The Future of Manufacturing Business:
Role of Additive Manufacturing

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Lecture-21
Additive Manufacturing Technologies and Categorization

Welcome to this NPTEL course, on the future of manufacturing business and role of additive manufacturing. I am Chandrasekhar from Wipro 3D Bangalore and collaborator with the professor R.K. Amit of IIT, Madras, Chennai. In the preceding sections of this particular program, Dr. Amit has captured the evolution of the manufacturing paradigms from those of craft and mass production to smart manufacturing.

He also gave wide array of examples how introduction of digital technologies has been impacting the product development cycles with a discernible impact. One such technology which has come to the forefront in a significant manner, the recent times is additive manufacturing.

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By giving a lot of examples corresponding to the metal and plastic additive manufacturing, I will be capturing the tremendous impact of this technology on the supply chains and design freedom and the entire process of product development from conceptualization to realization. If we have to capture the impact of additive manufacturing technology on the product development cycles, we can look at the resultant phenomenon in 3 different categories.

To start with the latitude or the freedom that has been given to the product developers through the induction of additive manufacturing into the product development cycle. The conventional concept of design for manufacturing or DFM has ceded to manufacturing for design and in the bargain several opportunities for value addition have been re-imagined. For example, the weight reduction possibilities, part consolidation for reducing the number of parts and integration of several functions into the single part.

In the conventional area, the concept of mass manufacturing was very prominent, unless certain minimum quantities are showed the techno commercial viability of manufacturing solutions is not considered compelling. But currently, we are talking about a concept of mass customization and beyond that mass personalization, which actually established the cause of economy of one instead of economy of scale.

One more important phenomenon in the recent times that we have observed is because of the introduction of additive manufacturing into the product development cycles, the dependence on the centralized resources has become insignificant. We are seeing more and more case studies where the distributed manufacturing models are coming to the rescue of accelerated product development cycles.

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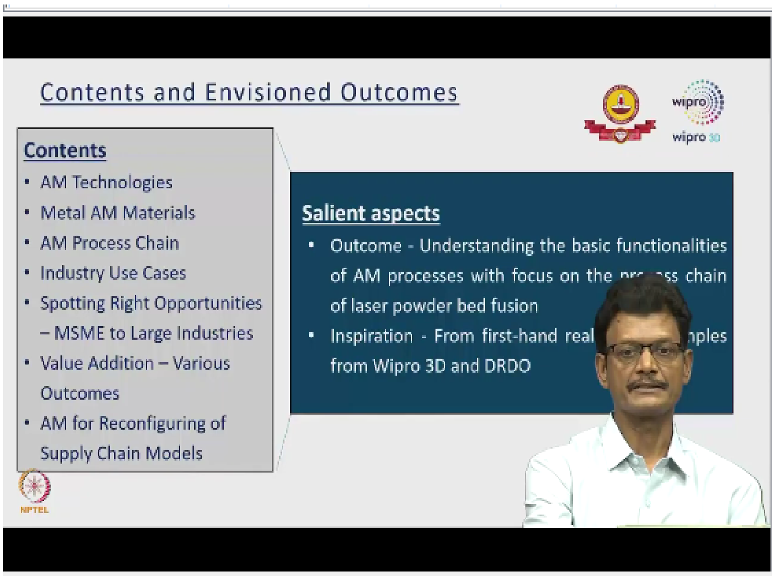

So, in this program I am going to talk about various AM technologies. If you are talking about additive manufacturing technologies, you have plethora of options, right from tabletop machines to the completely matured systems for industrial context and concurrent to this phenomenon of development in the variety of additive manufacturing systems is the choice of materials.

We can work with metals, we can work with plastics, ceramics, waxes, composites, so on and so forth and a portion of my presentation would also be capturing these material options. The process chain of additive manufacturing is very important, because we need to account for pre-processing, part building as well as post processing, all of them significantly contribute to the technical case and business cases.

So, I will be discussing this with the help of a few contemporary examples. The important thing that he has seen in recent time is the additive manufacturing is equally useful to a micro or small scale enterprise as it is to a large engineering conglomerate. It is important to find out the value addition opportunities, and once you identify the value addition option opportunities, it is possible that you can even think about configuring the supply chain models.

So, a lot of inputs to the deliberations on the technology are inspired by my firsthand experience while doing certain projects and missions, both for Wipro 3D and DRDO.

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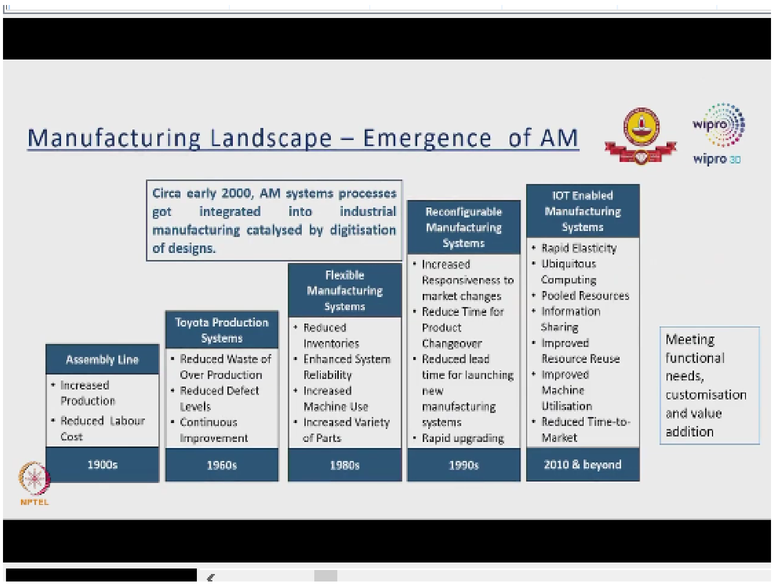

Now, let us examine the positioning of additive manufacturing in the landscape of manufacturing. In the current IOT enabled industry 4.0 concept kind of dominated scenario with that is prevalent in the manufacturing systems. We are talking about optimizing the resources, improving the machine utilization, real time sharing of the information based on tremendous sensorization, ubiquitous computing and more importantly rapid elasticity.

If you just contrast the scenario with that of the early models of manufacturing, where the focus was only limited to increase production, and reduce labour costs, it has been a tremendous metamorphosis. The early models of additive manufacturing came into existence way back in 1980 itself. In fact, the first ever patent to the concept of XYZ plotter could be credited to Kodama from a yoga municipal research institute from Japan.

Wherein he talked about producing a 3-dimensional plastic object directly from the digital definitions. But initial set of additive manufacturing systems were not capable of producing the parts out of engineering materials with necessary surface fidelity and dimensional accuracy that are commensurate with the expectations of serious engineering applications. So, most of the applications in the initial stages were confined to prototyping and design visualization.

But in course of time, there were tremendous contributions from laser physics, polymer chemistry, control systems, software engineering, in-situ process monitoring, and with all these contributions coming in, the systems became more versatile and the output was available in multitudinous materials. Hence, the industrialization of additive manufacturing became a possibility.

So, today, we are not looking at usage of additive manufacturing technology only for the sake of prototyping or for design visualization, we are looking at more powerful models through which additive manufactured parts can fulfil the end user needs or functional requirements of real-world applications.

