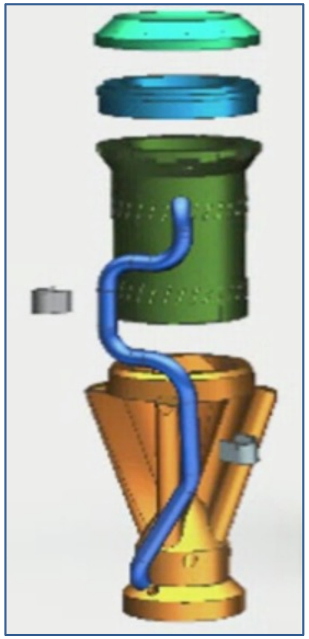
Additive Manufacturing

(MTN-318)

Gautam Agarwal

Metallurgical and Materials Engineering,
IIT Roorkee

Why AM?



Conventionally manufactured gas turbine burner

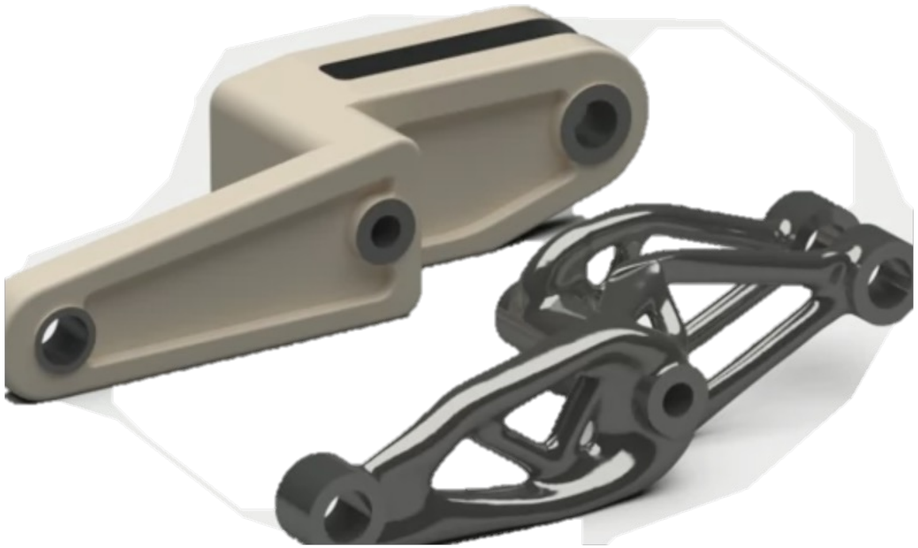
13 parts joined together
Lead time – 26 weeks
Mass – 4.5 kg

Additive manufactured gas turbine burner

1 single part
Lead time – 3 weeks
Mass – 3.5 kg

Courtesy – Siemens

Why AM?



