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

Prof. Bikramjit Basu

Materials Research Center, Indian Institute of Science, Bangalore

Lecture 03

Hello everybody, welcome to third lecture for this course on additive manufacturing. So, let us revisit this fundamental definition of additive manufacturing the way I have described and I have explained in last lecture. So, listen to me carefully, it is a computer controlled manufacturing process. The second keyword is layer by layer deposition or layer by layer building of materials. Third important keyword that this layer by layer building of materials must comply with the information contained in the CAD model or the digital model. And then last point that I have emphasized in the last lecture also that ultimate goal of additive manufacturing is to create 3 dimensional objects often with complex geometry and topology which otherwise cannot be manufactured using conventional manufacturing technique.

Now, what are conventional manufacturing technique, how conventional manufacturing technique have been used for decades to manufacture metals or ceramics and polymers and so on that I am going to cover in a subsequent lecture where I will be describing or I will be providing an overview of all the different engineering material classes, their properties, their different attributes and so on. So, as you may have noticed that I have been emphasizing or over emphasizing on the definition of additive manufacturing so that you cannot afford to forget this fundamental definition of additive manufacturing. Let us revisit history a little bit which is mostly related to 3D printing soon after 1950 this continuous inkjet printing was invented and in terms of more in the context of bio fabrication or additive manufacturing for biological constructs. This slide essentially provides you the overall evolution of additive manufacturing over last 7 decades or so.

So, after 1960 somewhere between 1960 and 1970 that first cell sorter was invented. Like then people found out that how to sort the cell population into different classes . Just before 1970, laser printing was invented. Around 1976-77, drop-on-demand inject printing was patented. After 1980, chondrocytes that is cartilage cells that can be re-differentiated in the three-dimensional environment that was discovered by researchers.

So, chondrocytes is the cartilage cells and if you speak to any orthopedic surgeon, he or she would immediately emphasize the importance of artificial cartilage during various orthopedic surgeries. Then in the same decade fused deposition modelling FDM printer as around 1990 FDM was invented before 1990 both the stereolithography and tissue engineering as an subject domain or as a scientific domain was essentially discovered there is a famous paper by. Professor Robert S. Langer from MIT that was published in one of the flagship journals. Between 1990 and 2000, there are several inventions that have taken place.

For example, microcontact printing, 3D printing, protein printing, hydrogels with RGD sequence. So hydrogels, it is a large macromolecular network of polymers. which has the ability to contain significant amount of water molecules. Soon after 2000, there are 2000-2010 as you see in this timeline it is a very busy period, busy decade. So, with multiple such Major inventions or discoveries were recorded for example organ printing, robotic dispensing of cell laden hydrogels, bio laser printing of cells, first in vivo use of additive manufacturing, also cell containing gels by SLA, inkjet printing of cells, laser direct writing of cells and tissue engineering scaffolds by fused deposition modelling.

So, this was more or less up to 2010 and this particular you know evolution picture is based on the paper published by Melchels et al. in Progress in Polymer Science in 2012. So, certainly we do not have the data up to 2020. So, this is the decade of additive tissue manufacturing and there is the International Society for Biomanufacturing was established and there are several research groups around the world who started working on bioactive hydrogels, digital voxel fabricators, vascularized constructs and so on. You will agree with me that you know last 7 or 8 decades have indeed witnessed significant progress in the field with the modest beginning from continuous inkjet printing to what we see in today's world like you know this additive manufacturing or biofabrication has been continuously revolutionizing this field.

I would like to also remind you that variants of additive manufacturing this is already explained to a large extent in one of the previous lectures and I have also mentioned again that some of the important that definition of additive manufacturing in the most brief manner like it represents that wide spectrum of manufacturing techniques computer aided design and even layer by layer addition of materials in a programmed manner. So if somebody would ask you very briefly in one minute what is additive manufacturing you can also explain them the most shortest manner. There are liquid based additive manufacturing, solid based additive manufacturing and powder based additive manufacturing. As I mentioned that powder based additive manufacturing is what we will be using most often or I will be showing you scientific case study. And in the same way I will be also showing you for the hydrogels like which is mostly liquid based additive manufacturing.

So powder based will be using this is the melting this is more for metals like SLS, EBM or lens and also binder jetting that will be also used for metals and in case of liquid based will be also seeing the extrusion based printing. So, it is not liquid but it is a viscoelastic gel that I will be showing you for the 3D extrusion printing. Now let me give you some information on metal 3D printing because this metal 3D printing has revolutionized that medical care with patient specific implants and also metal 3D printing used very extensively. for automotive or aerospace sector or are being investigated for the repair of aerospace components or some of the making of some of the automotive components and so on. So, this is the layer by layer implant manufacturing technique as I have mentioned.

