ADDITIVE MANUFACTURING

17ME82

MODULE 1

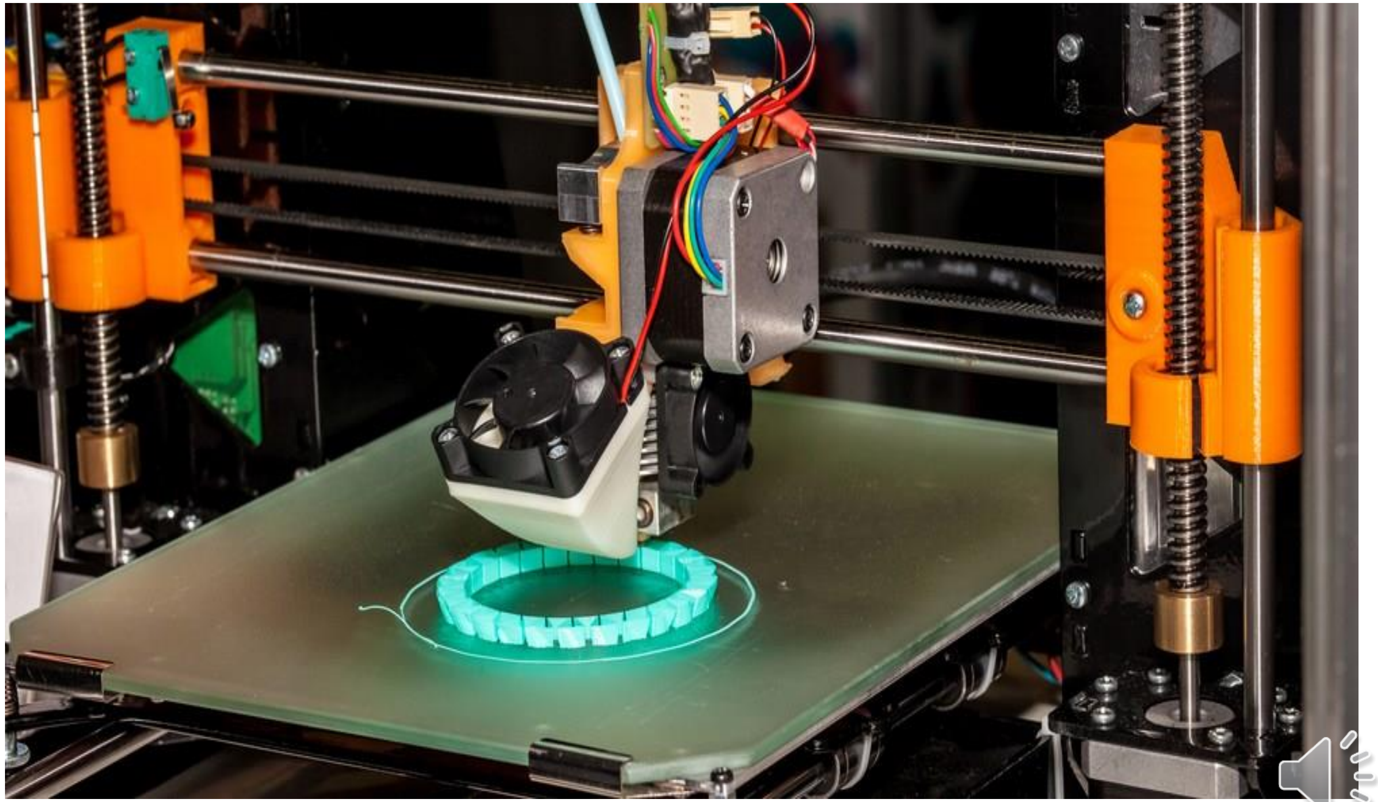
LECTURE 1

V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.



Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Content

What is Manufacturing?

subtractive manufacturing.

Additive manufacturing.

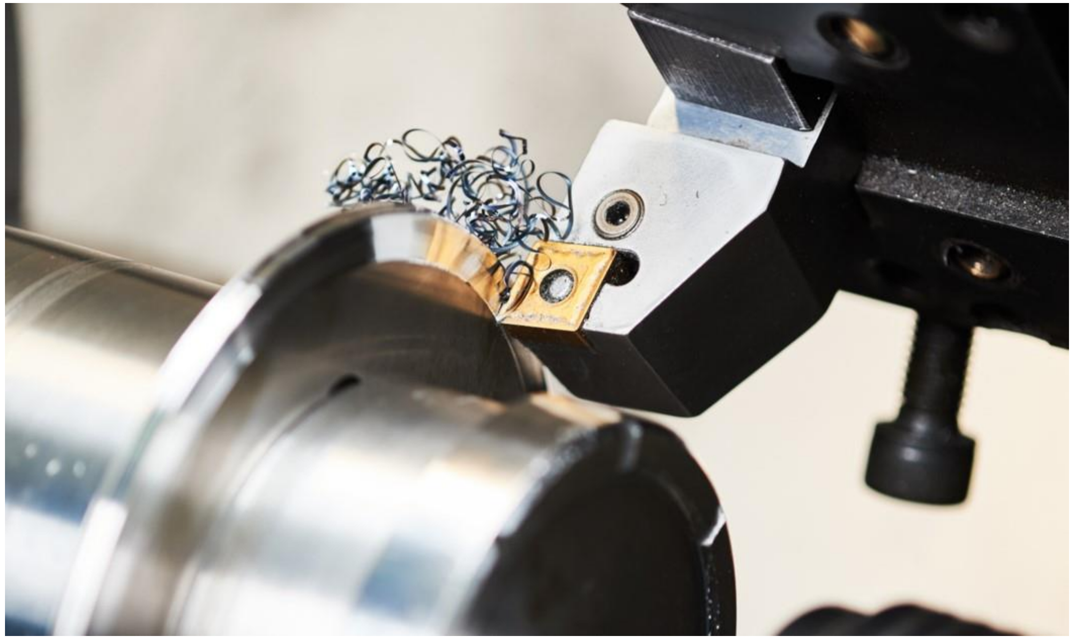
Difference between subtractive manufacturing and additive manufacturing.

What is Manufacturing?

- Manufacturing is the processing of raw materials or parts into finished goods through the use of tools, human labor, machinery, and chemical processing.
- Manufacturing processes can often be classified as either additive or subtractive.
- In both types of processes, companies build objects from materials.
- Materials can include plastics, thermoplastics, iron, steel, carbon and more.

What Is Subtractive Manufacturing?

- Subtractive manufacturing is process that involve building objects through the removal of materials. It often begins with a large piece of raw material. Companies then remove excess material from it so that it creates a new object in a smaller size and a different shape.
- **Example:** Turning and milling process are considered subtractive manufacturing processes.
- Turning is a form of cutting that specifically uses a rotary cutting tool to remove material from a workpiece. In comparison, milling uses a stationary cutting tool to remove material from a rotating workpiece. Since they both remove material from workpieces, turning and milling are considered subtractive manufacturing processes.



What Is Additive Manufacturing?

- Additive Manufacturing(AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing materials.

(from the International Committee F42 for Additive Manufacturing Technologies, ASTM)

- Involve building objects through the addition of materials. When a company builds an object by adding materials to it, it’s considered additive manufacturing. The materials are gradually added to a bed or substrate, allowing for the production of a new object in a different size and shape than that of the raw materials.
- Most additive manufacturing processes involve 3D printing. The term “additive manufacturing,” in fact, has become synonymous with 3D printing.
- 3D printers are machines that deposit material onto a print bed. Therefore, they build objects through the addition of materials. A typical 3D printer works by releasing extruded material out of a nozzle. It builds the base layer, after which it builds the next-highest level. The 3D printer will continue to build each individual layer until the object is completed.

Why Additive Manufacturing Is on the Rise

- While subtractive manufacturing isn’t expected to fade anytime soon, additive manufacturing has become increasingly popular among manufacturing companies.
- With additive manufacturing, companies can build objects while producing little or no waste. Subtractive manufacturing is more wasteful because it removes material from workpieces.
- Additive manufacturing is also a better choice for building objects in complex shapes. If a company is building an object in a complex shape, subtractive manufacturing processes may not work. Using a 3D printer or another additive manufacturing machine , companies can overcome this challenge.

History of 3D Printing:

1980-2000

- **80** First patent application for RP technology was filed by a Dr Kodama, in Japan, in May 1980.
- **86** The first patent was issued to Charles Hull for stereolithography apparatus (SLA).
- **87** SLA-1, was introduced.
- **89** SLS patent was issued to Carl Deckard.
- **90** EOS sold its first 'Stereos' system.
- **92** FDM patent was issued to Stratasys.
- **96** Sanders Prototype (later Solidscape) and ZCorporation were set up.
- **97** Arcam was established.
- **98** Objet Geometries launched.

The earliest 3D printing technologies first became visible in the late 1980's, at which time they were called Rapid Prototyping (RP) technologies. This is because the processes were originally conceived as a fast and more cost-effective method for creating prototypes for product development within industry.

1983 Charles Hull invents Stereolithography (SLA) Charles 'Chuck' Hull was the first to develop a technology for creating solid objects from a CAD/CAM file, inventing the process he termed 'stereolithography' in 1983. SLA works by curing and solidifying successive layers of liquid photopolymer resin using an ultraviolet laser. The field that came to be known variously as 'additive manufacturing', 'rapid prototyping' and '3D printing' was born.

2000-

- **00** MCP Technologies introduced the SLM technology.
- **02** EnvisionTec was founded.
- **04** Dr Bowyer conceived the RepRap concept of an open source, self-repli-cating 3D printer.
- **05** ExOne was established as a spin-off from the Extrude Hone Corpora-tion.
- **07** The first system under $10,000 from 3D Systems.
- **08** Desktop Factory was acquired by 3D Systems.
- **09** The first commercially available 3D printer – in kit form, based on the RepRap concept.
- **12** Alternative 3D printing processes were introduced at the entry level of the market.
- **13** Stratasys acquires Makerbot.

The AM value chain consists of five steps – AM system providers are active in most areas of the value chain

Material

Mainly: Creation of metal powder
> Powder with high purity and a very narrow distribution of the granular size (usually 30µm)
> Hard to get from large providers due to small orders
>Usually sold by AM system providers

Players:
> Höganäs
> TLS Technik
> San
> etc.

System

>Usually stand-alone powder bed fusion systems
> System providers with low levels of vertical integration, standard components usually made by contract manufacturers
> Providers integrate components system & software

Players:
> EOS
> SLM Solutions
> Concept Laser
> etc.

Software

>Differentiation between process control and enhancement software
> Process control from system prov.
> Add-on software such as automatic support generation, design optimization By specialized companies

Players:
> Materialise
> netfabb
> With
> etc.

Application design

> Support for end customers
> Can be complex and demanding
> Done by system providers, software developers and/or service providers
> Not every service provider is able to design applications

Players:
> 3T PRD
> Concept Laser
> EOS
> etc.

Production

>Different produc-tion scenarios:
- Large OEM
- Contract manu-facturer/service provider
- Specialized part manufacturer
> Production is normally not done by AM System providers

Players:
> 3T PRD
> Janke Engin.
> Layer Wise
> etc.

Distinction between AM & CNC machining

- CNC machining and additive manufacturing are both computer-controlled solutions to making products out of a given material.

1. Precision of Production

CNC machining is more precise and consistent than 3D printing.

because they have a higher tolerance for heat. 3D printers end up with distorted products when there's too much heat. They can offer precision but cannot remain consistent. 3D printers are often regarded as more user-friendly than CNC machines, but when they malfunction, someone has to troubleshoot them because the fault means production of unusable products.

2. **Speed of Production**

CNC is a faster solution than 3D printing.

Automated CNC machines can work around the clock as long as they're properly maintained.

A project that could take CNC machining an hour would equate to a 3D printer taking hours to get the final product because it has to build the product layer by layer.

Distinction between AM & CNC machining

3. Versatility of Machinery

When testing prototypes for a project, a CNC machine could quickly build a design so the developers can test it. 3D printers don’t have these kinds of options. It will slowly shape the design as it was programmed.

4. Noise and Mess Produced

. CNC machining is much noisier and messier than 3D printing because it uses a tool to cut away material. This creates noise and a lot of scrap metal or wood shavings. CNC machines cause a lot of vibrations, so they need to be in a space where they won’t bother anyone. 3D printing only uses the material it needs for the product. There’s little to no waste, and the printers don’t vibrate like a CNC machine.

Distinction between AM & CNC machining

5. Material Usage

CNC machining works with a variety of materials.

They can use:

- Metal alloys
- Woods
- Acrylic
- Modeling foam
- Thermoplastics
- Machining wax

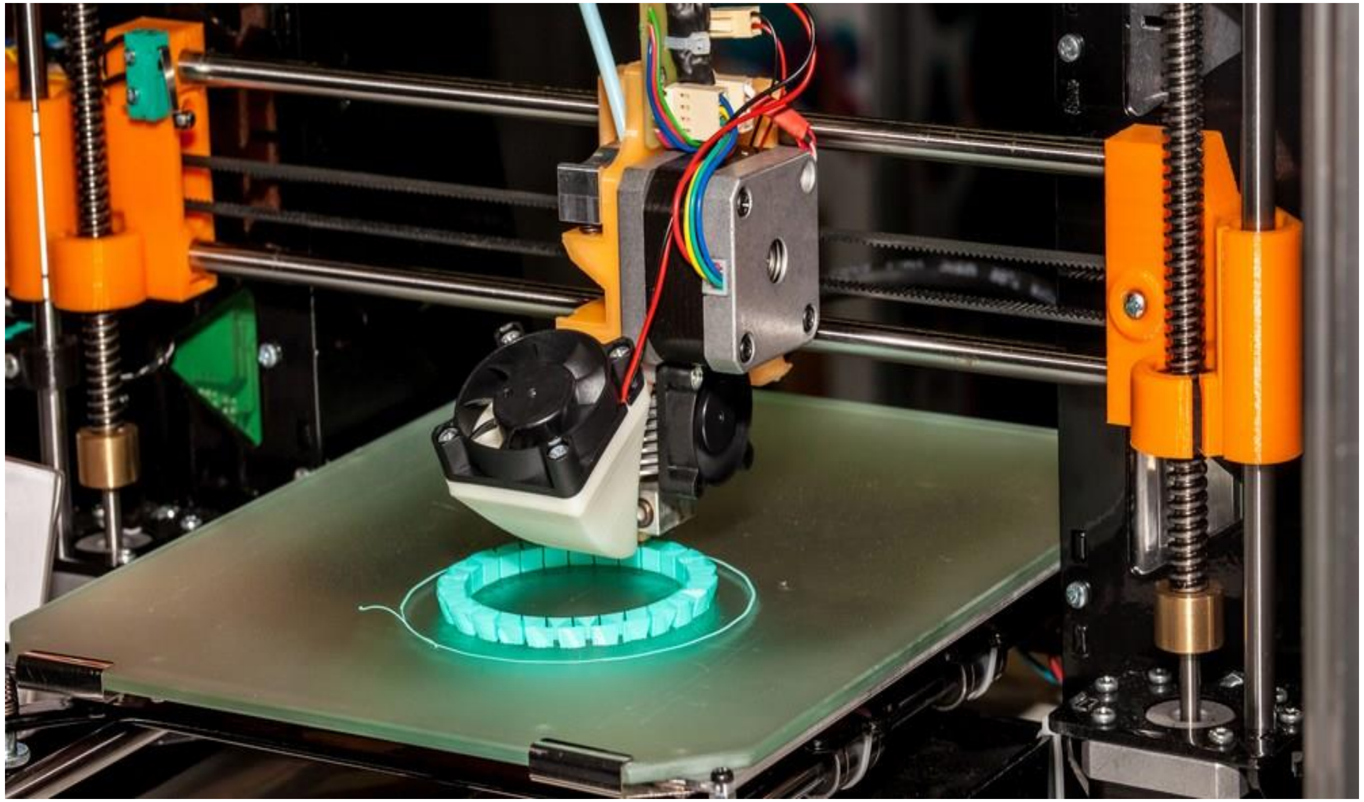
These materials are used to build substantial parts for engines, aircraft and other machines. They need to be exact, dependable and durable. The cutting tools for the design might have to switch, but most tools are standardized to fit any CNC machine.

3D printing doesn’t have this variety, using materials like plastics or resins. They can’t produce items strong enough to withstand intense environments like airplanes or other machinery. Also, 3D printers can’t switch between materials. Certain 3D printers are for specific kinds of material.

Advantages of AM

- Increased design freedom versus conventional casting and machining
- Light weight structures, made possible either by the use of lattice design or by designing parts where material is only where it needs to be, without other constraints
- New functions such as complex internal channels or several parts built in one
- Net shape process meaning less raw material consumption, up to 25 times less versus machining, important in the case of expensive or difficult to machine alloys. The net shape capability helps creating complex parts in one step only thus reducing the number of assembly operations such as welding, brazing.
- No tools needed, unlike other conventional metallurgy processes which require molds and metal forming or removal tools
- Short production cycle time: complex parts can be produced layer by layer in a few hours in additive machines. The total cycle time including post processing usually amounts to a few days or weeks and it is usually much shorter than conventional metallurgy processes which often require production cycles of several months.

ADDITIVE MANUFACTURING
17ME82
MODULE 1
LECTURE 2



V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.

Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

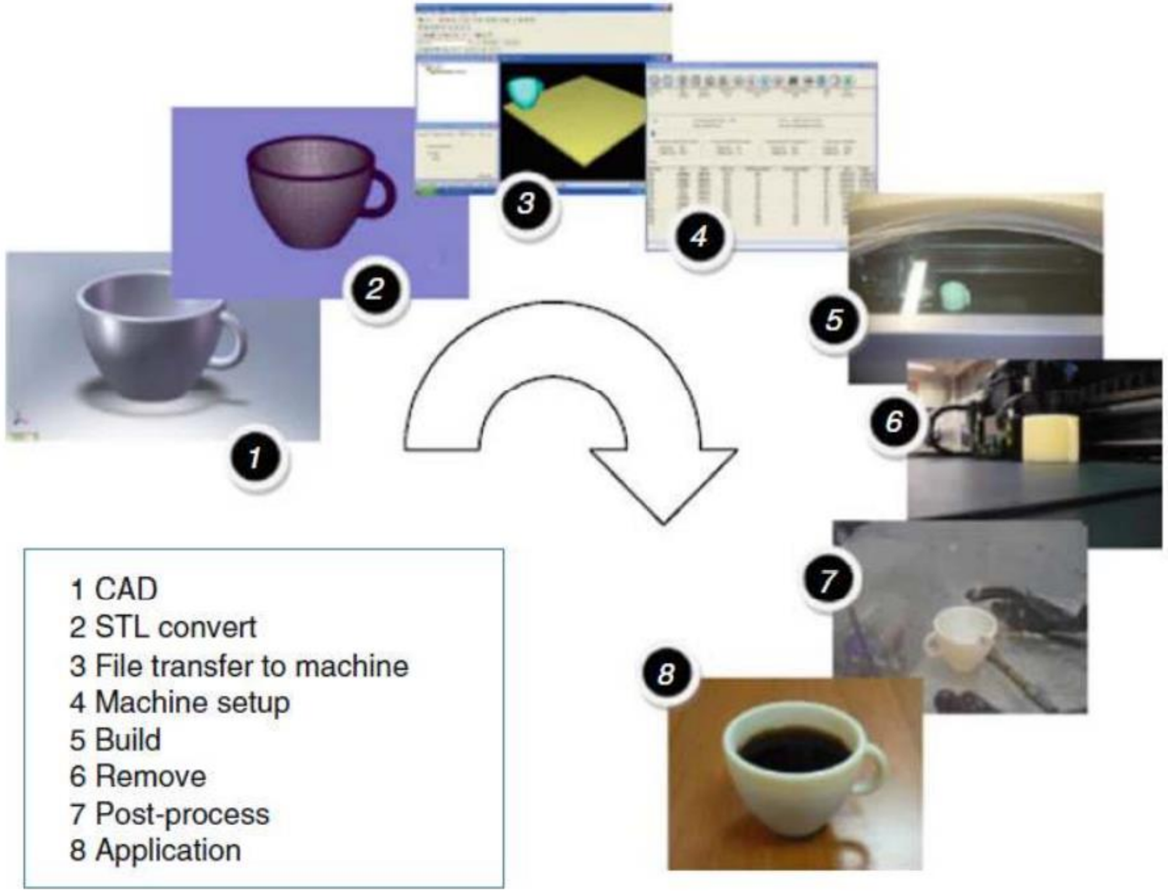
Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

AM process chain

AM process chain

1. Conceptualization & Generation of CAD model of the design
2. Conversion of CAD model into AM acceptable machine format (STL format)
3. File transfer to machine
4. Machine set up
5. build
6. Part removal
7. Post processing
8. Application



Source: Gibson, Additive Manufacturing

STEP 1:conceptilization & Generation of Computer-Aided Design Model of Design

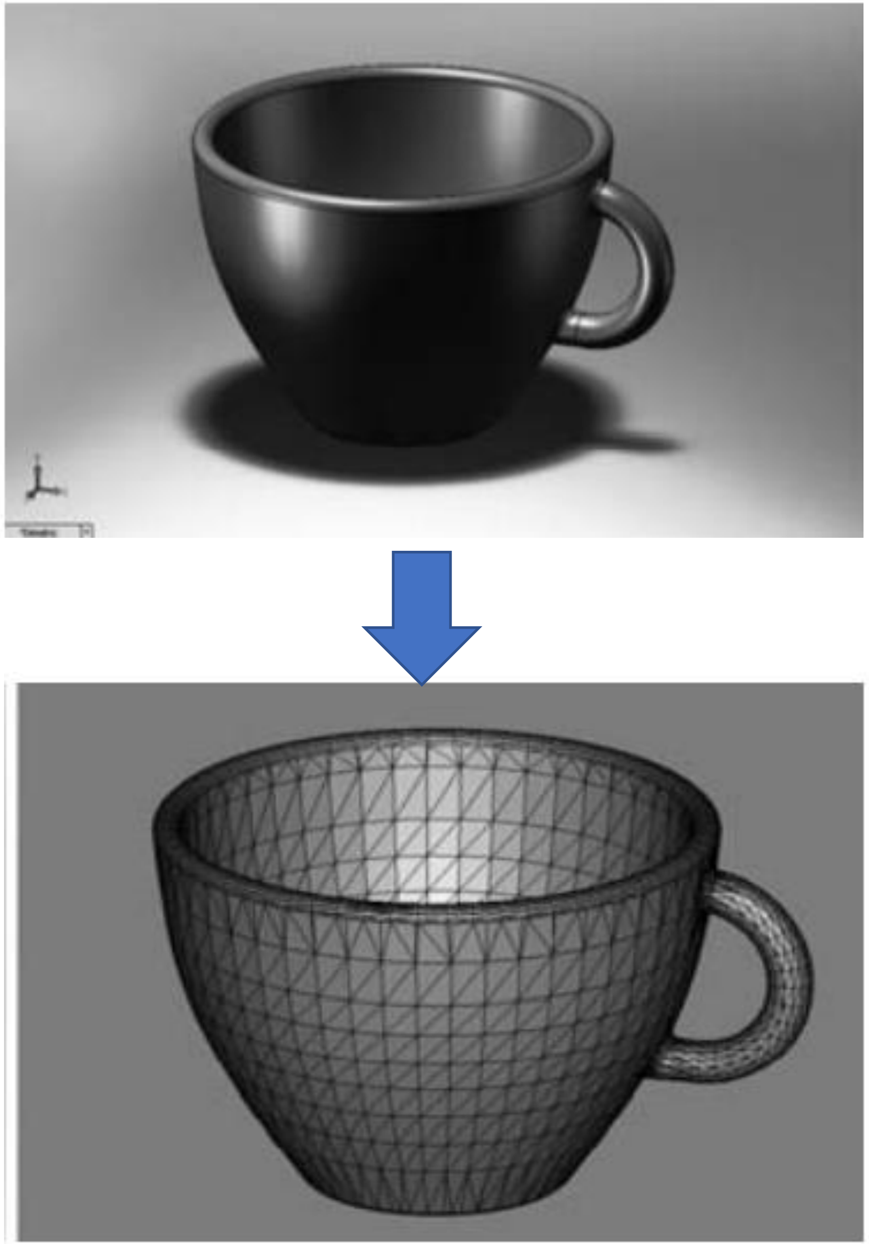
- The first step in any product development process is to come up with an idea for how the product will look and function. Conceptualization can take many forms, from textual and narrative descriptions to sketches and representative models.
- If AM is to be used, the product description must be in a digital form that allows a physical model to be made.

STEP 1:Generation of Computer-Aided Design Model of Design

- The AM process chains start with 3D CAD modeling- Computer Aided Design.
- The process of producing a 3D CAD model from an idea in the designer's mind can take on many forms, but all requires CAD software programs.
- There are a large number of CAD programs with different modeling principles, capabilities, accessibilities, and cost.
- Examples: Autodesk Inventor, Solid works, Creo, NX(Unigraphics), etc

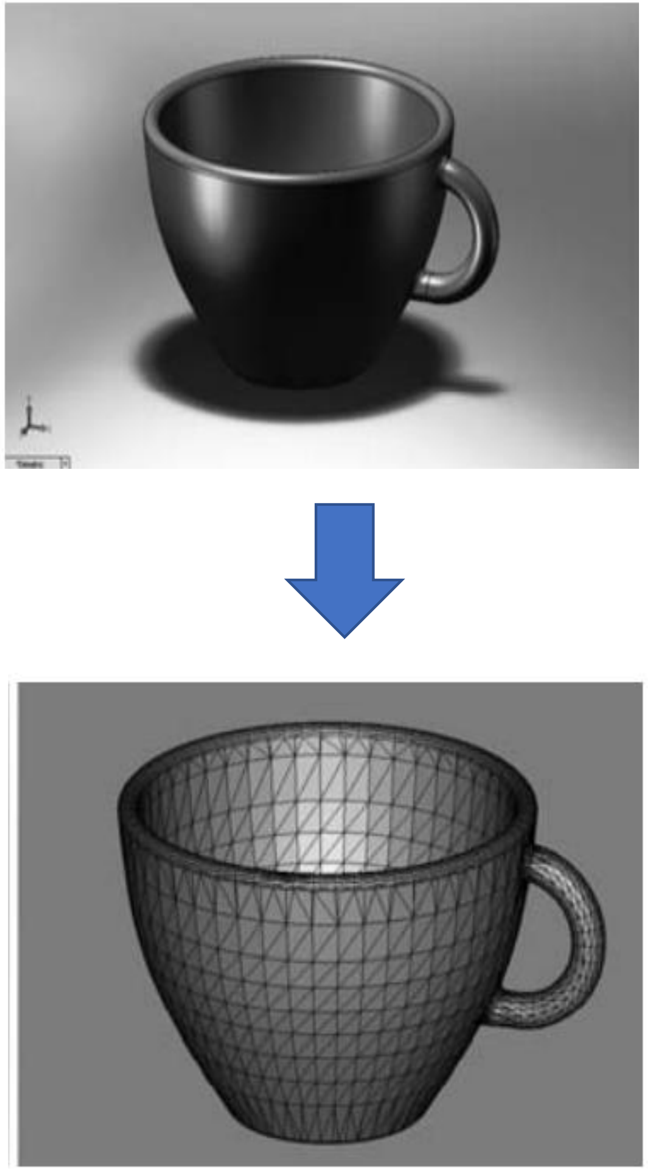
STEP 2: Conversion of CAD Model into AM Machine Acceptable Format

- Almost all AM technology available today uses the ***Stereolithography (STL)*** file format.
- The term STL was derived from *Stereolithograhy*, which was the first commercial AM technology from 3D Systems in the 1990s.
- STL is a simple way of describing a CAD model in terms of its geometry alone.
- The STL format of a 3D CAD model captures all surfaces of the 3D model by means of stitching triangles of various sizes on its surfaces.



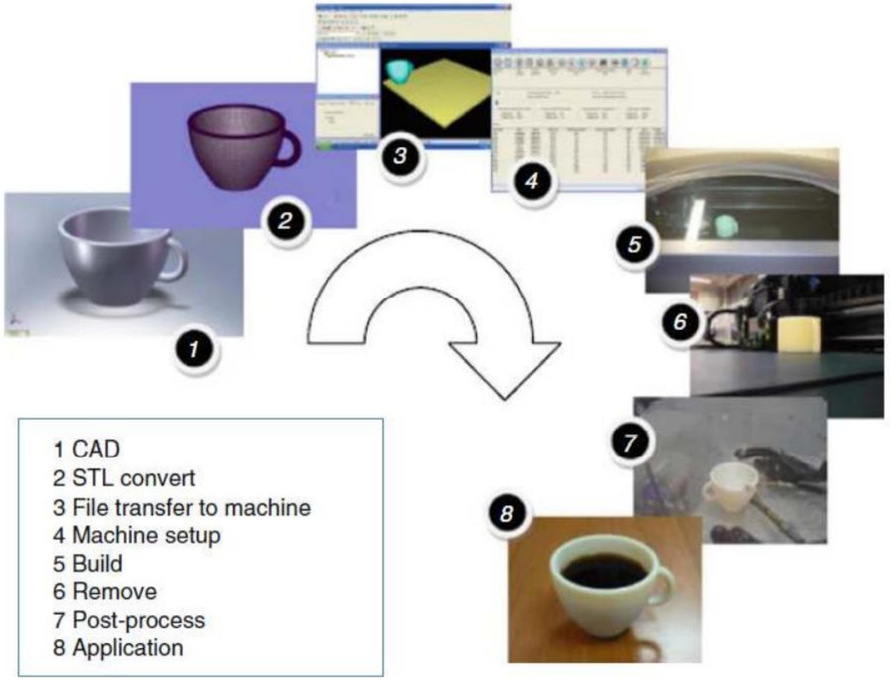
STEP 2: Conversion of CAD Model into AM Machine Acceptable Format

- The process of converting to STL is automatic within most CAD systems, but there is a possibility of errors occurring during this phase. There have therefore been a number of software tools developed to detect such errors and to rectify them if possible.
- STL files are an unordered collection of triangle vertices and surface normal vectors. As such, an STL file has no units, color, material, or other feature information. These limitations of an STL file have led to the recent adoption of a new “AMF” file format. This format is now an international ASTM/ISO standard format which extends the STL format to include dimensions, color, material, and many other useful features.
- STL file repair software, like the MAGICS software from the Belgian company Materialise, is used when there are problems with the STL file that may prevent the part from being built correctly. With complex geometries, it may be difficult for a human to detect such problems when inspecting the CAD or the subsequently generated STL data.



STEP 3: File transfer to machine & STL file manipulation.

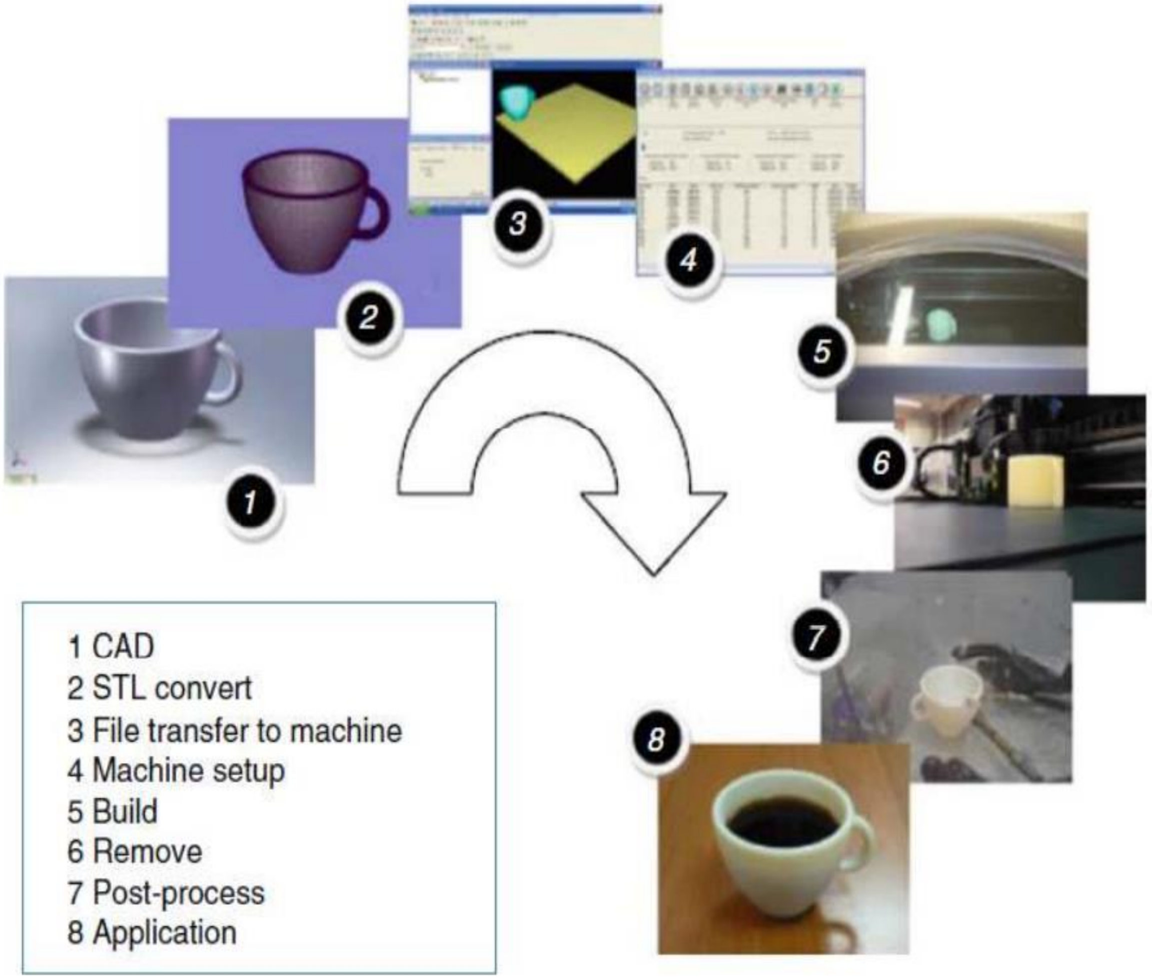
- The STL file describing the part must be transferred to the AM machine. Here, there may be some general manipulation of the file so that it is the correct size, position, and orientation for building.
- The needed information varies, depending on the technology but in general these steps start with repairing any errors within the STL file. Typical errors can be gaps between surface triangle facets, inverted normal where the "wrong side" of a triangle facet is identified as the interior of the part.



Source: Gibson, Additive Manufacturing

STEP 3: File transfer to machine & STL file manipulation.

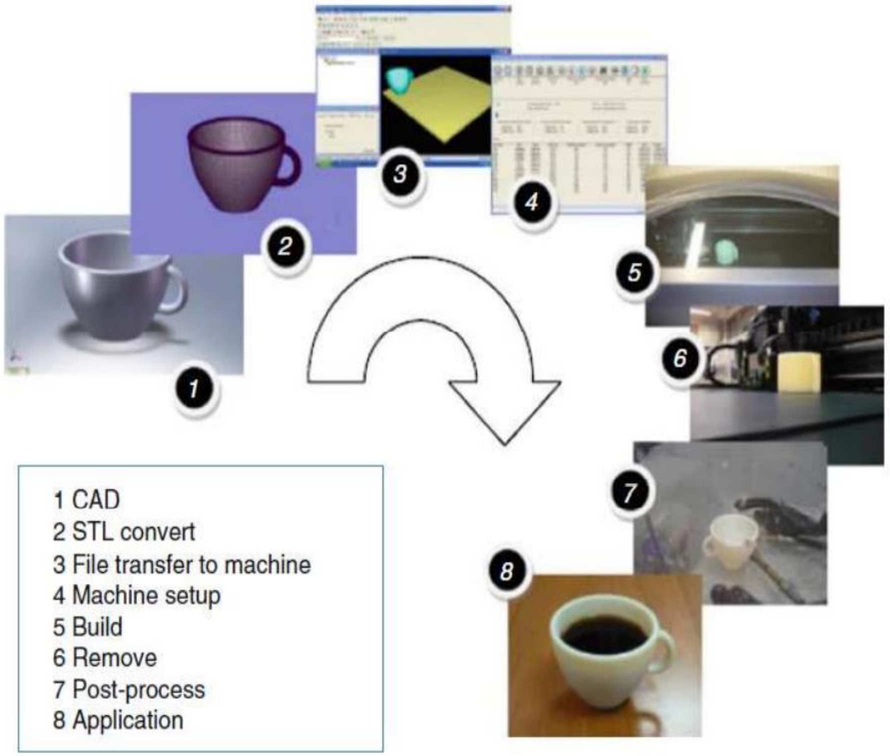
- The first task would be to verify that the part is correct. AM system software normally has a visualization tool that allows the user to view and manipulate the part.
- The user may wish to reposition the part or even change the orientation to allow it to be built at a specific location within the machine.



Source: Gibson, Additive Manufacturing

Step 4: Machine Setup

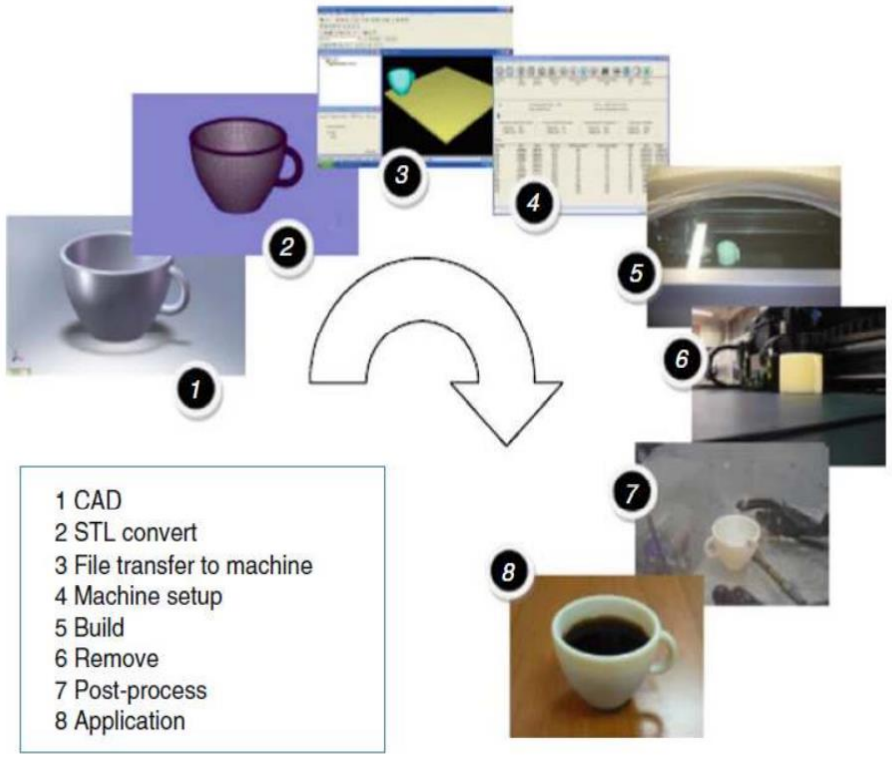
- The AM machine must be properly set up prior to the build process. Such settings would relate to the build parameters like the material constraints, energy source, layer thickness, timings, etc.
- All AM machines will have at least some setup parameters that are specific to that machine or process. Some machines are only designed to run a few specific materials and give the user few options to vary layer thickness or other build parameters.
- In addition to setting up machine software parameters, most machines must be physically prepared for a build. The operator must check to make sure sufficient build material is loaded into the machine to complete the build.
- For machines which use powder, the powder is often sifted and subsequently loaded and leveled in the machine as part of the setup operation. For processes which utilize a build plate, the plate must be inserted and leveled with respect to the machine axes. Some of these machine setup operations are automated as part of the start-up of a build, but for most machines these operations are done manually by a trained operator.



Source: Gibson, Additive Manufacturing

Step 5: Build

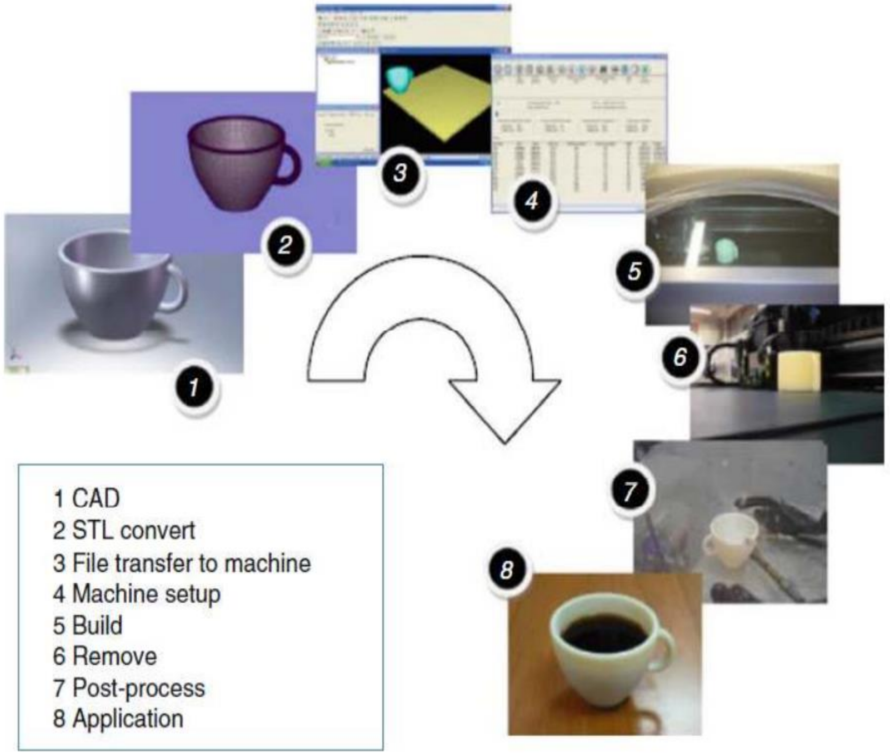
- Building the part is mainly an automated process and the machine can largely carry on without supervision. Only superficial monitoring of the machine needs to take place at this time to ensure no errors have taken place like running out of material, power or software glitches, etc.
- Although benefitting from the assistance of computers, the first few stages of the AM process are semiautomated tasks that may require considerable manual control, interaction, and decision making.
- Once these steps are completed, the process switches to the computer-controlled building phase. This is where the previously mentioned layer-based manufacturing takes place.
- All AM machines will have a similar sequence of layering, including a height adjustable platform or deposition head, material deposition/spreading mechanisms, and layer cross-section formation.