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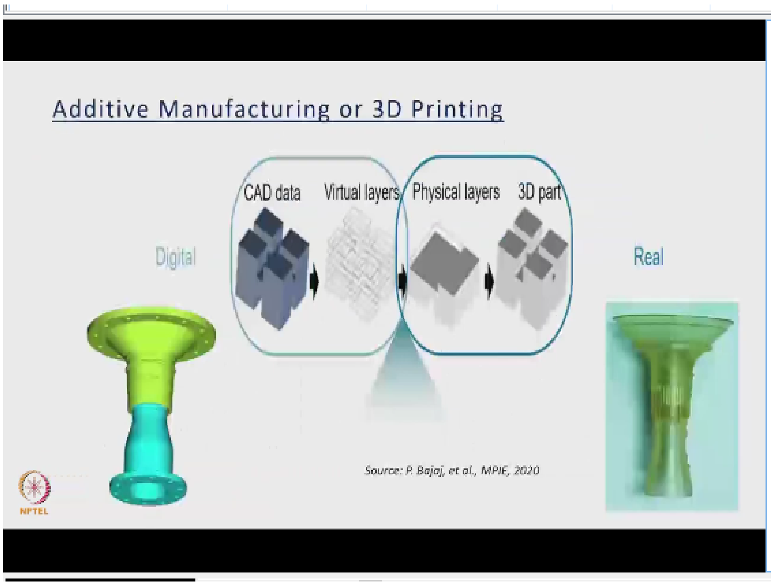

Now, if you look at the important aspects of additive manufacturing, there is a distinct phase where we are looking at only digital information. In the initial phase of the process of additive manufacturing, we are working on digital models or CAD models and slicing these models into series of layers mathematically using certain customized software solutions. Subsequent to that the slides data is converted into thin layers or to plastics and metals sequentially.

So, that digital definition is translated into physical part. The point which is to be appreciated is, there is a phase which is working only on the digital data and there is a phase which is largely confined to physical models. It is interesting to know that initially, when this technology came into existence, it was more known as rapid prototyping technology. In course of time, several phrases were used to refer to this technology including lead manufacturing, solid freeform fabrication.

The terminology called 3D printing came into existence, because of the research group of MIT that were talking about producing the additive manufactured parts using jetting kind of a principle or inkjet kind of principle out of plastic materials.

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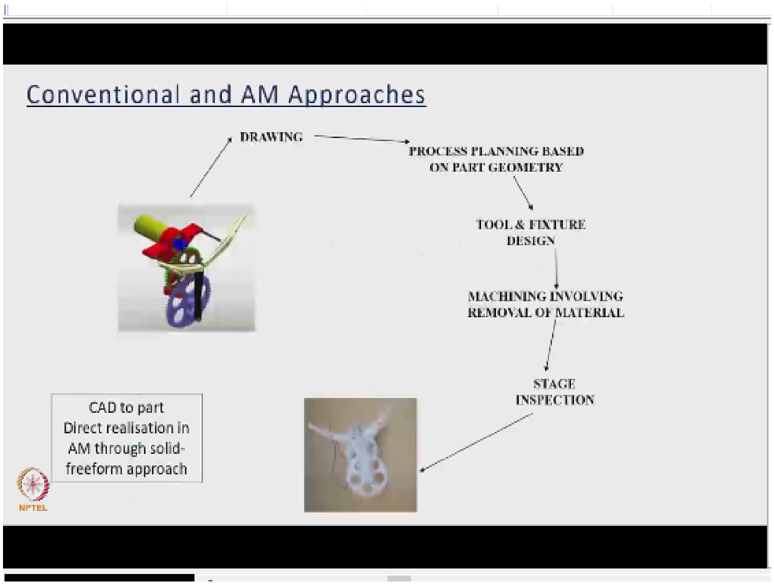

But currently, the terminologies like 3D printing and additive manufacturing are used fairly in interchangeable manner. So, if you are looking at the conventional manufacturing what is very apparent is, it is sequential from the stage of drawing to the stage of the realization of a part. There are certain steps sequentially you need to follow including development of the tooling's, fixtures, machining, which predominantly involves removal of the material.

Stage inspection depending upon the complexity of the geometry and final realization of the part. In contrast to that, additive manufacturing or 3D printing tend to be one step solutions that is direct translation of the digital data into physical part in a solid free form approach.

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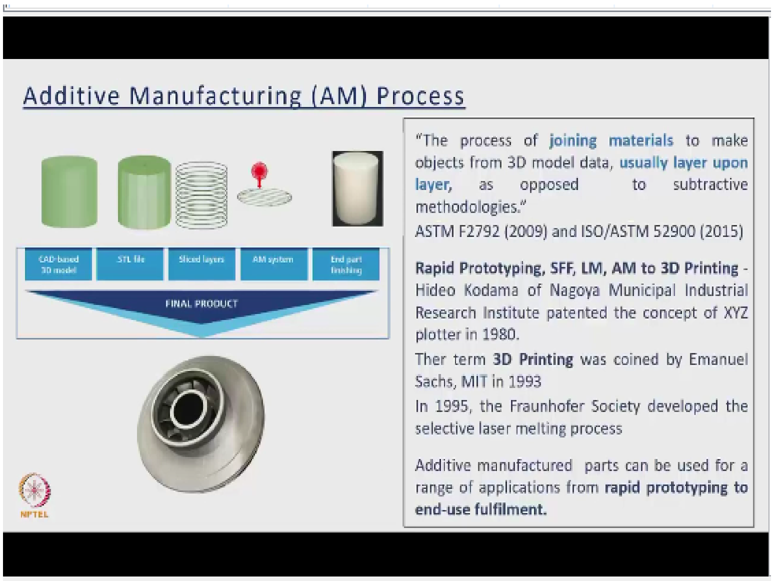

So, what is the formal definition of the additive manufacturing. As for the standard ASTM F2792 released in 2009, additive manufacturing can be described as a process of joining materials to make objects directly from the 3D CAD model data usually layer upon layer as opposed to the subtractive methodologies. The standard has been replaced by the ISO ASTM standard 52900 released in 2015 but the definition minds the same.

As I mentioned the terminology 3D printing was coined by the group at MIT Emanuel Sachs in 1993. The Fraunhofer society is credited with the development of the selective laser melting process through which you can work on range of metallic materials.

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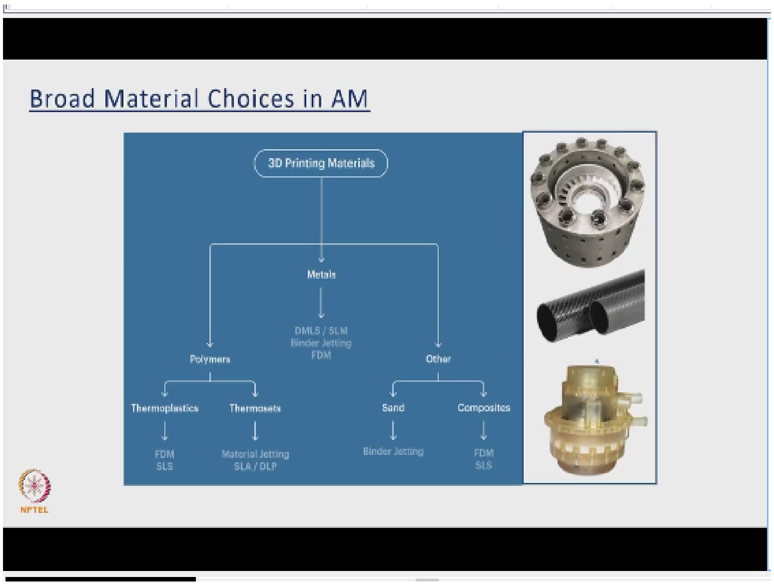

I f you look at the materials that can be processed using additive manufacturing, you can see 3 important characteristics, 3 important categories, right in the center we got metallic materials, that can be processed through powder bed fusion or binder jetting or direct energy deposition. You have got a set of processes which are connected with thermoplastics and thermoset plastics, thermoplastic plastics and other group the others could be connected with processing of sand, glass, composites, fiber optics, even organic tissues.