Original part
Volume – 263 m^3
Mass – 2.06 kg

AM part
Volume – 97 m^3
Mass – 0.76 kg

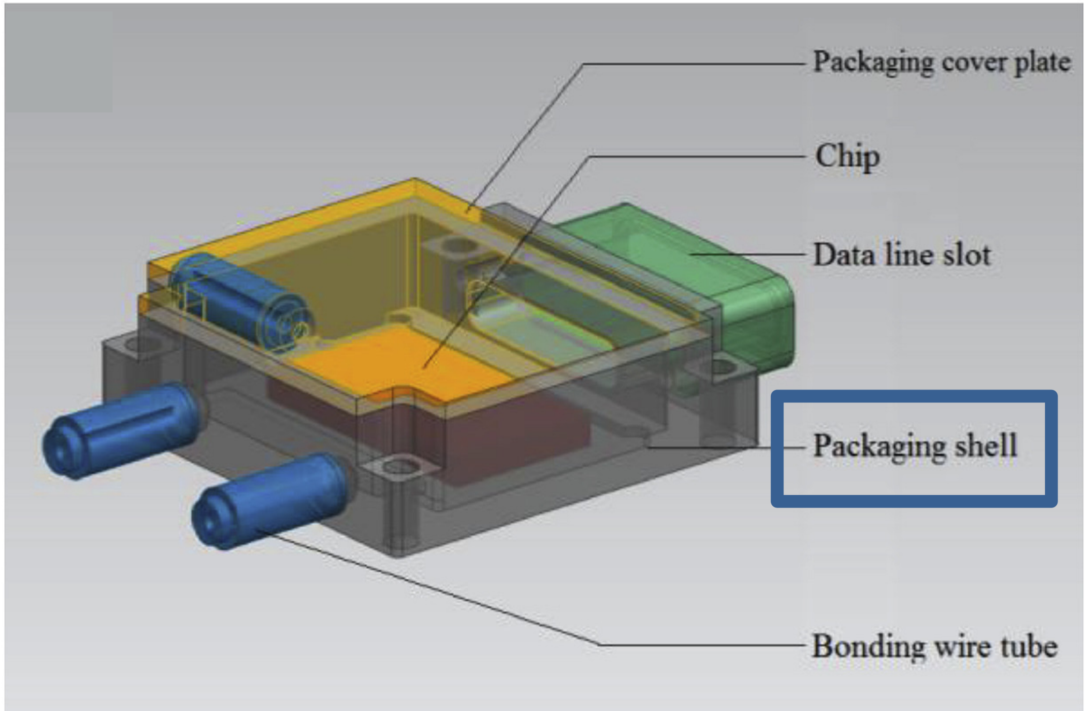
Courtesy – Siemens and U of M

Why AM?

3D Printed cryogenic engine with regenerative cooling

Courtesy – Skyroot

Why AM?



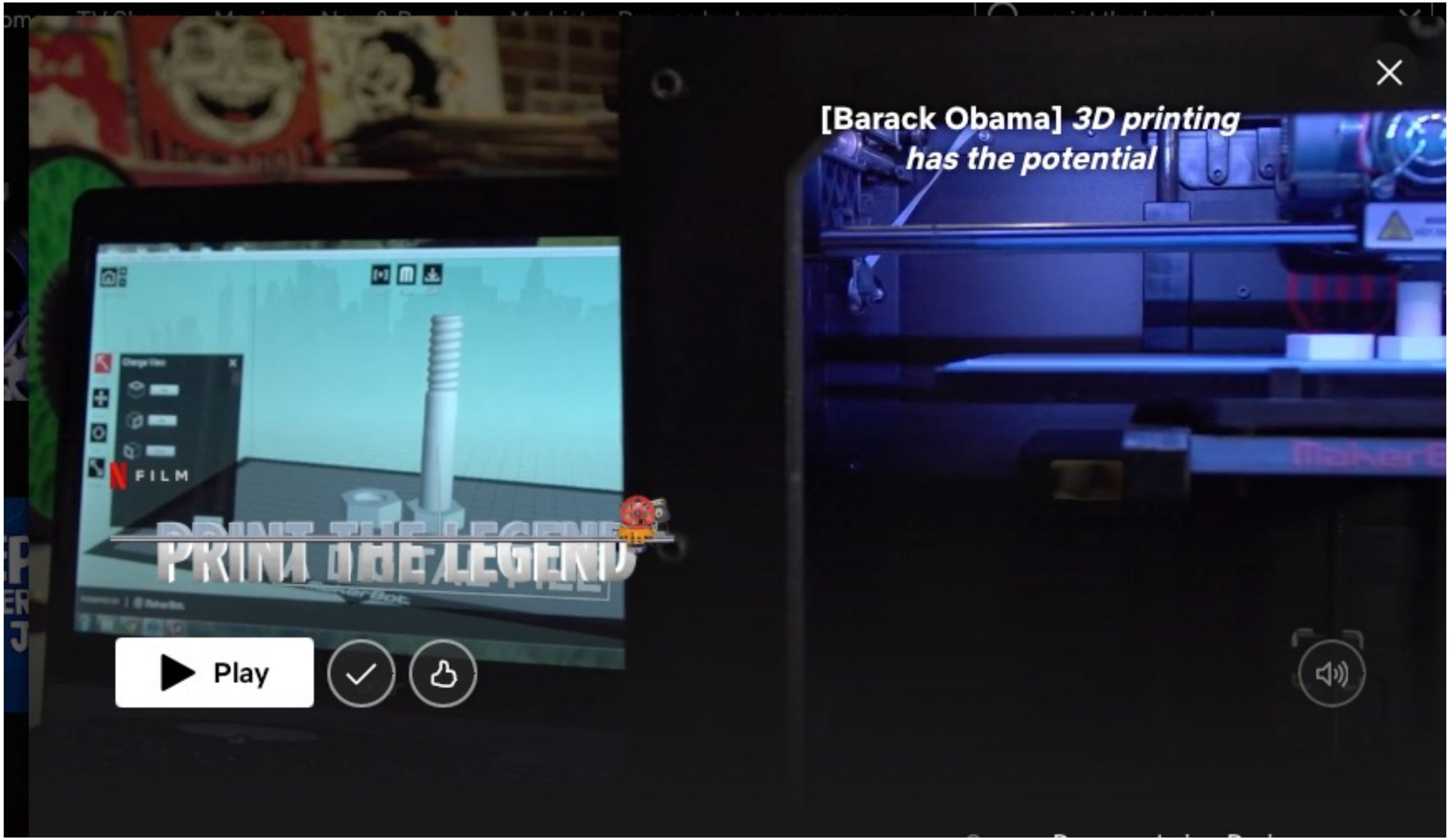
Typical electronic packaging assembly[1]

