The Future of Manufacturing Business:
Role of Additive Manufacturing
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Lecture-25
Design for Laser Powder Bed Fusion (LPBF)

Hello everyone, on behalf of advice Wipro 3D IIT Madras NPTEL I welcome all of you to the course on the role of additive manufacturing in the future of manufacturing business. Today we will be talking about the economic significance of the design guidelines for laser powder bed fusion process. We will also be discussing about the various opportunities for value addition through laser powder bed fusion process.

I am Krishna Kashyap Singh and I am an application engineer at Wipro 3D. I have certain expertise in the process. I will be taking you to the various design requirements or the various design modifications which will be required in order to make the part amenable to the process.

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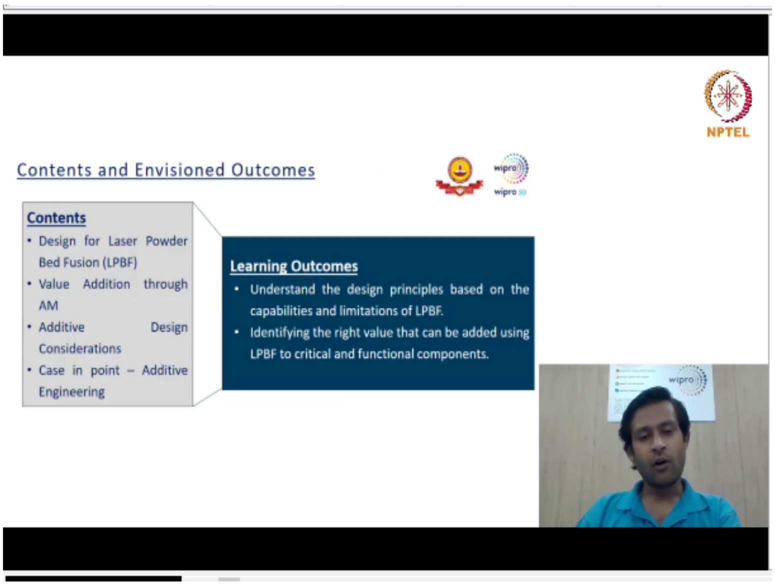

All of us are very well aware that additive manufacturing offers a wide variety of design freedom because of the nature of the process, since it is a layer by layer phenomena. It is a free form fabrication process and there is no tool required to make the components from powder. Today laser powder bed fusion process has been the most preferred choice for most of the industry users across the globe for additive manufacturing of materials all over.

So, this session will focus on laser powder bed fusion and the value addition that can be done using laser powder bed fusion process. The value addition can range from mass customization of a single component to light weighting in serious production or low batch production or making components lightweight components and high-performance components for rocket engines or to make satellite components to perform in cryogenic conditions.

But at the same time, we also need to pay attention to the limitations of the process, because the limitations of the process will create challenges in manufacturing the component as well as it will add an extra cost to the production. So, we need to develop certain design considerations which will help us in eliminating those challenges and limitations.

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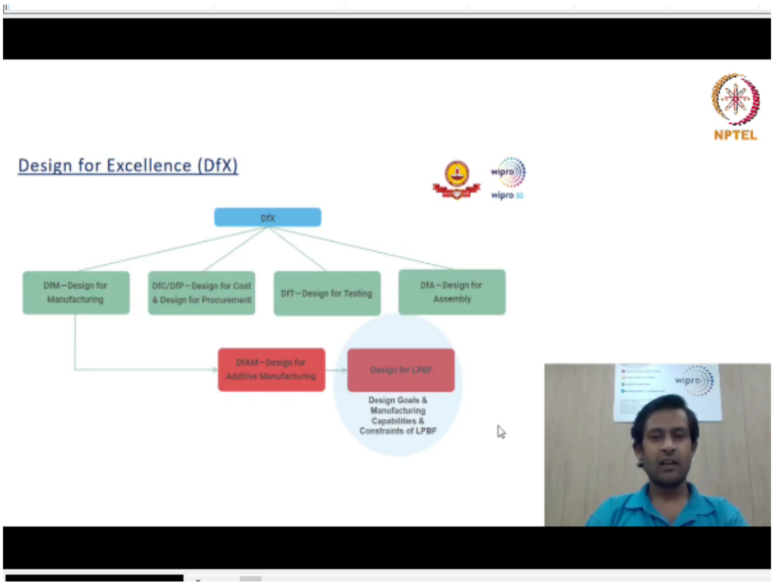

Design for excellence DfX. DfX is a very conventional strategy which has been adopted to optimize a product along with the production system to reduce development time and cost and also enhance the performance quality and profitability. Design for manufacturing has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize the cost of production.

However, with improvement of rapid prototyping or AM technologies we have been provided with opportunities to rethink design for manufacturing and take advantages of the unique capabilities ordered by additive manufacturing. Hence, in this module they will focus on the design guidelines for LPBF which are based on the limitations of the process and also the opportunities where we can add value to the end application or the component or the product by improving the design using complex geometry and hence achieving an enhanced performance.

For the rest of the session we will stick to the terminology as designed for LPBF because the process that is under study and under discussion is LPBF which is only used for metals.

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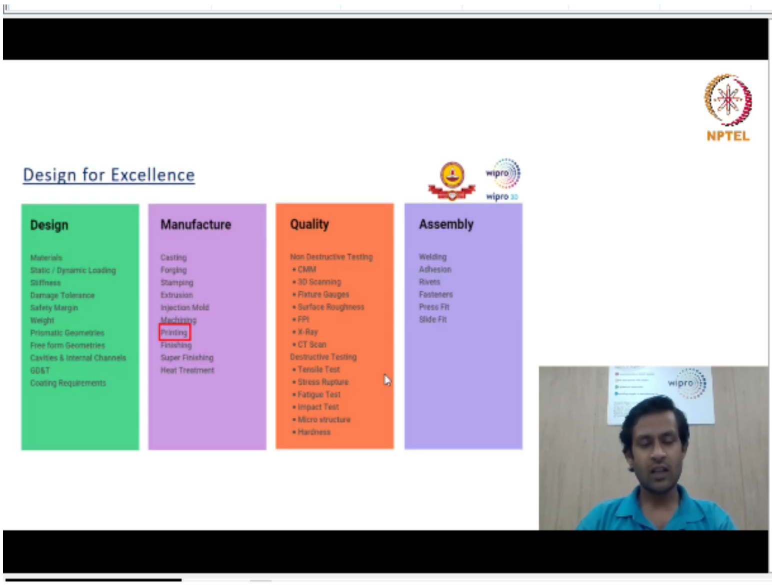

Designed for excellence encompasses four major verticals. One of them being designed and all four of them are interdependent with each other, none of them can be thought of an isolation and if they are thought in isolation they will not result in the optimized production of the component. Therefore, it is very much required that we understand the aspect of each and every of these verticals. So, for this I will get here with an example.

