Laser Based Manufacturing
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Module No # 06
Lecture No # 18
Additive Manufacturing Techniques

Hello everyone! I welcome you all to the week 6 of NPTEL online course on laser-based manufacturing. In this week, we will be studying how lasers can be used in the additive manufacturing technologies. We have already finished very important processes being used in the industry. And these processes are prominently the laser-assisted or laser employed process. We have seen laser-based material removal. We have seen laser-based welding. We have seen laser-based forming and the heat treatment in our previous week itself.

Now, in this week, as I mentioned, we will be studying a very fascinating and popular technology, which is there nowadays, that is additive manufacturing. Many people are calling this as the 3D printing. So, laser is an integral part of this manufacturing process or this manufacturing technology that is additive manufacturing technology. Let us begin our week with first lecture on the fundamentals of additive manufacturing. What are the various types of additive manufacturing processes that are used in the industry? And where the lasers are helpful to solve the problems? So, let us move.

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Fine! As I mentioned, today we will be studying additive manufacturing techniques. Some of the fundamentals of additive manufacturing techniques, the types of, additive manufacturing techniques, and then we'll start discussing laser-based additive manufacturing techniques. Well, for laser based additive manufacturing, we will be covering only one process today and the remaining processes would be presented or discussed in the subsequent lectures. Let us begin our first concept or first point of discussion today that is additive manufacturing technologies itself.

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As I mentioned right now its popularly being called 3D printing. And this 3D printing technique is being used by people basically for rapid prototyping to develop prototypes in a rapid way. So that we call as rapid prototyping. Why it is essential to develop the prototypes in a rapid way? In the product life cycle, in the development of a product, we are first designing the product and when we design the product, we are not only deciding its dimensions and size. We are also looking at its aesthetic, its shape, color, or texture. Now the designers want to realize the shape, size or its aesthetic look at very early stage, at the primary stage of its development itself, and that is the design stage.

To manufacture any component to manufacture any product, we have to first look at how we can manufacture that component. We have to arrange the tools required for that. If it is to be manufactured by using plastics, then we have to develop the dyes and molds and these dies and

molds itself is a is a tremendous task. To design the dyes and manufacturing of the dyes itself is a tremendous long task. Now if we design the dyes and molds for manufacturing or for developing or for realization of only one product, it would be meaningless. It will not serve the purpose. Consider after realization of certain mistakes, certain errors in the design we have to throw off, we have to dispose of the dies and molds, which is of no use, which is not economical. In this case the rapid prototyping or rapid tooling concept came into picture in the industry and the idea is to realize the product in early stage. It may not be of the same material that we are intended to have. For example, the product is of metal. We can realize its shape by developing a product of thermoplastic or of a plastic material. But some mechanism, some arrangement should be there to realize the product. Earlier people used to develop the products by using wood, by using carpentry or by developing the clay models. But now by using mechatronics by using manufacturing automation by using advanced techniques and with the use of polymeric techniques, we can easily generate the required product by using certain material, certain compatible material we can realize the shape and size of the product at very early stage. This process is layer by layer fabrication.

Here whatever the 3D complex shape we can generate or we can manufacture, but we are developing that product by layer by layer addition. That is why it is called as additive manufacturing. We are adding the layers over each other and then we are developing a 3D part. These layers are considered to be a 2D geometrical entities of unit thickness and by adding these 2D geometries over each other, we can get the three-dimensional part or three-dimensional product.

Let us see, what are the various other aspects of this 3-dimensional additive manufacturing? The 3D parts or 3D structures nowadays are possible with a wide range of materials. Mostly they are possible with the plastic materials or polymeric materials. But now people are developing the parts of metals as well by using DED that is a Direct Energy deposition-based material processes. Even by using concrete, we can even also develop 3D structures and furniture. The concrete can also be poured in and we can develop the 3D structures in a rapid way. The entire objective of additive manufacturing is to develop the complex shape, and these techniques nowadays are successfully providing geometrical complex shapes to us. They are providing many functions and we can also have a composition as well. Even it is possible to have now the multi material deposition. So, it's

not only that only one material we are depositing. We can deposit two different materials at two different layers. Only thing we have to see these layers are properly getting fused.

