The Future of Manufacturing Business: Role of Additive Manufacturing
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Lecture – 30
Extrusion of AM for Industrial Application

Welcome again to the NPTEL course on the future of manufacturing business and the role of additive manufacturing. I am Chandrashekhar from Wipro 3D Bangalore and along with my collaborator from IIT Madras professor R K Amit. We are presenting this program with primary focus on the future of manufacturing business and also the role of additive manufacturing in this metamorphosis.

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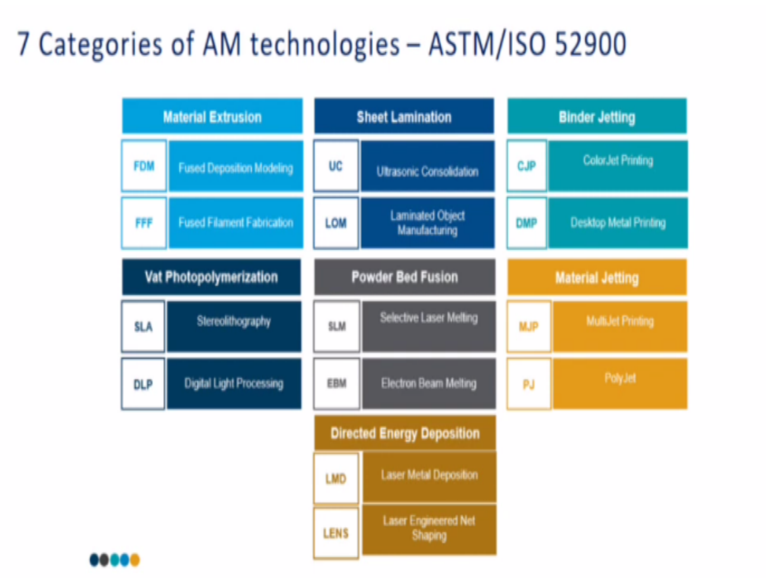

Fundamentally in the initial classes, we understood the categorization additive manufacturing technologies and we got to describe the characteristics of these 7 verticals encompassing extrusion, lamination, binder jetting, material jetting, vat polymerization and power bed fusion and the special technique called directed energy deposition which is connected with the repair and refurbishment scenario.

Most of our conversations were connected with the metal additive manufacturing technology of powder bed fusion with a primary focus on laser power bed fusion and we also got to briefly discuss the technique of stereolithography which works on the principle of instantaneous curing of photosensitive polymers using lasers.

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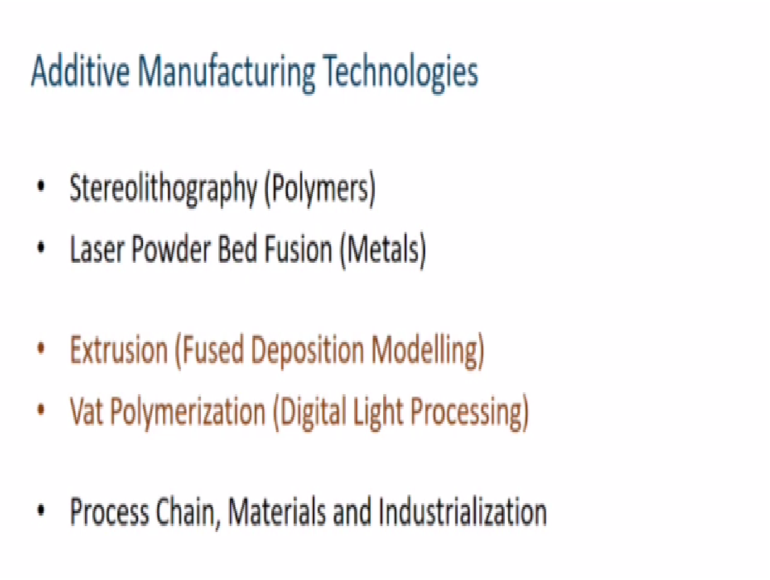

In today's discussion, we will focus on two techniques or two processes which have found favor with numerous industrial contexts as well as individual uses. One is connected with extrusion technology; other one is connected with vat polymerization.

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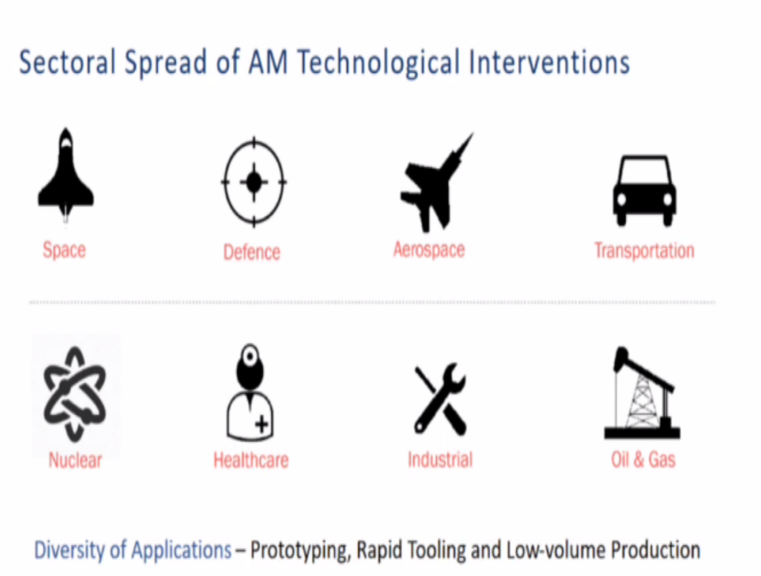

It is very important to note that these technologies though they are primarily connected with non-metallic materials that is that their primary application is connected with thermoplastics, they have formed an array of applications in sectors connected with aerospace, defense, transportation and healthcare specifically. These applications range from prototyping, part substitution, indirect use like a rapid tool and also low-volume production .

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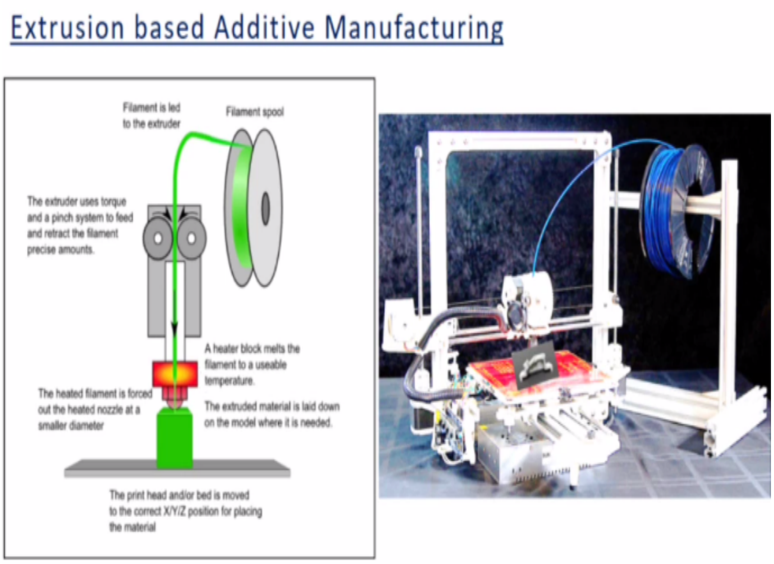

The technology which has gained widespread acceptance among the user groups from academy, research labs, design groups, small scale units and also large industrial enterprises is the one which is based on the principle of extrusion. What is shown in this particular picture is the operational principle of this technology which is widely known in the commercial context as the fused deposition modeling or FDM in short.

The original patent is credited to Scott Crump who started the premier AM company called Stratasys. If you look at the operational principle of this extrusion-based AM process, the feed stock typically is in the form of a filament, a thermoplastic filament and it is drawn into an extrusion by an extrusion head. The extrusion head consists of a driver gear, an idler, and a stepper motor. Fundamentally, the movement of the stepper motor influences the feed rate.

The thermoplastic filament which is being drawn by the extrusion head enters the hot end and it is drawn out in a liquefied state through a nozzle. The deposition of the material which is being delivered through the nozzle happens on a platform which is also known as print bed and the print bed has got provision for movement in the z direction and the cartridge consisting of the extrusion unit and the nozzle has got the provision to move in the x-y direction.

I am talking about typical configuration which is illustrated here. Indeed, there is going to be a pressure drop. There is a pressure drop across the extruder and the pressure drop depends on the viscous properties of the fluid, geometry of the nozzle and the geometry or the configuration of the liquid liquefied.

