

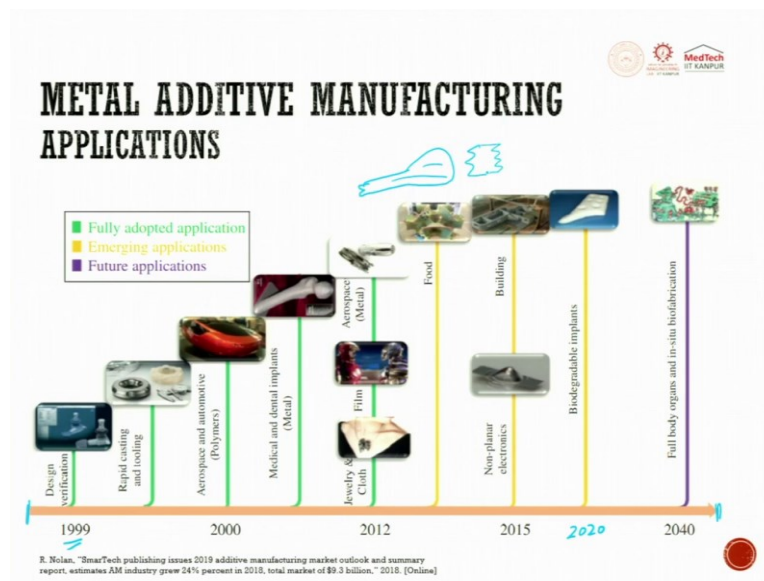
Metal Additive Manufacturing
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Lecture 03
Additive Manufacturing Processes:
Applications and Challenges

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Welcome to the next lecture on applications and challenges. Till now, we have seen the benefits of metal additive manufacturing and the market size, how exponentially it is growing. In this lecture, we will try to see various segments or sectors, how additive manufacturing are used.

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So, the applications were predominantly used in 1999. We were trying to talk about design verification, then, we were trying to talk about rapid tooling and rapid casting, and rapid tooling was the next somewhere in 1999 to 2000 we have been talking about it.

In 2000, aerospace and automobile parts, where polymers were used came into existence. Market was ready to make and it was used in a full extent then, by 2010, you had this medical and dental implants which are made out of metals, which found its place in real time usage.

In 2012, you can see jewelry and clothing industry, film and aerospace started using additive manufacturing in a big way. Then, in food industry, today, we are printing food, we are using additive manufacturing for as to print the icing layer, to print a complete cartoon figure to make the final product into a cookie or something like that.

So, food industry has started using additive manufacturing and then in 2015 non planar electronic structures have been made out of additive manufacturing, 3D rapid prototyping buildings are also constructed today. In 2020, you see biodegradable implants are made out of it.

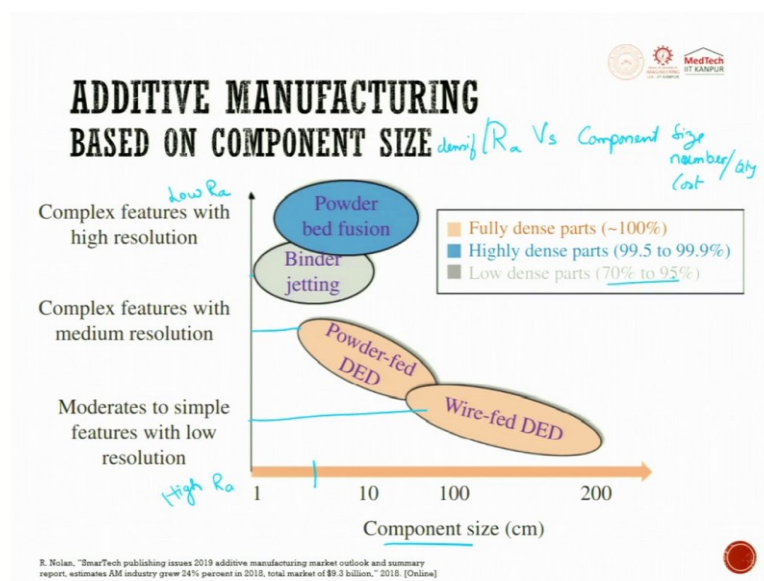
So, it is somewhere around about 2020. By 2040, we are hoping that full body organs and in-situ bio-fabrication will happen so that all the damaged parts of our body can be replaced by using additive manufacturing, but there it is more polymer based, but I have put the entire spectrum of the additive manufacturing which has played an important role from 1990s to

2040. If you look at it, fully adopted applications are all green, yellow is emerging application.

For example, if you want to have a chicken piece exactly like this, with some features like this, then the chicken is converted into a wire or into a powder and a liquid then it is extruded, it is extruded through your food based additive manufacturing it is printed and then it is either taken for heat treatment or either the final part. The cookies today are made to come in this form.

