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

Prof. Bikramjit Basu

Materials Research Center, Indian Institute of Science, Bangalore

Lecture 22

Scientific case study:SLM Printing of Ti6Al4V lattice structures and properties

Welcome back to this NPTEL course on additive manufacturing. In today's lecture I am going to continue my discussion on SLM printing but with a scientific case study. In previous lectures I have covered the process science of the SLM or DED printing and I have also emphasized that how multiple parameters both from the processing aspects of the 3D printing parameter aspect as well as material properties particularly powder particle size distribution and also the powder bed properties those influence the quality of the 3D printed products both in terms of the defects that are contained in the as printed parts as well as consequently the properties of this 3D printed parts. In this specific scientific case study, I will be showing you some of the experimental results from our own research group to illustrate how selected laser melting or selected laser sintering both are synonymous can be used to print some of the complex structures. Because if you remember correctly in many introductory lectures of this NPTEL course I have emphasized that one of the fundamental advantages of additive manufacturing is its ability to manufacture or to produce or to create complex structured parts which is otherwise extremely challenging when one uses conventional manufacturing route. in order to substantiate that statement I will be showing you that how this some of the complex lattice structures can be printed using this SLM printing and the material under investigation is titanium 6 aluminium 4 vanadium.

Just to give you some of the clinical perspective of what I am going to show you now in this particular slide what you see it is this video is essentially total hip joint replacement devices, how they are inserted into the damaged hip or that when a patient has experienced the hip fracture and when natural joint is not anymore functioning and one has to replace the natural joint by the artificial hip joint. first the orthopedic surgeon creates acetabulum then they place this acetabulum into the acetabulum cavity in this damaged cavity and after the acetabulum is placed then they will fix the femoral stem, this femoral stem is inserted along with femoral head then femoral head is inserted and then this will be articulating to restore the normal hip function. Now, this particular material is this particular femoral stem what I am showing you, this is made up of the Ti6Al4V that has been written here Ti6Al4V or stainless steel 316L. And femoral head is typically cobalt chrome.

Femoral head can be also ceramic. let me also write down those things. this is the stainless steel 316L. femoral head can be cobalt chrome or zirconia toughened alumina. and acetabular liner is ultra-high molecular weight polyethylene, UHMWPE stands for ultra-high molecular weight polyethylene.

this is the plastic liner, this is the ultra-high molecular weight polyethylene. This acetabular component is again made up of the Ti6Al4V this metallic materials are used for the femoral stem manufacturing. Metallic materials is also used for the acetabular component that acetabular socket manufacturing. And this entire things is called acetabulum and there are 2 ways you can place this total hip joint replacement device, one by using polymethyl methacrylate bone cement. PMMA bone cement.

when you see that acetabulum is placed, so if you see in this video that when the acetabulum is placed, then this acetabulum is essentially placed with the polymethyl methacrylate. So, this is for cemented total hip arthroplasty In case of uncemented, this acetabulum is essentially, so at the place of acetabulum, both the acetabular component and plastic liner is directly placed and then femoral head comes in direct contact with this acetabulum. this is that uncemented total hip replacement. Now, what you see in that acetabular shell or acetabular socket what we see this is made of the titanium 6 aluminum 4 vanadium and this is also stainless steel 316L. In this material is outer surface of this material is in direct contact with the host bone.

And therefore, their osseointegration is very important. what people used to, what industry used to do and then patient used to receive this total hip arthroplasty devices is that you can put hydroxyapatite coating onto it And hydroxyapatite, why hydroxyapatite? Because hydroxyapatite or HA or many people they are in the scientific community people also use HAP, hydroxyapatite, it is the inorganic component of the natural bone. there is a likelihood that if you give this hydroxyapatite coating, then the osseointegration or integration with the host bone of the acetabulum component is much more improved. Alternatively, one can also use the lattice structure design. this is the hydroxyapatite coating or this can be lattice structure.

this lattice structure essentially will give certain roughness and what clinically it has been observed or clinically it has been recorded that this lattice structure acetabular shell will have similar osseointegration properties like hydroxyapatite coated acetabular shell. Therefore these are the two materials based approach to improve the osseointegration or intense with host bone, one is the hydroxyapatite coating or one is a lattice structure on the outer surface of the cell. Total hip arthroplasty is used in elderly patients and thick wall acetabular liner is used and PMMA bone cement is used. Now, what you see in case of the un-cemented, this is more used for younger patients and porous hydroxyapatite for acetabular shell for improved osseointegration. this is that entire things, so one of the main things in the acetabular liner is that there is a human disease called reduction of bone density or osteopenia because of typical stress from the bone by the implant and bone is known to remodel.

in response to the mechanical stimulus according to the Wolff's law and bone as a smart material reserves the zone of stress shielding. suppose this is the application of load, now if there is a low stress is generated in the bone in this region which causes resorption, this is the low stress region. And in case of load is transmitted through the trabeculae of the cancellous bone, the load is essentially transferred to the cortical bone. Now, typically the bone structure, this is the normal hip bone structure you can see. in the normal hip bone structure, internal structure is more trabecular bone.

trabecular bone is also known as spongy bone or porous bone structure. Cortical bone, as you see this cortical bone is a dense structure Cortical bone is dense structure. if it is a dense structure, this particular bone has much better properties. Now if you look at this yield strength versus elastic modulus, you have seen these things in our description on mechanical properties of materials. So what you see in the yield strength versus elastic modulus and if you see that this particular plot essentially distinguishes the cancellous bone properties that is the spongy bone properties and cortical bone properties.