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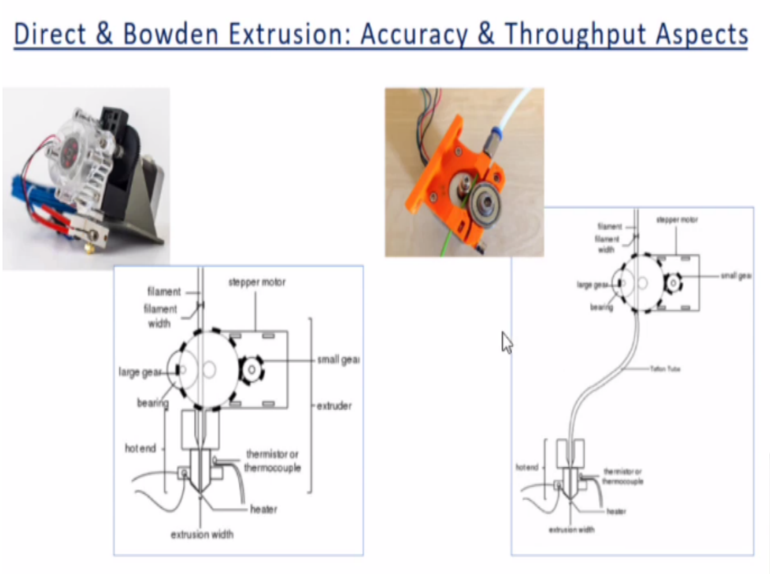

There are two popular methods of extrusion. One is the direct extrusion wherein the extrusion element is directly connected to the nozzle or hot end. The other one which is known by the name Bowden extrusion and this extrusion head is mounted on the machine frame. There are certain pros and cons of each of this configuration. In case of direct extrusion, the retraction response of the extruding unit is much better, but it has got one inherent disadvantage. The mass of this entire unit consisting of extruder as well as the hot end is much higher compared to the Bowden unit.

Because of this higher mass or higher inertia, they got problems connected with vibration and this may in turn adversely impact the accuracy, especially if you are talking about high speed printing. The Bowden extrusion has got inherent advantage of lower mass and hence high-speed printing is facilitated, but there is a problem since the filament has to move through this cable many materials including the abrasive materials cannot be handled in the Bowden extrusion.

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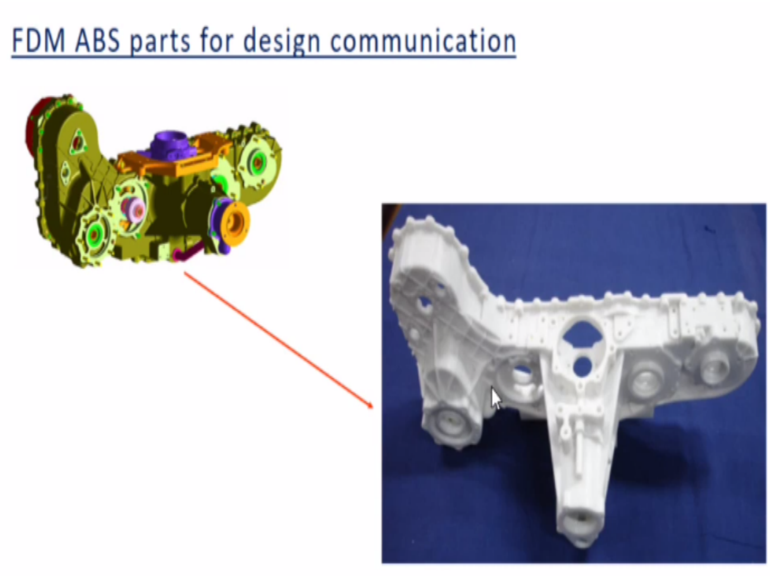

The primary application connected with FDM process in the initial stages was largely confined to design communication. The example what I have shown in this specific slide is relevant to an aeroengine accessory drive gearbox housing. As you can see the shape is extremely complex, the realization of the actual part which is made out of aluminium alloys or magnesium alloys takes extraordinarily long time in the conventional context. In this specific case after the concept was made ready, immediately the concept was converted into full scale FDM replica to facilitate design communication among the groups. It was also translated into a stereolithography model for enabling experimental tests.

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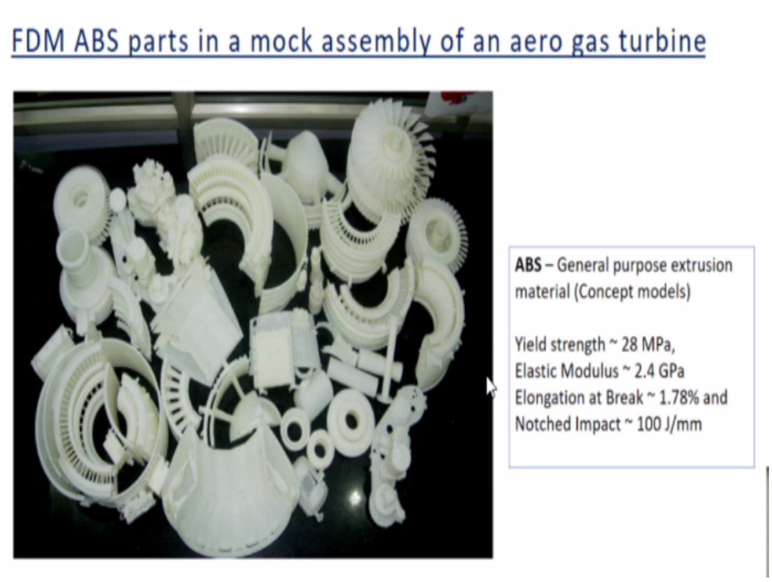

There are any number of applications of this particular technology connected with assembly integration studies and the original material which was synonymous with the extrusion technology was and is ABS material, a thermoplastic material, ABS stand for acrylonitrile butadiene styrene. It is an engineering plastic which has got adequate yield strength, good elongation at break, adequate modulus.

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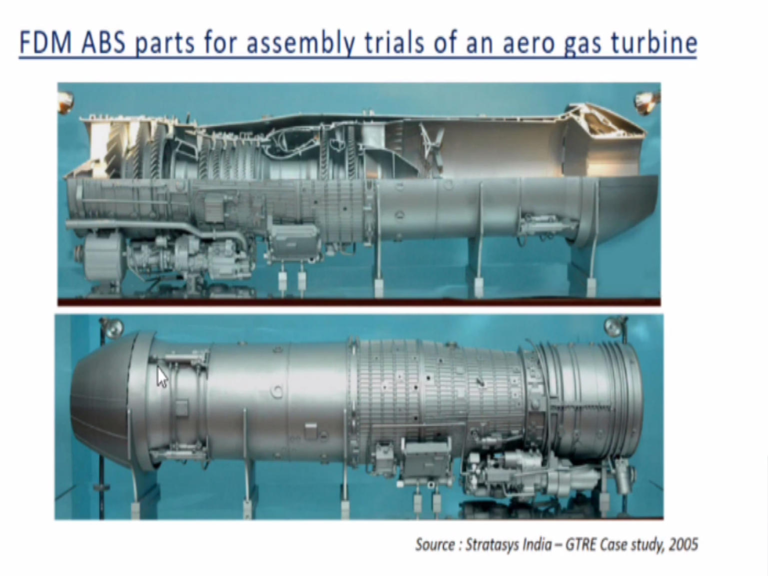

So many applications connected with the design visualization and assembly trials are greatly facilitated by this workhorse material of extrusion technology. This is one of the case studies corresponding to assembly integration of the entire aero gas turbine engine. You can see in this slide the mock unit of, a scaled down unit of aero gas turbine engine consisting of the fan module, the compressor, the combustor, the turbine, exhaust, the casing, several line replacement units.

They were all made using ABS parts and assembled together and fundamentally the scaled-down assembly was extremely useful not only in terms of design communication, but it was also used as a tool as a facilitator for optimizing the location of LRUs.

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The other material which has become synonymous as the workhorse material of the extrusion technology is PLA. PLA stands for polylactic acid. It can be made from starch and it is highly affordable. The PLA parts come with adequate stiffness and good detailing and if you look at the strength and yield properties, they are adequate enough to take care of the prototyping and also to take care of the testing. Especially in those situations and contexts where the max stress could be limited to less than 30 megapascal.

In this specific case, what is shown as the direct application of a PLA. FDM usage is fabrication of a transmission gear assembly of an ornithopter a mechanical bird and fundamentally this mechanism assembly is responsible for converting the rotary motion into the flapping motion of ornithopter. So, because of the affordability of this material and because of the adequate strength which is associated with PLA, the extrusion based additive manufacturing technology has become a favorite among the design groups,

Startups who are into the development of devices and most importantly the academia which are interested in conducting optimization studies on new products. So, in this specific case, about half a dozen variants of the mechanisms were designed, developed and tested in less than 2 months time without the usage of time-consuming injection molding options by virtue of integrating the extrusion-based item manufacturing into the development of ornithopters.

