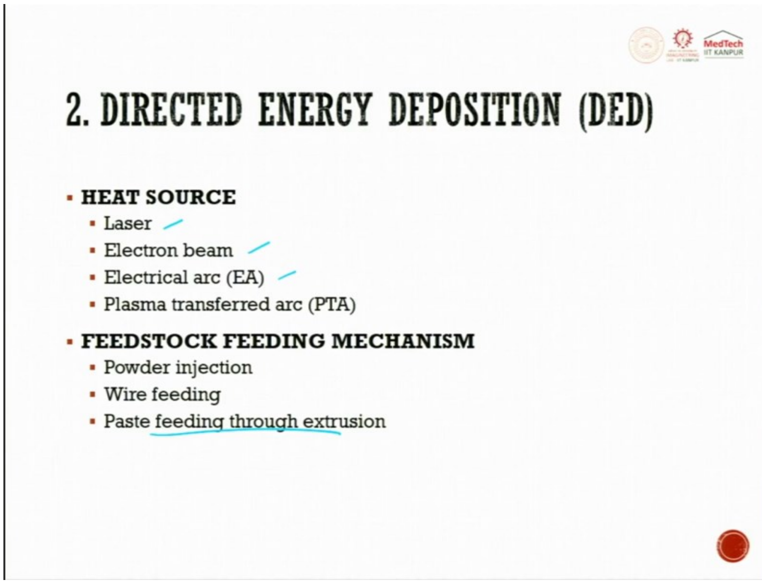

So, what are the heat sources? You can have laser, you can have electron beam, you can have electrical arc, you can have plasma transfer arc. So, you can see here all these electric arc is used in welding, plasma transfer arc is used plasma welding. So, all these four heat sources you can use to meet all the requirements.

For feedstock feeding mechanism, you can use powder injection, wire feeding and paste feeding through the extrusion. So, you mix the with a polymer and now you extrude it through a nozzle it tries to deposit and then you try to heat, remove the polymer and then you try to have a metal surface to do it.

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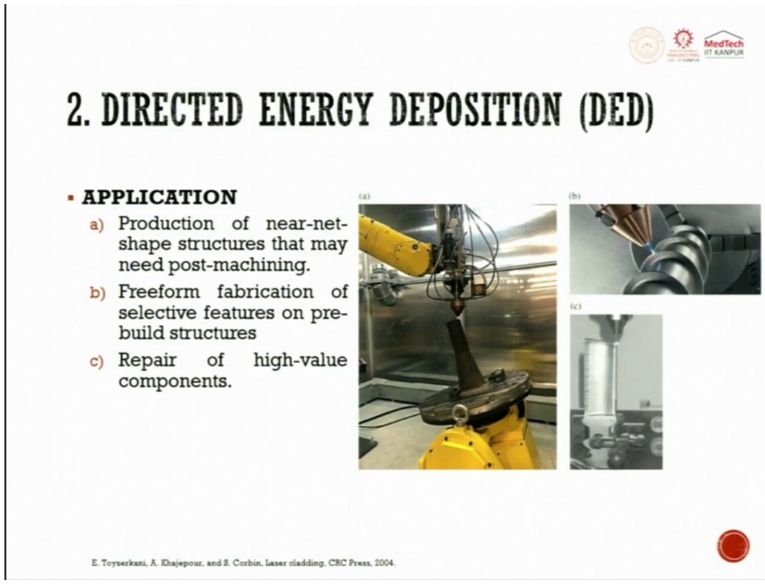

So, for some of the applications like the production of a near net shape structure that need post processing, we will try to use DED method. Next is freeform surfaces, fabrication of selective features on predefined structure, this is like feeding the material, the material hits the surface and it is almost like a cladding happens, it tries to deposit. The last one is going to be repair of high value components, for example turbine blades or an automobile component or in mold, they will use it.