This is an RF antenna of a satellite communication module, basically what is happening in this RF antenna that there is RF signal which is fed here, there is RF signal which is fed here and these are mounting points which are used for mounting the component and then the signal is transmitted using this helical structure. Now in this component the helical structural profile accuracy is very important.

And also, since this component will be used in a space communication satellite, we want to know that what are the working conditions? Therefore, it will help me in deciding the material. So, depending on the working conditions the working environment, what are the static and dynamic loading that is going to work on this component? What is the stiffness required for this component?

What is the factor of safety? What is the margin structural margin that we want the component to have? All these parameters will be decided based on the end application and also at the same time these parameters have to be converted into reality using a manufacturing process. So, the manufacturing process has to be taken into consideration as well.

Now suppose your application demands a prismatic geometry from you, then you will choose a suitable manufacturing process for producing prismatic geometries, but if your application is requiring a free from geometry from you then you have to go for a process which will allow you to produce flawless free from geometries. Similar way if you have a requirement of producing cavities or internal channels.

Then you need to go through a process which will allow you to produce these features with minimum effort. Hence design and manufacturing cannot be looked at isolation. They both are interrelated to each other. Your design will govern the selection of a manufacturing process and your selection of manufacturing process will in turn govern the design of certain features.

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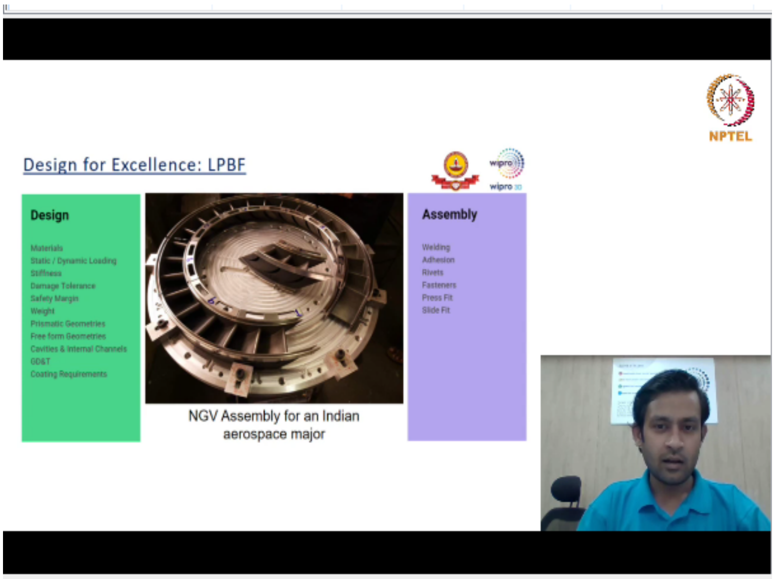

Assembly is another important factor which has to be considered in a well-planned manner during the design methodology, because as all of us know that design for manufacturing and assembly is a disciplined methodology which recognizes that 70 to 80% of a product's life cycle are actually determined in the design phase. So, the cost and time of assembly can be optimized if proper attention to assembly is being given in the design phase itself.

In case of LPBF, it plays a little bit more important role since there are certain features or certain limitations of the process which does not allow a LPBF feature or LPBF surface to be well suitable for an assembly purpose. Hence in any module we need to identify well in advance during the design phase itself that; what are going to be the assembly points?

What is exactly going to be the assembly mechanism? Whether it is going to be a bolting mechanism? It is going to be a mating mechanism or it is going to be a slight fit, press fit? Based on these assembly requirements we need to provide certain tolerances for these features and then we need to decide whether those tolerances will be met by as built condition or in 3D printed condition or if not, then a different post processing strategy has to be devised for that particular component.

In this case as you can see, this is a component of an aerospace engine from a very major aerospace Indian company and this particular component was made through AM, but there were certain features which were produced in 3D printing with stock and then later on they were machined. Why?, because there was a requirement of the component to be mating into the assembly.

In order to that all the mating features have been machined properly or not there was a fixture which was used. The fixture had similar mating tolerances as compared to the original assembly conditions. Therefore, we were able to evaluate each and every point where machining is required. We added stock there and later on we machined them together. So, these are 9 different pieces which were individually built.

Then they were pros process machined, after post processing machining they were again put on a fixture and during in assembly condition they were turned together. So, this particular strategy the series of operation that was decided in the design phases itself. Since we gave enough considerations to the assembly conditions in the design fed itself, we had to go through the minimum possible amount of rework.

Hence rework can be optimized if we are giving enough considerations to assembly in the design phase. Now I would like to I have the similar sector what you can see in the slide I have a similar sector of the component, you can see this was the component that was melt, something like this was the building orientation and you can see the surface roughness, you can see the surface finish where we have the as built surface.

Now if you want to use this surface as a mating surface that would not be possible because it is not within the geometric or profile tolerance which is required for the mating surface hence what we did we machined these surfaces; you can see the surfaces have been grinded. Now this grinding has been done for the purpose of machining. There are another set of holes which have been produced with stock.

Now they will be again hold because there is a requirement of 0.1 mm clearance which we thought would be better if we achieved through machining. Since we were already machining this particular surface. So, this is how in the design phase itself we have to take care of machining because when we are trying to do the machining and match the tolerance required as this surface, we want to have the extra material to machine out.

Therefore, machining allowance has to be given in the design phase itself. That is why you saw the manufacturing technique, the assembly both are very well required when I want to create the right cad data to produce in 3D printing.