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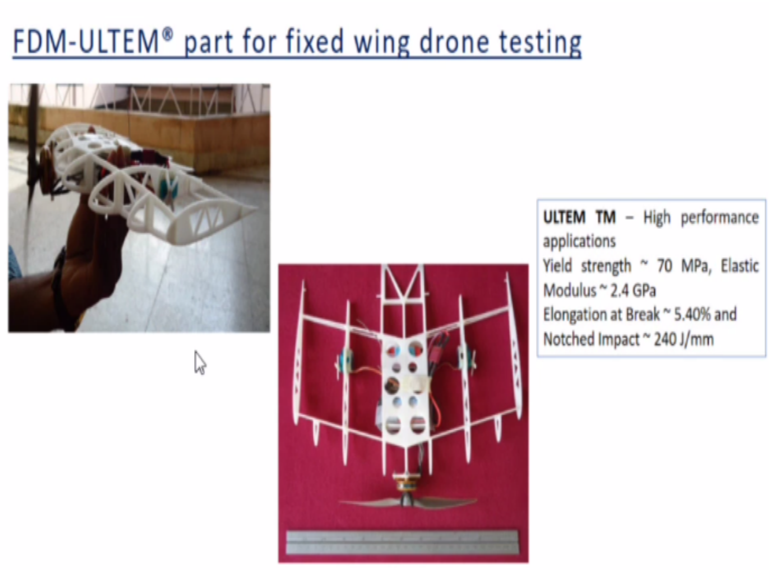

This is one more example connected with the drones, a fixed wing drone and what is notable in this case is high strength offered by the FDM material called ULTEM developed by Stratasys. The yield strength is close to 70 megapascal and it has got necessary notched impact characteristic also. In this case, the structural component connected with a fixed wing aircraft or drone was realized out of ULTE.

All the electronics including the motors and the sensors were directly integrated into this FDM structure and the resultant drone was successfully flown in the field drives. So, the newer materials have enabled the parts which come from extrusion manufacturing not to be confined only to the prototyping but also for field applications similar to the one which I have shown in the slide.

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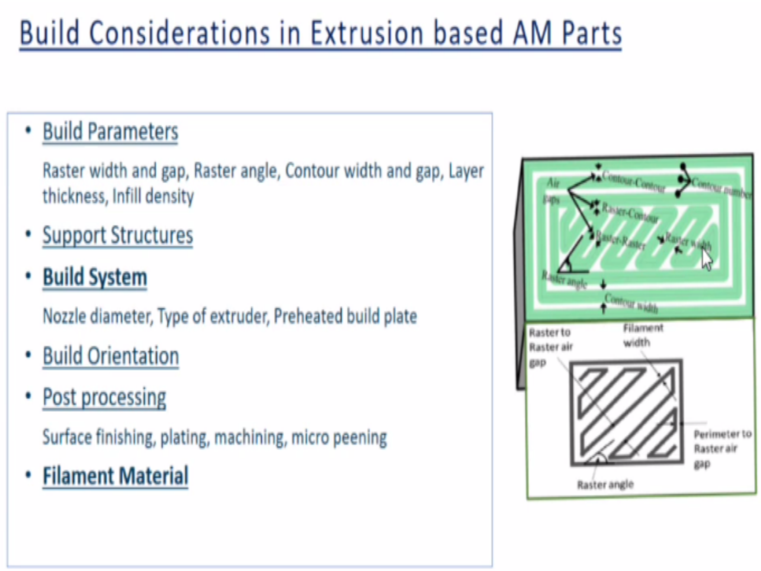

But it is very important to understand that there are several parameters which impact the strength of the part. The parameters could be connected with the build process like raster width, the air gaps, the angle, the contour width and the gap, the infill density that you use and the layer thickness. Several studies have been conducted by contemporary research groups through various methodologies.

So as to improve the strength of the part corresponding to the usage of ABS, nylon, polycarbonate and PLA material in extrusion additive manufacturing systems. It is also very important to plan the support structures and some of the characteristics of parts are also dependent upon the characteristics of the build system, the type of extrusion that we use, the nozzle diameter and whether there is a provision for preheating the build plate.

So, all these parameters connected with the build system also influence the properties and performance characteristics of the FDM parts. It is important to consider the extent of post processing to make these parts usable for induced context. A significant amount of time and effort is required corresponding to improving the surface finish and, in some cases, you may have to resort to secondary processes like plating and micro peening to improve the surface quality and to improve the surface integrity.

Incidentally, many parts made out of ABS when they are used for aesthetic purposes in the context of industrial design. They are subjected to electroless plating procedures by virtue of which nickel, copper, thin foils of nickel and copper are plated on the surface to improve the aesthetics.

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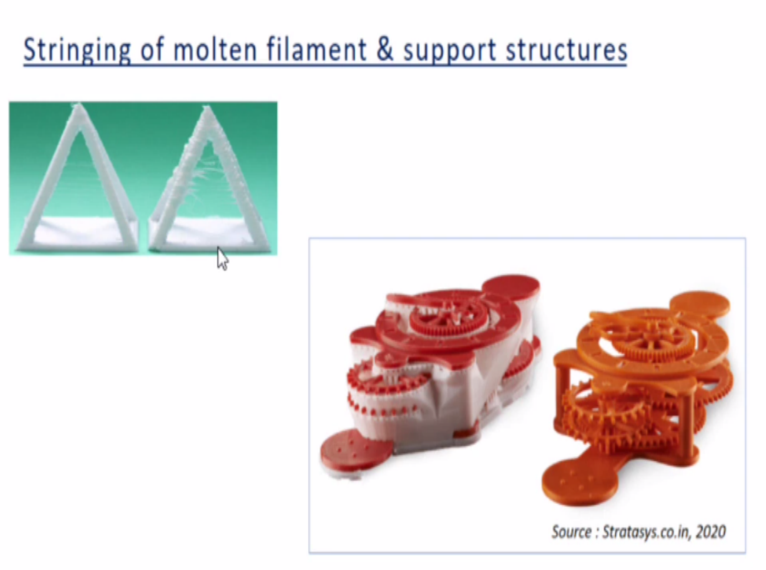

In case of the extrusion based additive manufacturing, it is important to consider phenomena called stringing or unwanted oozing of the material out of the nozzle. So, the speed of the extrusion head is controlled in such a manner that the oozing of the molten filament through the hot end does not lead to the creation of unwanted structures called strings. The other important consideration is about support structures. In all those instances where you have got thin overhang features, it becomes imperative to make use of support structures.

But thanks to water soluble support structures which have been brought to the forefront by Stratasys, removal of the supports no longer is a functional issue. So fundamentally in these cases, the extrusion-based AM systems are provided with two print heads, one corresponding to the build material, other one corresponding to the support material. In all those spatial locations where support structures need to be present, the supports are deposited out of water-soluble materials and these support structures are removed without considerable effort in the post-processing stage.

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Typical Engineering Materials for Extrusion Process

Nylon – High elongation at break (Panels and snap-fit parts)

Yield strength ~ 50 MPa, Elastic Modulus ~ 1.5 GPa

Elongation at Break ~ 6. % and Notched Impact ~ 140 J/mm

Carbon Filled Nylon – High strength-to-weight (Tooling)

Polycarbonate (PC) – High strength and dimensional stability (Industrial use)

Yield strength ~ 60 MPa, Elastic Modulus ~ 2.25 GPa

Elongation at Break ~ 5% and Notched Impact ~ 75 J/mm

The world of materials connected with extrusion-based additive manufacturing has seen several innovations. The current list is impressive ranging from thermoplastic polyurethanes to high impact polystyrenes, nylons, the carbon filled nylons especially in case of high strength-to-weight applications that are necessary in tooling context, the polycarbonates, polyetherketoneketone popularly known as PEKK and polyetheretherketone. All these materials have enabled the scope of applications to get enlarged.

