Design For Quality, Manufacturing And Assembly

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Lecture – 23
Design for Additive Manufacturing

Good morning everyone. In this course we have been looking at various manufacturing processes and how their attributes needs to be considered in the design or what we have generally been addressing the issue as design for a manufacturing. Today we are going to discuss about manufacturing process which is more recent and which is more often enabler which has broken down many of the constraints that were associated with the traditional manufacturing processes. So, this process is called as additive manufacturing. And this technology has evolved from 3-D printing or solid freeform fabrication as early as 1986 or 87.

The first technology was developed based on photo polymerization and the technology was called stereolithography. Then technologies like fused deposition modeling and selective laser sintering were introduced. So, these technologies have matured over years and now we have additive manufacturing for a metallic parts with consolidation as good as that are obtained by other near net processes like casting or a forging. So, mechanical properties have been greatly enhanced by a process monitoring and a technology has matured from prototyping to a manufacturing process.

So, today we are going to discuss how this manufacturing process is an enabler and how we can look at design for additive manufacturing. What are the new challenges that we might have to address from the design perspective or the tools that we have to design considering the capabilities of this new manufacturing process?

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So, a quick introduction to the process itself; as the name suggest the parts are built the layer by layer. So, the 3-D parts which are modeled in cad environment. They are exported to a manufacturing environment typically using a surface mesh which is a triangulated file format which you see in this picture to your left and this model is sliced because we are going to build parts layer by layer, either by adding material or by sintering a bed of powder or by selectively polymerizing a liquid a photopolymeric resin from a vat.

So, the contours of the sliced model they give the boundaries within which the model needs to be built. So, the boundary representation model as described by the surface model, in the cad is decomposed into a series of 2-D models there by building one over the other to create the 3 dimensional part.

And to a right you see a manufactured part using a technology called as fused deposition modeling. Now, there are plethora of technologies available. So, you have this fused deposition modeling where a wire plastic or a polymeric wire is melted and it is deposited the nozzle is moved on the bed to trace the path in which the material needs to be deposited. And the table moves down and subsequent layers are build in similar fashion. And you have selective laser sintering process where laser sinters selectively regions of interest in a bed of powder.

And also you have the ploy-jet process, where like inkjet printer the material which is the photopolymeric resin is printed on the bed. And you we have ultraviolet light source which will polymerize the printed resin. And layer by layer again the part is built in a sequential fashion. So, all these processes originally they were used as a rapid prototyping process, mainly for form visualization before we could take a decision on the design or do some modification to the design before we go for permanent tooling for the manufacturing.

But these technologies have evolved and now we have processes which are capable of producing end use parts. So, we can now think of small batch production or even customized parts. So, from a design perspective we have new challenges in terms of how do we make or enable the cad environment to quickly produce let us say mass customizable models. Because no longer we are talking about a single cad model which will be used for manufacturing of say millions of parts, but rather we are going to talk about making few 100s of several thousand designs maybe.

So, how do we quickly create designs which are essentially parametric variations or small shape variations about a mean shape? So, that these are customizable parts. Just to give an example we have several examples in the biomedical domain. You can think of a hearing aid. So, the hearing aids which are now used by a hearing impaired people used to enhance their hearing experience or to amplify the input. So, these devices can be placed inside the ear canal. And for each person the ear canal is different or it is shape is different. So, one can customize the hearing aid to fit exactly to the specific patient.

And similarly we can talk about customizing sports shoes which will enable a sports person to have enhanced performance. So, for creating such products we need such products are possible with this additive manufacturing technology because we can talk about a manufacturing process and then associated logistics which is enabling small batch production.

So, the design tools needs to be capable of producing or churning out the large variation or large varieties about a mean shape. Not only that because we are adding material it is possible to change the material composition. Conventionally we have been building parts which are homogeneous material we take a block of metal or a block of wood and we machine out. So, it is presumed that the material is a homogeneous and isotropic.

So, we have been representing in cad only the boundaries rather than representing what is inside. So, everything inside to the boundary was assumed to be made of the same material. So, as a representation scheme the cad models were presenting only the surfaces just as an example if we have this room this room is represented by the 6 walls or the 4 walls and the roof and the floor. So, these surfaces were represented to give the information about the interior. But if we are now going to talk about a manufacturing process which can change the material composition as it prints.

As an example we can think of this lens process which is an additive manufacturing process we have a laser and as a confocal laser we have powders being deposited using nozzles. The composition of these powders can be varied as the nozzle moves on the table to print the part. And in similar fashion in other technology as well one can think of heterogeneous part fabrication or functionally graded parts.

So, the modeling frameworks cannot now assume that in interior to the surface boundary is made of the same composition. So, we again need cad frameworks which can design heterogeneous parts right from the inception so that we could optimize the mechanical properties as desired from the end use.

So, these are some new challenges which needs to be addressed or which needs to be taken care of so that the manufacturing process that is additive manufacturing process can enable new or an innovative designs.

