The Future of Manufacturing Business:
Role of Additive Manufacturing

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Lecture-22
Process Chain for AM of Plastics and Metals

Welcome once again to this NPTEL course on the future of manufacturing business on the role of additive manufacturing. In the session 1 we got to know what the salient aspects of various additive manufacturing technologies and the application potentials and more importantly, we also got to know the categorization of all these technologies as per the ASTM and ISO standards.

In this session, we will spend more time on understanding the entire process chain of additive manufacturing technologies, just for the sake of illustration I picked up two technologies, one is connected with plastics, other one is connected with metallic materials.

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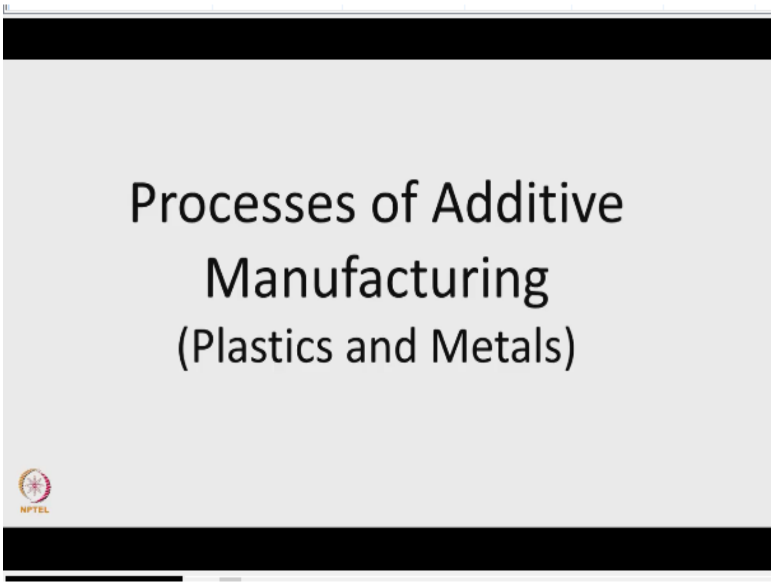

The first portion of the presentation will be on the process of laser powder bed fusion.

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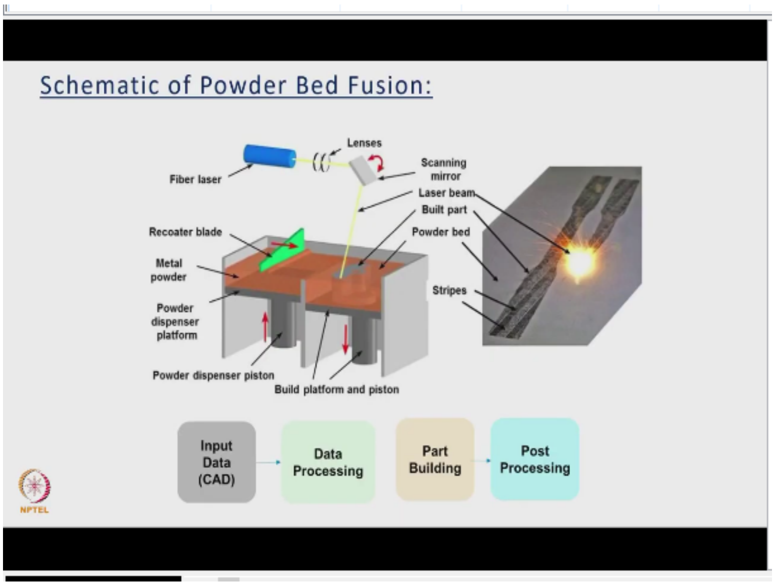

As I briefly mentioned in the session 1, this is a technology, which has created a niche for itself in the industrial context, because of the maturity of the process and also because of the industrialization opportunities. Fundamentally, if we look at the process you can see four distinct sets of operations which are associated with translation of a CAD data into a metallic part.

In the initial phase, you are dealing with the input data, then you do the data processing in such a way that it becomes amenable for the building, then the actual build process happens on the system of powder bed fusion. Subsequent to the part building we need to spend in considerable effort on post processing. So, that we can improve the strength surface as well as the dimensional aspects of the part.

At the core of this particular process we have got a laser beam, which is interacting with the powder particles that are spread on a built platform. You got a dispensing platform, you can call it as a source of the powder and a recoater blade, which is responsible for spreading thin layers of metallic powders on the built platform. After ensuring of the spreading of the powder on the build platform, you got laser beam which scans the patterns on the surface of the powder.

As the beam is interacting with the powder particles, they melt instantaneously, and solidify, and the entire part is realized through realization of individual layers, the thicknesses, ranging from 40 micron to about 150 microns.

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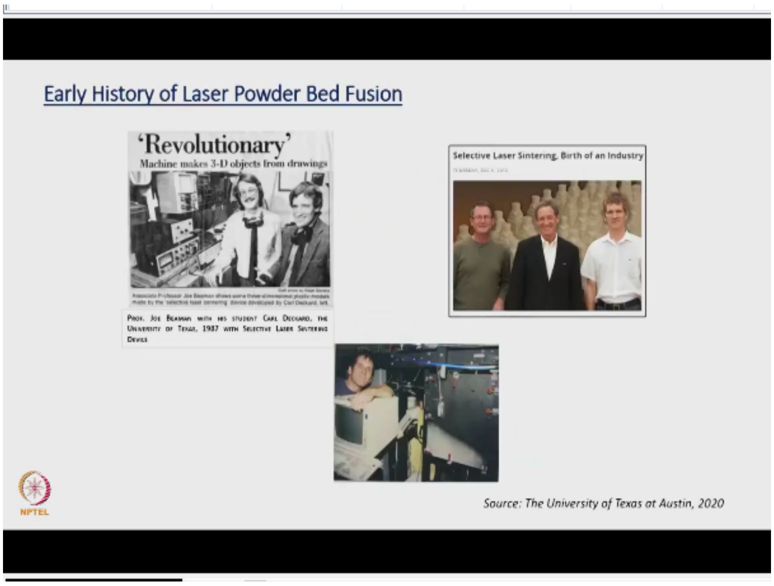

Interestingly, the origin of this particular technology could be attributed to the Austin technology incubator with the funding of the national science foundation at the University of Texas at Austin. The process of selective laser sintering was pursued by an undergraduate student Carl Deckard under the guidance of Professor Joe Beaman, and they were so very fascinated with this technology that is capable of translating the digital definitions into plastic parts.

Initially it was only confined to the plastic parts. He went on to pursue as part of his master's then PhD and this led to emergence of a dedicated business vertical within the realm of additive manufacturing.

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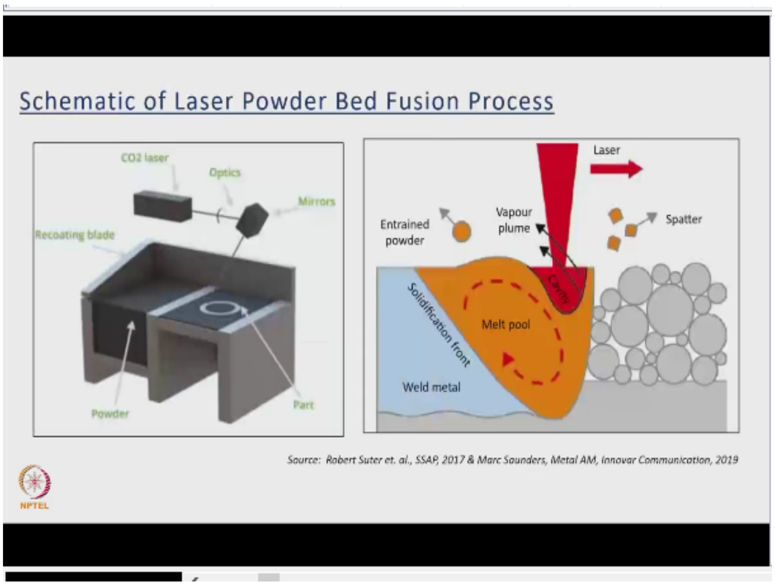

The core process, as you can see here is dependent on the interaction of the laser beam with the particles. So, you can see the powder, which is a non molten ahead of the laser beam. A melt pool and behind the melt pole you can see the previously melted layer, which is getting solidified. The entire process happens in a build chamber, which is typically filled with nitrogen or an inert gas, which are responsible for taking away the spatter.

The melt pool dynamics are extremely important because the melt pool dynamics directly impacts the integrity of the part that is structural integrity is the part, and also the strength of the fused particles. So, I would like to explain this by playing a video corresponding to the powder bed fusion of a turbine disk. You can see here, the forte route of the turbine disk, which is responsible for fastening of the blade to the disk.

You can see the distinct moment of the recoater, supplying a fresh coat of material, a thin layer of material on the built platform. Subsequent to the supplying of the thin layer we have got a laser beam in the action scanning as per a pre-determined path. So, the periphery of the layer is drawn, and also the interiors of the part are hatched in a specific way. The heat transfer rates which are associated with the powder bed fusion are typically in the range of 10 to the power of 5 to 10 to the power of 6 Kelvin per second. So, the process inherently leads to tremendous amount of thermal gradients.

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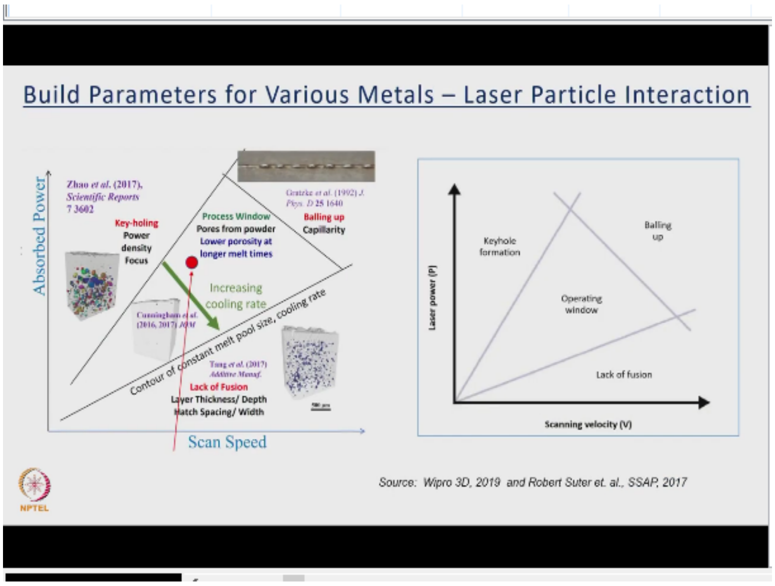

When you have thermal gradients, it is only but natural that there will be other repercussions connected with residual stresses and microstructure related ramifications. If you pick up two important parameters, there are a plethora of parameters which need to be controlled. For example, the velocity with which the beam scans on the surface, also known as scanning velocity is one of the variables, and the power.

The laser power is one of the variables, and the distance between two tracks also known as hatch spacing is a variable, and the layer thickness, corresponding to which the metallic particle layers are spread on the build platform is also one of the very important process variables. It goes without saying that, you need to have close control on this parameter to ensure that the hatching happens at right spacing.

You are able to ensure fusion of the particles, you are able to ensure the joining of one layer to the previously solidified layer. But while doing all these things you need to make sure that you are not infusing such an amount of energy that it can cause distress in form of key holes or excessive porosity. So, if you see this particular diagram called process window, wherein on x axis you have got scanning velocity, on the y axis you have got laser powder.

If you operate in this zone, which is synonymous with a very low laser powder and high scan velocity. Then the particles will not get the necessary energy for fusion. So, what you see is the lack of fusion, fundamentally you have got laser metallic particles that are not molten. So, which manifests in form of a discernible defect. Imagine the extremely contrast in scenario. You are putting too much of energy, and the laser beam is moving at very low levels at low speed.

Then immediate phenomena which is associated with this kind of a scenario is keyhole formation and if you put in too much of energy, but if the scanning velocity is also very high maybe it is a possibility that the material is getting molten but it does not get enough time to get connected with each other. So, they remind us distinctly separated solidified pools and you call this as a phenomenon of Balling.

So, with all these considerations, it is important to recognize the fact that for a given system for a given material, it is very important to identify the space within which the energy infusion could be optimal level, that is called the operating window. Depending upon the material that you are processing it is absorptivity, it is particle size distribution, it is morphology, and the type of the laser that we are using. You may have to spend significant amount of time in developing the know how connected with this operating window.