Source: Gibson, Additive Manufacturing

Step 6: Removal & clean-up

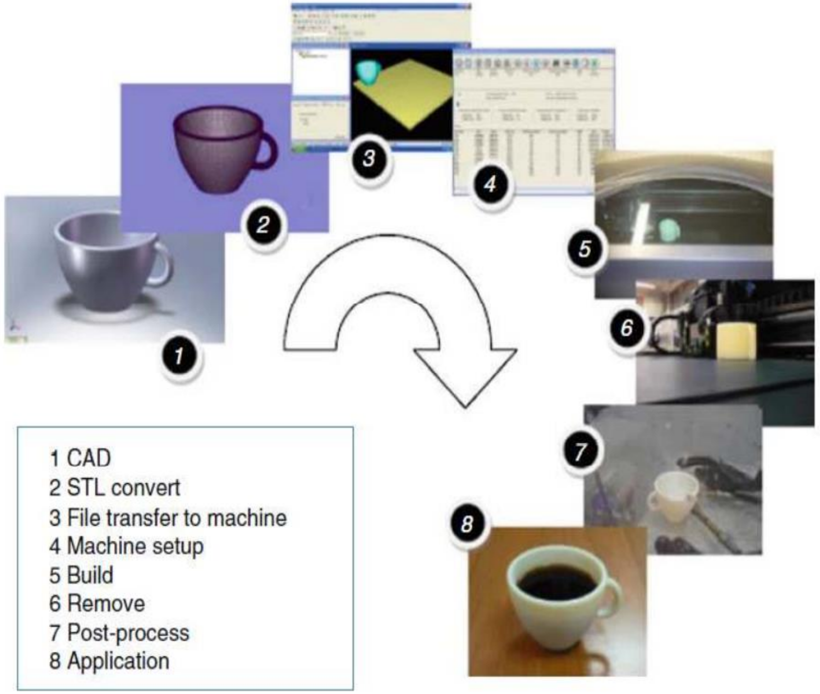
- Once the AM machine has completed the build, the parts must be removed. This may require interaction with the machine, which may have safety interlocks to ensure for example that the operating temperatures are sufficiently low or that there are no actively moving parts.
- Ideally, the output from the AM machine should be ready for use with minimal manual intervention. While sometimes this may be the case, more often than not, parts will require a significant amount of post-processing before they are ready for use.
- In all cases, the part must be either separated from a build platform on which the part was produced or removed from excess build material surrounding the part.



Source: Gibson, Additive Manufacturing

Step 7: Post-processing

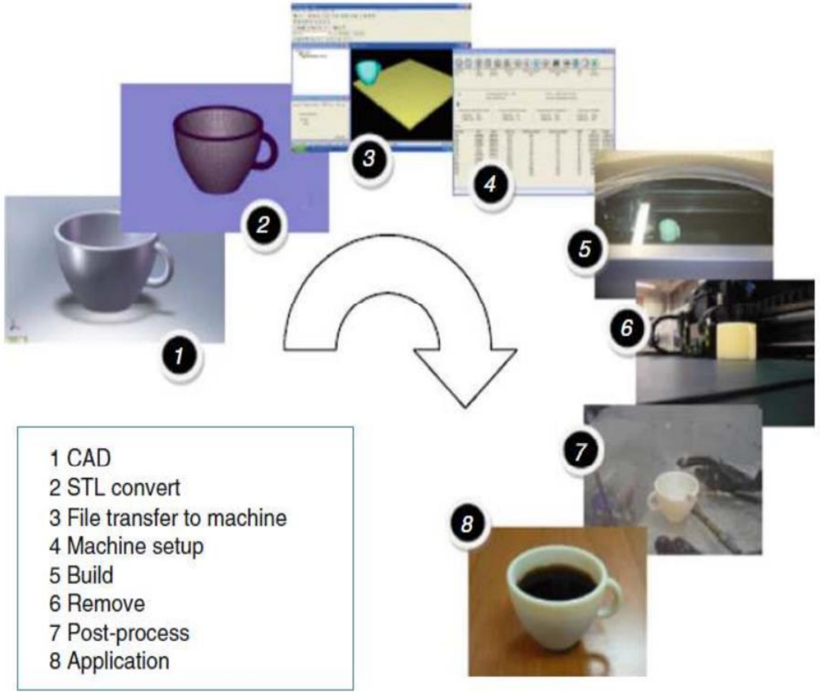
- Once removed from the machine, parts may require an amount of additional cleaning up before they are ready for use. Parts may be weak at this stage or they may have supporting features that must be removed. This therefore often requires time and careful, experienced manual manipulation.
- Post-processing refers to the (usually manual) stages of finishing the parts for application purposes. This may involve abrasive finishing, like polishing and sandpapering, or application of coatings.
- This stage in the process is very application specific. Some applications may only require a minimum of post-processing. Other applications may require very careful handling of the parts to maintain good precision and finish.
- Some post-processing may involve chemical or thermal treatment of the part to achieve final part properties.
- Different AM processes have different results in terms of accuracy, and thus machining to final dimensions may be required. Some processes produce relatively fragile components that may require the use of infiltration and/or surface coatings to strengthen the final part.



Source: Gibson, Additive Manufacturing

Step 8: Application

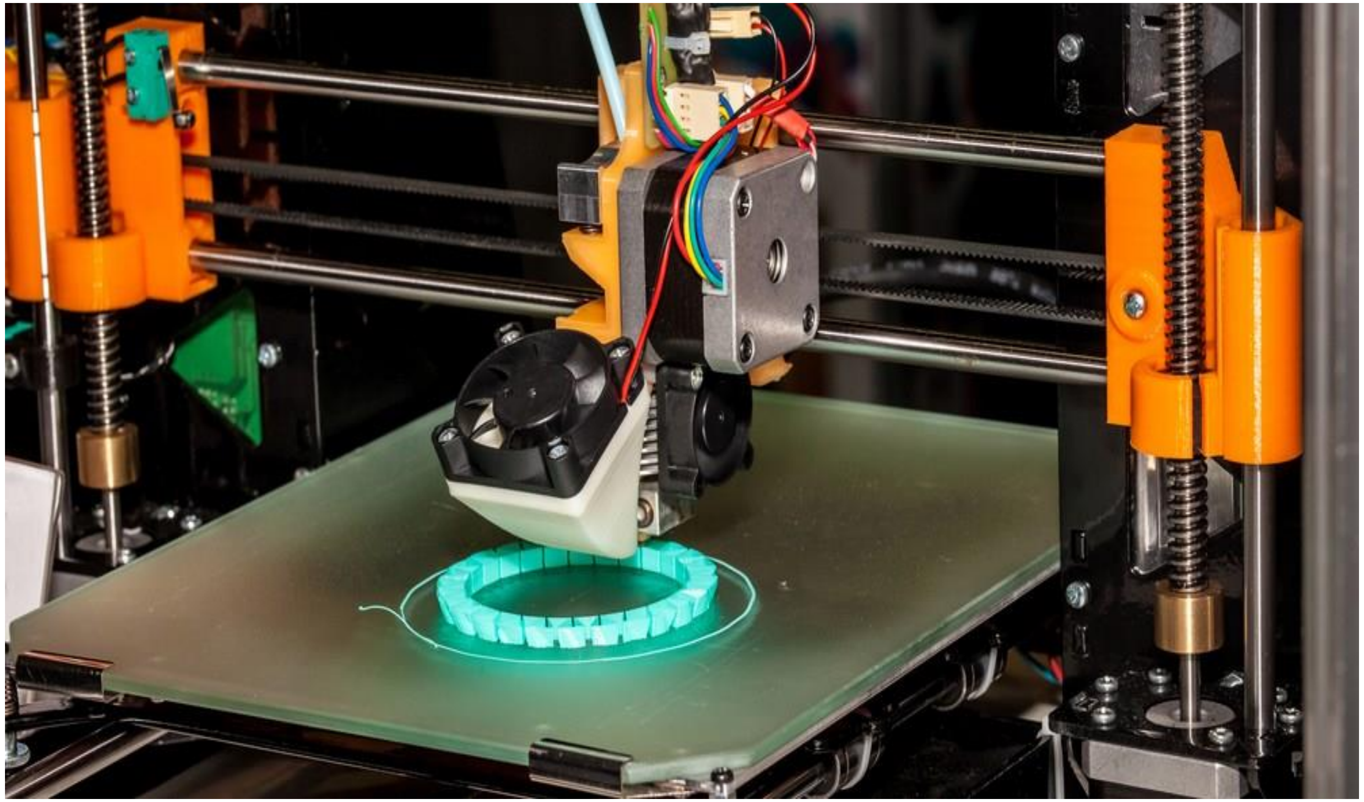
- Following post-processing, parts are ready for use. It should be noted that, although parts may be made from similar materials to those available from other manufacturing processes (like molding and casting), parts may not behave according to standard material specifications.
- For most metal AM processes, rapid cooling results in different microstructures than those from conventional manufacturing. As a result, AM produced parts behave differently than parts made using a more conventional manufacturing approach. This behavior may be better or worse for a particular application, and thus a designer should be aware of these differences and take them into account during the design stage.



Source: Gibson, Additive Manufacturing

ADDITIVE MANUFACTURING
17ME82
MODULE 1
LECTURE 3

V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.



Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Content

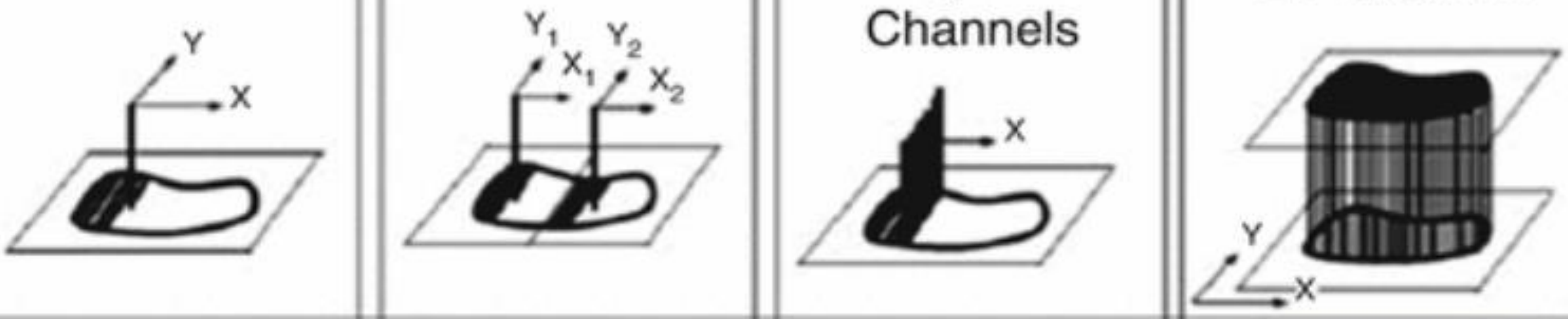
Classification of AM processes:

- ➢Liquid polymer system.
- ➢ Discrete particle system.
- ➢ Molten material systems.
- ➢ Solid sheet system.
- ➢Materials
- ➢Risk

Source: Gibson, Additive manufacturing

Classification of AM processes

- There are numerous ways to classify AM technologies. A popular approach is to classify according to *baseline technology*, like whether the process uses lasers, printer technology, extrusion technology, etc.
- Another approach is to collect processes together according to the type of *raw material input.*
- The problem with these classification methods is that some processes get lumped together in what seems to be odd combinations (like Selective Laser Sintering (SLS) being grouped together with 3D Printing) or that some processes that may appear to produce similar results end up being separated (like Stereolithography and material jetting with photopolymers). It is probably inappropriate, therefore, to use a single classification approach.
- An excellent and comprehensive classification method is described by Pham, which uses a two dimensional classification method as shown in Fig(next slide).



	1D Channel	2x1D Channels	Array of 1D Channels	2D Channel
Liquid Polymer	SLA (3D Sys)	Dual beam SLA (3D Sys)	Objet	Envisiontech MicroTEC
Discrete Particles	SLS (3D Sys), LST (EOS), LENS Phenix, SDM	LST (EOS)	3D Printing	DPS
Molten Mat.	FDM, Solidscape		ThermoJet	
Solid Sheets	Solido PLT (KIRA)			

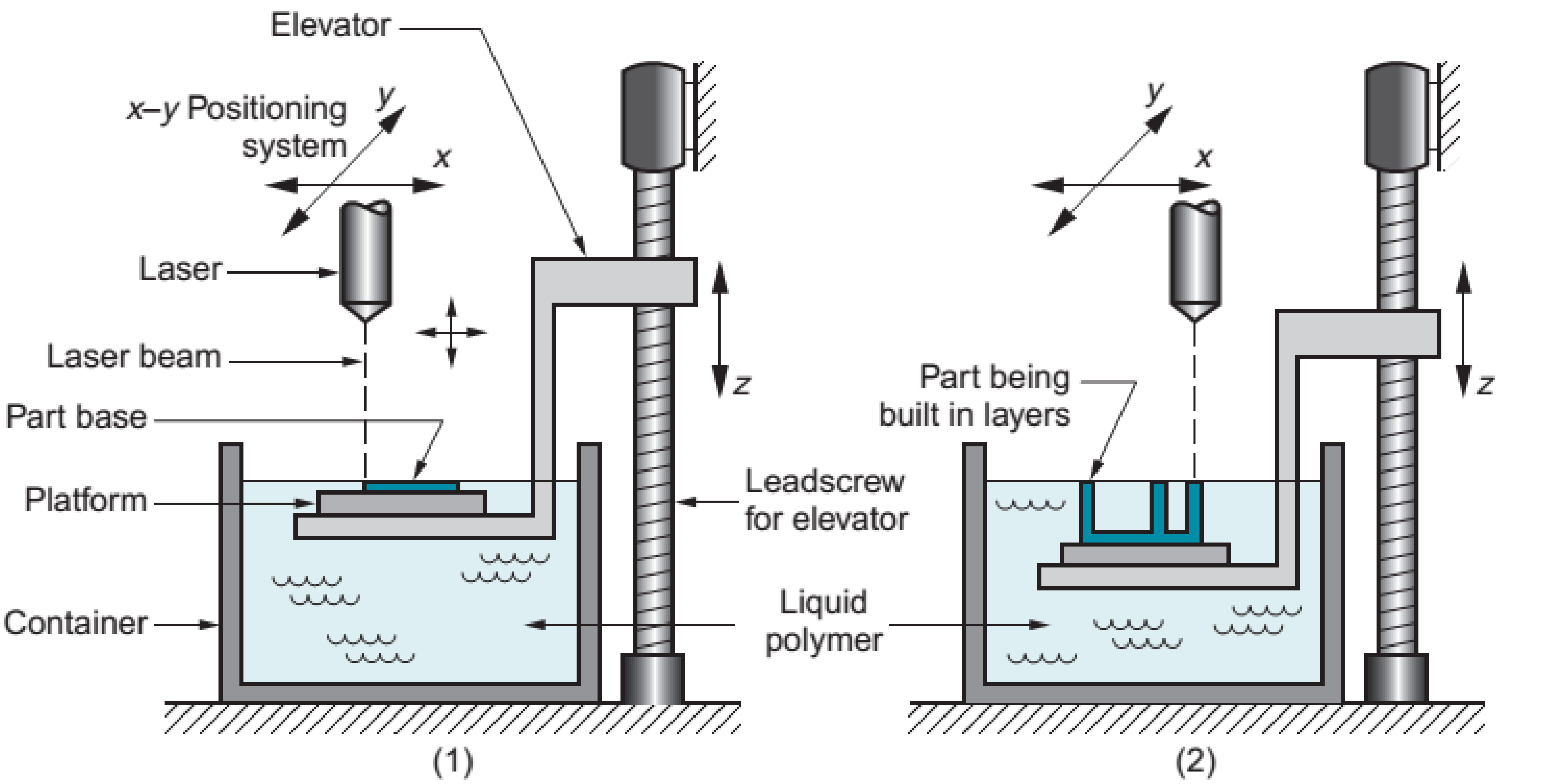
Liquid polymer system.

- liquid polymers appear to be a popular material.
- The first commercial system was the 3D Systems *Stereolithography process* based on liquid photopolymers.
- A large portion of systems in use today are, in fact, not just liquid polymer systems but more specifically ***liquid photopolymer*** systems.

STEREOLITHOGRAPHY

- One of the most important additive manufacturing technologies currently available.
- The first ever commercial RP systems were resin-based systems commonly called stereolithography or SLA.
- The resin is a liquid photosensitive polymer that cures or hardens Stereolithography when exposed to ultraviolet radiation.
- This technique involves the curing or solidification of a liquid photosensitive polymer through the use of the irradiation light source.
- The source supplies the energy that is needed to induce a chemical reaction (curing reaction), bonding large no of small molecules and forming a highly cross-linked polymer.
- The UV light comes from a laser, which is controlled to scan across the surface according to the cross-section of the part that corresponds to the layer.
- The laser penetrates into the resin for a short distance that corresponds to the layer thickness.
- The first layer is bonded to a platform, which is placed just below the surface of the resin container.
- The platform lowers by one-layer thickness and the scanning is performed for the next layer. This process continues until the part has been completed.

Stereolithography



Stereolithography

- **How layer by layer adhesion takes place in stereolithography?**
  - The new layer adheres to the previous one because the depth of penetration of each pulse of laser is greater than the thickness of the layer and hence over cures the prior layer.
  - This process is repeated as many times as is necessary to recreate the entire object layer by layer. When completed, the platen is raised from the vat and the model is ready for removal of the support structure and post curing.

DISCRETE PARTICLES SYSTEM

- Discrete particles are normally *powders* that are generally graded into a relatively uniform particle size and shape and narrow size distribution.
- The finer the particles the better, but there will be problems if the dimensions get too small in terms of controlling the distribution and dispersion.
- Again, the conventional 1D channel approach is to use a laser, this time to produce thermal energy in a controlled manner and, therefore, raise the temperature sufficiently to melt the powder.
- Application of printer technology to powder beds resulted in the (original) 3D Printing (3DP) process. This technique was developed by researchers at MIT in the USA.
- This basic technique has been developed for different applications dependent on the type of powder and binder combination.
- The most successful approaches use low-cost, starchand plaster-based powders with inexpensive glues, as commercialized by ZCorp, USA, which is now part of 3D Systems..
- Ceramic powders and appropriate binders as similarly used in the *Direct Shell Production Casting (DSPC)* process used by Soligen as part of a service to create shells for casting of metal parts.

MOLTEN MATERIAL SYSTEMS

- Molten material systems are characterized by a pre-heating chamber that raises the material temperature to melting point so that it can flow through a delivery system.
- The most well-known method for doing this is the ***Fused Deposition Modeling (FDM)*** material extrusion technology developed by the US company *Stratasys*.
- This approach extrudes the material through a nozzle in a controlled manner. Two extrusion heads are often used so that support structures can be fabricated from a different material to facilitate part cleanup and removal.
- Printer technology has also been adapted to suit this material delivery approach. One technique, developed initially as the Sanders prototyping machine, that later became Solidscape, USA and which is now part of Stratasys, is a 1D channel system.

Molten material systems

- A single jet piezoelectric deposition head lays down wax material. Another head lays down a second wax material with a lower melting temperature that is used for support structures.
- The droplets from these print heads are very small so the resulting parts are fine in detail.
- To further maintain the part precision, a planar cutting process is used to level each layer once the printing has been completed.
- Supports are removed by inserting the complete part into a temperature-controlled bath that melts the support material away, leaving the part material intact.
- The use of wax along with the precision of Solidscape machines makes this approach ideal for precision casting applications like *jewelry, medical devices, and dental castings.*

Molten material systems

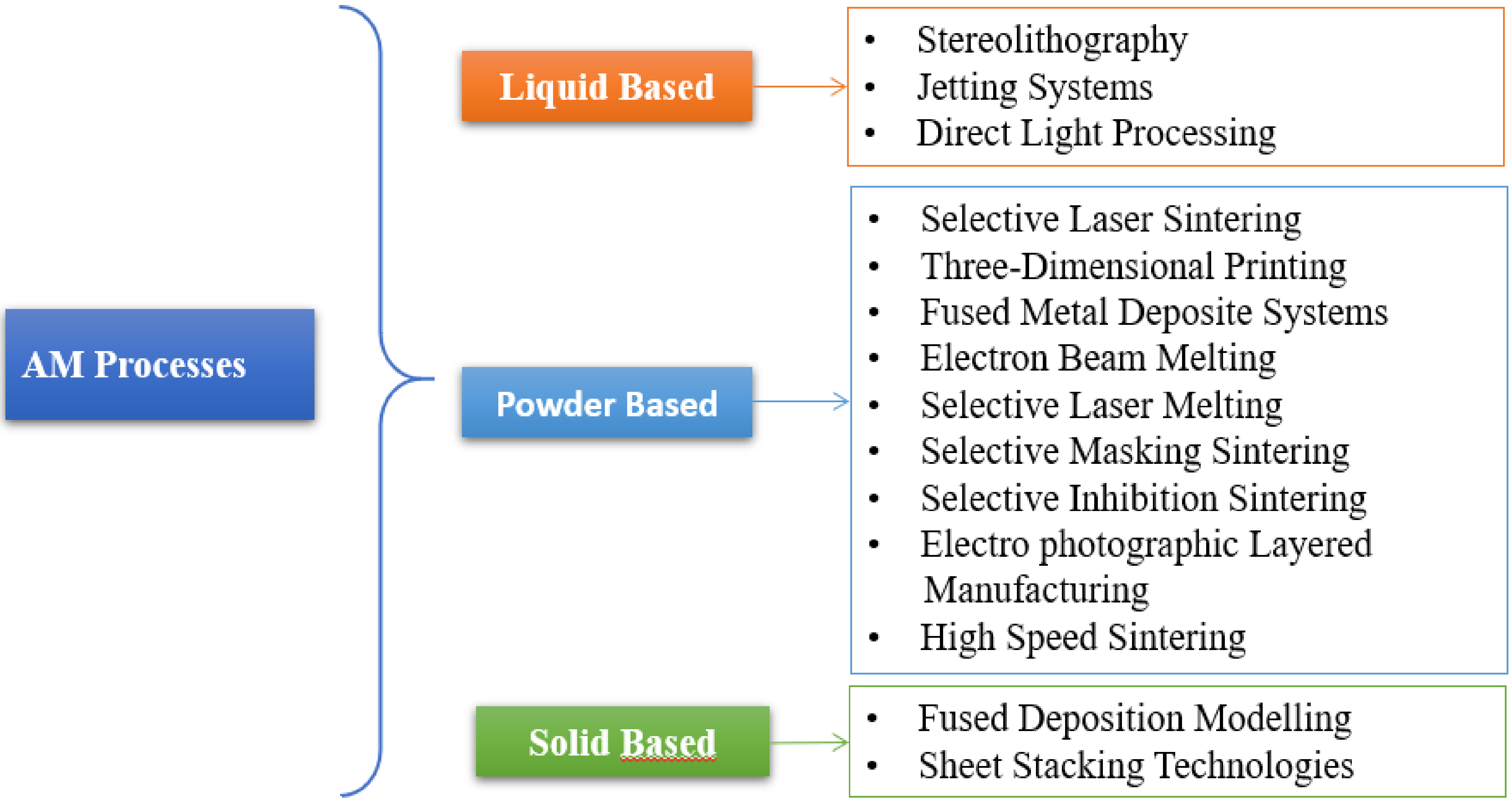
- The 1D channel approach, however, is very slow in comparison with other methods and applying a parallel element does significantly improve throughput.
- The ***Thermojet technology*** from 3D Systems also deposits a wax material through droplet-based printing heads.
- The use of parallel print heads as an array of 1D channels effectively multiplies the deposition rate.
- The Thermojet approach, however, is not widely used because wax materials are difficult and fragile when handled.
- Thermojet machines are no longer being made, although existing machines are commonly used for investment casting patterns.

SOLID SHEET SYSTEM

- One of the earliest AM technologies was the Laminated Object Manufacturing (LOM) system from Helisys, USA.
- This technology used a laser to cut out profiles from sheet paper, supplied from a continuous roll, which formed the layers of the final part.
- Layers were bonded together using a heat-activated resin that was coated on one surface of the paper.
- Once all the layers were bonded together the result was very much like a wooden block.
- A hatch pattern cut into the excess material allowed the user to separate away waste material and reveal the part.

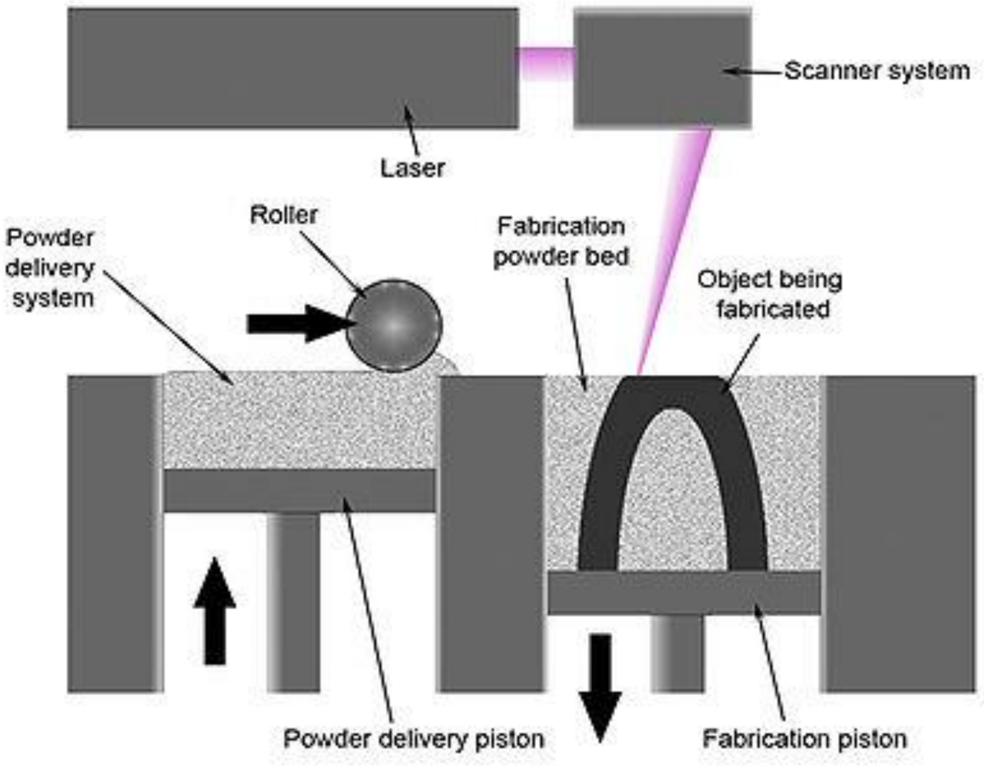
Solid sheet system

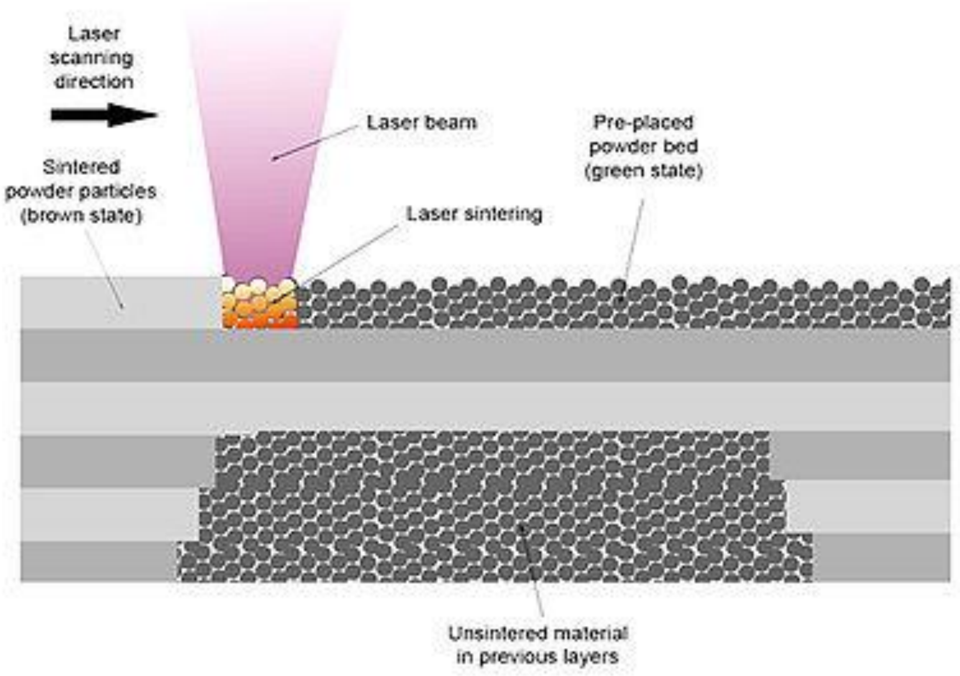
- A similar approach was used by the Japanese company Kira, in their Solid Center machine, and by the Israeli company Solidimension with their Solido machine.
- The major difference is that both these machines cut out the part profile using a blade similar to those found in vinyl sign making machines, driven using a 2D plotter drive.
- The Kira machine used a heat-activated adhesive applied using laser printing technology to bond the paper layers together.
- Both the Solido and Kira machines have been discontinued for reasons like poor reliability material wastage and the need for excessive amounts of manual post-processing.
- Recently, however, Mcor Technologies have produced a modern version of this technology, using low-cost color printing to make it possible to laminate color parts in a single process


AM Processes
Liquid Based
Stereolithography
Jetting Systems
Direct Light Processing
Powder Based
Selective Laser Sintering
Three-Dimensional Printing
Fused Metal Deposite Systems
Electron Beam Melting
Selective Laser Melting
Selective Masking Sintering
Selective Inhibition Sintering
Electro photographic Layered Manufacturing
High Speed Sintering
Solid Based
Fused Deposition Modelling
Sheet Stacking Technologies

SELECTIVE LASER SINTERING (SLS)

- The SLS process was developed and patented in the 1980s by Carl Deckard — then an undergraduate student at the University of Texas — and his mechanical engineering professor, Joe Beaman.
- Deckard and Beaman were involved in the founding of one of the first 3D printing startups, Desk Top Manufacturing (DTM) Corp., in 1989. In 2001, DTM was sold to 3D Systems, a company that had previously developed its own, though much different, method of 3D printing known as stereolithography.





SELECTIVE LASER SINTERING (SLS)

WORKING OF SLS

- Like all methods of 3D printing, an object printed with an SLS machine starts as a computer-aided design (CAD) file. CAD files are converted to STL format, which can be understood by a 3D printing apparatus.
- Objects printed with SLS are made with *powder materials*, most commonly plastics, such as nylon, which are dispersed in a thin layer on top of the build platform inside an SLS machine.
- A laser, which is controlled by a computer that tells it what object to "print," pulses down on the platform, tracing a cross-section of the object onto the powder.
- The laser heats the powder either to just below its boiling point (sintering) or above its boiling point (melting), which fuses the particles in the powder together into a solid form.
- Once the initial layer is formed, the platform of the SLS machine drops — usually by less than 0.1mm — exposing a new layer of powder for the laser to trace and fuse together. This process continues again and again until the entire object has been printed.
- When the object is fully formed, it is left to cool in the machine before being removed.

SELECTIVE LASER SINTERING (SLS)

- **Advantages:**
  - Unlike other methods of 3D printing, SLS requires very little additional tooling once an object is printed, meaning that objects don't usually have to be sanded or otherwise altered once they come out of the SLS machine.
  - SLS doesn't require the use of additional supports to hold an object together while it is being printed. Such supports are often necessary with other 3D printing methods, such as stereolithography or fused deposition modeling, making these methods more time-consuming than SLS.
  - SLS machines can print objects in a variety of materials, such as plastics, glass, ceramics and even metal (which is a related process known as direct metal laser sintering). This makes it a popular process for creating both prototypes as well as final products.
  - Using SLS, companies can create prototypes that are stored digitally as .STL files, which they can redesign or reprint as needed.

SELECTIVE LASER SINTERING (SLS)

- **Applications:**
  1. **Aerospace industry:**
     - SLS has proved to be particularly useful for industries that need only a small quantity of objects printed in high quality materials.
     - One example of this is the *aerospace industry*, in which SLS is used to build prototypes for airplane parts.
     - Because airplanes are built in small quantities and remain in service for many years, it isn't cost-effective for companies to produce physical molds for airplane parts. These molds would be too expensive to make and would then need to be stored for long periods of time without being damaged or corroded.
  2. SLS machines can print in a range of high-quality materials, from flexible plastic to food-grade ceramic, SLS is also a popular method for 3D printing customized products, such as *hearing aids, dental retainers and prosthetics.*

- **Material used in SLS:**
  - Nylon / Polyamide (PA), Polystyrene, Elastomers, Composites, acrylic styrene, carbon-filled PA

FUSED DEPOSITION MODELLING

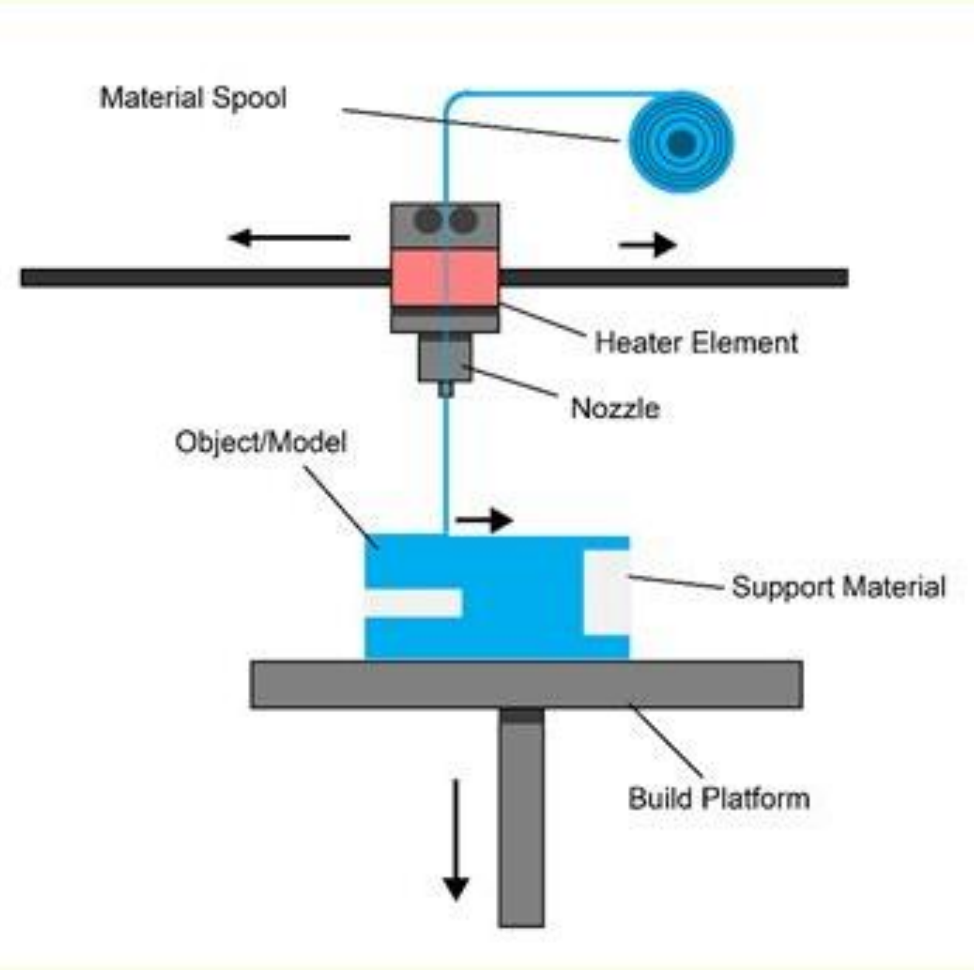
- Fused deposition modeling falls under the wider Material Extrusion.
- FDM has been around since the beginning of the history of 3D printing. Fused deposition modeling was developed by S. Scott Crump in the late 1980s before he founded Stratasys. With Stratasys, Crump commercialized FDM in 1990, and the successful 3D printer company continues to make FDM 3D printers to this day.
- Like Selective Laser Sintering, FDM uses thermoplastics to print parts. The difference between these two however is that FDM uses filaments, whereas SLS uses powders. Stereolithography differs from both as it uses thermosets, called resins.

FUSED DEPOSITION MODELLING

Working

- To print anything on your FDM 3D printer, you'll first need a 3D file. Usually an .STL file. you can either download these from sites such as Thingiverse or Shapeways, or design them on a 3D software program such as SolidWorks or CAD.

- Once you have your .STL file, you need to use a 3D slicer tool such as Cura to slice the file into layers. These are the individual layers the 3D printer will print, one at a time, until the three-dimensional model is finished. Once sliced, you just need to choose your printing parameters, and press print!



FUSED DEPOSITION MODELLING

- Fused deposition modeling involves feeding a *thermoplastic filament* into the 3D printer. The filament is heated to its melting point around 200ºC, though this depends on the material, through a heated nozzle and then extruded on to the build platform, tracing the part dimensions specified by the STL file.
- As the first full layer is finished, the print head moves up by one layer height, before tracing the next layer. This continues, layer-by-layer, until the part is complete.
- Once deposited, the filament solidifies to form a solid part, with each layer cooling before being heated briefly again when the layer on top of it is deposited. The layer sizes depend on your preferences, but are usually around a sixteenth of an inch.

Digital Light Processing (DLP)

is a similar process to Stereolithography in that it is a 3D printing

process that works with photopolymers. The major difference is

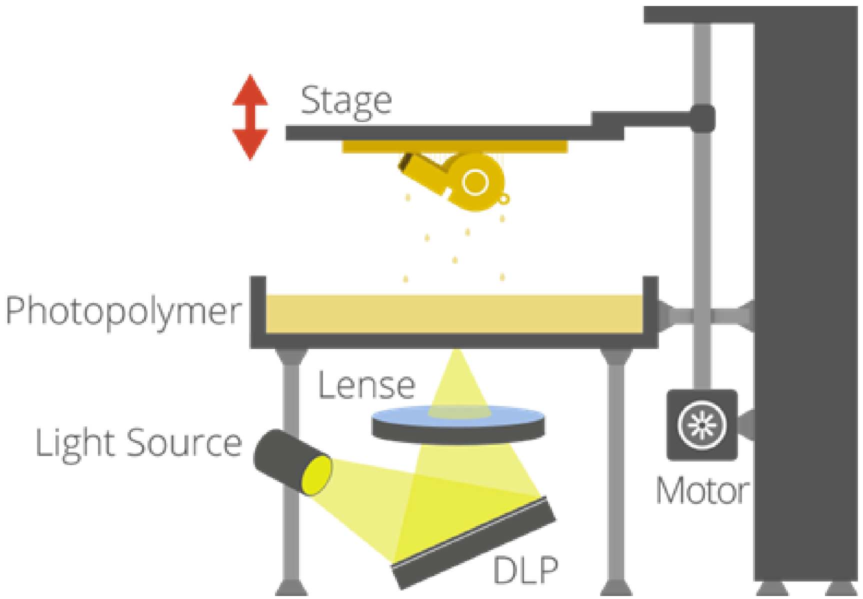
the light source. DLP uses a more conventional light source, such

as an arc lamp, with a liquid crystal display panel or a deformable

mirror device (DMD), which is applied to the entire surface of the

vat of photopolymer resin in a single pass, generally making it faster

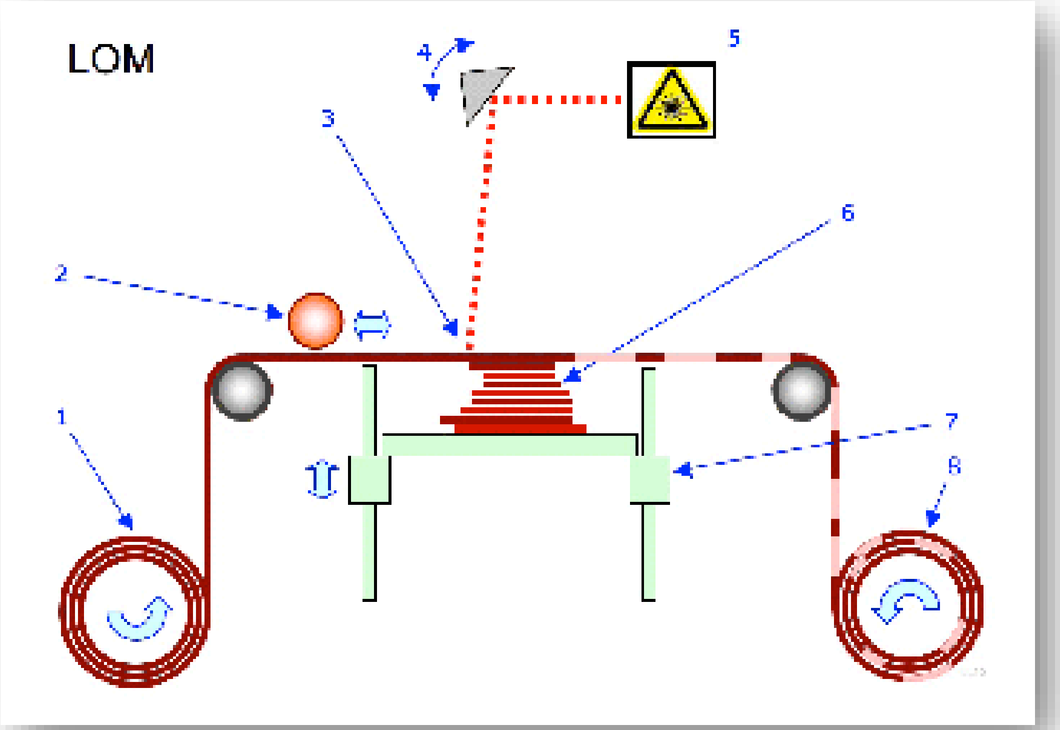
than SL.



Also like SL, DLP produces highly accurate parts with excellent resolution, but its similarities also include the same requirements for support structures and post-curing. However, one advantage of DLP over SL is that only a shallow vat of resin is required to facilitate the process, which generally results in less waste and lower running costs.

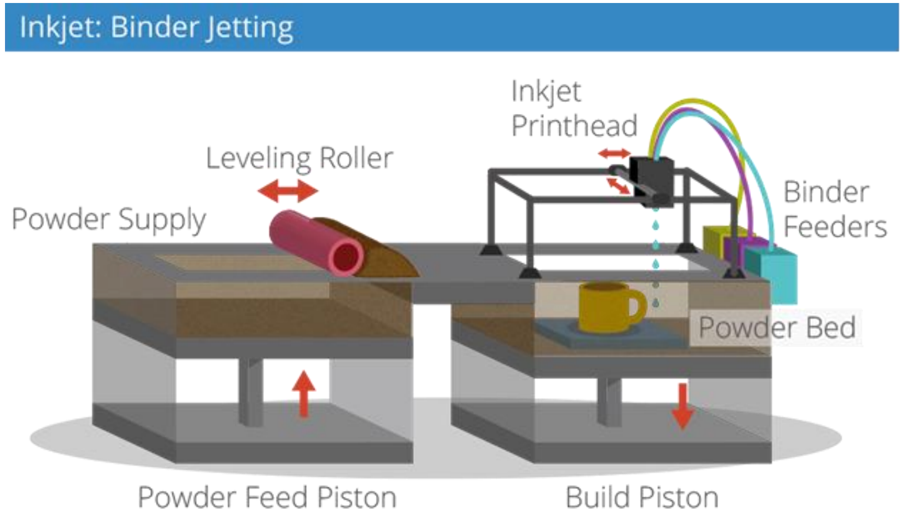
Laminated object manufacturing (LOM)

is a rapid prototyping system developed by Helisys Inc. In it, layers of adhesive-coated paper, plastic, or metal laminates are successively glued together and cut to shape with a knife or laser cutter. Objects printed with this technique may be additionally modified by machining or drilling after printing. Typical layer resolution for this process is defined by the material feedstock and usually ranges in thickness from one to a few sheets of copy paper.