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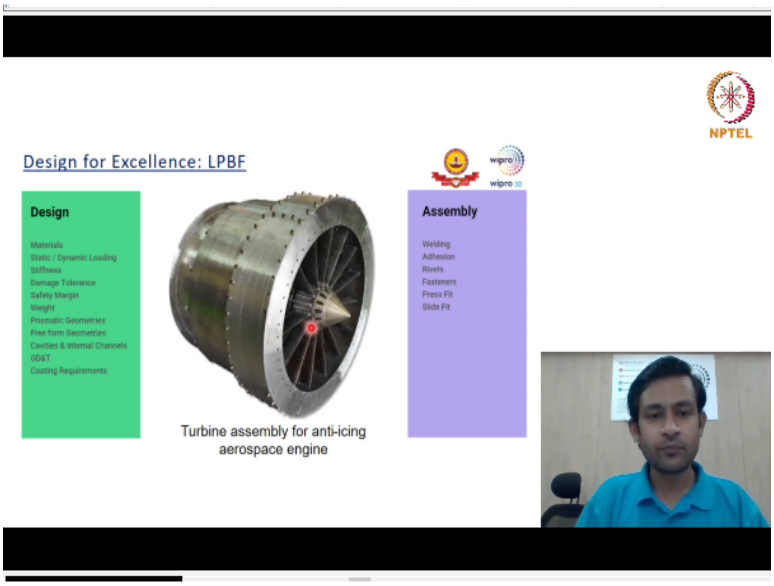

Another example of assembly consideration in the design phase. This is a turbine assembly for an anti-icing aerospace engine, another for an Indian major and in this component a few components are made through conventional manufacturing, sheet metal fabrication and few components, the critical components the aerofoil surfaces, the nozzle which has internal cooling channels.

All these things were made through additive manufacturing, but at the same time there was a strategy which was devised in order to reduce the rework when we are going to assemble the additive manufacturing components and the sheet metal components and the conventional manufactured machine components. So, a good strategy will help in reducing the number of joints.

If we reduce the number of joints that means we are reducing the number of components going into the assembly which will help in reducing the assembly time and assembly cost and at the same time if we can give some consideration to assembling 2 or 3 parts which we can join together and produce as a consolidated design then that is an icing to the cake.

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Now techniques we are going to use and to all the requirements of the manufacturing technique and the assembly technique. Now it is time to think about inspecting and validating your device design once it has been produced. Now in order to validate a design there are different types of techniques depending on the type of design you want to validate. For example, if you want to validate a design where you just have to measure the PCD.

Then you can go with a probing CMM where you can measure the center points of all the holes and you can conclude the PCD. Then now imagine you have to scan; you have to inspect something like this. This spiral surface, now it will be very difficult to scan this spiral surface using a CMM probe or using conventional methods like screw gauges, pin gauges and all these things.

Therefore, the best way is to use a 3D scanner. So, what you see in the image right now is a faro arm which is integrated with a probing unit as well as a red-light laser unit. Now what this laser in it does that? For free form surfaces it replicates the surface and creates cloud point data on the screen of the connected computer and for regular surfaces, for geometric surfaces we can take point measurements using the probe unit. So, this type of unit or in some cases.

For example, there are certain features which are not at all accessible. In this example where we are talking about this component, now why this component was made in AM? That is the question. So, I would like to answer that for you. Can you see the thin features here?. So, these are the internal features which we got after taking a cross section of this component.

Now this feature is something which I need to validate which has got a critical function because it is allowing the passage of air flow for cooling the turbine blades. So, what would be the methodology by which I can check this? We tried we thought of doing a CMM, we thought of doing x-ray inspection or CT scan in order to get the profile of this inner cavity but this profile was not well captured by a CT scan that was the input given by the quality person.

So, what was the methodology device there we built a component a trial component only to do the destructive testing. We bisected the component and then now we could easily see what is the continuity of the hollow profile. Whether it has been blocked by powder? Whether it has been sintered or not? Whether we are able to maintain the minimum gap in the profile or in the cavity channels that we want to maintain? So, this is that section you can see.

So, these are different type of techniques that needs to be employed. Because you want to check your design what you have made? A design again I would like to repeat the same thing, a design that cannot be validated is not a good design.

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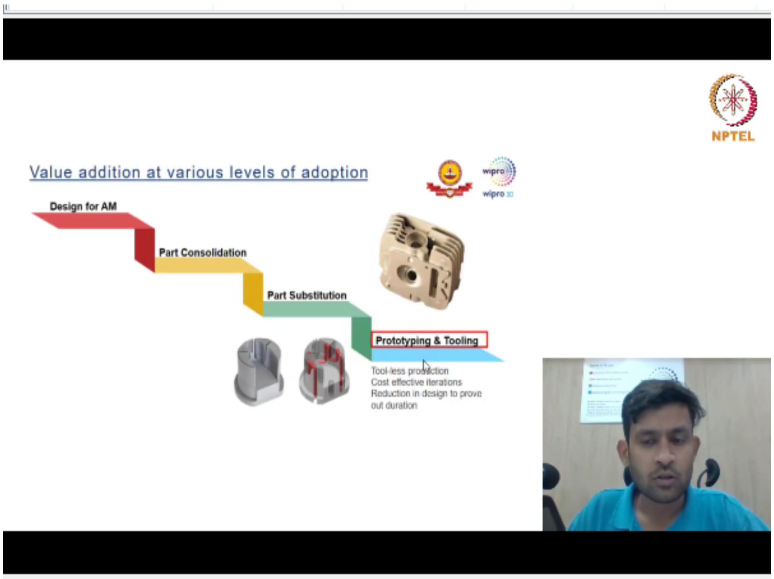

So, the extent of value addition depends on the level of adoption of AM, the four-tier model shown here demonstrates the value which is being added at each level of the tier. So, right now we will focus on the prototyping and tooling level and we will see that which kind of components are the right candidate for prototyping and tooling application and why do one need to go for additive manufacturing when it comes to prototyping and tooling?

First let us talk about the prototype. So, what you see here, this is a cylinder head, this is a cylinder head of a two-wheeler automotive, by these fins, you can feel or you can be you are very familiar of this fin, they are put for cooling of your engine. So, most of you would have seen such a component in any two-wheeler engine. Now this component is being made at a prototyping level.

So, what does it tell me about the quantity of the production? That it is a low volume component and these components if we go for AM they can be made directly from CAD either in near net shape configuration or in net shape configuration. When I say near net shape configuration that means you are adding some allowance and then machining. So, the basic point here is why does one would want to go for additive manufacturing for prototyping is; it is a free-form application.

It is free from fabrication, it is a tool less production, you do not need to invest any certain amount in tooling, hence you are not bounded by the minimum number for production. So, my design iteration basically my prototyping is enabling me to make my design iteration more cost effective and it is also at the same time giving me an advantage to reduce the total time involved in the prove out duration.

So, that was the word prototyping. Now, tooling is a way to take advantage of indirect advantage of any AM process. Your end application component will not be made through AM, but the tools that you are going to use for manufacturing your end application components, those tools will be made through AM. Now what is the advantage of making those tools through AM.