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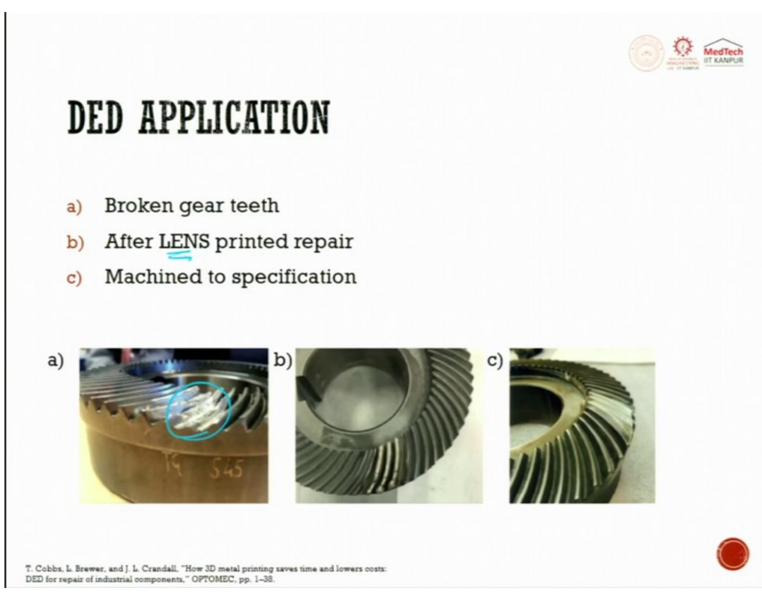

So, DED finds lot of application in broken gear teeth, which you cannot replace the entire casting. So, you will try to do some modification here and try to bring it back to the original version. So, after LENS is a process, we will see that in detail later. After lens printed repair or machined to specification, these are the places where you will see the DED finds lot of application.

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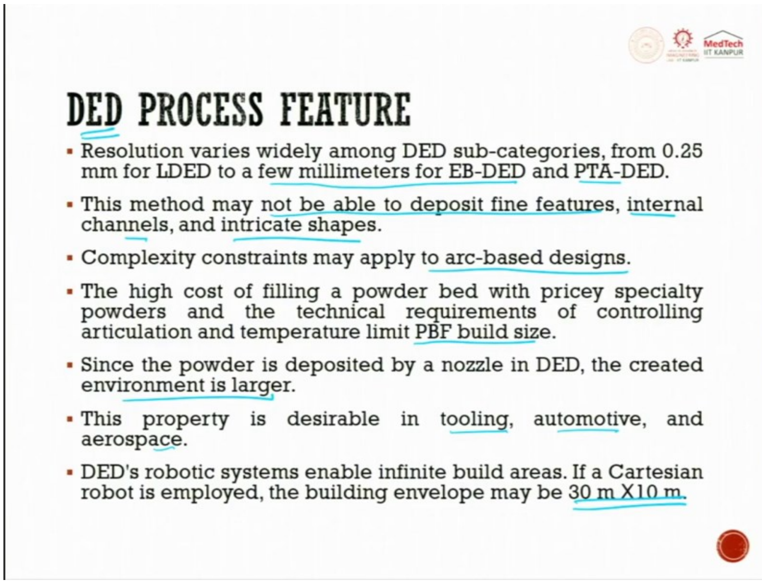

When we talk about the DED process features the resolution varies widely among the DED subcategories from 0.25 mm for laser DED to few mm for electron beam and plasma transfer technology DED. This method they will not be able to deposit fine features, internal channels and intricate shapes, it cannot do it because it is trying to deposit and it will be more like a cladding process. So, here the powder is spread and then the laser is asked to pass by.

So, the process of cladding comes into existence, moment you have a process of cladding then fine features cannot be done easily. The complexity constraints may apply to arc-based design. The high cost of filling a powder bed with pricy specialty powder and the technical requirements of controlling articulation and the temperature limits the powder bed fusion build size but whereas in DED you do not have this limitation.

Since the powder is deposited by a nozzle in DED the created environment is always larger, this property is desirable in tooling automotive and aerospace. The DED robotic system enable infinite building area if the cartesian robot is employed, the building envelope can go up to 30 m into 10 m. Look at the massive size which you can build by DED. Now, it should be clear, why do people use DED process as against that of PBF process.