What are the various applications of this additive manufacturing? Nowadays, the additive manufacturing is finding lot of applications in electron actuations, lot of actuators are manufactured by using additive manufacturing techniques. For example, the levers or the press buttons or any atom which can be used for actuation of certain operation or the action, if it is broken, if it is not working, we can easily replace the design which is available with us, we can go to the lab on the machine. We have to just create the 3D model, slice it and then apply that sliced models to the machine that 3D printing machine and we can easily generate within very less time. Biomedical engineering is the biggest beneficiary of additive manufacturing because here there is no limitation on the complexity of the shape or the parts. When we are dealing with the implants, when we want to insert some implants in our body, then we have to match up with the geometry of our body parts and as we know that our body parts or the bones are having free form surface complex shapes. In general, by using traditional manufacturing, it is very difficult to manufacture the free form surface, or to generate the complex surfaces. In 3D printing, it is very easy and it is very fast to manufacture 3D complex shapes of various bones of various body parts which we can use as implants in our body. Moreover, the sensors can also be manufactured by using additive manufacturing technique.

There are basically two ways, or two approaches in AM, and the first approach is extrusion-based 3D printing. It is very common, it's very general and even such systems are available in house as well, at domestic level, and in laboratories, in all the institutes, in all, everywhere you can find the extrusion-based 3D printing devices. Moreover, when we apply the lasers, of course, we are using or we are trying to exploit or trying to get help of the three properties of laser beam that is monochromaticity, coherency, and we are applying at a very small area control basically. So, by using these three characteristics we can easily generate very complex shapes of very small size with required surface finish, and surface quality.
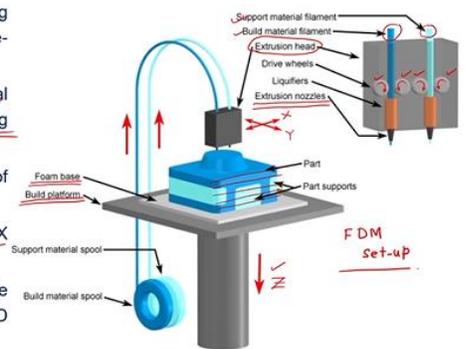
Lasers are helping a lot in this additive manufacturing. In what way they are helping let us see? And the first process is stereolithography process. Then lasers are being used for sintering

operation and by using the sintering we can generate various parts. The second one is the melting operation, laser-based melting and if we select a certain portion that to be melted and that will be get resolidified or it will get fused. And by using this SLM process you can generate the 3D parts. Then laser engineered net shaping that we call LENS. This is the fourth method we will be looking at these 4 methods 1 by 1 in our coming class. Let us first look at the stereolithography that is the first process in our coming slides. Before that, I would like to have fundamental discussion on the most popular technique that is the extrusion-based 3D printing. That we will see in our coming slides.

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The extrusion-based 3D printing is very simple and basic process. And it is allowing for extruding of the polymers and these extruded polymers are deposited layer by layer. To fabricate 3-dimensional structures. So here the definition is or the methodology is very much clear. We are extruding polymers through a nozzle and then we are depositing this extruded portion of the polymeric material over each other in a certain way in certain format to develop the 3D structure. And in this way, we can develop the 3D structures of whatever the shape that you require. In this approach that is extrusion-based 3D printing approach. There is most popular method that we call FDM. It is a fused deposition modeling. It is most typical and commonly used extrusion-based 3D printing technique which is used. Now what happens in this technique that we will see? The FDM is melting the wire of the polymeric material and that molten wire in its semi solid mode will get deposited on the material. These deposits of the filaments or in a filament type the material would be there according to the specific pattern according to a certain pattern we can deposit the wire.

Now on your screen you can see a typical arrangement of FDM i.e. the fuse deposition modeling. So, this is FDM setup. Now let us look at what are the various parts of this FDM setup. The first part of this FDM setup is the build platform, on which we are building the 3D part, so that is a build platform on which we are having a foam base to hold the part. Then this build platform you notice is moving in downward direction, so it can move in a downward direction. Then we are having the extrusion head, this is the extrusion head. Extrusion head has basically 2 filaments. The first filament is build material filament, this is the build material filament of dark blue color. And there is another filament we are using is support material filament. It is a light blue colored. There are two filaments that to be used to develop or to build up a 3D structure. The build material filament is the actual material that we need of that product.

However, when we are having some overhanging structures, overhanging shapes in our product. To support this overhanging shape we are using some sacrificial material, some support material and that support material is easy to remove from the parent material or the build material. These support materials are also to be deposited during the 3D printing operation. Now, these filaments are being operated by using rollers. These are two pairs of rollers which you can see over here. And by using these rollers we are just getting the filament inside the nozzle. And these extrusion nozzles are having some heating element. When the wire or the filament comes inside the nozzle the filaments are getting heated up, their temperature is increasing and then there is a change in the phase of the filament, the solid will be changed into semi solid or in a liquid stage and afterwards we are depositing that molten filament material over the foam base. And as we have a relative motion between the head of the FDM and the table we can generate various parts. But after every layer, the base has to get lowered by certain distance.