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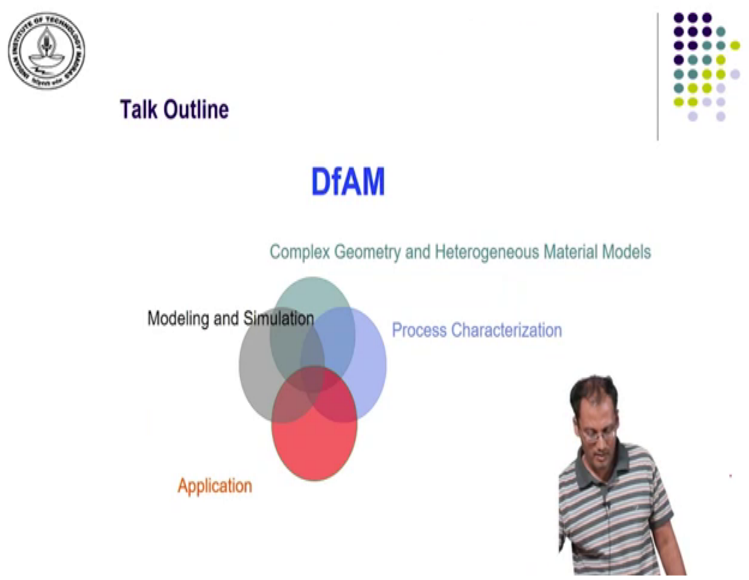

So, we will see some of the issues and some work that is been done globally across in these direction. This term is getting coined as design for additive manufacturing and there is lot of development work happening in the various domains that I have shown in this slide. There is lot of interest in creating very complex geometries which have originally been not possible with traditional manufacturing process.

Since we are adding materials it is possible to build very complex shapes because in subtractive machining processes, the accessibility of the tool becomes a constraint in creating very complex shapes. But when we add material such a constraint is typically not present and one can create a large variety of very complex shapes. So, what has not been possible earlier is possible now. So, we talk about this topology optimization or shape optimization or generative design, where rather than presuming the shape of the object the shape of the object is generated based on the loading condition for which the part needs to serve. So, such design processes like generative design process, needs to be developed and or needs to be integrated with this additive manufacturing process to enable a very complex shapes.

So, complex shapes could help in light weighting and even for enhanced functionality it could be a enhanced heat transfer functionality it could be an enhanced fluid flow functionality. The shape of the object is no longer a constraint from a manufacturing perspective. And not only the geometry we are now talking about the material variation that is what we call it as heterogeneous material models. So, the material is also non-homogeneous thereby now giving lot of scope from the design.

The process that will be used for manufacturing could be a plethora of process like the fused deposition modeling or it could be a selective laser sintering process. Each of these process has some specific process characteristics process variables; we need to have a complete understanding of how these process parameters will result in specific part characteristics. So, lot of research and development also needs to happen or it is happening in this direction. And a lot of modeling and simulation tools help in this direction and one has to tag all of this with specific applications; where such a small batch complex customized parts are required.

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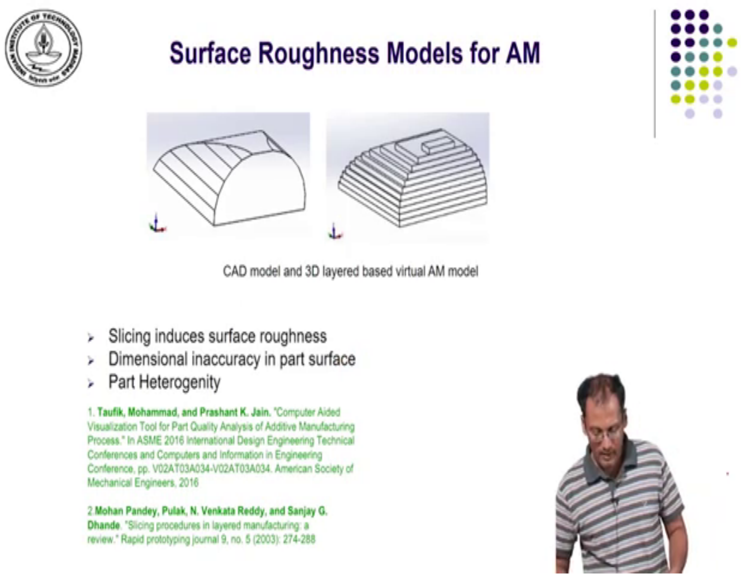

So, one of the traditional ways people look that design for additive manufacturing was the quality of the parts that were made by additive manufacturing. Since we are making the parts by stacking together layers, there is a discontinuity in the build direction. As seen in this picture, to the left you see the cad model or the design that we are interested to fabricate, to the right you see the approximation created by the layering effect. Because we are going to now start 2-D layers the model is essentially 2 and half d. There is a discontinuity across in the build direction which is typically the z direction.

So, this discontinuity causes material in homogeneity, there by compromising the strength of the part. Because the interlayer bonding is one of the weaker spots and the component may fail across the inter layer bond. Also it leads to surface regularity and leads to surface finish or form tolerance issues. So, the one of the foremost works in this direction have concentrated mainly on looking at the surface finish that is compromised because of the additive manufacturing process.