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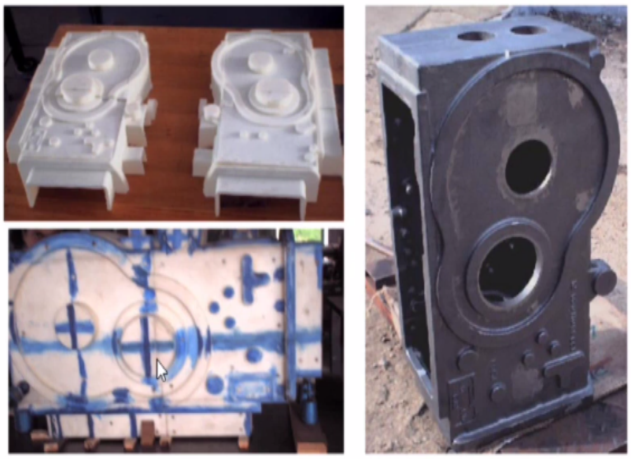
FDM ABS parts for casting of an automotive housing



Source : Stratasys India Casting Case study, 2005

I would like to pick up some applications in the automotive sector to illustrate the importance of the wide range of materials in terms of accelerating the use of the additive manufactured parts in conventional context. What you see in this case is the sand casting of an automotive housing. The CAD model of the same is indicated here, I think the longest linear dimension is about 680 mm. In a conventional scenario, this part could have been realized through carpentry and it could have taken easily about 12 to 16 weeks.

But thanks to the introduction of extrusion-based additive manufacturing the pattern in this case has been realized with a modular approach. You can see the bottom and top hunch here and the entire fabrication was done in less than 2 weeks time and the casting of the automotive housing was done using the engineering material of the need by using the master patterns that are realized through ABS material.

So, this is an indirect use of additive manufacturing wherein you recognize the fact that the eventual part needs to be in a certain engineering material and the pattern is made out of thermoplastic material. Either you can use this pattern in the context of sand casting as is illustrated in this case or it can also be used in a sacrificial manner in the context of investment casting. So, the applications of this kind which are plentiful in industrial context are known as the rapid tooling cases wherein you are making use of the parts indirectly for meeting the functional needs.

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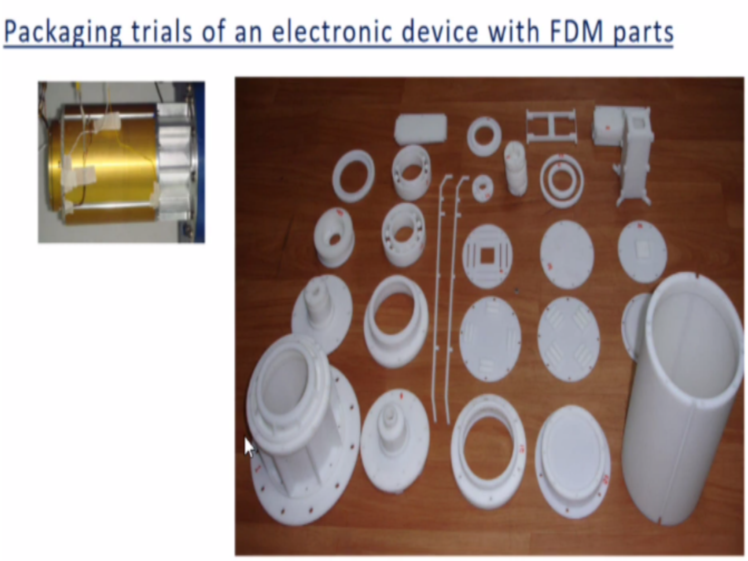

Here is an example corresponding to the packaging trials of an electronic device with FDM parts. As you can see here, the small electronic device with an outer diameter of about 65 mm and a wall thickness of about 3 mm consists of several integral parts including the heat pipes, including the PCB mounts. So, all these components from the CAD are directly translated into ABS parts and these parts are assembled and were tested not only to check the assembly integrity.

In this specific case one more important functional application which was fulfilled was availability of the cooling air in such a way that the max temperature within this module does not cross stipulated limits. So, this particular mock assembly was used repeatedly by introducing certain refinements in the parts and in an experimental rake the trials were conducted in terms of ensuring the availability of the cooling air for the electronic circuitry.

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Material Class	Examples	Typical applications
Thermoplastic Polymers & High strength plastics	PLA, ABS, Nylon, HDPE, PPSF, PC, PETG, , PTFE, PEEK, PEKK & ULTEM TM	These are used for general engineering applications and industrial applications that demand high strength & high temperature resistant materials
Polymer matrix composites	GFRP, CFRP	Structural applications
Ceramic slurries and clays	Alumina, Zirconia, Kaolin	Insulation, consumers objects, dental applications
Green ceramic/binder mixture	Zirconia, Calcium phosphate	Structural ceramics, piezoelectric components
Metal-Polymer Composites	Bronze, Copper, IN 625 & IN 718, Stainless Steel, Aluminium 6061, High Carbon Iron, Ti6242, Cobalt	Tooling, fixtures, Mechanical Parts, Series Production
Food pastes	Chocolate, sugar	Food industry
Biological materials	Bioink	Bio printed organs and scaffolds

Source : Wiki Article on Fused Filament Fabrication, October 2020

This busy slide shows cases the choice of materials that are prevalent in the world of extrusion-based additive manufacturing. Right on the top you see the thermoplastic polymers and high-strength plastics and the other one is the polymer matrix composites, could be GFRP or CFRP. They are used in the aeronautical and automotive sectors for structural applications.

The ceramic slurries and clays based on alumina and zirconia kind of solutions they are widely used in dentistry as well as for the purposes of insulation objects. The metal-polymer composites providing solutions based on pure metals like Copper, Cobalt and also alloys, high performance super alloys like in Inconol 718, Inconol 625, Aluminum 6061, Ti6242 have actually enabled the parts from extrusion based additive manufacturing to be directly used for tooling applications, for fixture development and also for series production.

Some of the esoteric applications of this particular technology are connected with food industry, even chocolate solutions or chocolate slurries have been tried out to make bespoke chocolates using the technology of extrusion. In the recent times we have also seen flurry of activities connected with bioprinting and fabrication of minute scaffold structures using bioinks. So, the entire facilitation of the applications in context ranging from bio sector to consumer goods to aeronautical to automotive and medical have been propelled to some extent by the technology related improvements and to a large extent by the material innovations.

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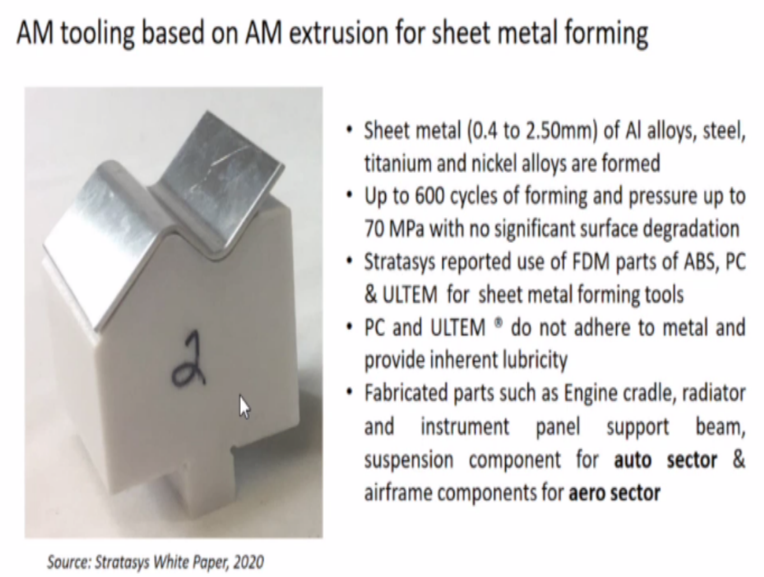

Here is an interesting case study connected with sheet metal forming using FDM tooling. This is one of the favorite applications in the world of auto sector for making parts such as engine cradle, radiator and instrument panel, support beams, suspension components and in few contexts, it has also been used for making the airframe components. The sheet metals with the thickness ranging from almost half mm to 2.5 mm out of aluminium alloys, steels, titanium, and nickel alloys are formed using the AM tooling.

It has been reported that the AM tooling was able to sustain pressures up to 70 megapascal and up to 600 cycles of forming with no designable surface degradation. Incidentally, the materials like polycarbonate and ULTEM provide one more functional advantage. They do not adhere to metal, so they have got inherent lubricity. So, especially in case of low volume manufacturing, it has been proven that there are several advantages connected with the cost reduction and time compression by using the forming tools through materials like polycarbonate and ULTEM based on the extrusion additive manufacturing technology.