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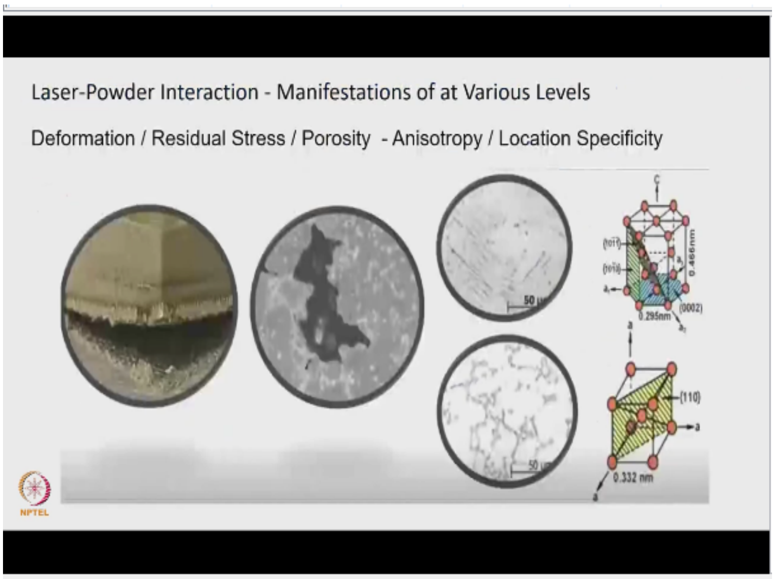

What happens in case we make use of sub optimal process parameters. The defects can manifest at the part level, at the macro level or at the micro level in form of the micro structural related defects or at the atomic level. So, some of the very well-known distress conditions associated with the powder bed fusion are warping or deformation, residual stress porosity and of course, anisotropy and location specificity are some of the parameters which are associated with most of the additive manufacturing processes powder bed fusion is no exception to that. But you can tackle to some extent these phenomena in the post processing scenario.

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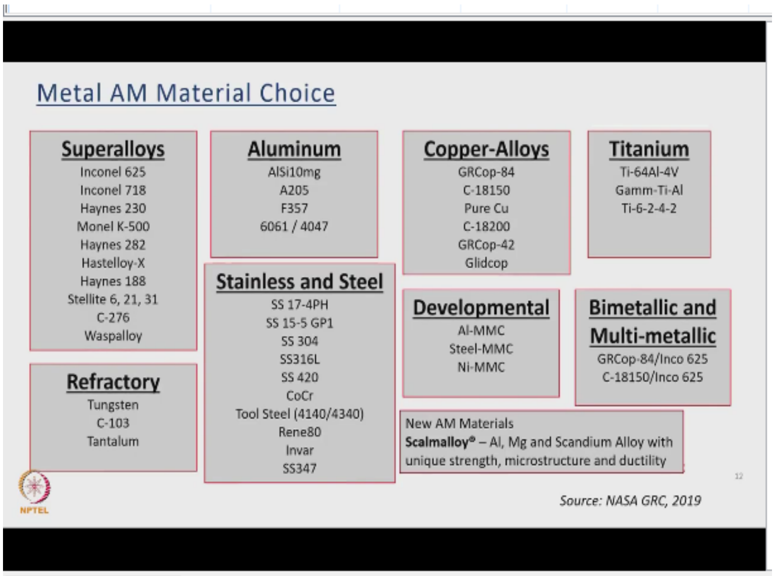

So, what are the material options that are associated with laser powder bed fusion? To start with you have got many materials which are significantly in great use in aerospace sector, like superalloys, including Inconel 625, 718, Haynes alloy, Hastelloy, Waspalloy. These are all the materials that are synonymous with applications in modules like high pressure, low pressure turbines, combustors, nozzle guide vanes, pulse detonation engines.

So, all these materials which are known for their excellent creep characteristics, high temperature performance are amenable to powder bed fusion. On the other side you can see the ready availability of titanium alloy like, Ti-6-2-4-2 and Ti-64, which are not only famous for the aerospace applications because of high specific strength and low cycle performance. They are also equally famous in case of the medical applications because of its biomedical compatibility.

You have got significant array of choices corresponding to steels starting from 17-4, 15-5, 31-6L tool steels. and the materials which are more famously used in case of space structures like aluminium alloys. The whole gamete of the waveguides, the communication modules are made out of materials like ALSI10mg using the powder bed fusion. In the recent times, because of the maturity of the processes and the no how or no why.

Even the refractory materials have been handled through powder bed fusion, including tungsten, tantalum and because of the proclivity of the automotive industry in the recent times to shift towards e vehicles, the processing of copper and copper alloys has become a matter of immense activity in the world of additive manufacturing. Because you can make the heat exchangers and you can make the parts with the conformal cooling channels, using copper.

In given volume the heat exchange of the highest orders are possible through processing of copper alloys, through powder bed fusion. It is been also seen that there are efforts to make processing of bimetallic structures, multi-metallic structures possibility, using the process of powder bed fusion.

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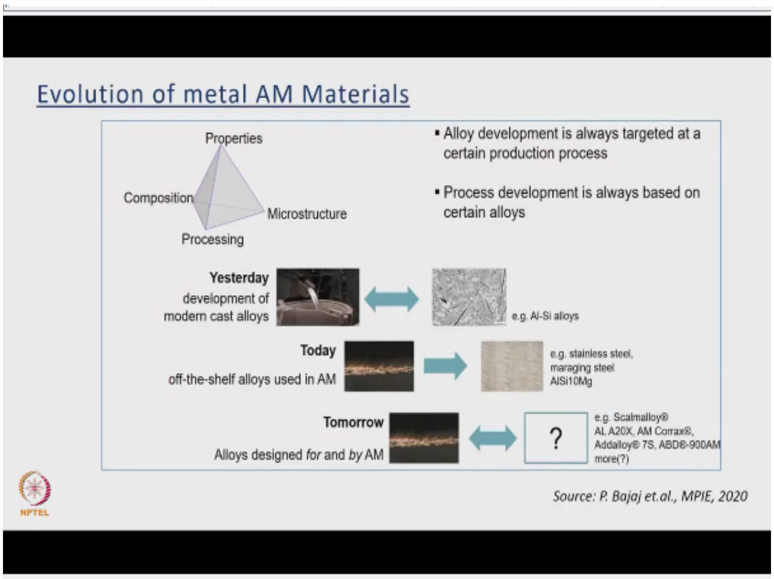

In the initial phases the existing materials, materials which are very friendly to casting or welding were made compatible, or were operated using powder bed fusion. Today, we are looking at developing or adapting some of these are non friendly materials to welding and casting to additive manufacturing. But in course of time, we are also seeing the emergence of new materials.

Because of the fact that we are able to design the parts for additive manufacturing, a phenomenon known as DfAM and when you design the parts for additive manufacturing it goes without saying that you can also design certain alloys for additive manufacturing. So, this is one activity which is attracting the attention of research groups, globally. But for doing these kinds of tasks, we need to clearly understand the interrelation among process, chemical composition, microstructure, and the properties.

So, the alloy development to start with is targeted towards high performance applications, and I am sure this kind of alloy development will slowly infiltrated different sectors, including non strategic sectors.

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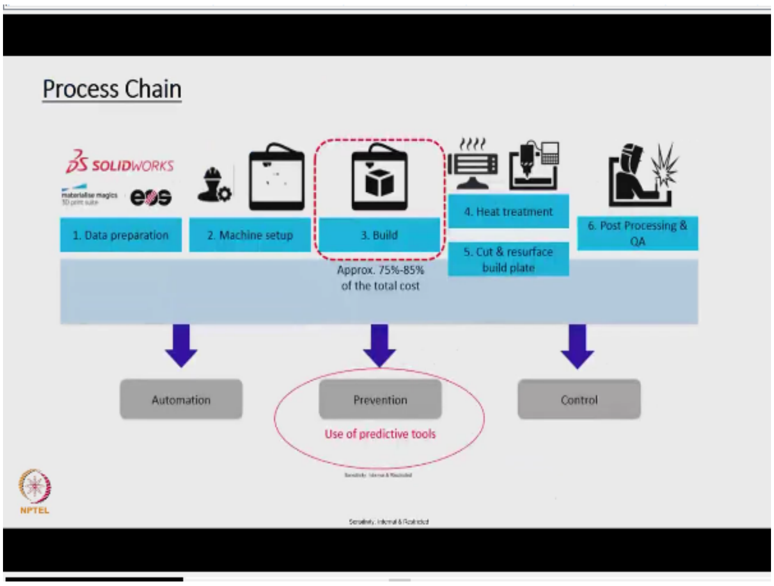

If you look at the process of powder bed fusion as I briefly mentioned, initially, you need to focus on the data preparation. Then spend effort on the machine setup, then build the part in the post processing phase significant amount of effort could be on the heat treatment and surface engineering, and eventually the part is taken to testing and certification phase. So, that the end user gets the necessary confidence in substituting conventionally manufactured part, or re-engineered part, using additive manufacturing.

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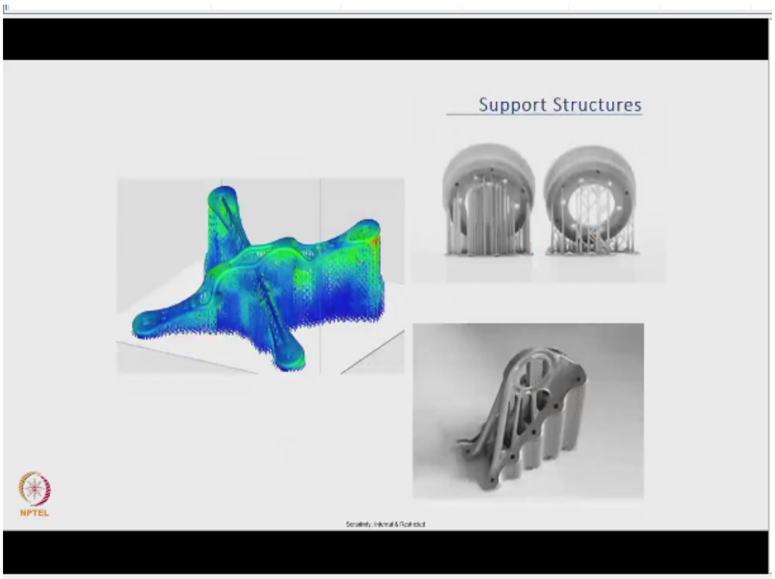

One important phenomenon in case of powder bed fusion is about designing the support structures, like in other processes, such as stereolithography. These support structures work like anchors. They provide the references for deposition of the new layers. In case of laser powder bed fusion, they have got one more important function of taking care of the thermal gradients.

Actually, they drive away the heat from the layer to the substrate. In this way, the thermal gradient management is significantly impacted by the styling, as well as the build density of the support structures.

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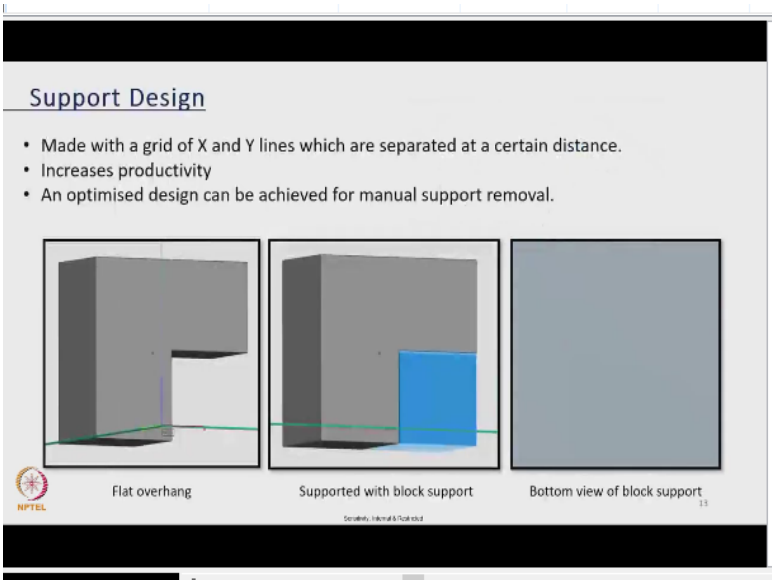

Let us look at some of the possibilities in terms of the support configuration. What you see in this case is a overhang feature that has been supported by a block support. This is one of the simplest forms of the support structures in case of powder bed fusion.