Now, if you see that this is that different structures like okay, let us take a particular case for the orthopedic surgery. In the orthopedic surgery for this case of typical hip surgeries, now you have this femoral stem, this is the femoral stem component. And this femoral stem component is attached to femoral head and then that is articulating against acetabular liner and that is in case of the cemented total hip arthroplasty, in case of uncemented there is one more titanium. shell that is used outside the acetabular liner. Now what is the new innovations in this femoral in the orthopedic surgery is to use some of the lattice structures and these lattice structures are essentially used to fabricate the acetabular shell in this total hip replacement arthroplasty.

This is one such case another case in case of abnormal hip surgeries like you know in case some of the patients come with abnormal hip anatomy so there one has to fabricate the acetabular shell in a more patient specific manner otherwise for most of the cases So, this total hip arthroplasty standard sized components are available and are provided to the clinicians. I will explain to this in much more details when I will show you clinical relevance of this kind of the 3D printing in arthroplasty or orthopedic surgeries. Just to give you more examples like directed energy deposition as I will show you again in the subsequent slides and powder based fusion processes in both the cases laser beam is used and these are mostly used for metal 3D printing applications. This gives you this left hand panel essentially gives you broad overview how it is done. So, you start with the CT scan data of a patients then you use different computational platforms.

I am going to discuss with you in little bit more details that what are the different computational platforms can be used. So, essentially you reconstruct the 3D CAD models of the based on the CT scan data or based on the CT scan images of the patients. After that you use this STL file you send it to 3D printer either LPVF or DED then you get the 3D printed physical model. Now if this 3D printed physical model meets the property and performance requirements according to the clinical regulatory authority standards and if they are being tested in certain performance limiting for example, hip simulator testing or knee simulator testing. And if it is being approved then only orthopedic surgeons are authorized to use the 3D printed components or structures in patients during clinical surgery.

I think this last statement I must emphasize. The 3D printed parts can only be allowed for human clinical surgeries if and only if they meet all the standard property requirements, performance requirements, functional requirements for this kind of implants in simulated or in physiological context and after going through all the preclinical studies then only it can be used for human clinical studies provided it pass through regulatory approval either US FDA or European MDR or Indian CDSCO or other regulatory agencies in different countries. So, one of the major things that you know that why conventional manufacturing cannot do if you look at this particular complex shaped implants for conventional manufacturing it will be very difficult to fabricate this kind of components with so much holes, the lattice structures and so much intricate design features. So, implant fitting, implant durability and biomechanical stability particularly in the context of orthopedic surgery, orthopedic or neurosurgical neurosurgery that is very important right. So, without that this patient might need to undergo revision surgery if these criteria are not fulfilled.

I emphasize again implant fitting, durability, biomechanical stability, these are very important. Now, let us discuss in more general terms that why additive manufacturing has attracted so much attention. Now if you consider the cost per part versus complexity because this is the complex geometry and topology that I have emphasized while defining the additive manufacturing to all of you guys and if you look at the dotted line essentially represents the traditional or conventional manufacturing. The straight line essentially, so this is only in the context of metals, right. This straight line essentially represents for metal 3D printing.

So, simple parts like less complex, so if you go to this direction, it is less complex. If you go to this direction, it is more complexity. So, simple parts are cost effective to fabricate traditionally because here cost of the parts is lower than that of the metal. conventional 3D printed parts. Whenever the complexity increases, you can see that conventional manufactured parts are more costly than 3D printed parts.

What it emphasizes? It emphasizes that as complexity of the parts increases we should move towards more additive manufacturing rather than conventional manufacturing. And although additive manufacturing machines and accessories may cost higher than conventional manufacturing tools. For the complex parts, complex design, complex topology additive manufacturing is the only solution that is a key message that you should absorb from this particular slide. Now here if you look at that estimated cost per unit part this is from US dollar. So if you look at the powders because it starts with the most in the powders the material cost is much much lower.

Printing part, printing cost also is similar to that of the powder and CAD design. STL file for printing that cost is much much less that setup. Print with support and finishing. Now what you notice that post processing the finishing part that actually costs much much higher than the printing. In fact, if you add material cost plus printing cost plus design cost, I think it will be similar in cost per part roughly as that of the post processing.

So, post processing is very important because all the overhanging structures also surface roughness needs to comply with the engineering requirements. So, there are two things that I have mentioned and it has been also mentioned in the statements made in this slide. The 3D printing can manufacture implants with complex geometries and part complexity can increase the material manufacturing cost. So, let me spend little bit more time on this slide. So, what you see in this slide that I have been emphasizing that for complex parts 3D printing is the only solution, only manufacturing solutions.

Now, let me substantiate this statement by showing you some of the most complex parts perhaps you will see in this particular slide. Now, these are FDA, US FDA approved complex designs for 3D printable spinal implants, right. And you can see that there are different components for example, posterior spine truss here. posterior spine truss here that how the different struts are connected to each other. You can see that ALIF and you can see that how the different struts are organized in a very very complex manner and this is the final components that you can see this particular row Now, if you consider the convention manufacturing to manufacture this kind of parts, then you will notice that you know that this will take enormous significant amount of time.