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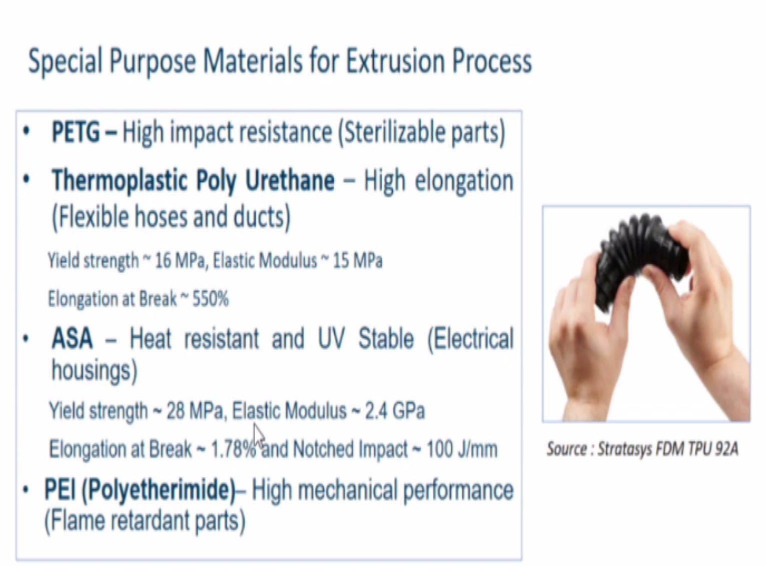

The other materials which are connected with the extrusion process are the thermoplastic polyurethanes similar to what you see in the insert diagram here. They are typically used in case of flexible hoses and ducts and the elongation at break is close to about 500 percentage and the handling of this thermoplastic polyurethanes is slightly different compared to more viscous materials.

It has been proven in multiple contexts that the making of customized solutions connected with flexible hoses can be done by integrating TPU into extrusion based additive manufacturing. PETG has also been configured for the extrusion based additive manufacturing and there are special materials which are connected with the flame-retardant performance as well as electrical housings using the polyetherimide and ASA options.

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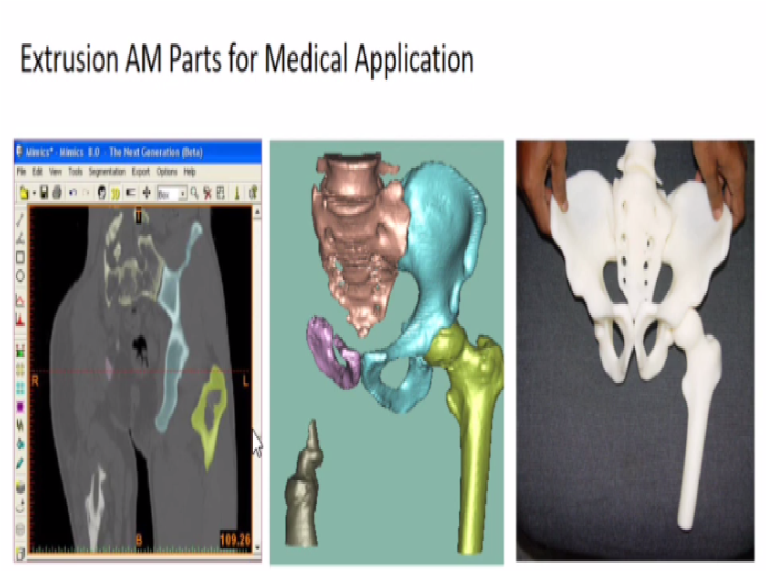

One important application which has found favor with orthopedic surgeons as well as maxillofacial surgeons is about developing patient specific tools using the technology of extrusion based additive manufacturing. In this case, the input data could come from an x-ray or a CT scan and using special purpose pre-processing software. This data is converted into a CAD model, a 3D CAD model and this data in turn is used as the input for 3D printing on an extrusion based additive manufacturing system.

It has been proved in different contexts that development of patient specific surgical tools and planning of implants are greatly facilitated because of these parts which come out of extrusion based additive manufacturing system and they can also be sterilized. They can be used for the purpose of patient communication, also communication with the peer medical practitioners.

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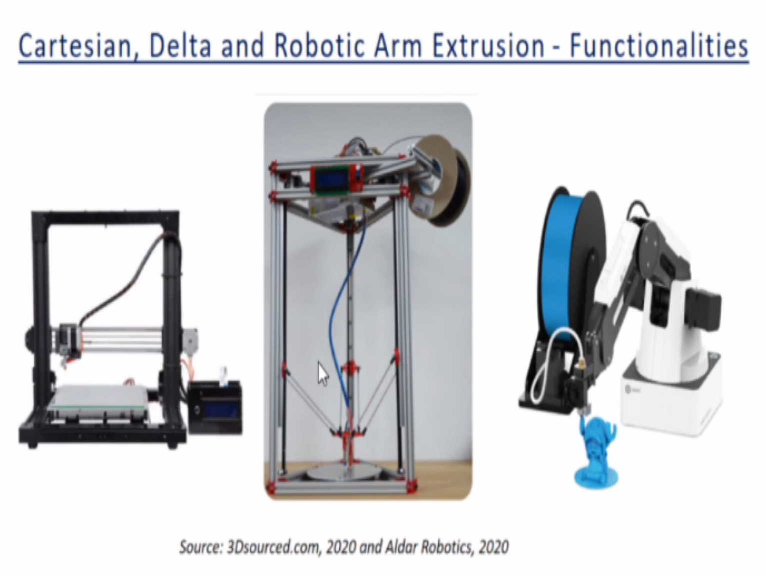

It is important to understand that the configuration of the extrusion-based additive manufacturing system has also undergone certain changes, certain refinements in the recent times. The original configuration was based on the cartesian model. So, we had the extrusion head moving across or along the orthogonal axis, but in course of time we had new configuration called the delta configuration wherein typically the build plate is stationary.

It does not move in the z direction and if you see it is circular in its shape and the extrusion head is mounted on three articulating arms. So fundamentally the extrusion head can move in any direction in xyz space and the z height in this specific configuration is substantially higher compared to the configuration connected with cartesian coordinate system. We have also seen the emergence of polar 3D printer wherein just need to use two engines.

One connected with r, other one connected with theta. So, in case of 3D printers which are based on polar configuration, you have a rotary table and you got a gantry system which moves in a radial direction. So, the advantage of the polar coordinate-based 3D printer is that you just need to use only two engines instead of three engines that are synonymous with the cartesian 3D printer.

The simplest form of extrusion based additive manufacturing is the usage of a robotic arm. A single robotic arm with mobility in xyz direction and connected with an extrusion source is found to be adequate enough for realization of the parts. Needless to mention in this case the surface finish as well as the part fidelity will be significantly inferior to what you see in case of systems that operate on cartesian coordinates.

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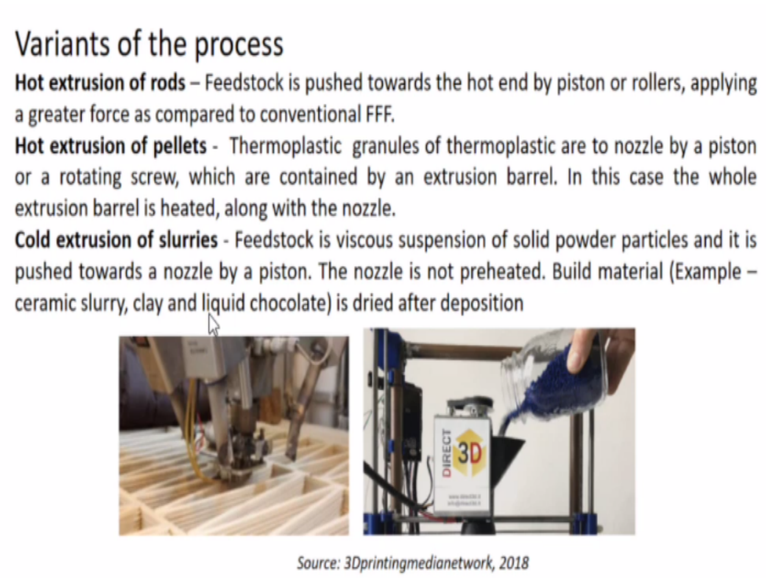

There are also other variants of the process. In some of the cases the feedstock comes in the form of rod, so it is not a filament but it is a rod. So, to push the rod we need to use greater amount of force, maybe this is facilitated by piston or rollers. In other cases, we have also seen usage of pellets. The pellets are small granules of thermoplastic. They are driven to the nozzle by a rotating screw or a piston and the entire unit is contained within an extrusion barrel.

So, the whole extrusion barrel is heated along with the nozzle, but the advantage of this particular variant is the cost of pellets is significantly less compared to the cost of the filaments and hence realization of large structures becomes economical. It has been reported that pedestrian bridges with a length of almost 24 meters with a width of almost 4 meters have been successfully printed by hot extrusion of pellets.