The basic advantage of making these tools through AM is that they are providing me a certain amount of design freedom to make my conformal cooling channels. So, this tool that you see here it is a tool made for injection molding process. Now in injection molding process the component that is being made is usually of plastic. In this particular plastic component, which is being made if the cycle period of the component is 10 seconds.

Then 7.5 seconds nearly 75% of the total cycle time is dictated by the cooling cycle, that means if you are able to cool your components faster you are able to do produce more number of components in the same amount of time. So, this is one economic benefit of using AM and how AM is facilitating this benefit is? If we are able to make very complex cooling channels as you can see here.

Then we have the freedom to design our cooling channels in such a way that they are conforming, they are completely conforming to the contour of the part that we are going to make using these tools and when they are conforming then they are able to control the temperature during the cooling time in a more efficient manner. Hence, they contribute in cooling down the part faster.

So, what we do instead of making conventional straight holes and plugging them later we design conformal cooling channels and then realize them through additive manufacturing and we end up in saving a lot of time in rejection of parts as well as we end up in reducing the total cycle time of one part produced which can also be expressed in another way that we are increasing our production capacity.

If in a day I was able to produce 2000 parts with the help of conformal cooling channels in a day I will be able to produce 2500 or maybe 300 parts. So, the numbers are just indicative but that was about tooling.

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The second level of adoption of AM is called as part substitution. So, what does basically part substitution means? That you are substituting the manufacturing method of the component without substituting, without making any design changes. Now this can depend whether on your end application whether you have the freedom to change the design or not? But you have the freedom to change the manufacturing process.

So, let us talk about the idle candidates, who would be the ideal candidates for part product, part substitution? So now batch production components, batch production components which have very complex manufacturing process where we are it is taking too much time or there are certain defects due to that manufacturing process which we are not able to eliminate even after controlling the process.

So, that means that manufacturing process, the existing manufacturing process is posing certain problems to me and that needs to be changed. So, that is one scenario where we can look at additive manufacturing as an option but then again, I would suggest that this is for small batch production, low volume production. Otherwise, the economics of it would not be justified.

Then the second scenario is spare parts for inventory management. Now I have the perfect candidate here for that. What you see here is an impeller, it is a impeller for a very efficient and suction pump oil and gas industry and this particular impeller it usually takes around 6 to 7 months to make such an impeller and the reason being that it has got a number of cavities.

It has got a number of cavities and in order to make this component through casting which is the conventional manufacturing process it takes around 2 to 3 months to only manufacture my tool, then a validation, check is being done, trials are run on those tools and design iterations are done for the tools also, even for the tools there is rework required. So, all these times I am losing out if I am depending on a manufacturing method which involves production of tools.

Because the complete reliability is on the tools, hence for such components additive manufacturing gives me the perfect solution by providing me a tool less fabrication. Also for example this particular component which takes around 6 months and it is from oil and gas industry. Now if this component is damaged, then their oil and gas line will be shut down for till the time there is no replacement done.

So, we actually are running short on time depending on the application. So, the application is also governing, is the application is actually demanding me that I try to choose a manufacturing method which has to be the most effective method in terms of time involved. So, what are the benefits? that we are trying to reap through part substitution.

One of the benefits is that we are trying to facilitate lower minimum buys. The other one is we are manufacturing a near net shape part which might save a lot of time for few of the designs where my 90% of the com material is being machined out. Hence, I am also able to achieve a higher flight to buy ratio when compared to any other manufacturing process in air. Also, my material can be saved if I am dealing with expensive material say Titanium.

Then I have the motivation of directly adopting to the manufacturing process of AM, even if I do not aim for any design change if I take the same design which is being made in conventional manufacturing in Titanium and if I take the same design and produce in additive manufacturing it can be cost effective because Titanium processing through conventional machining has challenges in its own.

So, see like this is one of the material workability issues. So, these are the various factors which govern the selection of a component for part substitution and at the same time they are giving all these value additions to the primary process which can be getting rid of a supply chain issue or trying to go for a distributed supply chain. Suppose if your supply chain demands from you that you have to provide 100 components in USA, 100 components in Europe and 100 components in India.

So, you would not want to manufacture all these components at a single place and then distribute it to 3 different locations to the world, because that will add a very high cost to the logistics. Sometimes the logistics cost can be higher than the actual manufacturing cost of the component. So, for such manufacturing logistic chain issues, supply chain issues additive manufacturing provides me the solution by putting up 3 different AM centres very close to the actual use of the end component.

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Now let us talk about part consolidation, once we have adopted components for AM or modules at AM only for the purpose of part substitution. Then the next year is part consolidation. In part consolidation what we are trying to do our basic objective is to create a monolith design which earlier was not possible because of various manufacturing constraints which were posed by the conventional manufacturing techniques.

But now since the advancement on AM as all of us know that AM allows a higher degree of complexity to be achieved in our design. Hence, now we can overcome those constraints and we can actually integrate 1, 2, 3 or more than 3-4 components into a single assembly and produce as a single design. Now what it will help me? It will help me in avoiding all the mechanical joints, it will help me in avoiding leakages in case the component is for fluid flow.

It will help me in reducing the total number of part counts. It will also help me since my part count is reduced it will also help me in managing my inventory in a better way or it will reduce the supply chain problems associated to the spare parts. Hence, making a consolidated design or a part consolidation is one of the factors which largely adds to the economic benefits of the organization or the enterprise.

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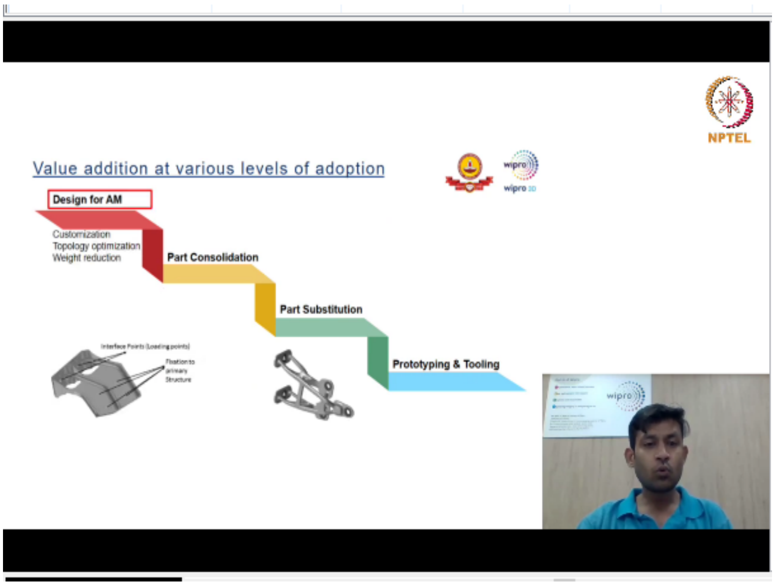

The next level; Once we are done with part consolidation the next level is to design the component for AM. Now by going through each tier step by step, now the user has a clear understanding of value being added at each and every level. They also have an understanding how the design or how the additive manufacturing process is going to affect their end application.