Material requirements
Fabrication
Issues
Motivation

- Thermal management for microelectronic circuits/ICs
  - Continuous miniaturization demands efficient heat dissipation for the ICs to function normally and prevent its failure
  - Electronic packaging protects and interconnects ICs with other components while dissipating heat quickly and efficiently
  - Challenges are there both in material selection and component fabrication

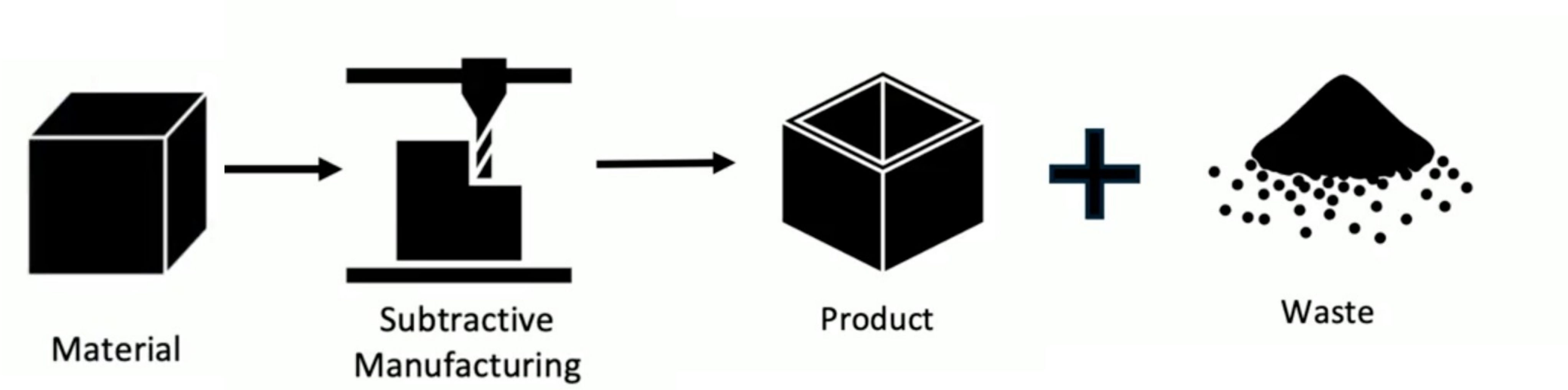
1. J. Alloys Compd., 763 (2018)

Why AM?