The other opposite of hot extrusion of the pellets is the cold extrusion of flurries. The feedstock in this case is a viscous suspension of solid powder particles and it could be ceramic slurry, it could be liquid chocolate or clay and you do not make use of hot nozzle in this case and after the material is deposited, we need to wait for certain time for the drying to happen.

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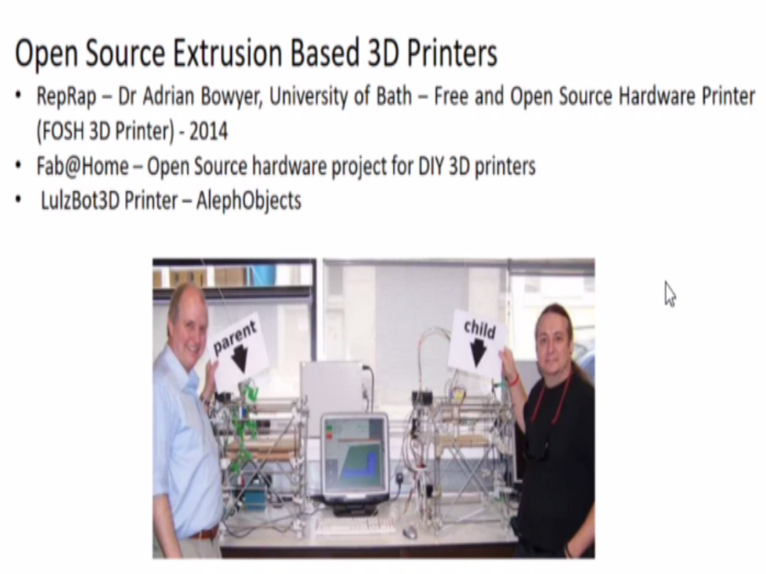

The technology of extrusion based additive manufacturing has seen several new phenomena emerging and one of the most important things is the development of free and open source hardware. Dr. Adrian Bowyer from University of Bath started this movement called RepRap in 2014. Fundamentally, RepRap stands for self-replicating rapid prototyping systems. The entire configuration corresponding to the hardware and software of this extrusion based additive manufacturing system saw active contribution of volunteers from several parts of the world.

This particular model also got repeated again in the projects connected with the Fab at Home and LulzBot3D printer and they were all associated with open source hardware projects for DIY 3D printers and these moments connected with open source hardware has led to emergence of several startups and also to reduction in the prices of the extrusion-based AM systems in a significant manner so much so that there are tens of thousands of extrusion-based additive manufacturing systems that are operating currently in high schools. In elementary schools and also in the tinkering labs spread across the length and width of the country.

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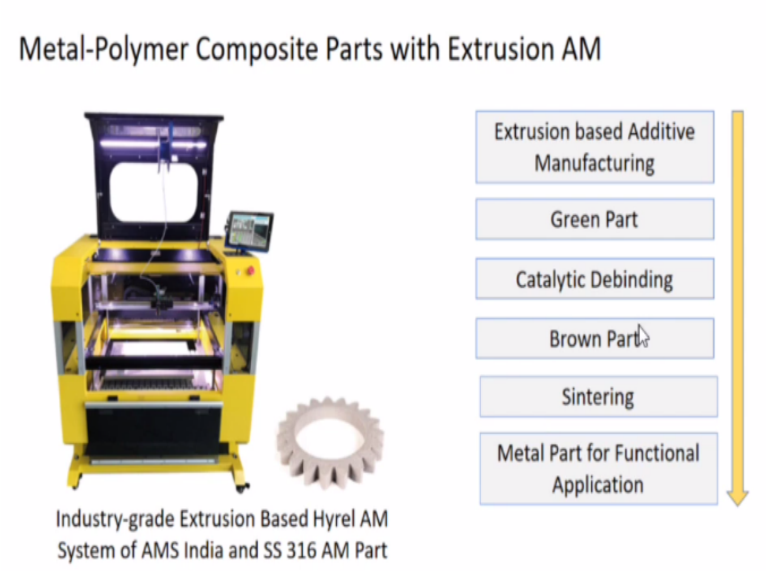

Coming to the industrial context, one important innovation which has marked the emergence of the usage of metal polymer composite parts needs our attention. In this case, the metal could be any of the choices like Bronze, Copper, Nickel, Aluminum, Inconel, titanium as I described a few minutes ago and the metal polymer composite is extruded akin to the process that I have described already.

It requires industry grade printers which have got provision for operations at high temperature and in many of the cases even the print bed on which the part is printed is preheated. So, what happens in handling metal polymer composite parts is the realization of a green part at the end of the extrusion site. So, the green part is not dimensionally stable and the green part consists of nearly 20% binder and approximately about 80% metallic material.

It has to be subjected to catalytic debinding so that we can get rid of the binder in the quickest turnaround time. The strength of the part may not see significant improvement, but after the catalytic debinding what you get is a brown part which is dimensionally stable and the brown part is subjected to sintering and post sintering it is subjected to series of post processing of operations making the part amenable for functional applications.

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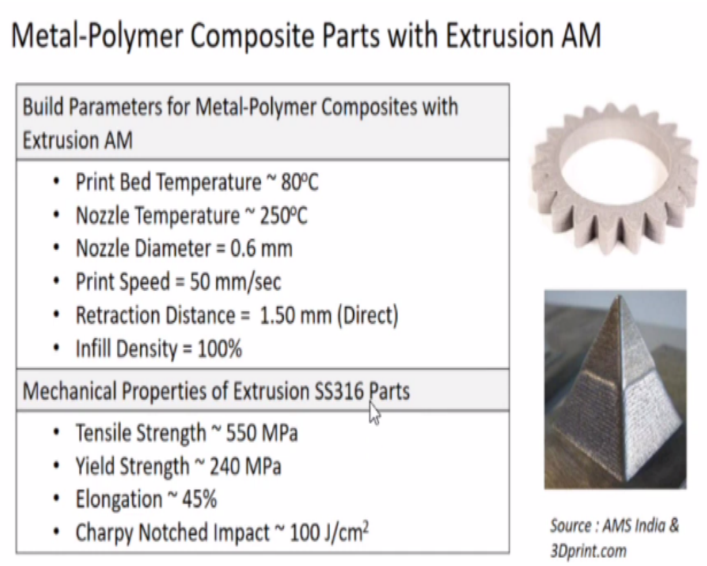

So important to note that in this case the nozzle temperature could be as high as 250 degree centigrade and the print speed could be limited and the print bed temperature need to be somewhere between 50 degrees centigrade to 80 degrees centigrade and we have to deploy 100% infill density, but after going through the necessary post-processing operations of debinding and sintering what you get are the metallic parts, in this specific case the properties corresponding to SS316 are shown. As you can easily infer the tensile strength, the yield strength, the elongation and the impact characteristics of what you get through a metal polymer-based composite are adequate enough for meeting the needs of wide area of industrial usages.

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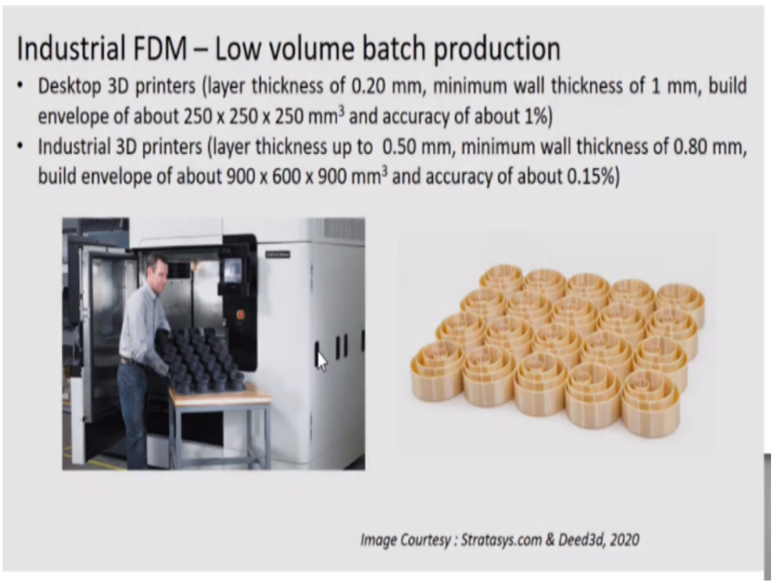

It is because of the phenomena of this kind that there are many instances which are emerging in the aeronautical, automotive, manufacturing and tooling sectors wherein the low volume batch production is being attempted through industry grade 3D printers. What do you mean by industry grade 3D printers? Typically, if you are talking about the desktop 3D printers, the build envelope is limited to about 250 mm in xyz directions.