Whether it be in terms of surface roughness, whether it be in terms of quality of the component which can be measured either in tensile strength or if it is a component the dynamic loading then we can also talk about strength such as fatigue strength, impact strength and other factors such as the geometrical dimensional accuracy of the process what is the accuracy that we are getting in the process.

and what is the accuracy that is required in the end application? By going through all these 3 tiers, all these fundamentals are clear to us. So, now we have sufficient knowledge of our process which will help us in designing the component or I would say rather redesigning the component for additive manufacturing where what we can do? we can bring in benefits such as customization, we can topology optimize the components.

So, when I say topology optimization this is a typical component that you would see. This is a topology optimized component, when I say topology optimized component then the topology is optimized based on the load parts and the stress that the component is going through. So, the funda is simple wherever the component is experiencing more stress or more load passing through there will be more material in those reasons.

Wherever there are minimum stresses and there are no load parts at all the software or the user will remove material from those points. So, just to make it clear this is a component, this is a conventional component which was designed for conventional manufacturing and this is the similar component for similar end use, but this one is a simulation driven design using topology optimization in all tier inspired print 3D platform.

And this one has been designed in solid works by IIT Bombay and VIT students. So, what is the value that you are adding when you are talking about 4 these different steps?

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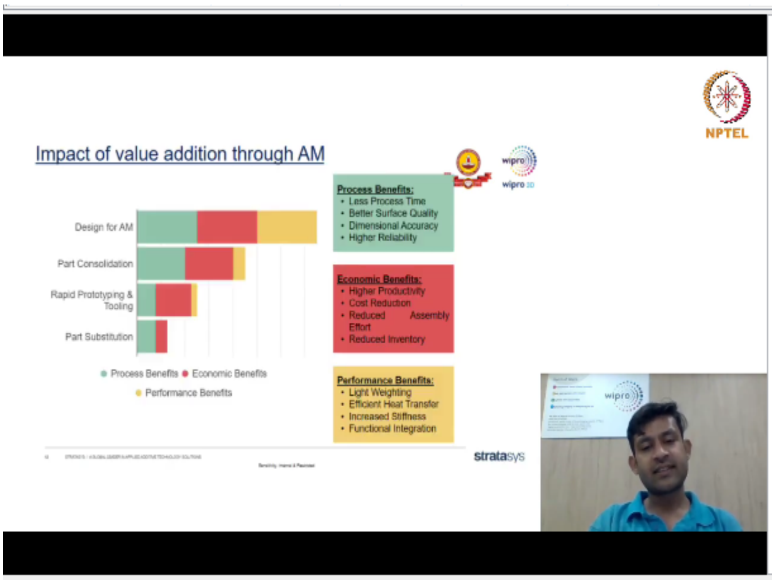

The value that is being added they have 3 different kind of impacts. These impacts can be realized at a component level, at a module level or at a process level, at an enterprise level.

So, let us try to understand what are these 3 different kinds of process or benefits, that we are getting by deploying AM in our manufacturing process. So, the first one is the direct benefit which is a process benefit.

You can reduce your process time because there is no tooling involved, you are not wasting time in removing material from a block. You are only utilizing your time in melting the material which is required to build the component. If you adopt your components for additive manufacturing then you also get an opportunity to optimize your surface quality, as all of us know that surface quality is a very big limitation or a challenge in additive manufacturing.

Especially when we are talking about powder bed fusion processes, because of the powder particles nature of the powder particles being the feedstock there is a surface bad surface quality which is inherent, usually this lies in the range of 4 RA to 20 RA-30 RA. This wide it can vary. So, it is very important that you design your component in such a way or when you are consolidating your components, your comparts together then you are keeping the printing orientation in mind.

Because the printing orientation will have a direct impact on the surface quality and hence, we can achieve benefits from the process by reducing the surface roughness by designing for AM process. Then we are talking about dimensional accuracy. So, the accuracy which is required for the end application sometimes can be achieved through AM directly if the critical dimensions where these accuracies have to be met or given enough attention during the time of orientation.

Then of course high reliability, if we are designing our components or we are having our components orientation of printing the machine, the blade, the base plate everything the whole environment is known to us and then we start designing our components, then obviously we will be getting a higher reliability in our manufacturing AM process. There will be less build failures and then there will be a minimum cost and optimized cost associated to the manufacturing process.

Now let us talk about what are the economic benefits that these processes? These process benefits are resulting into a set of economic benefits. Now we will talk about what are the economic benefits that these process benefits are getting us. The first one is productivity. The productivity increases, immensely it increases.

If you are designing for AM you can have an optimized platform where you can actually put multiple components and amortize the cost of printing per part. Also, if you are designing for your process you would want to have as least support structures as possible. When you are having the least amount of support structure you are wasting the least amount of time in printing the support structures actually you are not wasting support structures are very mandatory that will be understand in the further slides.

But my optimization of my orientation helps me in reduction of support structure will helps me in reduction of my build time. Hence my productivity increases, at the same time if I am able to adjust more number of components on my platform or if I am able to orient a component in such a way that I can reduce the build height, the total build height, then my number of players will reduce.

Hence, the cost associated to my process will reduce and not only could the cost resisted to the process. If you are making a lightweight component, if you are making a lightweight component where we have a weight reduction of around 25 to 30% and that component is suitable is going to be used in aerospace application. That means we are able to save that much amount of fuel.

So, it is having a direct economic benefit which is derived from the life cycle of the component or I would say the performance benefit which we will be discussing later. As I have already told that if we are going for steps like part consolidation, design for AM, then we are having a reduced number of assembly steps, when the assembly step reduces the manpower required for it reduces.

The time required for it reduces and hence the cost of assembly is reduced. Also, when we reduce the number of components, we have a smaller number of components in our inventory. So, maintaining the inventory, maintaining the supply chain becomes much easier which has a direct economic benefit on the business. So, upload of these economic benefits, a lot of these economic benefits are also due to the performance of the components.