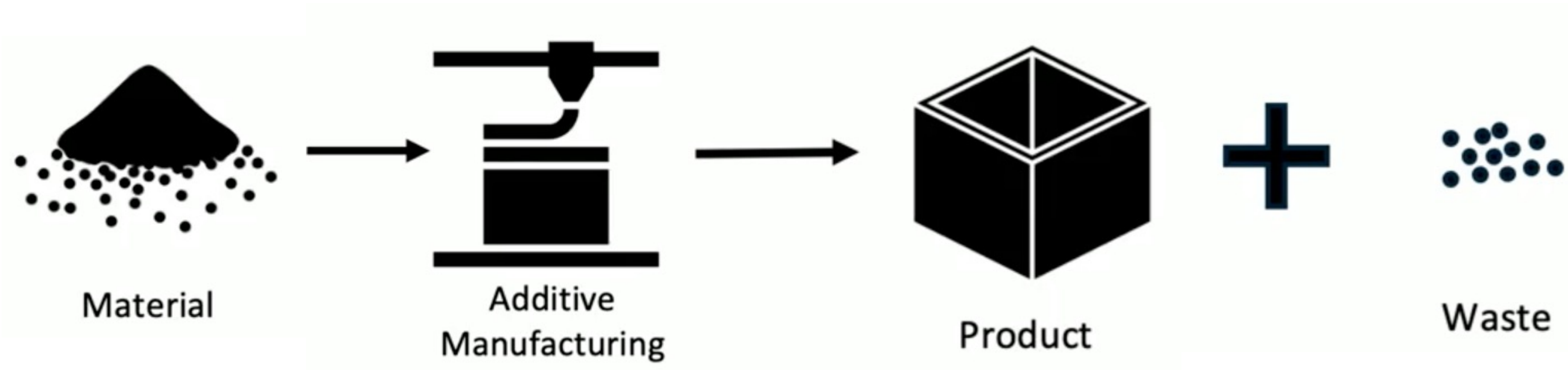


Print the legend

Subtractive manufacturing



Additive manufacturing



Course structure

- Introduction to AM
- Materials and processes under AM
  - Metals and alloys (powder, wire, laser, electron, arc)
  - Polymers and ceramics (photopolymerization, stereolithography, SLS, laser CVD)
- Process monitoring, modeling and control
  - *In-situ* temperature, mass flow
  - Heat and mass transfer
  - Residual stress, thermal management, microstructure control
  - Machine learning
- Case studies
  - Personalized surgery
  - Automotive, aviation, energy, electronics

Applications of AM will be discussed throughout!

Distribution of marks

Total marks = CWS (20-30) + MTE (30) + ETE (40-50)

CWS (20-30):

1. Attendance – 5
2. Class tests (2-4) – 10-15
3. Assignment – 5-10

Textbooks

Suggested Books:

S. No.	Name of Authors /Books/ Publisher	Year of Publication/ Reprint
1	Gibson, I., Rosen, D.W., Stucker, B., Additive Manufacturing Technologies, Springer	2014
2	J.D. Majumdar and I. Manna, Laser-assisted fabrication of materials, Springer Series in Material Science	2012
3	Zhang, J. Jung, Y.-G., Additive Manufacturing: Materials, Processes and applications, Elsevier	2018
4	Brandt, M., Laser Additive Manufacturing; Materials, Design, Technologies and applications, Elsevier	2020

What is additive manufacturing (AM)?

It is a term which describes a **family of various technologies** that build **3D objects** by **adding** material in a **layer-upon-layer** manner.