So, food industry is coming up in a very, very big way. So, this is what we are looking at it, so fully green. So, design verification, rapid casting and tooling, aerospace, medical application, clothing application, they are all fully adopted in use, now they are all in use. For example, the gold industry. International gold industry use material jetting process and they print the wax patterns for real time applications.

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So, when we look at the additive manufacturing based on component size, if you look at this side, you have powder bed fusion. So, in the y axis, you will have complex features with high resolution and at the bottom you have moderate to simple features with low resolution, resolution here we talk about so I can convert in terms of Ra, this is poor Ra or low Ra, this is good Ra or high Ra good. So, I will convert it into high Ra value and I will make this into low Ra value.

So, if you want moderate to simple features with low resolution can be built by using wire fed DED, directed energy deposition, wire can be used. If you want to have complex features with minimum then you can go for powder, you can also use the binder jetting where in which, the number of parts produced will be very less and powder bed fusion method can be used where the component size becomes smaller. But, you get low Ra highly complex features to meet out the requirements there is always a tradeoff between Ra versus component size. There is always a tradeoff component number, or quantity then cost .

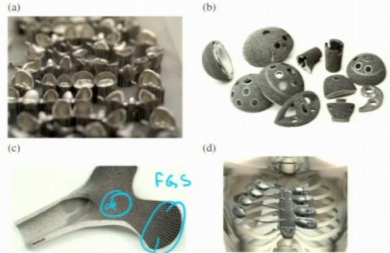
So, you can replace this Ra with densification etc. So, here fully dense parts are produced, here highly dense. Fully dense parts 100 %, highly dense parts 99.5 – 99.9 are done here, low dense parts are done between 70- 95.

So, here this is what we are doing. With binder jetting, we will always get low dense part. You get dense parts 99.5- 99.9 in this powder bed fusion method and the fully dense part 100% you get through wire and powder fed DED.

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ADDITIVE MANUFACTURING IN MEDICAL AND DENTAL

- a) Dental crowns printed by LPBF
- b) Joint implants printed by E-LPF
- c) Functionally gradient porous titanium load-bearing hip implant printed by LPBF → *Power bed Fusion*
- d) Customized ribs and sternum printed by E-PBF → *Electron beam*



(a) Dental crowns printed by LPBF

(b) Joint implants printed by E-LPF

(c) Functionally gradient porous titanium load-bearing hip implant printed by LPBF → *Power bed Fusion*

(d) Customized ribs and sternum printed by E-PBF → *Electron beam*

S. Fourrier, "The making of an orthopedic implant using 3D printing," [Online], 2018. Available: <https://orthostreams.com/2018/12/the-making-of-a-medical-metal-implant-using-3d-printing-from-black-to-grey-metal-powder-magic-of-3d-printing>.

Metal AM, "Remishaw showcases metal AM implants to American Academy of Orthopaedic Surgeons," 2018. [Online]. Available: <https://www.metal-am.com/remishaw-showcases-metal-implants-american-academy-orthopaedic-surgeons>.

H. R. Mendosa, "3D printing gives cancer patient new ribs and sternum in first-of-its-kind surgery," 2018. [Online]. Available: <https://3dprint.com/95371/3d-printed-ribs-and-sternum>

So, some of the applications which we would like to see for our interest is additive manufacturing in medical industry and dental industry. Medical crowns are being printed, joint implant printed by process E-LPF, then you can see functionally graded so, here it is dense, here it is loose loosely packed.

So, here again it is a functionally graded strength functionally graded strength material or functionally graded properties are their strength properties. So, here it can take toughness, here it can take maybe load.

So, functionally graded porous titanium load bearing hip implant is printed by laser-based powder bed fusion method. Here E is nothing but electron beam. See, there are only few heat sources it can be laser, it can be electron it can be plasma, so, you can use it. So, large electron and laser are used today.

So, by using electron beam, they have printed the ribs. So, all these things are being printed and now, few trials are going on. Some of the big companies internationally are already into market for producing it. So, here they do lot of mass customization to meet out to the customers' needs.

