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

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Lecture 10

In this lecture I will continue the overview of additive manufacturing processes. In the last lecture I have covered selected laser sintering, selected laser melting, directed metal laser sintering, then directed energy deposition. Then lens processes that is laser engineered net shaping processes, so this first set of processes are laser powder based fusion processes which are essentially SLS, SLM and DMLS where powder bed is used and laser beam actually preferentially melts and solidifies and sinters these powder particles as per the design file format or as per the information content in the STL file that is being exported to the SLM machine. The second category of techniques which are non-powder based fusion processes or non-powder based fusion, this is like directed energy deposition or laser engineered net shaping processes where powder particles are being fed into the laser substrate interaction zone. And this process is being synchronized in a sense that laser material interactions and powder delivery, these both are synchronized and they are being again done in a layer by layer manner to make the structural components. Having said that let me start with that electron beam melting processes.

This is that electron beam melting processes here accelerated electron beam which is 30 to 60 kilo volt. which is being used to melt the substrate and here this electron beam essentially first generated with some filament then it goes through astigmatism lens, focus lens, deflection lens. And this finally this electron beam enters this 3D printing chamber where powder hopper is there on both sides of the electron beam. And this powder hopper will supply these powders of a specific material whose component is to be manufactured in a regulated manner with inert gas shielding so that to minimize any oxidation of these materials.

And, here again base plate or start plate as it is mentioned and then powder must be of identical composition. you can see there is a rake and this is a build tank and it is a build platform. Essentially, as the material is being melted and then the structure is being built, so there is a Z direction movement of this, so this essentially can move in the upward things. First let us start with this 30 to 60 kilo electron volt. Now, if you remember some of the materials characterization techniques that I have mentioned earlier in one of the previous lecture like scanning electron volt, scanning electron microscope they are 20 kilo volt of the electron beam is used.

Another materials characterization technique where thin film of a material to be investigated is used and the thickness of the film must be less than 100 nanometer. This is like 100 nanometer metal foil or thin foil is used for this kind of transmission microscope and here they use 200 kilo volt or 300 kilo volt electron beam. Compared to both these techniques as you see it is almost in intermediate like it is between SEM and TEM this kind of accreditation techniques that you have learnt in the previous lectures and here this accelerating voltage is 30 to 60 kilo volt. This kind of gives you some idea about what are the different machines that you have learned before and how different processing techniques are also used in this electron beam of different voltage. Now, in terms of the capability of these particular materials and then functionality of these materials, so this particular material, this manufacturing processes is similar to that of the kind of SLS or DMLS or other kind of powder bed fusion processes or directed energy beam because you know directed energy deposition because here that major energy source is not laser but electron beam.

But again powder is used and powder is being deposited on a substrate and that is being melted and solidified using certain design file. Electron beam melting again is used in industrial scale production. I myself have seen in some of the Indian industries, medical device industries where they are using electron beam melting. Now if you look at the different kind of components which are used in the electron beam melting, you can see that this is a range of components which are of different size, shape and these are like different structures. You can see this kind of components, it consists of this kind of components.

This is like typical cube components but it is porous components. You can clearly see this is a femoral stem of different designs which are manufactured using electron beam melting technique like different mesh configuration, hole configuration, solid configuration. This electron beam melting has been in use since 1997. This is another technique called stereo lithography based manufacturing which is invented in 1984. How this stereo lithography, I think I will show you some movie in the next slide.

But let us first try to understand how the process work. Here we use laser or UV source, ultraviolet source. What is the material that are used? It is photo curable resin. it can contain the cells or it is without cells. Photocurable resin, this is like alpha photocleavage of type 1 photoinitiators which are used.

When photon beam will be interacting with this, so it will produce benzoyl radical. Essentially there is an irreversible transformation of photocurable monomer liquid to solid and semi-solid polymer and this is also keyhole from photoinitiator that is typically aryl ketones of type 1 that are used. There are 3 different transient stages, one is initiation, one is propagation, one is termination and these particular things also we avoid oxygen inhibition. This is what you can see in this particular case that laser beam is being focused this source laser beam focused on a UV photo curable resin and if required biological cells also can be transferred during this process and platform moves down after for every layer. And this is where this entire process has been described.