Binder Jetting

- There are two 3D printing process that utilize a jetting technique. **Binder jetting:** where the material being jetted is a binder, and is selectively sprayed into a powder bed of the part material to fuse it a layer at a time to create/print the required part.
- As is the case with other powder bed systems, once a layer is completed, the powder bed drops incrementally and a roller or blade smoothes the powder over the surface of the bed, prior to the next pass of the jet heads, with the binder for the subsequent layer to be formed and fused with the previous layer.
- Advantages of this process, like with SLS, include the fact that the need for supports is negated because the powder bed itself provides this functionality. Furthermore, a range of different materials can be used, including ceramics and food. A further distinctive advantage of the process is the ability to easily add a full colour palette which can be added to the binder.
- The parts resulting directly from the machine, however, are not as strong as with the sintering process and require post-processing to ensure durability.



MATERIALS

MATERIALS

Liquid Based

Powder Based

Solid Based

MATERIALS

- ***Nylon***, or ***Polyamide***,

is commonly used in powder form with the sintering process or in filament form with the FDM process. It is a strong, flexible and durable plastic material that has proved reliable for 3D printing. It is naturally white in colour but it can be coloured — pre- or post printing. This material can also be combined (in powder format) with powdered aluminium to produce another common 3D printing material for sintering Alumide.

- ***ABS(Acrylonitrile butadiene styrene)***

is another common plastic used for 3D printing, and is widely used on the entry-level FDM 3D printers in filament form. It is a particularly strong plastic and comes in a wide range of colours. ABS can be bought in filament form from a number of non- proprietary sources, which is another reason why it is so popular.

- ***PLA(Polylactic acid)***

is a bio-degradable plastic material that has gained traction with 3D printing for this very reason. It can be utilized in resin format for DLP/SL processes as well as in filament form for the FDM process. It is offered in a variety of colours, including transparent, which has proven to be a useful option for some applications of 3D printing. However it is not as durable or as flexible as ABS.

MATERIALS

- ***LayWood*** is a specially developed 3D printing material for entry- level extrusion 3D printers. It comes in filament form and is a wood/polymer composite (also referred to as WPC).

- A growing number of metals and metal composites are used for industrial grade 3D printing. Two of the most common are ***aluminium*** and ***cobalt*** derivatives.

- One of the strongest and therefore most commonly used metals for 3D printing is ***Stainless Steel*** in powder form for the sintering/ melting/EBM processes. It is naturally silver, but can be plated with other materials to give a gold or bronze effect.
- In the last couple of years ***Gold*** and ***Silver*** have been added to the range of metal materials that can be 3D printed directly, with obvious applications across the jewellery sector. These are both very strong materials and are processed in powder form.
- ***Titanium*** is one of the strongest possible metal materials and has been used for 3D printing industrial applications for some time.

- Supplied in powder form, it can be used for the sintering/melting/ EBM processes.

MATERIALS

- ***Ceramics***

Ceramics are a relatively new group of materials that can be used for 3D printing with various levels of success. The particular thing to note with these materials is that, post printing, the ceramic parts need to undergo the same processes as any ceramic part made using traditional methods of production - namely firing and glazing.

- ***Paper***

Standard A4 copier paper is a 3D printing material employed by the proprietary SDL process supplied by Mcor Technologies. The company operates a notably different business model to other 3D printing vendors, whereby the capital outlay for the machine is in the mid-range, but the emphasis is very much on an easily obtainable, cost-effective material supply, that can be bought locally. 3D printed models made with paper are safe, environmentally friendly, easily recyclable and require no post-processing.

- ***Bio Materials***

There is a huge amount of research being conducted into the potential of 3D printing bio materials for a host of medical (and other) applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external tissues for replacement body parts. Other research in this area is focused on developing food stuffs - meat being the prime example.

MATERIALS

- ***Bio Materials***

  There is a huge amount of research being conducted into the potential of 3D printing bio materials for a host of medical (and other) applications. Living tissue is being investigated at a number of leading institutions with a view to developing applications that include printing human organs for transplant, as well as external tissues for replacement body parts.

- ***Food***

  Experiments with extruders for 3D printing food substances has increased dramatically over the last couple of years. Chocolate is the most common (and desirable). There are also printers that work with sugar and some experiments with pasta and meat. Looking to the future, research is being undertaken, to utilize 3D printing technology to produce finely balanced whole meals.

- ***Other***

  And finally, one company that does have a unique (proprietary) material offering is Stratasys, with its digital materials for the Objet Connex 3D printing platform. This offering means that standard Objet 3D printing materials can be combined during the printing process — in various and specified concentrations to form new materials with the required properties. Up to 140 different Digital Materials can be realized from combining the existing primary materials in different ways.

RISK

RISK

Safety features

Powder handling & changing - The following risks may be experienced while working with the systems:

- ***Risk or damage to respiratory tract and lungs*** when handling metal powders and filter dust and suspected carcinogenic effect of the metal powder and filter dust. It is strongly recommended to wear breathing protection (respiratory mask; particle filter P2D or P3D) and NEVER inhale the dust when filling, emptying and cleaning the build envelope (build module, dosing chamber, coater, powder overflow) and when emptying the collecting container and filter cartridge of the extraction and filter unit.

- ***Risk of eye damage when handling metal powder and filter dust.*** It is strongly recommended to wear eye protection (close-fitting safety goggles) when filling, emptying and cleaning the build envelope (build module, dosing chamber, coater, powder overflow) and when emptying the collecting container and filter cartridge of the extraction and filter unit.

- ***Risk of compressed air outlet***. Compressed air can escape if compressed air lines and union joints are opened or damaged. It is strongly recommended to wear safety gloves due to risk of skin damage. The toxic nickel in the metal powder and filter dust can cause irreversible damage or a sensitisation through skin contact (allergic reaction).

RISK

Risk of suspected carcinogenic effect of the metal powder and filter dust. A longer period inhaling of powder dust may cause accumulation of powder in lungs, blood and other organs which has a strong carcinogenic effect.

- ***Laser system***

The principal risks of the laser system are the following:

Laser is “invisible” (Class 1). This means that the human eye cannot detect the beam if it impacts the eye. It is highly recommended to activate the laser only when the door is closed due to protective action of the door crystal.

Special precaution should be made with docking/undocking of the build chamber. The laser may impact with the part and suffer severe damage.

RISK

3D printers are energy hogs

When melting plastic with heat or lasers, 3D printers consume about 50 to 100 times more electrical energy than injection molding to make an item of the same weight, according to research by Loughborough University. In 2009, research at MIT's Environmentally Benign Manufacturing program showed that laser direct metal deposition (where metal powder is fused together) used hundreds of times the electricity as traditional casting or machining. Because of this, 3D printers are better for small batch runs. Industrial-sized 3D printers may not be the answer to lessening our use of coal power any time soon.

Unhealthy air emissions

3D printers may pose a health risk when used in the home, according to researchers at the Illinois Institute of Technology. The emissions from desktop 3D printers are similar to burning a cigarette or cooking on a gas or electric stove. The 2013 study was the first to measure these airborne particle emissions from desktop 3D printers. While heating the plastic and printing small figures, the machines using PLA filament emitted 20 billion ultrafine particles per minute, and the ABS emitted up to 200 billion particles per minute. These particles can settle in the lungs or the bloodstream and pose health risk, especially for those with asthma.

Reliance on plastics

One of the biggest environmental movements in recent history has been to reduce reliance on plastics, from grocery bags to water bottles to household objects that can be made from recycled materials instead. The most popular—and cheapest—3D printers use plastic filament. Though using raw materials reduces the amount of waste in general, the machines still leave unused or excess plastic in the print beds. PLA is biodegradable, but ABS filament is still the most commonly used type of plastic. The plastic byproduct ends up in landfills. If 3D printing is going to be industrialized, that byproduct or other recycled plastic needs to be reused.

RISK

IP and licensing deals

In January, 3D Systems acquired Gentle Giant Ltd., which owned the licensing rights to toy franchises such as The Hobbit, The Walking Dead, Harry Potter, Alien, and Star Wars. Gartner has said that companies may lose at least $100 billion in four years to licensing or IP owners. 3D printing will change the business market—and the black market for these items—and the legislation will have to rush to catch up. This potential digital piracy situation is comparable to the way the internet challenged the movie and music industries for copyrights, trademarks, and illegal downloads.

Gun control loopholes

The first successful 3D printed gun is old news, but its ramifications are very important. Companies are popping up around the world, attempting to sell these guns and/or the CAD designs for them. Engineering firm Solid Concepts has even fired rounds out of the first 3D printed metal gun. Congress' Undetectable Firearms Act, which bans guns that can't be detected by metal detectors or x-ray scanners, was renewed for 10 years. It left a loophole in the law, however: 3D printed guns with a tiny piece of metal aren't banned by the Act. Legislators are attempting to close that loophole now, after Congress ignored the issue for quite some time, with special requirements for printed guns.

Responsibility of manufacturers

Weapons can be 3D printed. So can safety equipment such as helmets, wheels for bikes, and toys for small children. Of course there is the issue of intellectual property and trademark, but the larger issue involves responsibility. If a person shoots a gun and harms or kills someone, stabs someone with a 3D printed knife, or breaks their neck while riding on a bike with a 3D printed helmet, who is held accountable? The owner of the printer, the manufacturer of the printer, or the irresponsible person who thought it was a good idea to produce and use an untested product?

RISK

Bioprinting ethics and regulation

Cornell bioengineers and physicians created an artificial ear that looks and acts like a natural one.

The conversations about the ethics of bioprinting have already begun. Organovo is printing liver cells as well as eye tissue cells in a partnership with the National Eye Institute and National Center for Advancing Translational Sciences. Scientists have also proposed mixing human stem cells with canine muscle cells to create enhanced organ tissue. Printing cartilage is still the most realistic type of bioprinting, and printing whole organs is still many years away, but 3D printing is growing in medicine quite rapidly. Conversations about the moral, ethical, and legal issues surrounding bioprinting have started, but they will inevitably cause a lot more controversy as it becomes more commonplace.

Possibility of 3D printed drugs

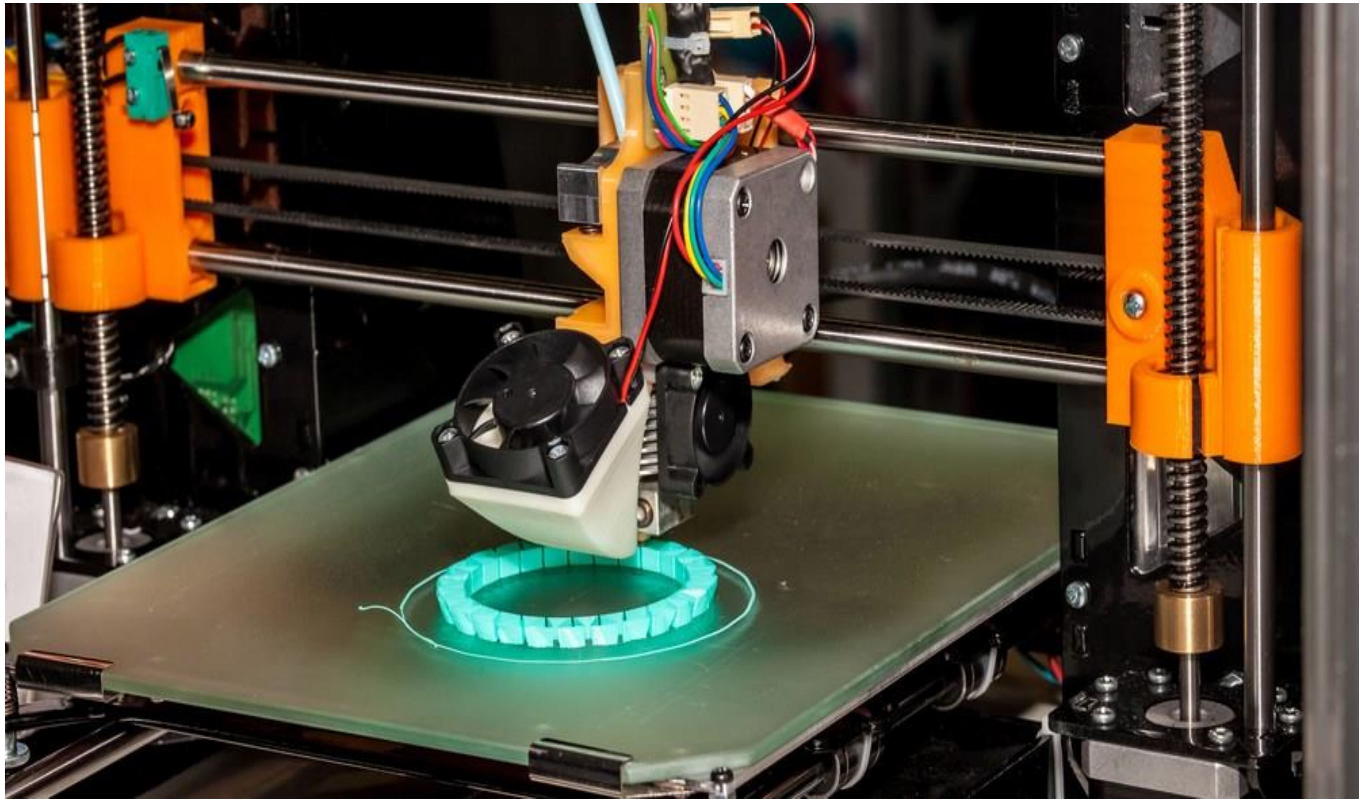
Assembling chemical compounds on a molecular level using a 3D printer is possible. A researcher at the University of Glasglow created a prototype of a 3D "Chemputer" that makes drugs and medicine. He wants to revolutionize the pharmaceutical industry by allowing patients to print their own medicine with a chemical blueprint they get from the pharmacy. Of course, this is a very long way off, but it stands to enable DIY chemists to create anything from cocaine to ricin.

Safety of items that come into contact with food

Kitchenware is popular to 3D print, but the safety of the materials used is questionable.

You can print out a fork or spoon with your MakerBot, but if you use ABS plastic, it is not BPA-free. Luckily, new filaments that are safer to put in your mouth are being created for this specific reason, but they aren't widely available yet. Many 3D printers have spaces where bacteria can easily grow if they aren't cleaned properly, as well. In order to more safely-produced 3D printed food and kitchenware, there may be a need for an FDA-approved machine. People probably don't want to eat genetically-engineered pizza off of toxic plates.

ADDITIVE MANUFACTURING
17ME82
MODULE 1
LECTURE 4- Post processing of AM parts



V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.

Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Post processing of AM parts

- What is post-processing?
  - ➢Post-processing is an essential stage of additive manufacturing. It’s the last step in the manufacturing process, where parts receive finishing touches such as smoothing and painting.
- Why is post-processing important?
  - ➢Post-processing improves the quality of parts and ensures that they meet their design specifications. The finishing process can enhance a part’s surface characteristics, geometric accuracy, aesthetics, mechanical properties, and more. For samples and prototypes, this can mean the difference between a sale or a loss. For production parts, finishing creates a part that is ready to use.

Post processing of AM parts

- Most AM processes require post-processing after part building to prepare the part for its intended form, fit and/or function. Depending upon the AM technique, the reason for post-processing varies.
- We will focus on post-processing techniques which are used to enhance components or overcome AM limitations. These include:
    1. Support material removal
    2. Surface texture improvements
    3. Accuracy improvements
    4. Aesthetic improvements
    5. Preparation for use as a pattern
    6. Property enhancements using non-thermal techniques
    7. Property enhancements using thermal techniques

1. Support material removal

- The most common type of post-processing in AM is support removal. Support material can be broadly classified into two categories:
  1. material which surrounds the part as a *naturally occurring by-product* of the build process (natural supports).
  2. rigid structures which are designed and built to support, restrain, or attach the part being built to a build platform (synthetic supports).

2. Surface Texture Improvements

- AM parts have common surface texture features that may need to be modified for aesthetic or performance reasons. Common undesirable surface texture features include: stair-steps, powder adhesion, fill patterns from material extrusion or DED systems, and witness marks from support material removal.
- The type of post-processing utilized for surface texture improvements is dependent upon the desired surface finish outcome. If a matte surface finish is desired, a simple bead blasting of the surface can help even the surface texture, remove sharp corners from stair-stepping, and give an overall matte appearance.
- If a smooth or polished finish is desired, then wet or dry sanding and hand-polishing are performed. In many cases, it is desirable to paint the surface (e.g., with cyanoacrylate, or a sealant) prior to sanding or polishing.
- Painting the surface has the dual benefit of sealing porosity and, by viscous forces, smoothing the stair-step effect, thus making sanding and polishing easier and more effective

3. Accuracy Improvements

- There is a wide range of accuracy capabilities between AM processes. Some processes are capable of submicron tolerances, whereas others have accuracies around 1 mm.
- Typically, the larger the build volume and the faster the build speed the worse the accuracy.
- This is particularly noticeable, for instance, in directed energy deposition processes where the slowest and most accurate DED processes have accuracies approaching a few microns; whereas, the larger bulk deposition machines have accuracies of several millimeters.

4. Aesthetic Improvements

- Many times AM is used to make parts which will be displayed for aesthetic or artistic reasons or used as marketing tools. In these and similar instances, the aesthetics of the part is of critical importance for its end application.
- Often the desired aesthetic improvement is solely related to surface finish.
- In cases where the color of the AM part is not of sufficient quality, several methods can be used to improve the part aesthetics. Some types of AM parts can be effectively colored by simply dipping the part into a dye of the appropriate color.
- This method is particularly effective for parts created from powder beds, as the inherent porosity in these parts leads to effective absorption. If painting is required, the part may need to be sealed prior to painting. Common automotive paints are quite effective in these instances.

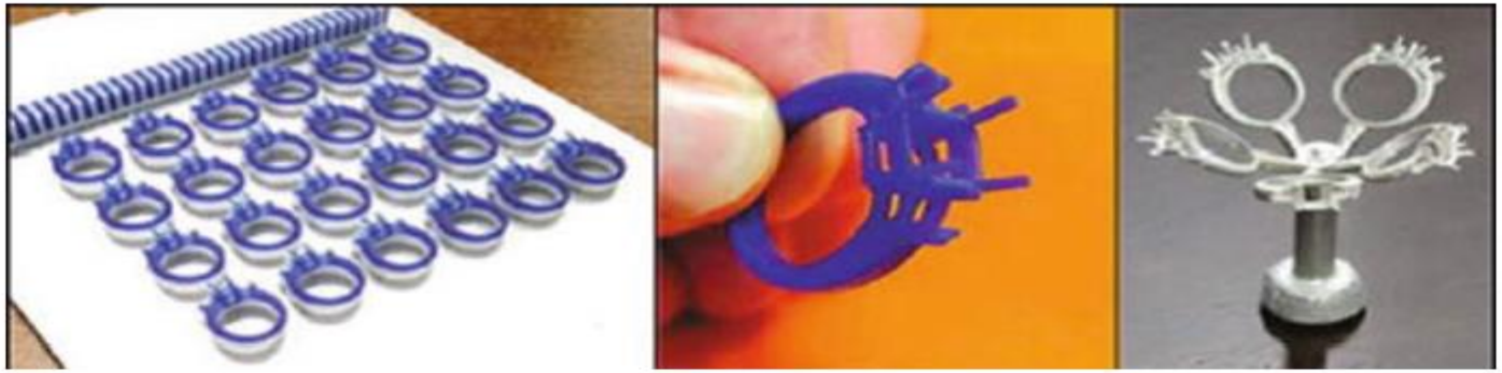
Stereolithography part (**a**) before and (**b**) after chrome plating (Courtesy of Artcraft

5. Preparation for Use as a Pattern

- Often parts made using AM are intended as patterns for investment casting, sand casting, room temperature vulcanization (RTV) molding, spray metal deposition, or other pattern replication processes.
- In many cases, the use of an AM pattern in a casting process is the least expensive way to use AM to produce a metal part, as many of the metal-based AM processes are still expensive to own and operate.
- The accuracy and surface finish of an AM pattern will directly influence the final part accuracy and surface finish. As a result, special care must be taken to ensure the pattern has the accuracy and surface finish desired in the final part. In addition, the pattern must be scaled to compensate for any shrinkage that takes place in the pattern replication steps.

Preparation for Use as a Pattern

- **Investment Casting Patterns**
  - In the case of investment casting, the AM pattern will be consumed during processing. In this instance, residue left in the mold as the pattern is melted or burned out is undesirable. Any sealants used to smooth the surface during pattern preparation should be carefully chosen so as not to inadvertently create unwanted residue.



Rings for investment casting, made using a ProJet® CPX 3D Printer (Courtesy 3D Systems)

  - AM parts can be printed on a casting tree or manually added to a casting tree after AM. Figure shows rings made using a material jetting system. In the first picture, a collection of rings is shown on the build platform; each ring is supported by a secondary support material in white. In the second picture, a close-up of the ring pattern is shown. The third picture shows metal rings still attached to a casting tree. In this instance, the rings were added to the tree after AM, but before casting.

Preparation for Use as a Pattern

- **Sand Casting Patterns**
  - Both binder jetting and PBF processes can be used to directly create sand mold cores and cavities by using a thermosetting binder to bind sand in the desired shape. One benefit of these direct approaches is that complex geometry cores can be made that would be very difficult to fabricate using any other process,
  - In order to prepare AM sand casting patterns for casting, loose powder is removed and the pattern is heated to complete cross-linking of the thermoset binder and to remove moisture and gaseous by-products. In some cases, additional binders are added to the pattern before heating, to increase the strength for handling. Once the pattern is thermally treated, it is assembled with its corresponding core(s) and/or cavity, and hot metal is poured into the mold. After cooling, the sand pattern is removed using tools and bead blasting.

Sand casting pattern for a cylinder head of a V6, 24-valve car engine (*left*) during loose powder removal and (*right*) pattern prepared for casting alongside a finished casting (Joint project between CADCAM Becker GmbH and VAW Südalumin GmbH, made on an EOSINT S laser-sintering machine, courtesy EOS)

Preparation for Use as a Pattern

- **Sand Casting Patterns**
  - In addition to directly producing sand casting cores and cavities, AM can be used to create parts which are used in place of the typical wooden or metal patterns around which a sand casting mold is created. In this case, the AM part is built as one or more portions of the part to be cast, split along the parting line. The split part is placed in a box, sand mixed with binder is poured around the part, and the sand is compressed (pounded) so that the binder holds the sand together. The box is then disassembled, the sand mold is removed from the box, and the pattern is removed from the mold. The mold is then reassembled with its complementary mold half and core(s) and molten metal is poured into the mold.

6. Property Enhancements Using Non-thermal Techniques

- Powder-based and extrusion-based processes often create porous structures. In many cases, that porosity can be infiltrated by a higher-strength material, such as cyanoacrylate (Super Glue®). Proprietary methods and materials have also been developed to increase the strength, ductility, heat deflection, flammability resistance, EMI shielding, or other properties of AM parts using infiltrants and various types of nano-composite reinforcements
- A common post-processing operation for photopolymer materials is curing. During processing, many photopolymers do not achieve complete polymerization. As a result, these parts are put into a Post-Cure Apparatus, a device that floods the part with UV and visible radiation in order to completely cure the surface and subsurface regions of the part. Additionally, the part can undergo a thermal cure in a low temperature oven, which can help completely cure the photopolymer and in some cases greatly enhance the part’s mechanical properties.

7. Property Enhancements Using Thermal Techniques

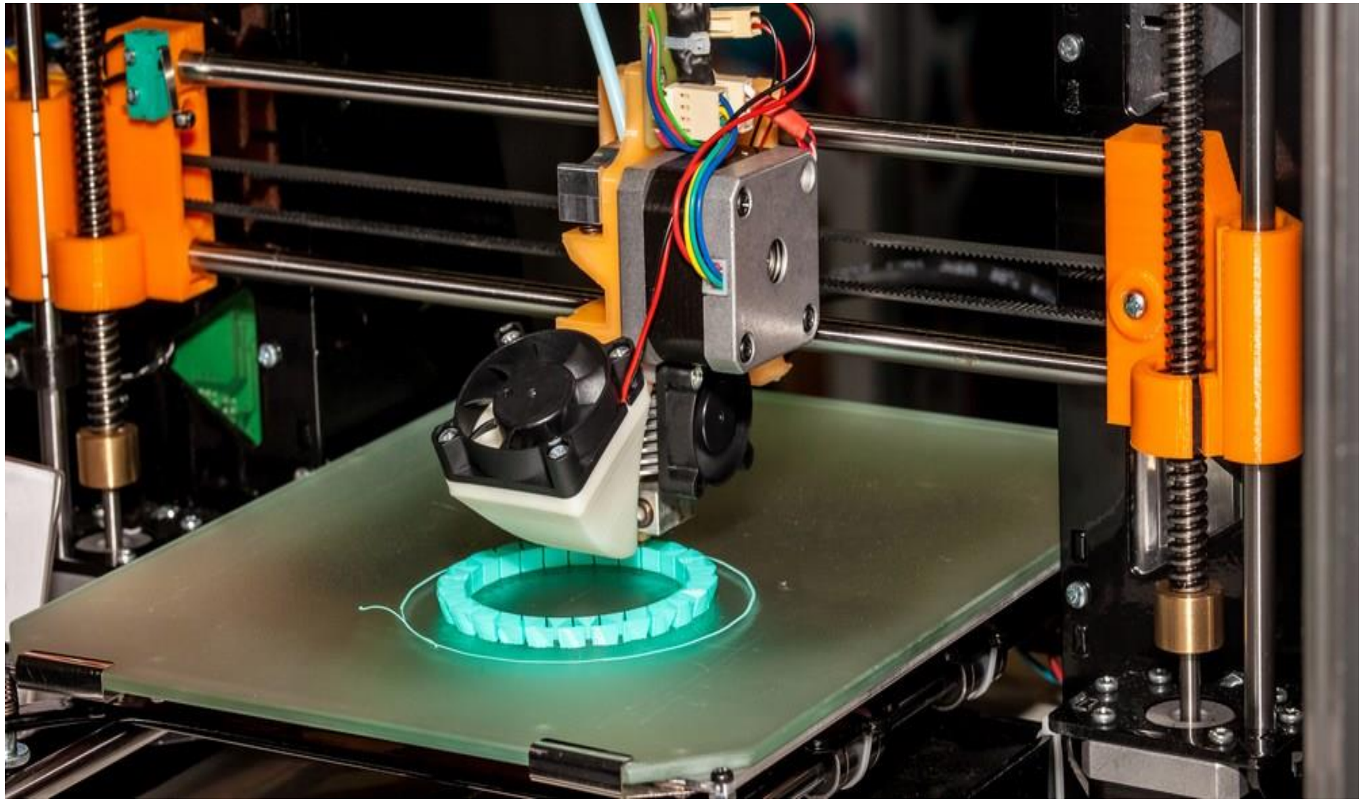
- After AM processing, many parts are thermally processed to enhance their properties. In the case of DED and PBF techniques for metals, this thermal processing is primarily heat treatment to form the desired microstructures and/or to relieve residual stresses. In these instances, traditional recipes for heat treatment developed for the specific metal alloy being employed are often used. In some cases, however, special heat treatment methods have been developed to retain the fine-grained microstructure within the AM part while still providing stress relief and ductility enhancement.

conclusion

- Most AM-produced parts require post-processing prior to implementation in their intended use.
- Effective utilization of AM processes requires not only a knowledge of AM process benefits and limitations, but also of the requisite post-processing operations necessary to finalize the part for use.
- When considering the intended form, fit and function for an AM produced part, post-processing is typically required.
- To achieve the correct form, support material removal, surface texture improvements, and aesthetic improvements are commonly required.
- To achieve the correct fit, accuracy improvements, typically via milling, are commonly required.
- To achieve the correct function, the AM part may require preparation for use as a pattern, property enhancements using non-thermal techniques, or property enhancements using thermal techniques. Whether using automated secondary support material removal, labor-intensive de-cubing, high temperature furnace processing, or secondary machining, choosing and

ADDITIVE MANUFACTURING
17ME82
MODULE 1
LECTURE 5- Guidelines for process selection

V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.



Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

Topics

- Introduction
- Selection Methods for a Part
  - ➢ Decision Theory
  - ➢ Approaches to Determining Feasibility
  - ➢ Approaches to Selection
- Challenges of Selection

Guidelines for process selection

- AM processes, like all materials processing, are constrained by *material properties*, *speed*, *cost, and accuracy*. The performance capabilities of materials and machines lag behind conventional manufacturing technology (e.g., injection molding machinery), although the lag is decreasing. Speed and cost, in terms of time to market, are where AM technology contributes, particularly for complex or customized geometries.
- The initial purpose of rapid prototyping technology was to create parts as a means of visual and tactile communication. Since those early days of rapid prototyping, the applications of additive manufacturing processes have expanded considerably. According to Wohlers and Associates , parts from AM machines are used for a number of purposes, including:
  - ➢Visual aids
  - ➢Presentation models
  - ➢Functional models
  - ➢Fit and assembly
  - ➢Patterns for prototype tooling
  - ➢Patterns for metal castings
  - ➢Tooling components
  - ➢Direct digital/rapid manufacturing

Guidelines for process selection

- With the growth of AM, there is going to be increasing demand for *software* that supports *making decisions* regarding which machines to use and their capabilities and limitations for a specific part design.
- In particular, software systems can help in the decision-making process for capital investment of new technology, providing accurate estimates of cost and time for quoting purposes, and assistance in process planning.
- Guidelines for process selection deals with three typical problems involving AM that may benefit from decision support:
    1. ***Quotation support***. Given a part, which machine and material should I use to build?
    2. ***Capital investment support***. Given a design and industrial profile, what is the best machine that I can buy to fulfill my requirements?
    3. ***Process planning support***. Given a part and a machine, how do I set it up to work in the most efficient manner alongside my other operations and existing tasks?

Selection Methods for a Part

1. Decision Theory

- there are three elements of any decision
  - Options—the items from which the decision maker is selecting
  - Expectations—of possible outcomes for each option
  - Preferences—how the decision maker values each outcome
- Assume that the set of decision options is denoted as $A = \{A_1, A_2, \ldots, A_n\}$. In engineering applications, one can think of outcomes as the performance of the options as measured by a set of evaluation criteria. More specifically, in AM selection, an outcome might consist of the *time*, *cost*, and *surface finish* of a part built using a certain AM process, while the AM process itself is the option. Expectations of outcomes are modeled as functions of the options, $X = g(A)$, and may be modeled with associated uncertainties.
- Preferences model the importance assigned to outcomes by the decision maker. For example, a designer may prefer low cost and short turn-around times for a concept model, while being willing to accept poor surface finish.

2. Approaches to Determining Feasibility

- The problem of identifying suitable materials and AM machines with which to fabricate a part is surprisingly complex.
- There are many possible applications for an AM part. For each application, one should consider the suitability of *available materials*, *fabrication cost and time*, *surface finish and accuracy requirements*, *part size*, *feature sizes*, *mechanical properties*, *resistance to chemicals*, and other application specific considerations.
- In order to solve AM machine and process chain selection problems, one must navigate the wide variety of materials and machines, comparing one’s needs to their capabilities, while ensuring that the most up-to-date information is available.
- To date, most approaches to determining feasibility have taken a *knowledge-based approach* in order to deal with the qualitative information related to AM process capability. One of the better developed approaches was presented by Deglin and Bernard.

2. Approaches to Determining Feasibility (continue…..)

- They presented a knowledge based system for the *generation*, *selection*, and *process planning* of production AM processes.
- Their approach utilized two reasoning methods, case-based and the bottom-up generation of processes; the strengths of each compensated for the other’s weaknesses. Their system was developed on the KADVISER platform and utilized a relational database system with extensive material, machine, and application information

2. Approaches to Determining Feasibility (continue…..)

- A group at the National University of Singapore (NUS) developed an AM decision system that was integrated with a database system.
- Their selection system was capable of identifying feasible material/machine combinations, estimating manufacturing cost and time, and determining optimal part orientations.
- From the feasible material/machines, the user can then select the most suitable combination. Their approach to determining feasible materials and processes is broadly similar to the work of Deglin and Bernard.
- The NUS group utilized five databases, each organized in a hierarchical, object-oriented manner: three general databases (materials, machines, and applications) and two part-specific databases (geometric information and model specifications).

2. Approaches to Determining Feasibility (continue…..)

- Several web-based AM selection systems are available. One was developed at the Helsinki University of Technology Finland.
- Through a series of questions, the selector acquires information about the part accuracy, layer thickness, geometric features, material, and application requirements. The user chooses one of 4–5 options for each question. Additionally, the user specifies preferences for each requirement using a 5-element scale from insignificant to average to important. When all 10–12 questions are answered, the user receives a set of recommended AM machines that best satisfy their requirements.

3. Approaches to Selection

- There have been a number of approaches taken to support the selection of AM processes for a part.
- Several methods have been developed in academia that are based on the large literature on decision theory.
- basic advantages of using DSPs(decision support problem) of any type lie in providing context and structure for engineering problems, regardless of complexity, they also facilitate the recording of viewpoints associated with these decisions, for completeness and future reference, and evaluation of results through post solution sensitivity analysis.
- The standard Selection Decision Support Problem (s-DSP) has been applied to many engineering problems and has recently been applied to AM selection.

3. Approaches to Selection

- The word formulation of the standard s-DSP(Selection Decision Support Problem) is given below.
- Note that the decision options for AM selection are feasible material-process combinations. Expectations are determined by rating the options against the attributes. Preferences are modeled using simple importance values. Rank ordering of options is determined using a weighted sum expression of importance and attribute ratings.

Given:	Set of AM processes/machines and materials (alternatives)
Identify:	Set of evaluation attributes. Create scales and determine importances.
Rate:	Each alternative relative to each attribute.
Rank:	AM methods from most to least promising

3. Approaches to Selection

- For the ***Identify*** step, evaluation attributes are to be specified. For example, accuracy, cost, build time, tensile strength, and feature detail (how small of a feature can be created) are typical attributes. Scales denote how the attribute is to be measured. For example, the cost scale is typically measured in dollars and is to be minimized. Tensile strength is measured in MPa and is to be maximized. These are examples of ratio scales, since they are measured using real numbers. Interval scales, on the other hand, are measured using integers. Complexity capability is an example attribute that could be measured using an interval scale from 1 to 10, where 10 represents the highest complexity.
- The decision maker should formulate interval scales carefully so that many of the integers in the scale have clear definitions. In addition to specifying scales, the decision maker should also specify minimum and maximum values for each attribute. Finally, the decision maker is to specify preferences using importance values or weights for each attribute.

3. Approaches to Selection

- For the ***Rate*** step of the s-DSP(Selection Decision Support Problem), each alternative AM process or machine should be evaluated against each attribute. From the Identify step, each attribute,a_i, has minimum and maximum values specified, $a_{i,min}$ and $a_{i,max}$ respectively.
- The decision maker specifies a rating value for attribute a_{ij} for each alternative, j, that lies between $a_{i,min}$ and $a_{i,max}$.
- The final step is to normalize the ratings so that they always take on values between 0 and 1.
- After computing the merit of each alternative, the alternatives can be rank ordered from the most favorable to the least. If two or more alternatives are close to the highest rank, additional investigation should be undertaken to understand under which conditions each alternative may be favored over the others. Additionally, the alternatives could be developed further so that more information about them is known. It is also helpful to run multiple sets of preferences (called scenarios) to understand how emphasis on certain attributes can lead to alternatives becoming favored

Challenges of Selection

- Different AM systems are focused on slightly different markets. For example, there are large, expensive machines that can fabricate parts using a variety of materials with relatively good accuracy and/or material properties and with the ability to fine-tune the systems to meet specific needs.
- In contrast, there are cheaper systems, which are designed to have minimal setup and to produce parts of acceptable quality in a predictable and reliable manner. In this latter case, parts may not have high accuracy, material strength, or flexibility of use.
- Different users will require different things from an AM machine. Machines vary in terms of cost, size, range of materials, accuracy of part, time of build, etc. It is not surprising to know that the more expensive machines provide the wider range of options and, therefore, it is important for someone looking to buy a new machine to be able to understand the costs vs. the benefits so that it is possible to choose the best machine to suit their needs.

Challenges of Selection (continue…)

- Approaching a manufacturer or distributor of AM equipment is one way to get information concerning the specification of their machine.
- Such companies are obviously biased towards their own product and, therefore, it is going to be difficult to obtain truly objective opinions.
- Conventions and exhibitions are a good way to make comparisons, but it is not necessarily easy to identify the usability of machines.
- Contacting existing users is sometimes difficult and time consuming, but they can give very honest opinions. This approach works best if you are already equipped with background information concerning your proposed use of the technology.

Challenges of Selection (continue…)

When looking for advice about suitable selection methods or systems, it is useful to consider the following points.

- The information in the system should be unbiased wherever possible.
- The method/system should provide support and advice rather than just a quantified result.
- The method/system should provide an introduction to AM to equip the user with background knowledge as well as advice on different AM technologies.
- A range of options should be given to the user in order to adjust requirements and show how changes in requirements may affect the decision.
- The system should be linked to a comprehensive and up-to-date database of AM machines.
- After the search process has completed, the system should give guidance on where to look next for additional information.

Challenges of Selection (continue…)

- The process of accessing the system should be as beneficial to the user as the answers it gives. However, this is not as easy a task as one might first envisage. If it were possible to decouple the attributes of the system from the user specification, then it would be a relatively simple task to select one machine against another.
- To illustrate that this is not always possible, consider the following scenarios:

Challenges of Selection (continue…)

1. In a Powder Bed Fusion (PBF) machine, warm-up and cool down are important stages during the build cycle that do not directly involve parts being fabricated. This means that large parts do not take proportionally longer times to build compared with smaller ones. Large builds are more efficient than small ones.

   In Vat Photopolymerization (VP) and Material Extrusion (ME) machines, there is a much stronger correlation between part size and build time. Small parts would therefore take less time on a VP or ME machine than when using PBF, if considered in isolation.

   Many users, however, batch process their builds and the ability to vertically stack parts in a PBF machine makes it generally possible to utilize the available space more efficiently.

   The warm-up and cool down overheads are less important for larger builds and the time per layer is generally quicker than most SL and ME machines.

As a result of this discussion, it is not easy to see which machine would be quicker without carefully analyzing the entire process plan for using a new machine.

Challenges of Selection (continue…)

2. Generally, it costs less to buy a Dimension or other low-end Material Extrusion(ME) machine compared to a Binder Jetting (BJ) machine.

   There are technical differences between these machines that make them suitable for different potential applications. However, because they are in a similar price bracket, they are often compared for similar applications.

   Dimension ME machines use a cartridge-based material delivery system that requires a complete replacement of the cartridge when empty. This makes material use much more expensive when compared with the 3D Systems BJ machine.

   For occasional use, it is therefore perhaps better to use a Dimension machine when all factors are equal. On the other hand, the more parts you build, the more coste ffective the BJ machine becomes.

Challenges of Selection (continue…)

3. Identifying a new application or market can completely change the economics of a machine. For example, in the metals area, *directed energy deposition machines* (e.g., LENS, DMD) tend to be slower and have worse feature detail capability than *powder bed metal machines* (e.g., SLM, EBM, DMLS).

   This has led to many more machine sales for ARCAM, Renishaw, and EOS. However, some companies identified a market for repairing molds and metal parts, which is very difficult, if not impossible, with a powder bed machine.

LENS- Laser Engineered Net Shaping

DMD- Direct Metal Deposition

SLM- Selective Laser Melting

EBM-Electron Beam Melting

DMLS- Direct Metal Laser Sintering

Challenges of Selection (continue…)

- These examples indicate that selection results depend to a large extent on the *user's knowledge* of AM capabilities and applications.
- Selection tools that include expert systems may have an advantage over tools based on straightforward decision methods alone.
- Expert systems attempt to embody the expertise resulting from extensive use of AM technology into a software package that can assist the user in overcoming at least some of the learning curve quickly and in a single stage.

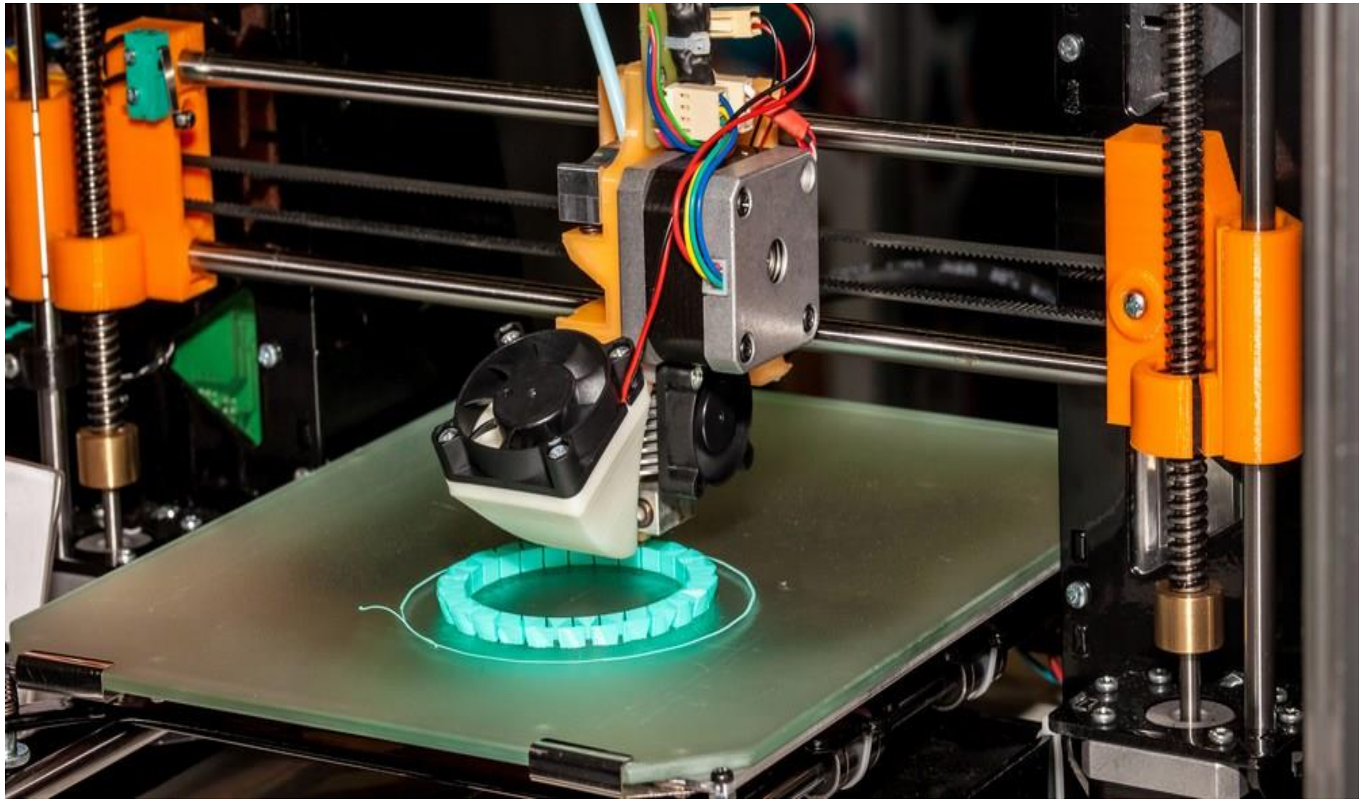
ADDITIVE MANUFACTURING
17ME82
MODULE 1
LECTURE 6- Applications of AM

V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.