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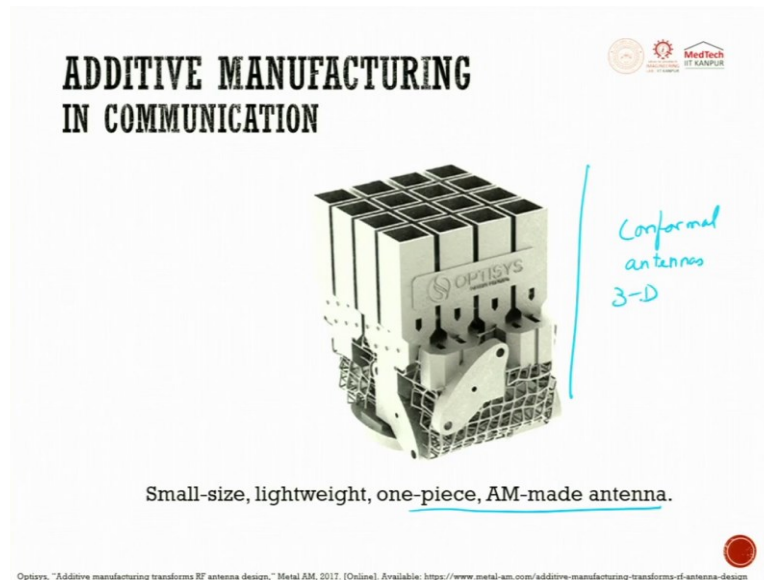


So, this is for aerospace conformal cooling system or a cooling channel generated or is fabricated inside this structure. Then conformal and lattice structure to improve heat dissipation is done for auto mobile applications.

So, you can see for defense and aerospace industry, metal print and additive manufacturing are finding a lot of applications in defense there will be complex jobs. So, complex job in the sense complex size, shape and features are there. So, all these things can be integrated and you should also understand the volume is low.

So, if you want to have a break between all these things, then additive metal manufacturing becomes your only way out.

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So, next in terms of communication, it is a small size lightweight one-piece additive manufactured antenna. This is exhaustively used today, there are conformal antennas which are three dimensional is being made. So, earlier they used to make it planar, now, they are making it three dimensional.

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Additive manufacturing in heavy engineering industry, several hydraulic valves are getting manufactured in one go. So, you will have so many channels which are getting integrated.

So, you can see all these things are made out of metal additive manufacturing which plays a very important role in oil and gas industry. So, I would say that instead of heavy engineering, you can make it also additive manufacturing in energy-based engineering applications.

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**ADDITIVE MANUFACTURING
IN AUTOMOTIVE INDUSTRY**

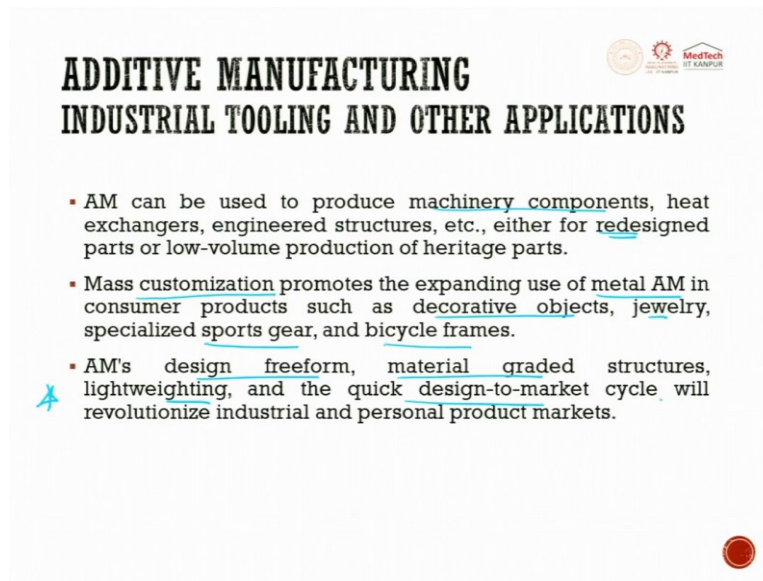
- a) Ford's custom anti-theft wheel lock being printed by PBF system
- b) Ford's custom anti-theft wheel lock
- c) Custom titanium door handle frame in DS3 Dark Side edition from DS Automobile

(a) (b) (c)

EOS. "The potential of additive manufacturing for serially produced vehicles." [Online]. Available: <https://www.eos.info/en/3d-printing-examples-applications/mobility-logistics/automotive-industry-3d-printing/serially-produced-vehicles>.
Ford. "Ford develops 3D-printed locking wheel nuts to help keep thieves at bay." 2020. [Online].
Available: <https://media.ford.com/content/fordmedia/new/en/news/2020/01/20/ford-develops-3d-printed-locking-wheel-nuts-to-help-keep-thieves.html>.