Is this AM?

Image – Wikipedia

What is additive manufacturing (AM)?

It is a term which describes a **family of various technologies** that build **3D objects** by **adding** material in a **layer-upon-layer** manner.

AM technologies –

- Representation of the geometry as a CAD (computer aided design) file
- Derivation of build information from the CAD geometry
- Equipment
- Feedstock (layering material)

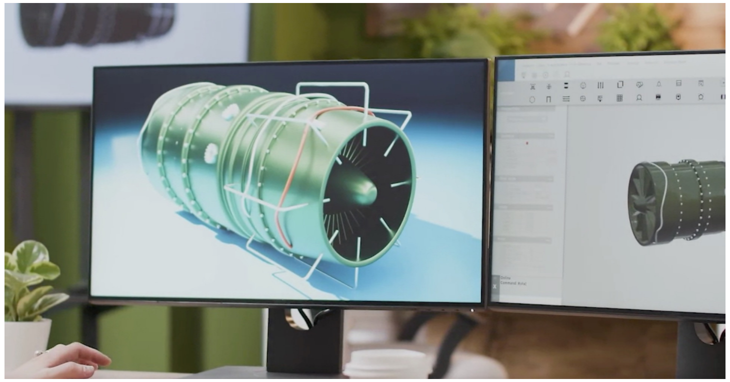
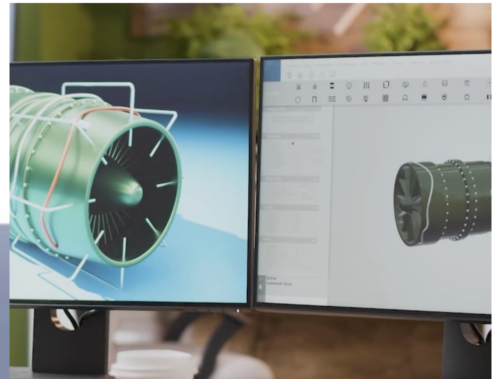


Image – Siemens

What is additive manufacturing (AM)?

It is a term which describes a **family of various technologies** that build **3D objects** by **add** ... er.



AM technolog

- Represe a CAD (
- Derivati the CAD
- Equipme
- Feedsto

Image – Additive Manufacturing Technologies, I. Gibson

Alternate terminologies of AM

- Rapid prototyping
- Solid freeform fabrication
- 3D printing
- Additive layer manufacturing
- **Additive Manufacturing (ASTM terminology)**

History of AM

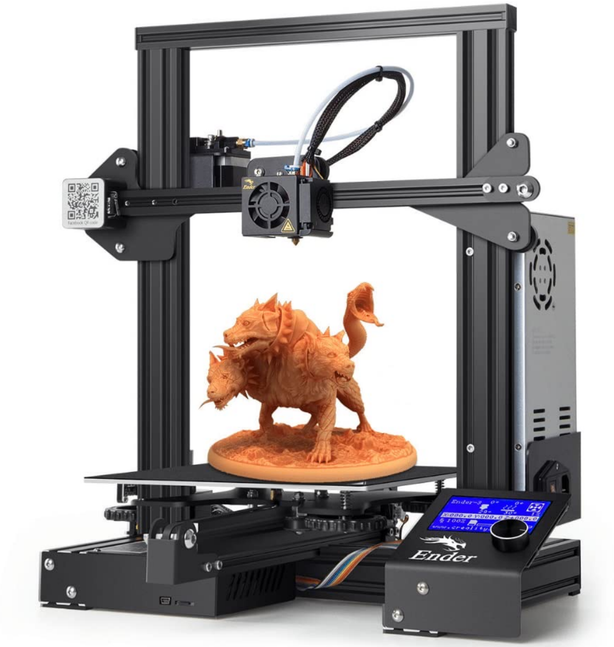
- Infographic: The History of 3D Printing
- History of Additive Manufacturing