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But the options of the support design provide even for incorporating perforations. What you see on the right side is block supports with perforations per building of an aluminum part, and in the middle of the slide you see block supports with perforation for making one stainless part.

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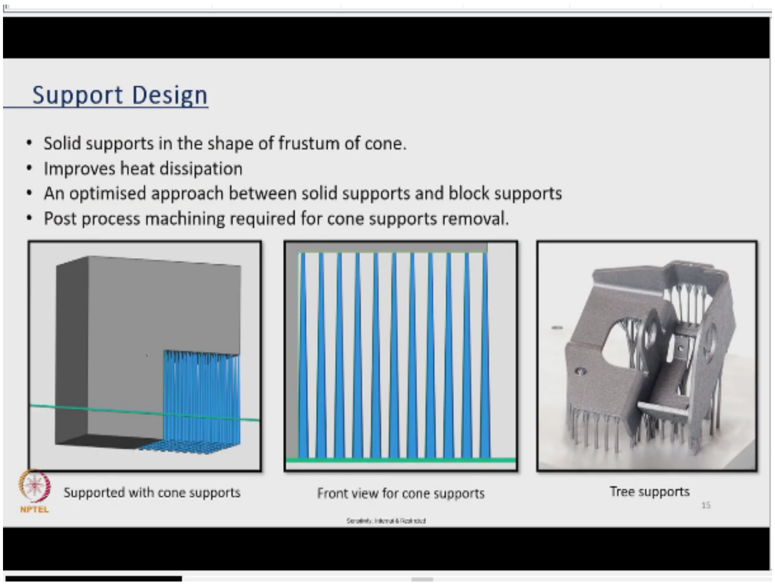

The implication of the support structures could also be understood by looking at one more possibility. In this case the support structure is in the form of the frustum of a cone. It improves dissipation and the post processing effort, which is necessitated for removal of this kind of cone kind of structures is much lesser than that of block supports.

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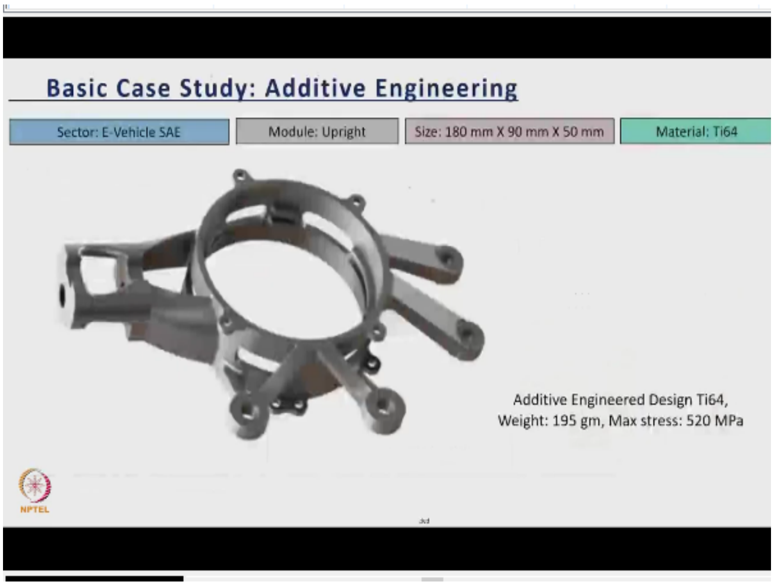

So, how exactly you define the support structures? How do you optimize? Let me pick up the example of a part called upright. The part which is shown in this case is part of the suspension system of a formula student Car. It is responsible for carrying the loads from the wheel hub, from the brake caliper. It is also connected to the wishbones.

In this case, the part with the envelops of almost like 180 mm by 90 mm by 50 mm has been re-engineered to take advantage of powder bed fusion manufacturing, as a substitute for conventional manufacturing with concomitant benefits of weight reduction, without compromising on the functionality.

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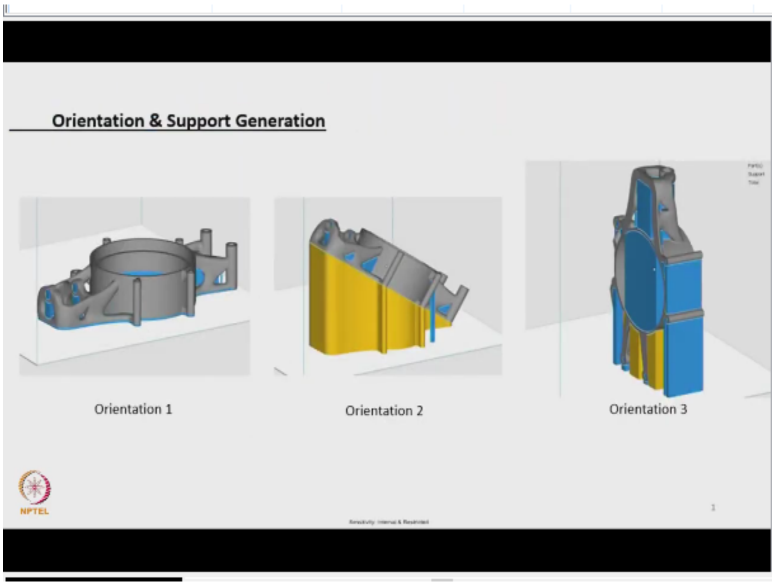

Now, if you were to orient the part in a completely horizontal condition. Look at the possible incidences of support in the orientation 1, which is very natural option. In the orientation 3 wherein the part is laid vertically, you can see the Z height going up tremendously higher compared to the orientation 1, Z height corresponds to a number of slices in the vertical direction. The orientation 2, which is that a certain inclination to the build platform lies between the orientation 1 and 2 option.

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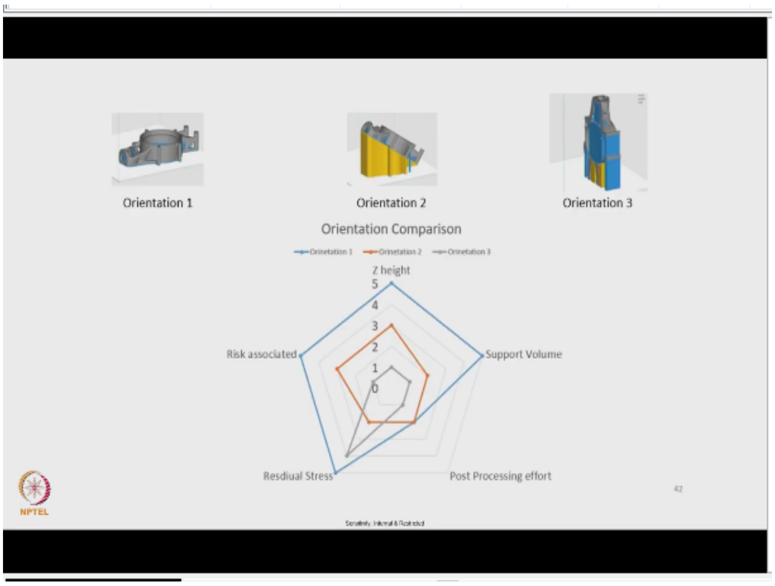

Now when you have got this kind of options, as support configurations, you would like to evaluate these options with reference to the Z height. The risk, which is associated, let us say with recoating, the possible residual stresses, and more importantly you are building the supports out of the same material as the actual part. So, you would like to keep an eye on support volume.

Last but not the least, the amount of time which is spent on the post processing is significantly impacted by the kind of supports and the density of supports. So, when you delineate all these options along all these possible vectors, you understand the compatibility of one particular orientation, compared to the other orientations.

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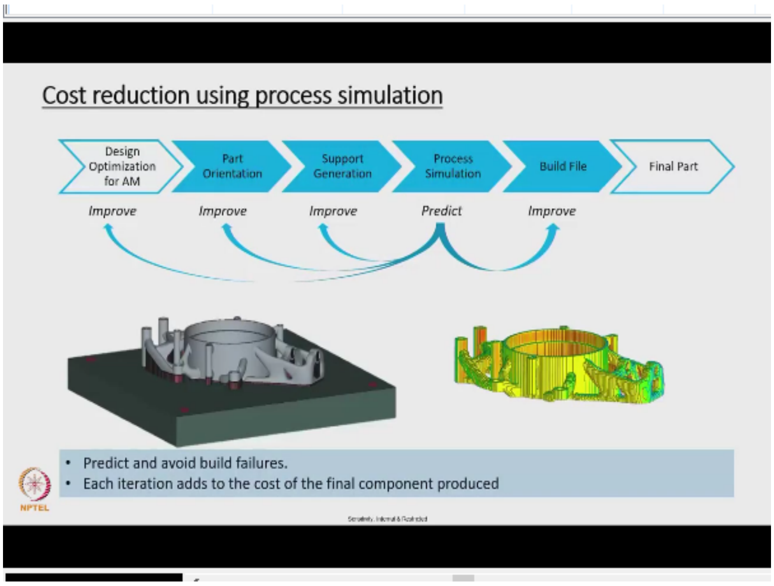

All these things can also be taken up through simulation. So, we see in the industrial context, more and more user groups, integrating the build simulation as a part of the process chain. What happens when you integrate the simulation as a practice into the powder bed infusion is, you are able to predict, you are also able to preclude the potential build failures. Any failed attempt is going to significantly contribute to the cost of the final component.

So, what do you aim and do is try to look at all the possible part orientations? Look at the support generation possibilities, support type possibilities and do all these iterated studies simulate and find out the specific option through which you are able to predict them properly, and you are also improve the buildability of the part.

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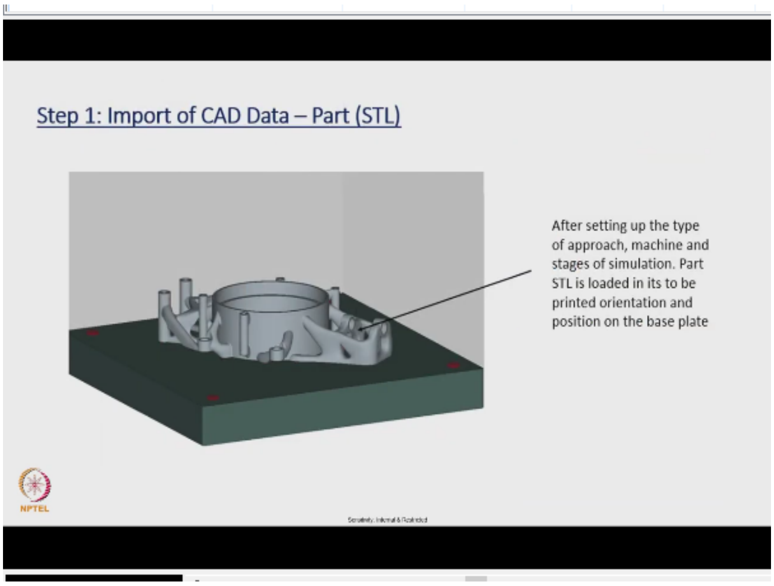

So, let us look at the specific case of building the upright. To start with that you import the data in the form of the STL file, you position the part on the bill platform at a specific location, and at a specific orientation to the recoater.

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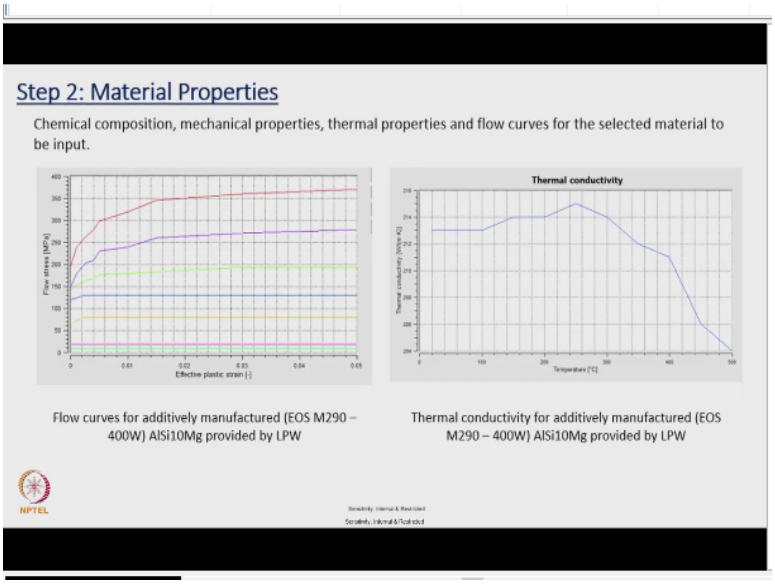

Then, depending upon your access to the data brochures supplied by the powder makers, you would be in position of the information corresponding to the chemical composition, mechanical properties, thermal properties and flow characteristics. All these things can be used as the inputs for build simulation.

