

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

Prof. Bikramjit Basu

Materials Research Center, Indian Institute of Science, Bangalore

Lecture 09

In this lecture, I will be providing an overview of different additive manufacturing processes and in providing these overviews, I will be just describing these processes in the simplest possible manner and also show you some of the key variables which are important in the functioning of these processes and wherever available I will give you some examples. I will not be getting into very finer details of each of these processes which I am planning to cover under my lectures on the process sciences of the selected additive manufacturing processes. Just to recall additive manufacturing or rapid prototyping or 3D printing these are all synonymous. They essentially represent a range of techniques that involve layer by layer deposition of materials using a 3D computer aided design model to fabricate physical objects or assemblies in 3 dimensions. This particular definition was discussed in earlier lectures and then sufficient explanations were provided to substantiate this definition. I am recalling this definition at this juncture so that you remember such an important definition of additive manufacturing during different phases of this course.

This was more important because in last few lectures I have provided sufficient fundamentals on different classes of engineering materials, how their structure or how they can be characterized using diffraction and microscopic techniques. At the same time, I have provided broader details on the mechanical properties of those different kind of materials. How 3D printing is different from conventional manufacturing? in the conventional manufacturing as you see that you have a material and this material can undergo like subtractive manufacturing for example what is shown here kind of drilling. Then you get a 3D solid object and in this 3D object has some designed holes of specific diameter and specific shape and so on.

and then this will be the material waste. In contrast additive manufacturing you start with the materials then you give a 3D printing machine a specific file in a desired format. Based on the information contained in that file, this machine will now fabricate the materials in a layer by layer manner. You can get the same 3D object with a specific holes but here the wastage of materials is minimal or almost negligible compared to the

wastage of the material in the conventional manufacturing. These differences between these two techniques conventional manufacturing and additive manufacturing must be cleared now in your mind after looking at these specific examples.

This is one such example of the nickel based super alloys. This is like Inconel 625 grade and in this Inconel 625 grade is widely used in aerospace and jet engines among many other engineering applications. Now this particular technique what you see is that SLM or SLS technique selected laser sintering, central laser melting technique and these are used in an interchangeable manner. You can see a very close up view how the laser beam is being used to make this specific in conal 6 to 5 components right. You can just slowly this entire structure is being built right of Inconel 625 components and so I am just showing that different stages of the operation and once this process is over.

then this component undergoes post processing treatment and after the post processing treatment this component will be ready to use. In the additive manufacturing community SLS, SLM and DMLS selected laser sintering, selected laser melting and directed metal laser sintering are all the variants of LPBF processes, laser powder based fusion processes which are used interchangeably. What it means that these processes essentially utilizes similar mechanisms to build any engineering structures in a layer by layer manner and they do the same thing but they are being developed and different stages and then depending on where it was invented or where it was discussed with subtle changes in their manufacturing parameters and so on. They are known in different names, but they essentially mean the same. I thought that I will mention this point very clearly.

There is another technique called metal laser engineered net shaping. It is not the same as selected laser powder based fusion processes. because here if you see laser beam is being focused on a substrate and at the interaction pool of the substrate with the laser beam, this powder is being delivered through the coaxial gas shielded stream. This way powder is being delivered, this way powder is being delivered. Essentially this is the powder delivery pathway, this is the powder delivery pathway.

Both ways powder is being delivered and this laser beam is being scanned in these directions, right. What it does? Laser beam melts the powder. Then it becomes solidified once it goes from position A to position B and here again you need to remember that substrate material and then powder must be of identical composition . If it is stainless steel 316 powder then stainless steel 316 substrate must be used and this gases must be inert gas because we are handling this metallic materials. Carrier gas argon, particle size distribution, particle feed rate, these are important.

Laser power is also important and spot size is also important. Now laser scan speed like

what is the scanning rate and then substrate rotation speed if you want to rotate the substrate I will show one such case as chamber pressure what is the argon pressure and shielding as flow rate. Out of this laser power is very important, spot size is important. Laser scan speed is important, powder feed rate is important. These 3-4 parameters essentially determine overall efficacy of the laser engineered net shaping process.

