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

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## Lecture 04

Welcome back to the next lecture. In this lecture, I will be discussing more on the design aspects which are relevant for 3D printing. Now, let me revisit one of the slides which I have shown in one of the previous lectures that is what are the key steps involved in 3D printing. First step is the designing of the CAD file of a structure to be made. either a new structure which was not existing before or a structure which will resemble or exactly the same way as a patient specific organs or tissue and so on based on the CT scan or MRI scan image. And there one has to use this virtual platform like computational platforms and use different softwares or computational tools to make these 3D structures.

And then once this CAD file is created then it has to be converted to STL what is STL I am going to explain to you in a few minutes time and then it needs to be sliced into N number of 2D planes and that information you need to provide to a 3D printing machine which is attached to a computer and based on this 2D planes this 3D printer will follow the instructions. in the strictest possible manner to build this design structure in a layer by layer manner. I emphasize layer by layer manner. After the 3D printing is over, then post-processing, remember I have emphasized that how post-processing is important for the metallic implants and what is the cost implication of the post-processing parts.

In this lecture, I am going to emphasize largely on the design aspects, what are the different computational tools are used and so on. Computer aided design, what is the definition of computer aided design? It is the application of specific software platform used on computers and in modern days we use workstations in many research labs for the creation, modification, analysis and optimization. Let me underline the importance of these particular terms, creation, modification, analysis or optimization of the design of a 3D structure. CAD output is often in the form of electronic files for print, machining or other operations. Slides in this lecture as well as previous lectures you have come across the file format called STL.

STL essentially stands for standard triangle language. So, standard triangle language means it describes a raw unstructured triangulated surface by the unit normal and vertices. and it also follows the construction of STL file follows a specific rule. There are certain thumb rules which I am going to explain to you in the next few slides of the triangles using 3D Cartesian coordinate system that means x, y, z. So, each triangle will be described by the vertices, by x, y, z coordinates, each triangle will be described by unit normal vector and also it is a raw unstructured triangulated surface.

In the conventional manufacturing like CNC manufacturing which is used in the conventional manufacturing, we use a different code it is called G code. G code essentially is the programming language used mainly in computer manufacturing to control automated machine tools. So, people have been using G code in CNC machine for ages now. Now, just to show you that how this STL file format that works. Now, if you look at this is the kind of femoral stem.

So, femoral stem of a patient. Now, this is the natural femoral stem and this is the natural femoral stem. So, one part has been zoomed here. This part how to construct the design. Basically, you can see that this part has been constructed.

So, I zoomed you for better clarity. Now, what you see here, this part when it is zoomed, you can see that this part can be described by N number of small triangles And then how these small triangles are being described? They are being described by their corresponding vertices in the Cartesian coordinates. And this Cartesian coordinates are being mentioned like what is the 64th elements, what is the 65 elements z is equal to minus 0.5, what is that in 70 elements x value, y value is there, in all these cases this has been mentioned like that. Now what is the EAM process flow that what is the 3D CAD modeling then you get CAD or standard triangle language that is STL interface and then you have this conversion of part geometry, creation of the prototype and you have also the auxiliary components.

Now, if you look at this cup, this cup can be reconstructed by use or cup this total structure of the CAD, this total structure of the cup can be represented by this STL file. And this STL file contains numerous small triangles and this must follow certain rules, I am going to that in the next couple of slides. This STL file then is exported to the machine and then machine follows the information content in the STL file that will print. So, STL file format is geolithography. This format describes the surface geometry of a virtual 3 dimensional object.

Central concept is the surface styling or tessellation. Now this is tessellation of a triangular facets. So now if you consider this sphere, this sphere is made up of the equal sized triangles as it appears to you here. And these equal size spheres not only oriented very regular manner but also oriented in different angular fashion and these triangles are characterized by vertices with unique coordinates. So, if you look at this particular cube here, this cube also can be constructed by using different triangles and you can see this base of this cube, it can be constructed using 2 triangles.

Every face of this cube can be described by 2 triangles. So a cube has a 6 face. So therefore total triangle would be around 12 triangles. But then there is also different lines are there. So that is mentioned on this slide.

Now, the particular structures that I am showing here are more complex. So this is a very regular structure, like a cube or sphere, and this is a more complex structure; this complex structure can also be described using numerous small triangles. So, what is the message that I am going to send? So if you decrease the size of the triangle or make the triangles finer, the closer you will get to the reality of the structure that is to be designed. So, for example, if N is 10,000 such triangles, and you reduce it to N equal to 15,000 triangles, this structure can be more closely resembled. So that is the message.

In terms of these thumb rules for constructing the HTML file format, one is a versatile tool. Each triangle must share two vertices with its neighboring triangles. These are the particular reasons why I have put a cross; these vertices are essential. This is one triangle, this is the second triangle, this is the third triangle, so it is constructed incorrectly. However, these particular vertices and this particular construct are correct; that is why I have put the correct marks and orientation rules in place.