Next, when we look at the automotive, such complex small thin features can be printed. So, Ford customized anti-theft V lock was being printed by powder bed fusion system. You can also have customized wheel locks. So, if you have to customize, you have to use automotive metal additive manufacturing, then custom titanium door handle frame with DS3 dark side edition from DS Automotive.

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ADDITIVE MANUFACTURING
INDUSTRIAL TOOLING AND OTHER APPLICATIONS

- AM can be used to produce machinery components, heat exchangers, engineered structures, etc., either for redesigned parts or low-volume production of heritage parts.
- Mass customization promotes the expanding use of metal AM in consumer products such as decorative objects, jewelry, specialized sports gear, and bicycle frames.
- AM's design freeform, material graded structures, lightweighting, and the quick design-to-market cycle will revolutionize industrial and personal product markets.

Logos: IIT Kanpur, MedTech, and a red circular logo.

When we talk about industrial tooling and other applications, AM can be used to produce machinery components, heat exchangers, engineering structures either for redesigned part or low volume production for heritage purpose.

So, machinery components can be used. Recently, for our aerospace industry, they approached us in redesigning and fabricating metal part which is used in our fighter jet planes, since the industry abroad are now closed. So, they wanted somebody to manufacture. We designed it and now it is under testing.

So, if you want to produce missionary components, heat exchangers, engineering structures either for redesigning parts or for raw production, then our metal additive comes in a big way. Mass customization promotes the expanding use of metal additive manufacturing in decorative objects, industry, jewelry, sports and bicycle framing.

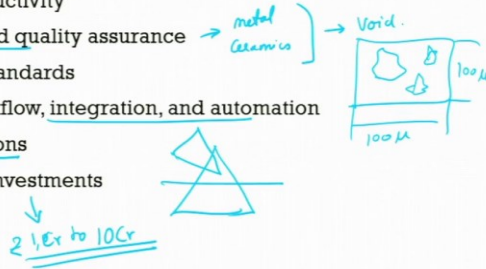
Everywhere this metal additive manufacturing is being used. AM designs free form material grade AM structures, light weighting and the quick design to market cycle with revolutionized industrial and personal product markets.

So, this is a very important point which consolidates everything designed freeform materially graded structures, lightweight, quick to designs quick to design cycle with revolutionizing industry and personal product market.

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ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES

1. Qualified materials →
2. Speed and productivity
3. Repeatability and quality assurance →
4. Industry-wide standards
5. End-to-end workflow, integration, and automation
6. Software limitations
7. Initial financial investments
8. Security
9. Skillsets gap



So, some of the challenges till now, I have been showing only the green part of it, some of the major challenges in additive manufacturing or in particular metal additive manufacturing is qualified material.

So, we have standards and these standards have to be maintained. So, the products which are produced the powder, the wire which are produced to maintain up to the standard, even today is a challenge. For pure materials it is okay, alloys of mixed to composition, it is still a challenge.

So, the qualified material is a big challenge, which is in front of us because we know additive manufacturing is going to be the future but the input raw material qualifying is a big challenge. The speed and the productivity of these machines are as of today low.

In Europe, there are big giants who are working with the technical universities in developing high speed and high productive additive manufactured machines to meet to customer demands, the repeatability and quality assurance is also a problem for metals and ceramic materials. Because, if there are wires inside, then it becomes safer. Wire inside means you have a part, there is a wire, there is a very small wire. Assume this, whatever I have done is around about $100\mu \times 100\mu$ cross-section.

So, in this you see wires, so, removing these wires or trying to optimize and get parameters such that these wires are not there is a major challenge even today. So, repeatability and quality assurance are a big challenge and wherein which there is lot of opportunities for

developing tools, process optimization, deep learning understanding, machine learning understanding, industry wise standards are still in a nascent stage.

Many of the standards are just tweaked a little bit to meet out to the requirements, but industry wide standards are still not established, end to end workflow integration and automation is not truly done.