Now, what are the limitations of these processes? One is the inhomogeneous microstructure, what is the residual stress and what is the high energy density of this particular laser beam. These are like working parameters which has been mentioned in the last slide and these are the limitations as well. There is another technique called directed energy deposition. As you see that how the substrate is being rotated as I have mentioned in the last to last slide, the laser beam is being continuously being incident on this particular rotating substrate and these powders are also being deposited which is synchronous with this laser beam interactions on the substrate. And you can see in this video how powder particles are being fed together with this laser beam and this laser beam is continuously melting and thereafter solidifying these materials.

This particular machine is currently in used at Indian institute of science, Bangalore and this particular right hand side video is mainly for titanium 6 aluminium 4 vanadium part manufacturing by directed energy deposition. Again in the additive manufacturing community. laser engineered net shaping and direct energy deposition are used interchangeably. What it means that they mean the same thing but they are often used in different names by different researchers. I will come back and continue on the overview of the additive manufacturing processes in the next class.

Thank you. Now we are at the first floor of the Amace Solutions Private Limited. What you can see on the left hand side, this is the machine assembly facility where all the different Amace systems metal additive manufacturing machines, the different parts are being assembled and tested and subsequently we'll be moving to the Amace Solutions Private Limited, that metal additive manufacturing machine facility where I'll be demonstrating that how this additive manufacturing takes place in real time and then where the different engineering components are manufactured. And this is the entire Amace Solutions Private Limited. This is the one that I told you earlier. This was established in 2018.

It has more than 50 people currently working in this manufacturing facility in Bangalore. And We'll start with the first is the build preparation to show you that how the design for additive manufacturing is followed in the pre-processing stage to prepare the machine readable format of this build then it will be followed by demonstration of the different type of machines particularly that which is most widely used machines in different

research labs as well as the industry that will be followed by post-processing steps like heat treatment and grid blasting steps. Once you import the file there will be some error in the model so that you can be able to fix it, then you can evaluate the part whether it found ok post that we will orient the part and will be orienting as a horizontal way, whereas these surface of the overhangs which require the supports, then we will be creating a support for this so we have a like a block supports, line supports and volume supports, since this is aluminum we will be going with the block supports. We can change the parameter for this supports like what should be the hash distance what should be the hatching teeth, usually the hatching teeth is like it will be connected with the pod so if you see here you will be able to see so this parameters you change parameters according to your machine as well as the printing parameters so in block support the main factors are we need to consider the perforation which is required for the powder removal from the supports then fragmentation to ease of support removal so once we did this support generation we can slice the file. Part design, designing of a part in a CAD software package. nowadays even the CAD software will also offer AM suite where we can get more option to use lattice structure or topology optimization. next step is once a part design is ready, we can convert into HDL. most of the software works on HDL, like 3D printing will work on HDL platform.

basically we will convert a CAD to HDL that is a triangulated surfaces so typical formats HDL.OBJ3MF so triangle mesh that will have two details like any triangle will have three vertices and one normal. normal will define the position of the material either towards outside or inside this is some parameter we use for the conversion any CAD geometry we use. closer the angle you will get a very precise but it will improve increase the file size.

Build orientation. orientation of the parts in a build impacts total part cost. build time, part strength, surface quality and support quantity so any part can be printed with multiple orientation. Each orientation will contribute on these aspects. for example any part printed with horizontally vertically that will have a different surface characteristics also tensile or mechanical properties so support structures are not desirable because these are wastages because of the design overhang constraints. We have to give supports in order to print successfully because we cannot print something in the air or directly on the powder.

So there is a contact between the part to the platform. because during the melting there will be tremendous heat will be generated that has to be transferred to the build plate so basically these supports are useful for anchoring the part to the build plate so reduce eliminate warping or supporting the overhang geometry and to improve the heat dissipation. In this image you can see multiple those are actually same design oriented in a

different ways. there is no standard solution. We need to find the best compromise because each part is having a different supports requirement. according to our application requirement we have to choose the right orientation.