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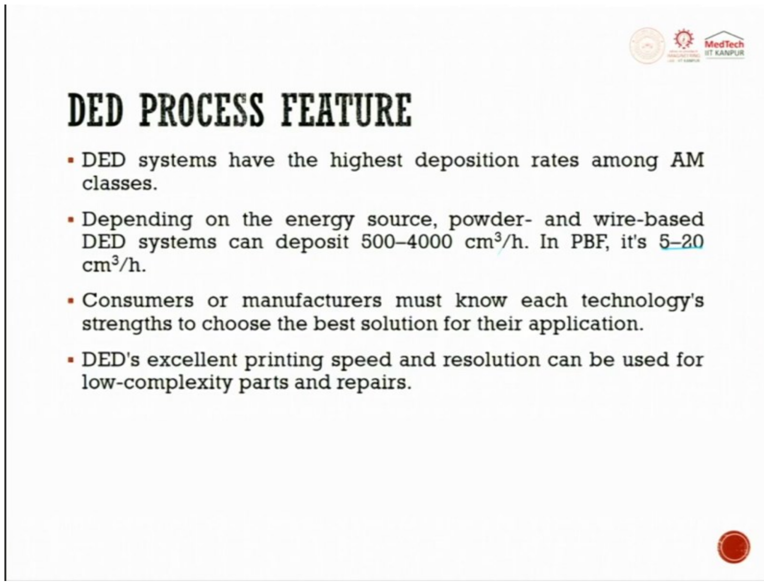

DED systems have the highest deposition rate among the AM class. Depending on the energy recovery powder and wire-based DED systems can deposit 500-4000 cm^3/h in powder bed fusion it is only 5-20 cm^3/h. The consumers or the manufacturers must know each technology's strength to choose the better solution for their application. DED excellent printing speeds and the solution can be used for low complexity parts and repair.

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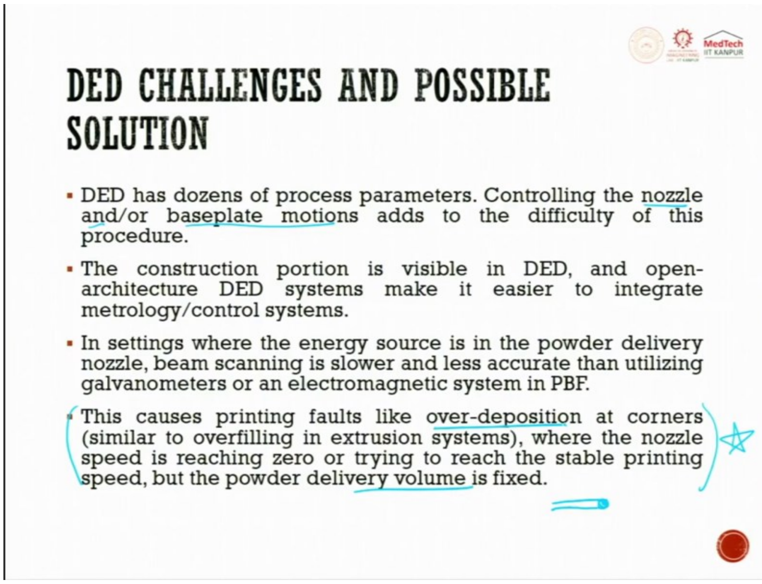

The DED has dozens of process parameters. In laser we had hundreds here we have dozens of parameters. Controlling the nozzle and or base plate motion adds to the difficulty of this procedure. Base plate motion and nozzle adds the complexity. The construction portion is visible in DED and open architecture DED systems make it easier for integration.

Today, we tried to build bridges where in Europe, people try to build the bridge three dimensionally via DED method. The setting where the energy source is in the powder delivery nozzle, beam scanning is slower and less accurate than utilizing galvanometer or electromagnetic system in PBF.