I have shown 3 examples in this case right on the top is a flame tube, which is made from high temperature nickel super alloy, made through powder bed fusion. In the bottom you see a transparent or bearing housing. In the centre, you see a compositor piping or with the thin wall realized through 3D printing out of peak like materials.

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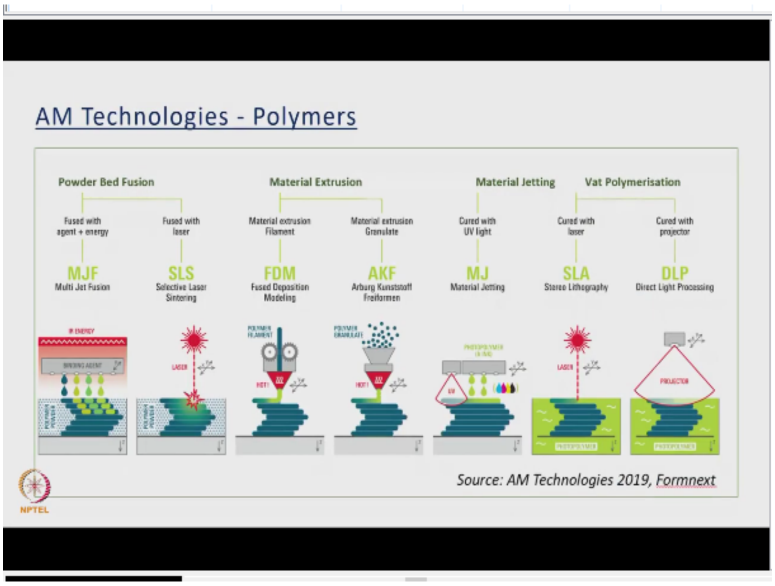

So, if you look at the possible options in processing of polymeric materials using additive manufacturing, you can see the important technology that has been available in the commercial form right from early 90s is the VAT polymerization technology. Then, you got extrusion technology, where in filaments are extruded into the physical parts. You have got a material jetting technology wherein the plastic materials are jetted out.

The fourth option, a versatile option is the powder bed fusion, it is also now more popularly known as selective laser sintering which involves the usage of high energy sources for realization of the polymer parts.

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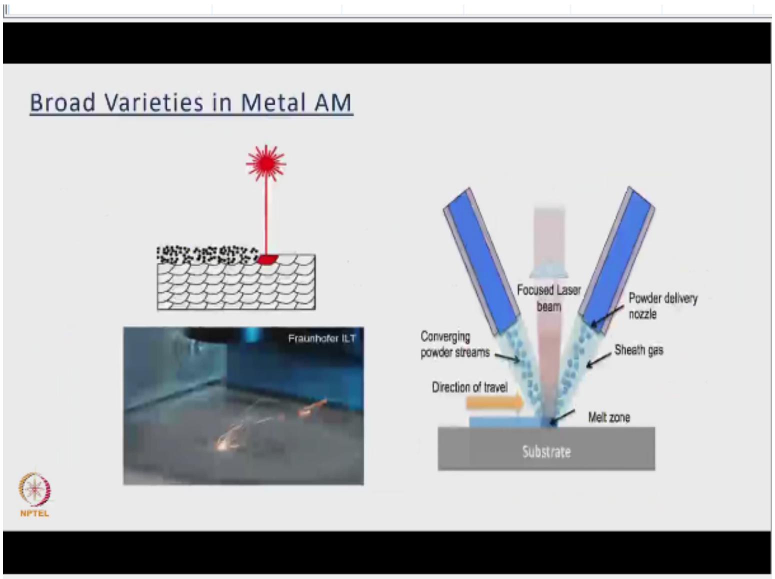

Now, let us look at the options connected with metal additive manufacturing. Predominantly you see two varieties in the commercially mature a mature form. The first one is the powder bed fusion, wherein you spread thin layers of powder on the bill platforms, make use of high energy laser sources could be lasers, could be electron beams, for melting of these particles, which resolidify as the beam passes along.

On the other side we have got direct energy deposition process where in to the stream of the high energy source, you are injecting fine metallic particles. So, these two are the distinct processes, which are used in the world of metal additive manufacturing.

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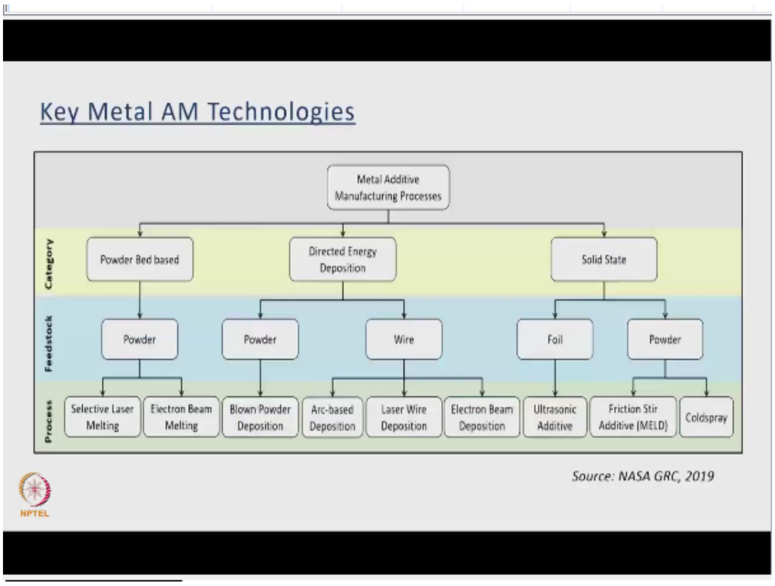

But if you look at the categorization of the key metal AM technologies with reference to the NASA's publication of 2019, you can see three categories corresponding to powder bed fusion, direct energy depletion and solid state. Important thing to notice the feedstock in case of direct energy deposition could be in the form of powder or could be in form of wire whereas, in case of solid state, it may also involve a foil.

There are a lot of options interesting options which are continuously emerging. But, one important option especially with reference to the repair and refurbishment of worn out parts is direct energy deposition technique. The cold spray technique, wherein fine powder particles are accelerated in a high velocity compressed gas stream is one of the emerging options.

These particles upon the impact with the substrate they deform and bond together creating a layer and eventually creating a pre-defined geometry. So, these are some of the options which are being used in the industrial contexts.

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In this slide, you will see an indicative representation of the parts that have been realized at the plant of Wipro 3D using powder bed fusion technology. You can see here parts made out of titanium alloys, aluminium alloys, nickel alloys and steels. What is interesting to see is the object which is shown in the left portion of the slide is an anti icing assembly for aero gas turbine engine.

Many of the parts which are got intricate geometrical definitions including the bullet nose and the airfoil sections have been realized using additive manufacturing technology of powder bed fusion whereas, the sheet metal components large in size have been realized using the conventional manufacturing. So, this is a manifestation of a synergistic combination of conventional manufacturing with additive manufacturing. This approach is becoming more and more popular as hybrid engineering approach.

