

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

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Lecture 12

In this lecture I will be presenting first scientific case study on the binder jet 3D printing of titanium 6 aluminum 4 vanadium. This titanium 6 aluminum 4 vanadium is one of the material which is used for spectrum of applications from aerospace to biomedical applications. We have started working on the binder jet 3D printing. We have started the first material that we have tried is the Ti6Al4V and we have used several binders. The first binder is a starch based ink. What are the experimental details? We have used this maltodextrin and deionized water in 1 is to 5 ratio and we have used certain additives like sodium azide, 1% triton X surfactant, layer thickness we kept it at 100 micron and binder saturation was 60 to 80% the shell to core.

what is core and what is shell mode of printing that I am showing here. And then I am going to show another scientific case study in the subsequent lectures where I will show that this core shell mode of printing essentially is not advantageous for ceramics and it leads to inhomogeneous microstructure and properties. But for metals It has not been that challenging and we have used some binder saturation 60 to 80% and what is the definition of binder saturation that is how much is the volume of binder to feature volume to be printed. That means 60% of the volume of the binder is used to print certain feature volume.

These are like interior areas of the core printed at lower saturation and this is the exterior walls that is printed at the higher saturation. This particular binder which was essentially maltodextrin and deionized based, it has a viscosity of around 4.2 millipascal second and ideally for binder jet printing the viscosity should be less than 30 millipascal second. That is fine, surface tension of the binder is 21.8 millinewton per meter and for deionized water it is 72.

Surface tension is greatly reduced by the use of maltodextrin pH is 6.5. Simple CAD models were constructed and one with gradient porosity, one is that uniform porosity, evenly porous means uniform porosity and one is gradient porosity. And then when these CAD models were exported to the 3D printer and then we printed then subsequently we

sintered it and we have found out that what is the as printed architecture and this is what is the shrinkage that was taken place from as printed to post processed cylindrical constructs. We also made some attempts but we need to still work on it that is that stem, femoral stem part of this materials and then what we did not do is that we find it challenging to fabricate femoral stem component with clinically acceptable strength properties and therefore we still need to work on that.

Now in terms of the homogeneously porous scaffolds and graded porous scaffolds we found in the lateral directions it is 22% shrinkage and in the longitudinal is 27% shrinkage. But the graded porous materials is much better because in both the directions we have found the uniform shrinkage. But homogeneously porous you have certain anisotropic shrinkage properties. From the manufacturing perspective, I think this uniform porous, uniform shrinkage and non-anisotropic shrinkage is much better. We use microcomputed tomography analysis.

This micro CT analysis is something that I have taught you before, right. Just to recall micro CT essentially uses the high energy X-ray beam. It is like 70 kilo volt X-ray beam. And in this particularly high energy X-ray beam which is focused on a 3D object, then it gives you 2D slices on the 2D projections, what we call ortho slices. Now, this 2D ortho slices when this reconstructed in a Z directions, then you get 3D reconstructed volume.

What you see here? These are essentially 3D reconstructed volume and this 3D reconstructed volume you can clearly see these are like porosity, these are like pores. And this is actually taken from this is your region of interest or volume of interest and this volume of interest when you put it in x, y, z directions you get this kind of porous structures. And we are more interested in the gradient in porosity and then see that by introducing the gradient in porosity you can develop better properties or properties are being optimized or compromised. We have used a specific software platform. This is Avizo software which are used for quantitative analysis of the 3D microstructure.

What we have done, we have taken this 3D microcomputed tomography results and then used as an input to the ANSYS workbench. There are 2 ways you can do this biomechanical analysis, one is that you essentially give original CAD models as an input to the ANSYS platform like either CAD models of the uniform porosity like even the porous or gradient porosity to the CAD model. But remember when you are doing compression tests on the cylindrical constructs like this, in this compression study The samples which are being 3D printed and post process, they do not have designed porosity like the way that you have made or that you have introduced in the 3D CAD model. Because they have micro porosity, very small pore size which are inherent in any 3D binder jet printing. Plus, there are shrinkages which are associated with this binder jet 3D

printing and post processing heat treatment or post processing sintering.

All these essentially change the 3D microstructure of the material. post printed of the as printed or post processed component compared to what you see in the 3D CAD model, right. Therefore, it is important for one to understand that after micro CT that whatever 3D reconstructed image that you get for entire cylindrical structure, it is better to use that as an input to the finite element analysis. And this has 3D printed scaffolds with design porosity and micropores and this structure with porosity input for effective material properties for finite element analysis. What you see here this is 600,000 elements in finite element model and from the finite element model analysis you know that finer the mesh size around the pores the better approximation, the better is the approximated material properties you get.

Compress and then what you have used in the mesh is this 10-noded tetrahedral elements that we used in the finite element analysis. You have the compression. linear response and then like any other brittle materials because it has lot of porosity it behaves more like a ceramic materials. Because I have shown you in earlier lectures that ceramics how they behave under compression and if you remember correctly then it is a linear response then non-linear yielding of the materials. After reaching the maximum load, then it shows a gradual decrease of the falling load part and this is what exactly has been shown here as I have put the arrow here.