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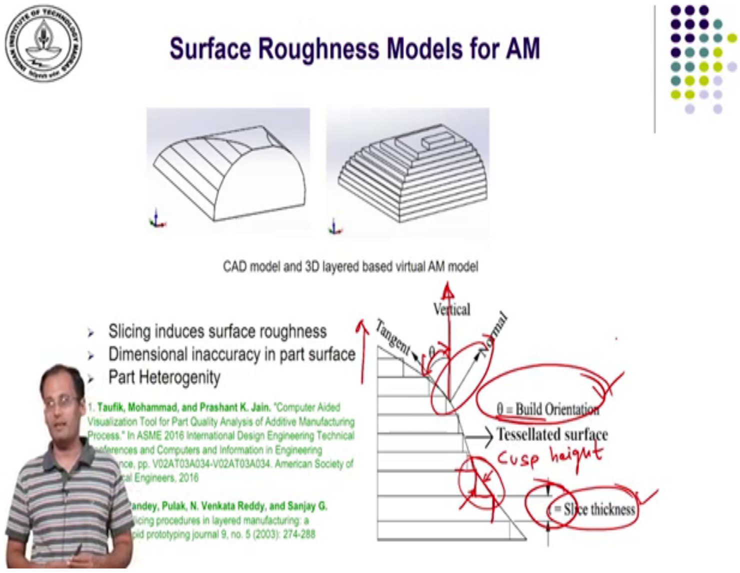

And depending upon the process characteristics, the stair stepping effect were what is called as this staircase effect can be different. Because the ideal representation of the staircase effect is what we see on the slide, but when this slice is manufactured, there is typically rounding off because the material is deposited let us say if it is a fused deposition process it is a filament and which is typically an oval cross section. And there by the edges will not be straight, but it will have the curvature. And because of the presence of this curvature the deviations as computed theoretically will be different from what is being manufactured.

So, one can account for such variation or process specific attributes to model how the surface finish will be affected because of the process parameters and the layering effect. So, traditionally people have been looking at the process and trying to understand the deviation of the part from the intended surface. So, this is the intended surface and the part is actually being fabricated in this fashion. The maximum deviation that occurs between the intended surface and the fabricated part has been used to understand the surface deviation and surface finish. This is called as the cusp height and has been used to understand how far is the part the actual fabricated part deviating from the design.

This depends on 2 important one is this slice thickness and other is the build orientation. Because if I change the build orientation, then the normal the local surface normal and it is angle with respect to the build direction will change. And one can see that when this angle, this angle theta that is marked here, when this angle changes the cusp height for the same layer thickness will also change. So, we could try to reduce this deviation by either manipulating this build orientation or by trying to manipulate the slice thickness.

If we reduce the slice thickness; obviously, the deviation is going to reduce, but the pitfalls are that we need to spend more time in having this part fabricated. Because we need to build more slices and the build time in an additive manufacturing process depends upon the total height of the part that needs to be built and the slice thickness. So, the build orientation affects the total height of the part, because if I can take this pen and I can build it vertically then my total build height is more I can build the same pen in an horizontal fashion the build height is less.

If I choose this orientation my build time is going to be less and if I choose this orientation it is going to be more. But other characteristics like surface finish or strength may not be in line with this objective and thereby I will have to compromise on one, when I try to gain on the other. That is if I try to gain on the build time I may loose on the part strength and so forth. So, we lot of people have looked that how this slice thickness and build orientation affects the part quality, both from the geometric deviation as well as from the mechanical strength.

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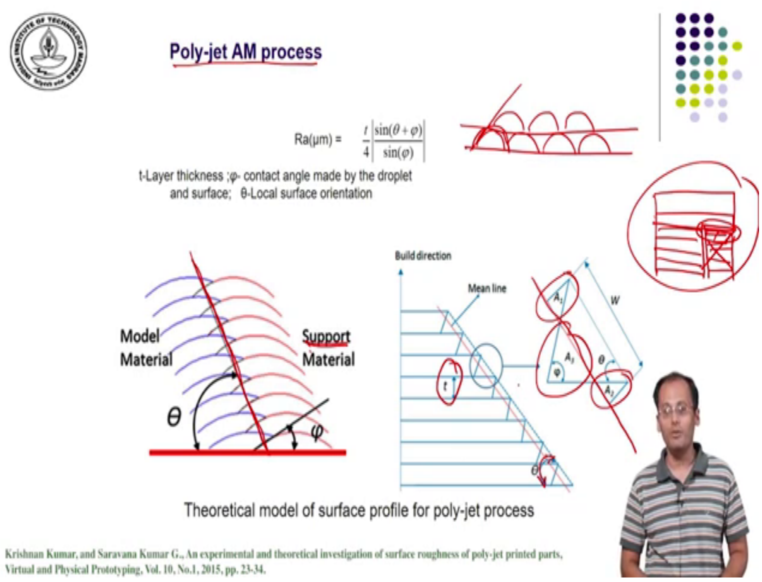

So, here I am describing one such process; which is a Poly-jet process, it is like a desktop printer where we have the printer head printing the liquid resin. Say let us say, if I have a 600 dpi printer it prints 600 dots per inch and. So, if there is a layer series of such droplets are deposited. And then the subsequent layer the drops are deposited each layer is cured by the ultraviolet light source.

So, when such a model is prepared, we can see that the drop shape as well as the part orientation will play a role in deciding, what will be the deviation from say the intended surface. So, the picture to your left shows that if there is a intended design surface, which is being built using the model material. Typically, in most of the additive manufacturing process we will have the support material. Because when we add material, we cannot add the material in app. Let us say if I have to build a part like this which is a cantilever. So, these layers can be built one top of the other. But when I am going to build this layer, I cannot build this portion of the layer without give providing a support. So, I need to provide a support structure here. So, this has also to be additively fabricated.

Once the complete fabrication is done, this support structure is removed. The presence of the support structure increases the build time, as well as wherever the support structure is aborting the model, the surface irregularities are typically more and one has to go for post process to remove such surface abrasion. So, if I have the support material which is marked in red and the model material which is marked in blue, because of the drop formation and the model orientation the surface irregularities as one can see as the junction of the support material and model material will be present which will create the surface abrasion.