The next step is slicing. Conversion of a 3D part into a format that suits AM process. we can print with a multiple layer thickness. Higher layer thickness will improve the productivity but also it will deteriorate the surface finish also the mechanical properties. we have to find the best compromise with the speed also finish wherever the productivity requirement is that we have to use the best layer thickness. Also, we have to ensure that the layer thickness will not have will not deteriorate or include porosity in the design or the part.

the final step is machine toolpath generation. where we will be defining the laser path, how laser should be scanned to complete the part, how it has to be scanned, what is the laser power required, scanning speed required, how contour should be scanned. there are almost 150 plus parameters which has influence on this. according to the material layer thickness we have to create the machine tool path. these are the six steps of build preparation.

Now we are standing in the Metallurgical Laboratory of Amace Solutions. here I'll start with some powder classification and all. here this is the SS316L powder that we are using for our 3D printing applications. normally before going into the machine, we have to test these powders. so that we will able to get to know that what is the flowability of this material because like for a better plan of packing efficiency of the powder in the bed the flowability do have very big role so here we are using Carney flowmeter as well as one more flow meter is there this is hall flowmeter so normally the orifice this is having around a 2.

5 mm diameter this is known to be as hall flowmeter when the diameter of the orifice is 5 mm it is known to be as Carney flowmeter. So based on the standard we will select the which flow meter or we can convert like one flow meter what is the range or other flow meter what should be the ideal range. this is the normal typical package that we got from Indo MIM company. from there we are going to be get the powder. the powder should be kept in a very closed manner so we won't be interact with the atmosphere so we can able to take off this and they will also put some desiccant like this so this desiccant will be act as whatever some kind of impurities or some kind of a moisture content will be there this desiccant will be absorbing that so the powder won't be able to damage or kind of a this thing so whenever we are using for a machine also after sometimes we have to check what is the oxygen, nitrogen, hydrogen content in the atmosphere so that all the basics of you need to know so to perform this Carney flowmeter test i just required

almost 50 grams of powder.

STLR 400 model laser powder based fusion system which is being manufactured and currently under operation at Amace Solutions Private Limited. this 400 series machine has the powder bed volume is 410 millimeter by 410 millimeter and then height is around 450 millimeter. here the layer thickness is 30 micron and then total layers that will be printed is 2840 number of layers so you can see build start time building time total build time and so on and if you look at this is the precipitation hardened steel that oxygen content here is around 630 ppm and the gas speed that inert gas flow rate is 16 meter per second and build plate temperature is currently 127 degrees Celsius. if you now if we now we will be looking at that more closely that build volume which we can see that multiple parts are being manufactured and each part has different design profile so all these different design profile what we have learned that you know mass customization is possible using this laser based powder based fusion processes you can see in real life that how that multiple parts are being manufactured using this amace stlr 400 model equipment once this entire build is being manufactured now you can see the recoating is done so the next layer of the powders that will be now exposed to the laser beam interactions and according to the design file exactly on the layer by layer process this part will be manufactured and you can see this is a dual beam laser system and each laser is simultaneously functioning. Each laser beam is simultaneously functioning and they are being spatially oriented at different location on the powder bed.

And then you can see as per the information or instruction which is contained in the design file, laser beam is continuously tracing its path on this particular powder layer. And then soon, once this powder layer will be, laser based melting and solidification is over, then next layer of powders will be exposed to this dual laser beam. this use of the multiple laser beam is the most recent concept because it is expected to enhance the productivity and also mass customization process using this metal additive manufacturing technique. once this part is manufactured, we'll be cleaning all the powders and also any overhang structures. Then after that, these components will be taken to the post-processing step, which will include grid blasting as well as the heat treatment process.

And before the post-processing starts, all the components will be machined from the base plate. So this is another new machine which is being manufactured at Amace Systems. It is a STLR 120 model. So essentially, if you see, this is the build plate. This build plate goes, and this is a single laser system.