The accuracy could be about 1 to 1.5% and layer thickness is just limited about 0.2 mm. So all these parameters contribute to two important characteristics. The accuracy could be limited and the throughput could also be limited, but if you look at the industrial 3D printers similar to the ones which are shown in this slide as the options, then the parts could be built with higher layer thickness and the build envelope in sometimes could be as high as about a meter in xyz directions.

The accuracy could significantly increase to about 0.15% to 0.2% which are commensurate with the expectations of a designable engineering user so it has been observed that low volume batch production in manufacturing and tooling industry has been facilitated with the parts made out of nylon and polycarbonate using these industry grade 3D printers. One more technology which has been used with the similar kind of felicity for low volume batch production in the context of dentistry and hearing aid industry is the digital light processor.

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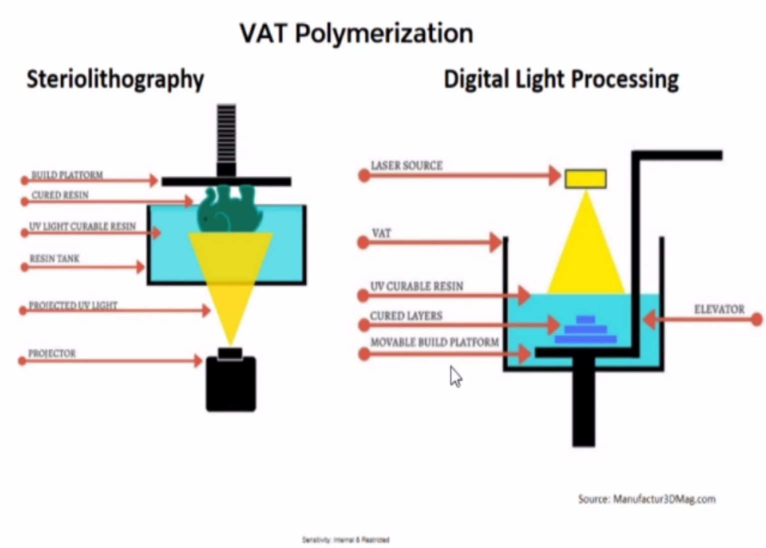

So, we did spend some time in understanding the operational principle of stereolithography. In case of stereolithography, what happens is the CAD data governs the movement of a UV laser beam on the surface of photosensitive polymer which is put in a VAT and because of the interaction between the laser beam and the UV curable resin, the resin undergoes instantaneous transformation from liquid phase to solid phase, but the fundamental element in this case happens to be a laser.

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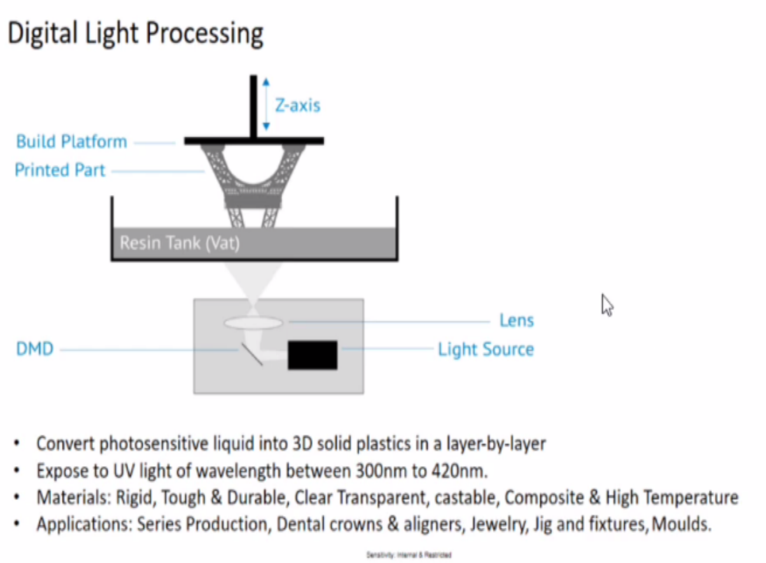

In recent times, the process of stereolithography has been substituted by a technology called digital light processor. What do you mean by digital light processing is there is no usage of any laser beam. You have got a light source and you have got micromirror assemblies.

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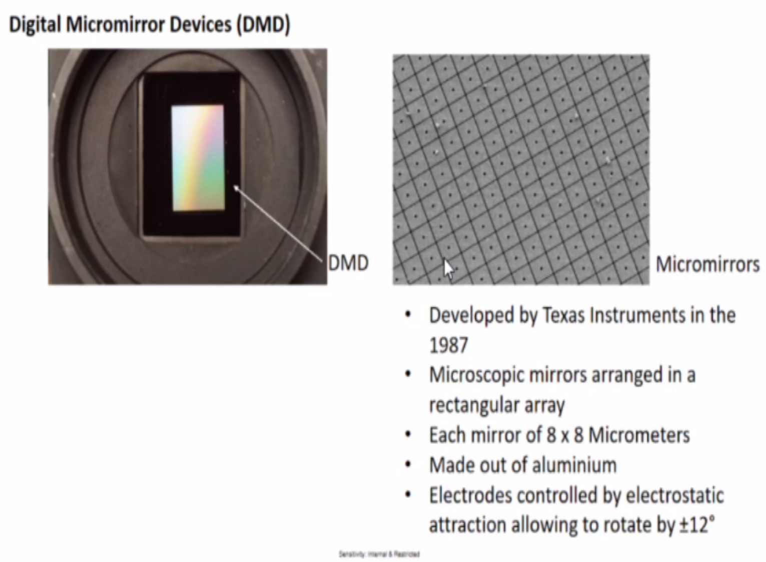

Fundamentally the light source, it was developed way back in 1987 by Texas Instruments, consists of tens of thousands of micromirrors of the dimensions of 8 by 8 microns which are arranged in a rectangular array. Each of this micromirrors is pivoted and depending upon the electrostatic attraction it can be made to swivel by about 12 degrees in either direction and the movement of this micromirror fundamentally leads to the curing of that small area which is in the line of focus. So, the introduction of this technology of the micromirrors has led to an emergence of new process of VAT polymerization and this process is known as digital light processing.

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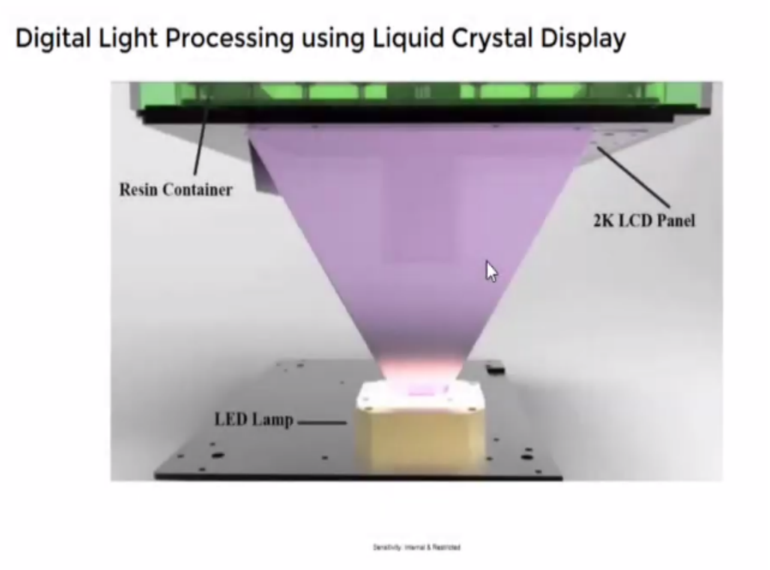

The other option is connected with LCDs.

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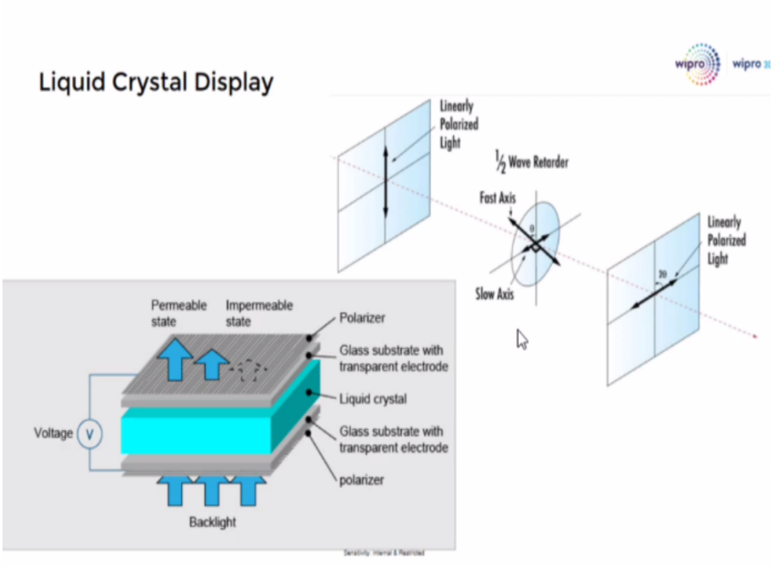

In this case you have got a backlight, there is a polarizer, you have got analyzer and between the polarizer and analyzer you have got a quarter wave plate. Fundamentally through optical elements, you are able to translate the movement of the light wave in such a manner that the light is enable to pass only in those zones where you want the polymerization to happen. In all other instances, the analyzer cuts off the signal and there are no moving parts.