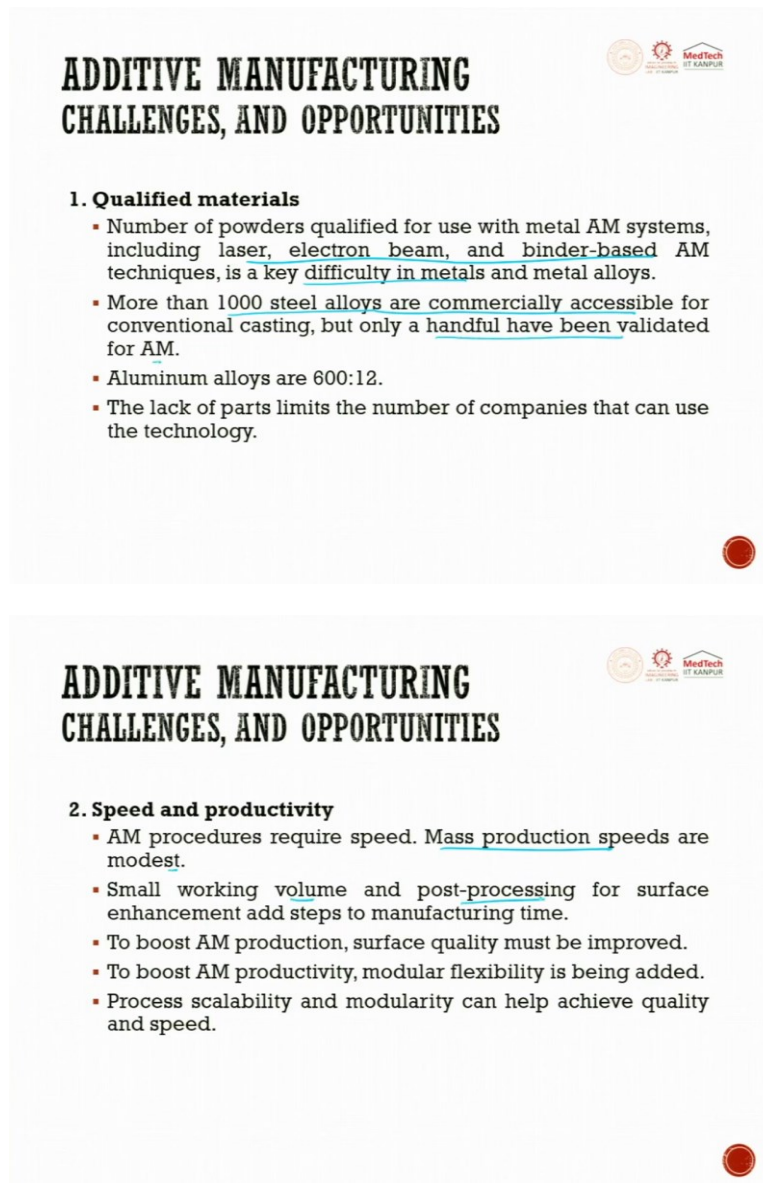
For example, we have done CAD after CAD pushing it into the machine without any error and then getting it printed, then doing post processing and getting the final product required, that is not still complete integration and automation has not happened in the workflow. Software has a lot of limitations, when we start looking into the tessellations, they are between the layers coming then there are tessellations intersecting.

So many software limitations are there today, there are errors, there are few custom build software, but they are pretty expensive to come to the open domain. So, software limitation is one then initial financial investment, metal additive manufacturing in Indian costs, they range from 1 crore to if you are looking for an industrial work, fast production means it goes up to 10 cr. The typical cost is 1 cr to 10 cr.

So, 1 cr means it is 100 lakhs, so, if you divide it by 80, so that will be USDs, then security is also a problem. So, whatever we try to have a CAD and this machines today are connected with a vendor like cloud and then they also try to give online suggestions, inspection of the machines all these things they do. Security is also a big challenge where in which when we talk about cyber security for producing parts, you have major challenge cyber security.

Then skilled set of labors are even now not available, people who start producing these additive manufactured parts, they just replaced from a conventional part to an additive manufacturing part, but they have not used the fullest extent of doing topology optimization, increasing, reducing the weight and increasing the strength is not part. So, topology optimization, deep learning, machine learning, software understanding, process to produce having good repeatability and quality assurance, all these things need lot of skill currently it lacks. So, these are some of the challenges and these challenges can be converted into an opportunity for you.