A is your laser beam, B is your essentially photo curable resin, C is the initiation of photo initiator, photo induced polymerization, D is the layer by layer building and E is the stepper motor driven build plate. These two slides actually I think I hope it gave you sufficient understanding on the stereolithography technique. Let us move on to the third one, third generic 3D printing processes. This is ink jetting of biomaterials. again this ink jetting of biomaterials people use in different names like drop on demand.

These inks supply and then ink is being deposited on the substrates in a drop-on-demand approach. These are thermal drop-on-demand, this is piezoelectric drop-on-demand. thermal drop-on-demand means there is a thin micro heater which triggers and bubble formed and this droplet is ejected and this is being shown more clearly in the next slide. you have a feed bed and you have a build bed. feed bed each time powder is moved to the build bed, the moment the powder is displaced here, through this print head, this binder is being deposited.

Now, these binder droplets as you can see traverses through the powder bed, then it will penetrate into the powder bed and then that will interact. And after the interactions depending on the viscosity, surface tension, density and pH of this material of the binders, this binder will penetrate. I will show you some of our fundamental study on that where we have used some of the synchrotron source to understand that how this binder interaction takes place particularly their spatio-temporal interactions of the binder with the materials. Now, since this binder droplet interacts with the powder bed and then binder is essentially fluid in nature, one can bring some of the fundamental fluid dynamics, dimensionless parameter like Ohnesorge number or Reynolds number. And if you plot OH versus RE, then you can see there are some range or some part of the Oh versus Re.

This is the region which essentially represents the printable fluid. And here you can see the combination of the Reynolds number is somewhere between 2, 3 to up to 30 or 40 because this scale is the log scale because 1, 10, 100, 1000 is the log scale. Ohnesorge number is also plotted in the log scale. This one Reynolds number varies up to 30 or 40, Ohnesorge number varies from 0.

1 to 1. This is the region that if any binder has this kind of combination of Oh and Re, it is expected that binder will give the best binder jet printing performance. What are the different variables which are important here? One is the powder characteristics like powder size distribution, powder shape. Perhaps these particular kind of parameters are important in all the powder based metal printing processes. In terms of the binder characteristics as I mentioned before, it is a pH, viscosity, surface tension that are important. Now there are also printing parameters or process parameters which are being mentioned here also that is the layer thickness, binder saturation, deposition speed and build orientation and there are post processing like chemical conversion at ambient temperature or high temperature heat treatment parameters.

this is that binder jet 3D printing processes and this particular machine was used extensively at my research group at Indian Institute of Science. what you see here it is a titanium 6 aluminum 4 vanadium powder printing. We are printing simple compression samples or some other structures with gradient porosity. So, this one side is the build bed and one side is the feed bed that you can easily recognize and then this is that essentially compressive graded stereolithography file which is being printed now and these are being tested later. this brings me to the summary of the different variations of additive manufacturing processes.

And these additive manufacturing processes as I mentioned, they are essentially divided into several generic processes like laser powder based fusion processes. Or electron beam melting processes, there is 2 different sources, one is laser source, one is electron beam melting source. Then directed energy deposition processes and DED that has been shown here. Then you have DLP processes, digital light based processing. Then you have powder bed fusion, I have done inkjet printing processes or powder jet printing processes or binder jet printing processes.

So, although all the processes are not covered in this particular lecture and previous lecture, but I have essentially described or I have given an overview of most of the processes which are most important for metal additive manufacturing. Now the question is that once you have that additive manufacturing, it is important for us to know the quality of the additively manufactured components. There is a lot of comprehension or there is a lot of apprehension in the manufacturing community. At least 10 to 20 years ago when this additive manufacturing processes were introduced initially, Now, by using additive manufacturing, one would essentially compromise the quality of these components, but over the years it has been proven that we do not compromise the quality of these components to any significant extent and this was reflected in different performance matrix of the additive manufactured components for a spectrum of engineering applications. This slide and then next few slides, I will be explaining that what are the traditional quality control measurements or techniques which were used in industries which are also used for checking the additive manufactured component quality and then similar set of methods or analysis techniques are also used in conventional manufactured components.