Module 1

Introduction to Additive Manufacturing: Introduction to AM, AM evolution, Distinction between AM & CNC machining, Advantages of AM.

AM process chain: Conceptualization, CAD, conversion to STL, Transfer to AM, STL file manipulation, Machine setup, build , removal and clean up, post processing.

Classification of AM processes: Liquid polymer system, Discrete particle system, Molten material systems and Solid sheet system.

Post processing of AM parts: Support material removal, surface texture improvement, accuracy improvement, aesthetic improvement, preparation for use as a pattern, property enhancements using non-thermal and thermal techniques.

Guidelines for process selection: Introduction, selection methods for a part, challenges of selection

AM Applications: Functional models, Pattern for investment and vacuum casting, Medical models, art models, Engineering analysis models, Rapid tooling, new materials development, Bi-metallic parts, Re-manufacturing. Application examples for Aerospace, defence, automobile, Bio-medical and general engineering industries.

AM Applications-Introduction

- Additive manufacturing is coming into its fourth decade of commercial technological development. During that period, we have experienced a number of significant changes that has led to improvements in accuracy, better mechanical properties, a broader range of applications, and reductions in costs of machines and the parts made by them.
- Driven by the automotive, aerospace, and medical industries, AM has found applications in design and development within almost every consumer product sector imaginable. As AM becomes more popular and as technology costs inevitably decrease, this can only serve to generate more momentum and further broaden the range of applications. This momentum has been added to with the recent addition of commercial AM machines that can directly process metal powders.

AM Applications-Introduction

- we have seen that AM technologies can vary according to the following nonexclusive list of parameters:
  - Cost: Since some machines employ more expensive technologies, like lasers, they will inevitably cost more than others.
  - Range of materials: Some machines can only process one or two materials, while others can process more, including composites.
  - Maintenance: With some machines being more complex than others, the maintenance requirements will differ. Some companies will add cost to their machines to ensure that they are better supported.
  - Speed: Due to the technologies applied, some machines will build parts faster than others. Versatility: Some machines have complex setup parameters where part quality can be balanced against other parameters, like build speed. Other machines have fewer setup variations that make them easier to use but perhaps less versatile.
  - Layer thickness: Some machines have a limitation on the layer thickness due to the material processing parameters. Making these layers thinner would inevitably slow the build speed.
  - Accuracy: Aside from layer thickness, in-plane resolution also has an impact on accuracy. This may particularly affect minimum feature size and wall thickness of a part. For example, laser-based systems have a minimum feature size that is based on the diameter of the laser beam.

AM Applications-Introduction

- This chapter discusses the use of AM for *medical*, *aerospace* and *automotive applications* which have consistently been the key industries driving innovation in AM.
- With aerospace and automotive industries, AM is valued mainly because of the complex geometric capabilities and the time that can be saved in development of products.
- With medicine, the benefit is primarily in the ability to include patient-specific data from medical sources so that customized solutions to medical problems can be found.

AM Applications-Introduction

- We begin with a brief survey of historical developments in rapid prototyping (RP), rapid tooling, and other advances, with a focus mostly on aerospace and automotive industries.
- In the late 1980s, 3D Systems started selling their first stereolithography machines. The first five customers of the SLA-1 beta program were
  1. General Motors- Automotive sector
  2. Baxter Health Care- Health care service
  3. Eastman Kodak-consumer products
  4. Pratt & Whitney-aerospace
  5. AMP Incorporated-consumer business group

AM Applications-Value of Physical Models

- Early adopters discovered that AM, through the rapid prototyping function, provided several benefits including enhanced visualization, the ability to detect design flaws, reduced prototyping time, and significant cost reductions associated with the ability to develop correct designs quickly.
- Of course, there were also significant costs associated with being an early adopter. AM machines were more expensive than conventional machine tools and people had to be hired and trained to run the AM machines.
- New post-processing equipment had to be installed and hazardous solvents used to clean SL parts. But, for those companies willing to take the risk, the significant investments in AM had a large return-on-investment when AM was integrated into their product development processes.
- Examples in next slide:

AM Applications-Value of Physical Models

1. in 1992, Texas Instruments reported several case studies demonstrating thousands of dollars and months of prototyping time saved through the use of stereolithography. Furthermore, they were one of the first companies to explore the use of SL parts as patterns for investment casting.
2. Chrysler purchased two SLA-250 machines in early 1990 and reported that they fabricated over 1,500 parts in the first 2 years of usage, with the machines running virtually 24 h per day and 7 days per week.

They also reported significant time and cost savings particularly for form/fit and packaging assessments. They and other companies soon realized that they could greatly increase their chances of winning contracts to supply parts if they included RP parts with their quotes. By including physical prototypes, they can demonstrate that they understand the design requirements and both customer and supplier can identify potential problems early on.

AM Applications-Value of Physical Models

3. In the medical industry, Depuy, Inc. was another early adopter of SL. They reported on a project that began in 1990 to develop a new line of shoulder implants with dozens of models for various component sizes.

They used SL models, fabricated on their in-house SLA-250 machines, of the implant components during several iterations of early project reviews, saved several months of development time, and avoided costly changes before production.

Furthermore, they used SL masters for urethane tooling to make wax patterns for investment casting for the first 500 pieces of each size. As they noted, this allowed them to proceed with product launch as part of their development process.

AM Applications

Functional Testing

- Engineers at aerospace, automotive, and medical device companies soon discovered that AM parts could be used for a variety of functional testing applications. Specifically flow testing was investigated by these companies, even with the early SL resins that were brittle and absorbed water easily.
- Example:
  - ➢ Chrysler tested air flow through several cylinder head designs in early 1992. They built a model of the cylinder head geometry in SL, installed steel valves and springs, then ran the model on their flow bench. They achieved a 38 % improvement in air flow.
  - ➢ Engineers at Pratt & Whitney pioneered several new types of flow apparatus and experiments with SL in the early years with both air and water
  - ➢ A report from Porsche in1994 described water flow testing in a series of engine models to study coolant flow characteristics. By using SL and an early epoxy resin, they could successfully design, fabricate, and test engine models within about 1 week per iteration

Functional Testing

- Concurrently, aerospace companies started using AM parts to perform wind tunnel testing. Wind tunnel models are typically instrumented with arrays of pressure sensors. Standard metal models required considerable machining in order to fabricate channels for all of the wiring to the sensors. With AM, the channels and sensor mounts could be designed into the model.

AM Applications

Rapid tooling

- Prior to 1992, Chrysler experimented with a variety of rapid tooling processes with stereolithography master patterns. This included vacuum forming, resin transfer molding, sand casting, squeeze molding, and silicone molding.
- An area of significant effort in both the aerospace and automotive industries was the use of SL parts as investment casting patterns. Early experiments used thin-walled SL patterns or hollow parts. Because SL resins expand more than investment casting wax, when used as patterns, the SL part tended to expand and crack the ceramic shell. This led to the development of the QuickCast™ pattern style in 1992, which is a type of lattice structure that was added automatically to hollow part STL files by SL machine pre-processing software. The QuickCast style was designed to support thin walls but not to be too strong. Upon heating and thermal expansion, the QuickCast lattice struts were designed to flex, collapse inward, break, but not transfer high loads to the part skins which could crack the shell.

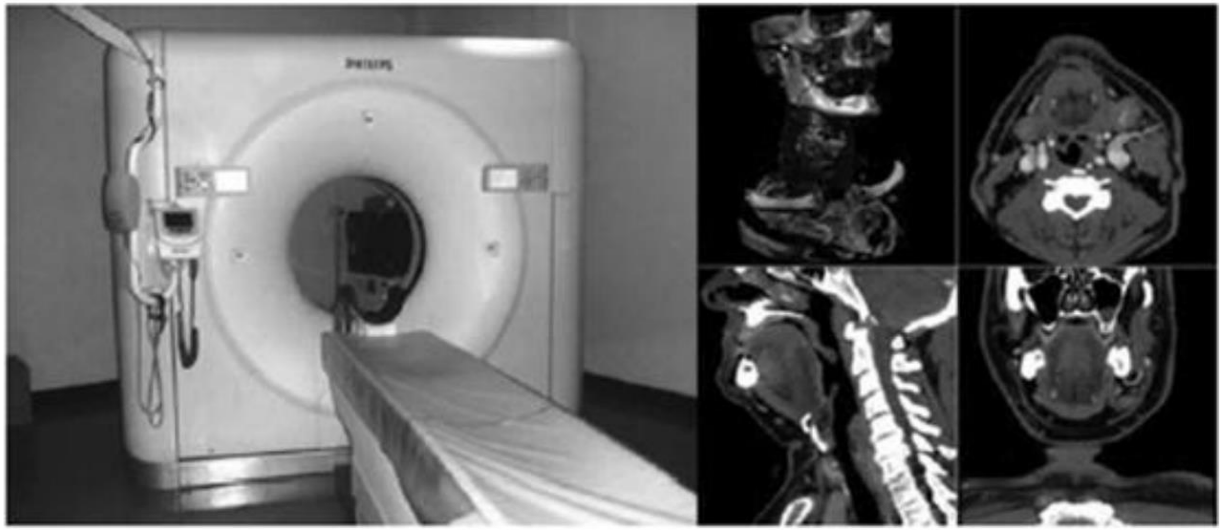
Rapid tooling

- Boeing, Northrop-Grumman and other aerospace companies have used material extrusion technology to fabricate tooling. They developed tooling designs for composite part lay-up that were suitable for ME fabrication. Other reported tooling applications included drill guides and various assembly tools.

AM Applications

Medical

- AM models have been used for medical applications almost from the very start
- Computerized Tomography (CT) was also a technology that developed alongside 3D representation techniques
- CT is an X-ray-based technique that moves the sensors in 3D space relative to the Xray source so that a correlation can be made between the position and the absorption profile.
- By combining multiple images in this way, a 3D image can be built up. The level of absorption of the X-rays is dependent on the density of the subject matter, with bone showing up very well because it is much denser than the surrounding soft tissue.
- this is one of a number of developing technologies working in the 3D domain, including 3D MRI, 3D Ultrasound, and 3D laser scanning



A CT scanner with sliced images and a 3D image created using this technology

- With this increasing use of 3D medical imaging technology, the need to share and order this data across platforms has led to information exchange standards like DICOM from the National Electrical Manufacturers Association in the USA, which allows users to view patient data with a variety of different software and sourced from a variety of different imaging platforms

Medical-Surgical and Diagnostic Aids

- The use of AM for diagnostic purpose was probably the first medical application of AM. Surgeons are often considered to be as much artists as they are technically proficient. Since many of their tasks involve working inside human bodies, much of their operating procedure is carried out using the sense of touch almost as much as by vision. As such, models that they can both see from any angle and feel with their hands are very useful to them.
- Surgeons work in teams with support from doctors and nurses during operations and from medical technicians prior to those operations. They use *models* in order to understand the complex surgical procedures for themselves as well as to communicate with others in the team.
- Complex surgical procedures also require patient understanding and compliance and so the surgeon can use these models to assist in this process too. AM models have been known to help reduce time in surgery for complex cases, both by allowing the surgeons to better plan ahead of time and for them to understand the situation better during the procedure (by having the model on hand to refer to within the operating theater).
- Machine vendors have, therefore, developed a range of materials that can allow sterilization of parts so that models can be brought inside the operating theater without contamination.

AM Applications

Manufacturing

- There are now examples where customized prosthetics have found their way into mainstream product manufacture. The two examples that are most well known in the industry are in-the-ear hearing aids from companies like Siemens and Phonak and the Invisalign range of orthodontic aligners as developed by Align Technology
- Both of these applications involve taking precise data from an individual and applying this to the basic generic design of a product. The patient data are generated by a medical specialist who is familiar with the procedure and who is able to determine whether the treatment will be beneficial. Specialized software is used that allows the patient data to be manipulated and incorporated into the medical device.

AM Applications

Tissue Engineering and Organ Printing

- The ultimate in fabrication of medical implants would be the direct fabrication of replacement body parts. This can feasibly be done using AM technology, where the materials being deposited are living cells, proteins, and other materials that assist in the generation of integrated tissue structures.
- However, although there is a great deal of active research in this area, practical applications are still in the main some way off. The most likely approach would be to use printing and extrusion-based technology to undertake this deposition process.

AM Application
CONCLUSION

1. ***Rapid Prototyping***

   Models and parts for research purposes can be easily manufacture whenever required. Easy to make changes in the models as per the research proceedings.

2. ***Food***

   Cornell Creative Machines Lab is making food items such as chocolates, candy, pasta, pizza using 3D printing technique since 2012.

3. ***Apparel***

   Products such as customize shoes, clothes and eye wears are being manufactured.

   Nike is using 3D printing to manufacture the “Vapor Laser Talon” football shoe for players of American football

4. ***Vehicle***

   In 2010 Urbee became the first car whose whole body was 3D printed (by US engineering group Kor Ecologic and the company Stratasys).

   In early 2014, Swedish supercar manufacturer, Koenigsegg, manufactured a supercar having many 3D printed mechanical parts in it.

AM Application
CONCLUSION

1. *Firearms*

Defense arms such as guns, rifles and safety equipment has also been manufacture byAM.

In 2012 US based group “Defense Distributed”, designed a working plastic gun that could be downloaded and reproduced by anybody with a 3D printer.

In 2013, ‘Solid Concepts’, based in Austin, Texas, USA succeeded in manufacturing first working metal gun.

2. *Medical*

Nowadays medical devices, specific implants, hearing aids, dental products and pills are being manufacture by AM.

During October 2014, a five year old girl born without fully formed fingers on her left hand became the first child in the UK to have a prosthetic hand made with 3D printing . Till now more than 400 hands have been transplanted by E-NABLE.

In august 2015, US FDA(Food and Drug administration) approved 3D printed pills which allows very porous pills to be produced, which enables high drug doses in a single pill which dissolves quickly and can be ingested easily

7. *Bioprinting*

Bioprinting refers to manufacturing artificial biological organs and body parts capable of working like original ones.

In this process, layers of living cells are deposited onto a gel medium or sugar matrix and slowly built up to form three dimensional structures including vascular systems.

The first production system for 3D tissue printing was delivered in 2009, based on NovoGen bio-printing technology.

In 2013, Chinese scientists began printing ears, livers and kidneys, with living tissue.

In 2014, researchers at the University of Hasselt, in Belgium had successfully printed a new jawbone for an 83 year old woman.

AM Application
CONCLUSION

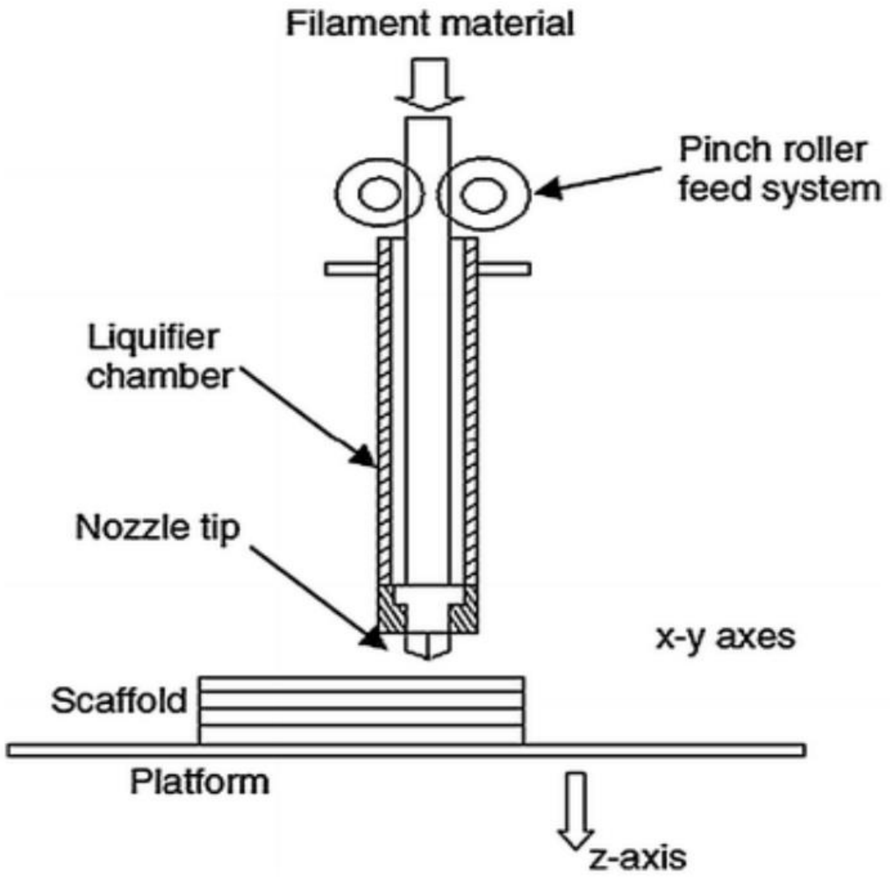
8. Space

In September 2014, “SpaceX” delivered the first zero gravity 3D printer to the International Space Station (ISS).

In December 2014, NASA emailed CAD drawings for a socket wrench to astronauts aboard the ISS, who then printed the tool using its 3D printer.

The European Space Agency plans to deliver its new advance Portable On Board 3D Printer to the International Space Station by the end of 2015.

ADDITIVE MANUFACTURING
18ME741
MODULE 2
EXTRUSION BASED SYSTEMS



V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.

Module 2

Photo polymerization processes: Stereolithography (SL), Materials, SL resin curing process, Micro stereolithography, Process Benefits and Drawbacks, Applications of Photo polymerization Processes.

Powder bed fusion processes: Introduction, Selective laser Sintering (SLS), Materials, Powder fusion mechanism, SLS Metal and ceramic part creation, Electron Beam melting (EBM), Process Benefits and Drawbacks, Applications of Powder Bed Fusion Processes.

Extrusion-based systems: Fused Deposition Modelling (FDM), Principles, Materials, Plotting and path control, Bio-Extrusion, Process Benefits and Drawbacks, Applications of Extrusion-Based Processes

Introduction

- Material extrusion technologies can be visualized as similar to cake icing, in that material contained in a reservoir is forced out through a nozzle when pressure is applied.
- If the pressure remains constant, then the resulting extruded material (commonly referred to as “roads”) will flow at a constant rate and will remain a constant cross-sectional diameter.
- This diameter will remain constant if the travel of the nozzle across a depositing surface is also kept at a constant speed that corresponds to the flow rate. The material that is being extruded must be in a semisolid state when it comes out of the nozzle. This material must fully solidify while remaining in that shape. Furthermore, the material must bond to material that has already been extruded so that a solid structure can result.
- Since material is extruded, the AM machine must be capable of scanning in a horizontal plane as well as starting and stopping the flow of material while scanning. Once a layer is completed, the machine must index upwards, or move the part downwards, so that a further layer can be produced.
- There are two primary approaches when using an extrusion process.
    1. By temperature control
    2. chemical change to cause solidification

Introduction

1. *By temperature control*: Molten material is liquefied inside a reservoir so that it can flow out through the nozzle and bond with adjacent material before solidifying. This approach is similar to conventional polymer extrusion processes, except the extruder is vertically mounted on a plotting system rather than remaining in a fixed horizontal position.
2. *By chemical change to cause solidification:* a curing agent, residual solvent, reaction with air, or simply drying of a “wet” material permits bonding to occur. Parts may therefore cure or dry out to become fully stable. This approach is can be utilized with paste materials.

Basic Principles:

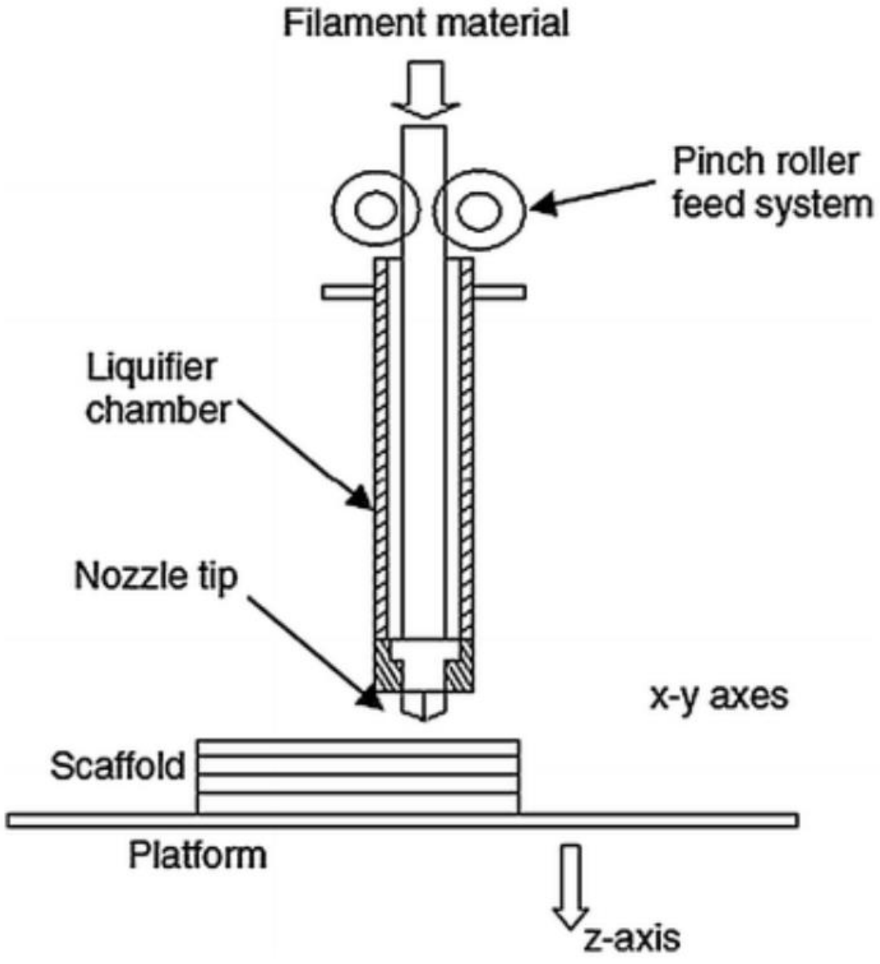
- There are a number of key features that are common to any extrusion-based system:
  1. Loading of material
  2. Liquification of the material
  3. Application of pressure to move the material through the nozzle
  4. Extrusion
  5. Plotting according to a predefined path and in a controlled manner
  6. Bonding of the material to itself or secondary build materials to form a coherent solid structure
  7. Inclusion of support structures to enable complex geometrical features

1. Loading of material

- Since extrusion is used, there must be a chamber from which the material is extruded.
- If the material is in a liquid form, then the ideal approach is to pump this material. Most bulk material is, however, supplied as a solid and the most suitable methods of supply are in pellet or powder form, or where the material is fed in as a continuous filament.
- The chamber itself is therefore the main location for the liquification process. Pellets, granules, or powders are fed through the chamber under gravity or with the aid of a screw or similar propelling process.
- Materials that are fed through the system under gravity require a plunger or compressed gas to force it through the narrow nozzle. Screw feeding not only pushes the material through to the base of the reservoir but can be sufficient to generate the pressure needed to push it through the nozzle as well.

2. Liquification of material

- heat would normally be applied by heater coils wrapped around the chamber and ideally this heat should be applied to maintain a constant temperature in the melt
- The material inside the chamber should be kept in a molten state but care should be taken to maintain it at as low a temperature as possible since some polymers degrade quickly at higher temperatures and could also burn, leaving residue on the inside of the chamber that would be difficult to remove and that would contaminate further melt. A higher temperature inside the chamber also requires additional cooling following extrusion



3. Application of pressure to move the material through the nozzle

- Material flow through the nozzle is controlled by the pressure drop between the chamber and the surrounding atmosphere.
- However, the extrusion process used for AM may not be the same as conventional extrusion. For example, the pressure developed to push the molten material through the nozzle is typically not generated by a screw mechanism.
- However, to understand the process it may be useful to study a traditional screw-fed extrusion process.
- Mass flow through a nozzle is related to pressure drop, nozzle geometry, and material viscosity.
- The viscosity is of course primarily a function of temperature. Since no special dies or material mixing is required for this type of application, it can be said to behave in a similar manner to a single Archimedean screw extruder.

4. Extrusion

- The extrusion nozzle determines the shape and size of the extruded filament.
- A larger nozzle diameter will enable material to flow more rapidly but would result in a part with lower precision compared with the original CAD drawing.
- The diameter of the nozzle also determines the minimum feature size that can be created.
- Extrusion based processes are more suitable for larger parts that have features and wall thicknesses that are at least twice the nominal diameter of the extrusion nozzle used.

Solidification

- If the material is extruded in the form of a gel, the material may shrink upon drying, as well as possibly becoming porous.
- If the material is extruded in a molten state, it may shrink when cooling.
- The cooling is also very likely to be nonlinear. If this nonlinear effect is significant, then it is possible the resulting part will distort upon cooling. This can be minimized by ensuring the temperature differential between the chamber and the surrounding atmosphere is kept to a minimum (i.e., use of a controlled environmental chamber when building the part) and also by ensuring the cooling process is controlled with a gradual and slow profile.
- It is reasonable to assume that an extrusion-based AM system will extrude from a large chamber to a small nozzle through the use of a conical interface. As mentioned before, the melt is generally expected to adhere to the walls of the liquefier and nozzle with zero velocity at these boundaries, subjecting the material to shear deformation during flow.

Positional Control

- Like many AM technologies, extrusion-based systems use a platform that indexes in the vertical direction to allow formation of individual layers. The extrusion head is typically carried on a plotting system that allows movement in the horizontal plane. This plotting must be coordinated with the extrusion rate to ensure smooth and consistent deposition.

Bonding

- For heat-based systems there must be sufficient residual heat energy to activate the surfaces of the adjacent regions, causing bonding.
- gel or paste-based systems must contain residual solvent or wetting agent in the extruded filament to ensure the new material will bond to the adjacent regions that have already been deposited.
- If there is insufficient energy, the regions may adhere, but there would be a distinct boundary between new and previously deposited material. This can represent a fracture surface where the materials can be easily separated. Too much energy may cause the previously deposited material to flow, which in turn may result in a poorly defined part.

Support Generation

- All AM systems must have a means for supporting free-standing and disconnected features and for keeping all features of a part in place during the fabrication process.
- With extrusion-based systems such features must be kept in place by the additional fabrication of supports. Supports in such systems take two general forms: – Similar material supports – Secondary material supports.

Fused Deposition Modeling from Stratasys:

- By far the most common extrusion-based AM technology is fused deposition modeling (FDM), produced and developed by Stratasys, USA
- FDM uses a heating chamber to liquefy polymer that is fed into the system as a filament. The filament is pushed into the chamber by a tractor wheel arrangement and it is this pushing that generates the extrusion pressure.
- The major strength of FDM is in the range of materials and the effective mechanical properties of resulting parts made using this technology.
- The main drawback to using this technology is the build speed. The inertia of the plotting heads means that the maximum speeds and accelerations that can be obtained are somewhat smaller than other systems. Furthermore, FDM requires material to be plotted in a pointwise, vector fashion that involves many changes in direction

Fused Deposition Modeling from Stratasys:

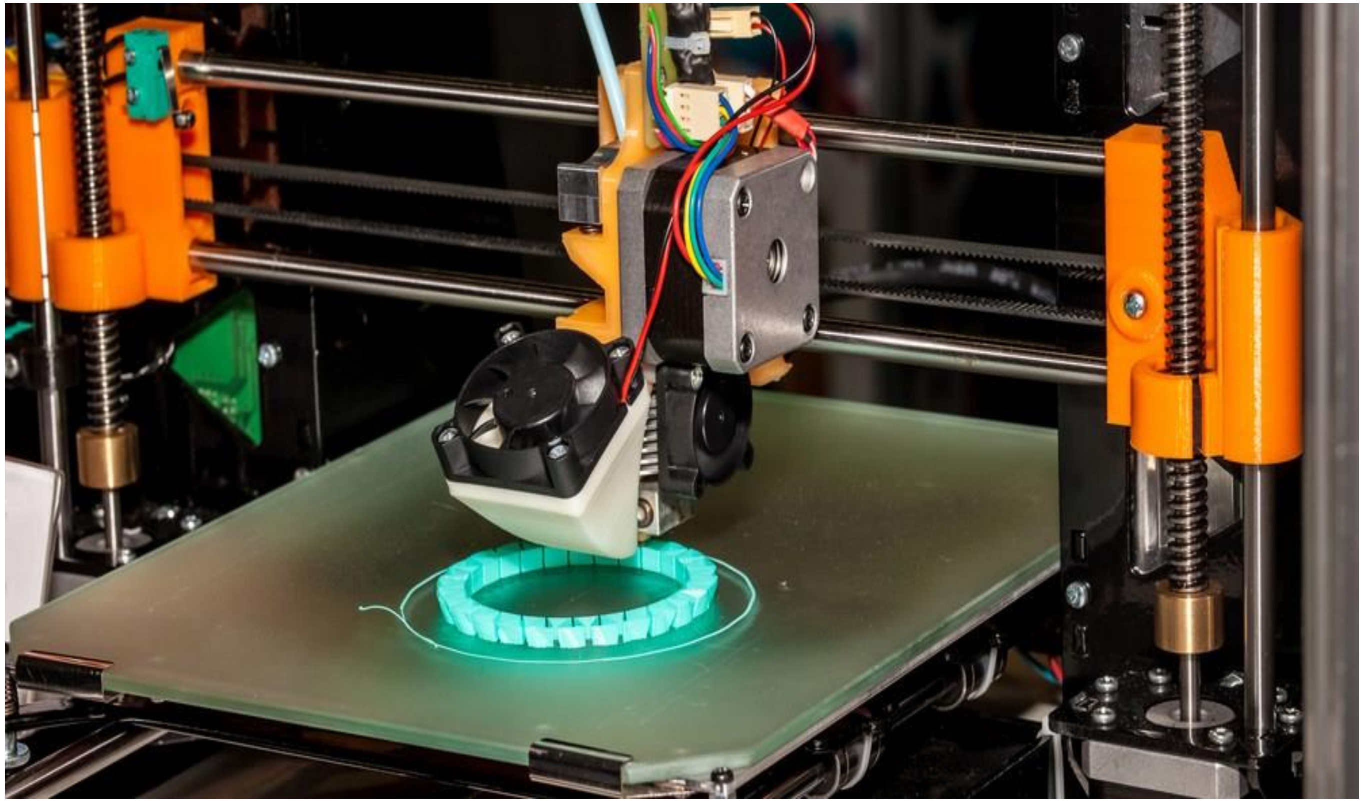
- **Materials:**
  - The most popular material is the ABSplus material, which can be used on all current Stratasys FDM machines.
  - his is an updated version of the original ABS (acrylonitrile butadiene styrene) material that was developed for earlier FDM technology.
  - PC-based can provide higher tensile properties, with a flexural strength of 104 MPa.
  - A variation of this material is the PC-ISO, which is also PC-based, formulated to ISO 10993-1 and USP Class VI requirements. flexural strength of 90 Mpa
- **Limitations of FDM:**
  - they have a layer thickness option of 0.078 mm, but this is only available with the highest-cost machine and use of this level of precision will lead to longer build times.
  - nozzles are circular and therefore it is impossible to draw sharp external corners. Internal corners and edges will also exhibit rounding. The actual shape produced is dependent on the nozzle, acceleration, and deceleration characteristics, and the viscoelastic behavior of the material as it solidifies.

Bioextrusion:

- ***Definition:*** Bioextrusion is the process of creating biocompatible and/or biodegradable components that are used to generate frameworks, commonly referred to as "scaffolds," that play host to animal cells for the formation of tissue (tissue engineering). Such scaffolds should be porous, with micropores that allow cell adhesion and macropores that provide space for cells to grow.
- There are a few commercial bioextrusion systems, like the modified FDM process used by Osteopore to create scaffolds to assist in primarily head trauma recovery.
- This machine uses a conventional FDM-like process with settings for a proprietary material, based on the biocompatible polymer, polycaprolactone (PCL).
- Most tissue engineering is still, however, in research form; investigating many aspects of the process, including material choice, structural strength of scaffolds, coatings, biocompatibility, and effectiveness within various clinical scenarios. Many systems are in fact developed in-house to match the specific interests of the researchers. There are however a small number of systems that are also available commercially to research labs.
- One common method of creating scaffolds is to use hydrogels. These are polymers that are water insoluble but can be dispersed in water. Hydrogels can therefore be extruded in a jelly-like form.
- Where stronger scaffolds are required, like when used to generate bony tissue, melt extrusion seems to be the process of choice.

ADDITIVE MANUFACTURING
18ME741
MODULE 3
PRINTING PROCESSES

V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.



Module 3

Printing Processes: evolution of printing as an additive manufacturing process, research achievements in printing deposition, technical challenges of printing, printing process modelling, material modification methods, three-dimensional printing, advantages of binder printing

Sheet Lamination Processes: Materials, Laminated Object Manufacturing (LOM), Ultrasonic Consolidation (UC), Gluing, Thermal bonding, LOM and UC applications.

Beam Deposition Processes: introduction, general beam deposition process, description material delivery, BD systems , process parameters, typical materials and microstructure, processing–structure–properties relationships, BD benefits and drawbacks.

Direct Write Technologies: Background ,ink-based DW, laser transfer, DW thermals pray, DW beam deposition, DW liquid-phase direct deposition.

Evolution of Printing as an Additive Manufacturing Process :

- Printing technology has been extensively investigated, with the majority of that investigation historically based upon applications to the two dimensional printing industry. Recently, however, it has spread to numerous new application areas, including electronics packaging, optics, and additive manufacturing.
- The employment of printing technologies in the creation of three-dimensional products has quickly become an extremely promising manufacturing practice, both widely studied and increasingly widely used.
- Printing as a three-dimensional building method was first demonstrated in the 1980s with patents related to the development of Ballistic Particle Manufacturing, which involved simple deposition of “particles” of material onto an article.
- The first commercially successful technology was the ModelMaker from *Sanders Prototype* (now Solidscape), introduced in 1994, which printed a basic wax material that was heated to liquid state.
- In 1996, *3D Systems* introduced the Actua 2100, another wax-based printing machine. The Actua was revised in 1999 and marketed as the ThermoJet.

Evolution of Printing as an Additive Manufacturing Process :

- In 2001, Sanders Design International briefly entered the market with its Rapid Tool Maker, but was quickly restrained due to intellectual property conflicts with Solidscape.
- It is notable that all of these members of the first generation of RP printing machines relied on *heated waxy thermoplastics* as their build material; they are therefore most appropriate for concept modeling and investment casting pattern.
- More recently, the focus of development has been on the deposition of *acrylate photopolymer*, wherein droplets of liquid monomer are formed and then exposed to ultraviolet light to promote polymerization.
- Quadra from Object Geometries of Israel in 2000, followed quickly by the revised Quadra Tempo in 2001. Both machines jetted a photopolymer using print heads with over 1,500 nozzles.
- In 2003, 3D Systems launched a competing technology with its InVision 3D printer. Multi-Jet Modeling, the printing system used in this machine, was actually an extension of the technology developed with the ThermoJet line.

Materials for Material Jetting

- Polymers- candelilla wax, microcrystalline petroleum wax, thermoplastics
- Ceramics- zirconia powder,
- Metals-copper, aluminium, tin
- Solution- and Dispersion-Based Deposition

research achievements in printing deposition

POLYMER

- *Gao and Sonin* present the first notable academic study of the deposition and solidification of groups of molten polymer microdrops. They discuss findings related to three modes of deposition: columnar, sweep (linear), and repeated sweep (vertical walls). The two materials used in their investigations were a candelilla wax and a microcrystalline petroleum wax, deposited in droplets 50 μm in diameter from a print head 3–5 mm from a cooled substrate.
- Reis et al. also provide some discussion on the linear deposition of droplets. They deposited molten Mobilwax paraffin wax with a heated print head from SolidScape. They varied both the print head horizontal speed and the velocity of droplet flight from the nozzle. For low droplet speeds, low sweep speeds created discontinuous deposition and high sweep speeds created continuous lines
- Feng et al. presented a full system, based on a print head from MicroFab Technologies Inc. that functions similarly to the commercially available machines. It prints a wax material which is heated to 80 °C, more than 10° past its melting point, and deposits it in layers 13–60 μm thick. The deposition pattern is controlled by varying the droplet size and velocity, as well as the pitch and hatch spacing of the lines produced.

research achievements in printing deposition-*CERAMICS*

- experiments were conducted with a mixture of zirconia powder, solvent, and other additives, which was printed from a 62 μm nozzle onto substrates 6.5 mm away. The authors found that on substrates that permitted substantial spreading of the deposited materials, neighboring drops would merge to form single, larger shapes, whereas on other substrates the individual dots would remain independent.

research achievements in printing deposition-*METALS*

- Much of the printing work related to metals has focused upon the use of printing for electronics applications—formation of traces, connections, and soldering.
- Liu and Orme et al. presented an overview of the progress made in solder droplet deposition for the electronics industry. Because solder has a low melting point, it is an obvious choice as a material for printing. They reported use of droplets of 25–500 µm, with results such as the IC test board, which has 70 µm droplets of Sn63/Pb37. In related work, a solder was jetted whose viscosity was approximately 1.3 cP, continuously jetted under a pressure of 138 kPa. Many of the results to which they refer are those of researchers at MicroFab Technologies, who have also produced solder forms such as 25 µm diameter columns.
- Orme et al. report on a process that uses droplets of Rose's metal (an alloy of bismuth, lead, and tin). They employ nozzles of diameter 25–150 µm with resulting droplets of 47–283 µm. In specific cases, parts with porosity as low as 0.03 % were formed without post-processing, and the microstructure formed is more uniform than that of standard casting. In discussion of this technology, considerations of jet disturbance, aerodynamic travel, and thermal effects are all presented.

research achievements in printing deposition-*METALS*

- Yamaguchi et al. used a piezoelectrically driven actuator to deposit droplets of an alloy (Bi–Pb–Sn–Cd–In), whose melting point was 47 °C. They heated the material to 55 °C and ejected it from nozzles 200 µm, 50 µm, and less than 8 µm in diameter. As expected, the finer droplets created parts with better resolution. The density, or "packing rate," of some parts reached 98 %.
- More recently, several research groups have demonstrated aluminum deposition . For example near-net shape components, with fairly simple shapes, have been formed from Al2024 alloy printed from a 100 µm orifice. In another example, pressure pulses of argon gas in the range of 20– 100 kPa were used to eject droplets of molten aluminum at the rate of 1–5 drops per second. To achieve this, the aluminum was melted at 750 °C and the substrate to 300 °C. The nozzle orifice used was 0.3 mm in diameter, with a resulting droplet size of 200–500 µm and a deposited line of width 1.00 mm and thickness 0.17 mm. The final product was a near-net shape part of density up to 92 %.

research achievements in printing deposition ***-SOLUTION AND DISPERSION based deposition***

- A number of investigators have used solution and dispersion techniques in accurate deposition of very small amounts of polymer in thin layers for mesoscale applications, such as polymer light-emitting displays, electronic components, and surface coatings and masks.
- Tay and Edirisinghe, for example, used ceramic powder dispersed in industrial methylated spirit with dispersant, binder, and plasticizer additives resulting in a material that was 4.5 % zirconia by volume. The resulting material had a viscosity of 3.0 cP at 20 °C and a shear rate of 1,000 s^{-1}.
- Zhao et al. tested various combinations of zirconia and wax carried in octane and isopropyl alcohol, with a dispersant added to reduce sedimentation. The viscosities of these materials were 0.6– 2.9 cP at 25 °C; the one finally selected was 14.2 % zirconia by volume.
- ***Drawback-***Despite the success of solution and dispersion deposition for these specific applications, however, there are some serious drawbacks, especially in considering the potential for building complex, large, 3D components. The low concentrations of polymer and solid used in the solutions and dispersions will restrict the *total amount of material* that can be deposited. Additionally, it can be difficult to control the *deposition pattern* of this material within the area of the droplet's impact.

Technical challenges of printing:

- material jetting already has a strong foothold in terms of becoming a successful AM technology. There are, however, some serious technical shortcomings that have prevented its development from further growth.

1. formulation of the liquid material

- If the material is not in liquid form to begin with, this may mean suspending particles in a carrier liquid, dissolving materials in a solvent, melting a solid polymer, or mixing a formulation of monomer or prepolymer with a polymerization initiator.
- In many cases, other substances such as surfactants are added to the liquid to attain acceptable characteristics. Entire industries are devoted to the mixture of inks for two-dimensional printing, and it is reasonable to assume that in the future this will also be the case for three-dimensional fabrication.

2. droplet formation

- To use inkjet deposition methods, the material must be converted from a continuous volume of liquid into a number of small discrete droplets.
- This function is often dependent upon a finely tuned relationship between the material being printed, the hardware involved, and the process parameters;
- Small changes to the material, such as the addition of tiny particles, can dramatically change its droplet forming behavior as well, as can changes to the physical setup.

Technical challenges of printing:

3. control of the deposition of droplets

- this involves issues of droplet flight path, impact, and substrate wetting or interaction
- In printing processes, either the print head or the substrate is usually moving, so the calculation of the trajectory of the droplets must take this issue into account.
- In addition to the location of the droplets' arrival, droplet velocity and size will also affect the deposition characteristics and must be measured and controlled via nozzle design and operation
- The quality of the impacted droplet must also be controlled: if smaller droplets, called satellites, break off from the main droplet during flight, then the deposited material will be spread over a larger area than intended and the deposition will not have well-defined boundaries.
- In the same way, if the droplet splashes on impact, forming what is called a "crown," similar results will occur. All of the effects will negatively impact the print quality of the printed material.

Technical challenges of printing:

3. control of the deposition of droplets

- the conversion of the liquid material droplets to solid geometry must be carefully controlled. material jetting relies on a phase change of the printed material. Examples of phase change modes employed in existing printing technologies are: solidification of a melted material (e.g., wax, solder), evaporation of the liquid portion of a solution (e.g., some ceramic approaches), and curing of a photopolymer (e.g., Objet, ProJet machines) or other chemical reactions.
- The phase change must occur either during droplet flight or soon after impact; the time and place of this conversion will also affect the droplet’s interaction with the substrate and the final deposition created. To further complicate the matter, drops may solidify nonuniformly, creating warpage and other undesirable results.