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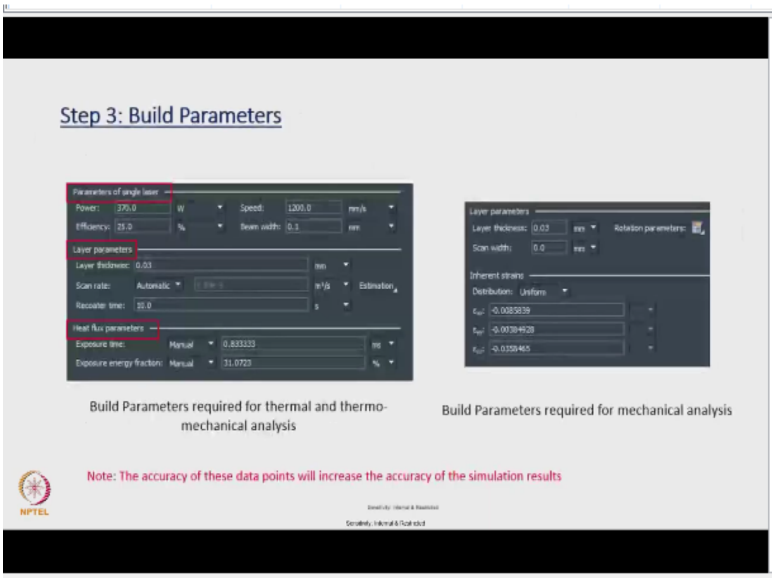

In addition to this, you may have to feed in the values corresponding to the build parameters, could be layer thickness, could be hatch spacing could be laser powder. So, when you have got control over all these parametric selections.

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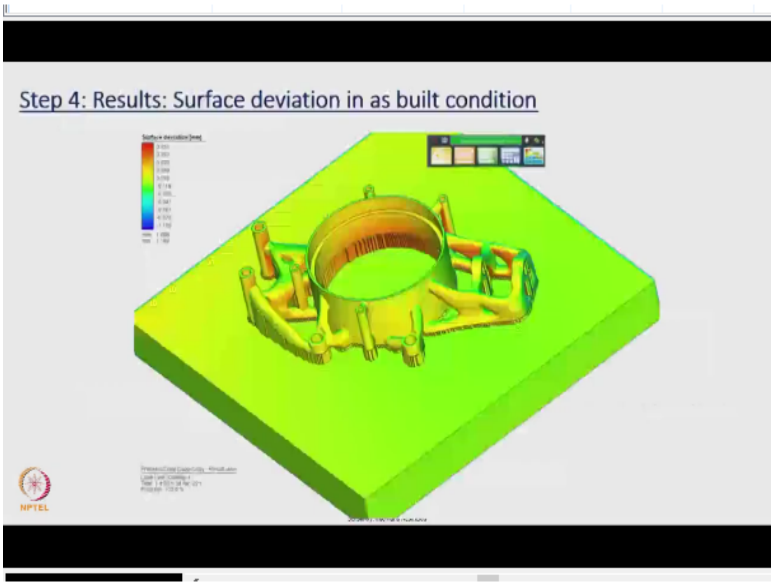

Then what happens is you will be able to do the simulation of the build process, and be in a position to identify possible de-laminations, surface deviations, excessive thermal gradients, and once you are able to get hold of all these estimations with a fair degree of conviction, then the realizability of the build gets tremendously enhanced.

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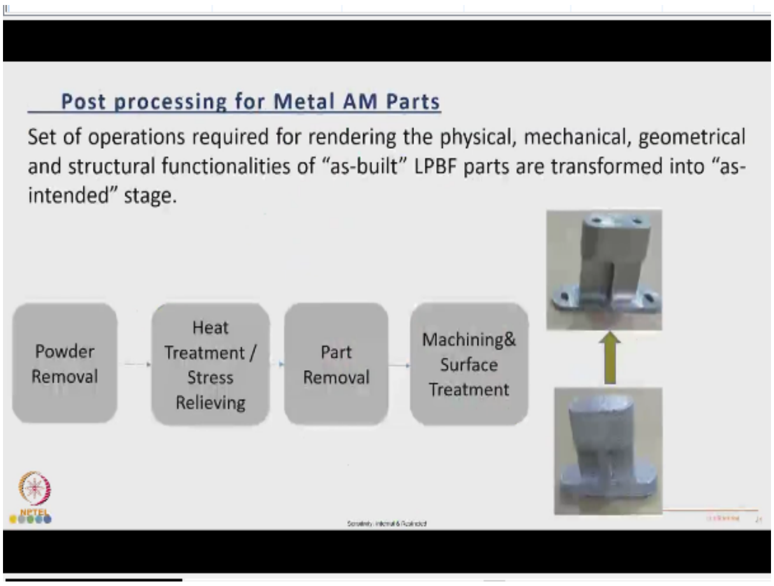

As I mentioned the post processing of the part is also an aspect which needs to be treated a priori. When you are talking about post processing it is not just a single operation. You are talking about removing the unused powder or trapped powder. We are also referring to the heat treatment and relieving of the stresses and removing the part from the build platform.

Finally, you are talking about employment of several processes, machining processes and surface treatment processes. These are all extremely you can say they are unavoidable when you're interested in translating the as-built part for end use application.

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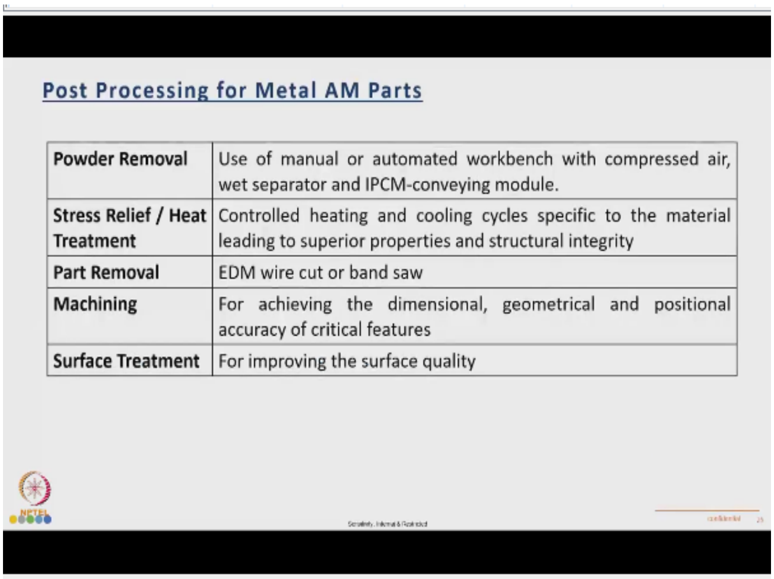

Powder Removal	Use of manual or automated workbench with compressed air, wet separator and IPCM-conveying module.
Stress Relief / Heat Treatment	Controlled heating and cooling cycles specific to the material leading to superior properties and structural integrity
Part Removal	EDM wire cut or band saw
Machining	For achieving the dimensional, geometrical and positional accuracy of critical features
Surface Treatment	For improving the surface quality

So if you are talking about the powder removal. There are some industry grade modules for employing optimal processes, and with reference to some of the well-known materials, the heating and cooling cycles are specified by the powder suppliers.

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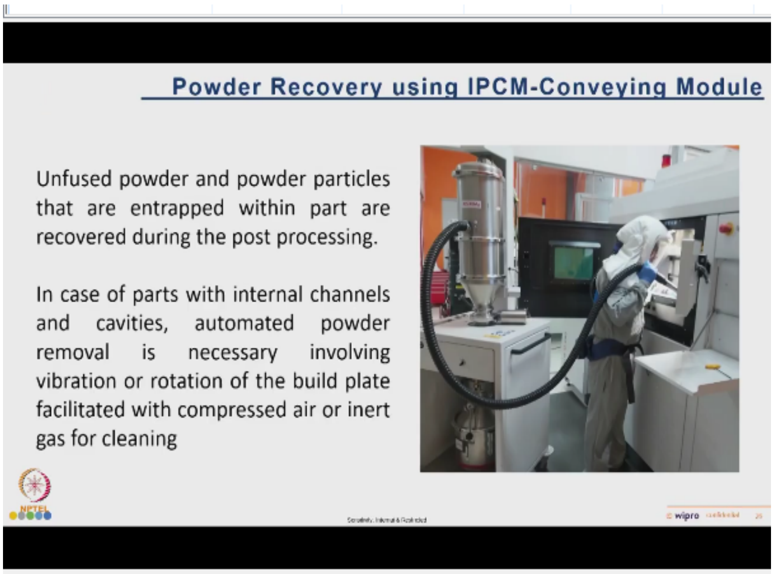

The powder recovery using IPCM conveying module is one of the important things which improves the process economics. Depending upon the geometrical definition the unfused powder and the particles which are entrapped within the part, could be significant. Especially when you are building the parts with internal channels, conformal cooling configurations, and cavities, it becomes imperative that you make use of automated powder removal involving vibration and rotation of the built plates and uses of the compressed air and inert gas for removing the powder, and also for cleaning the part.

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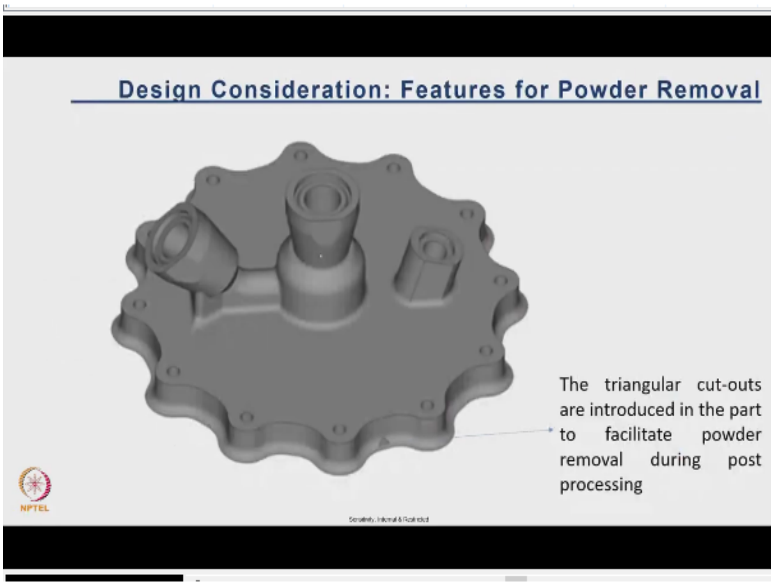

As you developed more and more confidence on a particular part or a geometry you may would like to introduce certain cutouts, certain provisions, in the part for facilitating the powder removal in the ensuing post processing operations.

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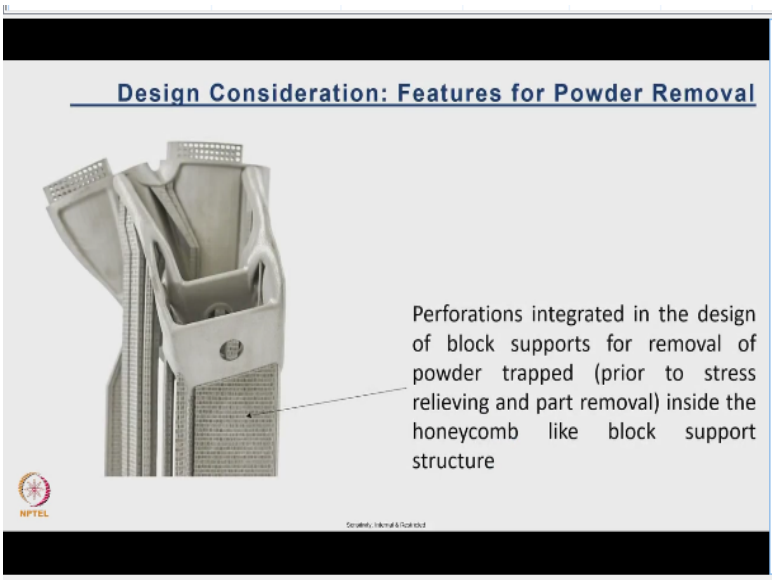

So, the design considerations are required with reference to post processing and this design considerations may have to be treated right in the early stages of the process chain. So, in this specific case perforations are integrated into the block supports for removal or for facilitating the removal of the trap part and especial when you are making use of lattice structure and honey comb like structures. It becomes very important to understand what are the access points and what are the possibilities of removing this powder.