The analysis techniques are the same but the two different manufacturing techniques are used for the same components so that you essentially measure the same thing. for the similar components but manufactured by 2 different methods. This is what has been mentioned in this slide that quality control and engineering component refers to the systematic process of evaluating and ensuring the conformity of the manufactured parts or components to the established quality standards and specification. And many times these standards qualifications are essentially some of the ISO guidelines and ISO has several hundreds and thousands of the guidelines. Some of the generic guidelines are essentially used for several different type of applications.

It involves the use of various techniques, tools and methods to inspect, measure and analyze the physical characteristics, dimensional accuracy and functional attributes of the engineered components. These are very important. Any dimensional deviation or defect that may affect the performance quality and reliability that needs to be identified before they are used in practice or before they are used in reality. This quality control is indeed is very important for as far as the industrial scale application of these additively manufactured components are concerned. First one is a perhaps most simplest one is a Vernier Calipers which we have been using right from the high school or engineering test like it gives you precision measurements 0.

01 to 0.001 millimeter not beyond that and this essentially measure both external dimensions such as length and width. and as well as internal dimensions like the diameter of a hole or the depth of a cavity. This is a simple operation that has been mentioned in this particular slides. Coordinate measuring machine. Coordinate measuring machine by perhaps is little more complicated than that of the vernier calipers.

As the name suggests, so it essentially gives you dimensions along the y-axis. along X axis and along Z axis. They are precisely measuring the geometric characteristics of the complex components including dimensions, shapes and positional tolerances. And this high-accuracy and repeatability because they use advanced technology like precise probe sensors and sophisticated software to provide you accurate and reproducible measurements. And versatile inspection, this is like component sizes and geometries and making them a valuable tool for quality control across diverse engineering applications.

The third one is video measuring system. Now video measuring system is essentially based on non-contact measurements. you put the component here, this is your measuring component and they uses the different zoom of 30 times to 200 times like a microscope. And, then you can essentially check the components on this screen and you can do this auto edge detection and this is essentially a touch smart PC. And, what you can simultaneously measure? You can simultaneously measure multiple features of a component.

It improves efficiency and speed compared to traditional manual inspection. Video measuring system is essentially more for automated analysis and it can automatically analyze the captured images providing rapid and accurate measurements of various features and dimensions. The fourth one is the microprobe. In the microprobe is essentially used to examine and measure features at micro level, detection of any defects like surface roughness and other macroscopic details. This is also high resolution measurements.

This is the fine tipped probe and these probes essentially allow incredibly detailed and accurate measurements at the microscopic scale. And this has specialized applications, this is particularly valuable for inspecting components with intricate geometries and complex microstructures and extremely small tolerances in precision engineering and microelectronics. And it is a comprehensive analysis for microprobes can be also be used to analyze surface characteristics, texture and other micron level features of the engineering components. Fifth one is more on internal and surface defect analysis. Internal and surface defect analysis, there are different techniques.

One is ultrasonic testing. This utilizes high frequency sound waves to detect internal defects like voids, cracks, inclusions. More powerful perhaps is the X-ray based inspection. You can say this is a X-ray radiation or gamma rays you have an object and this is a foil or inspected image and this is the image that is being you can see this image in the detection film. And this actually reveals internal structure and hidden defects of a component and for example, this is one engineered component, this is one of the polymeric component for example, we are interested after injection molding whether this entire area of this component whether there is blow holes or whether there is any kind of other defects but this essentially shows no defect. If it is a case for no defect, then quality control essentially passes these components for further analysis or commercialization.

Dye penetrant testing essentially identifies surface defects by applying penetrating liquid that seeps into cracks and discontinuities making them visible. Eddy current testing, this is essentially it detects surfaces or near surface defects inducing electrical currents in the components and measuring their response. This brings us to the essentially end of this overview of additive manufacturing processes as well as the different defects internal defect analysis and then quality control analysis of the additively manufactured components. In subsequent lectures, I will not only provide process science of some of these additive manufactured processes, I will be also using some of the scientific case study based on the published study from my own research group to show how different materials are being additively manufactured using different techniques and mostly binderjet 3D printing or using some of the laser based 3D printing processes. With this I close this set of lectures and I will come back to you with more detailed description of the specific additive manufacturing processes or some of the scientific case studies of the different materials which are being additively manufactured. Thank you.