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

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Lecture 02

So, welcome back to this second lecture in this series on NPTEL course. So, I think I will start from the place where we stopped. In the last lecture, I have given you the textbook type of definitions of additive manufacturing and I ended with the historical perspective. So let me go back to this additive manufacturing definition. So it is a computer controlled manufacturing process. involving layer by layer deposition of involving layer by layer deposition of materials in a predefined manner using CAD model or digital model to be constructed leading to creating three dimensional objects often with complex geometry and topology.

I wish to reemphasize certain keywords in this definition layer by layer building of materials CAD model or digital model 3 dimensional objects complex geometry and topology. So, this complex geometry and topology. This complex geometry and topology I have mentioned in the last lecture that this cannot be constructed or manufactured using conventional manufacturing and that places the greatest importance to the field of additive manufacturing. I thought that I will emphasize that aspect once again in this lecture to start with.

Now, let me skip this historical overview, which I have explained in the last lecture, I think quite in detailed manner. Now there are 3 different kind of manufacturing processes what has been mentioned here. One is called formative manufacturing like you pour the material to a particular mold or cavity, you allow the material to set or to get cooled or to get solidified. then you remove the mold material you get the component out that component will have a will have exact replica of the inner surface the components outer surface will have exact replica of the inner surface of the mold cavity. Second one is a subtractive manufacturing like conventional machining you get a feedstock and you have a tool.

So, you program the tool or you program the tool path in a manner that that tool path will sequentially go and remove the materials in a predefined manner. And that is the fundamentals of the CNC machining processes which again revolutionize the field for

quite a number of decades that is computer numerically controlled machining processes. the way the tool path will move during that entire machining processes are embodied in G code capital G code. So, this G code essentially is very important. So, this so essentially I am saying that based on the G code the materials will be removed and then particularly you will get the components will have a particular shape.

after the traversing of this entire tool path in a predefined manner. In the additive manufacturing the fundamental thing if you see is a layer by layer right I repeat the definition layer by layer deposition or manufacturing of the materials. So, you can see this is a wire now it is get melted and deposited on the particular substrate and then you can see this is the kind of layer by layer that is forming. But additive manufacturing also certainly needs a program and this is called STL file I will come back to that STL file. What are the key characters of the STL file and so on which needs to be given to the 3D printing machine to start the additive manufacturing process.

So, you can see that in the conventional subtractive manufacturing materials are removed. So, material removal, material wastage and also this cannot be avoided right in this conventional manufacturing processes and also here again you can make complex shapes but to the extent that complexity can be introduced the additive manufacturing in their component geometry in the component internal topology that cannot be achieved in the conventional manufacturing process. I wanted to emphasize that point once again. So, now if you look at this as I said that you need to give a design and this design essentially are shown here. So, this is the design concept, this is the computer that you can see for example, there is a cube and this cube is being printed in additive manufacturing process you can give these material specific printing parameters and then you can use it.

But this basic concept of the design its translation to the component manufacturing based on the design can be utilized for polymers like soft hydrogels or polymers can be utilized for metals for engineering components as you can see this is the complex engineering components can be used for ceramics and can be used for living cells. Like you know you can do cell printing like you know eukaryotic cell printing, you can mix the cells with the hydrogels, you can place the cells within the hydrogel framework in a manner that essentially gives rise to 3D bioprinted constructs. So all those things is possible and I am going to show you multiple such examples where you can clearly see that how this 3D printing can be indeed used for a wide spectrum of materials and also components. Now, what are the steps involved in the 3D printing? Now, we need a designing of the CAD file. Now that CAD file needs to be converted to STL file.

What is STL file? That I am going to show you in subsequent lectures. And what are the characteristics of the STL file? Then slicing of the 2D planes that is essential right

because as you learn from the basic definition that additive manufacturing essentially layer by layer deposition. So, unless the machine knows that what are the characteristics of the 2D slices which will constitute this particular STL file. the machine will not be able to perform on its own in the process of constructing the 3D object. And that is what I have mentioned about this is just a generic 3D printing machine that was shown just to illustrate the concept of layer by layer materials deposition.

Third one is the post processing this is very very important. Now post processing it is mostly used for the removal of support materials this is for example metals. Then you use either some machining to remove some of the extra parts, curing is used for some of the polymers, then some infiltration process also used to give sufficient strength and for metallic based heat treatment. So, this post processing, entire post processing essentially is materials dependent. Generally for 3D printing of metals, heat treatment is quite widely used and these are different heat treatment depending on whether you are developing cobalt chrome materials, developing titanium materials, developing stainless steel materials.

I will be showing you in one of the scientific case study that infiltration process is important for ceramic based materials. And cross-linking is very important for polymeric based materials like hydrogels which are used for biomedical applications. So this cross-linking can be either by treating that as printed hydrogel in calcium chloride solution or it can be dual cross-linking like UV cross-linking and calcium chloride solution step stage by stage or simply UV crosslinking and whenever you have to use this crosslinking UV crosslinking then you have to use that photo curable crosslinker with the hydrogel so that you know when you do this UV crosslinking that can be crosslinked to improve the strength properties or elastic modulus properties or safe fidelity properties of these materials. To summarize from this slide, I want to emphasize that this designing part is important, as important is the 3D printing part, but equally important is the post processing part. Because post processing part will directly have an impact on the properties and performance of the 3D printed components.