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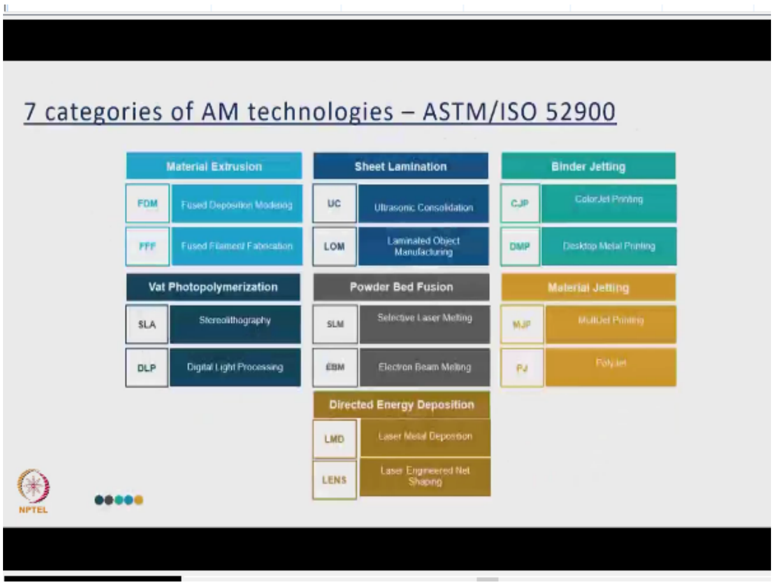

So, if you look at formal categorization of additive manufacturing technologies, as per ASTM, ISO standard 52900, you see seven distinct categories of the technologies including the vat polymerization, material extrusion, powder bed fusion, material jetting, binder jetting, directed energy deposition, and sheet lamination. Each of the technologies comes with its own set of possibilities, merits and some of the associated challenges.

But it is very important to know that you need to pick up the technology, you need to pick up the material depending upon the application that you would like to show.

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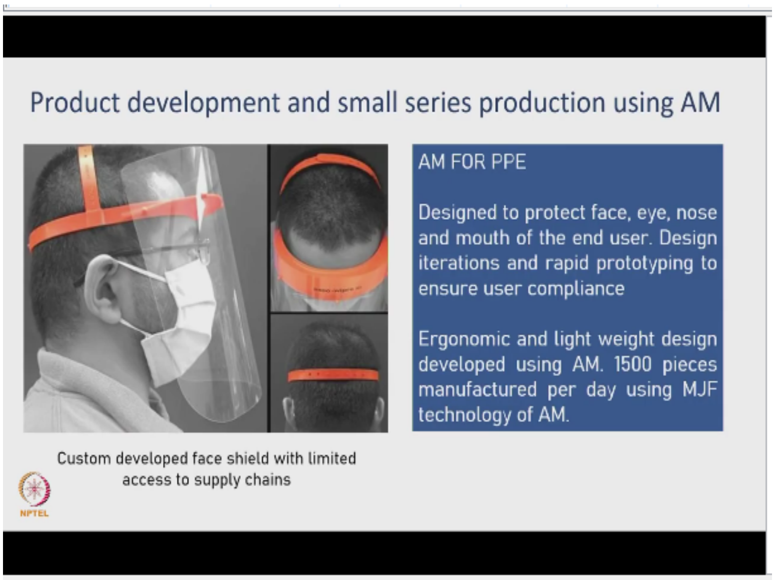

One of the recent examples which I would like to project is the one connected with development of the face shield very important product during the pandemic situation. In this case, the supply chains were severely disrupted and what you see in here is a custom developed face shield with the limited access to the supply chains using multi jet fusion technology for production of face, eye and nose.

Despite the fact that there are no access to the injection molding resources, in these disrupted times, the MJF technology was used to produce close to 1500 pieces per day and what happens in this technology is a fusing agent is jetted selectively where particles need to be processed, plastic particles need to be processed and the detailing agent is jetted across the contour or the periphery to get top notch geometrical definition.

So, fundamentally can process the polyamides and also thermoplastic polyurethane kind of materials in steps of 80-micron layers and the small series production of this kind is greatly facilitated using the additive manufacturing technology of multi jet fusion.

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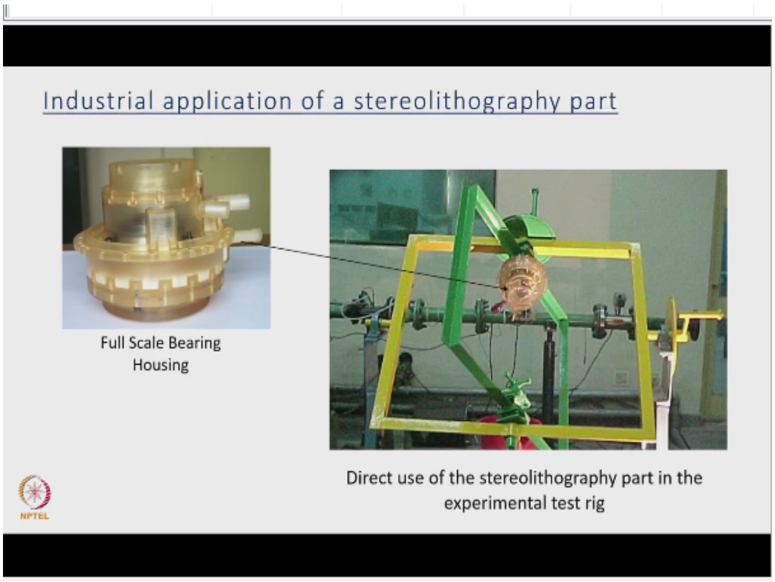

The other example I would like to give connected with an industrial context is application of a stereolithography part, a stereolithography is part of the vat polymerization context. You can see on the left-side a full-scale bearing housing on the material is a photocurable resin and it happens to be translucent. So, you can even see the fluid motions happening within this part and this full-scale bearing housing has been fitted in an attitude test facility.

The moment of the fluids within this full-scale model of the bearing housing over captured for flows visualization studies. So, this represents one example, wherein a part made out of additive manufacturing was directly used as a test article.

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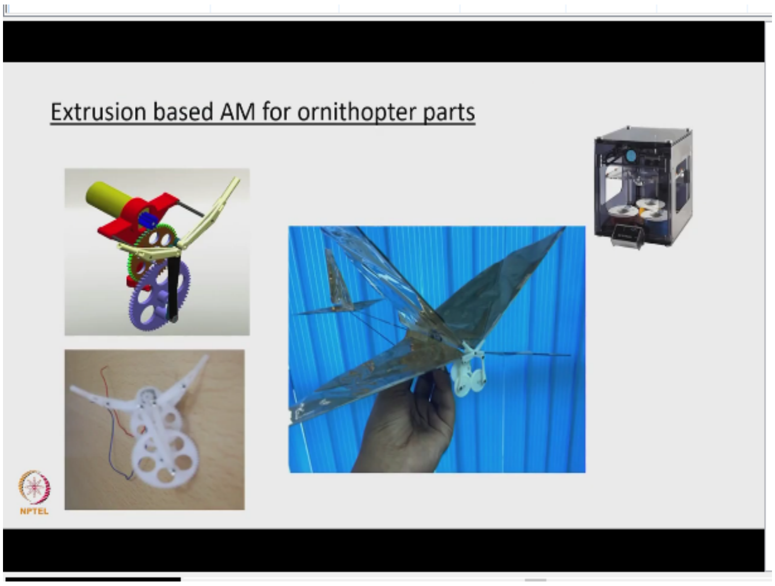

The next application is connected with fused deposition modeling, one of the ubiquitous models of additive manufacturing. In this case, the parts can be made out of thermoplastic materials like polycarbonates, PLA, ABS, glass filled nylon. What you see in this case is a micro sized transmission gear wheel assembly realize directly using fused deposition modeling and fitted into an ornithopter for converting the rotary motion into the flapping motion of the wings.

This ornithopter is ready for fuel application, do demonstrate what kind of thrust and lift can be generated by the configuration under examination. So, this is one more example of direct utilization of additive manufactured plastic part in real world context, without dependence on the conventional tooling and conventional manufacturing processes.