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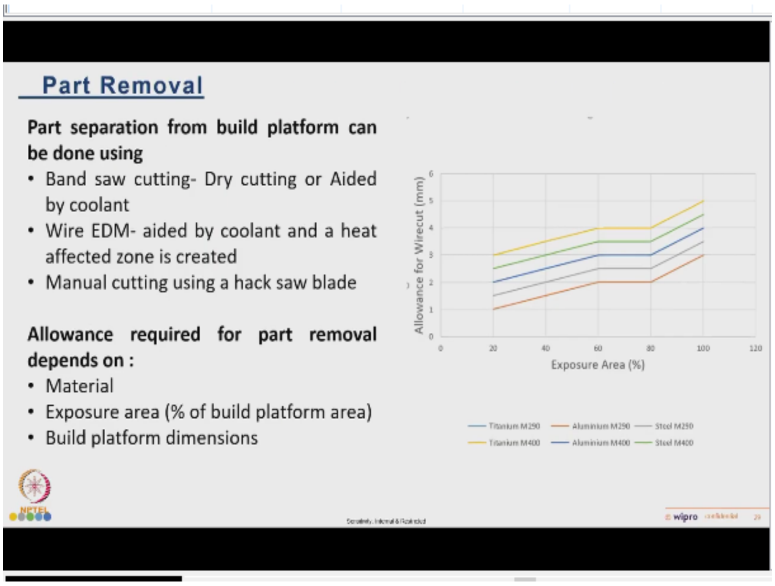

In such a way the parts remain clean after the post processing is completed. Now, I also briefly made a mention of the removing of the part from the build platform. So, it may involve the manual cutting with this ubiquitous hack saw blade, or you may would like to use wires are EDM aided by coolant or band saw cutting. So, what are the allowances that you need to account for while you are doing the build plan?

It depends on the material. It depends on the exposure area and it also to some extent depends on the dimensions of the build platform. As you can see here in this case, we have analyzed the allowances which are required for the part separation for Titanium and Aluminum some steels with reference to different exposure areas, and with reference to different build plate considerations.

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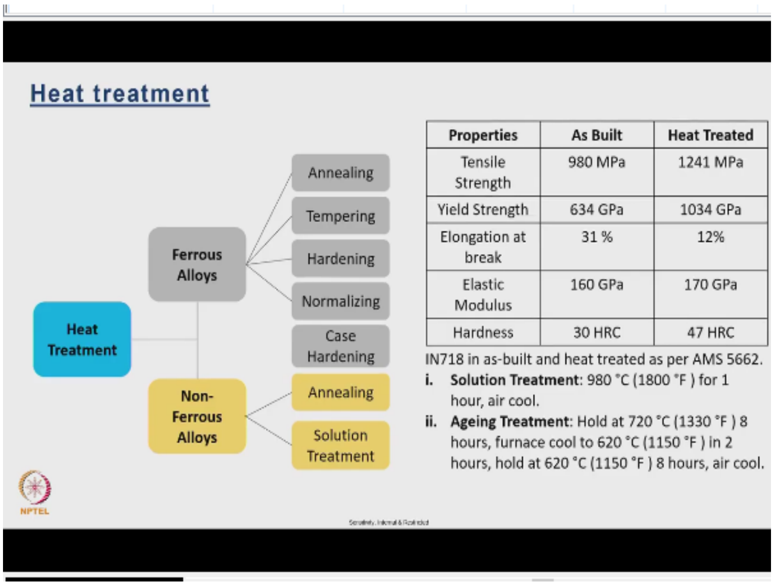

When it comes to post processing the ferrous alloys may require a specific treatment consisting of annealing, tempering, hardening, normalizing, and case hardening and in case of non ferrous alloys, you may employ annealing and solution treatment, through proper heat treatment, you can achieve significant improvements in tensile properties, yield properties, to some extent in the elastic modulus and hardness.

So, you could develop these kinds of functional insights into the materials, and depending on that the users of the powder bed fusion can specify the solution treatment and aging treatment corresponding to a specific material on a specific system.

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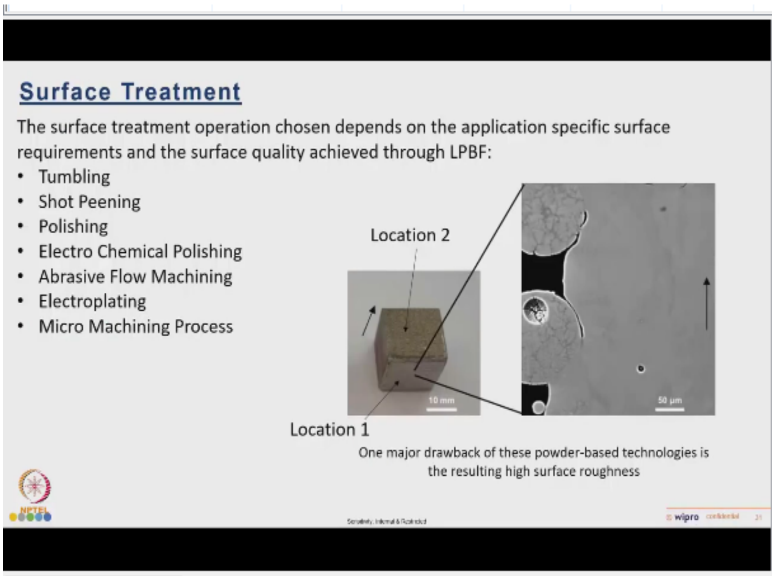

Now when it comes to surface treatment there are several possibilities, including highly affordable shot peening and tumbling and polishing or when you have to deal with high quality surface finishes that you encounter in case of an aerofoil of a compressor blade. You can even employ abrasive flow machining electrochemical polishing and slightly expensive micro machining processes for converting relatively coarse surfaces into acceptable surface quality situation.

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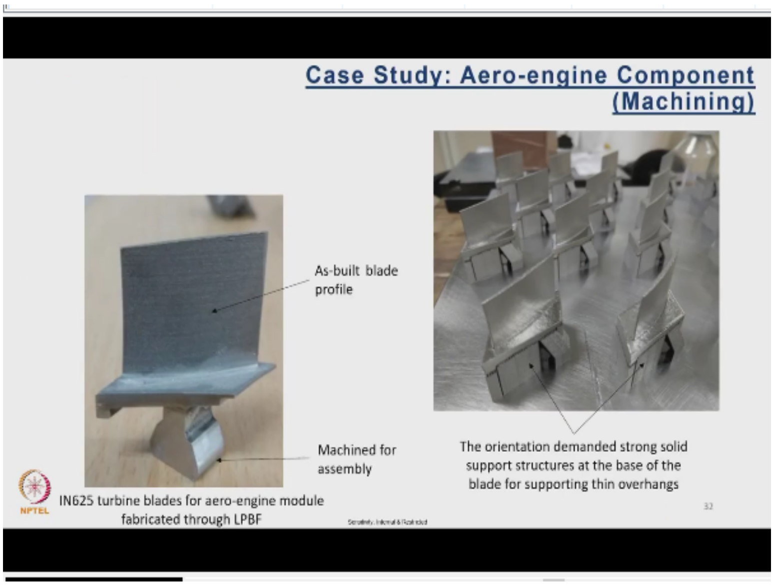

So, you can see here in this case, a turbine blade made out of IN625, what you see in the bottom is the duotail zone, which are responsible for connecting this blade to the turbine disk?

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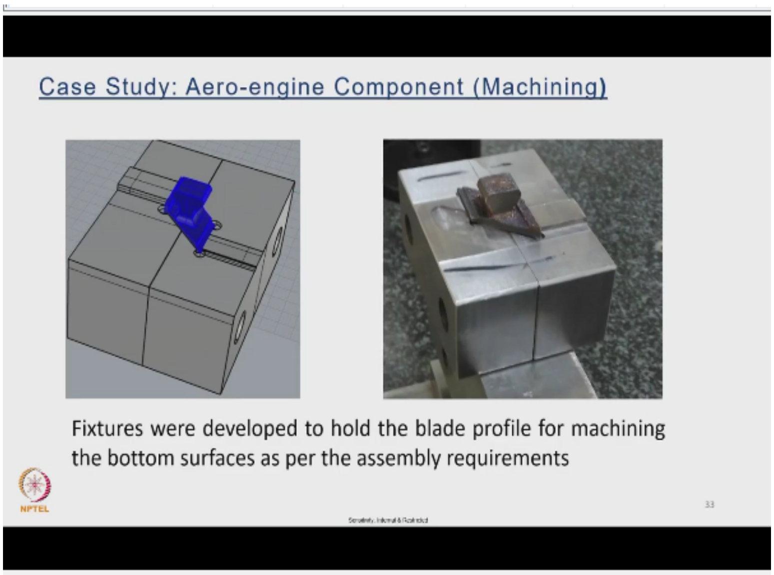

So, in this case, the whole planning with reference to fixturing was done right in the initial stage of the process development. So, that the thin cross sections corresponding to the blade profile are held properly without causing any damage to the aerofoil portion, while you are doing the machining of the duotail portion. So, the thin platform as well as the thin aerofoil sections were very carefully handled, while ensuring that the duotail that has got impressions created due to the surface removal is finished using substantial post processing effort.

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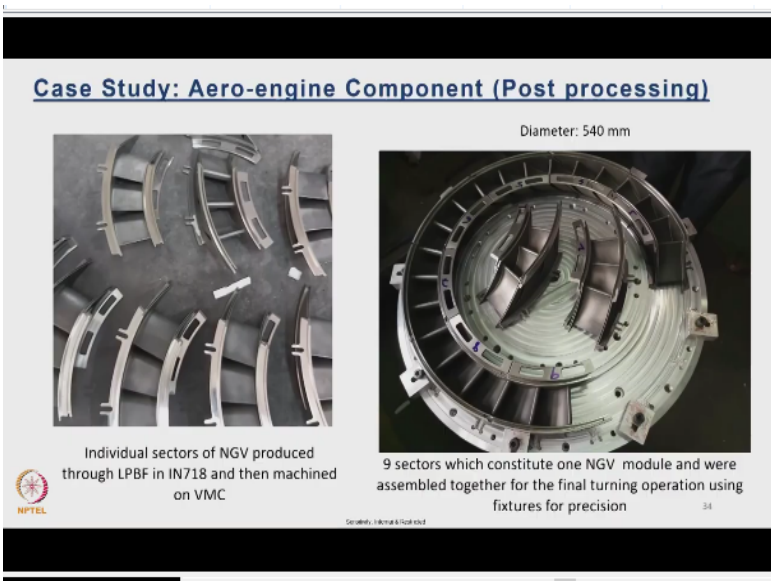

In this case you see an aero engine nozzle guide vain assembly with a diameter of almost like 540 mm, where in the post processing related planning it as significant as the part building, because in this case each sector, consisting of 3 nozzle guide vanes, was made as a single part, 9 of these sectors were assembled together. They were subjected to machining, and a VMC, and the post processing stays.

The importance of this particular operation is the airfoils that control the flow of hot gases on this are sacrosanct with reference to the operation efficiency of the nozzle gate vanes, at the same time these modules operate at very high pressures and temperatures, and it goes without saying that the residual stress management while doing the part building is extremely crucial to the integrity of the part.