I have mentioned that each vertex will have unique 3D Cartesian coordinates and that the unit normal of this particular triangle is always directed outward. All positive octant rules state that the coordinates of the triangle vertices must all be positive: x, y, and z, as mentioned—this is x, this is y, and this is z. Therefore, all positive octant rules must be followed. So, these are the three specific rules that must be followed when constructing the STL file. Now, what are the computational platforms used for CAD design? For engineering structures, it includes SOLIDWORKS, AutoCAD, Autodesk Fusion 360, Rhinoceros 3D, and nTopology.

I believe that AutoCAD and Autodesk Fusion are taught in other relevant NPTEL courses. Related to additive manufacturing. I will mention a little more detail about SOLIDWORKS, Rhino, and nTop. For biomedical implant design, there are two platforms: Mimics and 3-Matic. So, in the next five slides, I am going to give you some salient features and characteristics of these five computational platforms.

The first one is SolidWorks. This software platform is used on computers or workstations for creation, modification, analysis, and more. So it creates complex assemblies by combining individual parts that are essential for additive manufacturing. SOLIDWORKS offers tools for topology optimization. I said that 3D printing is essentially used for parts with complex symmetry and topology, which helps to reduce material wastage.

That is important. A key advantage of additive manufacturing is its ability to create complex geometries. The software simulation and optimization tools help refine designs before printing and reduce trial and error. SOLIDWORKS Simulation provides 3D models for finite element analysis. SOLIDWORKS built the model, which can be exported to finite element platforms like ANSYS, for example. This is essentially used to analyze the mechanical properties of the materials.

So, in a nutshell, what I am going to emphasize is that SOLIDWORKS is not only used to create designs for additive manufacturing, but is also used to create designs for finite element analysis; for example, to analyze the mechanical properties, stress distribution, deformation, and fatigue properties under various loading conditions. There is another platform called Rhinoceros. It is also known as Rhino by the user community. It is another powerful piece of software used for designing 3D models for additive manufacturing and medical implants. This is versatile and can handle both simple and complex designs, from organic shapes to mechanical parts.

Rhino supports a wide range of file formats. Triangular Language, object files, and STEP stand for the Standard for the Exchange of Product Data. STEP files are often used in conventional manufacturing processes. Once you create the STEP file, you will send it to the CNC machine. CNC machines will follow the G-code contained in the STEP file, and then they will essentially create these implants.

IGES format, or the Initial Graphics Exchange Specification, ensures compatibility with various 3D printers and other CAD/CAM software. Specifically, Rhino can export models in STL format, the standard format for 3D printing, ensuring that the designs can be used directly in 3D printing workflows. This is another computational platform. The first one I mentioned is SOLIDWORKS, and the second one is Rhinoceros.

The third one is n-TOP. Now, n-TOP is also used for the intricate lattice structures of digital models. Now, this lattice structure design is very important for many orthopedic implants, and I will later show in some case studies how it is useful. This platform uses mathematical fields to control geometry, enabling highly customized and functional designs that can adapt to specific performance requirements. It is used again for topology optimization. And to reduce material usage, it allows designs to incorporate material properties directly into the design process.

So that a specific performance criterion can be established. It allows for rapid iteration and the development of complex geometries. All of this software must have some common attributes. These common attributes include the ability to create digital models, which must be complex in nature, and the software must also allow for rapid iterations of design modifications. So, all of these are specific or common attributes of these computational platforms.

The fourth one is MIMICs. MIMICS stands for Materialized Interactive Medical Imaging Control System. Mimics is a software suite primarily used in the medical field for converting 2D image data from CT or MRI scans into 3D models. These models are used for various purposes, including surgical planning, implant design, and patient-specific simulations. I must mention that the Mimics software is perhaps the most widely used program in the medical field. So, it essentially excels at segmenting 2D image data to isolate specific anatomical structures and regions of interest (ROIs).

This segmentation is crucial for creating accurate 3D models from CT or MRI scans. It allows extensive editing of 3D models. The smoothing, refining, and correcting of anatomical details ensures the accuracy and usability of these models for various applications. It can export 3D models in STL format, and this allows for the direct use of these models in additive manufacturing workflows. So, again, as you can see from this description of the key features of the mimics, they are very versatile in the fields of medical implants and medical imaging, and so on.

Thematically, this is much less explored and is receiving more attention today. It is a software tool that works alongside Mimics to enhance and optimize 3D models for various applications, including additive manufacturing. It is a powerful tool for repairing and refining meshes, ensuring that 3D models are watertight and free of errors, which is crucial for successful 3D printing. To improve the functionality or aesthetics of a part and create a porous structure for biomedical applications, it provides tools for precise mesh editing and repair, ensuring high-quality and printable 3D models for medical device design and industrial product development. So what you have seen in the last five slides that I have mentioned are the key features of SOLIDWORKS, Rhinoceros, nTOP, Mimics, and 3-matic; and I must say that out of all these, I feel MIMICS is the most extensively used in the medical field.

