

# **Advances in Additive Manufacturing of Materials: Current status and emerging opportunities**

**Prof. Bikramjit Basu**

**Materials Research Center, Indian Institute of Science, Bangalore**

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welcome back to this NPTEL course on additive manufacturing. In today's lecture I am going to continue my discussion on SLM printing of lattice structures but I will show you that how lattice structures can be printed using stainless steel 316 alloy. stainless steel 316 alloy, it has this D50, so this is the particle size and you can see particle size varies between 10 to 100 micron. It is a pure gamma austenitic phase and we are using the laser powder based fusion processes. And, you can see that you might have seen number of times that how SLM printing takes place in industry. when I was showing you some of the experimental results in our discussion on process science, I have shown you how linear energy density is important and this you can see that energy density and porosity.

If these two things are varied then you can say there is a lack of fusion related porosity and key-holing related porosity and this particular curve actually goes down remains flat and then increases. here what you see in the process map you have a laser power and you have a scan speed. this is the specific region which is the region of the conductions and you can see that this is the acceptable range without any defect. Outside the region you will have either balling the blue one or lack of fusion.

this is the balling region. This is the lack of fusion region and this is the key holding region. these particular regions there are specific defects which are intrinsic to SLM processes. In case of stainless steel 316 alloy this D10 is 21, D50 is 32 and D90 is 48.5 micron.

From the SEM images of the morphology it should be very clear that it has perfect spherical morphology which is what is desired or which is required for SLM based printing. while constructing the printability map, we have also used the machine learning, but those I am going to cover it in the subsequent lectures. What I have mentioned in the discussion of an earlier lecture that one can vary the scan speed and laser power and by varying the scan speed and laser power you can essentially investigate that what kind of defects that it can generate. And those defects can be plotted as a function of the process parameters and you can see that how key-holing also diameter to width ratio can be changed in this specific defect region. What we would like to have always in particular

engineering applications, we would like to have conduction region, This is the conduction region and this is the most acceptable combination of process parameters which are required.

Roughness of the additively manufactured sample this roughness you know you can see this roughness can be around 6 to 8 micron and volumetric energy density it can go up in up to 100 joules per millimeter. And this roughness as the layer thickness goes, if you see the trend as the layer thickness goes up to 90 microns, the roughness will also go up to 3 micron, the surface roughness is somehow related, is certainly related to the layer thickness that you use in the additive manufacturing technique. Now universal testing machine or tensile testing is very very commonly used in almost all university research labs and which what particularly important here this digital image contrast setup which is being attached to this particular UTM and also UTM is equative strain gauge. When you have this strain gauge and also DIC setup you are essentially very sure that you are reliably measuring the strain. this strain property therefore the elastic modulus values what you report is also reliably determined.

the use of strain gauge and use of DIC setup essentially are useful not only for reliable measurement but also to see how the material deforms, how the damage accumulates and progresses leading to the failure of the materials. what you see here you are essentially seeing that different process parameter combinations like laser power and scan speed and also hatch spacing. Hatch spacing can go from 100 to 140 micrometer and layer thickness can go from 30 to 90 micrometer. independent of this combination of the process parameters, what you see here very clearly that the relative density you are getting is very close to full density like 99.8% and above.

And when you are using the different type of samples samples in UTM machine what you see that their elastic modulus properties is almost same. The elastic modulus this is very clear and then the strain to failure is different. Maximum strain to failure is 80% that is recorded, but for other materials strain to failure is decreased to 60%. And you can see also the yield strength it can vary from 400 to some around 550 megapascal which is very common for the metallurgically processed stainless steel 316L materials. Now what you see also that when you use the DIC digital image contrast.

You can always see that you know at the onset of nicking and then how the plastic flow also spreads during the continuous deformation processes. materials is experiencing tension and you can see the occurrence of the material And in this particular region, you can see that if you step it up at fracture is epsilon 53%, you can see this particular area reduction cross sectional area is much more compared to the increase in the length. And this is the case for the uniform deformation. Uniform deformation essentially means the

increase in the length is commensurate with the decrease in the cross sectional area. therefore, the material deforms very nicely.

There is no anisotropic deformation behavior. But in the necking conditions this triaxillary stress condition arises and in the necking region you know you have more localized strain and then also in the necking region the reduction across this area is much more than increase in the length. you can see in this video that as the material deforms under tension then you can just look at this particular region here that how the necking I can run this video again. This is the video taken at that materials engineering at Indian Institute of science using the DIC setup. available at Professor Praveen Kumar's facility, you can see how  $\epsilon_{yy}$  here right that changes, so it is 2.