4. control the deposition of droplets on top of previously deposited layers

- The droplets will interact differently, for example, with a metal plate substrate than with a surface of previously printed wax droplets. To create substantive three-dimensional parts, each layer deposited must be fully bound to the previous layer to prevent delamination, but must not damage that layer while being created. Commercially available machines tend to approach this problem by employing devices that plane or otherwise smooth the surface periodically

Technical challenges of printing:

5. Operational considerations

- Operational considerations also pose a challenge in process planning for MJ. For example, because nozzles are so small, they often clog, preventing droplets from exiting. Much attention has been given to monitoring and maintaining nozzle performance during operation.
- Most machines currently in use go through purge and cleaning cycles during their builds to keep as many nozzles open as possible; they may also wipe the nozzles periodically.
- Some machines may also employ complex sensing systems to identify and compensate for malfunctioning or inconsistent nozzles. In addition, many machines, including all commercial AM machines, have replaceable nozzles in case of permanent blockage.
- To achieve the best print resolution, it is advantageous to produce many small droplets very close together. However, this requires high nozzle density in the print head, which is unattainable for many nozzle manufacturing processes. An alternative to nozzle density is to make multiple passes over the same area, effectively using process planning instead of hardware to create the desired effect. Even in cases where high nozzle density is possible, however, problems arise due to crosstalk— basically an “overlapping” of the thermal or pressure differentials used to drive adjacent nozzles.

printing process modelling:

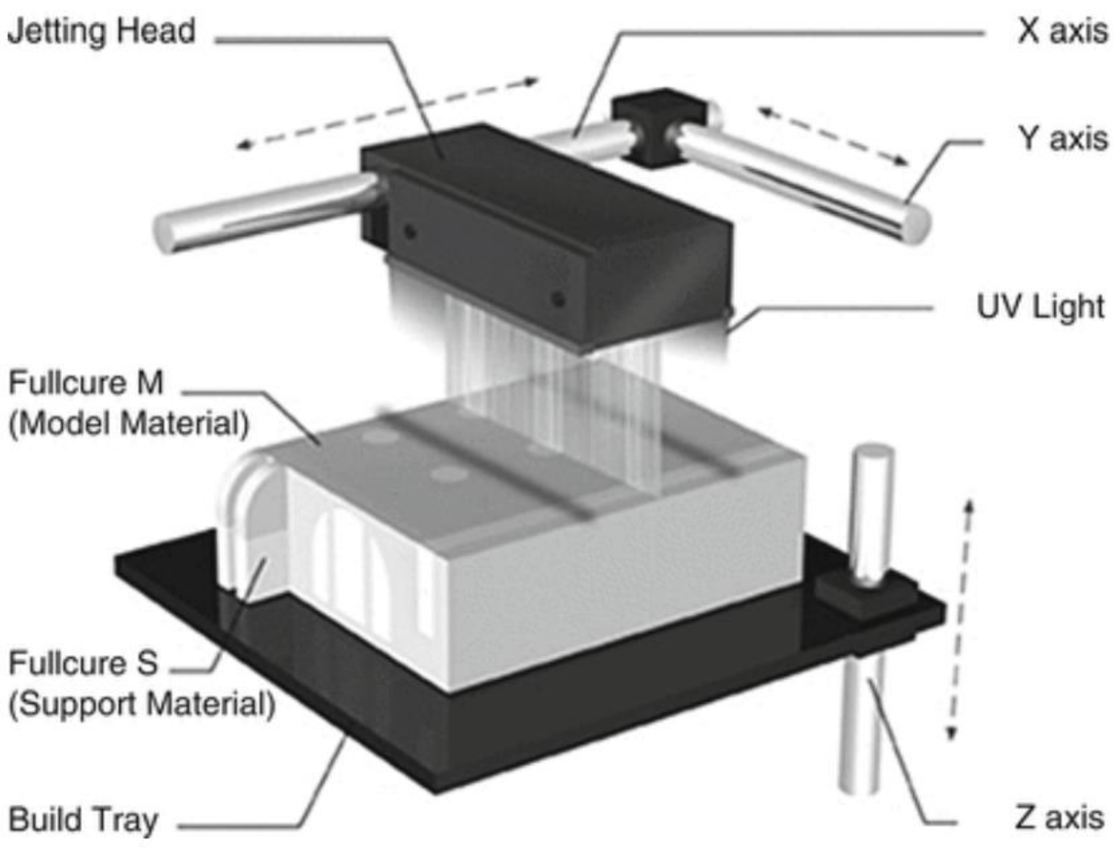
- Conservation of energy concepts provides an appropriate context for investigating droplet generation mechanisms for printing. Essentially, the energy imparted by the actuation method to the liquid must be sufficient to balance three requirements: fluid flow losses, surface energy, and kinetic energy.
- The losses originate from a conversion of *kinetic energy* to *thermal energy* due to the viscosity of the fluid within the nozzle; this conversion can be thought of as a result of internal friction of the liquid. The surface energy requirement is the additional energy needed to form the free surface of the droplet or jet. Finally, the resulting droplet or jet must still retain enough kinetic energy to propel the liquid from the nozzle towards the substrate.
- This energy conservation can be summarized as $E_{imparted} = E_{lss} + E_{surface} + E_{kinetic}$
- Energy conservation can also be thought of as a balance among the effects before the fluid crosses a boundary at the orifice of the nozzle and after it crosses that boundary. Before the fluid leaves the nozzle, the positive effect of the driving pressure gradient accelerates it, but energy losses due to viscous flow decelerate it. The kinetic energy with which it leaves the nozzle must be enough to cover the kinetic energy of the traveling fluid as well as the surface energy of the new free surface.

Material Jetting Machines:

- The three main companies involved in the development of the RP printing industry are still the main players offering printing-based machines: Solidscape, 3D Systems, and Stratasys (after their merger with Objet Geometries)
- Solidscape sells the T66 and T612, both descendants of the previous ModelMaker line and based upon the first-generation melted wax technique. Each of these machines employs two single jets—one to deposit a thermoplastic part material and one to deposit a waxy support material— to form layers 0.0005 in thick.
- Because of the slow and accurate build style as well as the waxy materials, these machines are often used to fabricate investment castings for the jewelry and dentistry industries.
- 3D Systems and Stratasys offer machines using the ability to print and cure acrylic photopolymers. g.
-

Material Jetting Machines:

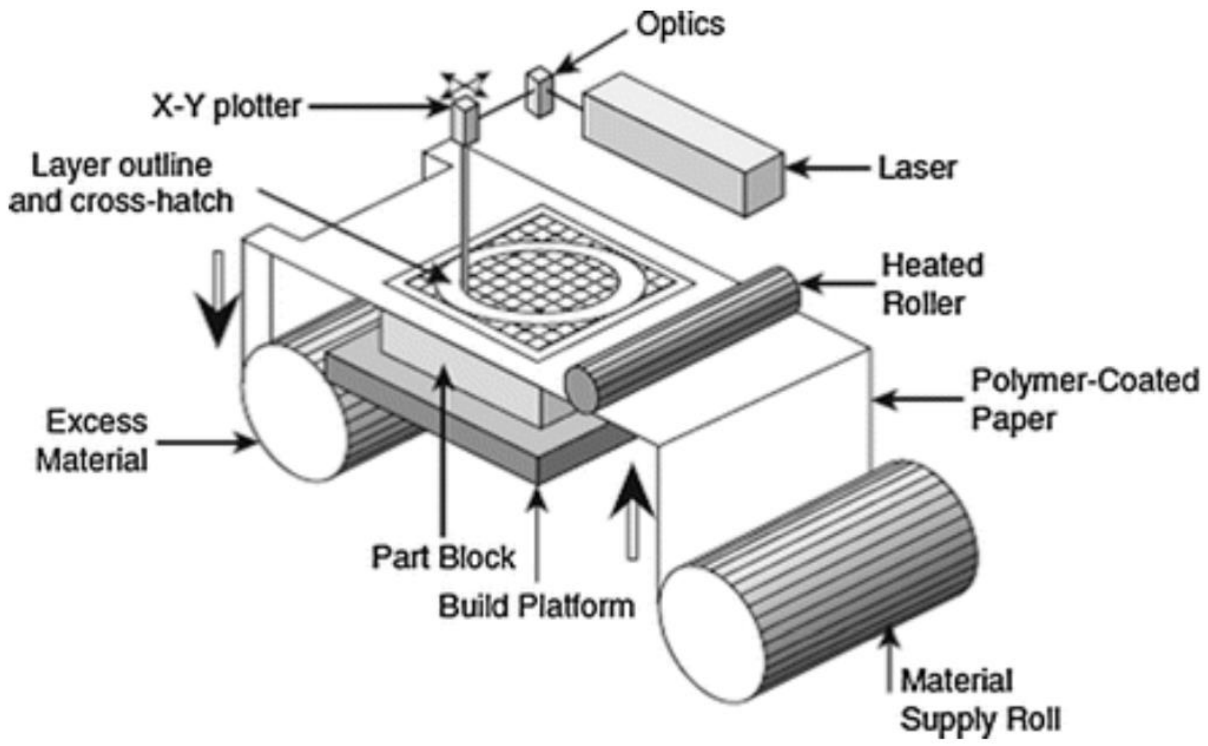
- Stratasys markets the Eden, Alaris, and Connex series of printers. These machines print a number of different acrylic-based photopolymer materials in 0.0006 in
- layers from heads containing 1,536 individual nozzles, resulting in rapid, line-wise deposition efficiency, as opposed to the slower, point-wise approach used by Solidscape. Each photopolymer layer is cured by ultraviolet light immediately as it is printed, producing fully cured models without post-curin
- Support structures are built in a gel-like material, which is removed by hand and water jetting [64]. See Fig. 7.14 for an illustration of Stratasys' Polyjet system, which is employed in all Eden machines.



Benefits of AM printing:

- Advantages
- *Low cost*- Printing machines are much lower in cost as compared AM machines, Perticularly ones that use lasers.
- *High speed*
- *Scalability*- High speed and scalability are related: by using print heads with hundreds or thousands of nozzles, it is possible to deposit a lot of material quickly and over a considerable area. Scalability in this context means that printing speed can be increased by adding another print head to a machine, a relatively easy task, much easier than adding another laser to a SL or SLS machine
- Ease of building parts in multiple materials.
- Capability of printing colours.

ADDITIVE MANUFACTURING
18ME741
MODULE 3
SHEET LAMINATION PROCESS



V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.

Module 3

Printing Processes: evolution of printing as an additive manufacturing process, research achievements in printing deposition, technical challenges of printing, printing process modelling, material modification methods, three-dimensional printing, advantages of binder printing

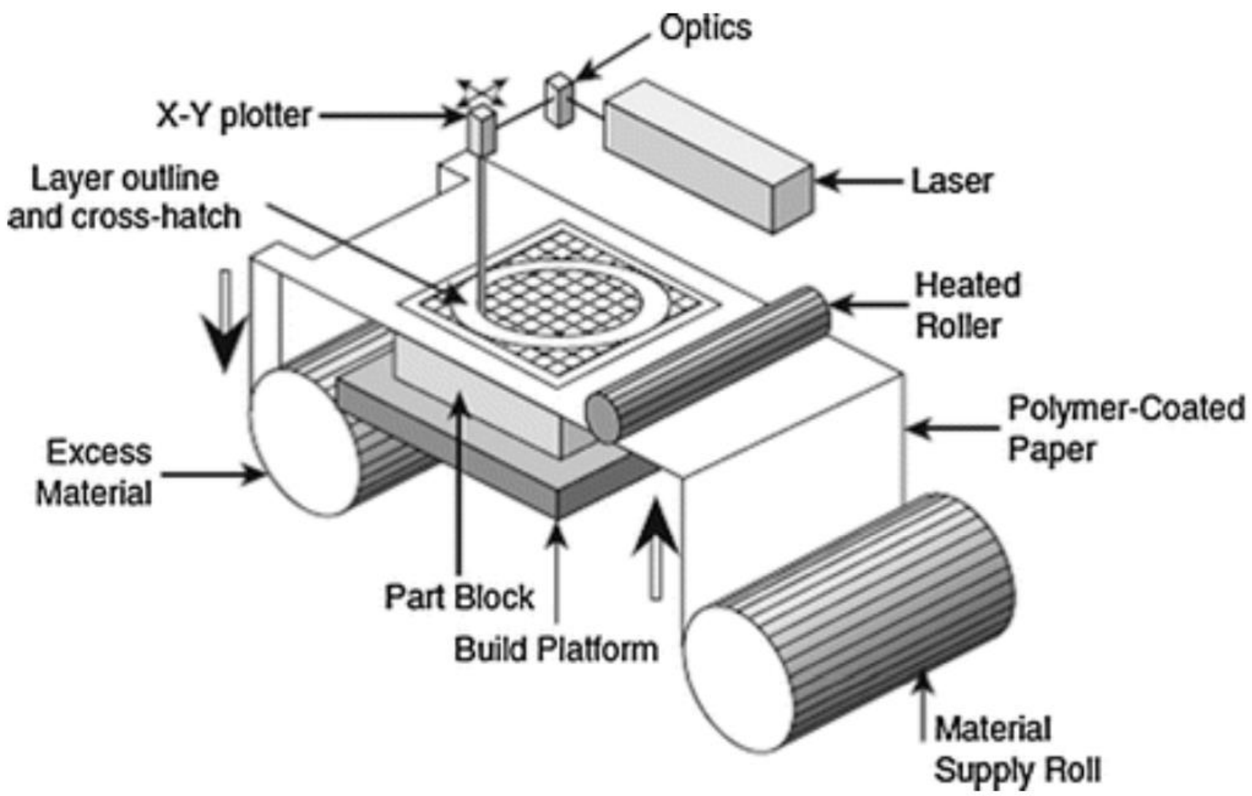
Sheet Lamination Processes: Materials, Laminated Object Manufacturing (LOM), Ultrasonic Consolidation (UC), Gluing, Thermal bonding, LOM and UC applications.

Beam Deposition Processes: introduction, general beam deposition process, description material delivery, BD systems , process parameters, typical materials and microstructure, processing–structure–properties relationships, BD benefits and drawbacks.

Direct Write Technologies: Background ,ink-based DW, laser transfer, DW thermals pray, DW beam deposition, DW liquid-phase direct deposition.

Sheet Lamination Processes

- One of the first commercialized (1991) additive manufacturing techniques was Laminated Object Manufacturing (LOM).
- LOM involved layer by layer lamination of paper material sheets, cut using a CO2 laser, each sheet representing one cross-sectional layer of the CAD model of the part. In LOM, the portion of the paper sheet which is not contained within the final part is sliced into cubes of material using a crosshatch cutting operation. A schematic of the LOM process can be seen in Figure.
- A number of other processes have been developed based on sheet lamination involving other build materials and cutting strategies.
- Because of the construction principle, only the outer contours of the parts are cut, and the sheets can be either cut and then stacked or stacked and then cut.



Sheet Lamination Processes

- These processes can be further categorized based on the mechanism employed to achieve bonding between layers:
  1. Gluing or adhesive bonding
  2. Thermal bonding
  3. Clamping
  4. Ultrasonic welding

Gluing or Adhesive Bonding

- The most popular sheet lamination techniques have included a paper build material bonded using a polymer-based adhesive.
- Paper thicknesses range from 0.07 to 0.2 mm.
- Potentially any sheet material that can be precisely cut using a laser or mechanical cutter and that can be bonded can be utilized for part construction.
- In some processes the laminate is bonded first to the substrate and is then formed into the crosssectional shape ("bond-then-form" processes). For other processes the laminate is first cut and then bonded to the substrate ("form-then-bond" processes).
- In **"bond-then-form"** processes, the building process typically consists of three steps in the following sequence: placing the laminate, bonding it to the substrate, and cutting it according to the slice contour. The original LOM machines used this process with adhesive-backed rolls of material.
- A heated roller passes across the sheet after placing it for each layer, melting the adhesive and producing a bond between layers.

Gluing or Adhesive Bonding

- A laser (or in some cases a mechanical cutting knife) designed to cut to a depth of one layer thickness cuts the cross-sectional outline based on the slice information. The unused material is left in place as support material and is diced using a crosshatch pattern into small rectangular pieces called “tiles” or “cubes.” This process of bonding and cutting is repeated until the complete part is built. After part construction, the part block is taken out and post-processed.

Gluing or Adhesive Bonding

Fig. 9.2 Support material removal for three golf balls made using a Solidimension machine, showing: (**a**) the balls still encased in a central region, being separated from the larger block of bonded material; (**b**) the support material is glued in an accordion-like manner so that the excess material can be pulled out easily as a continuous piece; and (**c**) the balls after complete removal of excess support material (Courtesy 3D Systems)

Gluing or Adhesive Bonding

- **Bond-then-form sheet lamination:** principles have also been successfully applied to fabrication of parts from metal, ceramic, and composite materials. In this case, rather than paper or polymer sheets, ceramic or metal-filled tapes are used as the build material to form green parts, and high-temperature furnace post-processing is used to debind and sinter the structure. These tapes are then used for part construction employing a standard sheet lamination process.

Gluing or Adhesive Bonding

- **form-then-bond processes :** In form-then-bond processes, sheet material is cut to shape first and then bonded to the substrate. This approach is popular for construction of parts in metallic or ceramic materials that are thermally bonded but implementation has primarily been at the research level.
- example of a glue-based form-then-bond process is the "***Offset Fabbing***" system patented by Ennex Corp., USA. In this process, a suitable sheet material with an adhesive backing is placed on a carrier and is cut to the outline of the desired cross section using a two-dimensional plotting knife. Parting lines and outlines of support structures are also cut. The shaped laminate is then placed on top of the previously deposited layers and bonded to it. This process continues until the part is complete.

Gluing or Adhesive Bonding

- The form-then-bond approach facilitates construction of parts with internal features and channels. Internal features and small channels are difficult or impossible with a bond-then-form approach because the excess material is solid and thus material inside internal features cannot be removed once bonded (unless the part is cut open).

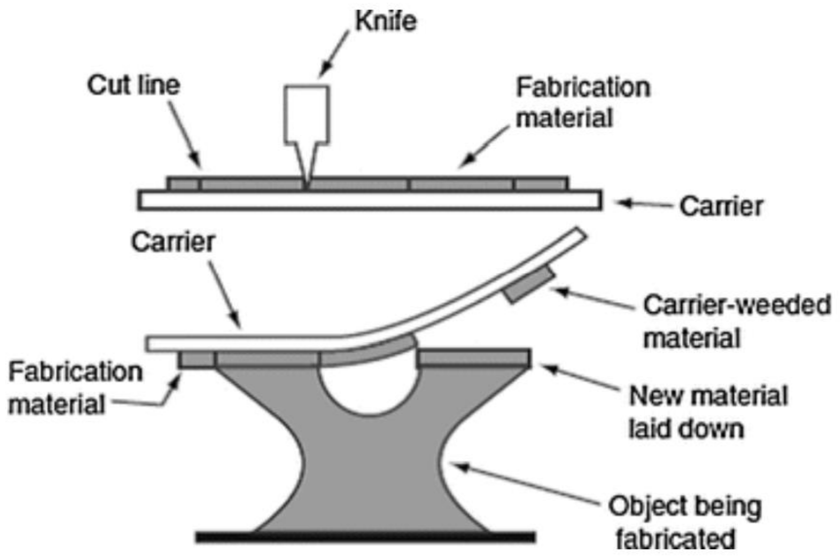


Fig. 9.3 Offset Fabbing system, Ennex Corp (http://www.ennex.com/fab/Offset/)

Gluing or Adhesive Bonding

- Another advantage of form-then-bond approaches is that there is no danger of cutting into the previous layers, unlike in bond-then-form processes where cutting occurs after placing the layer on the previous layer; thus, laser power control or knife pressure is less demanding. Also, the time-consuming and potentially damage-causing decubing step is eliminated. However, these processes require external supports for building overhanging features; some type of tooling or alignment system to ensure a newly bonded layer is registered properly with respect to the previous layers; or a flexible material carrier that can accurately place material regardless of geometry.

2. Thermal bonding

- Many organizations around the world have successfully applied thermal bonding to sheet lamination of functional metal parts and tooling.
- Yi et al. have successfully fabricated 3D metallic parts using precut 1- mm thick steel sheets that are then diffusion bonded. They demonstrated continuity in grain structure across sheet interfaces without any physical discontinuities.
- Himmer et al. produced aluminum injection molding dies with intricate cooling channels using Al 3003 sheets coated with 0.1- mm thick low-melting point Al 4343 (total sheet thickness 2.5 mm). The sheets were laser cut to an approximate, oversized cross section, assembled using mechanical fasteners, bonded together by heating the assembly in a nitrogen atmosphere just above the melting point of the Al 4343 coating material, and then finish machined to the prescribed part dimensions and surface finish.
- Himmer et al. also demonstrated satisfactory layer bonding using brazing and laser spot welding processes.

2. Thermal bonding

- Obikawa manufactured metal parts employing a similar process from thinner steel sheets (0.2 mm thick), with their top and bottom surface coated with a lowmelting-point alloy.
- Wimpenny et al. produced laminated steel tooling with conformal cooling channels by brazing laser-cut steel sheets. Similarly, Yamasaki [8] manufactured dies for automobile body manufacturing using 0.5-mm thick steel sheets. Each of these, and other investigators, have shown that thermally bonding metal sheets is an effective method for forming complex metal parts and tools, particularly those which have internal cavities and/or cooling channels.

4. Ultrasonic additive manufacturing:

- Ultrasonic Additive Manufacturing (UAM), also known as Ultrasonic Consolidation (UC), is a hybrid sheet lamination process combining ultrasonic metal seam welding and CNC milling, and commercialized by Solidica Inc., USA in 2000, and subsequently licensed to Fabrisonics (USA).
- In UAM, the object is built up on a rigidly held base plate bolted onto a heated platen, with temperatures ranging from room temperature to approximately 200°C. Parts are built from bottom to top, and each layer is composed of several metal foils laid side by side and then trimmed using CNC milling.
- UAM provides unique opportunities for manufacture of structures with complex internal geometries, manufacture of structures from multiple materials, fiber embedment during manufacture, and embedding of electronics and other features to form smart structures.

4. Ultrasonic additive manufacturing

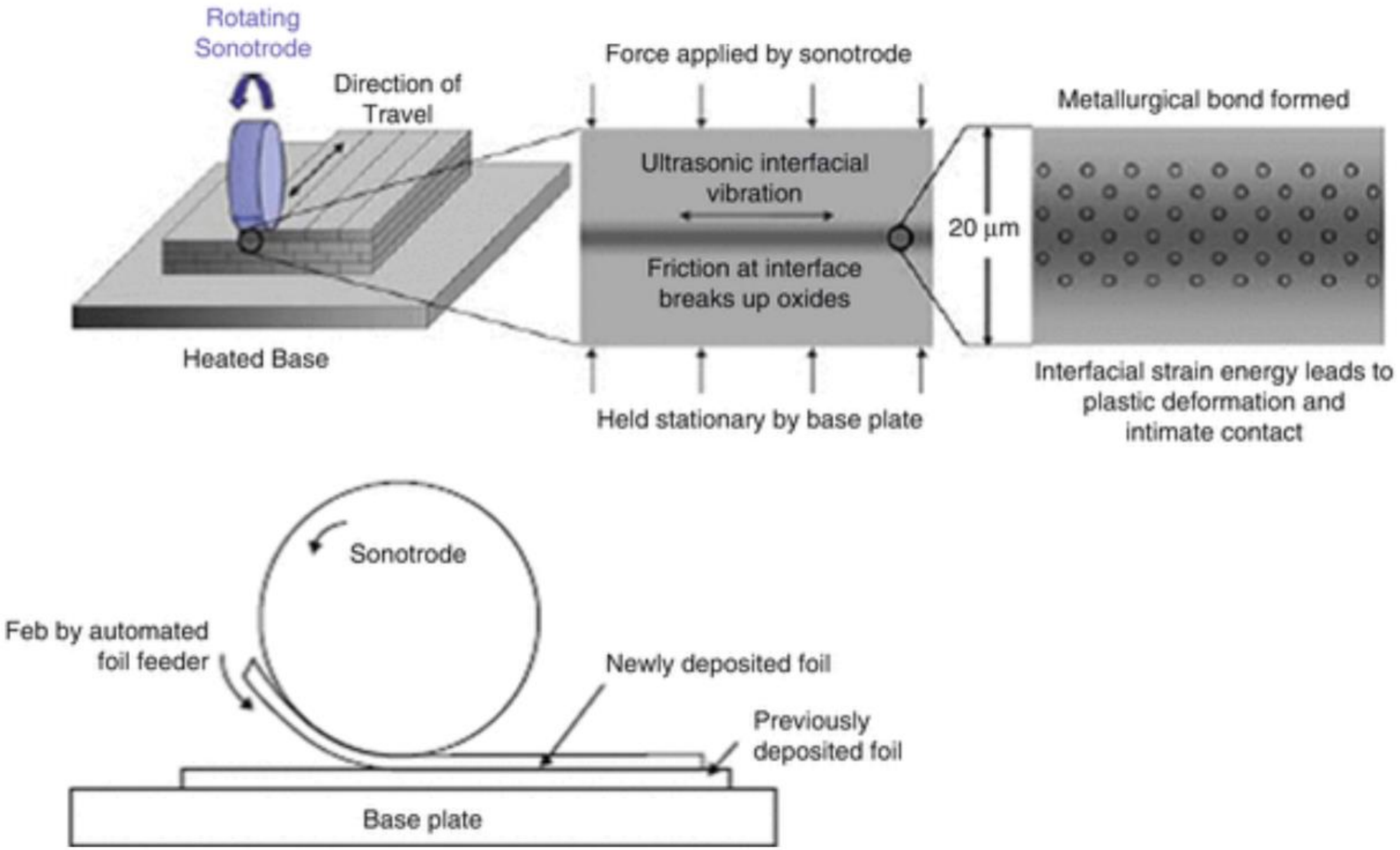


Fig. 9.7 Schematic of ultrasonic consolidation

4. Ultrasonic additive manufacturing

- During UAM, a rotating sonotrode travels along the length of a thin metal foil (typically 100–150 μm thick). The foil is held closely in contact with the base plate or previous layer by applying a normal force via the rotating sonotrode, as shown schematically in Fig. 9.7. The sonotrode oscillates transversely to the direction of motion, at a constant 20 kHz frequency and user-set oscillation amplitude. After depositing a foil, another foil is deposited adjacent to it. This procedure is repeated until a complete layer is placed.
- The next layer is bonded to the previously deposited layer using the same procedure. Typically four layers of deposited metal foils are termed one level in UAM. After deposition of one level, the CNC milling head shapes the deposited foils/layers to their slice contour (the contour does not need to be vertical, but can be a curved or angled surface, based on the local part geometry). This additive-subtractive process continues until the final geometry of the part is achieved.
- Thus, UAM is a bond-then-form process, where the forming can occur after each layer or after a number of layers, depending on the settings chosen by the user. Additionally, each layer is typically deposited as a combination of foils laid side by side rather than a single large sheet, as is typically practiced in sheet lamination processes.

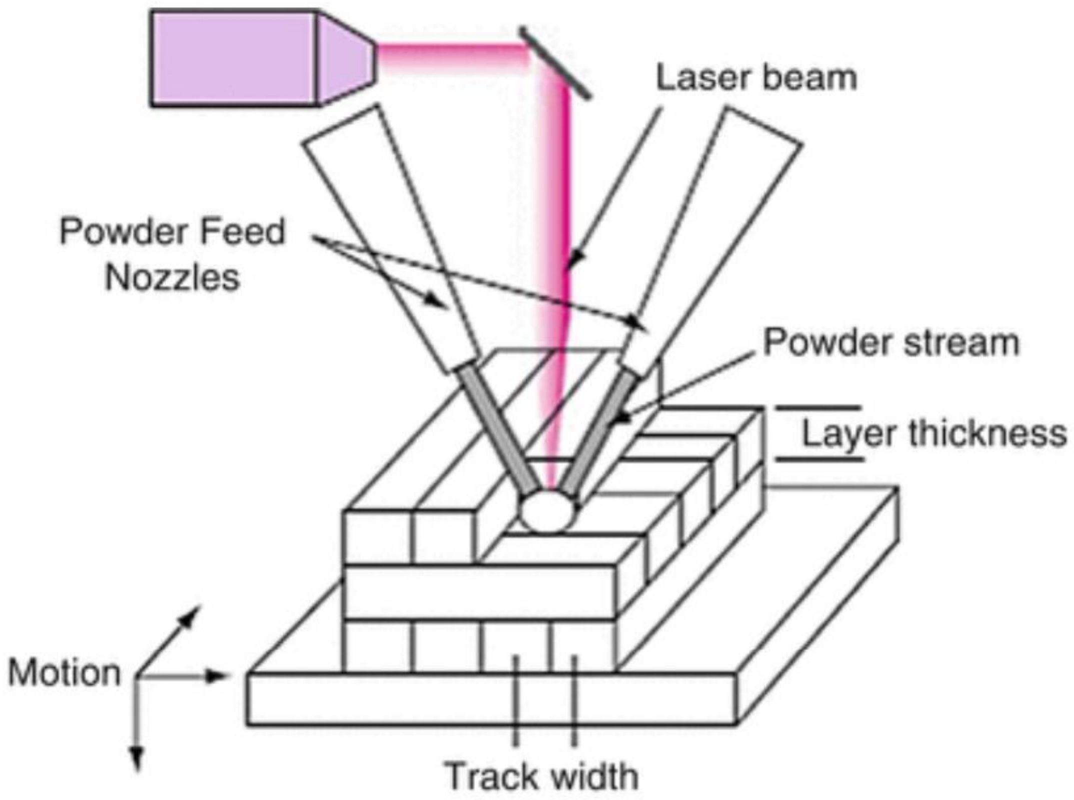
ADDITIVE MANUFACTURING

18ME741

MODULE 3

BEAM DEPOSITION PROCESS

V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.



Module 3

Printing Processes: evolution of printing as an additive manufacturing process, research achievements in printing deposition, technical challenges of printing, printing process modelling, material modification methods, three-dimensional printing, advantages of binder printing

Sheet Lamination Processes: Materials, Laminated Object Manufacturing (LOM), Ultrasonic Consolidation (UC), Gluing, Thermal bonding, LOM and UC applications.

Beam Deposition Processes: introduction, general beam deposition process, description material delivery, BD systems , process parameters, typical materials and microstructure, processing–structure–properties relationships, BD benefits and drawbacks.

Direct Write Technologies: Background ,ink-based DW, laser transfer, DW thermals pray, DW beam deposition, DW liquid-phase direct deposition.

Beam deposition process

- Directed energy deposition (DED) processes or ***<u>Metal deposition</u>*** process enable the creation of parts by melting material as it is being deposited.
- Although this basic approach can work for polymers, ceramics, and metal matrix composites, it is predominantly used for metal powders. Thus, this technology is often referred to as "metal deposition" technology.
- DED processes direct energy into a narrow, focused region to heat a substrate, melting the substrate and simultaneously melting material that is being deposited into the substrate's melt pool.
- Unlike powder bed fusion techniques DED processes are NOT used to melt a material that is pre-laid in a powder bed but are used to melt materials as they are being deposited.
- DED processes use a focused heat source (typically a laser or electron beam) to melt the feedstock material and build up three-dimensional objects.
- Each pass of the DED head creates a track of solidified material, and adjacent lines of material make up layers. Complex three-dimensional geometry requires either support material or a multi axis deposition head.

Working of DED process:

- most common type of DED system is a **Laser Based Metal Deposition (LBMD)** system optimized for metals.
- “deposition head” is utilized to deposit material onto the substrate. A deposition head is typically an integrated collection of laser optics, powder nozzle(s), inert gas tubing, and in some cases, sensors.
- Deposition is controlled by relative differential motion between the substrate and deposition head.
- In LBMD, the laser generates a small molten pool (typically 0.25–1 mm in diameter and 0.1–0.5 mm in depth) on the substrate as powder is injected into the pool. The powder is melted as it enters the pool and solidifies as the laser beam moves away.
- The passing of the beam creates a thin track of solidified metal deposited on and welded to the layer below. A layer is generated by a number of consecutive overlapping tracks.

Material Delivery:

- DED processes can utilize both powder and wire feedstock material.

Powder Feeding:

- Powder is the most versatile feedstock, and most metal and ceramic materials are readily available in powder form.
- However, not all powder is captured in the melt pool (e.g., less than 100 % powder capture efficiency), so excess powder is utilized. Care must be taken to ensure excess powder is recaptured in a clean state if recycling is desired.
- Powder is typically fed by first fluidizing a container of powder material (by bubbling up a gas through the powder and/or applying ultrasonic vibration) and then using a pressure drop to transfer the fluidized powder from the container to the laser head through tubing. Powder is focused at the substrate/laser interaction zone using either coaxial feeding, 4-nozzle feeding, or single nozzle feeding.

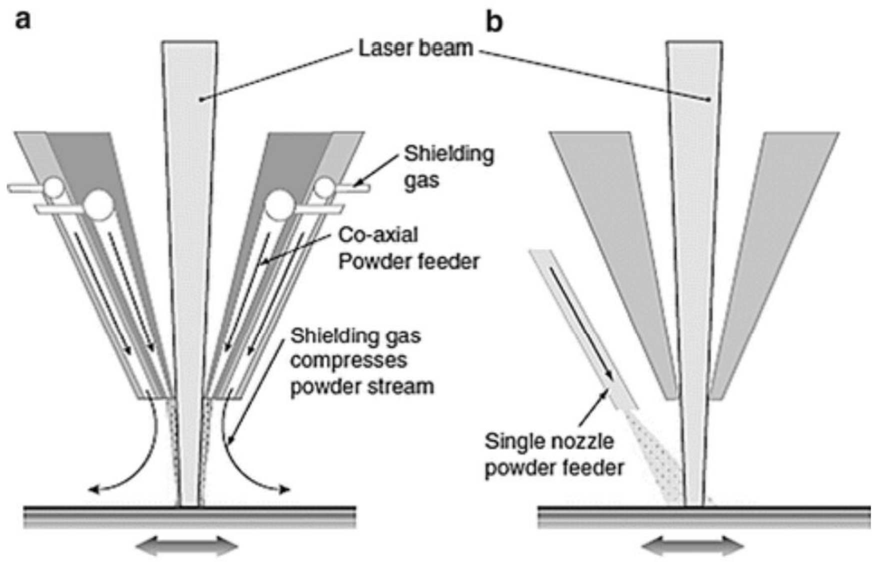


Fig. 10.5 Illustration of powder nozzle configurations: (**a**) coaxial nozzle feeding and (**b**) single-nozzle feeding

Material Delivery:

Wire Feeding:

- In the case of wire feeding, the volume of the deposit is always the volume of the wire that has been fed, and there is 100 % feedstock capture efficiency.
- Wires are most effective for simple geometries, “blocky” geometries without many thin/thick transitions, or for coating of surfaces.
- When complex, large, and/or fully dense parts are desired, geometry-related process parameters (such as hatch width, layer thickness, wire diameter, and wire feed rate) must be carefully controlled to achieve a proper deposit size and shape.

PROCESS PARAMETRS:

- Most AM machines come pre-programmed with optimized process parameters for materials sold by the machine vendors, but DED machines are sold as flexible platforms; and thus DED users must identify the correct process parameters for their application and material.
- Important process parameters are
  - track scan spacing
  - powder feed rate
  - beam traverse speed
  - beam power
  - beam spot size
- Powder feed rate, beam power, and traverse speed are all interrelated. for instance, an increase in feed rate has a similar effect to lowering the beam power. Likewise, increasing beam power or powder feed rate and decreasing traverse speed all increase deposit thickness.
- From an energy standpoint, as the scan speed is increased, the input beam energy decreases because of the shorter dwell time, resulting in a smaller melt pool on the substrate and more rapid cooling.
- Scan patterns also play an important role in part quality. , it may be desirable to change the scan orientation from layer to layer to minimize residual stress buildup. Track width hatch spacing must be set so that adjacent beads overlap, and layer thickness settings must be less than the melt pool depth to produce a fully dense product.
- To control deposit thickness, travel speed can be dynamically changed based upon sensor feedback. Similarly to control solidification rate, and thus microstructure and properties, the melt pool size can be monitored and then controlled by dynamically changing laser power.

Materials and Microstructure:

- **METALS:** metals with high reflectivity's and thermal conductivities are difficult to process, such as gold and some alloys of aluminum and copper. Most other metals are quite straightforward to process, unless there is improper atmospheric preparation and bonding is inhibited by oxide formation. Generally, metallic materials that exhibit reasonably good weldability are easy to process.
- **CERAMICS:** Ceramics are more difficult to process, as few can be heated to form a molten pool. Even in the event that a ceramic material can be melted, cracking often occurs during cooling due to thermal shock. Thus, most ceramics that are processed using DED are processed as part of a ceramic or metal matrix composite.
- For powder feedstock, the powder size typically ranges from approximately 20–150 μm. It is within this range that powder particles can be most easily fluidized and delivered using a flowing gas.
- When using elemental powders for generation of an alloy in-situ, the enthalpy of mixing plays an important role in determining the homogeneity of the deposited alloy. A negative enthalpy of mixing (heat release) promotes homogeneous mixing of constituent elements and, therefore, such alloy systems are quite suitable for processing using elemental powders.

Processing–Structure–Properties Relationships:

- Parts produced in DED processes exhibit high cooling rate cast microstructures. Processing conditions influence the solidification microstructure in ways that can be predicted in part by rapid solidification theory.
- For a specific material, solidification microstructure depends on the local solidification conditions, specifically the solidification rate and temperature gradient at the solid/liquid interface.
- By calculating the solidification rate and thermal gradient, the microstructure can be predicted based upon calibrated “solidification maps” from the literature.
- To better understand solidification microstructures in DED processes, Beuth and Klingbeil have developed procedures for calculating thermal gradients, G, and solidification rates, R, analytically and numerically.
- These calculated G and R values can then be plotted on solidification maps to determine the types of microstructures which can be achieved with different DED equipment, process parameters, and material combinations.

DED Benefits and Drawbacks:

- LIMITATIONS:
  - poor resolution and surface finish. An accuracy better than 0.25 mm and a surface roughness of less than 25 µm (arithmetic average) are difficult with most DED processes.
  - Slower build speed is another limitation. Build times can be very long for these processes, with typical deposition rates as low as 25–40 g/h.
  - DED processes cannot produce as complex of structures as powder bed fusion processes. This is due to the need for more dense support structures (or multiaxis deposition) for complex geometries and the fact that the larger melt pools in DED result in a reduced ability to produce small-scale features, greater surface roughness, and less accuracy.
  - Post-processing of parts made using DED typically involves removal of support structures or the substrate, if the substrate is not intended to be a part of the final component.
  - Finish machining operations because of relatively poor part accuracy and surface finish are commonly needed.
  - Stress relief heat treatment may be required to relieve residual stresses. In addition, depending upon the material, heat treatment may be necessary to produce the desired microstructure(s).

ADVANTAGES:

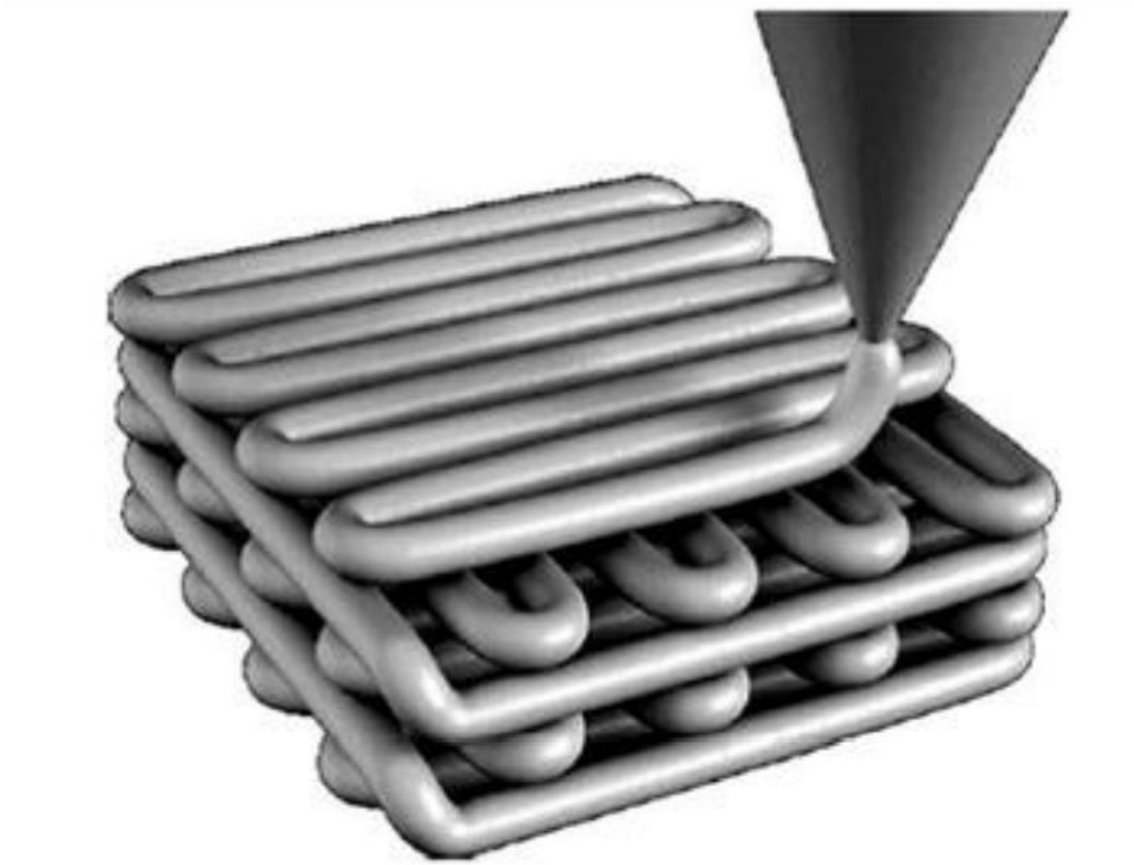
- DED processes are capable of producing fully dense parts with highly controllable microstructural features.
- These processes can produce functionally graded components with composition variations in the X, Y, and Z directions. DED offers the capability for unparalleled control of microstructure. The ability to change material composition and solidification rate by simply changing powder feeder mixtures and process parameters gives designers and researchers tremendous freedom.
- DED is capable of producing directionally solidified and single crystal structures.
- DED can be utilized for effectively repairing and refurbishing defective and service damaged high-technology components such as turbine blades.
- DED can be used to deposit thin layers of dense, corrosion resistant, and wear resistant metals on components to improve their performance and lifetime. One example includes deposition of dense Ti/TiC coatings as bearing surfaces on Ti biomedical implants.
- DED has been highly utilized by research organizations interested in the development of new material alloys and the application of new or advanced materials to new industries
- DED can be used to improve the life of injection molding or die casting dies by depositing wearresistant alloys in high-wear location.