SOLIDWORKS is most extensively used in engineering to design structures that can be used for either medical or nonmedical applications. I have not covered AutoCAD, and I am sure that it has already been covered in other additive manufacturing courses. Now, at this point, I will also mention how to characterize the 3D microstructures and the 3D structures. So this is a micro-computed tomography facility. It is one of the companies, but it is not the only company in which X-RADIA is used.

But more than a company, it is not for promotional purposes, as I mentioned before. So, what is most important for this kind of academic course is the working principle of microcomputed tomography. You have an X-ray source that emits the X-ray beam; this is the sample rotation stage, and this is your three-dimensional sample. The condenser lens focuses the X-ray beam and rotates it. So it will rotate in a 360-degree rotation, and with that rotation, two-dimensional slices are collected.

These are all 2D slices, and these 2D slices are reconstructed to create the 3D structure of this component. The way it has been shown in this particular slide is that this is a very simple component; micro CT is mostly used for very complexly structured components, I must say. So, as I mentioned in the previous slide, it has all these 2D slices, and then the 2D slices are stacked one after another; they are then reconstructed to create the 3D volume. And then the software they use for this, Avizo and Amira, is more suited for the quantification of 3D structures. So, microcomputed tomography essentially uses an X-ray source, images, radiographs, incremental projection angles, and so on.

So, one of the components that I am going to cover under these emerging opportunities is the concepts of artificial intelligence and data science. I am going to show you at least two or three slides just to emphasize why it is important and how it is relevant to additive manufacturing because, as I have been telling you, this is the fourth lecture, and in all these lectures, I have been touching on some of the very basic or fundamental aspects related to additive manufacturing. At the same time, I am also covering some relevant topics that I will discuss in much more detail, but I am just touching on those topics here to remind you of them when I explain them in more detail than I am doing now. So, artificial intelligence, as I said, I think perhaps in the first or second lecture, is one of those technologies that is going to revolutionize the field across multiple scientific disciplines. What is artificial intelligence? It uses algorithms and techniques that leverage computers to mimic human intelligence.

It essentially mimics human intelligence. Machine learning is one of the subfields of artificial intelligence. It uses algorithms whose performance improves over time as they are exposed to increasingly larger amounts of data. The same algorithm may perform better and better if you use a larger number of data sets. Therefore, one has to test these different algorithms over a large number of datasets to show that they actually follow the increasing trend in terms of the performance metrics that these algorithms use. What are the different topics in computer science that are more relevant to many people than to other communities that use artificial intelligence day in and day out? It is like supervised learning.

It is trained on labeled data to predict outcomes for new, unseen data. Then comes unsupervised learning. It learn about the data set without labels like unlabeled data. The third one is reinforcement learning; its goal is to take actions to change the state so that you can receive rewards. So, deep learning is a subset of machine learning in which multilayer neural networks learn from vast amounts of data.

So, for deep learning, you essentially need to have a much larger quantity of data than that used in machine learning. So, why are AI and ML fundamental? This question arises because it is most relevant in the absence of any established relationship between the dependent and independent variables. What it means is that if you recall Newton's second law, force is equal to mass times acceleration. So there is an established relationship, which is Newton's second law, and it is widely known. But when you confirm that multiple variables are at work in 3D printing, I will show you an example: one such example is that any laser-based system, such as laser power, scan speed, and powder feed rate, constitutes the input parameters.

What are the output parameters? The output parameter can be the surface roughness of the material components, correct? Our output parameter can specify what the defects contained in the structures are. Output parameters can be the porosity or density of the materials being developed. Now, these output parameters cannot be correlated with the input parameters by any established relationships. Therefore, artificial intelligence is the only option you have.

I am going to explain this here. This is the case for additive manufacturing for metals, as I mentioned: you have the laser power, the scan speed, and the hatch spacing; these are different parameters. I am going to show you more of that when I present a scientific case study. This totals 25 parameters, and this is the minimum number of experiments that are required: 2 to the power of 5 times 25, which is a 2-factor design of experiments. And if you look at the time, the line used for powder handling, maintenance, printing hours, and total downtime is known for each machine. The total time for all these things is 70 to 100 hours, and a huge cost is involved.

Machine learning can induce this particular parameter space, conduct trial-and-error experiments, and improve quality. It also allows you to predict processing structures and structure-property correlations in the materials. This is one of the things that I am going to explain to you in the last few lectures of this course: how artificial intelligence and machine learning can be adapted or can be very useful in accelerating additive manufacturing. Scalable and faster manufacturing methods are needed in the industry. Additive manufacturing industries have to gear up to take on or absorb some of the newer advances in this field; therefore, we need to educate the next generation of researchers who want to pursue additive manufacturing in that profession with the necessary concepts and ideas of artificial intelligence and machine learning.

Remember, it sounds more like a computer science-based topic. But I will try to explain in the simplest form, with a lot of examples, for you to appreciate how artificial machine learning can be used and has been used with good predictability in the field of IT manufacturing. Thank you. I will get back to you in the next lecture.