So, each part has its own significance or own importance in the overall context of the additive manufacturing. Now what are the advantages over conventional processing? The conventional processing the approach is like either replacement of affected bone with implant with limited integral leaving tissues. But additive manufacturing since it can be used as for the patient specific implants, we can expect for better integration with leaving tissue. Structural complexity is very limited as I mentioned multiple times in last lecture as well as this lecture. And additive manufacturing can indeed produce very complex structural features.

Then we have porosity, this suppose you want to develop a complex porous structure which is very difficult to control the pore distribution, pore size, pore morphology, wherever in additive manufacturing gradient porosity can be introduced. Mechanical strength, typically it is stronger than 3D printed prototype. But porosity and absence of sufficient pressure during scaffold design essentially can decrease the strength which can be recovered by subsequent post processing technique as I have mentioned either using cross linking mechanism or by heat treatment mechanism. Time, it is a time consuming process and here the build speed is much faster in additive manufacturing. Just to give some examples you know in the left figure you can see conventional 3D porous scaffolds, in the right figure you can see 3D printed porous structures.

Of the same materials PLA scaffolds with pore size 500 micrometers. Now you can see that in the left side the conventional 3D porous scaffolds you cannot see this porosities very clearly although it can be porous you can if you can go to individual this part you can see the porosity right. But, this porous material, this porous structure is somehow hidden, right. But, here you can see that individual pores are of square pores, right. So, and this you can see this is one strut and this is several square pores are aligned in a very regular sequential manner in this particular 3D printed scaffolds, PLA polylactic acid scaffold.

So applications of the 3D printing technologies, now it can be either for creative and decoration purposes, it can be sports also, it is also used for automotive components, some auto industries they are using for aerospace components, rocket nozzles and so on, people are trying architecture. There are many museums around the world, they use 3D printed parts, for example, food industry, 3D printed, bio printed meat, I know in researchers are kind of utilizing 3D printing or 3D bio printing to produce artificial meat in countries like Canada or Germany. So, they use this 3D printing technique. Then human health care. Many of the scientific case studies or many of the examples I will be going to show you in next few lectures, those are largely related to the human healthcare and that is close to my heart because biomaterials and implants is the research area that our group has been pursuing for more than last 15 years.

And one of the examples I can show you here, it is a 3D printing is utilized to make the scaled down cranium model of the human patients and those were used to make the bone flaps of the specific materials which were implanted after sterilization in the human patients. And subsequently the functional outcomes of this particular cranioplasty surgery was monitored over 2 years and we have shown the 3D printed grafts helped the patients to recover the neurological functionality over post-operative periods. So, this is one such examples, but also we have been working on the 3D bioprinting or pseudo 4D printing of the scaffolds for different applications related to human healthcare. Now, what are the

different generic classifications of the additive manufacturing? It can be either powder based or sheet or filament based or liquid or gel based. So, in our group, we are focusing more on the powder based 3D printing.

This is for metals. As I said, SS316, cobalt chrome alloys. titanium alloys and this is for laser-based treatment. We are also using 3D printing for the gel-based, hydrogel-based like Gelma. This is widely used globally or gelatin methacrylate or alginate gelatin-based. biomaterial inks or biomaterial or bio inks or biomaterial inks.

And powder based we are mostly using the binder jetting and then after that this is the post or the sintering or the melting. So, we are using both for binder jetting I will be showing you some case studies. We are also using laser beam melting process like either Laser powder based fusion processes where this melting and SLS and DMLS or SLM we are using, DED we are using. These two we are using and binder jetting also we are using. So, these star mark additive manufacturing techniques, how they are used for different materials, I will be showing in different case studies.

In sheet or filament based techniques, actually it is used by two techniques called LOM and FDM. This will not be shown to any greater details in this course. Viewers and students of this course can refer to two of the NPTEL SWAYAM course or similar other courses which are available online to get more details, to get more scientific case studies which are relevant for this sheet or filament based techniques. Now liquid or gel based techniques, this is I am going to put a star on this extrusion based techniques, the 3D extrusion based techniques. I am not going to show scientific case study in vat polymerization or drop on demand kind of techniques but more on the extrusion based techniques.

And this is what we call 3D printing extrusion or 3D bioprinting processes. So, patient specific 3D bioprinting Now here again what we when it is called patient specific so that means we need to get the patient data first. So this patient data comes from either MRI or CT scan imaging and for example you want to print the artificial heart which is indeed a dream for every bioengineering researchers to develop a full sized functional human hearts which can be used for heart transplant and the way I am saying this is indeed a real dream. Now what are the things you need to use you need to develop a scaffold right this scaffold can be made up of these available materials and these materials must be biocompatible. Now what is biocompatibility and so on that I am going to explain to in more details in the subsequent lectures.