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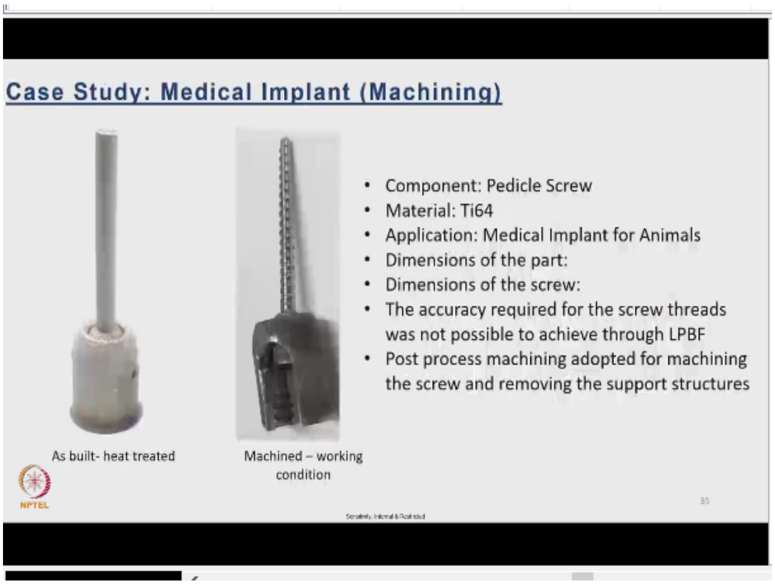

It is important to note and appreciate that not all the features are compatible to powder bed fusion. In this case of pedicle screw an implant for animal applications, made out of Ti64, the part you can see as built heat-treated part on the left side. As you can see, the pedicle screw portion which has been mentioned, which has been realized through post processing on the right side.

So, in this case, the extent of additive manufacturing was decided in such a way that you are able to take advantage of conventional manufacturing, while ensuring the compatibility of the pedicle screw to the intended application.

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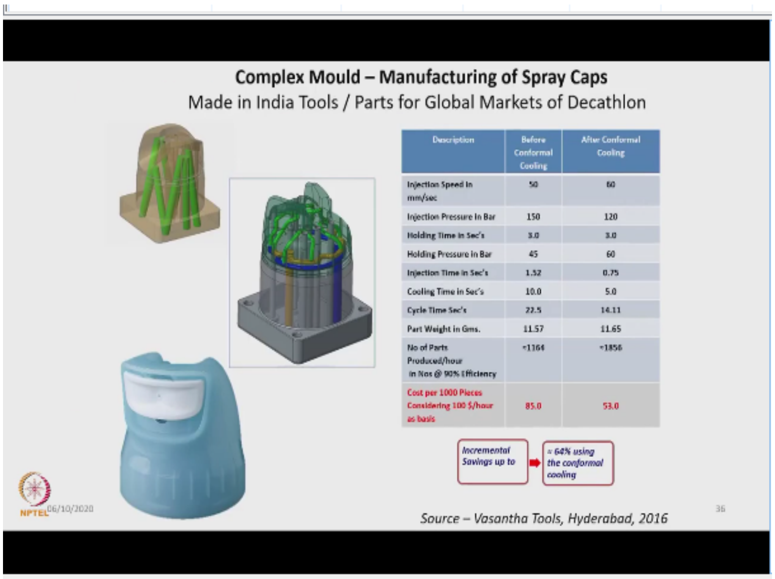

One more very popular application of powder bed fusion is with reference to the development of the injection tools with the conformal cooling channels. In one of the case studies published by a tool manufacturing company based out of Hyderabad in 2016. You can see the injection tooling, corresponding to realization of the spray caps, has been reconfigured using the conformal cooling design approach, and powder bed fusion.

In this case is the surface finish within the cavity becomes paramount in ensuring the heat transfer characteristics.

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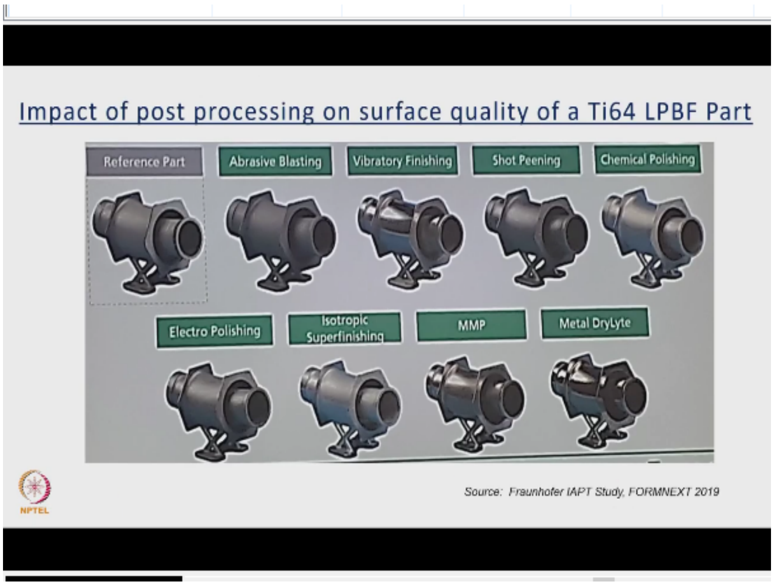

So, the post processing of different types and different possibilities, need to be considered while ensuring the application of the part in the intended context. You can see in this case, a titanium 64 part processed through various options, including abrasive blasting, vibratory finishing, short peening, super finishing and electro polishing and chemical polishing in a competitive study carried out by Fraunhofer.

Depending upon the intended application, depending upon the intended surface quality the post processing, could be chosen and integrated into the entire process of powder bed fusion.

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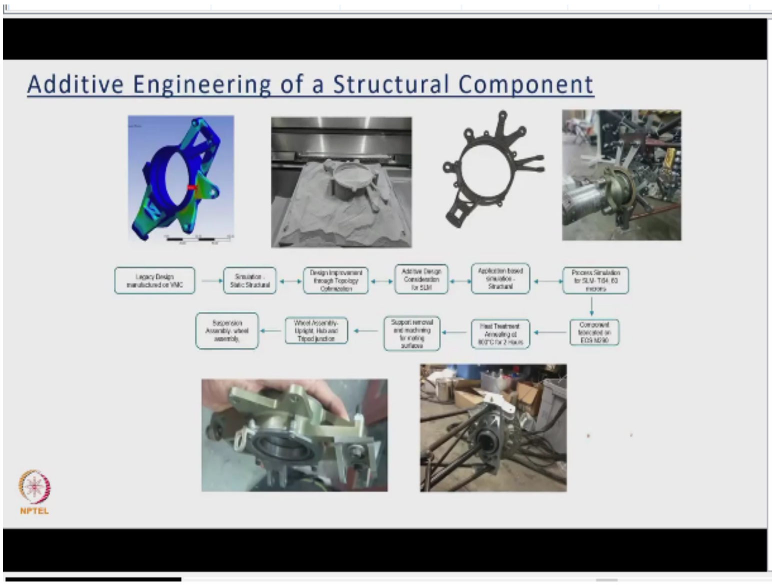

As I mentioned, in this case of upright, which is the part of the formula student Car. The, original configuration has been re-imagined in such a way that you are able to cut down the weight without compromising the structural requirements or commitments, or requirements to meet the performance characteristics of the suspension system. So, in this case some of the features were re-engineered to suit the design for additive manufacturing approach.

Needless to mention, once you start reimagining the designs, you need to go through the engineering simulation to understand how exactly the part is going to deform or function, under the expected operating loading conditions and once you gain confidence on the suitability of modified part to meet the functional requirements, then you look at the configuration, corresponding to suitability for powder bed fusion.

Once this aspect is ensured, then you build the part, do the necessary post processing and quickly inducted into the test bed, understand the performance possibilities with this re-engineered part and after necessary testing and qualification, you induct the part into the final system of relevance.

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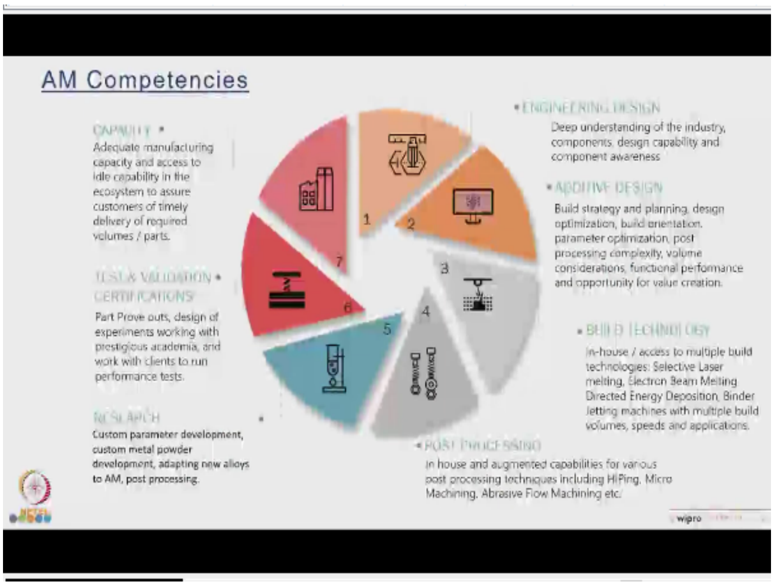

So, to be able to do this kind of additive engineering approach the departments which are connected with additive manufacturing need to develop different sets of proficiencies. On one side, you are talking about running the system, which is the build technology, on other side you're talking about reengineering the parts, reimagining the designs and ensuring that they perform with reference to envisioned operating loading conditions.

So, these specific instances demand enough insight, and proficiency in the simulation practices. There are occasions you are developing the material specific to the application. So, material related research becomes an integral piece and the post processing, as I have illustrated is an extremely important consideration, with reference to controlling the costs of production in additive manufacturing and also for ensuring the thermo mechanical characteristics on par with the expectation.

So, all the post processing related considerations, need to be accounted for, right in the beginning of the process development and last but not the least, having realized the part, it is imperative that you need to prove out the part for its performance with reference to envisaged loading conditions.

So, testing of the part validation of the performance and certification of the part are also extremely important when you are talking about strategy applications with additive manufactured parts.

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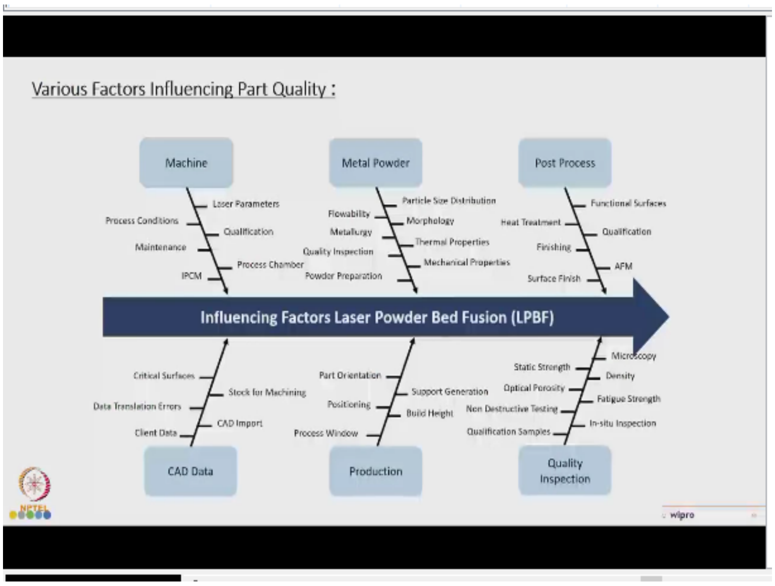

So, if you look at the parameters that need to be controlled and that can also have significant impact on the part quality. They could be mission related or they could be metal part related. For example, the powder can have certain flowability characteristics. The particles may have certain PSD values, that is particle size distribution values, the morphology of the same material coming from one source, compared to the other sources could be different.

So, all these things need to be taken care and within the production, you may be using specific support style, some specific type of recoater. You might be developing the process window corresponding to the material, and the orientation of the part. The extent of packing could be dependent on the space. So, all these things need to be accounted for and very importantly, even the input data need not have to come always in the classic CAD model form.

You may simply have an access to a physical part which needs to be replicated or you may also be required to look at the existing design and redesign in such a way that you can take advantage of the additive manufacturing. So, even the input data becomes very important. The final considerations are with reference to the post processing and quality inspection.