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The image shows two presentation slides side-by-side. Both slides have a white background with a light blue header area. The title 'ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES' is written in a bold, black, serif font. In the top right corner of each slide, there are three logos: a circular logo with a gear, a red logo with a gear, and a logo for 'MedTech IIT KANPUR'. The first slide is titled '1. Qualified materials' and lists four bullet points. The second slide is titled '2. Speed and productivity' and lists five bullet points. Both slides have a small red circular logo in the bottom right corner.

ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES

1. Qualified materials

- Number of powders qualified for use with metal AM systems, including laser, electron beam, and binder-based AM techniques, is a key difficulty in metals and metal alloys.
- More than 1000 steel alloys are commercially accessible for conventional casting, but only a handful have been validated for AM.
- Aluminum alloys are 600:12.
- The lack of parts limits the number of companies that can use the technology.

2. Speed and productivity


- AM procedures require speed. Mass production speeds are modest.
- Small working volume and post-processing for surface enhancement add steps to manufacturing time.
- To boost AM production, surface quality must be improved.
- To boost AM productivity, modular flexibility is being added.
- Process scalability and modularity can help achieve quality and speed.

So, all these materials are also qualified material you can see with metal additive system including laser. Electron beam binder base has difficulty in getting the metals, then there are more than 1000 steel alloys that are commercially accessible, but only a handful of them are validated by additive manufacturing, same is the case with aluminium alloys.

Then speed and opportunity. I have said mass production speeds are the modest. So, small working volumes and post processing of surface enhances this step.


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ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES




2. Speed and productivity

- Multiple heat sources (e.g. laser beams) are being combined into a larger operating envelope.
- Automation and intelligent software are being developed to improve subsystem production.
- Computer modeling of AM processes can enhance production through dependable simulation rather than costly experimentation.
- Few models have been developed, adding R&D costs to high material costs to prevent enterprises from using AM.




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ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



3. Repeatability and quality assurance

- Reliability and reproducibility remain major AM issues, especially for mass manufacturing.
- AM is sensitive to environmental and process disturbances including shifting temperature, humidity, and particle size.
- Full control of the process and environment is difficult, thus solutions that use sensors to monitor conditions and quality control algorithms to automatically modify process parameters, such as laser power or process speed, are preferred.
- Due to their speed, DED is adding closed-loop control while PBF is adding intermittent controllers.
- For PBF operations (e.g. LPBF), hardware speed and accuracy are bottlenecks for closed-loop control.



So, repeatability and reliability. We are nowadays looking for closed loop control system. In the closed loop control system we are looking at environmental conditions like temperature around and the dust around.

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**ADDITIVE MANUFACTURING
CHALLENGES, AND OPPORTUNITIES**

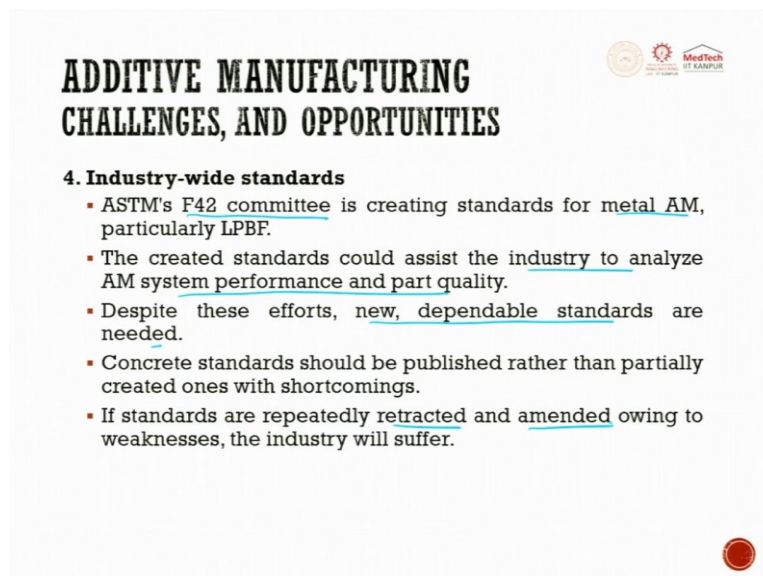
4. Industry-wide standards

- Despite AM's recent advances, the industry lacks a complete set of technical standards.
- Lack of standards may hamper industrial AM adoption.
- Several key players have identified the challenge and begun acting. ASTM, ANSI, ISO, and other organizations are developing AM standards platforms and methods.

The slide features a title in bold, a section header, and a bulleted list. Logos for IIT Kanpur and MedTech are in the top right, and a red seal is in the bottom right.