The entire motion of the light waves is only enabled through optical elements. This particular technology which is devoid of the usage of laser beams and moving elements has led to mass customization of the products in medical industry, both for dentistry as well as the hearing aids.

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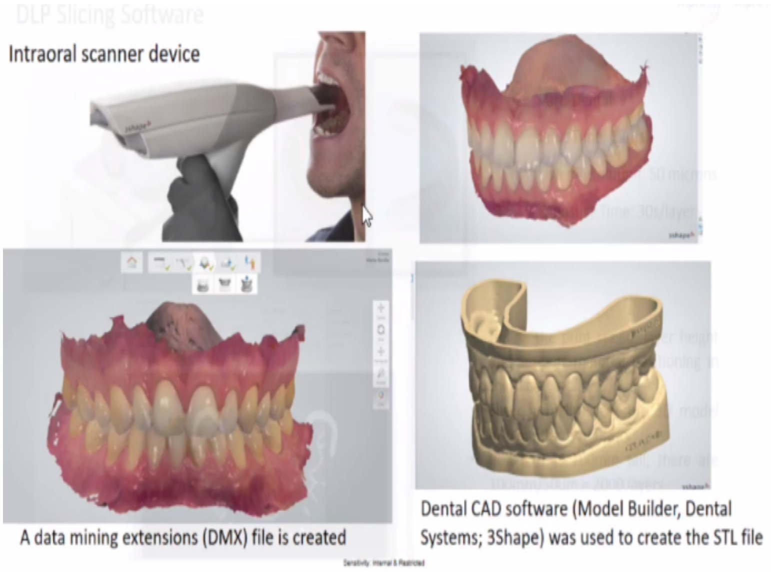

Typically, in a dental context, the data is generated by usage of an intraoral scanner device and you have got special purpose dental CAD software which converts the scanned data into a CAD model.

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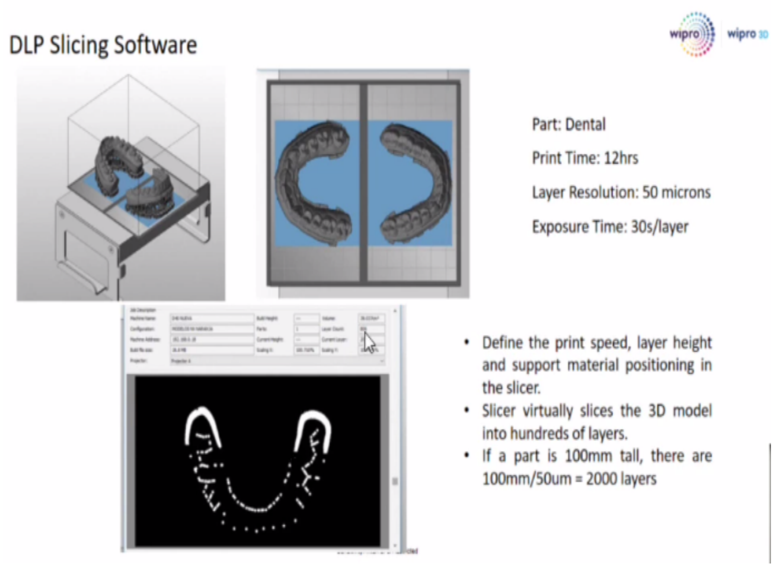

So when you do the necessary pre-processing, we set up parameters such as exposure time and the layer thickness and if fundamentally let us say the part is about 100 mm tall and if you use a layer thickness of about 50 microns, you are talking about 2000 layers, but unlike the case of stereolithography where the laser beam has to move discretely point to point, here entire layer is exposed at one go. So, the processing time is phenomenally compressed. So, we are able to make parts of this kind in few hours.

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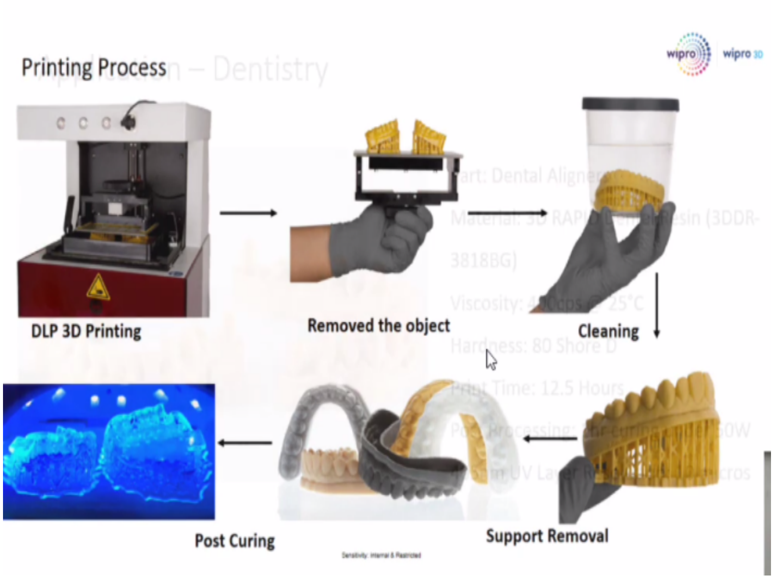

So, post printing on a DLP system, cleaning of the parts has to be done in terms of removing the support structures, in terms of getting rid of unqueued resin if any and then the parts are ready for applications in dental context connected with both maxillofacial applications as well as orthodontic aligners.

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As you have seen in this specific case a part with Shore D hardness of about 80 has been realized in less than 13 hours of time.

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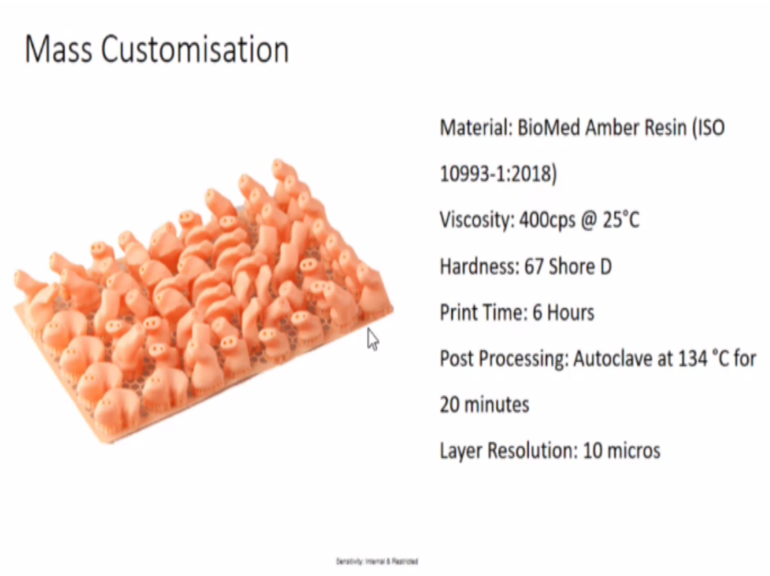

What has been remarkable in extending the usage of this technology is connected with mass personalization or mass customization in case of hearing aid industries. You can see in this case in just about 6 hours time, dozens of these mass customized casings for hearing aid industry have been realized through the application of digital light processing and successfully used in such a way that the eventual customer gets an experience of superior fitment.

So, the applications of this kind have come to the forefront in a significant manner both in the national and international context and several and several models are connected with gifting solutions, packaging solutions and device solutions are taking advantage of making these parts out of the technologies of digital light processing for providing mass customized solutions. So, I just described the applications of two important technologies connected with plastic materials in the world of additive manufacturing.

One connected with extrusion process, other one connected with VAT polymerization. The purpose of describing these two processes and the pertinent applications is to showcase the possibility of new business models that are based on the digital manufacturing technologies in providing timely solutions and delivering the products at the point of care without the tooling penalties that are associated with conventional manufacturing. Thank you so much.