The build volume, maximum build volume can be printed in this particular machine. It is a cylindrical shaped build volume. It has 120 millimeter diameter, and maximum height of the cylinder can be 200 millimeter. This particular machine can be used by the

academic institutions and also R&D labs or research labs to demonstrate the capability of the laser-based powder-based fusion processes to manufacture components of different materials. now I'll show you this after this laser powder based fusion processing that what are the different materials can be printed with different shape and size for different applications.

what you see in my hand, it is the titanium based alloys which is being printed and these particular samples can be machined to get the tensile samples and to get that typical tensile strength of tensile properties of the titanium samples. this is one of the cobalt chrome based materials which can be used for the knee implant applications and this is a commercial design of the knee implants and these particular knee implants has been manufactured here before it goes for the post-processing technique using grid blasting and heat treatment techniques here at Amace But I must mention that as additively manufactured materials cannot be used directly for any kind of application. therefore, post-processing is mandatory for any materials which are being printed using laser powder based fusion processes. this is also another material.

You can see this is very lightweight. This is an aluminum based alloys which are being 3D printed here at Amace Solutions Private Limited. what I mentioned just a few minutes ago that these laser powder based fusion processes has been used for manufacturing knee implants and you can see that series of knee implants which are being currently manufactured at Amace Solutions this is as additively manufactured implants now these implants will go to the further post processing so this is the heat treatment furnace you can see so this heat treatment furnace can go up to 1200 degrees Celsius, and then it can be heat treated for longer time period as per the requirement. And then after the heat treatment, the samples will be grid blasted. This heat treatment furnace has been used for all metallic structures, whether it's aluminum alloys, whether it's stainless steel, whether it is titanium alloys or cobalt chrome alloys. The purpose of the heat treatment is to relieve the residual stresses which are generated during the laser powder fusion processes.

As I mentioned that during this interaction of the very intense laser beam with the metal powders, there is a significant amount of residual stresses that has generated during the processing itself the purpose of heat treatment is to relieve this residual stress and before it can go for the grid blasting techniques. after the heat treatment the support structures from the additive manufactured implants are being removed and you can see this is the support structure is removed and then subsequently this goes to the grid blasting this is the last stage of the post-processing stage and the grid blasting machines generally 500 to 600 micron size stainless steel 316 grids are being blasted continuously on the surface to make the surface more smooth to reduce the surface roughness of the as machine structures And after all these post-processing techniques, if required, these components,

additive manufacturer components has to undergo further polishing to make the surface much smooth and also acceptable to the customer for the specific engineering application. now I'm going to demonstrate that how complex structured materials can be additively manufactured using the laser powder based fusion processes. what you see in my hand, it is a waveguide component and this is made up of the aluminum alloys. Now if you look at that side view, top view, as well as front view, you can see that how complex the structure is.

And these kind of structures cannot be manufactured very easily using conventional manufacturing processes like machining. And that establishes the clear advantage of additive manufacturing process. I'm going to show you, this is the original structures and original structures and you know this is the same structure designed using the topology optimization process and you can see this in topology optimization process the one of the major advantages of topology optimization is for the weight saving and this is now made up of the aluminum 10 silicon magnesium alloys and this is also used for tool holder applications This one you can see, this is also, this is the same materials, aluminum, tin, silicon, magnesium alloys. This is that applications is for the aerospace applications. you can see this is that lattice structures which you have seen in the, or which I'm discussing in this NPTEL course.

And you can see that how this lattice structure can be manufactured with different unit cell size as well as the strut design for many applications right from the dental to acetabular to knee joint applications. I hope that with this you now have much broader overview how additive manufacturing technique is being implemented and being practiced in industries in India. or elsewhere in the world. as part of the NPTEL lecture, it was indeed important for me to show the current practice of additive manufacturing in one of the leading manufacturing metal additive manufacturing company in India. you also have got that comprehensive knowledge from the design for additive manufacturing to build preparation to real-life demonstration of the dual beam metal additive manufacturing machines working status as well as the two different type of additive manufacturing machines, one for more industrial scale applications, one for more educational purpose applications, what is the typical build volume and build size that can be used in these manufacturing machines and that was followed by the demonstration of the additive manufactured components which has to go through post-processing step first is the heat treatment followed by grid blasting techniques and subsequently polishing stages if required and finally i have also shown you that how different materials with different design complexity including topology optimization techniques can be manufactured using that laser powder based fusion processes. Thank you.