35 here. And this is the region the necking actually sets in. This is the total red area is the gauge length. Gauge length is the area in the undeformed sample it has uniform cross section. having uniform cross section is important because the material is then will then experience uniform deformation under the tensile loading. And this kind of curvature, this kind of tensile sample is also known as a dog bone geometry.

This kind of curvature and this kind of shape of the sample is also known as dog bone shaped samples and this is according to the ASTM standard, this particular samples are being prepared, what is the gauge length and what is the initial cross section area, what I am trying to show you here it is possible as the material deforms you can essentially capture the tensile strain and you can see that one of the strain tensor is  $\epsilon_{yy}$  and that essentially you can measure dynamically during the tensile experiment. one of the things that is very important in 3D printing and that in the community it is quite known that because of the nature of the 3D printing processes, one can expect that the 3D printed materials or 3D printed components will have anisotropic properties. anisotropic properties means that you are essentially building layer by layer materials, if you consider that in the build direction and transverse to the build directions, the material properties will be very different, if you take the tensile coupon samples. what I am trying to show you is that for example, materials is getting printed in a layer by layer manner, Now, you are trying to see that whether this material will have anisotropic properties. you are taking a coupon samples, what we call dog bone type of geometry in this direction, in the build directions.

you also essentially measure the tensile properties in the transverse to the build directions. If there is differences in properties, In most often, in almost many 3D printed components people have reported that depending on whether you measure the properties in the build direction BD or transverse direction TD, the properties will be different and that is very inherent to the 3D printing processes and this is what I was telling about the

anisotropic properties. there is two way you can see that in the horizontal directions that is you know when you essentially strain them. what happens? This is the stress strain plot and what you can see this is the combination of V is equal to 500 millimeter per second. P is 180 watt, h is 140 micron.

AP stands for as processed and heat treatment 1 there is one type of heat treatment, heat treatment 2 there is a different combination of heat treatment conditions. what you see and then we have taken multiple samples like for as processed let us say 3 samples, for HT1 three samples, HT2 three samples. We are also trying to see reproducibility in the properties while understanding the anisotropic properties by measuring the tensile properties along the peel direction, transfers to the peel direction. more or less what is the common here in every plot is that the material behave in an elastic plastic manner. Their strain to failure is roughly restricted up to 60%, .

In some cases, in case of the high LT values, it goes up to 90 micron, then the strain to failure decrease to 40%. Otherwise, you know this strain to failure is mostly 50 to 60%. that is number 1. Number 2 is that ultimate tensile strength in almost all the cases is around 700 megapascal except in the last plot. However, depending on the as processed to HT1 to HT2, we are able to see HT1 perhaps is giving maximum better combination of the strength and ductility properties.

essentially what we are trying to see is that strength ductility combination. You would agree with me irrespective of these process conditions elastic modulus is constant and typically this elastic modulus is around 210 gigapascal. There is no difference in the slope. In the case of the vertical case, we essentially see little bit lower strength properties like around 600 megapascal. In some cases, it goes above 600 megapascal.

Here again, compared to the as processed perhaps HT1 heat treat after heat treatment, the material has better ductility. it is not only strength because strength is essentially quite good and that is the strength properties one would get also metallurgically processed or conventionally manufactured SS316. What we are more interested to see because of the inherent microporosity in the 3D printed structures which I have emphasized in some of the previous lectures, whether we are compromising the ductility property of the materials. therefore I put a star so that you do not forget in the 3D printed structures it is important to maintain the strength ductility combination. While maintaining high strength is important but at the same time having good ductility is also equally important.

And you can see that you know different orientation like vertical, horizontal orientations for different process parameters, how you get different combination of ductility like in all the cases when it is vertically oriented it has a better ductility. And then strength, yield

strength and ductility. Ultimate tensile strength is lowered, yield strength is lowered. essentially horizontal it has little lower ductility but better strength properties. Vertical orientation has lower strength properties, better ductility.

it clearly shows that there is sign of anisotropic properties in this 3D printed structures. Now mechanical properties wise, AP is the as processed, AN is the annealed. it was annealed in 1095 degree Celsius 1 hour. These are laser powder based fusion processes. Now when you compare with the metallurgically processed stainless steel 316L materials, this is the wrought materials.