So, this can be modeled theoretically as you can see on the right side. So, if t is the slice thickness which is typically the droplet height. Then the surface abrasions will take this form for a given model orientation theta. So, the deviation from the intended surface which is this red line, these are the deviations. So, this is to the inside and this is to the outside. So, this deviation could be modeled and can be used to determine optimum layer thickness or optimum part orientation.

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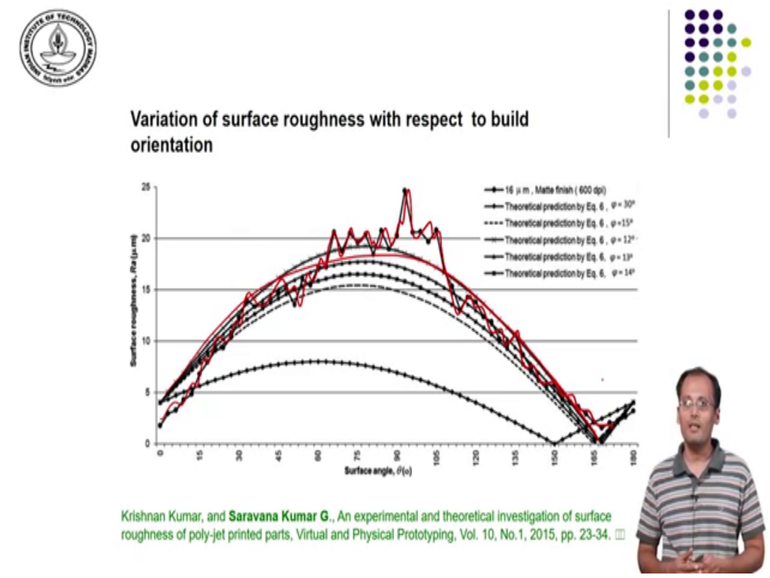

Theoretical model such as this has been developed. So, this is the theoretical model curve and the experimental data is what we see as these patterns. These are the experimental data for a given fabrication.

Such models are available for different processes like for the fused deposition process or for the selective laser sintering process. And one can use these models to predict the surface roughness and introduce this in optimizing the part build orientation, so, as to build the part with sufficient strength or sufficient part quality or with least build time. So, these could be the objectives for which I could optimize once I have these theoretical models or predictive models available.

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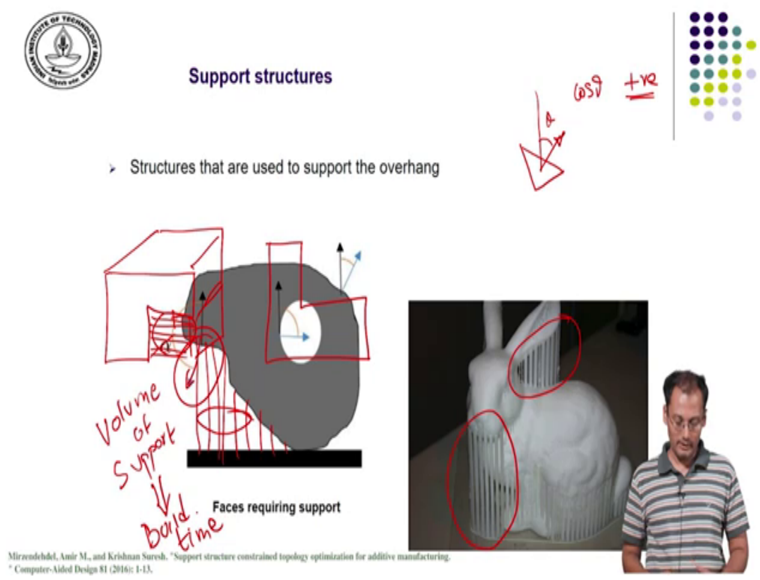

The support structures as I have mentioned, these cause surface abrasion as well as increase the build time and they also intern depend upon the part build orientation. If I take this example part, if I build the part in this orientation, so, what I am trying to represent is this object. I need to provide support here; I need to build the support structure here. But if the same part is built with this orientation, I do not need to provide any support structure. So, part build orientation affects the build time presence or absence of a support structure also on the surface quality.

So, people have looked that how surface roughness or the build time is affected by surface orientation and predictive models have been developed. To create such a predictive model, one needs to understand what surfaces will require a support. So, here you see a picture in which I have shown an object. So, the object is represented by series of facets or triangles. So, if I have a triangle and whose normal is facing upward. So, if this is a build direction, by taking the dot product of this normal to the build direction that is estimating this angle theta or the cos theta. So, if this is positive, then this face is facing upward and upward facing facets do not need support. Only the facets which are facing downwards they need the support from the bottom.

So, these surfaces which have the downward facing normal will need the support. And by knowing the facet the facet can be projected down to create the volume element. And by summing up all such projected volumes one could estimate the volume of support that is required and thereby estimate the build time. Irrespective of whatever orientation that I choose the total model volume remains unaltered. So, the build time is a function of typically the support volume which in turn depends upon the orientation.