Here you can see. This entire 3D geometry is first converted into layers. This information would be given to the machine and this layering would be done by using CAD based technique. We have to 1st generate a CAD model of the product and then we have to slice it into finite number of. 2D layers and this layering would be done by using another computer-based system that we call computer-aided manufacturing. And then based upon the geometry of the layers, the FDM will be carried out by the machine tool. This movement of the tool over the work part would be again is

an interesting and important area that we call computer-aided tool path planning. You have to plan the relative motion of the FDM head with respect to the work part.

Here you can see the extrusion head can be moved in x- and in y-direction and the platform is moving in Z direction. FDM consist of a print head which is able to move along x- and y- directions above the build platform. The polymer is extruded through the heated nozzle and let down as filaments according to the CAD design. The build platform is then lowered and another layer can be built until the part is completed. So, what we are doing here we are slicing it off, we are using CAD and CAM-based technologies to generate the computer rate tool paths, that would be given to the controller of the FDM machine, and then accordingly the extrusion head will move in XY plane and the platform will move along Z direction.

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Now let us see what are the various materials which are used in FDM process? Mostly we are using polymeric materials. In FDM process and the popular materials are ULTEM. ULTEM is polyetherimide. So here, as just mentioned it is polyetherimide. We can deposit or we can build up our part of polycarbonate, then polyphenyl sulfone, polylactic acid. And this is very common or popular material and short form or acronym is ABS. This is acro nitrile butadiene styrene, ABS. And it has various grades as well. All these materials are available in the form of filaments and we have to just extrude them to generate the 3D parts.

FDM has tremendous applications. Because this is quick and inexpensive. We can afford it. We can have the 3D printer at our home as well. And we can easily build up the prototypes. at a faster rate. It has been noted that these parts are tough and rigid. And suitable for the end user as well. There is the biggest advantage of these 3D printed parts or they are slowly substituting traditional metal parts. They are replacing traditional metal parts which are being used in aviation industry, in particular. In aviation industry, we need to have a lightweight, high strength materials or lightweight high strength structures where the metals can be replaced with these 3D printed plastic material which can serve the same purpose of the metals. Moreover, the 3D printing is also helping to reduce the turnaround time for the repairs. Suppose some part is get damaged. And without that part, the machine cannot be run. In that case we have to quickly replace the part, but it is not available. However, if you are having the part dimensions or part drawing, you can easily print it within few hours and we can start the production operation. We can save a lot of time. We can reduce the turnaround time for the part repairs by using 3D printing.

However, one point we have to note here that although these parts are getting manufactured at a rapid rate, their resolution or surface finish is not that good. In that case, to just realize the part shape to realize the part, size, texture, we can have this rapid prototype part by using FDM. To have the required surface finish or the high-quality finish and more complexity as per the geometry, we have to go for some advanced level of techniques and that is the laser-based techniques. The FDM based parts are found to be very economical, not that expensive. And they do not require any chemical post processing. Whatever the part that is getting generated by having a simple cleaning of the part, we can directly use for your application.

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Additive manufacturing (AM) technologies

When precision and a smooth surface finish is important

When high resolution, fine detail, and accuracy is necessary

For creating molds for casting to facilitate mass production

Laser based additive manufacturing technologies
- ❖ Stereolithography (SLA)
- ❖ Selective Laser Sintering (SLS)
- ❖ Selective Laser Melting (SLM)
- ❖ Laser Engineered Net Shaping (LENS)

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But as I mentioned, when we want to have a precision in part development. The part has to be very precise as per as its dimensions, surface quality i.e. the smooth surface finish is required. Then what? When we want high resolution, fine details over the part and the accuracy is also essential. Then what is the answer to this? Than creating the molds for the casting, which can be used for the mass production. When we want to change the material, say we do not want to use the plastic. And for casting as you know, for casting we have to have some refractory material. So, thermoplastics may not be useful for the casting of metals.