ADDITIVE MANUFACTURING

18ME741

MODULE 3

DIRECT WRITE TECHNOLOGIES



V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.

Module 3

Printing Processes: evolution of printing as an additive manufacturing process, research achievements in printing deposition, technical challenges of printing, printing process modelling, material modification methods, three-dimensional printing, advantages of binder printing

Sheet Lamination Processes: Materials, Laminated Object Manufacturing (LOM), Ultrasonic Consolidation (UC), Gluing, Thermal bonding, LOM and UC applications.

Beam Deposition Processes: introduction, general beam deposition process, description material delivery, BD systems , process parameters, typical materials and microstructure, processing–structure–properties relationships, BD benefits and drawbacks.

Direct Write Technologies: Background ,ink-based DW, laser transfer, DW thermals pray, DW beam deposition, DW liquid-phase direct deposition.

- The term “Direct Write” (DW) in its broadest sense can mean any technology which can create two- or three-dimensional functional structures directly onto flat or conformal surfaces in complex shapes, without any tooling or masks.
- Although directed energy deposition, material jetting, material extrusion, and other AM processes fit this definition; for the purposes of distinguishing between the technologies discussed in this chapter and the technologies discussed elsewhere in this subject, we will limit our definition of DW to those technologies which are designed to build freeform structures or electronics with feature resolution in one or more dimensions below 50 μm.
- DW technologies are those processes which create meso-, micro-, and nanoscale structures using a freeform deposition tool.

Background:

- Although the initial use of some DW technologies predate the advent of AM, the development of DW technologies was dramatically accelerated in the 1990s by funding from the US Defense Advanced Research Projects Agency (DARPA) and its Mesoscopic Integrated Conformal Electronics (MICE) program.
- Many different DW technologies were developed or improved following funding from DARPA, including Matrix-Assisted Pulsed Laser Evaporation (MAPLE), nScrypt 3De, Maskless Mesoscale Materials Deposition (M3D, now known as Aerosol Jet), and Direct Write Thermal Spraying.
- As a result, most people have come to consider DW technologies as those devices which are designed to write or print passive or active electronic components (conductors, insulators, batteries, capacitors, antennas, etc.) directly from a computer file without any tooling or masks.
- DW devices have found broad applicability outside the direct production of circuitry and are now used to fabricate structures with tailored thermal, electrical, chemical, and biological responses, among other applications.

Background:

- DW processes can be subdivided into five categories,
  1. Ink based
  2. laser transfer
  3. Thermal spray
  4. Beam deposition
  5. liquid-phase and beam tracing processes.
- Most of these use a 3D programmable dispensing or deposition head to accurately apply small amounts of material automatically to form circuitry or other useful devices on planar or complex geometries.

Ink-Based DW :

- The most varied, least expensive, and most simple approaches to DW involve the use of liquid inks. These inks are deposited on a surface and contain the basic materials which become the desired structure.
- A significant number of ink types are available, including, among others:
  - Colloidal inks
  - Nanoparticle-filled inks
  - Fugitive organic inks
  - Polyelectrolyte inks
  - Sol–gel inks
- After deposition, these inks solidify due to evaporation, gelation, solvent-driven reactions, or thermal energy to leave a deposit of the desired properties.
- A large number of research organizations, corporations, and universities worldwide are involved in the development of new and improved DW inks.
- DW inks are typically either extruded as a continuous filament through a nozzle or deposited as droplets using a printing head.

Ink-Based DW :

- properties of DW inks include their ability to
  1. flow through the deposition apparatus
  2. retain shape after deposition
  3. either span voids/gaps or fill voids/gaps, as the case may be.
- To build three-dimensional DW structures it is highly desirable for the deposited inks to be able to form a predictable and stable 3D deposition shape, and to bridge small gaps.
- For 2D electronic structures built onto a surface, it is highly desirable for the deposited inks to maintain a constant and controllable cross section, as this will determine the material properties (e.g., conductivity, capacitance, etc.).

Ink-Based DW :

- Figure illustrates the two most common methodologies for DW ink dispensing.
    a) *Continuous dispensing*:-has the merits of a continuous cross-sectional area and a wider range of ink rheologies. Nozzle dispensing and quill processes both create continuous deposits from DW inks.
    b) *Droplet dispensing:*- can be parallelized and done in a very rapid fashion; however, the deposit cross sections are discontinuous, as the building blocks are basically overlapping hemispherical droplet splats, and the rheological properties must be within a tighter range. Printing and aerosol jet processes both create droplets from DW inks.

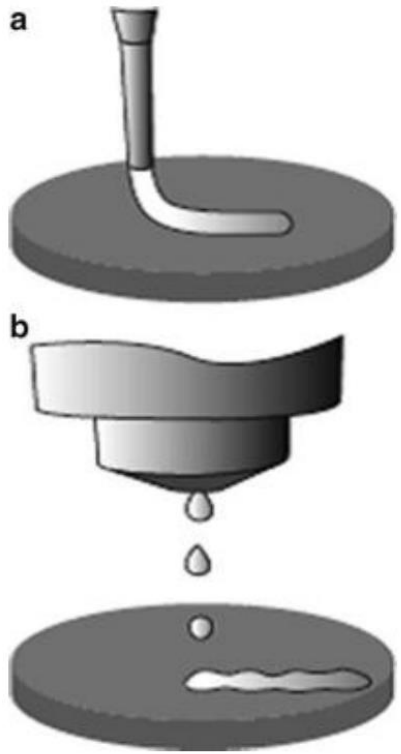


Fig. 11.1 Schematic illustration of direct ink writing techniques: (**a**) continuous filament writing and (**b**) droplet jetting [4] (courtesy nScrypt)

Laser Transfer DW :

- When a focused high-energy laser beam is absorbed by a material, that material may be heated, melted, ablated, or some combination thereof.
- In the case of ablation, there is direct evaporation (or transformation to plasma) of material. During ablation, a gas or plasma is formed, which expands rapidly as further laser energy is added. This rapid expansion can create a shock wave within a material or it can propel a material. By focusing the expansion of the material during ablation (utilizing shock waves produced by laser ablation) or taking advantage of rapid thermal expansion inherent with laser heating, materials can be accurately transferred in a very repeatable and accurate manner from one location to another.
- Laser transfer DW makes use of these phenomena by transferring material from a foil, tape, or plate onto a substrate.
- By carefully controlling the energy and location of the impinging laser, complex patterns of transferred material can be formed on a substrate.

Laser Transfer DW :

- Two different mechanisms for laser transfer are

1. laser transfer process where a transparent carrier (a foil or plate donor substrate which is transparent to the laser wavelength) is coated with a sacrificial transfer material and the dynamic release layer (the build material). The impinging laser energy ablates the transfer material (forming a plasma or gas), which propels the build material towards the substrate. The material impacts the substrate and adheres, forming a coating on the substrate. When using a pulsed laser, a precise amount of material can be deposited per pulse.

2. Figure 11.5b shows a slightly different mechanism for material transfer. In this case the laser pulse ablates a portion of the surface of a foil. This ablation and absorption of thermal energy creates thermal waves and shock waves in the material. These waves are transmitted through the material and cause a portion of the material on the opposing side to fracture from the surface in a brittle manner (known as spallation). The fractured material is propelled towards the substrate, forming a deposit coating on the substrate

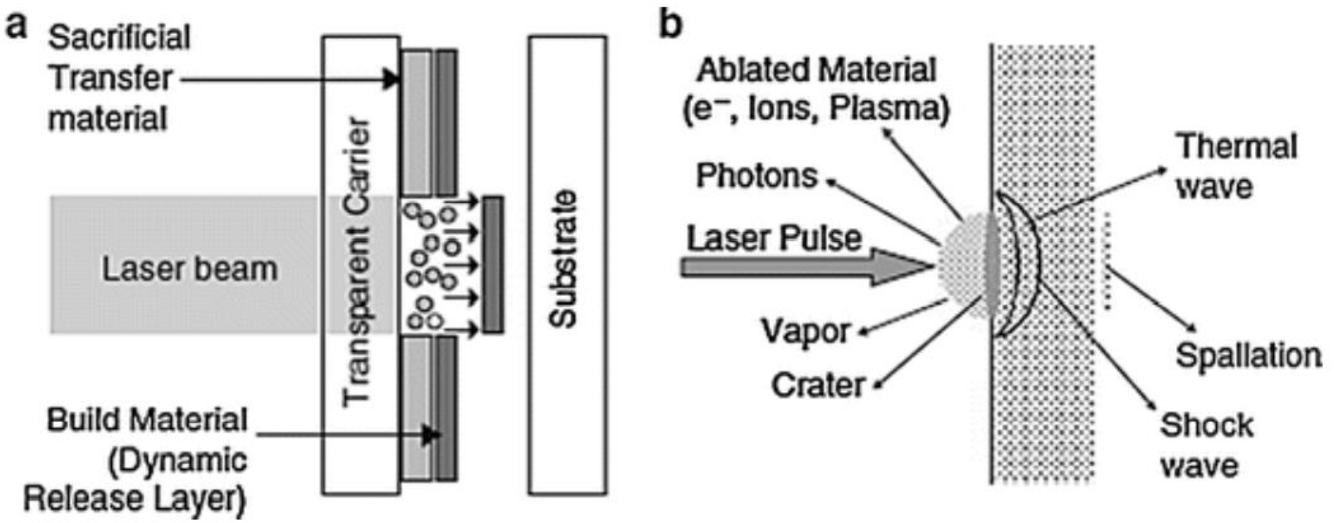


Fig. 11.5 (**a**) Mechanism for laser transfer using a sacrificial transfer material (based on [10]). (**b**) Mechanism for laser transfer using thermal shock and spallation (based on [11]) (courtesy Douglas B. Chrisey)

The Matrix-Assisted Pulsed Laser Evaporation Direct Write (MAPLEDW)

- In this process, a laser transparent quartz disc or polymer tape is coated on one side with a film (a few microns thick), which consists of a powdered material that is to be deposited and a polymer binder.
- The coated disc or tape is placed in close proximity and parallel to the substrate. A laser is focused onto the coated film.
- When a laser pulse strikes the coating, the polymer is evaporated and the powdered material is deposited on the substrate, firmly adhering to it.
- By appropriate control of the positions of both the ribbon and the substrate, complex patterns can be deposited. By changing the type of ribbon, multimaterial structures can be produced.
- Laser transfer processes have been used to create deposits of a wide variety of materials, including metals, ceramics, polymers, and even living tissues.
- ***drawbacks*** :of a laser transfer process are the need to form a tape with the appropriate transfer and/or deposit materials, and the fact that the unused portions of the tape are typically wasted.
- ***Benefits:*** The benefits of the laser transfer process are that it produces a highly repeatable deposit.
    - It can be as accurate as the laser scanners used to manipulate the laser beam,
    - Deposited materials may not need any further post-processing

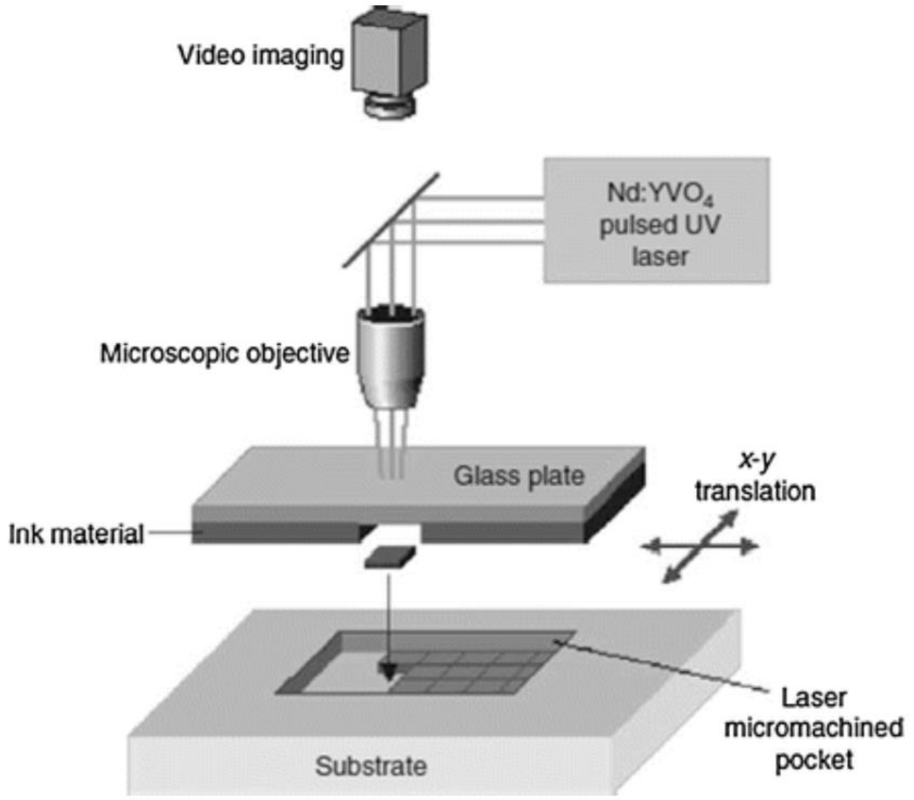
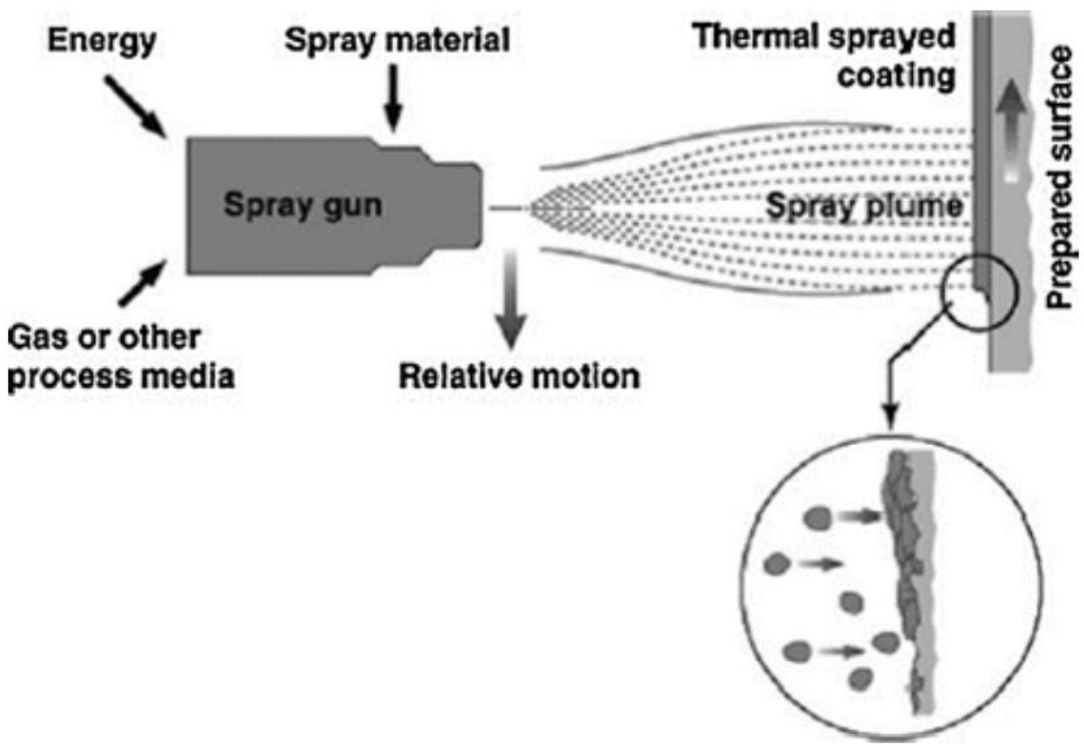


Fig. 11.6 Matrix-Assisted Pulsed Laser Evaporation Direct Write (MAPLE-DW) process [13] (Courtesy PennWell Corp., Laser Focus World)

Thermal spray DW:

- Thermal spray is a process that accelerates material to high velocities and deposits them on a substrate.
- Material is introduced into a combustion or plasma flame (plume) in powder or wire form.
- The plume melts and imparts thermal and kinetic energy to the material, creating high-velocity droplets.
- By controlling the plume characteristics and material state (e.g., molten or softened) it is possible to deposit a wide range of metals, ceramics, polymers, or composites thereof.
- Particles can be deposited in a solid or semisolid state, which enables the creation of useful deposits at or near room temperature.
- Thermal spray techniques for DW have been commercialized by *MesoScribe Technologies, Inc*.



Thermal spray DW:

- A deposit is built-up by successive impingement of droplets, which yield flattened, solidified platelets, referred to as splats. The deposit microstructure, and thus its properties, strongly depends on the processing parameters utilized.
- Key characteristics of thermal spray DW include:
  1. A high volumetric deposition rate
  2. Material flexibility
  3. Useful material properties in the as-deposited state (without thermal treatment or curing)
  4. Moderate thermal input during processing, allowing for deposition on a variety of substrates.

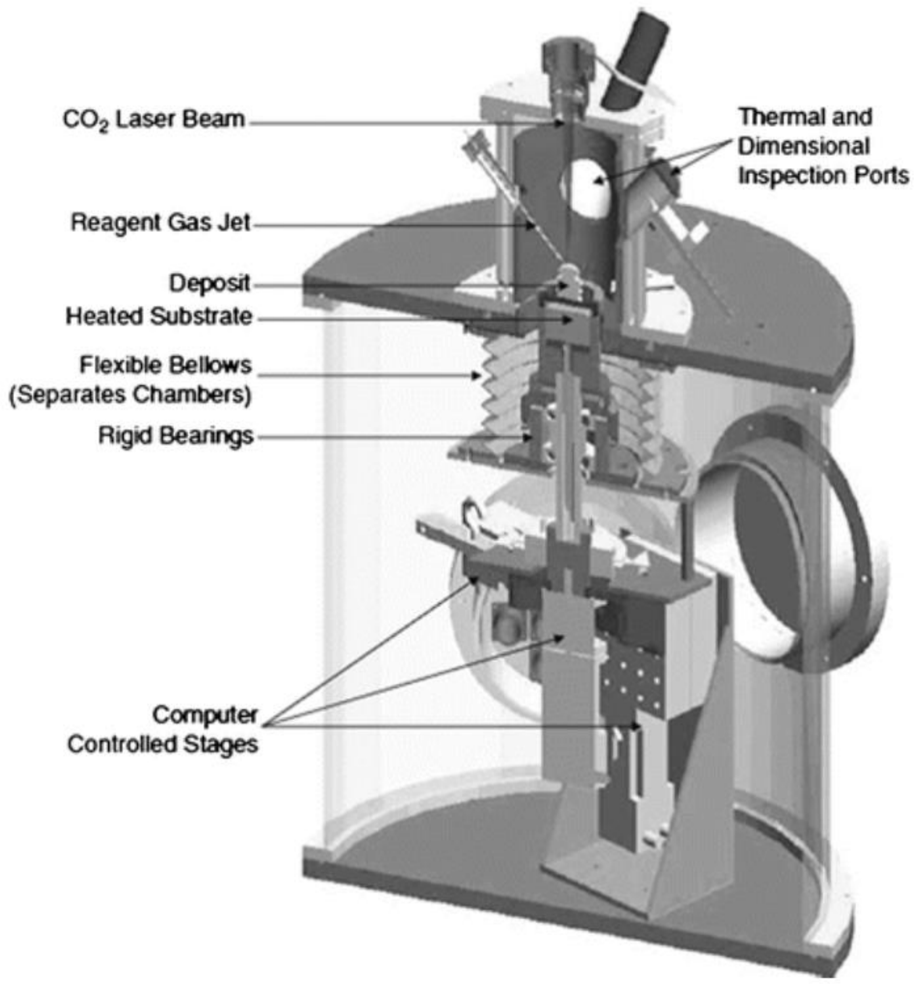
Beam deposition DW:

- Several direct write procedures have been developed based upon vapor deposition technologies using, primarily, thermal decomposition of precursor gases.
- Vapor deposition technologies produce solid material by condensation, chemical reaction, or conversion of material from a vapor state.
- n the case of chemical vapor deposition (CVD), thermal energy is utilized to convert a reactant gas to a solid at a substrate. In the regions where a heat source has raised the temperature above a certain threshold, solid material is formed from the surrounding gaseous precursor reactants.
- Types
  1. Laser Chemical Vapor Deposition(CVD)
  2. Focused Ion Beam CVD
  3. Electron Beam CVD

Beam deposition DW:

Laser CVD:

- Laser Chemical Vapor Deposition (LCVD) is a DW process which uses heat from a laser to selectively transform gaseous reactants into solid materials. In some systems, multiple gases can be fed into a small reactant chamber at different times to form multimaterial structures, or mixtures of gases with varying concentrations can be used to form gradient structures. Sometimes flowing jets of gas are used to create a localized gaseous atmosphere, rather than filling a chamber with the gaseous precursor materials.
- The resolution of an LCVD deposit is related to the laser beam diameter, energy density, and wavelength (which directly impact the size of the heated zone on the substrate) as well as substrate thermal properties.
- Depending on the gases present at the heated reactive zone, many different metals and ceramics can be deposited, including composites. LCVD has been used to deposit carbon fibers and multilayered carbon structures in addition to numerous types of metal and ceramic structures.
- LCVD systems are capable of depositing many types of materials, including carbon, silicon carbide, boron, boron nitride, and molybdenum onto various substrates including graphite, grafoil, zirconia, alumina, tungsten, and silicon

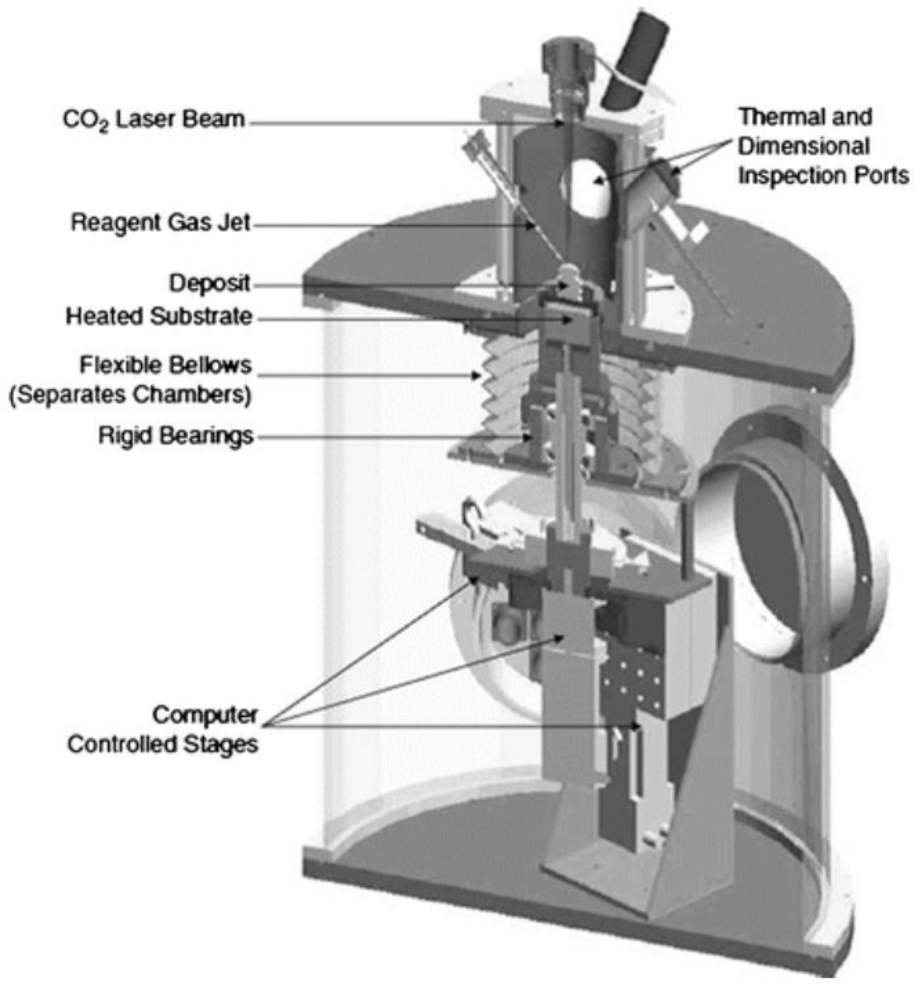


The LCVD system developed at Georgia Tech

Beam deposition DW:

Laser CVD:

- A LCVD system developed at the Georgia Institute of Technology is displayed in Fig.
- This design constrains the reactant gas (which is often highly corrosive, and/or biologically harmful) to a small chamber that is separated from the motion controllers and other mechanisms.
- This small, separated reaction chamber has multiple benefits, including an ability to quickly change between reagent gas materials for multimaterial deposition, and better protection of the hardware from corrosion.
- By monitoring the thermal and dimensional characteristics of the deposit, process parameters can be controlled to create deposits of desired geometry and material properties.



The LCVD system developed at Georgia Tech

Beam deposition DW:

Focused Ion Beam CVD:

- A focused ion beam (FIB) is a beam of ionized gallium atoms created when a gallium metal source is placed in contact with a tungsten needle and heated. Liquid gallium wets the needle, and the imposition of a strong electric field causes ionization and emission of gallium atoms. These ions are accelerated and focused in a small stream (with a spot size as low as a few nanometers) using electrostatic lenses. A FIB is similar in conceptualization to an electron beam source, and thus FIB is often combined with electron beams, such as in a dual-beam FIB-scanning electron microscope system.
- Direct write deposition using FIB is possible in a manner similar to LCVD. By scanning the FIB source over a substrate in the presence of CVD gaseous precursors, solid materials are deposited onto the substrate.These deposits can be submicron in size and feature resolution.
- **Application:** FIB CVD for DW has been used to produce combinations of metallic and dielectric materials to create three-dimensional structures and circuitry. In addition, FIB CVD is being used in the integrated circuits (IC) industry to repair faulty circuitry.

Beam deposition DW:

Electron Beam CVD:

- Electron beams can be used to induce CVD in a manner similar to FIB CVD and LCVD. Electron beam CVD is slower than laser or FIB CVD; however, FIB CVD and electron beam CVD both have a better resolution than LCVD.

Liquid-Phase Direct Deposition :

- Similarly to the vapor techniques described above, thermal or electrical energy can be used to convert liquid-phase materials into solid materials. These thermochemical and electrochemical techniques can be applied in a localized manner to create prescribed patterns of solid material.
- **Advantages:** Thermochemical and electrochemical techniques can be used to produce complex-geometry solids at small length scales from any metal compatible with thermochemical or electrochemical deposition, respectively. These processes are also compatible with some ceramics. However, these approaches are not available commercially and may have few benefits over the other DW techniques described above.

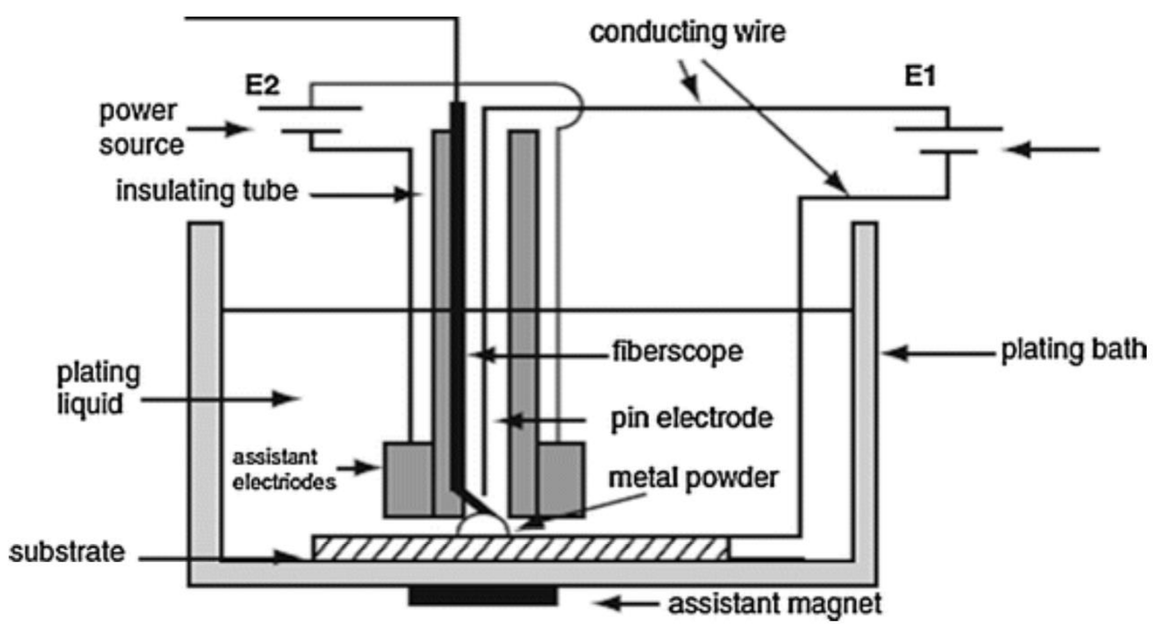
1. ***ThermoChemical Liquid Deposition (TCLD):***

- In TCLD, liquid reactants are sprayed through a nozzle onto a hot substrate. The reactants thermally decompose or react with one another on the hot surface to form a solid deposit on the substrate. By controlling the motion of the nozzle and the spraying parameters, a 3D shape of deposited material can be formed. This is conceptually similar to the ink-based DW approaches discussed above, but requires a high-temperature substrate during deposition.
- Drawbacks of TCLD-based approaches are the need for a heated substrate and the use of chemical precursors which may be toxic or corrosive.

Liquid-Phase Direct Deposition :

2. Electrochemical Liquid Deposition (ECLD):

- In ECLD, a conductive substrate is submerged in a plating bath and connected to a DC power source as the cathode, as in Fig. A pin made up of the material to be deposited is used as the anode. By submerging the pin in the bath near the substrate and applying an appropriate voltage and current, electrochemical decomposition and ion transfer results in a deposit of the pin material onto the substrate. By moving the pin, a prescribed geometry can be traced. As electrochemical plating is a slow process, the volumetric rate of deposition for ELCD can be increased by putting a thin layer of metal powder in the plating bath on the surface of the substrate.
- In this case, the deposited material acts as a binder for the powdered materials, and the volumetric rate of deposition is significantly increased.
- Drawbacks of ECLD-based approaches include the slow deposition rate of electrochemical processes and the fact that, when used as a binder for powders, the resultant product is porous and requires further processing (such as sintering or infiltration) to achieve desirable properties.



Applications of Direct Write Technologies:

- variety of materials which are available, including semiconductors, dielectric polymers, conductive metals, resistive materials, piezoelectrics, battery elements, capacitors, biological materials, and others.
- These materials can be deposited onto various substrate materials including plastic, metal, ceramic, glass, and even cloth.
- *Broad application:*The combination of these types of materials and substrates means that the applications for DW are extremely broad.
- *fabrication of sensors:* DW approaches have been used to fabricate thermocouples, thermistors, magnetic flux sensors, strain gages, capacitive gages, crack detection sensors, accelerometers, pressure gages, and more.
- *antenna fabrication:* Since DW, like other AM techniques, enables fabrication of complex geometries directly from CAD data, antenna designs of arbitrary complexity can be made on the surface of freeform objects; including, for instance, fractal antennas on conformal surfaces.

Applications of Direct Write Technologies:

- *a freeform tool to connect combinations of electronic components on freeform surfaces:* One area where this is particularly useful is in harsh environments.
- In this example, direct write thermal spray is used as a method for producing and connecting a series of electronic components that monitor and feed back information about the state of a turbine blade. A thermocouple, labeled High-Temperature Sensor in the figure, is deposited on the hot region of the blade, whereas the supporting electronics are deposited on the cold regions of the blade. DW-produced conductors are used to transmit signals between regions and components.

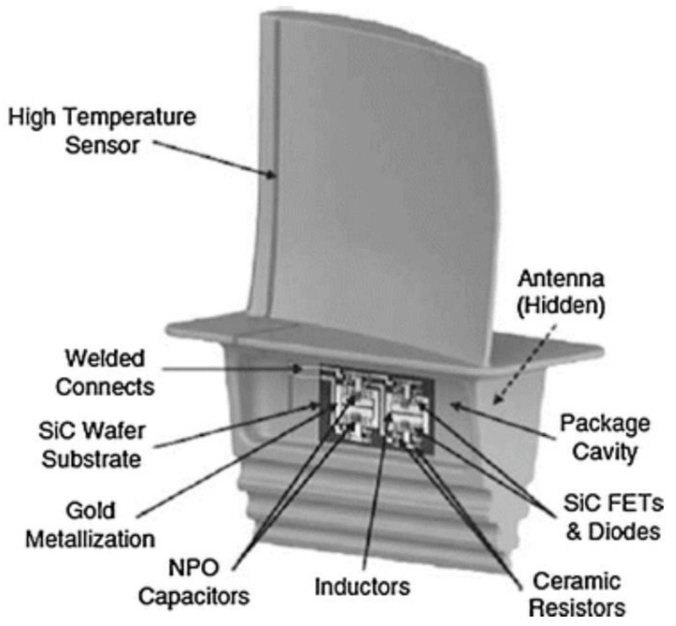


Fig. 11.12 A direct write sensor and associated wiring on a turbine blade structure. Signal conditioning electronics are positioned on a more shielded spot (Courtesy MesoScribe Technologies, Inc. and Arkansas Power Electronics Int.)

ADDITIVE MANUFACTURING

18ME741

MODULE 4

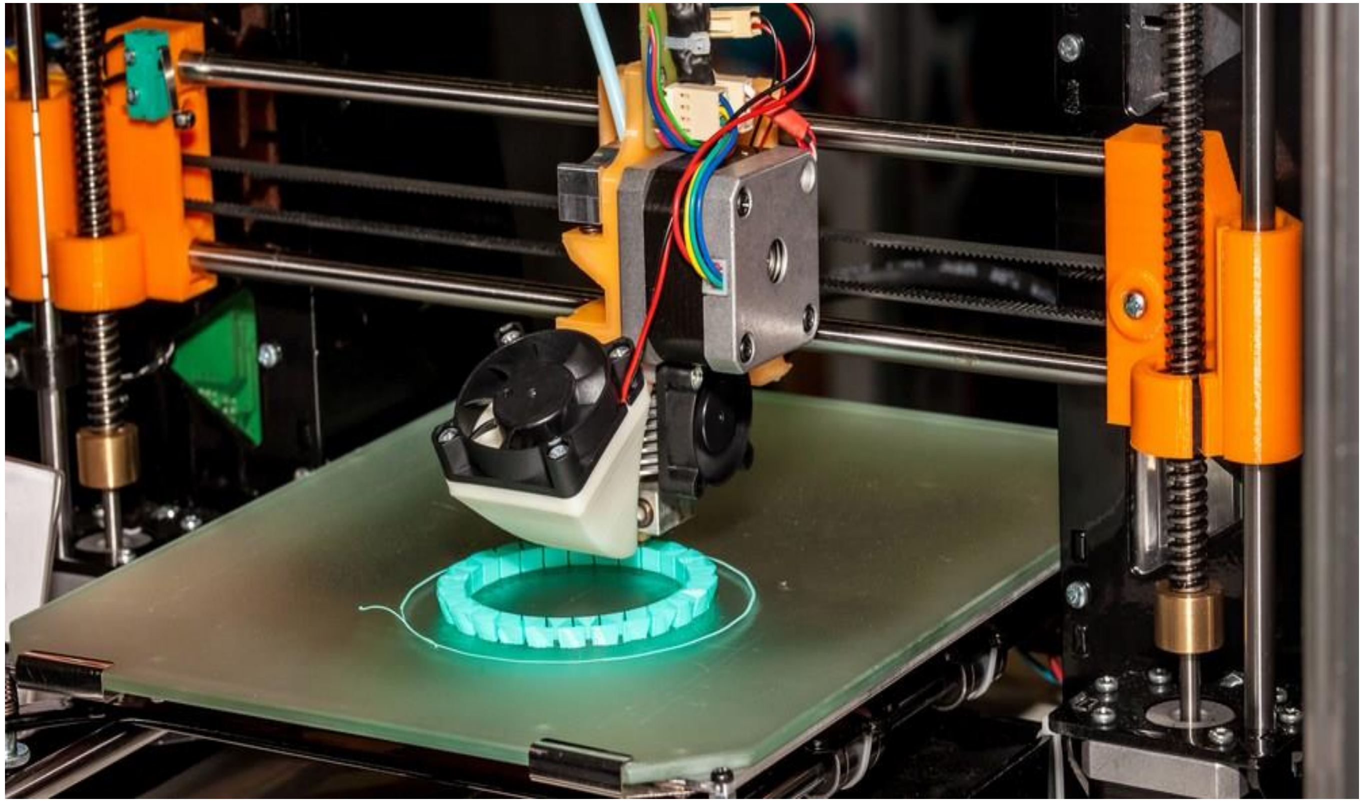
GUIDELINES FOR PROCESS SELECTION

V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.



Module 4

Guidelines for Process Selection: Introduction, selection methods for apart, challenges of selection, example system for preliminary selection, production planning and control.

Software issues for Additive Manufacturing: Introduction, preparation of cad models – the STL file, problems with STL files, STL file manipulation.

Post- Processing: Support material removal, surface texture improvements, preparation for use as a pattern, property enhancements using non-thermal techniques and thermal techniques.

INTRODUCTION

- AM processes, like all materials processing, are constrained by material properties, speed, cost, and accuracy. The performance capabilities of materials and machines lag behind conventional manufacturing technology (e.g., injection molding machinery), although the lag is decreasing. Speed and cost, in terms of time to market, are where AM technology contributes, particularly for complex or customized geometries.
- With the growth of AM, there is going to be increasing demand for software that supports making decisions regarding which machines to use and their capabilities and limitations for a specific part design.
- In particular, software systems can help in the decision-making process for capital investment of new technology, providing accurate estimates of cost and time for quoting purposes, and assistance in process planning.
- This chapter deals with three typical problems involving AM that may benefit from decision support:
  1. *Quotation support.* Given a part, which machine and material should I use to build?
  2. *Capital investment support*. Given a design and industrial profile, what is the best machine that I can buy to fulfill my requirements?
  3. *Process planning support*. Given a part and a machine, how do I set it up to work in the most efficient manner alongside my other operations and existing tasks?

Selection Methods for a Part:

1. Decision Theory**:**

- Decision theory has a rich history, evolving in the 1940s and 1950s from the field of economics.
- Although there are many approaches taken in the decision theory field, the focus in this chapter will be only on the utility theory approach.
- there are three elements of any decision
  - Options—the items from which the decision maker is selecting
  - Expectations—of possible outcomes for each option
  - Preferences—how the decision maker values each outcome
- Assume that the set of decision options is denoted as $A = \{A_1, A_2, \ldots, A_n\}$. In engineering applications, one can think of outcomes as the performance of the options as measured by a set of evaluation criteria. More specifically, in AM selection, an outcome might consist of the time, cost, and surface finish of a part built using a certain AM process, while the AM process itself is the option. Expectations of outcomes are modeled as functions of the options, $X = g(A)$, and may be modeled with associated uncertainties.
- Preferences model the importance assigned to outcomes by the decision maker. For example, a designer may prefer low cost and short turn-around times for a concept model, while being willing to accept poor surface finish.
- F. Mistree, J.K. Allen, and their coworkers have been developing the Decision Support Problem (DSP) Technique over the last 20 years. The advantages of DSPs, compared with other decision formulations, are that they provide a means for mathematically modeling design decisions involving multiple objectives and supporting human judgment in designing systems.

Selection Methods for a Part:

2. Approaches to Determining Feasibility:

- The problem of identifying suitable materials and AM machines with which to fabricate a part is surprisingly complex.
- there are many possible applications for an AM part. For each application, one should consider the suitability of available materials, fabrication cost and time, surface finish and accuracy requirements, part size, feature sizes, mechanical properties, resistance to chemicals, and other application specific considerations.
- to solve AM machine and process chain selection problems, one must navigate the wide variety of materials and machines, comparing one's needs to their capabilities, while ensuring that the most up-to-date information is available.
- To date, most approaches to determining feasibility have taken a knowledge-based approach in order to deal with the qualitative information related to AM process capability.
- One of the better developed approaches was presented by ***Deglin and Bernard***. They presented a knowledge based system for the generation, selection, and process planning Of production AM processes.
- Their approach utilized two reasoning methods, case-based and the bottom-up generation of processes; the strengths of each compensated for the other's weaknesses. Their system was developed on the KADVISER platform and utilized a relational database system with extensive material, machine, and application information.
- A group at the ***National University of Singapore (NUS)*** developed an AM decision system that was integrated with a database system. Their selection system was capable of identifying feasible material/machine combinations, estimating manufacturing cost and time, and determining optimal part orientations. From the feasible material/machines, the user can then select the most suitable combination. Their approach to determining feasible materials and processes is broadly similar to the work of Deglin and Bernard. The NUS group utilized five databases, each organized in a hierarchical, object-oriented manner: three general databases (materials, machines, and applications) and two part-specific databases (geometric information and model specifications).

Selection Methods for a Part:

3. Approaches to Selection:

- The basic advantages of using (Decision support problem) DSPs of any type lie in providing context and structure for engineering problems, regardless of complexity, they also facilitate the recording of viewpoints associated with these decisions, for completeness and future reference, and evaluation of results through post solution sensitivity analysis.
- The standard Selection Decision Support Problem (s-DSP) has been applied to many engineering problems and has recently been applied to AM selection. The word formulation of the standard s-DSP is given below.

Given:	Set of AM processes/machines and materials (alternatives)
Identify:	Set of evaluation attributes. Create scales and determine importances.
Rate:	Each alternative relative to each attribute.
Rank:	AM methods from most to least promising

Word formulation of the selection decision support problem

- Note that the decision options for AM selection are feasible material-process combinations. Expectations are determined by rating the options against the attributes. Preferences are modeled using simple importance values. Rank ordering of options is determined using a weighted-sum expression of importance and attribute ratings. An extension to include utility theory has recently been accomplished.