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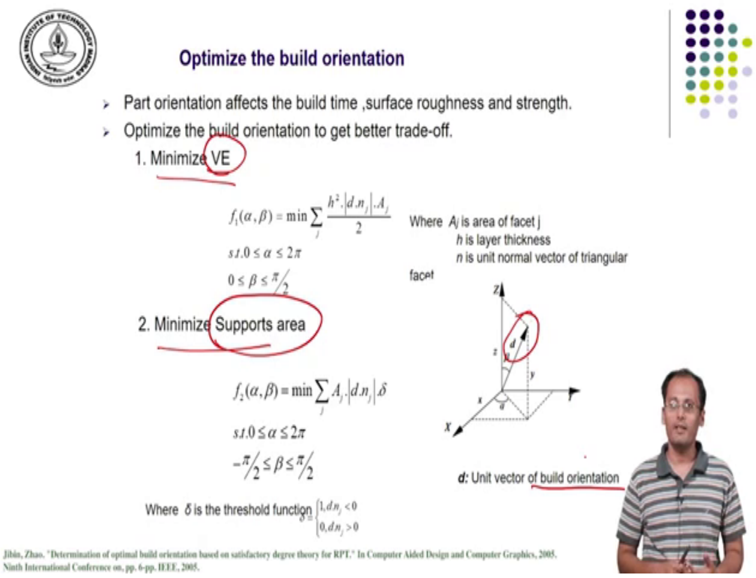

Several optimization models can be proposed based on estimating the volumetric error or estimating the support volume and thereby the build time. So, one could formulate a optimization problem to minimize say the error or to minimize the support structure and take the variables as the build orientation which is determining the orientation of each facet and keeping this as the design variable that is the build orientation one could optimize for the build orientation.

So, optimized build orientation can be obtained for either minimized error total volumetric error or for minimized build time. Or one can solve this as a multi objective problem and create a Pareto so that one can choose a solution from this Pareto optimal front.

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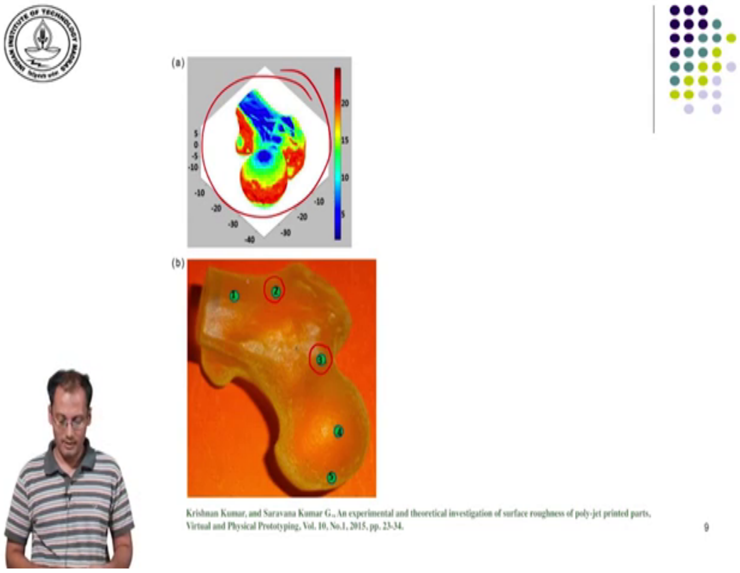

This is an example showing biological model this is a femur model. This is the predicted surface finish distribution for a given orientation and these are measured orient errors for comparison or for validation. So, such kind of models will help in judiciously to orienting the part for building the same in additive manufacturing.

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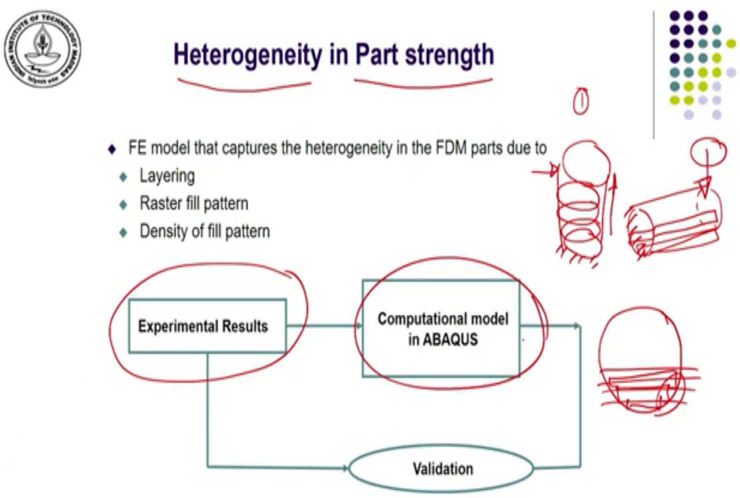

The next important aspect about the additive manufacturing and considering the same in design is the part strength. The part strength is invariably heterogeneous, because even if you are building a homogeneous model, because the model is built layer by layer heterogeneity is introduced. Even though my model is isotropic I wanted an isotropic model, but because I am building the part in an additive fashion, I will introduce an isotropy. The properties in a transverse directions will be having certain values and the properties along the build direction will be different.

So, if I change the part build orientation, the part strength that I am going to get is going to be different. Just give you an example if I take a cylinder and if I build it in the vertical orientation. Each of these slices are going to be series of such circle if I am going to build in this direction. But the same cylinder if I make it to lie on the table, that is on the build table, then I am going to build series of layers in this fashion.