The performance enhancement that we have done in the component using additive manufacturing. So, as you can see the performance benefits that we are talking about they are nearly null at the part substitution level, at part prototyping and tooling level we have enhanced performance of our tooling by incorporating conformal cooling channels which have been specifically designed for additive manufacturing.

Hence, we are able to take some advantage of the performance benefits in the prototyping tooling and in the tooling stage. Now as we move up to the part consolidation level, we are able to take slightly more performance benefits why? Because there are fewer mechanical joints so, there are less number of failures. Hence my component performance has been enhanced.

Because I have stretched the boundary of failure or I can say that I have increased the factor of safety. Then when we move on to the design for AM, this is the place where we are able to fetch maximum process benefits, maximum economic benefits and maximum performance benefits. Why? Because right from the beginning I have been designing my part for AM and it has also been designed for the end application.

All the considerations, the loading conditions, the boundary conditions and the service conditions, the part life has been taken well into consideration right before redesigning the component for AM or designing the component for AM from scratch.

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Understanding the requirements of LPBF is a critical part for the pre-designing or design for LPBF. Because it helps the designer to understand the process and accordingly, he can pay attention to maximize the process benefits by minimizing the risk associated to build failures and this at the same time we can use the process to enhance the quality benefits and the performance of the component.

Now what are these different requirements? All these requirements they emanate from a very basic principle of laser powder bed fusion that is that the powder particles are being heated to a temperature somewhere between the melting point and the evaporation point of the component and the thus generated heat needs to be dissipated. If the heat is not dissipated through proper channels which in this case we are calling as support structures then there can be quality issues.

If the quality issues exceed a certain limit then they can result into build failures. Hence what is going to help me here is adapting my design to make to provide the most proper and organic way of heat transfer to my melt pool. The second thing is how I am designing my support structures? Because at the same time my support structures need to be strong enough and solid enough to dissipate all the heat from the melt pool where the layer is being formed?

And at the same time, I do not want to expend or put extra effort in machining out the support structures which will also add time to the process as well as an extra cost to the process. So, what we do we optimize the support structures and when we are optimizing the support structures there are other things which needs to be taken care of what is a machine I am using? what is the architecture of the machine?

What is the built base plate that I am using? What is the thickness of the build base plate? Is there any internal cavity or not? If there is how would I be removing it? If I am using a honeycomb type of support structure, then how I am ensuring that there is no powder particles stuck in between those honeycomb structures and then in order to meet the certain quality what will be the next post-producing efforts.

So, these are the requirements of LPBF which has to be taken care in the beginning before starting the design of your component, by design I mean design for LPBF.

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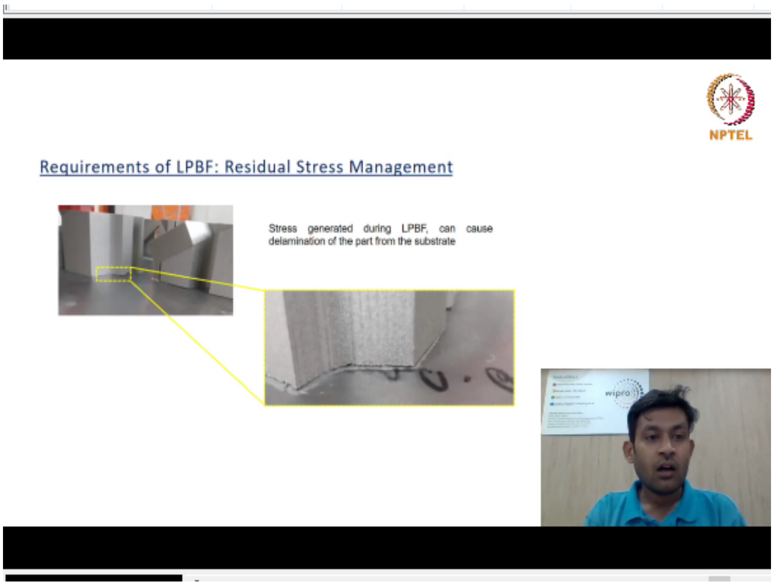

Moving forward, so what you see here? This is a typical example of a support failure due to excessive residual stresses. Now the component that we were making here it is a component for an aero engine module and the component was made in Inconel 718. So, Inconel 718 is a material which is generally difficult to deal with in LPBF if you compare to maraging steel or SS316L because of its microstructure.

In this case what happened that my support structures what you see here? What you see here which are being delaminated from the base plate. This is a support structure and it has been delaminated why? Because the residual stresses as there were layers upon layers building up the residual stress also kept on building and when the residual stress reached a certain limit which was at part than the yield strength of the material then the delamination occurred.

Hence, if a proper support structure where the heat transfer had been optimized which would have prevented the residual stresses to be built upon layer by layer, then we could have avoided this particular delamination.

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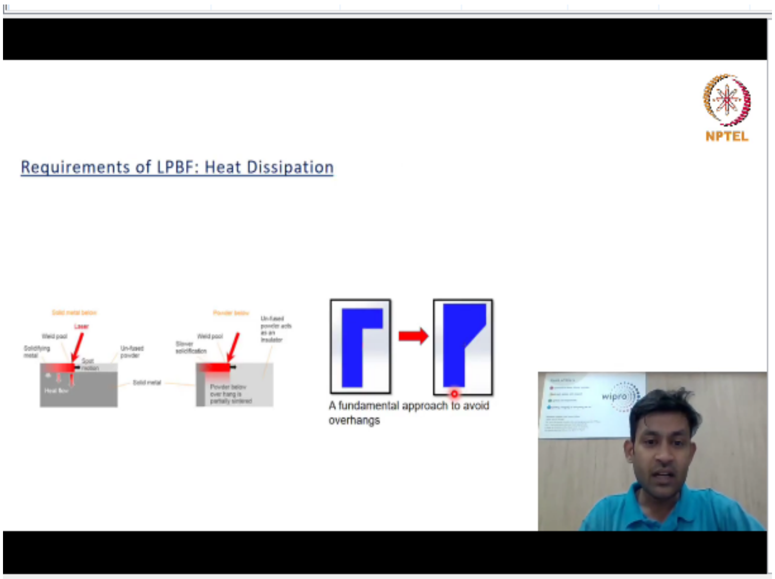

Now this is one case of delamination, now we will talk about the basic reason why it is happening? As you can see on the left-hand bottom in this case the red one is the melt pool, when the laser interacts with the powder it creates a melt pool and below the melt pool there is a solid part which has already been melt or it can be the base plate. So, when I am exposing a melt pool over a solid part it has a solid medium.