But at the same time by looking at these parts, you will also realize that these parts must comply with this lot of requirements in terms of surface finish, in terms of the you know, overall macroscopic appearances and then lack of surface distortion, particular sized implants that size, dimensional tolerance of these implants, these are some of the most important things in this medical device manufacturing sector. So, I hope with this slide you will be convinced that these kind of parts can be manufactured by additive manufacturing which can be used for clinical studies and these are the designs which has been approved by US FDA for their clinical applications. So, you cannot use any implant design. do the 3D printing and use it for clinical studies or clinical treatment. So, those designs are to be approved.

Those designs had to be manufactured using US FDA approved biomaterials. using a machine which also comply with ISO 13485 guidelines in a GMP compliant facility has been tested by regulatory approved laboratories for the properties and performance. After that one has to apply for the regulatory approval then only you can use it for human clinical use. So, implant design with intricate geometry is possible only using additive manufacturing. I think that part needs to be emphasized once more.

So, just to explain you more and more on this part what you see here again cost per part by number of parts. So, earlier you have seen cost per part by complexity and in this slide you see that cost per part number of parts. Now, again in the context of metal. Green line is a metal 3D printing and you can see that with number of parts more and more number of parts the cost remains same whereas this other line the non-linear distribution a non-linear variation there is a high pressure die casting. Now high pressure die casting has been used as a conventional manufacturing tool for years in the industries in a very very successful manner.

Now if you look at this number of parts there is a break even point here. If you see that for small number of parts additive manufacturing or metal 3D printing the cost per part is lower than the high pressure die casting. The message is low number of parts, low number of complex shaped parts, additive manufacturing is the better option, okay. So, the right hand picture essentially shows us percentage of total cost per part and here manufacturing versus material. So, there are different type of materials that has been mentioned.

One is stainless steel 316, one is 17-4, precipitation hardened steel, another one is aluminum, silicon, tin, magnesium alloys. So, this SS316 by far is most widely investigated by 3D systems and different other individual research groups. So, 3D system is a company which sells the manufacturing machines and if you see the manufacturing cost is much much higher compared to the material cost in those kind of cases. Okay, I have emphasized this in the last lecture I think to some extent that now let me also emphasize it again in this lecture that is the 3D bioprinting. So, 3D printing means it mostly refers to the metals, 3D bioprinting means it mostly refers to making or creating the structures with the biological components either cells or proteins and so on.

Step 1 is the imaging for example this is the image that you or CT scan image from CT or MRI image of a patient. Stage 2 is the design based on that what is the design approach. Step 3 is the materials like what is the scaffold that you are going to use. Step 4 is the cell selection, cell selection means what are the cell types that you will be using for this targeted application. Step 5 is the bioprinting that you need to do to take the scaffold to consider the cells impregnate and then do these scaffolds and step 6 is the application.

These applications is more for clinical applications. So, what are the things I have mentioned in the writing panel? In step 3, one should consider the targeted tissue specific biomaterials which can be either natural or synthetic biopolymers. This I will be explaining during my lecture on scientific case study in more details. In step 4, essentially this is in the step 4, the cell should be selected according to targeted clinical applications like HUVECs for angiogenesis, human bone marrow derived mesenchymal stem cells for bone tissue regeneration and so on. Cell aggregates or tissue fragments can be combined with biomaterials to fabricate printable hydrogels.

What is hydrogel? I have just mentioned few minutes ago and then biomaterials and cells can be printed simultaneously to build the pre-designed structures. Now the way you navigate through step 1 to step 6. and optimize particularly on the material selection part, cell selection part, tissue maturation part which I have also mentioned. This takes years and also preclinical studies before you can construct this particular tissues and get the regulatory approval like the way I have mentioned it before and use it for the patients. So, there are two things that I would like to highlight here and which I will be using in an interchangeable manner when I will be showing you the scientific case study on bio-inks and biomaterial inks.

So, in the context of 3D printing, biomaterial ink essentially means it is a viscoelastic gel which is composed of hydrogels without cells or without any biological component, okay. whereas without any biological components. Whereas bio ink essentially means that cells must be contained with the biological components. with the hydrogel or biomaterial ink and that may be optional or combined with materials. You can use it as a biofabrication technique and this leads to bio ink.

Jurgen Groll from University of Würzburg led an international group of authors to define all the relevant terms bio-ink and biomaterial ink they have published in the journal Biofabrication a few years ago. So before I conclude this lecture, let me go through once more in the definition of bio-inks and bio-material inks and then what I have mentioned very categorically, bio-material ink does not contain any biological component. But it is essentially viscoelastic gels which are used to construct a 3D design structures by using one of the additive manufacturing technique. In contrast, bio ink must contain cells as the mandatory component along with other biological components. So these definitions along with other key terms can be found in the review paper by Jurgen Groll who along with other distinguished researchers from across the world they have written an authoritative paper which is published in biofabrication a few years ago.

I will come back to you in the next lecture on on some of the other relevant topics which I am going to introduce before I move on to more detailed lectures related to this course content.