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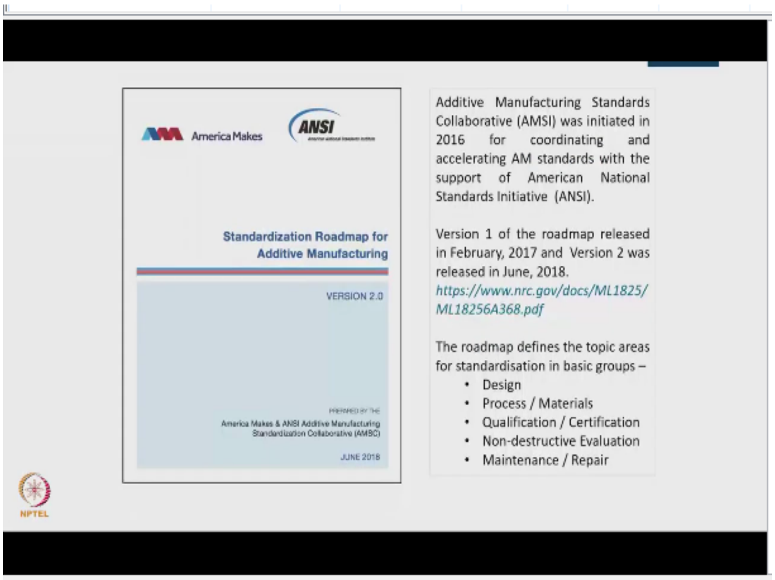

So, to account for some of these variables standardization roadmaps for additive manufacturing are getting developed. This roadmap defines the topic areas for standardization in basic groups like design, processes and materials, qualification and certification, non destructive evaluation, and finally connected with maintenance and report.

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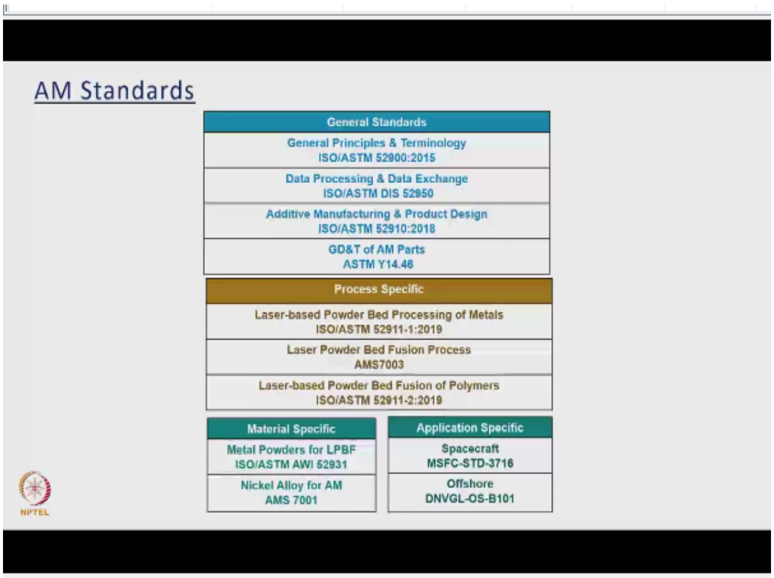

It is very relevant to talk about these standards corresponding to these processes. There are standards, released by ISO ASTM just with reference to the general principles of additive manufacturing and the terminology, which is associated with this technology. If you are doing the dimensioning and tolerancing of the AM parts there are certain standards, released by ASTM that can be compliant with.

With the maturity coming in the standards are also getting delivered specific to the process. For example, if you are talking about laser powder bed fusion based processing of polymers and metallic materials, they award the relevant standards and sometimes the standards could be specific to the material. For example, if you are talking about processing of nickel alloys you have a standard released by AMS wide AMS 7001.

Currently, we are not talking about standards which are being relevant only to the aerospace and defense applications, we are talking about offshore standards.

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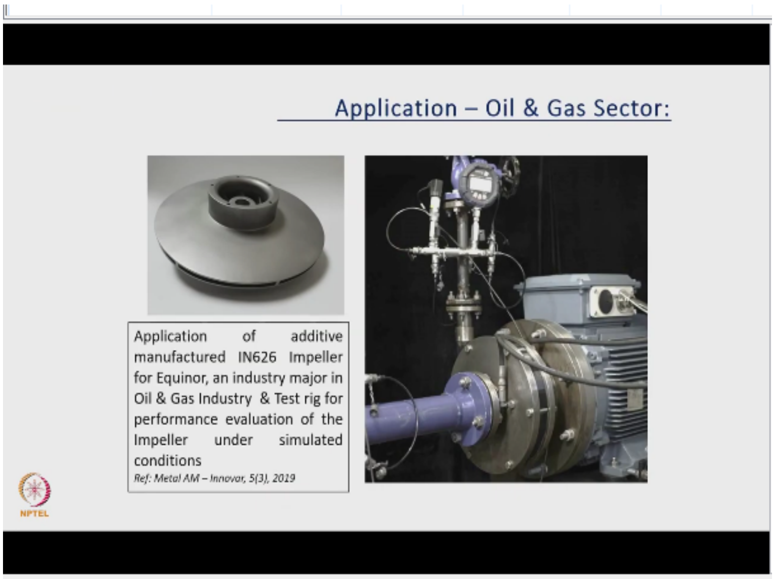

The standards released by DNBGL talks about how do you make the part out of additive manufacturing process of powder bed fusion and how do you ensure that they can be used in the context of oil and gas industry, through proper testing? So, the standards of this kind are going to play a significant role in ensuring the industrialization and widespread use of additive manufactured parts.

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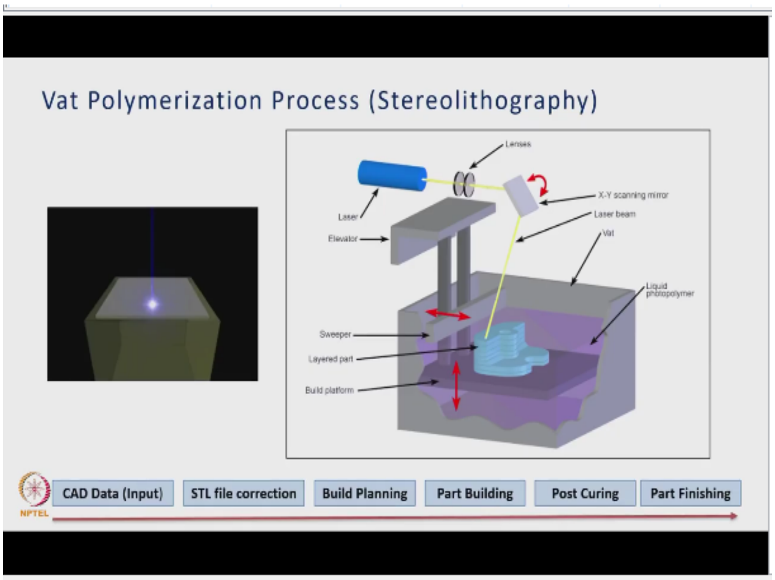

Let me go to the other process of vat polymerization synonymous with the processing of photosensitive polymers. In this case, you have got a UV laser beam, working on photosensitive or photocurable resins, the resin has got photoinitiators and premixed proportions of hardener, as the laser beam is scanning on the surface of the photopolymer. There is instantaneous solidification and very similar to powder bed fusion after a specific layer is cured.

The build platform moves down by an extent, equivalent to the layer thickness. Typically, it could be 50 to 100 microns. You have got a pair of galvanometric scanning mirrors that are responsible for a movement of the laser beam in the x axis and y axis, and you have got a perforated the build platform, through which the polymer material flows for making the current layer, and similar to the quarter, in case of a powder bed fusion.

You have got a sweeper, or a Z fire controller in stereolithography system. The process has got 5 or 6 discernible phases, starting from input data to correcting the STL files to planning the build to part building to the post curing and finally, part finishing before you take the stereolithography part.

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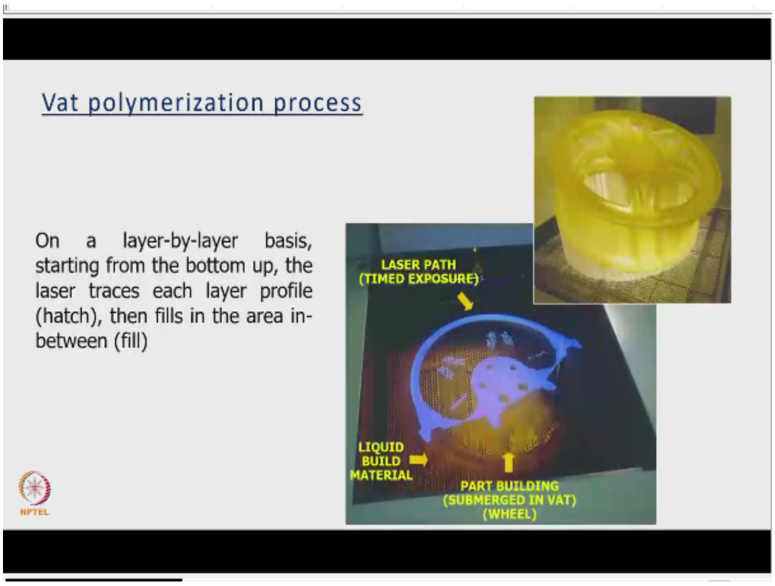

and start using for intended application in the context of industrial users. So, what happens in case of stereolithography is part building is captured in the slide. You can see here, a cross section, corresponding to a steering wheel of a car. So, the liquid material, photosensitive material is residing on the perforated build platform and on exposure to the UV layer or laser it is instantaneously solidified.

The tracing of the layer with reference to the infields and with reference to the external periphery follows a distinct pattern.

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So, this slide shows the snapshots, taken from industry grade stereolithography systems. The typical build sizes can range anywhere between 100 mm by 100 mm by 100 mm to about half a meter by half a meter by half a meter for making large sized parts.

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In this slide you can see the support structures for overhand features of the part which is getting built on in a stereolithography system. Incidentally, this part happens to be the housing of a combustor or combustor casing and what you are looking at is sectoral modules of the combustor housing; and you can see the distinct support structures for ensuring non sagging of the overhanging geometrical features.

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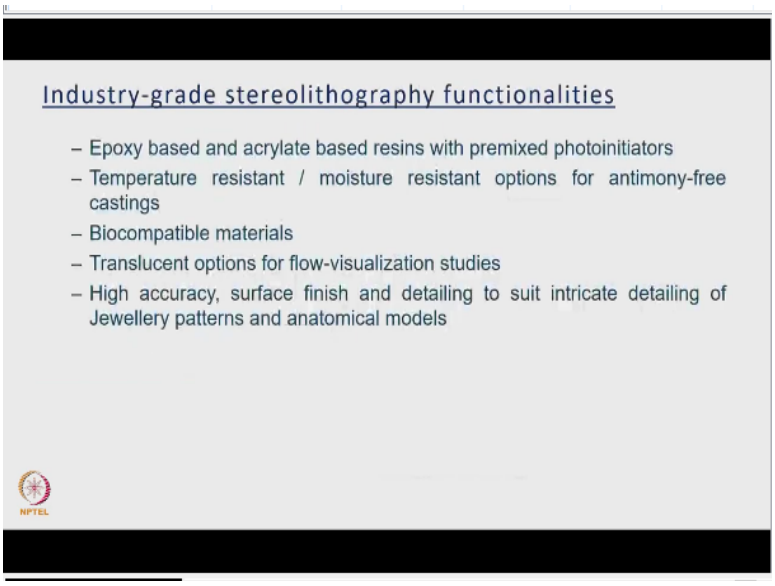

The materials in case of industry grade stereolithography systems could consist of epoxy based, acrylate-based resins or you have got specific materials for high temperature applications with the necessary moisture assistance for scenario connected with the castings, you have got biocompatible materials, specific to the flow visualization studies. There are material options which are extremely translucent.

One of the important applications of stereolithography is with reference to jewelry patterns and anatomical modeling, in case of health sector. So, these applications demand high accuracy very high levels of surface fidelity and detailing.