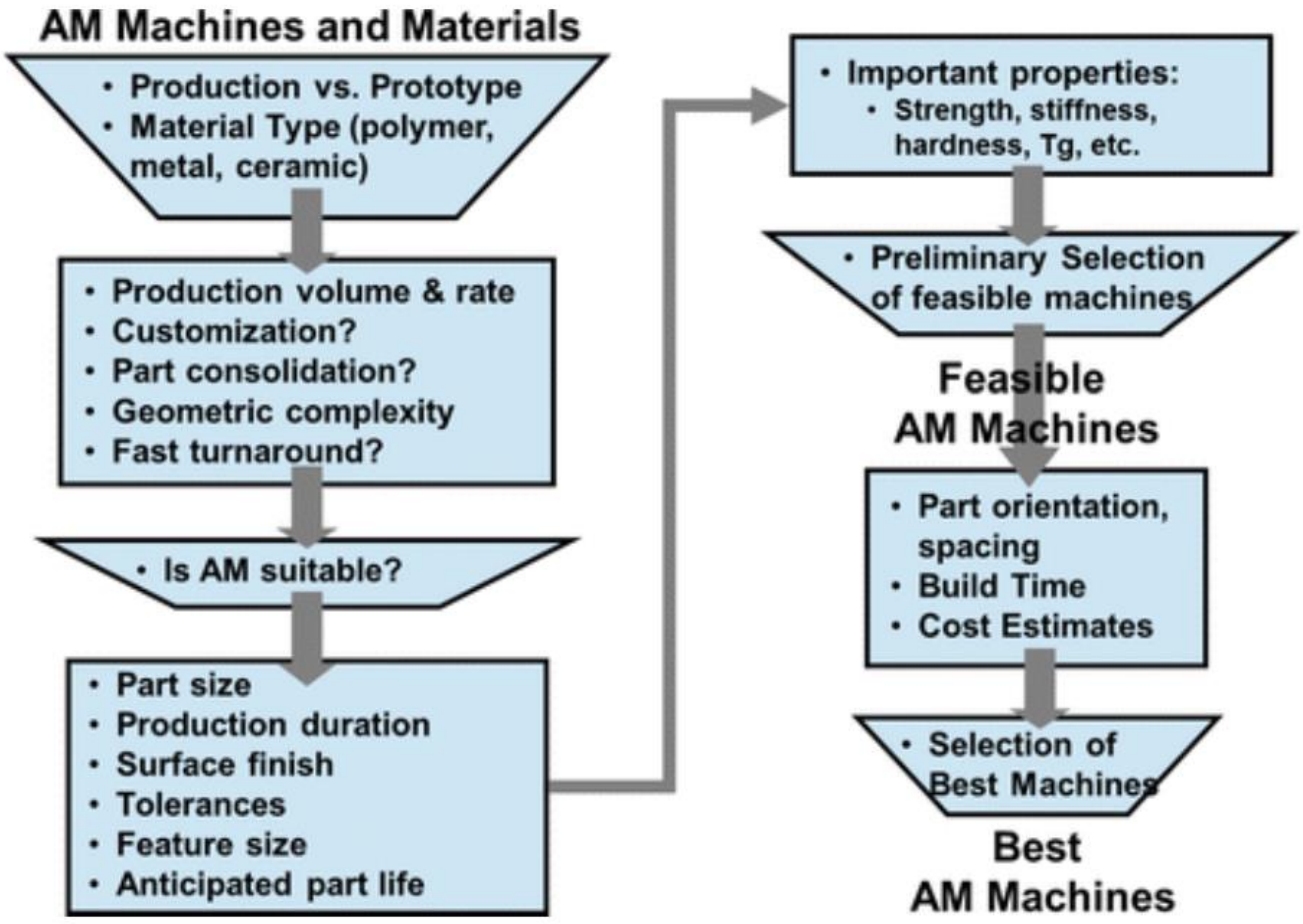
Challenges of Selection:

- Different AM systems are focused on slightly different markets. For example, there are large, expensive machines that can fabricate parts using a variety of materials with relatively good accuracy and/or material properties and with the ability to fine-tune the systems to meet specific needs. In contrast, there are cheaper systems, which are designed to have minimal setup and to produce parts of acceptable quality in a predictable and reliable manner. In this latter case, parts may not have high accuracy, material strength, or flexibility of use.
- Different users will require different things from an AM machine. Machines vary in terms of cost, size, range of materials, accuracy of part, time of build, etc.
- It is not surprising to know that the more expensive machines provide the wider range of options and, therefore, it is important for someone looking to buy a new machine to be able to understand the costs vs. the benefits so that it is possible to choose the best machine to suit their needs.
- Conventions and exhibitions: Approaching a manufacturer or distributor of AM equipment is one way to get information concerning the specification of their machine. Such companies are obviously biased towards their own product and, therefore, it is going to be difficult to obtain truly objective opinions. Conventions and exhibitions are a good way to make comparisons, but it is not necessarily easy to identify the usability of machines.
- Contacting existing users: Contacting existing users is sometimes difficult and time consuming, but they can give very honest opinions. This approach works best if you are already equipped with background information concerning your proposed use of the technology.

Example System for Preliminary Selection:

- A preliminary selection tool was developed for AM, called AMSelect, that walks the user through a series of questions to identify feasible processes and machines
- Build times and costs are computed, but quantitative rating and rank-ordering are not performed. More specifically, the software enables designers, managers, and service bureau personnel to:
  - Explore AM technologies for their application in a possible DDM project
  - Identify candidate materials and processes
  - Explore build times, build options, costs
  - Explore manufacturing and life-cycle benefits of AM
  - Select appropriate AM technologies for DDM applications
  - Explore case studies, anticipate benefits
  - Support Quotation and Capital Investment decisions
- Figure below illustrates the logic underlying AMSelect. A database of machine types and capabilities is read, which represents the set of machines that the software will consider. The software supports a qualitative assessment of the suitability of DDM for the application, then enables the user to explore the performance of various AM machines. Build time and cost estimates are provided, which enable the user to make a selection decision.

Example System for Preliminary Selection:



Flowchart of AMSelect operation

- To use AMSelect, the user first enters information about the production project, including production rate (parts per week), target part cost, how long the part is expected to be in production, and the useful life of the part.
- After the user enters information about the part to be produced and its desired characteristics, the user answers questions about how the application may take advantage of the unique capabilities of AM processes.
- In this version of the software, the questions ask about part shape similarity across the production volume, part geometric complexity, the extent of part consolidation compared to a design for conventional manufacturing processes, and the part delivery time.
- Based on the responses, the software responds with general statements about the likelihood of AM processes being suitable for the user’s application; for example, see the responses for the fictitious problem from. If the user is satisfied that his/her application is suitable for DDM, then they can proceed with a more quantitative exploration of AM machines.

Production Planning and Control :

- It is probably most relevant to the activities of service bureaus (SBs), including internal organizations in manufacturing companies that operate one or more AM machines and processes.
- The SB may know which machine and material a part is to be made from, but in most circumstances, the part cannot be considered in isolation. When any new part is presented to the process planner at the SB, it is likely that he has already committed to build a number of parts. A decision support software system may be useful in keeping track and optimizing machine utilization.
- Consider the process when a new part is presented to the SB for building. In general, the information presented to the process planner will include the following:
  - Part geometry
  - Number of parts
  - Delivery date or schedule for batches of parts
  - Processes other than AM to be carried out (pre-processing and postprocessing)
  - Expectations of the user (accuracy, degree of finish, etc.)

Production Planning and Control :

❑ *Production Planning:*

- A suitable AM process and machine must be identified from among those in the facility. This was probably done during the quoting stage before the customer selected the SB. After that is settled, AM machine availability must be considered. If the SB has more than one suitable machine, a choice must be made as to which machine to use. If the job is for a series of part batches, the SB may choose to run all batches on the same machine, or on multiple machines. If multiple machines, the SB must ensure that all selected machines can provide repeatable results, which is not always the case. Otherwise, potentially lengthy calibration builds may be needed to ensure consistent part quality from all machines used.
- A job scheduling system should be used, particularly for production manufacturing applications, so that part batches can be produced to meet deadlines. If the SB has insufficient resources, it may need to invest in further capacity, necessitating a machine selection scenario. Alternatively, the SB could retain the services of other SBs if the economics of further machine investments is questionable.

❑ *Pre-processing :*

- Pre-processing means software-based manipulation. This will be carried out on the file that describes the geometry of the part. Such manipulation can generally be divided into two areas, modification of the design and determination of build parameters.
- Modification of the design may be required for two reasons. First, part details may need adjustment to accommodate process characteristics
- For example, shaft or pin diameters may need to be reduced, to increase clearance for assembly, when building in many processes since most processes are material safe (i.e., features become oversized). Second, models may require repair if the STEP, IGES, AMF, or STL file has problems such as missing triangles, incorrectly oriented surfaces, or the like.

Production Planning and Control :

❑ *Part build:*

- For some processes, like material extrusion or LENS, it does not really matter in terms of time whether parts are built one after another (batches of 1) or parts are grouped together in batches. However, most processes will vary significantly regarding this factor.
- This may be due to significant preparation time before the build process takes place (such as powder bed heating in PBF), or because there is a significant delay between layers. In the latter case, it is obvious that the cumulative number of layers should be as low as possible to minimize the overall build time for many parts.
- Another factor is part orientation. It is well known that because of anisotropic properties caused by most AM processes, parts will generally build more effectively in one orientation compared with another. This can cause difficulties when organizing the batch production of parts. Orientation of parts so that they fit efficiently within the work volume does not necessarily mean optimal build quality and vice versa.

❑ *Post processing:*

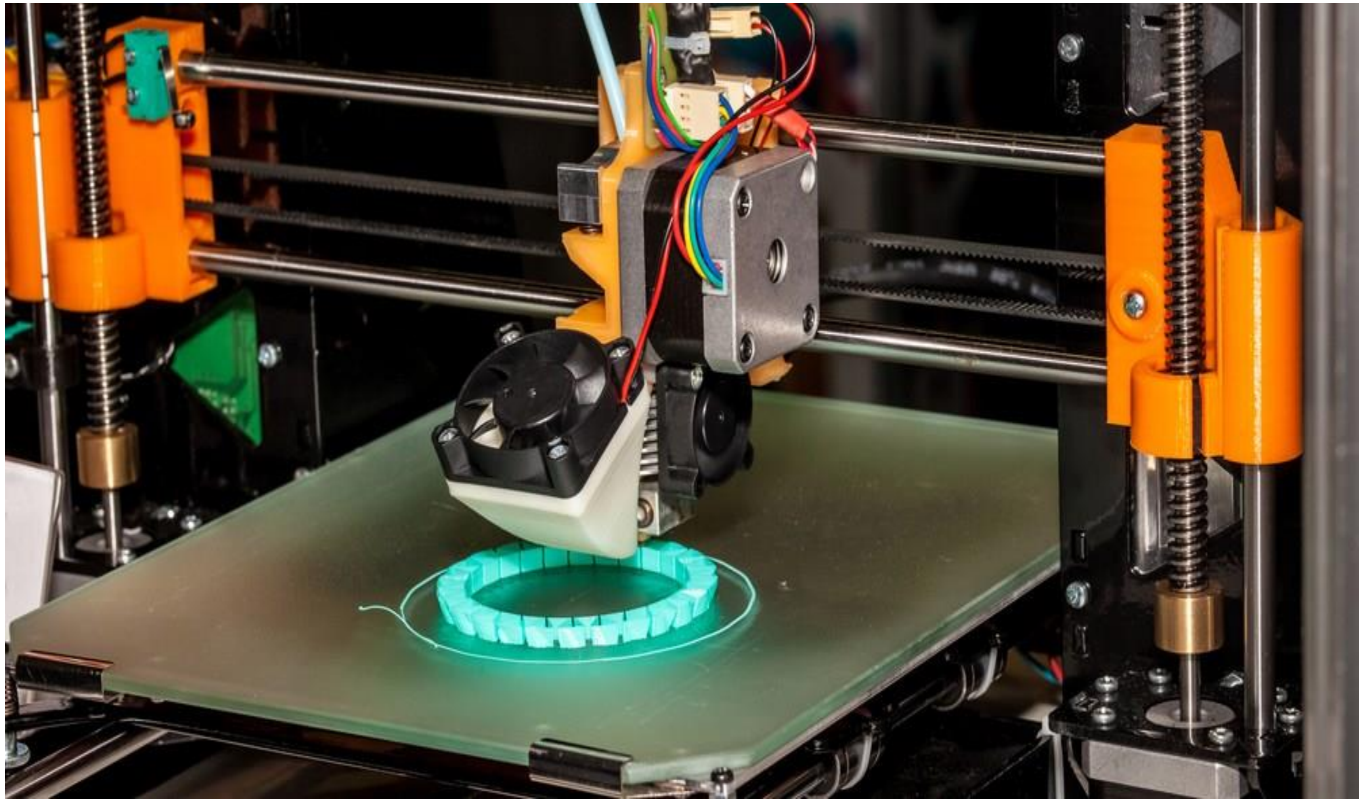
- All AM parts require a degree of post-processing. At the low end, this may require removal of support structures or excess powder for those who merely want quick, simple verification.
- At the high end, the AM process may be a very insignificant time overhead in the overall process. Parts may require a large amount of skilled manual work in terms of surface preparation and coating. Alternatively, the AM part may be one stage in a complex rapid tooling process that requires numerous manual and automated stages. All this can result from the same source machine. It can even be an iterative process involving all of the above steps at different stages in the development cycle based on the same part CAD data.

ADDITIVE MANUFACTURING
18ME741

MODULE 4

SOFTWARE ISSUES FOR ADDITIVE MANUFACTURING

V. SUSHANTHKUMAR
Dept. of Mechanical Engg.
Angadi Institute of Technology and Management.
Belagavi.



Module 4

Guidelines for Process Selection: Introduction, selection methods for apart, challenges of selection, example system for preliminary selection, production planning and control.

Software issues for Additive Manufacturing: Introduction, preparation of cad models – the STL file, problems with STL files, STL file manipulation.

Post- Processing: Support material removal, surface texture improvements, preparation for use as a pattern, property enhancements using non-thermal techniques and thermal techniques.

Introduction:

- It is clear that additive manufacturing would not exist without computers and would not have developed so far if it were not for the development of 3D solid modeling CAD.
- The quality, reliability, and ease of use of 3D CAD have meant that virtually any geometry can be modeled, and it has enhanced our ability to design.
- Some of the most impressive models made using AM are those that demonstrate the capacity to fabricate complex forms in a single stage without the need to assemble or to use secondary tooling.
- Virtually every commercial solid modeling CAD system has the ability to output to an AM machine. This is because, for most cases, the only information that an AM machine requires from the CAD system is the external geometric form. There is no requirement for the machine to know how the part was modeled, any of the features or any functional elements. So long as the external geometry can be defined, the part can be built.

preparation of cad models – the STL file:

- The STL file is derived from the word STereoLithography, which was the first commercial AM process, produced by the US company 3D Systems in the late 1980s.
- although some have suggested that STL should stand for Stereolithography Tessellation Language. STL files are generated from 3D CAD data within the CAD system. The output is a boundary representation that is approximated by a mesh of triangles.
    1. STL File Format, Binary/ASCII
    2. Creating STL Files from a CAD System
    3. Calculation of Each Slice Profile
    4. Technology-Specific Elements

1. STL File Format, Binary/ASCII

- STL files can be output as either binary or ASCII (text) format.
- The ASCII format is less common (due to the larger file sizes) but easier to understand and is generally used for illustration and teaching.
- Most AM systems run on PCs using Windows.
- The STL file is normally labeled with a ".STL" extension that is case insensitive.
- These files only show approximations of the surface or solid entities and so any information concerning the color, material, build layers, or history is ignored during the conversion process.
- any points, lines, or curves used during the construction of the surface or solid, and not explicitly used in that solid or surface, will also be ignored.

preparation of cad models – the STL file:

1. STL File Format, Binary/ASCII(continue…)

- An STL file consists of lists of triangular facets.
- Each triangular facet is uniquely identified by a unit normal vector and three vertices or corners.
- The unit normal vector is a line that is perpendicular to the triangle and has a length equal to 1.0. This unit length could be in mm or inches and is stored using three numbers, corresponding to its vector coordinates.
- The STL file itself holds no dimensions, so the AM machine operator must know whether the dimensions are mm, inches, or some other unit.
- Since each vertex also has three numbers, there are a total of 12 numbers to describe each triangle. The following file shows a simple ASCII STL file that describes a right-angled, triangular pyramid structure, as shown in Fig.

```
solid triangular_pyramid
     facet normal 0.0 -1.0 0.0
      outer loop
       vertex 0.0 0.0 0.0
       vertex 1.0 0.0 0.0
       vertex 0.0 0.0 1.0
      endloop
     endfacet
     facet normal 0.0 0.0 -1.0
      outer loop
       vertex 0.0 0.0 0.0
       vertex 0.0 1.0 0.0
       vertex 1.0 0.0 0.0
      endloop
     endfacet
     facet normal 0.0 0.0 -1.0
      outer loop
       vertex 0.0 0.0 0.0
       vertex 0.0 0.0 1.0
       vertex 0.0 1.0 0.0
      endloop
     endfacet
     facet normal 0.577 0.577 0.577
      outer loop
       vertex 1.0 0.0 0.0
       vertex 0.0 1.0 0.0
       vertex 0.0 0.0 1.0
      endloop
     endfacet
    endsolid
```

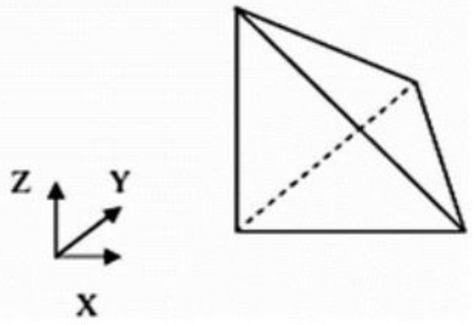


Fig. 15.1 A *right-angled triangular pyramid* as described by the sample STL file. Note that the *bottom left-hand* corner coincides with the origin and that every vertex coming out of the origin is of unit length

preparation of cad models – the STL file:

1. STL File Format, Binary/ASCII(continue…)

- Note that the file begins with an object name delimited as a solid.
- Triangles can be in any order, each delimited as a facet.
- A binary STL file can be described in the following way:
  - An 80-byte ASCII header that can be used to describe the part
  - A 4 byte unsigned long integer that indicates the number of facets in the object
  - A list of facet records, each 50 bytes long
- The facet record will be presented in the following way:
  - 3 floating values of 4 bytes each to describe the normal vector
  - 3 floating values of 4 bytes each to describe the first vertex
  - 3 floating values of 4 bytes each to describe the second vertex
  - 3 floating values of 4 bytes each to describe the third vertex
  - One unsigned integer of 2 bytes, that should be zero, used for checking

```
solid triangular_pyramid
     facet normal 0.0 -1.0 0.0
       outer loop
         vertex 0.0 0.0 0.0
         vertex 1.0 0.0 0.0
         vertex 0.0 0.0 1.0
       endloop
     endfacet
     facet normal 0.0 0.0 -1.0
       outer loop
         vertex 0.0 0.0 0.0
         vertex 0.0 1.0 0.0
         vertex 1.0 0.0 0.0
       endloop
     endfacet
     facet normal 0.0 0.0 -1.0
       outer loop
         vertex 0.0 0.0 0.0
         vertex 0.0 0.0 1.0
         vertex 0.0 1.0 0.0
       endloop
     endfacet
     facet normal 0.577 0.577 0.577
       outer loop
         vertex 1.0 0.0 0.0
         vertex 0.0 1.0 0.0
         vertex 0.0 0.0 1.0
       endloop
     endfacet
   endsolid
```

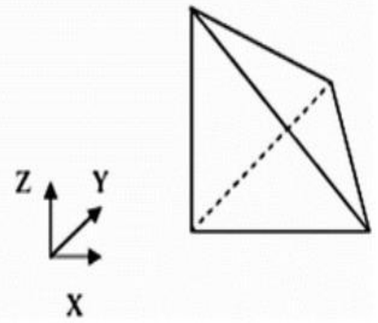


Fig. 15.1 A *right-angled triangular pyramid* as described by the sample STL file. Note that the *bottom left-hand* corner coincides with the origin and that every vertex coming out of the origin is of unit length

preparation of cad models – the STL file:

2. Creating STL Files from a CAD System

- Nearly all geometric solid modeling CAD systems can generate STL files from a valid, fully enclosed solid model. Most CAD systems can quickly tell the user if a model is not a solid.
- This test is particularly necessary for systems that use surface modeling techniques, where it can be possible to create an object that is not fully closed off. Such systems would be used for graphics applications where there is a need for powerful manipulation of surface detail (like with Autodesk Alias Studio software or Rhino from Robert McNeel & Associates) rather than for engineering detailing.
- Most CAD systems use a "Save as" or "Export" function to convert the native format into an STL file.
- Since STL uses planar surfaces to approximate curved surfaces, then obviously the larger the triangles, the looser that approximation becomes. Most CAD systems do not directly limit the size of the triangles since it is also obvious that the smaller the triangle, the larger the resulting file for a given object.
- An effective approach would be to minimize the offset between the triangle and the surface that it is supposed to represent.

preparation of cad models – the STL file:

2. Creating STL Files from a CAD System

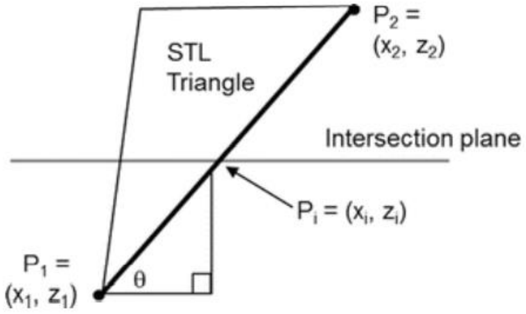


Fig. 15.3 A vertex taken from an STL triangle projected onto the $y = 0$ plane. Since the height z_i is known, we can derive the intersection point x_i. A similar case can be done for y_i in the $x = 0$ plane

Fig. 15.4 Supports generated for a part build

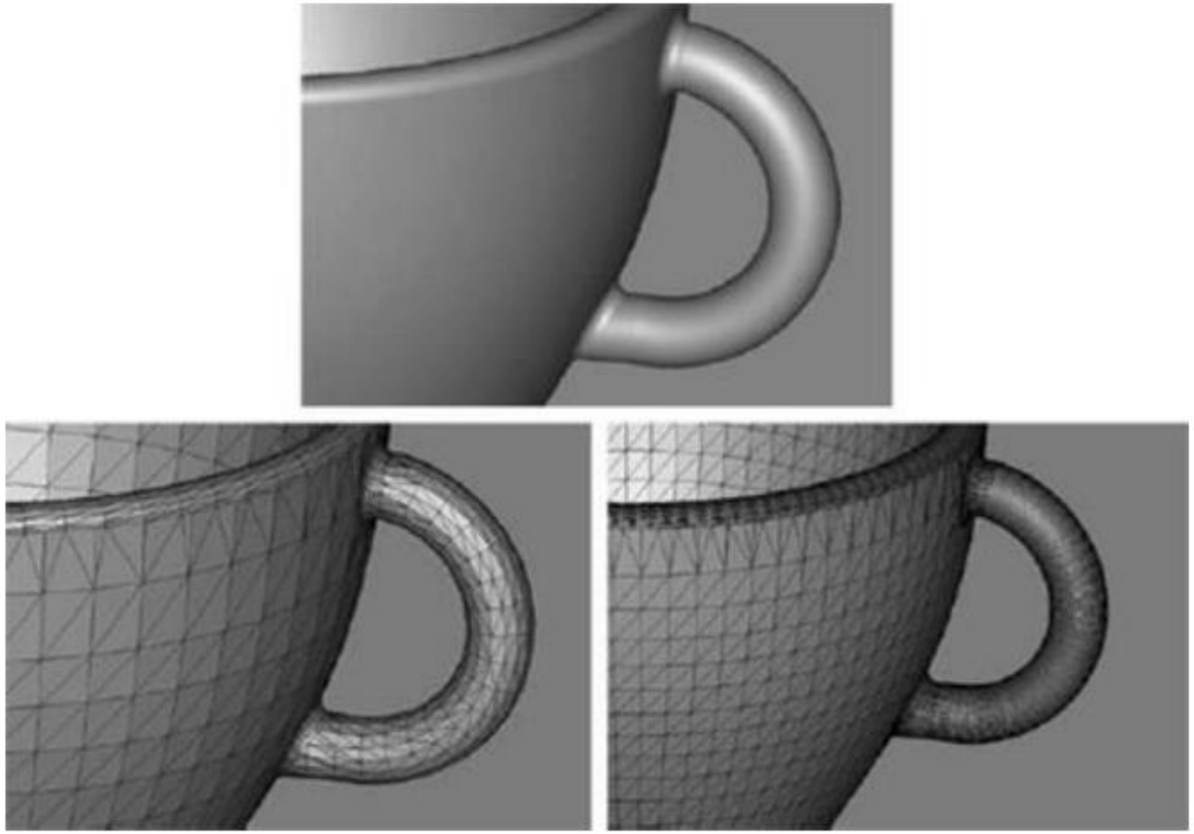


Fig. 15.2 An original CAD model converted into an STL file using different offset height (cusp) values, showing how the model accuracy will change according to the triangle offset

preparation of cad models – the STL file:

2. Creating STL Files from a CAD System

Fig. 15.5 A scan pattern using vector scanning in material extrusion. Note the outline drawn first followed by a small number of zigzag patterns to fill in the space

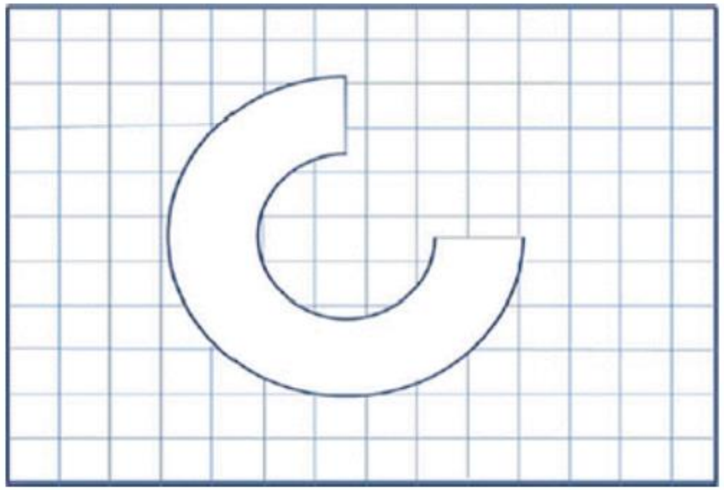


Fig. 15.6 Hatching pattern for LOM-based (sheet lamination) processes. Note the outside hatch pattern that will result in cubes which will be separated from the solid part during post-processing

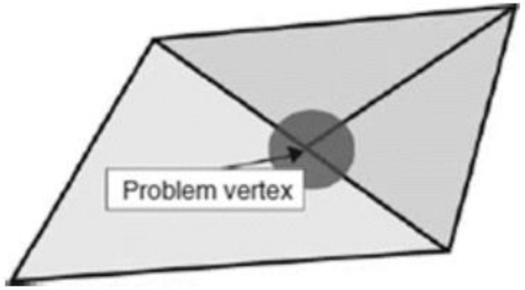
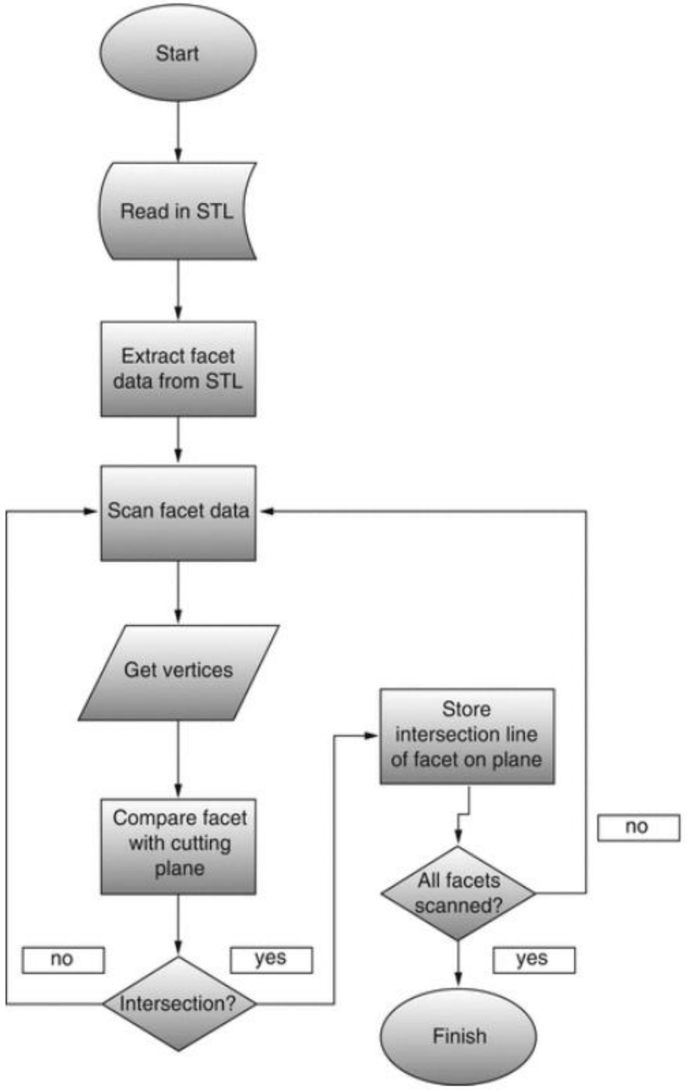


Fig. 15.7 A case that violates the vertex-to-vertex rule

preparation of cad models – the STL file:

3. Calculation of Each Slice Profile

- Virtually every AM system will be able to read both binary and ASCII STL files.
- Since most AM processes work by adding layers of material of a prescribed thickness, starting at the bottom of the part and working upwards, the part file description must therefore be processed to extract the profile of each layer.
- Each layer can be considered a plane in a nominal XY Cartesian frame. Incremental movement for each layer can then be along the orthogonal Z axis.
- The XY plane, positioned along the Z axis, can be considered as a cutting plane. Any triangle intersecting this plane can be considered to contribute to the slice profile. An algorithm like the one in Flowchart 15.1 can be used to extract all the profile segments for a given STL file.



Flowchart 15.1 Algorithm for testing triangles and generating line intersections. The result will be an unordered matrix of intersecting lines (adapted from [4])

problems with STL files:

- Although the STL format is quite simple, there can still be errors in files resulting from CAD conversion.
- The following are typical problems that can occur in bad STL files:
    - **Unit changing**
    - **Vertex to vertex rule**
    - **Leaking STL files**
    - **Degenerated facets**
- ***Unit changing***: Since US machines still commonly use imperial measurements and most of the rest of the world uses metric, some files can appear scaled because there is no explicit mention of the units used in the STL format.
- ***Vertex to vertex rule:***Each triangle must share two of its vertices with each of the triangles adjacent to it. This means that a vertex cannot intersect the side of another. This is not something that is explicitly stated in the STL file description and therefore STL file generation may not adhere to this rule. However, a number of checks can be made on the file to determine whether this rule has been violated. For example, the number of faces of a proper solid defined using STL must be an even number.
- ***Leaking STL files:*** STL files should describe fully enclosed surfaces that represent the solids generated within the originating CAD system. In other words, STL data files should construct one or more manifold entities according to Euler's Rule for solids. If this rule does not hold then the STL file is said to be leaking and the file slices will not represent the actual model.
- ***Degenerated facets:*** These facets normally result from numerical truncation. A triangle may be so small that all three points virtually coincide with each other. After truncation, these points lay on top of each other causing a triangle with no area. This can also occur when a truncated triangle returns no height and all three vertices of the triangle lie on a single straight line. While the resulting slicing algorithm will not cause incorrect slices, there may be some difficulties with any checking algorithms and so such triangles should really be removed from the STL file.

STL file manipulation:

- Once a part has been converted into STL there are only a few operations that can be performed. This is because the triangle-based definition does not permit radical changes to the data.
- A point or vertex can be moved, which will affect the connected triangles, but creating a regional affect on larger groups of points would be more difficult.
- Consider the modeling of a simple geometry, like the cut cylinder in Fig.

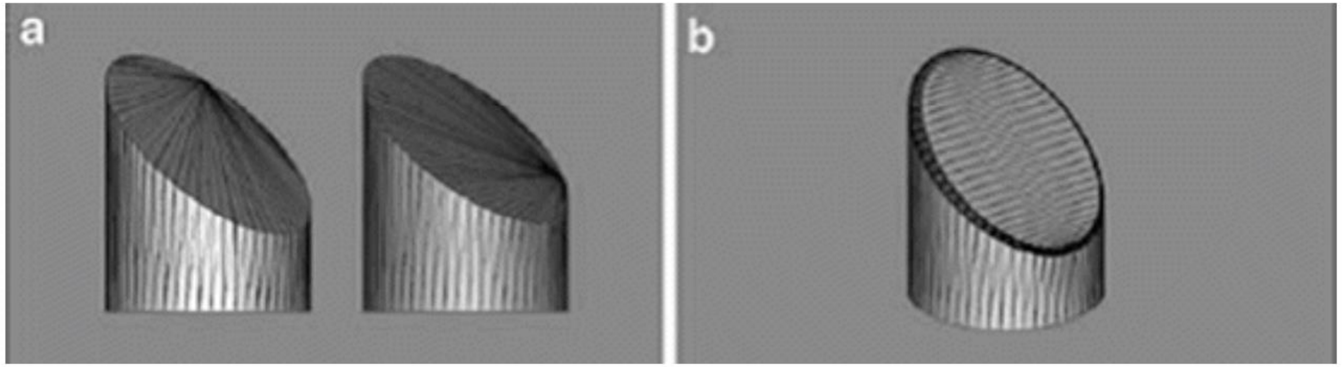


Fig. 15.10 STL files of a cut cylinder. Note that although the two models in (**a**) are very similar, the location of the triangles is very different. Addition of a simple filet in (**b**) shows even greater change in the STL file

- Making a minor change in one of the measurements may result in a very radical change in distribution of the triangles. While it is possible to simplify the model by reducing the number of triangles, it is quite easy to see that defining boundaries in most models cannot be easily done.
- The addition of a fillet in Fig. 15.10b shows an even more radical change in the STL file. Furthermore, if one were to attempt to move the oval that represents the cut surface, the triangles representing the filet would no longer show a constant-radius curve.

STL file manipulation:

- Building models using AM is often done by people working in departments or companies that are separate from the original designers. It may be that whoever is building the model may not have direct access to the original CAD data. There may therefore be a need to modify the STL data before the part is to be built.
- The following sections discuss STL tools that are commonly used.
  1. **Viewers**
  2. **STL Manipulation on the AM Machine**

1. Viewers

- There are a number of STL viewers available, often as a free download.
- Like many other systems, this software allows limited access to the STL file, making it possible to view the triangles, apply shading, show sections, etc. By purchasing the full software version, other tools are possible, for example, allowing the user to measure the part at various locations, annotate the part, display slice information, and detect potential problems with the data.
- Often the free tools allow passive viewing of the STL data, while the more advanced tools permit modification of the data, either by rewriting the STL or supplying additional information with the STL data (like measurement information, for example).

STL file manipulation:

2. STL Manipulation on the AM Machine

- STL data for a part consist of a set of points defined in space, based on an arbitrarily selected point of origin.
- This origin point may not be appropriate to the machine the part is to be built on. Furthermore, even if the part is correctly defined within the machine space, the user may wish to move the part to some other location or to make a duplicate to be built beside the original part. Other tasks, like scaling, changing orientation, and merging with other STL files are all things that are routinely done using the STL manipulation tools on the AM machine.
- Creation of the support structures is also something that would normally be expected to be done on the AM machine. This would normally be done automatically and would be an operation applied to downward-facing triangles.
- With some AM operating systems there is little or no control over placement of supports or manipulation of the model STL data. it may be necessary to purchase additional third party software, like the MAGICS and 3-matic systems from Materialise
- Such third party software may also be used to undertake additional roles. MAGICS, for example, has a number of modules useful to many AM technologies.

ADDITIVE MANUFACTURING

18ME741

MODULE 4

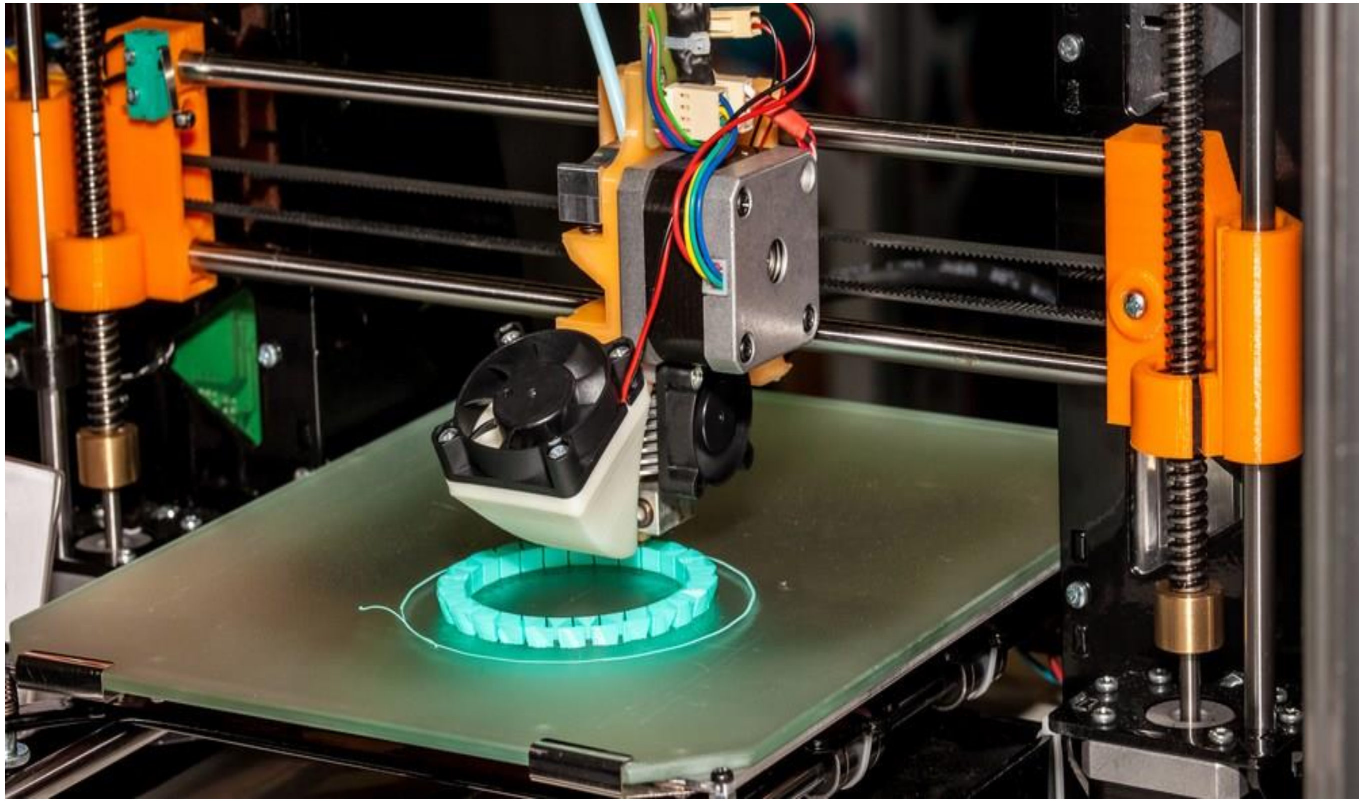
POST PROCESSING

V. SUSHANTHKUMAR

Dept. of Mechanical Engg.

Angadi Institute of Technology and Management.

Belagavi.



Module 4

Guidelines for Process Selection: Introduction, selection methods for apart, challenges of selection, example system for preliminary selection, production planning and control.

Software issues for Additive Manufacturing: Introduction, preparation of cad models – the STL file, problems with STL files, STL file manipulation.

Post- Processing: Support material removal, surface texture improvements, preparation for use as a pattern, property enhancements using non-thermal techniques and thermal techniques.

Introduction:

- Most AM processes require post-processing after part building to prepare the part for its intended form, fit and/or function. Depending upon the AM technique, the reason for post-processing varies.
- Some of the post processing methods are listed below.
  1. Support material removal
  2. Surface texture improvements
  3. Accuracy improvements
  4. Aesthetic improvements
  5. Preparation for use as a pattern
  6. Property enhancements using non-thermal techniques
  7. Property enhancements using thermal techniques
- The skill with which various AM practitioners perform post-processing is one of the most distinguishing characteristics between competing service providers. Companies which can efficiently and accurately post-process parts to a customer’s expectations can often charge a premium for their services; whereas, companies which compete primarily on price may sacrifice post-processing quality in order to reduce costs.

1. Support material removal:

- The most common type of post-processing in AM is support removal. Support material can be broadly classified into two categories:
    1. Material which surrounds the part as a naturally occurring by-product of the build process (natural supports).
    2. Rigid structures which are designed and built to support, restrain, or attach the part being built to a build platform (synthetic supports).

1. Natural Support Post-processing

- In processes where the part being built is fully encapsulated in the build material, the part must be removed from the surrounding material prior to its use.
- Processes which provide natural supports are primarily *powder based* and *sheet-based processes*.
- Specifically, all *powder bed fusion (PBF)* and *binder jetting* processes require removal of the part from the loose powder surrounding the part; and *bond-then-form sheet metal lamination* processes require removal of the encapsulating sheet material.
- After the part is built is allowed to cool down . Then parts are moved to breakout station, where the parts are removed manually from surrounding powdered material.
- Brushes, compressed air, and light bead blasting are commonly used to remove loosely adhered powder;

1. Support material removal:

- The most common type of post-processing in AM is support removal. Support material can be broadly classified into two categories:
  1. Material which surrounds the part as a naturally occurring by-product of the build process (***natural supports***).
  2. Rigid structures which are designed and built to support, restrain, or attach the part being built to a build platform (***synthetic supports***).

2. Synthetic Support Removal

- when using PBF techniques for metals, synthetic supports are also required to resist distortion.
- Synthetic supports can be made from the build material or from a secondary material.
- The development of secondary support materials was a key step in simplifying the removal of synthetic supports as these materials are designed to be either weaker, soluble in a liquid solution, or to melt at a lower temperature than the build material.
- All material extrusion, material jetting, and vat photopolymerization processes require supports for overhanging structures and to connect the part to the build platform.
- For polymers, the most common secondary support materials are polymer materials which can be melted and/or dissolved in a water-based solvent.
- The water can be jetted or ultrasonically vibrated to accelerate the support removal process. For metals, the most common secondary support materials are lower-melting-temperature alloys or alloys which can be chemically dissolved in a solvent (in this case the solvent must not affect the build material).