So, we can see that in the first orientation the surface finish will be good, because I am going to build series of circles one top of the other. But if I take the part and load it let us say I constrain this end and I apply a load in the transverse direction. You will see that the part will fail in share, because the layers the inter layer bonding is the weakest link. And in the present loading scenario under share this component will fail. But if we take the other orientation, the surface finish will be bad because if you take a particular cross section this is being built in slices like this.

So, you will see that the staircase effect will be there and thereby causing deviation and the surface quality will be compromised, but for the same loading condition that is fixing one end and applying the same load on the other we can see that these sequence of layers which are essentially like plies in a composite, can take the load better in bending and can support higher loads. So, the build orientation affects the mechanical properties and the heterogeneity is introduced because we are building the part layer by layer.

To understand this and reflect it in the design we need to have computational models or simulations which will enable us to understand the effect of the heterogeneity. So, here you see a framework which accomplishes the same. So, using experiments one can determine the behaviour and use the same in a computational model. So, if I am building an abs plastic part using injection molding and the same abs plastic part using additive manufacturing even with let us say 100 percent density, the behaviour under the loading for these 2 is going to be different. So, unless I reflect this in my design, I may not be optimally designing a part which is going to be additively manufactured.

So, we are we are looking at how we are going to design parts which are going to be additively manufactured. So, one cannot use a computational model which has been used for let us say understanding the mechanical behaviour of an injection molded component.

So, we need models that will reflect upon how the additively manufactured component will behave.

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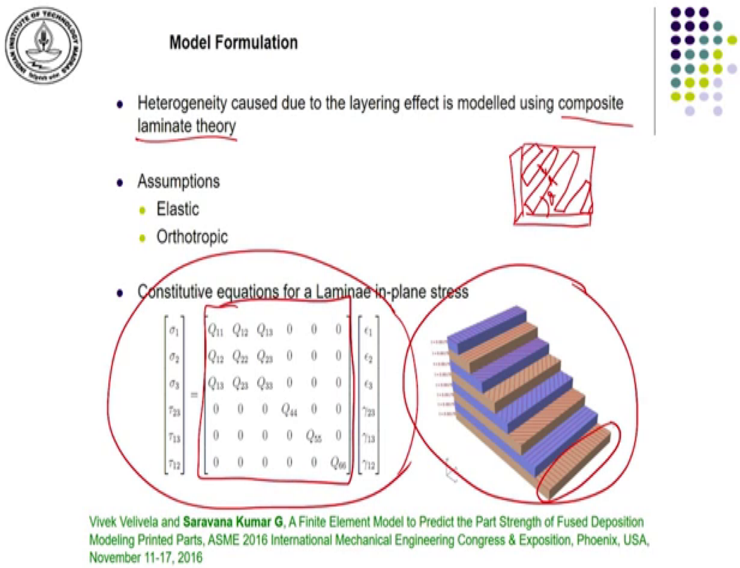

So, I am showing one example work there are lot of work in this direction lot of developments are happening.

So, here you see model in a computational framework; where each of these layers are modeled along with layer specific properties. Like, the hatch pattern, let us say if I am going to build a component using additive manufacturing, the material is laid up inside in each layer using some hatch pattern. So, these could be the parts that are being traversed by let us say the fused deposition nozzle the nozzle that dispenses the plastic. Or these could be the parts that are traced by the laser for sintering the plastic that is available on the table.

So, the hatch spacing, the hatch orientation and as well as the layer thickness and the part orientation. So, all these are variables that will affect the mechanical properties of the component. So, these things could be modeled. So, here you see a layup of layup of the layers with different orientation of the rasters and also with different layer thicknesses and the associated properties.

So, one can use a composite laminate theory to create a computational model which will reflect upon the relationship between the strains and the stresses. More details can be obtained from several literatures.

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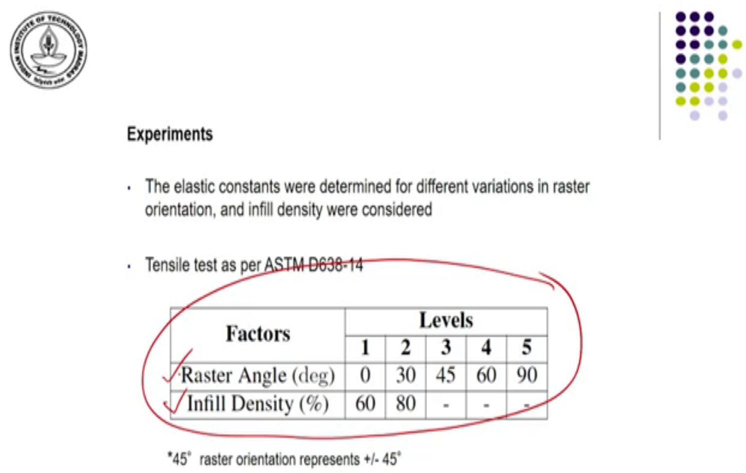

Factors	Levels				
	1	2	3	4	5
Raster Angle (deg)	0	30	45	60	90
Infill Density (%)	60	80	-	-	-

So, here I am just quoting some example work. So, this is the experimental framework to understand the effect of various process parameters like the raster angle or the infill density and the part strength. By varying these one can create the sample mechanical test pieces or the tensile coupons and estimate these constants.

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So, these are the example test coupons to understand the stress strain behaviour.