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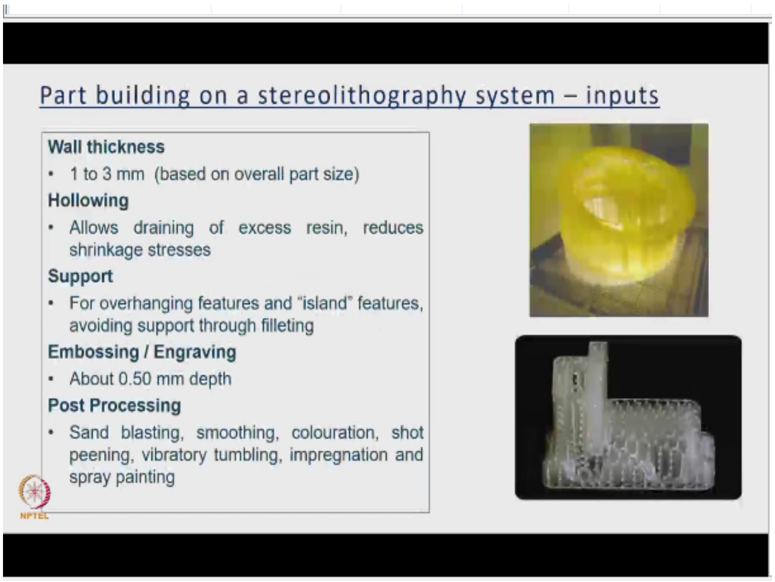

These are all imminently enabled, because of proper selection of materials. Typically, the wall thickness, depending upon the overall part size could be between 1 to 3 mm. Most of the preprocessing software prompts for hollowing of thick parts, because of the fact that it allows draining of the excessive resin. It also reduces the shrinkages which are connected with the face transformation.

It is also possible to impose the features to a depth of 0.5 mm and post processing typically is done using processes like sandblasting, shot peening, tumbling. You can also do impregnation and spray painting to improve the overall aesthetics of the stereolithography parts.

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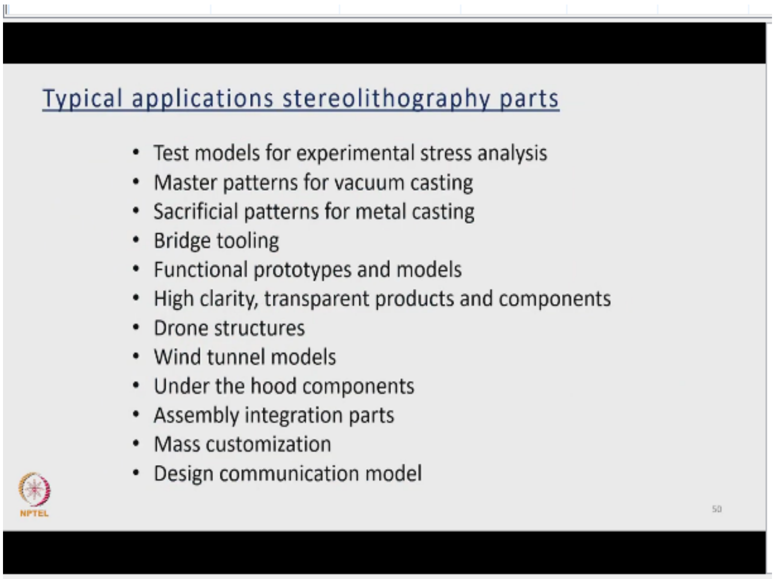

The applications of stereolithography part are wide ranging, starting from stress analysis to flow visualization to structural parts where in the mechanical loadings are not significant to wind tunnel applications to design communication models as you can see in the next slide.

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This is the gearbox housing of an aircraft. The original part is made through investment casting out of aerospace Aluminum alloy or Magnesium alloy. The part which has dimensions of about 700 mm by 500 by about 450 mm could take close to 18 months for realization. In this specific case the part was made out of acrylate resin-based photopolymer using stereolithography within a week of the CAD model or design being frozen.

So, this greatest utility associated with this specific application is for about 17 to 18 months. This full-scale model of gearbox housing was used as a design communication model.

Among disparate groups connected with the design, connected with assembly practices, connected with casting, connected with prose parsing and connected with assembly. So, in several instances of the gearbox development.

The user groups connected with upstream activities and downstream activities were able to connect seamlessly because of the availability of the part and many times, the principles of concurrent engineering were facilitated because of the early availability of very accurate transparent part.

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This is our own experience in the recent times, Wipro 3D in association with Sree Chitra Tirunal institute has developed emergency breathing assistive system called AirBridge. In this case as evident there are certain parts which are translucent, there are certain parts which are transparent. There are some parts which are conventionally manufactured. In these specific cases when you are doing the product development in an accelerated way without depending upon the conventional injection molding practices.

You can translate your designs into very accurate physical replicas using stereolithography and use them for your assembly integration studies.

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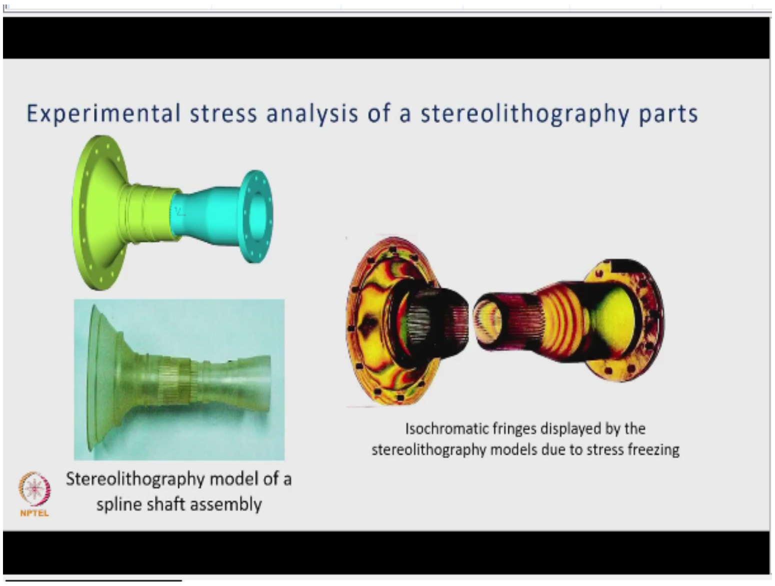

One more salient aspect of stereolithography part is its compatibility to 3-dimensional photoelasticity. It is a specific property of this epoxy resins wherein they develop these colorful patterns, because of the property of birefringence. When you make geometrically accurate replicas of the parts and subject them to simulated loading conditions and see through the Polaris scope.

They develop fringe pattern, known as isochromatic fringe patterns that can be seen using a Polaris scope and you can identify the stress concentration zones using this experimental stress analysis studies, and the data which is generated from this experimental stress analysis is extremely useful for a validation of the FAM studies in this case of complex loading scenario.

Be it is also useful for redistribution of the mass from non loaded zone to the loaded zones in the bargain, you may end up, contributing to the light weighting of this part. This part happens to be an important part of the transmission assembly. It is called spline shaft of a gas turbine engine.

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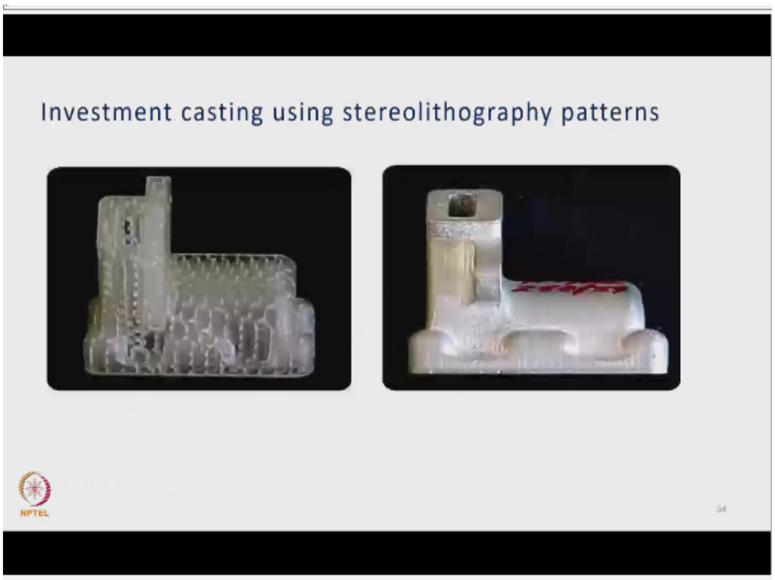

This is a specific case wherein a stereolithography part is indirectly used for engineering context. What you see in this case is a housing with a complete complex internal geometry. So, the part on the left side is called liquid gas part is a quasi hollow part. The amount of resin material which is used for a given volume is about one fifth compared to the solid part.

This geometrically accurate quasi hollow pattern can be used as a substitute for the wax patterns in case of investment casting with the tremendous contribution to the time compression, the applications of this kind have been significant in the context of automotive industries. Specifically, while they are doing the batch production with the limited quantum t rather than depending upon traditional pattern making options.

These automotive design groups have been using the patterns through both stereolithography and the extrusion process of fused deposition modeling and converting the patterns into casting in a remarkably reduced time frame.

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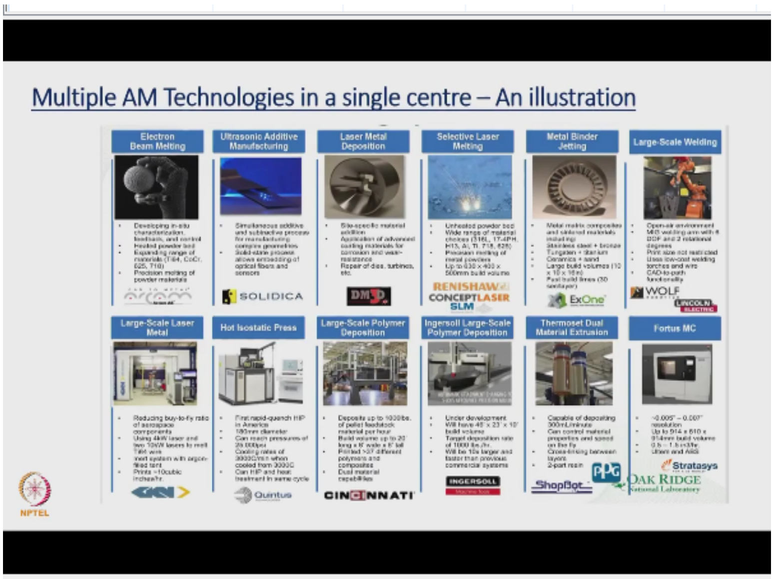

So, what is very relevant to recognize and appreciate with reference to industrial practices of various additive manufacturing processes? There is no universal solution. So, depending upon the engineering application the intensity of the application and the material compatibility, it goes without saying that you may have to use metal additive manufacturing processes, alongside of the plastic additive manufacturing processes.

One of the contemporary examples which are taken from OAK RIDGE National Labs publication. You can see their uses of electron beam melting, laser powder bed fusion selective laser melting, metal binder jetting practices, alongside of the practices like the extrusion using large format polymer deposition as one process, other one is the classic fused deposition practice manifesting in the form of Fortus machine of Stratasys. So, a combination of these technologies is enabling this state-of-the-art lab to take care of the product development needs.

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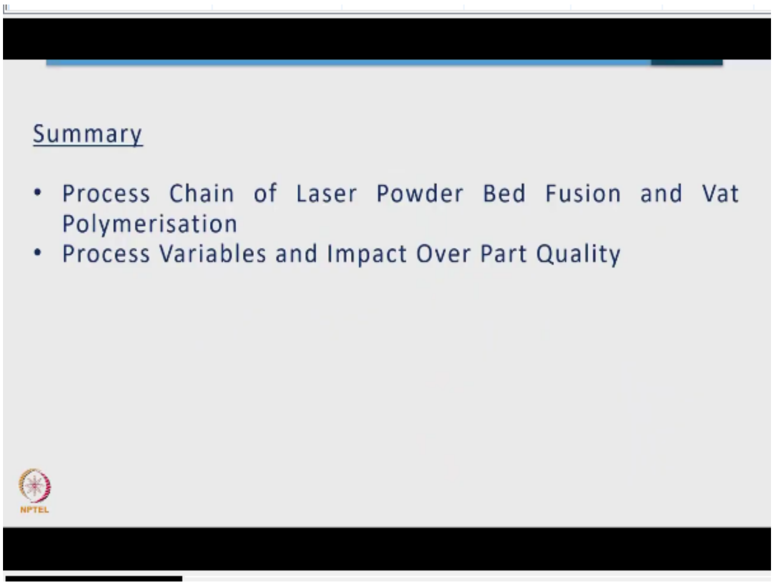

So, to sum up this particular session, we understood what are the standard characteristics of the process chain, in case of the laser powder bed fusion of metallic materials and Vat polymerization of photosensitive polymers. We also discuss briefly about the process variables, and the possible impact of these process variables or the part quality, look forward to meeting you again in the next session. Thank you.