Sn that case, what is the solution to this problem? Here we have to take help of the laser-based technologies, where the lasers can be used to deposit the materials in a layer by layer mode and they can melt any material as we have seen in our previous class as well in laser surface alloying and laser cladding we can easily melt the metal powder as well. By melting the metal powders, by melting the ferrous as well as nonferrous materials, we can easily build up the 3D metallic structures as well. And by using these 3D metallic structures, you can easily build dice molds or to certain extent the casting molds as well.

Now, as I mentioned in my previous slide itself, the lasers are helpful. In what way they are useful? We can go for the prominent method that is a stereolithography, SLA. Laser sintering in a selective mode that is a selective laser sintering. Laser melting in selective mode that is selective laser melting. Laser engineered net shaping, that is the lens technology. In this way, the lasers can be

used to solve some of the problems of the FDM techniques. We will see these techniques one by one.

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Stereolithography (SLA)

- Stereolithography: a localized photopolymerization process -> triggered by ultraviolet (UV) radiation and takes place within a bath containing liquid monomers, oligomers, and photoinitiators.
- It is versatile -> generates a variety of highly complex 3D structures with high precision and at affordable cost.
- Soft robotic actuators, sensors, medical implants, microfluidics devices and energy storage components.
- Successive layers with a thickness of 0.10 to 0.15 millimeters.
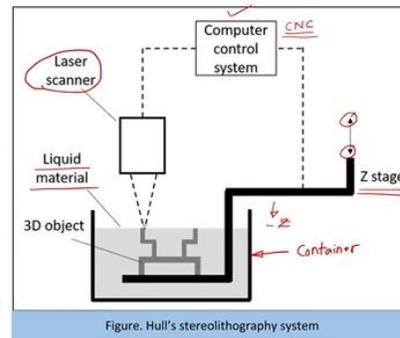
Figure. Hull's stereolithography system

Huang, J.; Qin, Q.; Wang, J. A Review of Stereolithography: Processes and Systems. Processes 2020, 8, 1138. https://doi.org/10.3390/pr8091138

Now let us study the first process that is a stereolithography process. It is very interesting and important technique. Stereolithography is consisting of a localized photopolymerization. Here we are carrying out photopolymerization. And to carry out this operation, we are using ultraviolet radiations and these ultraviolet radiations are the laser-based radiations that we are using. And this entire operation of Photopolymerization would be carried out in a bath, and that is containing liquid monomers, oligomers and photo-initiators. We are taking a bath, liquid bath of monomers, oligomers and photo-initiators and then we are irradiating this bath at its surface by using UV radiation. And this UV radiation is generated by using lasers. This process is versatile and we can generate a variety of highly complex 3D structures with very high precision and at a affordable cost. On your right side we can see a typical arrangement of the stereolithography.

Here you can see we are having, a container, and inside the container, the liquid material is there, a bath of monomers, oligomers and photo-initiators. There is a stage, the stage is moving along Z direction. It's a vertical up and down. Here we are using laser scanner and this laser scanning would be done by using a computer control system. It is a CNC based laser scanner. Fine! Wherever the laser is getting interacted with the liquid material, that much portion will get cured. And after curing, it will get solidified. What we are doing after first layer is getting solidified? We are moving
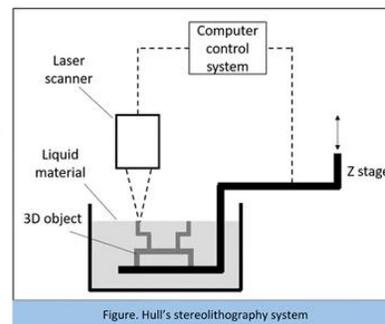
the stage in downward direction along negative Z direction. If I consider this as negative Z it will go down negative Z direction and then another layer of liquid will come at the surface. Again, we are applying the laser beam energy UV radiations and there would be curing as per the direction given by the CNC controller.

After the curing of the second layer then the stage Z stage will go down by a fixed distance and that is typically within 0.1 mm or 0.2 mm. It all depends upon the thickness that we want. What are the various applications of this stereolithography? We can manufacture soft robotic actuators, sensors, medical implants which already I have talked to you about, Microfluidics devices, energy storage components, all these can be manufactured by using stereolithography technique. As I mentioned, there is layer thickness which can be achieved in the SLA. So, this process is popularly called as SLA, stereolithography. the SLA is capable of generation of layers up to 0.1 to 0.15mm. There may be advanced SLA as well which where we can even go below these values.