So, industrial wide standards, there are several key players that have identified the challenges and began to act on it. So, they have now come up with ASTM standard, ANSI standard, ISO standards, these are some of the standards which are now coming into existence which are getting honed and polished for meeting to AM standards.

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**ADDITIVE MANUFACTURING
CHALLENGES, AND OPPORTUNITIES**

4. Industry-wide standards

- ASTM's F42 committee is creating standards for metal AM, particularly LPBF.
- The created standards could assist the industry to analyze AM system performance and part quality.
- Despite these efforts, new, dependable standards are needed.
- Concrete standards should be published rather than partially created ones with shortcomings.
- If standards are repeatedly retracted and amended owing to weaknesses, the industry will suffer.

The slide features a title in bold, a section header, and a bulleted list. Logos for IIT Kanpur and MedTech are in the top right, and a red seal is in the bottom right.

So, ASTM F-42 committee is creating standards for metal additive manufacturing. Creating Standards Code assists the industry to analyze the system performance and the part quality. Despite these efforts, new and undependable standards are still needed. Concurrent standards should be published rather than particularly creating ones with shortcomings, if standards are

repeatedly retracted and amended owing to the weakness, the industry will suffer. So, if standards are repeatedly retracted and amended, then industry will suffer from producing.

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ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



5. End-to-end workflow, integration, and automation

- All major industrial and nonindustrial AM system providers propose end-to-end workflow integration.
- Any integration/automation must consider AM's limitations and features.
- The lack of digital infrastructure hinders the AM industry's progress to automated workflows.



ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



5. End-to-end workflow, integration, and automation

- Design for AM (DfAM) solutions, driven by digital warehouses and digital twins, expedite the part design and optimization for automation.
- Manufacturing execution software should automate material supply lines (e.g. powders) for AM systems and workflow stations.
- Machine learning, AI, simulation, inline process monitoring software, and nondestructive testing (NDT) should oversee the AM process to fix faults by having robots for depowdering and recycling powder for AM machines.
- The workflow should include automated post-processing heat treatment, polishing, etc. Automated AM is part of the factory of tomorrow and the industry 4.0 revolution.



ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



6. Software limitations

- Commercial software systems for AM component design, support structure construction, and machine interface have limitations in assessing print feasibility and recognizing process limits.
- In many cases, 3D-modeled ideas are difficult to print due to unaccounted-for process restrictions.
- Current workflow software limits AM's ability to track individual goods through each process stage to manage resources and delivery timelines.
- The quality of information and transmission mechanisms affects inter-and intra-communication and collaboration.
- Current software and hardware need enhancements for AM communication.



So, here the quality of the information and transmission mechanism affects the inter and intra communicational and collaboration in additive manufacturing.

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ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



7. Initial financial investments

- A large investment in AM money and ecosystem is required to put metal AM into production.
- AM includes software, supplies, experts, post-processing equipment, certification, and employee training.
- This investment may prevent companies from adopting this technology.
- AM service firms can be integrated throughout the supply chain to derisk early AM adoption.
- Universities and R&D institutions can help companies implement AM by providing basic R&D and training platforms.



ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



8. Security

- AM's cyber-physical nature has caused considerable problems.
- When AM promotes distributed manufacturing, hackers exist.
- They can change AM designs to generate purposeful faults with catastrophic effects in real systems.
- Commercial AM services' weaknesses and large-scale tasks may make it hard to verify printed parts' quality.