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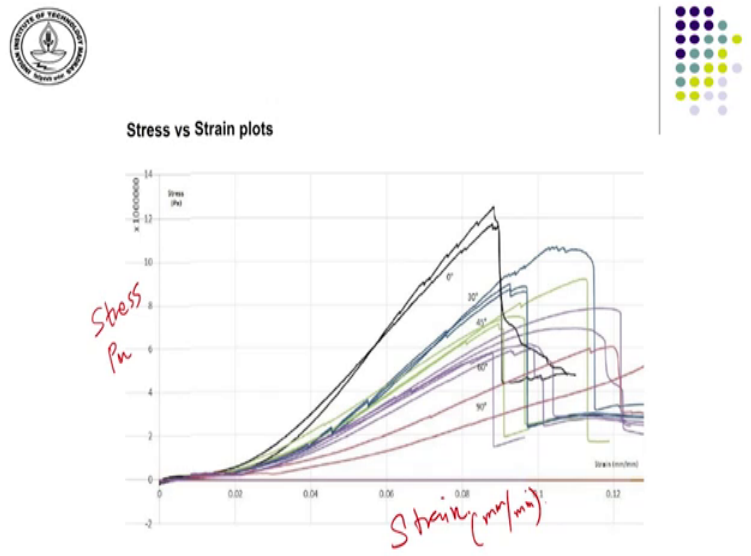

So, once we have the stress strain relationship, this can be used inside the model to estimate or to predict the model response.

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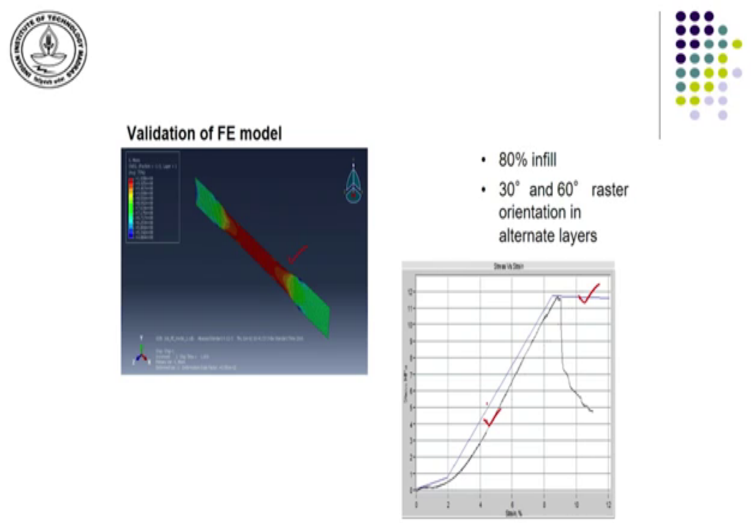

So, what we see here is a validation of such a computational model this is a computational domain and here we see the computational models response, against an experimental response. So, once we have these kind of validated models, we can use these models in an optimization framework to optimize the part design considering these process variables.

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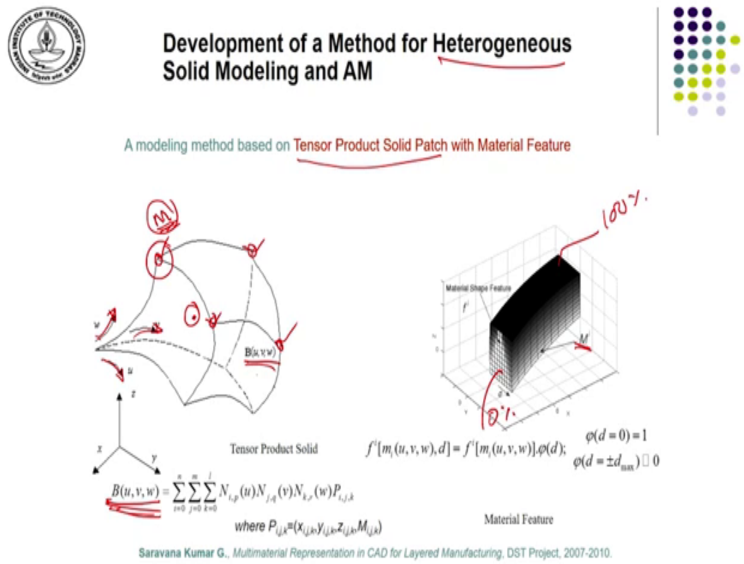

The additive manufacturing as I have described before can help in creating heterogeneous parts. And traditional cad models only store the boundary information they do not have the volumetric information. So, lot of developments have happened or are happening in the direction of trying to incorporate modeling framework which will enable the design to have such heterogeneity. And thereby the same could be used in the manufacturing process which is the additive manufacturing process.

And since we can create functionally graded parts or parts with multiple materials, one can optimize and get better designs both from light weighting perspective or for an enhanced functionality for a given you know choice of materials. To represent the volume one can go with several different approaches, one of the approach is to use a tensor product solid patch; where we represent solid as a trivariate entity that is which varies with parameters that is u, v and w.

One can use a b's plane or a basis function to obtain the interpolating function for a given domain. And once we have the control points say, the corner points or other you know control points. Then any other position vector can be modeled as a interpolation of location of these control points. So, along with these geometric characteristics that is the location of the control point, one can also have material features associated with each of these control points. So, once I have a material feature associated with each of the control points, these basis functions will interpolate the material feature to give an information about specific material attribute at a given location in the object.