2. surface texture improvements:

- AM parts have common surface texture features that may need to be modified for aesthetic or performance reasons.
- Common undesirable surface texture features include: stair-steps, powder adhesion, fill patterns from material extrusion or DED systems, and witness marks from support material removal.
- The type of post-processing utilized for surface texture improvements is dependent upon the desired surface finish outcome. If a matte surface finish is desired, a simple bead blasting of the surface can help even the surface texture, remove sharp corners from stair-stepping, and give an overall matte appearance.
- If a smooth or polished finish is desired, then wet or dry sanding and hand-polishing are performed. In many cases, it is desirable to paint the surface (e.g., with cyanoacrylate, or a sealant) prior to sanding or polishing.
- Painting the surface has the dual benefit of sealing porosity and, by viscous forces, smoothing the stair-step effect, thus making sanding and polishing easier and more effective.
- Several automated techniques have been explored for surface texture improvements. Two of the most commonly utilized include tumbling for external features and abrasive flow machining for, primarily, internal features. These processes have been shown to smooth surface features nicely, but at the cost of small feature resolution, sharp corner retention, and accuracy

3. Accuracy improvements:

- There is a wide range of accuracy capabilities between AM processes. Some processes are capable of submicron tolerances, whereas others have accuracies around 1 mm.
- Typically, thlarger the build volume and the faster the build speed the worse the accuracy. This is particularly noticeable, for instancee, in directed energy deposition processes where the slowest and most accurate DED processes have accuracies approaching a few microns; whereas, the larger bulk deposition machines have accuracies of several millimeters.
- **Sources of Inaccuracy:**
  - Process-dependent errors affect the accuracy of the X–Y plane differently from the Z-axis accuracy. These errors come from positioning and indexing limitations of specific machine architectures, lack of closed-loop process monitoring and control strategies, and/or from issues fundamental to the volumetric rate of material addition (such as melt pool or droplet size)
  - operator skill.
  - Material-dependent phenomena also play a role in accuracy, including shrinkage and residual stress-induced distortion.
- **Machining Strategy:**Machining strategy is very important for finishing AM parts and tools. Considering both accuracy and machine efficiency, adaptive raster milling of the surface, plus hole drilling and sharp edge contour machining can fulfill the needs of most parts.

4. Aesthetic improvements:

- Many times AM is used to make parts which will be displayed for aesthetic or artistic reasons or used as marketing tools.
- ***Colouring:*** Some types of AM parts can be effectively colored by simply dipping the part into a dye of the appropriate color. This method is particularly effective for parts created from powder beds, as the inherent porosity in these parts leads to effective absorption.
- ***chrome plating:*** Several materials have been electroless coated to AM parts, including Ni, Cu, and other coatings. In some cases, these coatings are thick enough that, in addition to aesthetic improvements, the parts are robust enough to use as tools for injection molding or as EDM electrodes.

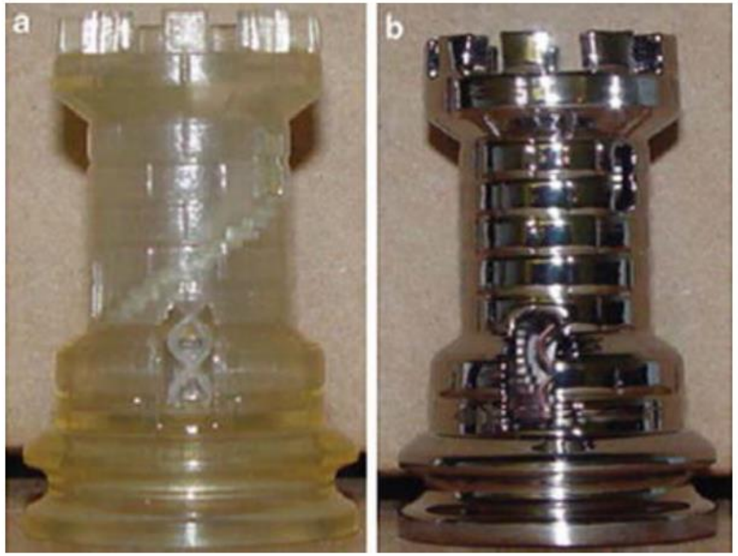


Fig. 14.10 Stereolithography part (**a**) before and (**b**) after chrome plating (Courtesy of Artcraft Plating)

5. Preparation for Use as a Pattern:

- Often parts made using AM are intended as patterns for investment casting, sand casting, room temperature vulcanization (RTV) molding, spray metal deposition, or other pattern replication processes.
- The accuracy and surface finish of an AM pattern will directly influence the final part accuracy and surface finish. As a result, special care must be taken to ensure the pattern has the accuracy and surface finish desired in the final part. In addition, the pattern must be scaled to compensate for any shrinkage that takes place in the pattern replication steps

❑ **Investment Casting Patterns:**

- In the case of investment casting, the AM pattern will be consumed during processing.
- AM parts can be printed on a casting tree or manually added to a casting tree after AM.
- Figure 14.11 shows rings made using a material jetting system. In the first picture, a collection of rings is shown on the build platform; each ring is supported by a secondary support material in white. In the second picture, a close-up of the ring pattern is shown. The third picture shows metal rings still attached to a casting tree. In this instance, the rings were added to the tree after AM, but before casting.

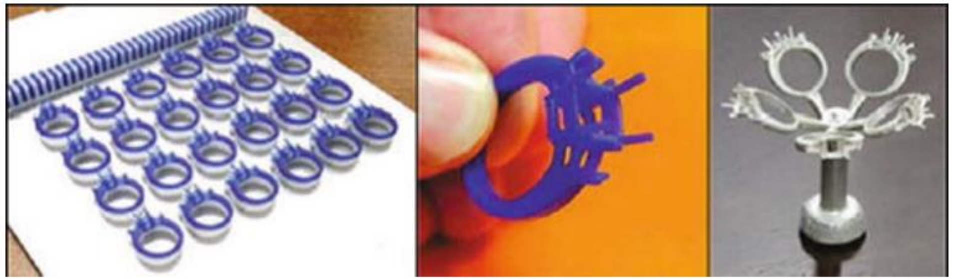


Fig. 14.11 Rings for investment casting, made using a ProJet® CPX 3D Printer (Courtesy 3D Systems)

5. Preparation for Use as a Pattern:

❑ Sand Casting Patterns :

- binder jetting and PBF processes can be used to directly create sand mold cores and cavities by using a thermosetting binder to bind sand in the desired shape.
- One benefit of these direct approaches is that complexgeometry cores can be made that would be very difficult to fabricate using any other process.
- In order to prepare AM sand casting patterns for casting, loose powder is removed and the pattern is heated to complete cross-linking of the thermoset binder and to remove moisture and gaseous by-products. In some cases, additional binders are added to the pattern before heating, to increase the strength for handling. Once the pattern is thermally treated, it is assembled with its corresponding core(s) and/or cavity, and hot metal is poured into the mold. After cooling, the sand pattern is removed using tools and bead blasting.

Fig. 14.12 Sand casting pattern for a cylinder head of a V6, 24-valve car engine (*left*) during loose powder removal and (*right*) pattern prepared for casting alongside a finished casting (Joint project between CADCAM Becker GmbH and VAW Südalumin GmbH, made on an EOSINT S laser-sintering machine, courtesy EOS)

6. Property Enhancements Using Non-thermal Techniques:

- Powder-based and extrusion-based processes often create porous structures. In many cases, that porosity can be infiltrated by a higher-strength material, such as cyanoacrylate (Super Glue®).
- Proprietary methods and materials have also been developed to increase the strength, ductility, heat deflection, flammability resistance, EMI shielding, or other properties of AM parts using infiltrants and various types of nano-composite reinforcements.
- A common post-processing operation for photopolymer materials is curing. During processing, many photopolymers do not achieve complete polymerization. As a result, these parts are put into a Post-Cure Apparatus, a device that floods the part with UV and visible radiation in order to completely cure the surface and subsurface regions of the part. Additionally, the part can undergo a thermal cure in a low temperature oven, which can help completely cure the photopolymer and in some cases greatly enhance the part’s mechanical properties.

7. Property Enhancements Using Thermal Techniques:

- After AM processing, many parts are thermally processed to enhance their properties.
- . In the case of DED and PBF techniques for metals, this thermal processing is primarily heat treatment to form the desired microstructures and/or to relieve residual stresses.

❑ **furnace post processing:**

- Before the advent of DED and PBF techniques capable of directly processing metals and ceramics, many techniques were developed for creating metal and ceramic green parts using AM. These were then furnace post-processed to achieve dense, usable metal and ceramic parts. Binder jetting is the only AM process which is commonly used for these purposes.
- Figure 14.14 shows the steps for preparing a metal green part made from LaserForm ST-100 for furnace infiltration.

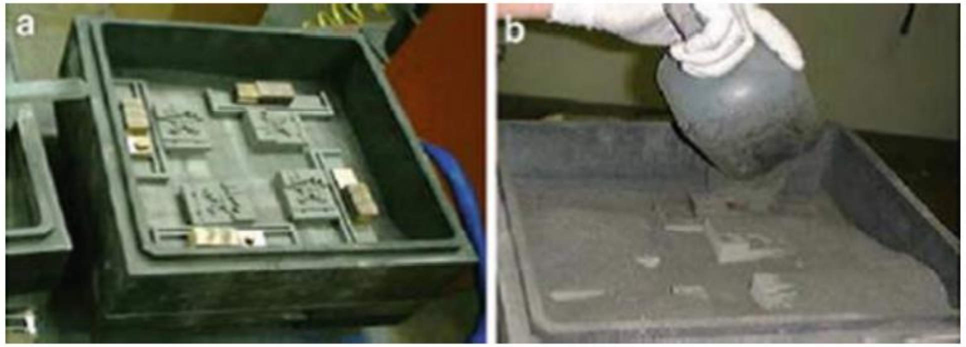
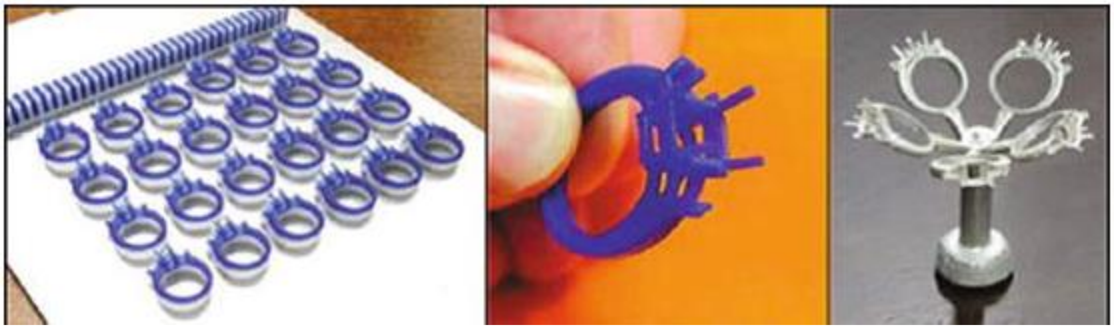


Fig. 14.14 LaserForm ST-100 green parts. (**a**) Parts are placed next to "boats" on which the bronze infiltrant is placed. The bronze infiltrates through the boat into the part. (**b**) The parts are often covered in aluminum oxide powder before placing them in a furnace to help support fragile features during debinding, sintering, and infiltration, and to help minimize thermal gradients

Additive Manufacturing Module :5

AM Applications:

InvestmentCasting:



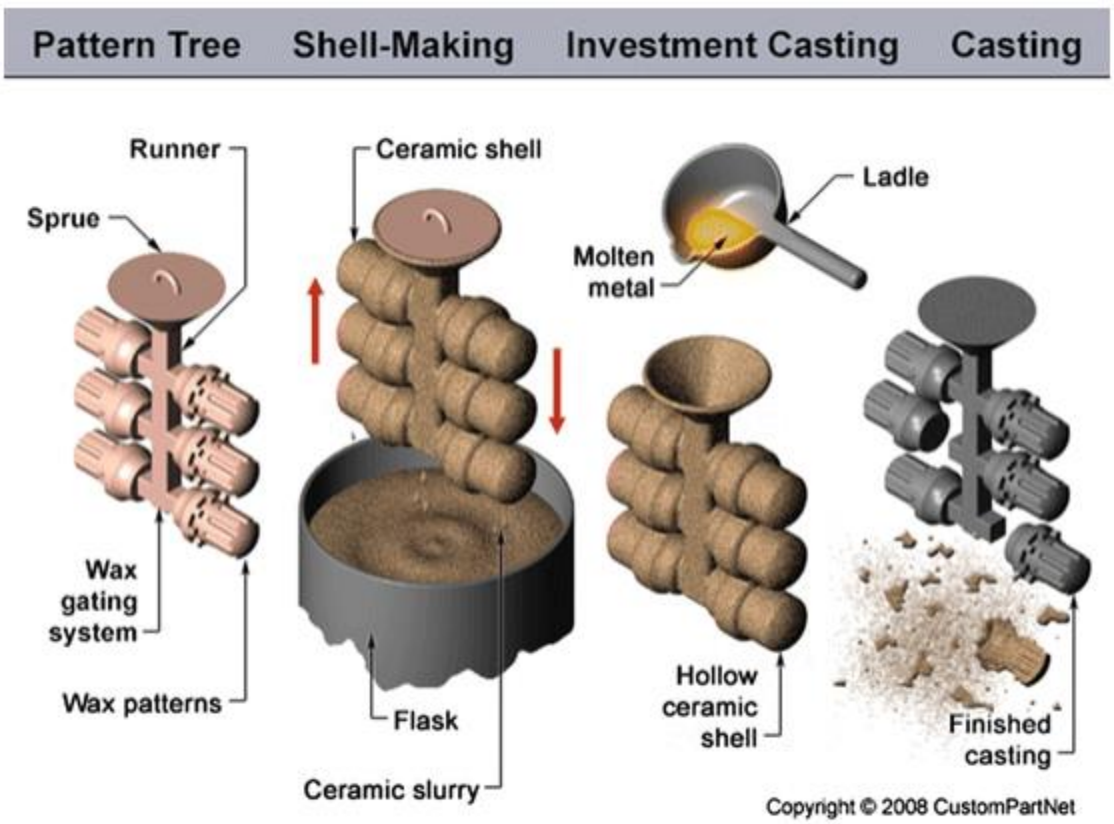


Fig: Schematic of the investment casting process

Investment casting is the process of generating metal parts from a nonmetal pattern. The patterns are in some way assembled into a structure that can be coated with ceramic to produce a shell. The ceramic starts as a slurry into which the structure, referred to as a "tree" for obvious reasons, is dipped to produce a closely forming skin. Once this has dried, it is strengthened by applying more coats until it is strong enough to withstand the casting process. Prior to casting, the pattern is removed by burning out the material. Care must be taken at this stage to ensure all the material has been burned out of the shell, leaving no residue. The ceramic shell can withstand the high temperature of molten metal during the pouring process, which can then be left to cool before the shell is broken from the tree. The metal replicas of the original pattern are cut from the "trunk" of the structure prior to post-treatment.

Vacuum Forming Tools: Vacuum forming is commonly used in packaging, where plastic parts are formed from a flat sheet. A typical example is the clear blister packaging that is commonly used to display consumer products. Other examples include parts that form an outer shell for a product, like a plastic safety helmet for example. After the forming, it is common to cut away the material that surrounds the shaped plastic. Heat and vacuum are applied when the sheet is placed over a tool, which has holes through which the vacuumed air is extracted. This allows the sheet to conform to the shape of the tool. If a small number of formed parts are required in a series plastic, then the tool could be fabricated using AM. Locating the vacuum holes would be a straightforward process and can be included during the build. Since the heat is not directly targeted at the tool and with the pressures and other forces not being very high, it is acceptable to use polymeric materials that are commonly used in AM, like ABS or nylon.

Rapid Tooling: Chrysler experimented with a variety of rapid tooling processes with stereolithography master patterns. This included vacuum forming, resin transfer molding, sand casting, squeeze molding, and silicone molding. An area of significant effort in both the aerospace and automotive industries was the use of SL parts as investment casting patterns. Early experiments used thin-walled SL patterns or hollow parts. Because SL resins expand more than investment casting wax, when used as patterns, the SL part tended to expand and crack the ceramic shell. This led to the development of the QuickCast™ pattern style in 1992, which is a type of lattice structure that was added automatically to hollow part STL files by SL machine pre-processing software. The Quick Cast style was designed to support thin walls but not to be too strong. Upon heating and thermal expansion, the Quick Cast lattice struts were designed to flex, collapse inward, break, but not transfer high loads to the part skins which could crack the shell.

More recently, Boeing, Northrop-Grumman and other aerospace companies have used material extrusion technology to fabricate tooling. They developed tooling designs for composite part lay-up that were suitable for ME fabrication. Other reported tooling applications included drill guides and various assembly tools.

Automotive Applications: As mentioned, the automotive industry was one of the early adopters of AM and personnel at these companies pioneered many types of AM applications in product development. Companies in this industry continue to be heavy users of AM, accounting for approximately 17 % of all expenditures on AM in 2013. This positions the automotive industry behind only industrial/business machines (18.5 %) and consumer products/electronics (18 %), which are very large and broad industries in terms of the largest users of AM. Since production volumes in the automotive industry are often high (100,000s per year), AM has typically been evaluated as too expensive for production manufacturing, in contrast to the aerospace industry. To date, most manufacturers have not committed to AM parts on their massproduced car models. However, there have been niche applications of AM that are worth exploring. As mentioned in the Historical Developments section, a variety of rapid prototyping applications were developed by automotive companies and their suppliers. In addition to RP and rapid tooling, suppliers to this industry used AM parts to debug their assembly lines. That is, they used AM parts to test assembly operations and tooling to identify potential problems before production assembly commenced. Since model line change-over involves huge investments, being able to avoid problems in production yielded very large savings. In the metal PBF area, Concept Laser, a German company, introduced their X line 1000R machine recently, which has a build chamber large enough to accommodate a V6 automotive engine block. This machine was developed in collaboration with Daimler AG. It is not clear if they intend their automotive customers to fabricate production engine blocks in this machine, but they claim the machine was developed with production manufacture in mind. According to Concept Laser, the 1000R is capable of building at a rate of 65 cm3 per hour, which is fast compared to some other metal PBF machines. Additionally, the machine was designed with two build boxes (powder chambers) on a single turntable so that one build box could be used for part fabrication, while the other could be undergoing cool-down, part removal, pre-heating or other non-part-building activities. For specialty cars or low-volume production, AM can be economical for some parts. Applications include custom parts on luxury cars or replacement parts on antique cars. The example of Bentley Motors was given in Chap. 17. Polymer PBF was used to fabricate some custom interior components, such as bezels, that were subsequently covered in leather and other materials. Typically, Bentley has production volumes of less than 10,000 cars for a given model, so this qualifies as low production volume.

MedicalAMApplications:

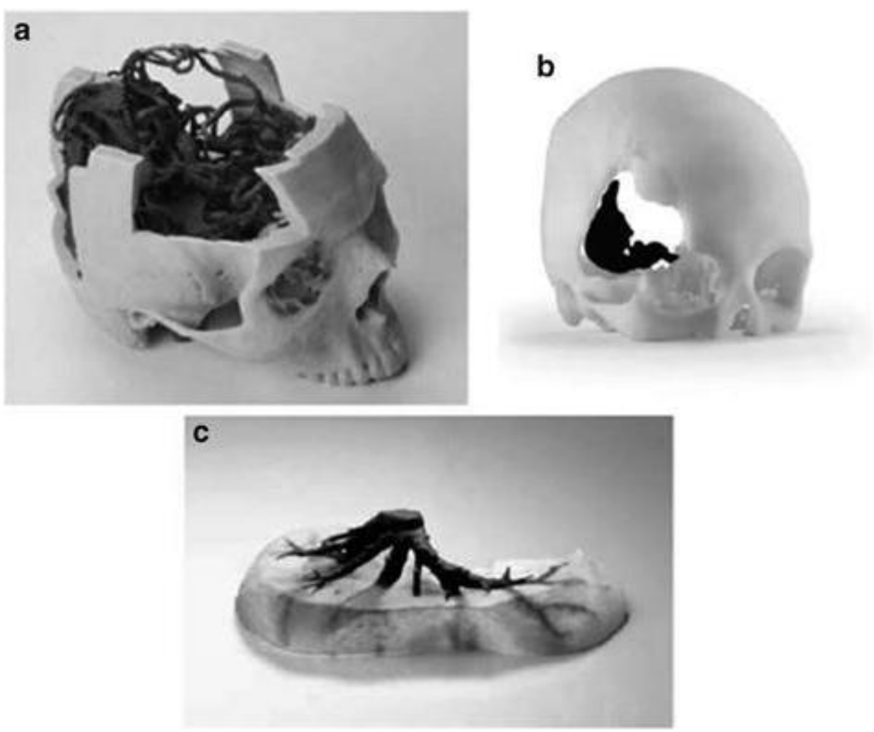


Fig. 19.2 Images of medical parts made using different colored AM systems. (**a**) 3DP used to make a skull with vascular tracks in a darker color. (**b**) A bone tumor highlighted using ABS. (**c**) Stratasys Connex process showing vascularity inside a human organ

It is difficult to say whether a particular AM technology is more or less suited to medical applications. This is because there are numerous ways in which these machines may be applied in this field. One can envisage that different technologies may find their way into different medical departments due the specific benefits they provide. However, the most common commercial machines certainly seem to be well suited to being used as communication aids between surgeons, technical staff, and patients. Models can also be suitable for diagnostic aids and can assist in planning, the development of surgical procedures, and for creating surgical tools and even the prosthetics themselves. Direct fabrication of implants and prosthetics is however limited to the direct metal AM technologies that can produce parts using FDA (The US Food and Drug Administration) certified materials plus the small number of technologies that are capable of nonload-bearing polymer scaffolds. For more of these technologies to be properly accepted in the medical arena, a number of factors must be addressed by the industry: Approvals Insurance Engineering training Location of the technology 19.6.1 Approvals While a number of materials are now accepted by the FDA for use in medical applications, there are still questions regarding the best procedures for generating models. Little is known about the materials and processes outside of the mainstream AM industry. Approval and certification of materials and processes through ASTM will certainly help to pave the way towards FDA approval, but this can be a very long and laborious process. Those (relatively few) surgeons who are aware of the processes seem to achieve excellent results and are able to present numerous successful case studies. However, the medical industry is (understandably) very conservative about the introduction of these new technologies. Surgeons who wish to use AM generally have to resort to creative approaches based on trusting patients who sign waivers, the use of commercial AM service companies, and word of mouth promotion. Hospitals and health authorities still do not have procedures for purchase of AM technology in the same way they might purchase a CT machine. 19.6.2 Insurance Many hospitals around the world treat patients according to their level of insurance coverage. Similar to the aforementioned issue of approvals, insurance companies do not generally have any protocols for coverage using AM as a stage in the treatment process. It may be possible for some schemes to justify AM parts based on the recommendations of a surgeon, but some companies may question the purpose of the models, requiring additional paperwork that may deter some surgeons from adopting that route. Again, this issue may be solvable through a process of legitimizing the industry. In the past, AM was considered as a technology suitable mainly for prototypes in the early phases of product development. As we move more and more into mainstream manufacturing, the industry and consumers become more demanding. Part of the satisfying of this demand is the certification process. Insurance companies are also more likely to accept these technologies as part of the treatment process if there are effective quality control mechanisms in place. Also, the increasing number of successful applications using metal systems may lead to the polymer-based machines also becoming more acceptable. 19.6.3 Engineering Training Creating AM models requires skills that many surgeons and technicians will not possess. While many of the newer, low-cost machines do not require significant skill to operate, preparation of the files and some post processing requirements may require more ability. The most likely skills required for the software-based processing can be found in radiology departments since the operations for preparation of a software model are similar to manipulation and interpretation of CT and MRI models. However, technicians in this area are not used to building and manipulating physical models. These skills can however be found in prosthetics and orthotics departments. It is generally quite unusual to find radiology very closely linked with orthotics and prosthetics. The required skills are, therefore, distributed throughout a typical hospital. 19.6.4 Location of the Technology AM machines could be located in numerous medical departments. The most likely would be to place them either in a laboratory where prosthetics are produced, or in a specialist medical imaging center. If placed in the laboratories, the manual skills will be present but the accessibility will be low. If placed in imaging centers, the accessibility will be high but the applications will probably be confined to visualization rather than fabrication of medical devices. Fortunately, most hospitals are now well equipped with high-speed intranets where patient data can be accessed quickly and easily. A separate facility that links closely to the patient data network and one that has skilled software and modeling technicians for image processing and for model post-processing (and associated downstream activities) may be a preference. 19.6.5 Service Bureaus It can be seen that most of the hurdles for AM adoption are essentially procedural in nature rather than technical. A concerted effort to convince the medical industry of the value of AM models for general treatment purposes is, therefore, a key advancement that will provide a way forward. There are small but increasing number of companies developing excellent reputations by specializing in producing models for the medical industry. Companies like Medical Modelling LLC [7] and Anatomics [17] have been in business for a number of years, not just creating models for surgeons but assisting in the development of new medical products. These service bureaus fill the skill gap between the medics and the manufacturers. At the moment, this technology is not well understood in the medical industry and it may be some time before it can be properly assimilated. Eventually, AM technology will become better suited to a wider range of medical applications and at this point, the hospitals and clinics may have their own machines with the inbuilt skills to use them properly. Furthermore, the large medical product manufacturers will also see the benefits of this technology in product development and DDM. As the technology becomes cheaper, easier to use and better suited to the application, such support companies may no longer be necessary to support the industry. This is something the AM industry has seen in other application sectors. In the meantime, these companies provide a vital role in supporting the industry from both sides.

AerospaceApplications:

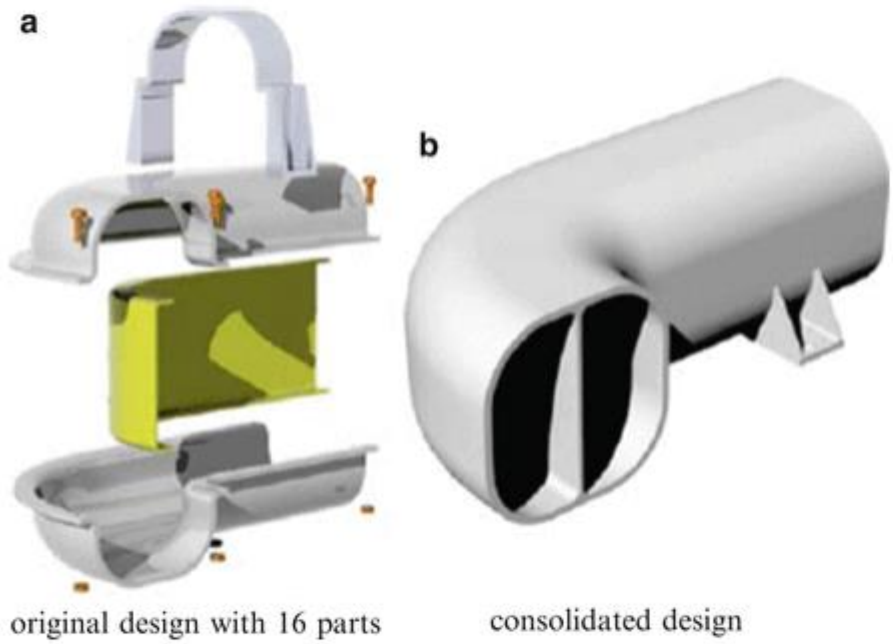
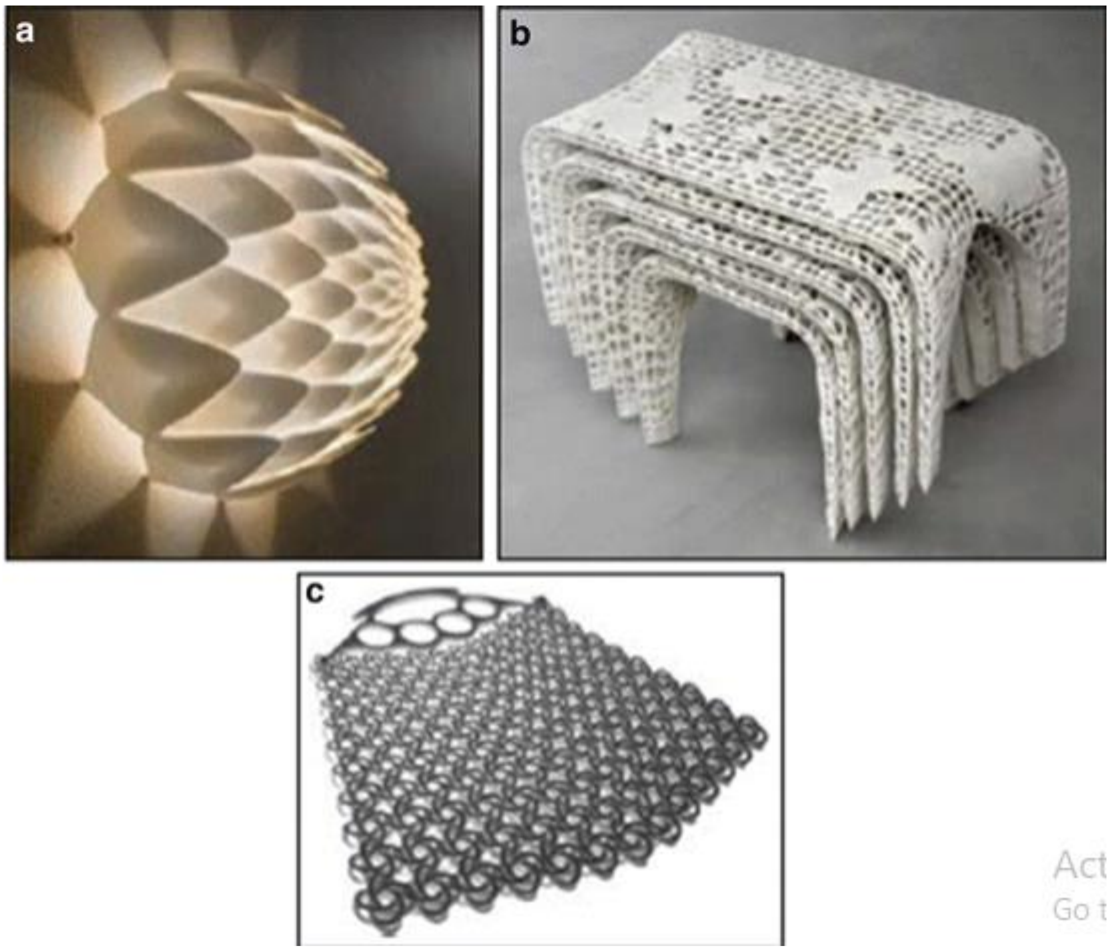


Fig : Aircraft duct example

As mentioned, aerospace is another industry that has traditionally applied AM since it was introduced. The primary advantage for production applications in aerospace is the ability to generate complex engineered geometries with a limited number of processing steps. Aerospace companies have access to budgets significantly larger than most industries. This is, however, often necessary because of the high performance nature of the products being produced.

Industrial Design Applications:



FOC began operations in the late 1990s. Their first commercial products were lamp shades fabricated in VP and PBF an example of which is shown in Fig. They have since developed many families of lampshade designs. In 2003, they partnered with Materialize to market lampshades, which retail for 300 to 6,000 euros (as of 2009). Many other classes of products have been developed, including chairs and stools, handbags, bowls, trays, and other specialty items. See Fig for examples of other products. Also, they have partnered with large and small organizations to develop special “give-aways” for major occasions, many of which were designed to be manufactured via AM. In the early 2000s, they developed the concept of manufacturing textiles. Their early designs were of chain-mail construction, manufactured in PBF. Since then, they have developed several lines of products using similar concepts, including handbags, other types of bags, and even shower scrubs.

Direct digital manufacturing:

Align Technology:

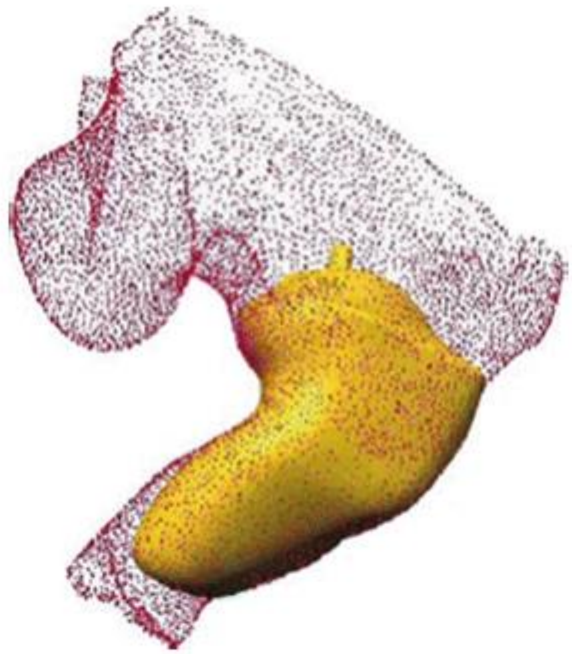
Aligner from Align Technology (Courtesy Align Technology)

Align Technology, in Santa Clara, California, is in the business of providing orthodontic treatment devices Their Invisalign treatments are essentially clear braces, called aligners, that are worn on the teeth Every 1–2 weeks, the orthodontic patient receives a new set of aligners that are intended to continue moving their teeth. That is, every 1–2 weeks, new aligners that have slightly different shapes are fabricated and shipped to the patient's orthodontist for fitting. Over the total treatment time (several months to a year typically), the aligners cause the patient's teeth to move from their initial position to the position desired by the orthodontist. If both the upper and lower teeth must be adjusted for 6 months, then 26 different aligners are needed for one patient, assuming that aligners are shipped every 2 weeks. The aligner development process is geographically distributed, as well as highly engineered. Obviously, the patient and orthodontist are separated from Align Technology headquarters in California. Their data processing for the aligners is performed in Costa Rica, translating customer-specific, doctor-prescribed tooth movements into a set of aligner models. Each completed dataset is transferred electronically to Align's manufacturing facility in Juarez Mexico, where the dataset is added into a build on one of their SL machines. After building the mold using VP from the dataset, the molds are thermal formed. After thermal forming, they are shipped back to Align and, from there, shipped to the orthodontist or the patient.

Siemens and Phonak:

Siemens LASR® hearing aid and shell

Siemens Hearing Instruments, Inc. and Phonak Hearing Systems are competitors in the hearing aid business. In the early 2000s, they teamed up to investigate the feasibility of using polymer powder bed fusion (PBF) technology in the production of shells for hearing aids. The production of hearing aid shells (housings that fit into the ear) required many manual steps. Each hearing aid must be shaped to fit into an individual's ear. Fitting problems cause up to 1 out of every 4 hearing aids to be returned to the manufacturer, a rate that would be devastating in most other industries. Traditionally, an impression is taken of a patient's ear, which is then used as a pattern to make a mold for the hearing aid shell. An acrylic material is then injected into the mold to form the shell. Electronics, controls, and a cover plate are added to complete the hearing aid. To ensure proper operation and comfort, hearing aids must fit snugly, but not too tightly, into the ear and must remain in place when the patient talks and chews (which change the geometry of the ear). To significantly reduce return rates and improve customer satisfaction, Siemens and Phonak sought to redesign their hearing aid production processes. Since AM technologies require a solid CAD model of the design to be produced, the companies had to introduce solid modeling CAD systems into the production process. Impressions are still taken from patients' ears, but are scanned by a laser scanner, rather than used directly as a pattern. The point cloud is converted into a 3D CAD model, which is manipulated to fine-tune the shell design so that a good fit is achieved. This CAD shell model is then exported as an STL file for processing by an AM machine.



Hearing aid within scanned point cloud

In the mid-2000s, Siemens developed a process to produce shells using vat photopolymerization (VP) technology to complement their PBF fabrication capability. VP has two main advantages over PBF. First, VP has better feature detail, which makes it possible to fabricate small features on shells that aid assembly to other hearing aid components. Second, acrylate VP materials are similar to the materials originally used in the hearing aid industry (heat setting acrylates), which are biocompatible. As mentioned, Siemens originally adopted PBF fabrication; PBF has strengths in that the nylon polyamide materials typically used in PBF are biocompatible and the surface finish of PBF parts aided hearing aid retention in the ear, since the finish had a powder-bed texture. In the late 2000s, Siemens Hearing Instruments produced about 250,000 hearing aids annually. In 2007, they claimed that about half of the in-the-ear hearing aids that they produced in the USA were fabricated using AM technologies. Since the introduction of AM-fabricated hearing aid shells, most hearing aid manufacturers in the Western world have adopted AM in order to compete with Siemens and Phonak. Recent surveys estimate that about 90 % of all custom in-the-ear hearing aid shells are fabricated using AM, which totaled approximately two million AM fabricated shells in 2012 [1]. Since the adoption of AM, hearing aid return rate has fallen dramatically with improved design and manufacturing processes. A number of technology advances have targeted this market. 3D Systems developed a variant of its SLA Viper Si2 machine to manufacture shells, called the SLA Viper HA. The machine contains two small vats, one with a red-tinted resin and the other with a blue-tinted resin. The idea is to fabricate both the left and right hearing aid shells for a patient in one build, where each shell is a different color, enabling the patient to easily distinguish them. Of course, the resins can be swapped with flesh-colored resin in both vats, if desired by a patient. Envision TEC has also focused on this market, developing several VP machines that are designed for hearing aid shells. Additionally, companies such as Rapid Shape, in Germany, and Carima, in South Korea, have entered the market with mask projection VP machines. The hearing aid shell production is a great example of how companies can take advantage of the shape complexity capability of RP technologies to economically achieve mass customization. With improvements in scanning technology, it is likely that patients' ears can be scanned directly, eliminating the need for impressions [3]. If desktop AM systems can be developed, it may even be possible to fabricate custom hearing aids in the audiologist's office, rather than having to ship impressions or datasets to a central location.

Custom Footwear and Other DDM Examples

Assassin model soccer shoe. Courtesy prior 2 lever

In 2013, Nike developed a line of football cleats called the Vapor Laser Talon. The cleat plate was specially designed to improve player performance, particularly for speed positions. It has an intricate, lattice design and was fabricating using PBF in a proprietary polymer material. The examples presented so far all relate to body-fitting, customized parts. However, many other opportunities exist, even in the medical arena. Many companies worldwide are investigating the use of PBF technologies for the creation of orthopedic implants. For instance, Adler Ortho Group of Italy is using Arcam's EBM system to produce stock sizes of acetabula cups for hip implants made from Ti–6Al–4V. The use of AM techniques enables a more compact design and a better transition between the solid bearing surface and the porous bone-ingrowth portion of the implant. Although a porous coating of titanium beads or hydroxyapatite on an implant's surface work well, they do not provide the optimum conditions for Osseo integration. The hierarchical structure capabilities of AM enable the creation of a more optimal bone-ingrowth structure for Osseo integration. As of early 2014, more than 40,000 cups have been implanted and more than 90,000 implants have been produced in series production by companies such as Adler Ortho and Lima Corporate SpA. More generally, approximately 20 different AM medical implant products have received FDA clearance for implantation in patients.

DDM Drivers: It is useful to generalize from these examples and explore how the unique capabilities of AM technologies may lead to new DDM applications. The factors that enable DDM applications include: Unique Shapes: parts with customized shapes. Complex Shapes: improved performance. Lot Size of One: economical to fabricate customized parts. Fast Turnaround: save time and costs; increase customer satisfaction. Digital Manufacturing: precisely duplicate CAD model. Digital Record: have reusable dataset. Electronic “Spare Parts”: fabricate spare parts on demand, rather than holding inventory. No Hard Tooling: no need to design, fabricate, and inventory tools; economical low-volume production. As indicated in the Align Technology and hearing aid examples, the capability to create customized, unique geometries is an important factor for DDM. Many AM processes are effective at fabricating platforms full of parts, essentially performing mass customization of parts. For example, 100 aligner molds fit on one SLA-7000 platform. Each has a unique geometry. Approximately 25–30 hearing aid shells can fit in the high-resolution region of an SLA Viper Si2 machine. Upwards of 4,000 hearing aid shells can be built in one PBF powder bed in one build. The medical device industry is a leading—and growing—industry where DDM and rapid tooling applications are needed due to the capability of fabricating patient-specific geometries.

Manufacturing versus Prototyping: Production manufacturing environments and practices are much more rigorous than prototyping environments and practices. Certification of equipment, materials, and personnel, quality control, and logistics are all critical in a production environment. Even small considerations like part packaging can be much different than in a prototyping environment.

Table compares and contrasts prototyping and production practices for several primary considerations

Key characteristic	RP company	DDM company
Equipment	From equipment manufacturer	Production machines and calibration equipment
Personnel	No formal testing, certification, or training typical	On-going need for certification
Practices	Trial-and-error, no formal documentation of practices	Formal testing for each critical step, periodic recertification
Quality	Basic procedures; some inspection	ISO 9000 compliance. Extensive, thorough quality system needed
System	Basic system; controls and documentation not essential	Developed system; controls and documentation required
Planning	Basic. Requires only modest part assessment	Formal planning to ensure customer requirements are met. Developed process chains, no experimentation
Scheduling and delivery	Informally managed; critical jobs can be expedited; usually only one delivery date	Sophisticated scheduling, just-in-time delivery
Personnel	Informal training, on-the-job training; certification not necessary; redundancy not essential	Formal training for certification and periodic recertification. Redundant personnel needed for risk mitigation

Life-Cycle Costing: In addition to part costs, it is important to consider the costs incurred over the lifetime of the part, from both the customer’s and the supplier’s perspectives. For any manufactured part life-cycle costs associated with the part can be broken down into six main categories: equipment cost, material cost, operation cost, tooling cost, service cost, and retirement cost. Material and operation costs are related to the actual manufacturing process and are one-time costs associated only with one particular part. For most conventional manufacturing processes, tooling is required for part fabrication. This may include an injection mold, stamping dies, or machining fixtures. The final two costs, service and retirement, are costs that accrue over the lifetime of the part. This section will focus on tooling, service, and retirement costs, since they have not been addressed yet. Service costs typically include costs associated with repairing or replacing a part, which can include costs related to taking the product out of service, disassembling the product to gain access to the part, repairing or replacing the part, re-assembling.

Future of DDM: There is no question that we will see increasing utilization of AM technologies in production manufacturing. In the near-term, it is likely that new applications will continue to take advantage of the shape complexity capabilities for economical low production volume manufacturing. Longer time frames will see emergence of applications that take advantage of functional complexity capabilities (e.g., mechanisms, embedded components) and material complexities. To date, tens of thousands of parts have been manufactured for the aerospace industry. Many of these parts are flying on military aircraft, space shuttles, the International Space Station, and many satellites. Several small AM service companies have been created to serve the aerospace market. The machine vendors have re-conceptualized some of their machine designs to better serve manufacturing markets. An example of this is the development of the 3D Systems Sinter Station Pro, and the similar public announcements by EOS that all future models of their machines will be designed with production manufacturing in mind. Flame-resistant nylon materials have been developed to enable parts manufacturing for commercial aircraft, as well as higher-temperature and higher-recyclability materials.

Other markets will emerge: One needs only consider the array of devices and products that are customized for our bodies to see more opportunities that are similar to aligners and hearing aids. From eye glasses and other lenses to dentures and other dental restorations, to joint replacements, the need for complex, customized geometries, hierarchical structures and complex material compositions is widespread in medical and health related areas. New design interfaces for non-experts have enabled individuals to design and purchase their own personal communication/computing device (e.g., cell phones) housings or covers in a manner similar to their current ability to have a physical representation of their virtual gaming characters produced. File sharing sites such as thingiverse.com and storefronts such as shapeways.com are very popular and many expansions and generalizations are to be expected. Structural components will have embedded sensors that detect fatigue and material degradation, warning of possible failures before they occur. The opportunities are bounded only by the imagination of those using AM technologies.