And cortical bone properties, if you look at the elastic modulus, it is somewhere around 10 to 30 gigapascal, whereas cancellous bone properties is 20 gigapascal. much less than 10 gigapascal. Whereas yield strength or strength wise cortical bone has much much higher strength than the cancellous bone because cancellous bone is a spongy bone it is a porous structure therefore mechanically weaker. It is very difficult to mimic the cortical bone like properties using any artificial or synthetic materials like whether stainless steel or titanium and so on. Metallic lattices or lattice structure is one of those approaches that I am going to discuss which can be used to mimic fairly closely to the properties of the cortical bone properties that I am going to show you.

in the next few slide. What is lattice structure? Lattice structure is the interconnected network of struts which can reduce stress shielding that in the high strength to weight ratio and increase bone growth because it has a high surface area to volume ratio. And varying densities and pore sizes of lattice structures tailors the mechanical properties of the implant closer to the bone anatomy. Now just you can look at this lattice structure, the left figure that is acetabular cell with lattice architecture and this is a conventional manufactured of the femoral stem. You can also give lattice structure on the femoral stem.

So there are two places where you can give lattice structure. One is this femoral stem and one is this acetabular shell This has been mentioned. this is one is this component and one is this particular component. this has been shown here as well. you can see this is that SLM printed lattice structure.

this is also lattice structure, lattice architecture, this is femoral stem. I wish to introduce you to the lattice structure. Lattice structure essentially can be described by various combination of the interconnected struts architecture as I mentioned few minutes ago. this is one such structure what is called TPMS unit cell, triply periodic minimal surface you can see that as the name suggests that means the periodicity in space is triply periodic minimal surface. what you see natural TPMA structures are found in wings of butterfly and weevil of exoskeletons.

this is that one such example of the natural structure. Now, if you put this live animal structure under microscope and you zoom it, you will see that what kind of structure it has. Now, the question is that whether it will be easier to replicate this kind of structures in artificial materials, to what extent this kind of complexity can be brought onto the design of materials and that specific complex designs can be manufactured. design is not enough. One has to manufacture this kind of structures using 3D printing.

there are three structures I have mentioned here Schoen gyroid, then Schwarz diamond and Neovius. And this structure their isosurfaces can be described by a combination of cosine and sine function. And periodicity is essentially defined by a factor called ki where ki is equal to 2pi ni/ li. this essentially t is equal to constant to alter the relative density. Now, this particular, T parameter This is the T parameter.

both this first two structures, this T parameter is there, but Neovius structure is T parameter is 0. Now, if you look at this sine and cosine function, it is simply not sine x. or it is not cos x. , it is cos ky y and ky is equal to 2 pi ny / ly. i can be x, y, z that has been mentioned in the periodicity.

these periodicity values what you can see in this video, this particular lattice structure is essentially being printed using the SLM technique. And what is the parameter that has been optimized, scan speed is 3000 millimeter per second, power is 120 watt. then hatch spacing is 113 micron. You can see that there is lot of optimization has gone into this experimental research and thereby we are able to print this kind of as printed structures and this their unit cell is this size like either 2.

5 millimeter, 2.7 millimeter and 3 millimeter. we have started with this particular unit cell

structure because we are not knowing that what kind of unit cell size would give the best combination of the mechanical properties. therefore, we have done 3D printed tensile coupon, tensile bar and this tensile bar as you can see when there is a gauge length, this is the gauge length region. In this gauge length region, we have introduced the lattice structure and that we not only we printed but also we have investigated using the microcomputed tomography and you can see in the microcomputed tomography how these 2D orthoslices were manufactured. As I said that typically cortical bone structure has elastic modulus is of the order of 10 to 30 gigapascal or little bit higher up to 50 to 60 gigapascal.

We are more interested to know if this kind of structure can be used. to mimic the cortical bone properties and for example for that we have used universal testing machine in tensile mode and this was attached with digital image contrast facility which can essentially capture the images as the material experiences tensile strain of different amount For example, epsilon is 0.008, you can see that how the 2.5, 2.7 and 3 millimetre, for example, this is the 3 millimetre, this is 2.

7, this is 2.5. essentially 2.5, 2.7 and 3 millimetre unit cell size this kind of lattice structures experience the tensile stress strain response. what you see very clearly that initial part is perfectly linear. and that is followed by nonlinear part and this nonlinear part goes up to the strain value of roughly around 0.02. , this nonlinear part it is not showing clearly ductile behavior, so it goes up to the maximum stress value of 500.