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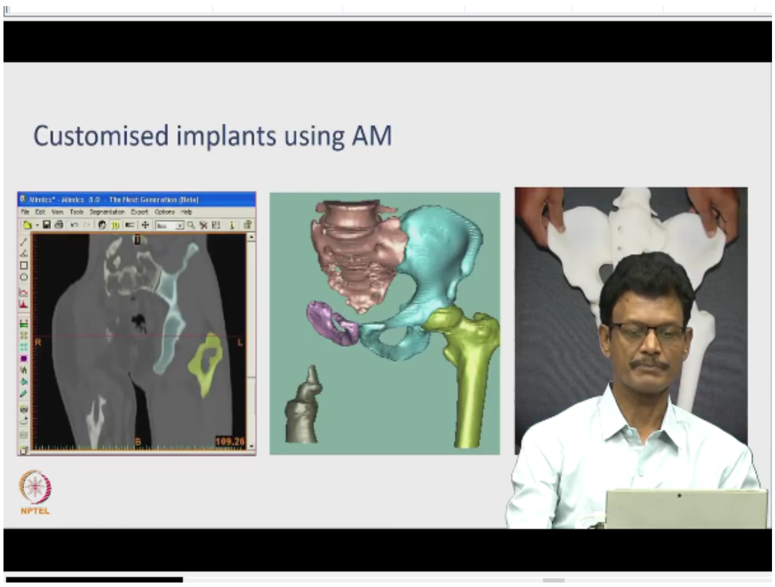

This is an example corresponding to the customization of the implants. You can see here the X-ray data corresponding to the patient who has lost a significant portion of the pelvic girdle and this is a 3D visualization and what you see on the right side is the translation of the reconstructed CT data into a full-scale thermoplastic assembly made through the fused deposition modeling system out of ABS material.

This is used both for communication purposes as well as surgical planning. So, this is one more example of using the additive manufactured part or model for planning a complex surgical procedure.

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This is an interesting example corresponding to the development of spare parts for legacy systems. In this case, the stakeholder had only access to the use part. So, the geometry corresponding to the part had to be captured using 3D scanning and using that as a reference, the part was made out of powder bed fusion using speciality steel. This is one excellent example of developing reliance in case of spare parts for strategic sectors.

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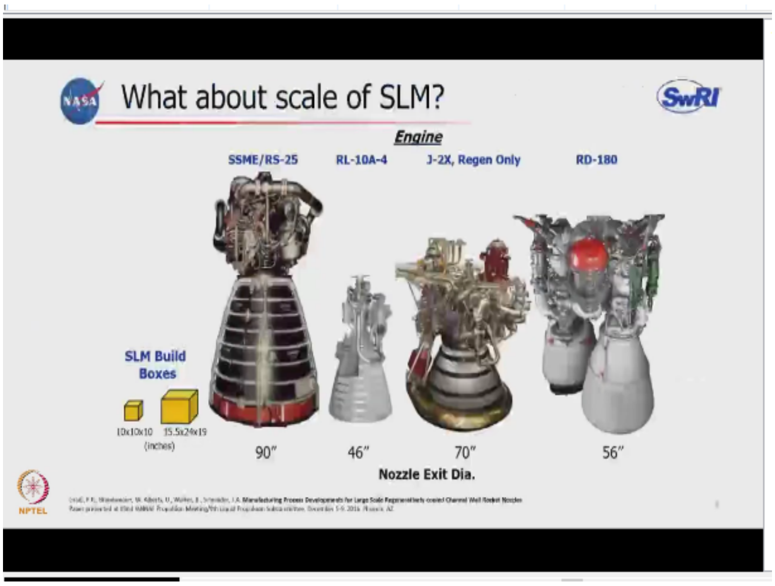

So, there were resize limitations in the initial stages, because of the fact that the concept of design for additive manufacturing was still evolving. But if you look at the current set of applications published by NASA in association with the southwest research institute, there seems to be no apparent limitations with reference to the size of the part that can be tackled using additive manufacturing.

In this case of RS-25 engine project of NASA, the parts as big as 2.5 meter in diameter with the wall thickness of 6 mm have been realized using additive manufacturing.

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So, this is a very busy slide or wherein you can see the parts corresponding to the gas turbine engines, communication systems, small turbofan engines, instrumentation housings, made out of diversified material, using additive manufacturing. You can even see one orthomode transducer, a waveguide competent made out of a ALSI 10 mg, made through powder bed fusion using one of the prominent technologies in additive manufacturing. The common denominator to all these applications is the geometries are relatively more complex.

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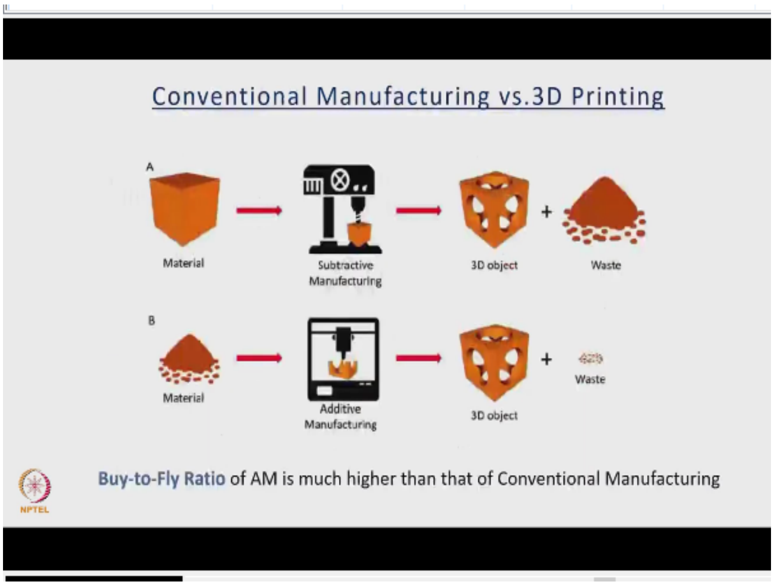

In these cases, if you were to rely on the conventional manufacturing, the waste that is associated with conversion of your design into the part could be significantly high. Because you start with a block of material, you remove unwanted material with the help of geometry specific tools and processes. In the bargain, you are continuously generating the waste. In contrast to the situation, if you were to employ additive manufacturing, as the process for translating the designs into the part, especially in case of complex designs, the waste could be significantly less because you are only adding the material at the location of necessity.

Hence, in the context of aeronautical systems a phrase is called buy-to-fly ratio has become extremely relevant. The amount of material that; you are buying as compared to the amount of material which is finally used in the system that is flying.

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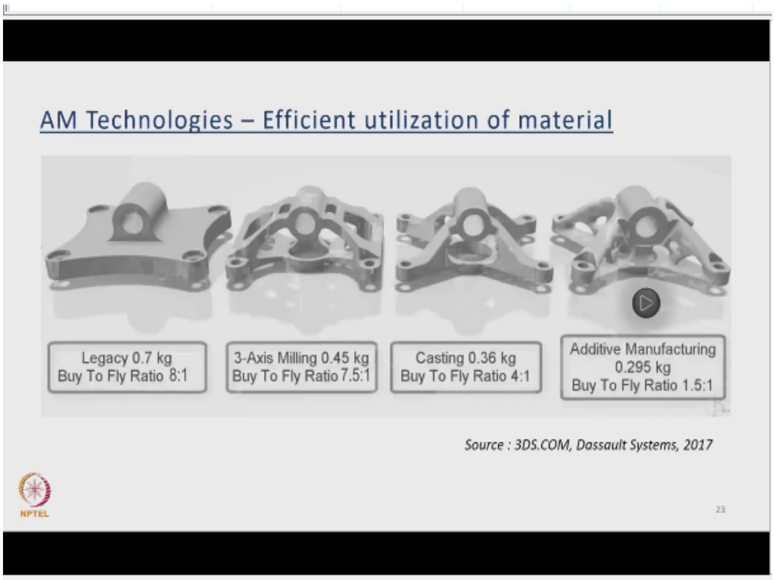

So, in case of conventional manufacturing, the buy-to-fly ratios, whether you are talking about milling, or casting, or sheet metal and machining, it could range anywhere between 8 is to 1 to 4 is to 1 ah depending upon the geometry of the part. But if you apply the principles of design for additive manufacturing, and if we use additive manufacturing as an alternative to the conventional manufacturing, it has been seen in some cases, the buy-to-fly ratio could become as favourable as very close to 1 is to 1 and coterminous to this concept is also significant reduction in the weight, which actually adds to the overall impact on the system.