This is as cast and this is annealed sample and what you see here in the as cast you have 365 this is the yield strength close to 600 is UTS and elongation is 70%. if you compare with the UTS is close to 600 megapascal. and elongation to failure is 70%, 70% is epsilon f elongation to failure, you will see that even in the present work you are getting almost close to that combinations. But only thing you have to notice that if the strength is 661, elongation to failure is 53%. If the strength is little lower 544, elongation to failure is 83%.

If the strength is modest close to 600, elongation is 69% it is possible to optimize the heat treatment conditions. in the 3D printed stainless steel 316L to obtain what one can get in the as cast and annealed structures of the same material this is the combination that I was trying to show you. Now, what you see in this particular slide is that how complex structures, so earlier I have mentioned that triply periodic minimal surface TPMS structure that is the combination of the lattice structures, now what you see here in this particular slide that how one can design different strut thickness in a face centered cubic FCC structure where cell size is around 1 millimeter. earlier unit cell dimensions were varied from 2.

5, 2.7 and 3 millimeter. Here the strut thickness is varied 160 micron, 240 micron and 340 micron. Now, we have designed these struts, so more the thickness, lesser is the porosity, inter-strut porosity, that should be very clear, And if you look at the cell size, it is a faceted cubic structure, but from these particular design descriptions, it should be very clear that this kind of complex strut interconnections, It is very difficult to do it in the conventional manufacturing which is why additive manufacturing has attracted wider attention. Now, what we have done? First, we have designed the structure, then we have established the 3D printability of the structure or 3D printing manufacturability of the structures. We have not only made this coupon samples, you can see this is the coupon samples, like this is the sample volume 25 by 10 by 4 millimeter cube. So, it is 25 is the long directions, width is the 10 millimeter, height is your 4 millimeter.

Now, the same tensile samples you can process and you can measure the tensile properties. Ultimately, when we are satisfied with this either 160 or 240 or 340 micron strut size, we have also fabricated femoral stem. of the similar 160 micron strut or 340 micron strut. We have designed the femoral stem and we have essentially made attempts to use the SLM technique to manufacture this kind of femoral stems. Let us see what is the results we have got.

we have done, we have essentially varied different combination of 3D printing parameters like laser power, scan speed and energy density. what is the strut thickness and what is the width, these two parameters are varied and after varying so many different parameters, we are able to get this is the kind of femoral stem components, right. We are also trying to find out that what is the density of the different struts in this particular case and we have found out that 160 micron, 240 and 280 micron, there is a local thickness of the struts that we have measured and we have also measured actual strut thickness and how they essentially correlate to each other. You can see the vertical side these are mostly close to the 45 degree line. In the one is that below or one is above there that we can see certain variation between the local thickness and actual strut thickness.

we have done microcomputed tomography analysis. This is a typical analysis that we always do to characterize the 3D structures, 3D lattice structures and you can see micro CT images of the different strut size 240 micron to 340 micron. You can see the 3D view of the lattice structures, how they are generated in the as printed structures. we have also quantitatively analyzed what is the distribution of the pore size and what is the lattice design strut structures. You can see while this is the 240 micron, this should be the mean but how this strut thickness is also distributed across the 3-dimensional space.

At the same time you can see that what is the porosity. Porosity is roughly around 200-300 microns. This is relatively large size porosity for typically for osseointegration purpose the porosity is 100 to 200 micron. overall in last two lectures, I have emphasized that how 3D printing and one of its or in particular the selected laser melting or directed energy deposition. can be scientifically studied to establish the process map of any material and I have taken 2 model materials, one is the stainless steel 316L and one is Ti6Al4V and both these two model materials I have shown you that not only the construction of the process map but also showed you the different defects and all subsequently I have also shown you that how the complex lattice structures whether it is strictly periodic minimal surface structures or this is the complex strut structures can be printed.

with good quality and what is the quantitative analysis of the strut thickness distribution

or pore size distribution. And more importantly, how the different TPMA structures of different unit cell dimensions can be constructed and tested to mimic the properties of the cortical bone structures and there we have shown this larger the unit cell diameters more is the reduction in the elastic modulus as well as strength properties and it is possible to mimic the the cortical bone properties with higher unit cell dimensions like 4 millimeter or so. I hope you are happy to see the different examples in last two lectures and so that you will also firmly believe that 3D printing, additive manufacturing indeed has great potential and has demonstrated its potential to manufacture the complex design structures in a reasonable and reproducible manner. not only in one materials but also multiple materials which are of larger engineering relevance. And these two materials that I have shown you is Ti6Al4V and stainless steel 316L materials.

I will come back to you with other scientific contents that are part of this NPTEL course syllabus. Thank you.