So, you want biomaterials that is a scaffolding materials, you want cells. and in case of heart we want cardiomyocyte cells. Then we have growth factors and then those growth

factors are essentially low molecular weight proteins which are used for multiple biological attributes. And then biometrics are mentioned here as gels.

So, this is like gels. Now these gels are used for this particular scaffold. So, scaffold essentially 3 dimensional complex structure which is expected to mimic the physiological complexity of the organs or tissues that we are going to regenerate right. So, this scaffolding materials their properties and performance indeed very important. Now, equally important is that is the functionality of the cells when they are embedded or when they are contained in this hydrogel or scaffold structure right. For example, cardiomyocytes you should as you know that heart beats right and the normal heart beating is 72 pulse per minute.

So, we need to have a beating cardiomyocytes and beating should not beating performance should not be compromised in this particular artificial heart. So, then we use different type of techniques like some of the techniques what has been used what has been attempted may be inkjet, stereolithography, laser based and extrusion and you can see that artificial heart is being printed here in a very schematic manner. It is not a real experiments but it is just to show that how different techniques can be potentially used. Now post processing and that is post processing is that you have to take the scaffolds with cells and then you have to put it in the bioreactor. Then you let the tissue maturation process to take place and then you can get the final 3D printed tissues and as I mentioned in this particular slide a number of challenges remain to be addressed during each step of bio fabrication to develop patient specific fully functional artificial tissues.

I am going to emphasize the word fully functional artificial tissue organs with clinically acceptable results. If these clinically acceptable results are not obtained, no clinician is going to take the risk of using artificial heart and use for heart transplant. This is the rationale for the fact that the 3D bio printing is not still not used for in clinics for the patient care. Again, I would like to highlight this part. 3D bioprinting, 3D printing in general has been investigated or is under investigation to the extent that if you use any online platform you can find at least hundreds of papers are being published every month from around the world in different journals and there are journals which is named as additive manufacturing per se.

So that there is one specific journal called additive manufacturing which is solely devoted to publish additive manufacturing related papers. and various other journals related to materials like for example Acta Materialia or material science and engineering A or in the flagship journals in the field of biomaterials like biomaterials, bio fabrication there is one specific journal bioprinting there is one specific journals So, these journals acta biomaterial, these kind of journals, they are like very high impact factor flagship

journals, which are considered very important in this field of 3D printing. They also publish several papers, either fully focused on 3D printing, 3D bioprinting or preclinical studies. or other aspects of the studies where 3D printers has been used as a method to fabricate this kind of structures. I hope I have been able to explain you that how tremendously research is being pursued in this particular area.

This is just an example that directed energy deposition which is used in for metal 3D printer. So, this is the machine that we use at Indian Institute of Science. So, if you look at this particular schematic, this is the laser beam, right. So, laser beam is falling here and this powder delivery system. So, this is the powder delivery system and it is for metallic powder.

So, it is carrier gases, some of the inert gas like argon or helium. This powder delivery process essentially delivering the powders at the melt pool. So, this entire process is being synchronized and you can see that how these laser beam melts the substrate at the same time deposits the powders as it melts. So, therefore, the substrate and then powder should be of the same material. If you are going to build stainless steel structures, then you have to use stainless steel substrate and you have to use stainless steel powders.

If you have to build titanium 6 Al4V structures, then you have to use the titanium 6 aluminum 4 vanadium substrate and you have to use Ti6Al4V powders as well. This is that full machines, this is under operations. I am going to show you more videos of the same machines to see how this essentially this process looks like. So, as you watch this particular video, I am also showing you that some of the computational platform which are used for the design purpose is the SOLIDWORKS.

This is one such platforms. And, this is the tool path, the tool path designing that how this tool path essentially laser based tool path is moving and that is actually embodied in this that should be used as an input to this specific directed energy deposition process. Now what you look at this particular design based on the design concepts, this structure has been divided into several 2D layers. So when you give this as an input to directed energy deposition machine, DED machine, so the machine will read only these individual layers. and then it will try to print individual layers in a layer by layer manner in a very integrative way so that this particular 3D printed structure can be obtained. So as I said these kind of videos I will be showing more often.

during the subsequent lectures and there is one disclaimer that I have mentioned I repeated these videos should not be considered for any promotional purposes neither it is not my objective to show or highlight the machine of any specific company but at the same time it is important for the reader for the viewers and the students of this course to

know how the actual machine looks like, how the actual machine performs in reality. So, from that academic learning purposes or for the holistic learning purposes, I am going to show this video you know very regular interval in the next few lectures. So, I think I conclude this very introductory lectures and in the next lectures I am going to again revisit some of the concepts and then also show that why data science is important, how data science can be useful, these things. Very brief introduction to data science so that you remember this concept when I will be using and utilizing these concepts again in the subsequent lectures because this data science is something which is very new. to material science community as such but also at the same time it is new to many bioengineering students   or   biomedical   scientists   in   general.

 So therefore it is important for me to introduce very briefly in the beginning and then I will follow in more details when I will be showing you some examples that how data science concepts and ideas have been utilized using some of the case studies. Thank you very much. I will see you again. Bye.