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One very important thing that has been associated with the application of powder bed fusion in case of aeronautical systems is the concept of monolithising or converting multiple parts into single part. It is also known as part consolidation, whether you are talking about a flame tube or whether you are talking about a complex shape gyro housing.

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What has been seen in these cases is significant weight reduction opportunity through consolidation and in the bargain the functional requirements may also get additionally augmented. So, here is a case study corresponding to the GSAT-19 a communication satellite of ISRO launched into the orbit in June 2017 with a mission life of 10 years.

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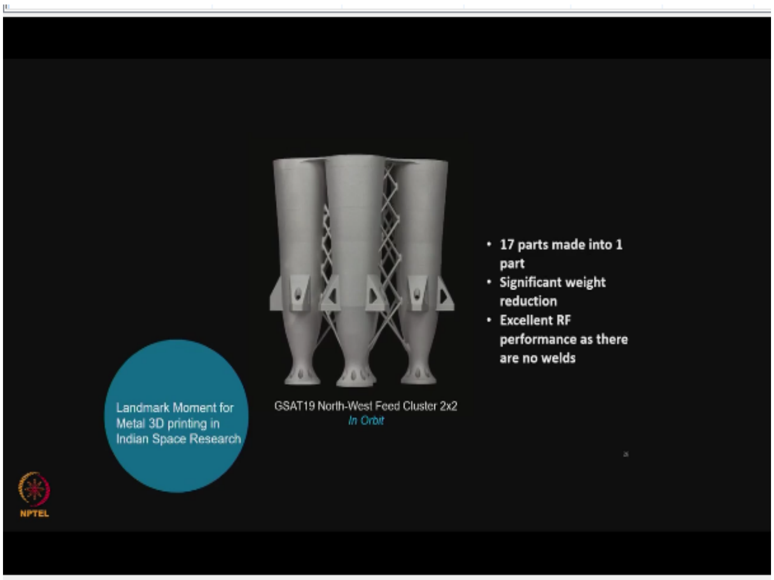

The part that is shown here is the Northwest feed cluster made out of aluminium alloy called ALSA 10 mg using powder bed fusion at Wipro 3D in close association with SAC Ahmadabad. So, in this specific case 17 different parts of the feed cluster were combined into a single part naturally, it resulted in a weight reduction, significant reduction in the assembly effort and hence the compression of the overall development cycle.

More importantly, because of the absence of the welded joints, the RF quality of the additive manufactured part turned out to be quite superior to the conventional part.

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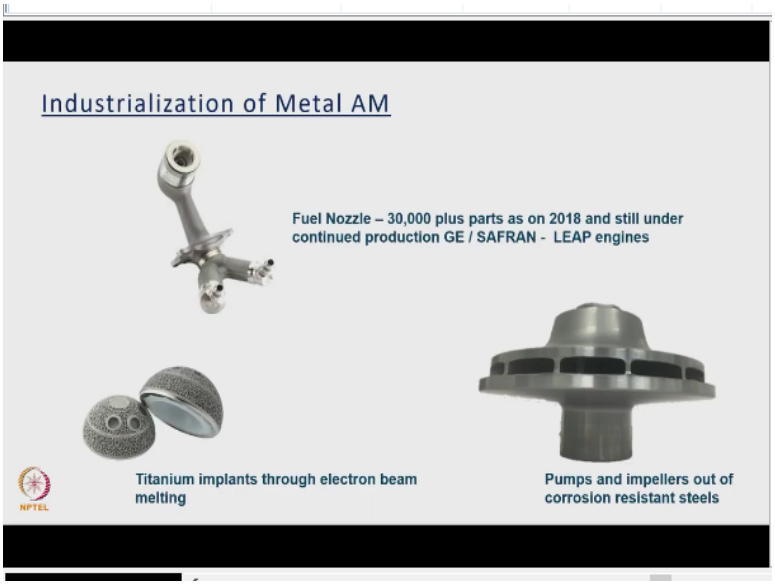

Because of these examples and possibilities and we have seen the global leaders like GE giving a new shape to the manufacturing cycle in case of fuel nozzle an important part of the leap engine. Wherein this specific part made out of cobalt chromium alloy has undergone a tremendous change as far as the process is concerned because of the infusion of powder bed fusion process into the development cycles.

As of 2018 GE has reported that more than 30,000 parts the nozzle tapes have been made using additive manufacturing using more than 40 plus metal 3D printers in 300,000 square feet facility and each of the engines the leap engines contained 19 of this 3D printed fuel nozzles and till now whatever is the quantum that has been reported to be produced, only accounts for the requirements of about 1600 engines.

So, looking at the order book of GE and SAFRAN, you can understand the quantum leap or quantum improvement in the status of the industrialization of additive manufacturing in the context of aerospace sector. The other one, which is to be noted is the customization of the implants using electron beam melting, whether we are talking about tissue grafts or cancer treatment, knee implants, or the hearing aids, we are seeing rapid advances in the procedures using 3D printing.

The processes allow one of manufacturing or mass specialisation and the healthcare product companies are quickly reconfiguring their supply chains. So that, the distributors and the health care providers, they are getting seamlessly connected and are able to meet the requirements of mass personalization or mass customization using 3D printing hubs. We have seen in certain cases, that some of the medical device manufacturers are able to produce these parts and deliver at the point of need in about 48 to 72 hours of time from the date of the receipt of the CT data corresponding to the patient in need.

One more significant observation from the energy sector is the manufacturing of the pumps and impellers out of corrosion the system steels and rather than depending on the traditional inventory maintenance systems, they are producing the parts just in time and delivering at the point of care or point of need.

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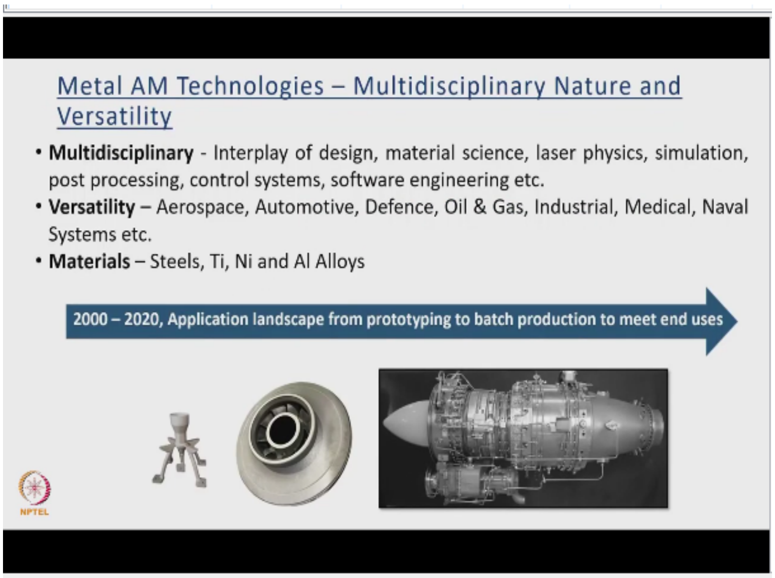

So, the current uses of metal additive manufacturing in industrial context has become an interplay of design, material science, laser physics, simulation technologies, post processing control systems and software engineering. You are also seeing that there is a continuous shift in the application landscape from the prototyping to batch production, so, as to meet the complex needs of the end users.