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So, this process basically involves curing reaction of resins, which is an exothermic polymerization process. And it is characterized by chemical cross-linking reactions. This reaction is basically initiated by supplying the energy, by the energy of the UV. And there are two transitions during the curing reaction process. When we apply the UV light there is curing will occur. But there are basically 2 transitions of this curing. First one is gelation and the second one is vitrification. Let us see what is the meaning of gelation and vitrification. Gelation is a liquid to rubber transition

process that is getting realized when there is a dramatic increase in the viscosity of the processed material.

During this dilation process there is a dramatic increase in the viscosity of the process material. During this transition, both gel phase and solid phase coexist in the system. During enhancement in the viscosity, we are getting both the phases, that is the gel phase as well as the sol phase. Now let us look at the meaning of vitrification. Vitrification comparatively is a gradual process. It is Thermo reversible process. And it is leading to the transition from liquid or rubber resin to a glassy solid resin. It is a gradual process, Thermo reversible process, and there is a transition of a liquid or rubber resin to a glassy solid resin that we call the vitrification process.

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As I mentioned now let us look at how this building up of the product or the 3D part is carried out. As I mentioned previously, the stereolithography process requires CAD module, as well as CAM module. We have to have the designing using computers, Computer-aided design and Computer aided manufacturing. Right now, we will be focusing on the CAD and then the CAM. The basic part of the 3D printing technique is the STL file or the standard tessellation language-based file. So, every part which is getting generated, first of all we have to develop its 3D model. 3D modeling is very essential when we want to utilize or when we want to develop certain parts or products by using 3D printing technique. 3D digital modeling is essential.

Afterward, we have to generate the STL file, standard tessellation language file of that 3D model part, and then we have to carry out the further operation. So, we will see these operations one by one. Here we are taking a 3D model and then we are slicing the STL file. We are slicing the 3D model. let us consider a cone is to be built up. Now we got a 3D model of a cone. This is its axis. And to generate this cone by using a 3D printing device, we have to first develop its 3D model. Then you develop its STL file and then this STL file will get sliced into number of finite layers. Of course, every layer would be of circular shape only, but their radius or diameter would be increasing when we move from top to bottom. the translated 2D slices, 3D model will get translated into number of 2D slices. Of course, the geometric information provided in the 2D slices would be dependent upon the geometry of the 3D itself. It will not be same. If it is a simple cylinder, then each file will have the same information, but in case of the products where the cross section is varying then certainly 2D information would be different.

Typical product can be seen on your screen. Here we are having a cuboid. So, this is a cuboid. And at the center of the cuboid, there is a circular feature, circular hole. This is a hole of certain diameter. And now we have to approximate or we have to develop STL file of that. typical STL file would be there on your screen. Here you can see the flat surfaces the cuboid is having its faces and the faces are perfectly flat. this is face number one, then two, three, four, the top is five and the bottom is six. out of these six faces, face number 1, 2, these adjacent phases are plane, they do not have any features on it. these features can easily be approximated, can be easily be represented by using two triangles. This is triangle number 1, TR1 and TR2. when we are having very plane surfaces, it is very easy to approximate.

In STL file the plane surfaces are considered or they are approximated, they are represented. By using the triangles and each triangle as we know has three vertices, the coordinates of three vertices would be inside the file. It would be easy for us to represent, or even to read the geometric information provided in that particular file. But now you take a circular feature that is a hole which is there inside. This is the circular feature. It has non-planar surface. This is the non-planar surface. And this non-planar surface is now approximated by using number of triangles and this approximation would be done first by approximating the top circle and the bottom circle by using lines. Here we are considering a circle which is there at the top which is made-up of finite number

of lines. Here we are considering this top surface or the top circle of the hole which is made-up of a finite number of lines. And each line is having 2 ends, 2 vertices and the vertices are having the coordinates, XYZ coordinates. So, we are approximating a circular feature into number of linear features. This is called as piecewise approximation. We are cutting the circle into finite number of points and then we are joining these points by using lines.

Once we have finite number of points on the top circle in a similar way, we can also have the finite number of points on the bottom as well. Then, by using the top circle points and the bottom circle points, we can easily have the formation of triangles over the curved surface. So, curved internal geometry which is here is a curved geometry. And this curved geometry can easily be represented by using set of triangles. once we slice the components or once we slide the 3D model, then by using these slides when we add these slices, we can create physical model by using the laser-based technique that is a stereolithography. The 3D model of STL format is represented with many small triangular facets. Each triangular facet is described by the coordinates of three vertices. And a unit vector pointing outside of the facet to indicate the normal direction.