550 megapascal, elastic modulus 60 gigapascal for the 2.5 millimeter unit cell size, 52 gigapascal for 2.7 and 38 gigapascal for 3 millimeter unit cell size. If you go simply larger unit cell size looking at this trend it should be clear to you, you can even reduce the elastic modulus to less than 30 gigapascal even you are going closer and closer to the cortical bone properties. Now the question is that whether this combination of strength and ductility and elastic modulus is kind of well suited for the cortical bone properties.

what you can see in that yield strength and elastic modulus wise, it shows a very clear trend with increase in unit cell size essentially both the properties systematically decreases. Now when you look at the fractured surface with varying unit cell size, so this is this fractured surface images were taken in the scanning using scanning electron microscope and scanning electron microscope operates under the two kind of imaging mode. One is a secondary electron mode and one is a backscattered electron mode. this is the secondary electron mode, this is called topographic contrast. when you look at the fractured surface, you would be more interested to see what is the kind of morphology of the fracture surface.

typically if the material undergoes ductile fracture as is the present case, one would be seeing this kind of a wavy pattern or what they call in scientific literature river pattern. If there are some defects like lack of fusion voids, if there are some defects in the structure, you can clearly see. strategy here is to print this kind of 3D printed structures with the lattice structures, but at the same time you cannot compromise the strength properties if you have the different defects in the structures. Within the structures this kind of defects are contained, a lack of fusion voids or dimple. this is the classical signatures of the ductile failure of materials.

And what you see in the previous slides, so it is essentially linear and follows by non-linear that is a plastic behaviour or plasticity. onset of plasticity is clearly starting at the yield strength and yield strength is roughly around 400 or in case of 3 millimetre unit cell size, yield strength is certainly at 300 megapascal. even in the 3 millimeter unit cell size where the strength is reduced, elastic modulus is reduced, you can see still the signatures of the ductile fracture behavior. And whenever we analyze that scanning electron microscopy of the fracture surface, what we call is a fractography, we always look at the fracture surface at increasingly higher and higher magnification. The learning that you get it from this kind of slide that when you start using that kind of microscope you should start with the lower magnification.

Then progressively you increase you step up the magnification to see more and more finer details and eventually you would be able to see that signatures of these ductile fractures what has happened in this particular material. This TPMS structures for acetabular shell commercialization, so what we have done, we have been collaborating with one of the company in India and this collaboration we have also introduced our artificial machine learning based process optimization that you can see in some of the subsequent lectures and they are utilizing this kind of technology to see that how they have been also developing these acetabular liners. and spinal fusion components fairly routinely. In next few minutes, I am going to show you some of the experimental results related to directed energy deposition of stainless steel 316L. In some of the previous lectures, you may recall that this directed energy deposition is not the powder-based fusion processes because you are not starting with the powder bed as such.

You are essentially delivering the powder to be deposited in a synchronous manner with the laser beam. So powder beam is constantly being fed into the heat affected zone at the laser beam substrate interactions. And then powder and then substrate material, substrate should be same material. what we are trying to see here, you are essentially seeing the stainless steel 316L, this is one of the materials most widely used or under high demand. you can see this is spherically gaseous atomized powders, it is more or less unimodal type of distributions except few larger size powders.

this D10 is 45 micron, D50 is 60.5 micron. And after the DED printing what you see typically these materials develop a weld pool, this is a single scan. there are 3 different parameters you can see, one is the D that is melt pool depth, this is H, this is what is the height of the weld pool and this is what is the W is the width of the weld pool. in the DED technique which is relatively less investigated or less explored than SLM or SLS, we were initially interested to see that how to develop the process map for that and therefore we have done some design of experiments and based on the design of experiments, the design of experiments were constructed by varying the scan velocity and laser power and you can see some of the representative structures that are generated when laser power is 400 watt or 600 watt or 400 or 1000 watt. And you can see here this is the scan velocity like 1400 or 900 or even 600. from 600 to 1400 millimeter per second scan velocity were varied.

Now we want single track continuous track without any defect and in this combination of 400 watt laser power and 900 millimeter per second scan velocity you can see lack of fusion. In the other case, high scan velocity, you can see clearly the signatures of bowling. In the case of high laser power like 1000 watt, you can see it is key holing. Only in case of 600 watt and 1100 millimeter per second, This particular case you can see the single track is defect free, it is a clear case of conduction. based on that we have essentially developed the process map where you can see lack of fusion.

conduction, key-holing and balling and then you can see that how this process map is constructed where along the y-axis GAN speed is plotted, along the X-axis pressure is plotted and you can see that which is the area is essentially conduction region. this is the area that is acceptable. this is a combination of the scan speed and the power and it has almost showing the inverse diagonal kind of ratio. In this particular lecture what you can see clearly that you have seen that how SLM technique can be used for constructing the lattice structures in titanium 6 aluminum 4 vanadium alloy. this is one of the alloys which is as I mentioned which is not only used for aerospace applications but also for biomedical applications and what example you have seen in this lecture that was more relevant for biomedical applications where our aim was to mimic the cortical bone properties.

And while mimicking the cortical bone properties you have seen that how lattice structures with different unit cells can be constructed and which has properties which is closer to that of the cortical bone properties. Thank you.