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Reflecting this kind of an improvement in the usage pattern of additive manufacturing, several publications have referred to the 3D printing as the third industrial revolution and during the 2010 to 2015 kind of a timeframe many impactful publications brought out how this technology is enabling the next industrial revolution.

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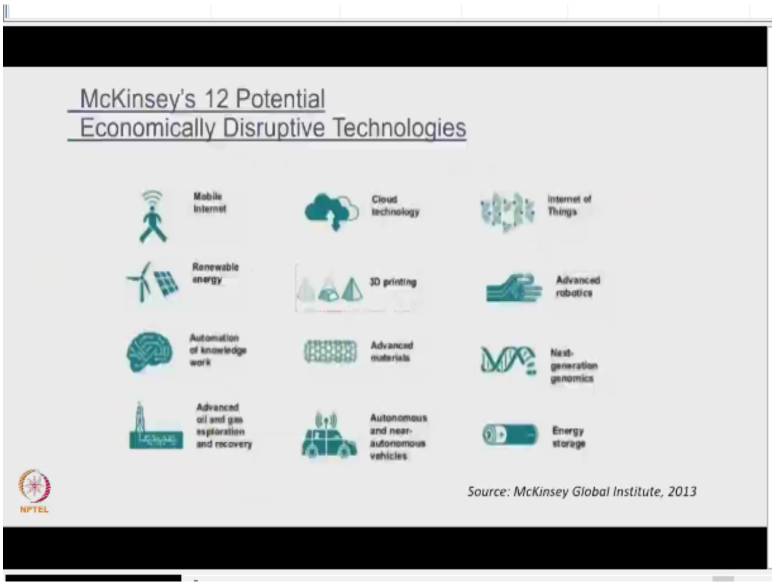

One of the important references in this case is the report of McKinsey global institute in 2013, where in the 3D printing was placed alongside of other disruptive technologies like cloud technology, internet of things, the renewable energy, advanced materials and energy storage solutions as one important technology that can bring in disruption into the way the future businesses are run.

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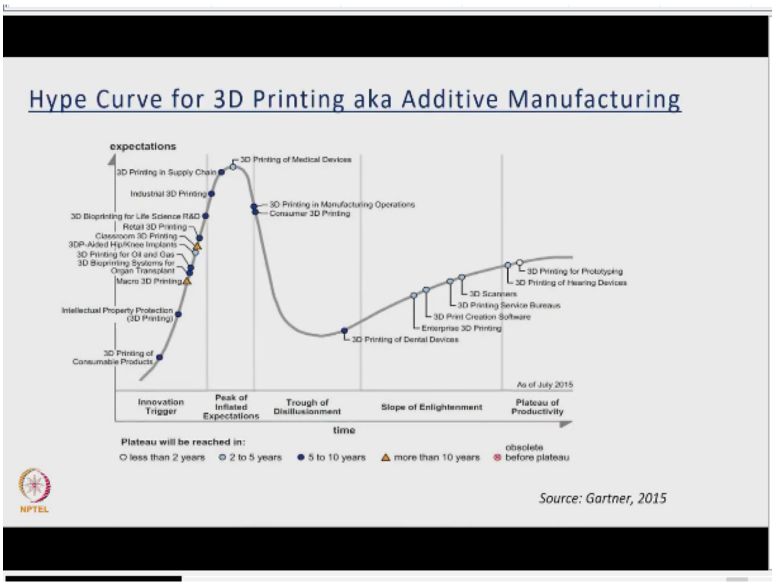

So, this is a very famous Gartner hype curve additive manufacturing is no exception to this kind of a trend. When this technology was introduced about 25 years ago, there was tremendous amount of enthusiasm among the stakeholders from multiple sectors. There was a peaking of expectations. Soon they realized what are the limitations that are synonymous with additive manufacturing, especially with reference to the strength, surface quality, as well as dimensional accuracy.

So, there was a phase which is synonymous with disillusionment. We are in a phase where the users are able to understand the possibilities in much better way. They are also able to spot the specific instances where induction of or infusion of this technology can produce the parts with the necessary technical as well as business impact.

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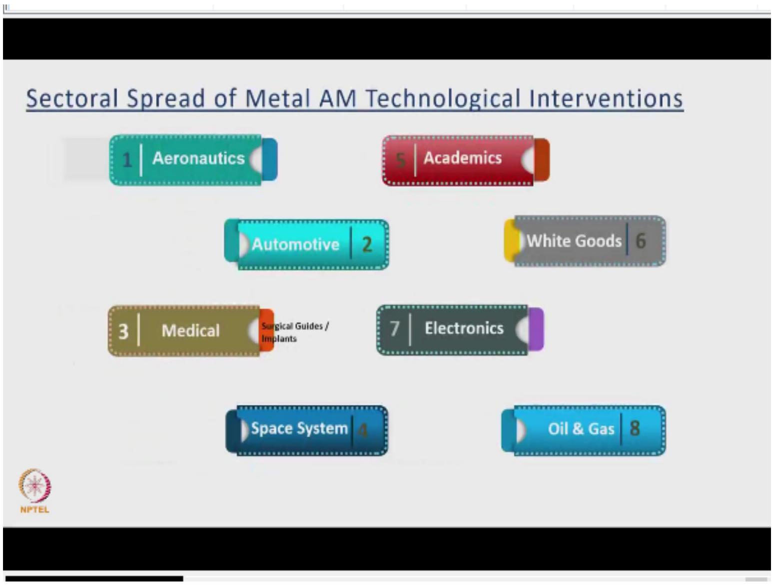

So, what are those instances when you are talking about aeronautics, there are many gas turbine manufacturers who are able to produce the parts connected with the turbine combustor, exhaust and compressor modules with a lot of discernible impact on the time compression using powder bed fusion technology. They are also able to make use of directed energy deposition technology for repair and refurbishment of worn out parts.

We are seen in automotive sector especially in case of electrical vehicles and motorsports, the metal additive manufacturing and plastic additive manufacturing technologies are repeatedly used for producing even the one of parts and maintaining the competitive advantage compared to the peers. As I explained in case of medical industry, the surgical implants customized solutions for orthopaedic applications, for maxillofacial and craniofacial applications are becoming more and more prevalent.

In case of space systems, development of monolithic rocket engines, and development of small satellites are being pursued by research groups across the world using additive manufacturing as an enabler. We have also seen in case of white goods sector, customized gifting solutions, and the businesses connected with the customized gifting have evolved by integrating 3D printing into the supply chain.

Similar examples can be cited from the world of electronics, the world of oil and gas. One important thing which can be seen in case of academic context is development of fab labs and maker spaces by introducing additive manufacturing as one important constituent technology.