From this initial part, linear part you can find the slope and then slope essentially shows you that what is the elastic modulus. What is the dotted line? Dotted line essentially is the finite element approximation. What is the thick line? Thick line is essentially your experimental results. Here finite element analysis only can provide you the linear response part, not the non-linear response part because here the model is the linear elastic model. This homogeneously porous CAD model was scaled down anisotropically considered anisotropic shrinkage while the gradient porous scaffolds were scaled down homogeneously in lateral and longitudinal directions.

Because if you remember in the gradient porous scaffolds, this has undergone uniform shrinkage both in lateral and longitudinal direction of 22%. uniformly porous materials, scaffolds that has undergone anisotropic shrinkage. What you see this is that same 3D binderjetted microporous scaffold. You can get this compression strength up to around 200 megapascal, somewhere around 200 megapascal. And this shows a very linear increase and this kind of non-linear initial part can be neglected because there the samples is getting settled during the placement of the samples on the machine.

This is more distribution, more results on the analysis of the stresses around the pores.

What you see from the earlier slides that in our finite element model around the pores, this is the uniform pore size, right and around the pores this mesh concentration increased, right to capture more realistic distribution of stresses. for the same 3D reconstructed images when you consider the Von Mises stresses, local stress distribution around the pores, σ_{yy} is in Pascal, so it is 10 to the power 6, this is mega Pascal. So, it is 1.3 mega Pascal, so around the pores and around the pores if you see this is the reddish region, this is the more stress concentration.

In the gradient porous region where there is a pore size there is a gradient initially in the very small pores going to the large pores and here stress concentration is more and what you see here that red region essentially represent 7.6 mega Pascal. This is the more stress concentration here compared to the homogeneously porous structures. This is just a comparison between experiments and finite element analysis and what you see in the experiments and finite element analysis in both the cases captures very clearly the experimentally measured linear response with similar kind of slopes that means the modulus also are very similar. The elastic modulus in the graded porous scaffolds is 3.

3 gigapascal whereas you know cortical bone has 2 to 12 gigapascal and we can be used as a cortical bone replacement material. Compression properties in case of homogeneous porosity, total porosity is around 57 volume percent whereas in case of gradient porous structures, total porosity is 45 percent. elastic modulus and compressive strength is more in the less dense hatched region as compared to the more dense hatched region and this is the elastic modulus, this is the left one. Now, if you compare between uniformly porous and gradient porous, the elastic modulus is certainly more, one is around 2, one is around 3.

2 gigapascal. If you compare the strength, strength also increased in the clearly from almost like 40 MPa to around 90 MPa which is more than 2 times strength increase in gradient porous. It is very clear that gradient porous structures, so gradient porous structures have better compression properties. That is very clear, right. Last several such slides as part of this scientific case study, what you have learnt this how to basically design simple cylindrical structures with uniform gradient porosity using SOLIDWORKS as a computational platforms. Then how to do finite element analysis, essentially by constraining on one end of the cylinder, applying the load on the other end and then by introducing the concentrated mesh around the pores so that you can capture realistic distribution of the stresses.

And from there you can also see that how the strength profile can be predicted in case of the homogeneously porous structures and gradiently porous structures. In both the cases linear responses in the FE can clearly show that linear responses is very close to that of

the experimentally measured linear response. One of the things that we have learned that when you use finite element analysis and these experiments together particularly in the context of 3D printing or metal 3D printing, one has to use the final component structure after the 3D printing is over and post processing is over that particular 3D structure. as an input to the finite element model and certainly not the initial component design which you have produced in the CAD models on the SOLIDWORKS platform or similar platform. Simply because that when you do 3D printing and post processing material undergo shrinkage, material develops micro porosity which is inherent disadvantage of this 3D printing based processes which you cannot avoid.

And all those microstructural elements or all those defect elements cannot be captured a priori in the design file on the CAD model. So, therefore, I repeat micro CT based 3D reconstructed images must be used as an input to the finite element model and then only you can get very good correlation with the experimental results. We have also seen that how this stress concentration particularly σ_{yy} actually varies in both homogeneously porous and gradiently porous materials. And these materials were essentially printed using starch based binder like maltodextrin added to deionized water. Therefore, surface tension is much lower than that of deionized water.

And, then viscosity is also within the range that of the printable binder range. This scientific case study was essentially published a few years ago. And, again the lead author was Srimanta Barui who is currently postdoc in United States. And, it is 3D powder printed Ti6Al4V scaffolds with design porosity. Overall this kind of study can be conducted and then I must emphasize that there is a need to do both the experiments and computational analysis or theoretical analysis in the 3D printing community so that our understanding will be based on a more solid platform to realize these processes and properties in a much better predictable manner.

I will continue with more case studies, scientific case studies in the next few lectures related to the binder jet 3D printing and subsequently I will start with the process science description of the laser based 3D printing because I believe that you know binder jet 3D printing does not involve the use of any laser beam or any electron beam. It is much more simpler process wise but at the same time it is not extremely well understood when it is process science was explored. And then we have discussed that process science and also we will discuss more scientific case study. you will be in a position to appreciate the use of the binder jet 3D printing not only for metals but also for ceramics and then I will show you couple of examples through the case study to substantiate our discussion in today's lecture. Thank you.