This causes printing faults like over depositions at corners, whereas the nozzle speed is reaching zero or trying to reach the stable printing speed, but the powder delivery volume is always fixed. So, this is a very important point which you should know, this causes printing fault like over depositions at corners. So, what will happen? over depositions at corners and then it will try to turn. So, here you will have over depositions whereas the nozzle speed is reaching 0 to try to reach a stable printing speed, but the delivery of powder volume is constant that is why you get over depositions.

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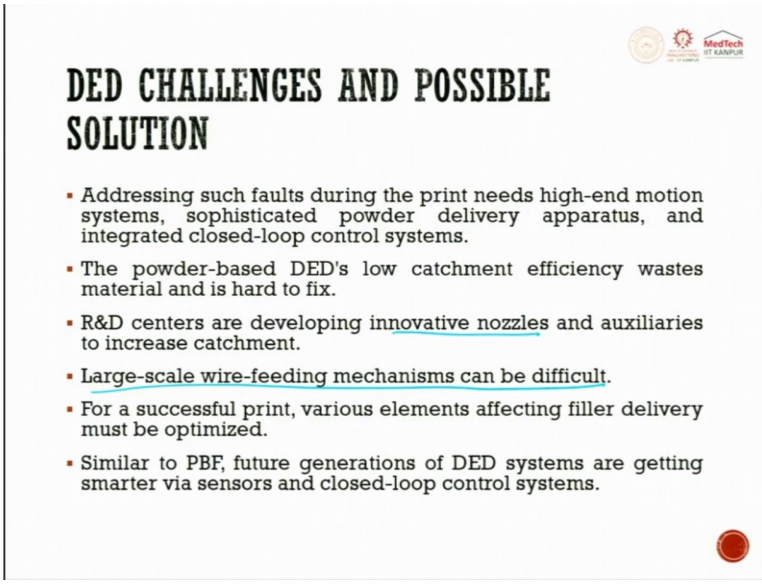

Addressing such faults during printing needs high end motion system, sophisticated powder delivery apparatus, and integrated closed loop control system. So, in the powder-based DED low catchment efficiency waste material is hard to fix. R&D centers are developing innovative nozzles and auxiliaries to increase the catchment. Large scale wire feeding mechanism can be difficult. For a successful print, various elements affecting filler delivery must be optimized.

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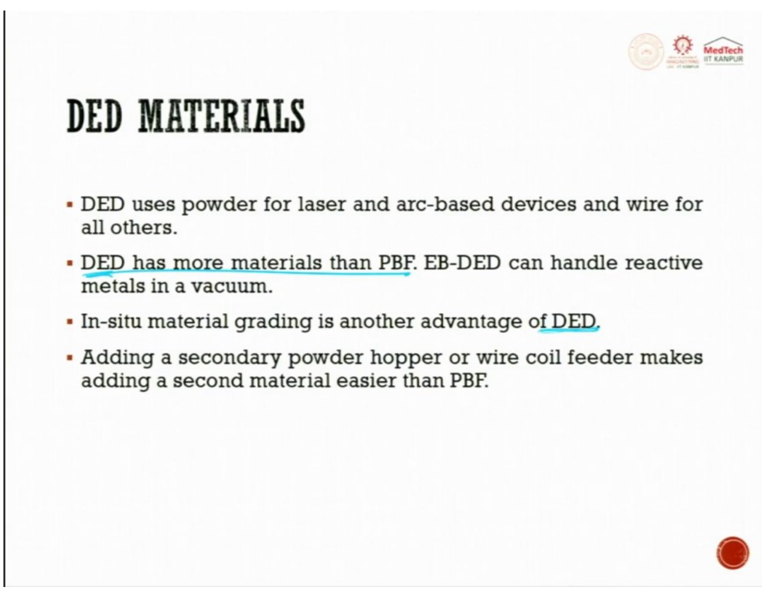

DED uses powder for laser and arc-based devices and wire for all other processes. DED has more materials than PBF. EB-DED can handle reactive metals in vacuum. In-situ material grading is another advantage of DED. Adding a secondary powder hopper or a wire coil feeder mechanism makes adding a secondary material easier than PBF.