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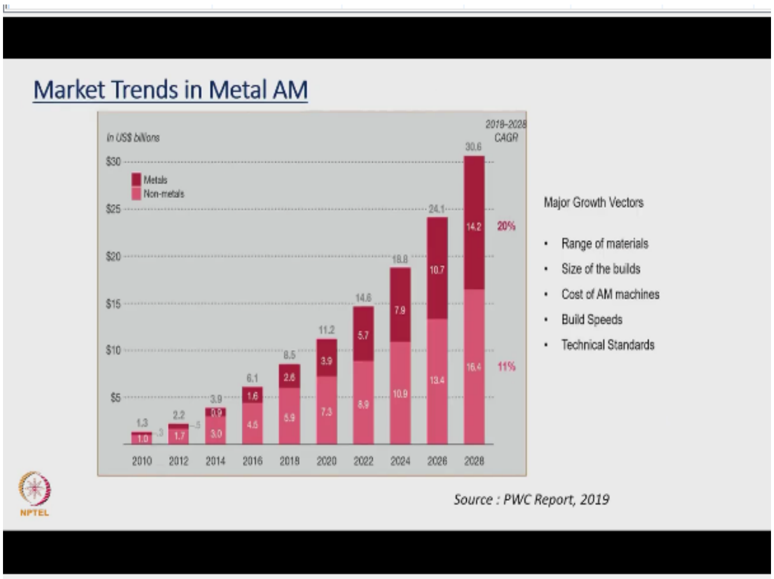

So, with all these applications emerging, we have seen the overall business volume of additive manufacturing has crossed the levels of 11 billion US dollars, approximately 35 to 38% of this business volume is contributed due to metal additive manufacturing and the remaining is because of the plastic additive manufacturing.

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It is also important to understand that not in all instances additive manufactured parts are directly used. As shown in this case, the part that you see on the left side of the slide is a quick cast pattern. It is a quasi hollow pattern made out of photopolymer resin using stereolithography, and this can be used as a substitute for conventional patterns in case of investment casting cycle.

On right side, you see an intricate statue of Sri Ganesha made using wax through the process of material jetting technology. This is once again a pattern an intricate pattern that has been realized using an additive manufacturing technology. So, there are direct uses of additive manufacturing technology in the engineering context and there is a small but noticeable portion of indirect uses for patterns as well as for the bridge tooling.

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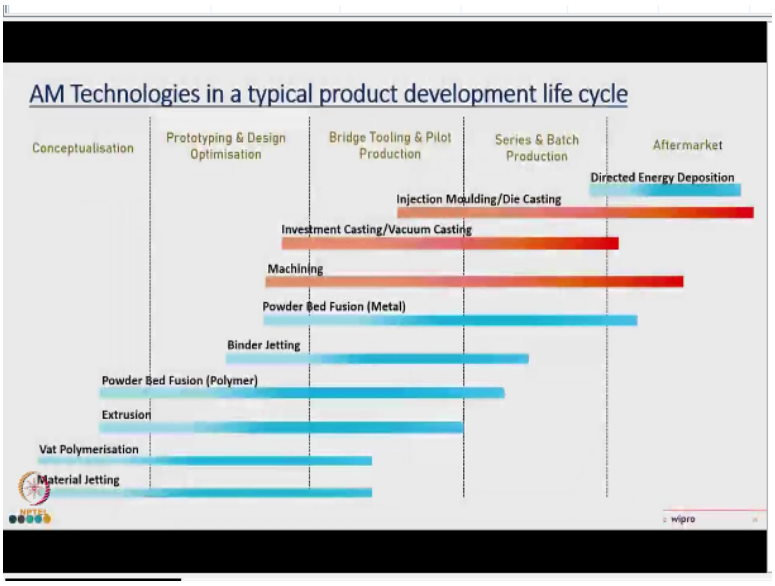

So, if you look at the overall product development cycle, and try to place these technologies for enabling the various phases of product development, you can see here the processes like material jetting, vat polymerization, extrusion and selective laser sintering that can handle the polymeric materials. They become significant very relevant during the conceptualization stage, wherein you are looking at several design iterations to be completed in the limited time and arriving at the optimal solution as soon as possible.

If you are looking at the aftermarket or repair and refund point of use parts, you will see a distinct use case for directed energy deposition technology and in between, there is a space for technologies like powder bed fusion and binder jetting, wherein you are talking about meeting the end user requirements using various metallic materials, and in these cases, we are not looking at only 1 or 2 parts, we may be looking at series production or small volume production.

There are many case studies where in the enablement of this kind of a need has been attributed to the uses of powder bed fusion by the engineering groups.

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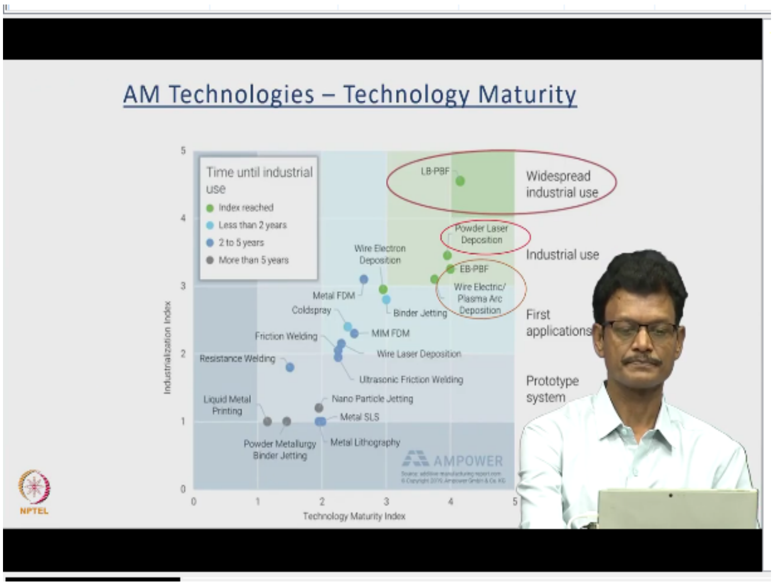

So, if you look at the technology options, you and try to position them with reference to two important vectors. One is called industrialization and the other one is technology maturity; you can see that the technology of laser powder bed fusion is right on the top. So, it is synonymous with widespread industrial users. Just below that you can see powder laser deposition technique.

Below that you can see plasma arc technique and other technologies are also catching that. So, in my coverage of the topic I will give plenty of examples corresponding to the usage of laser powder bed fusion that signify the matured applications of the technology in the industrial context.

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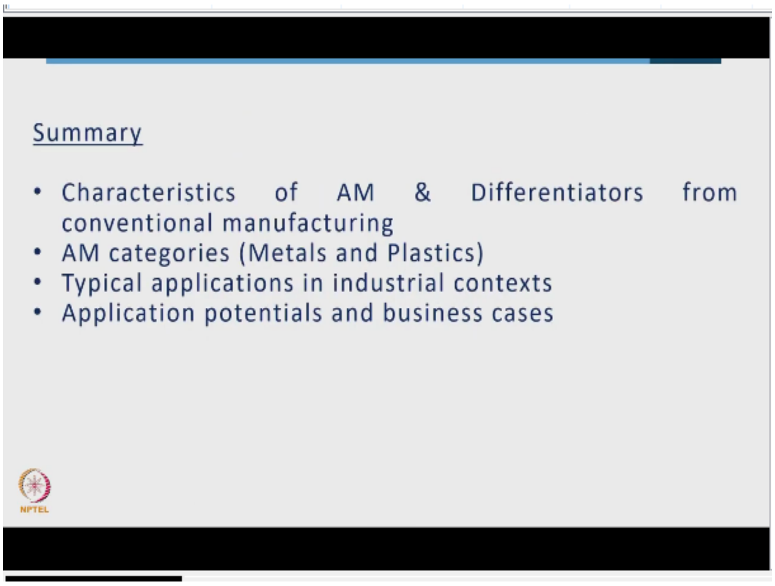

Just to sum up in this first session we understood the important characteristics of additive manufacturing processes and we also got sensitized to the differentiators those are the conventional manufacturer. We also discussed the various categories of additive manufacturing technologies based on the operation principles and the compatibility with different materials and the business cases and application potentials that are synonymous with these technologies have also been discussed in brief. So, we will further explore the typical applications of these technologies in the various face set of product development in the ensuring session. Thank you.