Because my bulk material you take Aluminium, Inconel anyone they are good conductors of heat. So, they will dissipate the heat immediately which is being formed in the melt pool and thus we can achieve the required rate of solidification which is favourable for the process. But what happens when I am exposing or my laser is interacting with the powder over a layer of powder?

What I mean is when the melt pool is being formed then the layer beneath this is not a solid metal instead it is powder, as you can see in this image it will not get any medium for the heat to dissipate why? Because loose powder is a bad conductor of heat, you can almost say that is insulated to heat. So, kindly in order to understand the fund of heat dissipation kindly keep these 2 points in mind that bulk metal is a good conductor of heat whereas powder is insulated to heat.

Half of the problems related to part orientation and support generation can be taken care by applying this basic funda. So, what do I do? Now as you can see in this image that I have a inverted L. Now in this image there is an overhang of around 10 to 12 mm. If I build this overhang over powder then my build will crash. This I know for sure we have tried this.

Now what happens or how to prevent the build from crashing? So, what are the different methods? One is you either have pull block support and connect it to the base plate till bottom. The second one is converting this flat 12 mm 0-degree overhang to a 45-degree angle. By converting it to a 45-degree angle what will happen? That my reliability of the process will increase and I am spending less amount of material.

I have not connected this overhand to the base plate. If I connect this overhand to the base plate the total volume of the support structures involved will be much higher than the extra material that has been added as a chamfer over here. So, the recommendation is that any overhang you get depending from one material to another say it is LSI 10 mg.

You can fix a self-supporting or critical angle, you can call it self-supporting angle or critical angle as 30 degree, if you are dealing with Titanium you should put it at somewhere at 55 60 degree. So, this varies from 30 to 60 degree the set supporting angle of any material used in LPBF can vary, based on this you need to either redesign or add support structures. Now what happens if you do not do so? That is what we are going to see in the next slide.

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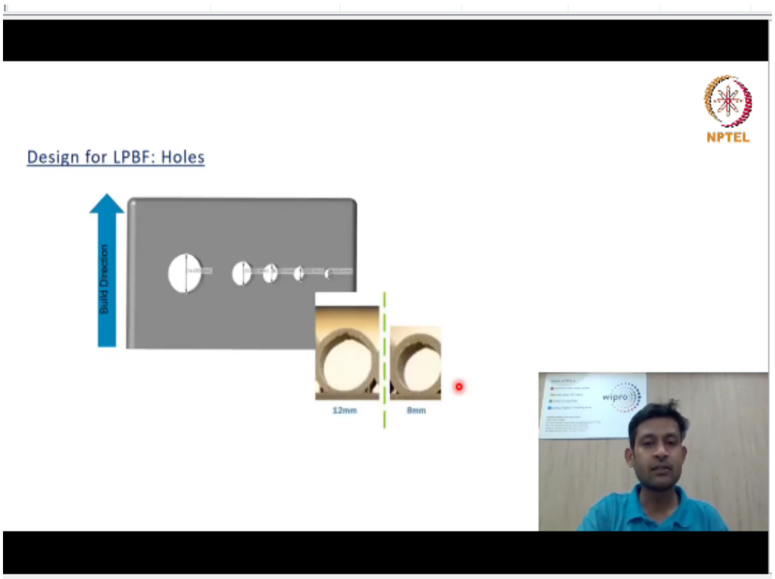

Here I have a different hole ranging from 4 mm diameter to 16 mm diameter. Now in this particular case you can see I also have a part where we try to produce a 12 mm hole without any support structure and an 8 mm hole without any support structure. So, based on a practical experience I would like to tell that holes with 4 mm diameter, 6 mm diameter are can be produced through AM without using support structures or without giving them support structures or without doing any post processing activity, a general accuracy of 0.5 mm can be achieved in them.

But in case you require a better accuracy it is good to provide stock material in those holes and later machine them out. So, you can see what is happening here, the surfaces when the holes become bigger the surfaces, they get warned out why? Because when this particular layer is being formed the heat is being sustained in that particular lesion for a longer time because that particular layers are being formed over powder.

And as I told before powder is insulated to heat. So, in this particular case what is happening that my part is in molten form for a very long time which causes all the powder particles around it beneath it to come and stick to the surface, that makes the surface very rough and practically these surfaces cannot be used for end application or mating applications at least.

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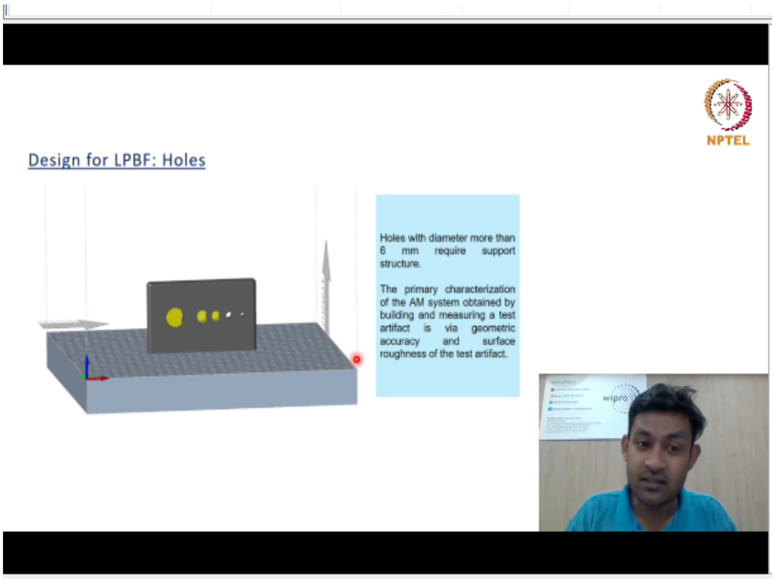

What is the solution to this? Any hole greater than 4mm 5mm 6mm we go for support structures and later machine it out. Now in case your hole is a functional hole then what would you like to do? If your hole is a functional hole or there is a certain mating component designed for that hole then you need to have a particular dimensional positional tolerance. Now in order to maintain that tolerance in 99 of the cases these tolerances cannot be met through AM hence we go for post-process machining.