As an example to the right you see one material feature which is the density of the solid. And you see a variation in terms of grayscale in this solid domain. You see dark face here meaning 100 percent dense and you have regions which are fairly very close to say 0 percent dense. So, one can think of modeling varying porosity object or varying density object using this approach, the same modeling approach can also model varying alloy composition. Because if I choose this m to represent the concentration of a specific alloying element, then one can think of this modeling framework to model a varying alloying you know composition in the given domain.

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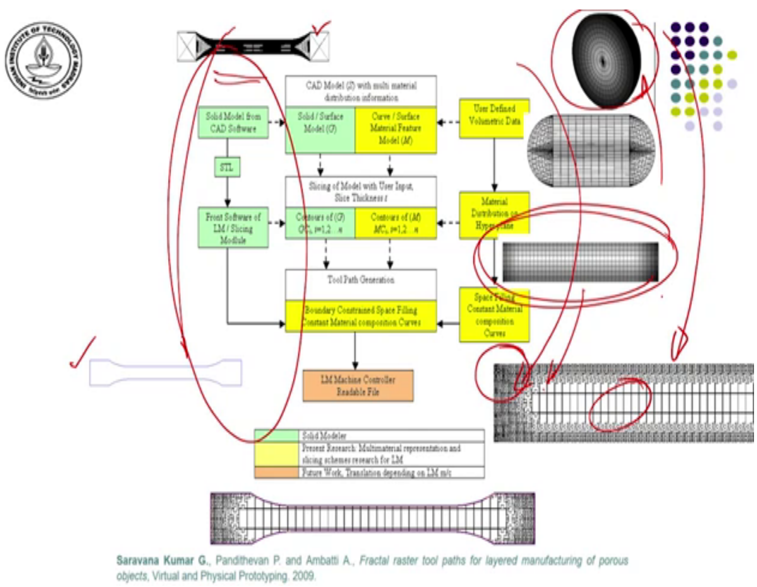

As an example, I will show a framework where this is used to create varying porosity model. So, this is a conventional modeling and the processing framework where we have the cad model of the solid object which is a surface file. And which is used to create the layer wise data and fabricator. In the volumetric approach which is shown on the right side. Apart from the geometric information that is available or which is being processed in the lefts in the left side of the framework, we also have the volumetric distribution of the material and the corresponding layer distribution of the material and which is being translated to additive manufacturing using tool parts.

So, one can presume these parts that are shown here as parts taken by the nozzle which is depositing the material or one can think of this as the parts that are being traced by the laser to sinter the material. So, we can see that more material is deposited or sintered in this region as compared to this region. There by creating the material heterogeneity as described in this layer by this model. So, we have a geometric model, along with that we have a volumetric description of how the material heterogeneity should be there and combining this 2 one could create parts which are heterogeneous. And the such modeling framework can be used to design and optimize heterogeneous objects.

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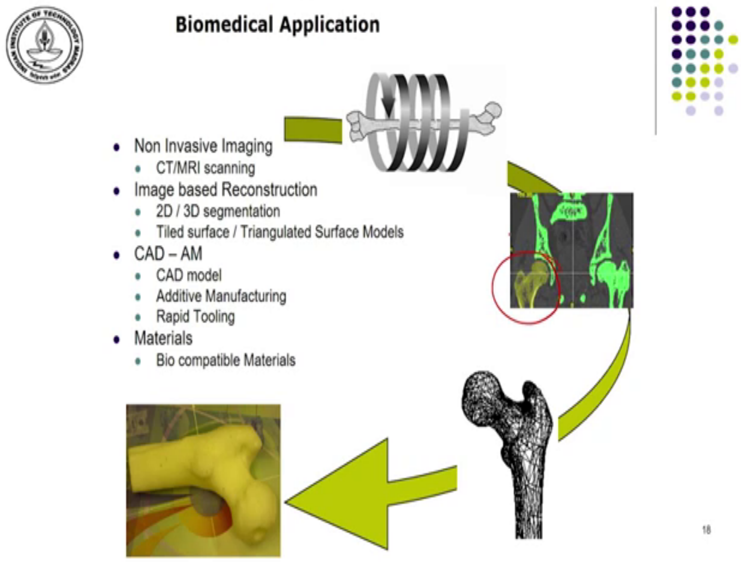

There are lot of applications to this one of the application domain that one can think of is trying to understand how the bones which are the natural bones are heterogeneous; which have varying density the trabecular bone the cortical bone they have different densities and one can use such modeling frameworks to create implants which will mimic the bone or one can think of using these as tissue engineering scaffolds. So, there are plethora of applications which can use these kind of modeling frameworks.

So, I have shown few challenges that are available when we want to use this additive manufacturing as an enabler to the design. So, one of the challenge is the mass customization. How do we rapidly create geometric models, which can be mass customized? And the other area of understanding is how the complex geometry and material heterogeneity can be used for creating novel designs or novel application and create modeling frameworks which will enable modeling such complex geometries are or complex material variation.

Complex geometries are already been enabled using topology optimization framework. One has to also now have frameworks which can use a heterogeneous material distribution or functionally graded material materials and try to create object or part design frameworks which can use these enabling factors. One has to also understand how the additive manufacturing process will have an effect on the surface quality or the parts strength and how to develop predictive models that will enable the design of such parts.

So, as a new technology as a enabling technology, the technology poses several challenges and development scope in the domain of design. And looking at design for additive manufacturing is one of the very prosperous areas that will enable development of a novel designs using this technology.

Thank you.