As I mentioned, every plane face or the feature is approximately represented by using triangular facets. here we are not only recording the coordinates of its vertices. We are also recording or we are also taking help of the normal to that particular facets. one such example is there on your screen, this is the example. as I mentioned, we are developing a CAD model. It's a circle, the inside feature is also circle. And now the STL model is something different, the STL model is a set of or a bunch of triangles which are getting connected on the points on the outer circle as well as the inner circle. Not only these points, now we are also making use of the normal to the facets, each and every triangular facet will have a normal. these are the vertices. And these vertices are defining the triangle. each vertex is having X coordinate, Y coordinate, Z coordinate. X1, Y1, Z1 and X3, Y3, Z3. And this is the normal to the first facet.

This all information is needed to slice the component and then make use of the slices for building up the 3D model. Well, on your screen there are three spheres that you can see. Here I would like to point you that if you increase the number of triangular facets you will have more accurate representation. So here the first sphere is having a raw filling or you can say a sphere which is

made-up of some triangular facets, but its surface is not that smooth. To make it much smoother, what we are doing, we are increasing the number of elements, number of points on the surface and by using these points again we are approximating the outer sphere by connecting these points by using triangles. Many triangles will create a smoother surface. It would be helpful for the controller to have the precise control over the parts.

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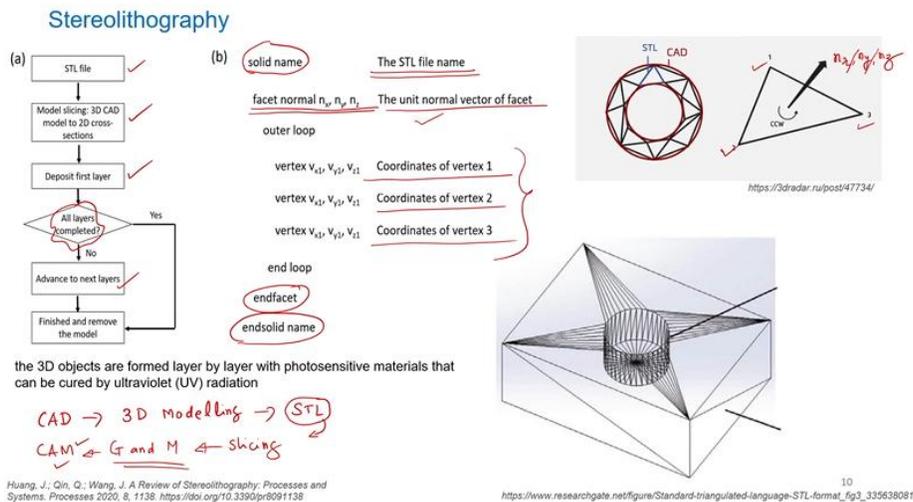
Now let us look at a typical STL file, which is very essential and would be very helpful to you. here the file is having typically the solid name and that is the STL file name. And it is having the information about n_x, n_y, and n_z. these are n_x, n_y, and n_z information about that. That is the unit normal vector of facet, it may be n_x, n_y or n_z. Then the coordinates of the vertex 1, vertex 2 and vertex 3. vertex 1. Vertex 2 and Vertex 3 its coordinates are there and then there is a end of the facet and end of the solid name. every solid will have a finite number of facets, and every facet there would be definition about its vertices as well as unit normal vectors.

the stepwise operations that are being carried out in CAD of stereolithography, that we will see. We are getting the STL file first. Then we are slicing it, 3D CAD model will be sliced to 2D cross sections. Then we are depositing the first layer and when the layers deposition is getting completed, then we are going for the next layers. in the CAD part, we have seen that a 3D model is required.

And, in the CAM part this 3D model, which is converted into STL file, the slicing would be carried out. And based upon the slicing, there is G and M code that to be developed. G and M code are nothing but the instructions to the machine tool i.e. the CNC based machine tool. G and M code to be given to the machine tool by using the CAM software. modelling, then slicing, and then deposition, these three steps are very vital and crucial during this additive based manufacturing process.

With this I would like to stop for today's discussion on additive manufacturing, its fundamentals, various parts or construction of a typical additive manufacturing system. We have seen FDM that is a fused deposition modeling, very popular or common technique. And then we started discussing about using lasers for additive manufacturing. we have started the laser scanning based additive manufacturing that is the stereolithography. we will continue our discussion and we will discuss more about the stereolithography, what are its variants in the next lecture. Moreover, we move ahead and look at the selective laser sintering as well in the next lecture. till then goodbye. Thank you for watching this lecture. Ok! Bye!