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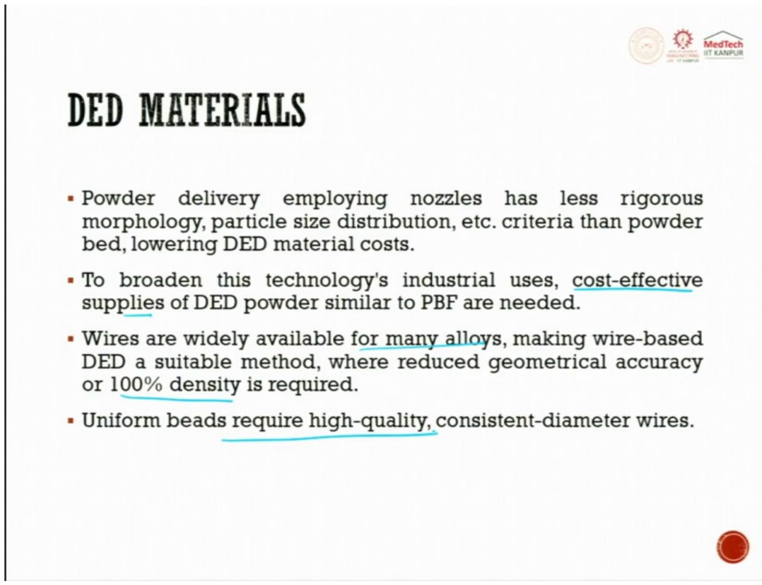

Powder delivery employing nozzle has less rigorous morphology, particle size distribution, etc. crtiteria than powder bed, lowering DED cost. To broaden this technology's industrial use, cost effective supplies of DED powders similar to PBF are needed. Wires are widely available for any alloy and it gives you 100% densification. Uniform beads require high quality consistent wire diameter in DED.

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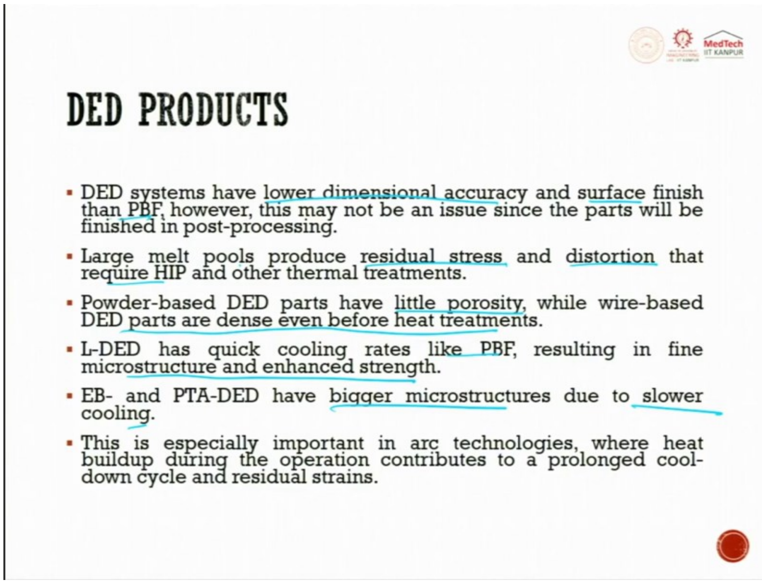

DED products are going to have lower dimensional accuracy, surface finish, lower surface finished than PBF. Large melting pools produce residual stresses and distortion require HIP. Powder based DED parts have little porosity while wire-based DED has dense even before heat treatment. The laser DED has quick cooling rates like PBF resulting in a microstructure and enhanced structure.

EB and PTA, plasma Transfer App-DED have bigger microstructure due to slower cooling. This is especially important in arc technologies, where heat buildup during the operation contributes to a prolonged cooling down cycle and residual strengths.

With that, we come to the end of part one of the basic process used in metal additive manufacturing. So, in this we saw laser powder bed fusion, electron beam powder bed fusion, we saw DED where in which single nozzle, coaxial nozzle and we also saw wire DED processes. So, thank you very much.