ADDITIVE MANUFACTURING CHALLENGES, AND OPPORTUNITIES



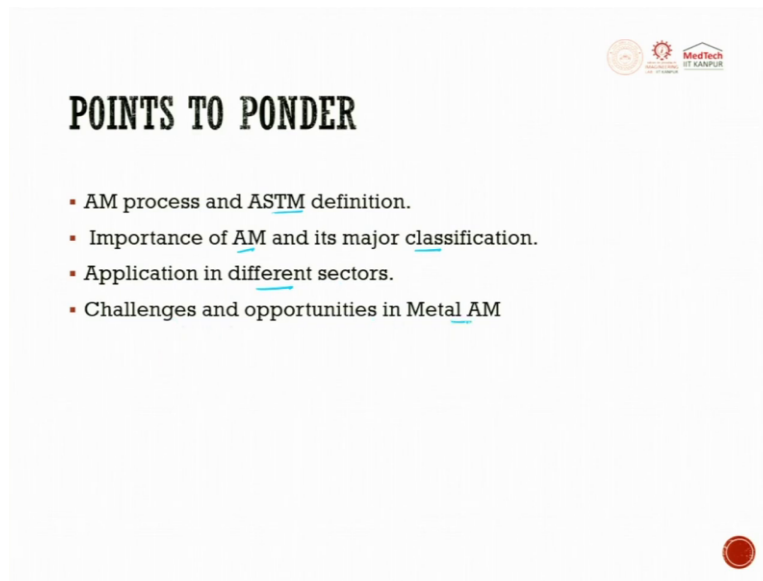
8. Security

- To solve security problems, process and supply chains must be firewalled.
- These measures could be the same as other manufacturing industries like electronic printing
- However, due to typical applications of AM-made parts in critical applications like jet engines, special validation procedures must be developed to give assurance that the parts are not affected by a malicious attack involving undetectable design alterations.



So, initial finance has been discussed. Then security cyber are physical in nature. So, this is there. So, distributed manufacturing hackers are also coming in. So, they try to weaken the system. To solve security problems, process supply chain must be firewalled, skill set we have discussed in length. So, these are some of the challenges and opportunities.

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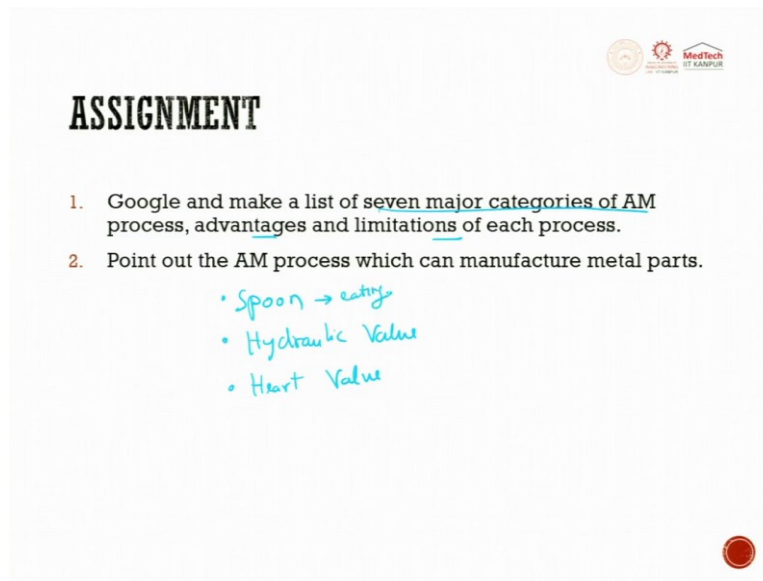
POINTS TO PONDER

- AM process and ASTM definition.
- Importance of AM and its major classification.
- Application in different sectors.
- Challenges and opportunities in Metal AM

So, points to ponder. AM process and ASTM definition, can you just look into drafted and you do not have to submit to me. Make the classifications and then you can also try to see the ASTM standards. Importance of aim and its major classification which we have seen. You can try to add some more. Try to look at different sectors apart from what I have spelt it out here, to find out the fields where metal additive manufacturing can be done. Challenges and opportunities in metal additive manufacturing I have already spelt it out if you can add some more just by going through the literature these are something which you should look forward to enrich your horizon.

So, AM processes and ASTM definition, importance of aim in your own words apart from whatever I have discussed, then major classification, applications in different sectors apart from whatever I have spelt it out, challenges and opportunities in metal additive manufacturing.

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The slide is titled "ASSIGNMENT" in bold black letters. It contains two numbered tasks. Task 1 asks to Google and list seven major categories of AM process, advantages, and limitations. Task 2 asks to point out the AM process which can manufacture metal parts. Handwritten in blue ink are three examples: "Spoon → eating", "Hydraulic Valve", and "Heart Valve". The slide has logos for IIT Kanpur and MedTech IIT Kanpur in the top right corner and a red circular logo in the bottom right corner.

ASSIGNMENT

1. Google and make a list of seven major categories of AM process, advantages and limitations of each process.
2. Point out the AM process which can manufacture metal parts.
 - Spoon → eating
 - Hydraulic Valve
 - Heart Valve

So, assignment- Google and make a list of seven major categories of additive manufacturing process, their advantages and limitations. Then, point out AM process which can manufacture metal parts like spoon, hydraulic wall, heart wall, so you just do Google search and try to figure out what process they use and you can see some videos and understand these spoons are for eating, this is used in the cosmetic industry or aesthetic industry. Thank you very much.