And if based on your end application you have already deployed a post processing technique in your manufacturing cycle then it is always advisable to avoid support structure,

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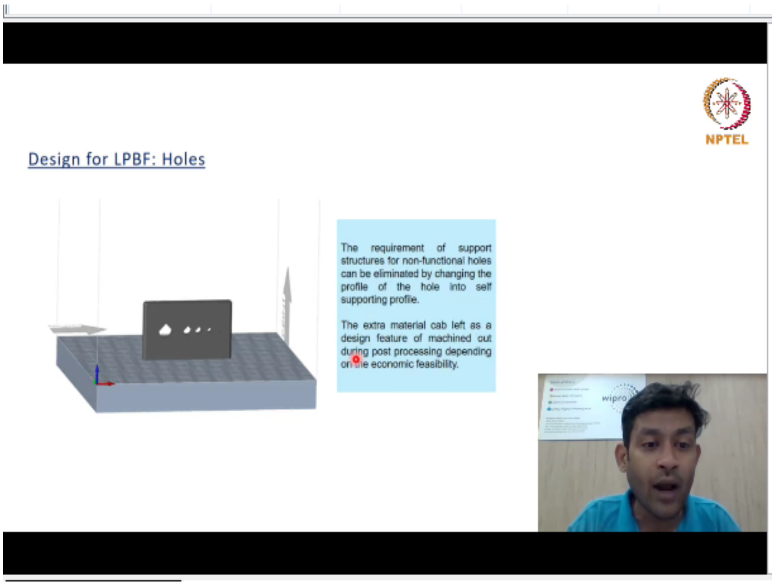

and provide some extra amount of material which will help me in realizing the component without any difficulty and which can be easily machined out during the machining of that particular feature as you can see in this image. What we have done here that we have converted a hole into a teardrop shell, which relieves me of the support generation requirement. Because now the features are self-supporting and there is not going to be the impact that we have seen in the earlier cases.

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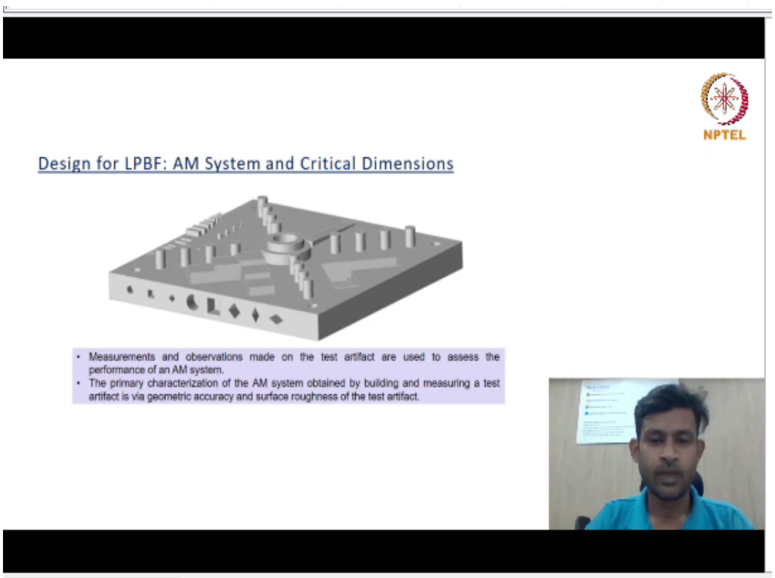

As discussed in the previous slides that in order to design the parameters or in order to define a certain set of guidelines for design for additive manufacturing one of the most important requirement that we need to understand is the machine architecture, the type of laser that is being used and what are the critical dimensions like what is the capabilities of that particular AM system?

So, in order to understand the typical capabilities of an AM system there are certain evaluations that needs to be performed. What you see here is a typical example of an NIST artifact which was developed by NIST. The purpose of this artifact is to tell the user that what is the minimum critical dimension for each of the feature? For example, what is the minimum cylinder, thickness, diameter that we can produce?

What is the minimum hole, which diameter which we can produce in the horizontal direction? and what is the similar minimum dimension which can be realized in the vertical direction? So, with respect to different kind of shapes and geometries such as circular, rectangular and with respect to different type of overhangs such as 0.1 mm overhang, 0.3 mm overhang, 0.5 mm overhang.

Also with respect to different kinds of wall thicknesses ranging from the minimum possible wall thickness that can be built to the highest aspect ratio that can be built all these things are something that defines the characterization of a machine, the characteristics of the machine.

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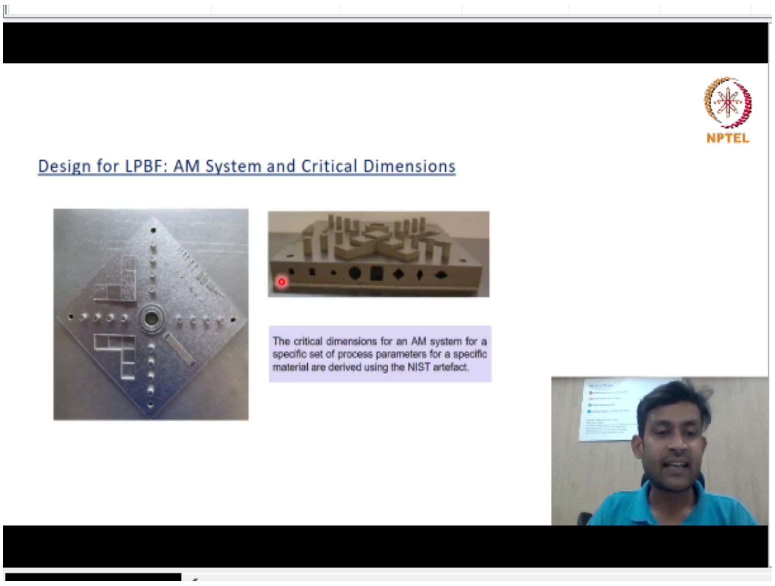

In this particular slide you can see we have printed an NIST artifact for SS316L which gave us the basic fundas like 0.6 mm is the minimum hole diameter that we can produce when the hole is aligned in the horizontal direction and also you can see in the artifact that a square of 5 mm into 5 mm cross section has been produced where the 5 mm top edge is a complete flat overhang and because of the support not being there and because of it being a flat overhang instead of a flat edge we have received a curved edge, because a lot of material has been lost.

So, these considerations we need to define and then we have to adopt this in our design for additive manufacturing or design for LPBF. So, what we covered in the session today was the various design requirements which will add value using the benefits that are being offered by additive manufacturing.

We also tried to explore how to compensate for the limitations of the process or the nature of the process by using certain additive design considerations or additive design guidelines. In the next session we will try to learn about all these fundas using few industrial case studies. Thank you.