Key features of an AM process

1

Feedstock

- Powder
- Filament/wire
- Liquid
- Sheet



2

Energy source/principle

- Arc
- Laser
- Heating filament
- Electron beam
- Binder
- Acoustic energy

3

Motion (XYZ)

- Motors, drives
- Magnetic lenses
- Galvano mirrors

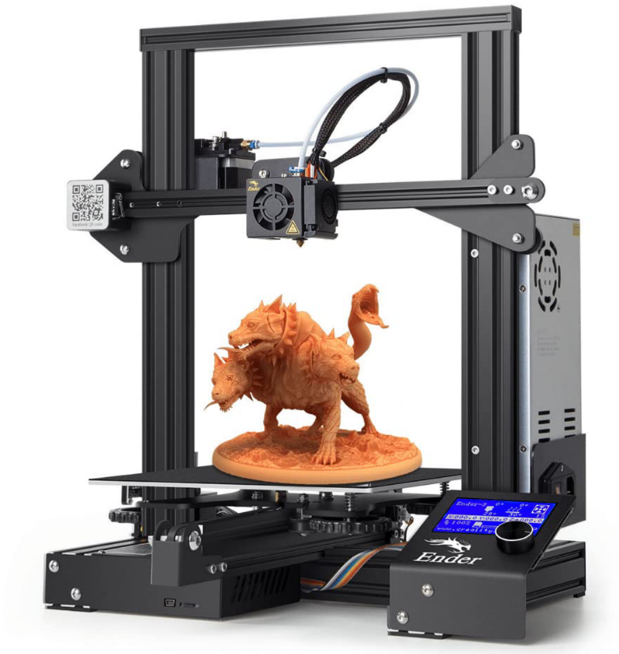
Image source – Amazon

Key features of an AM process

1

Feedstock

- Powder
- Filament/wire
- Liquid
- Sheet



2

Energy source/principle

- Arc
- Laser
- Heating filament
- Electron beam
- Binder
- Acoustic energy

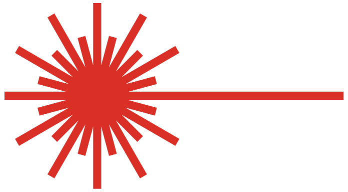
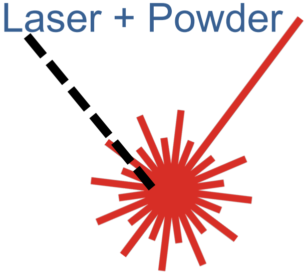
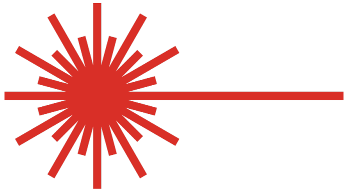
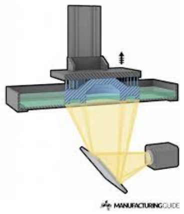
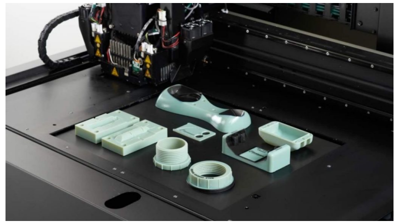
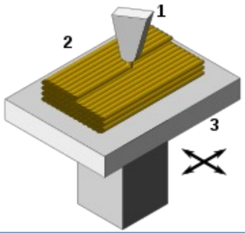
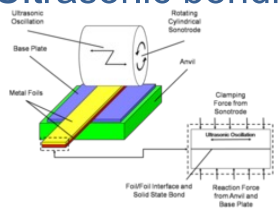
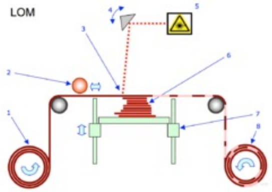
3

Motion (XYZ)

- Motors, drives
- Magnetic lenses
- Galvano mirrors

Image source – Amazon

Classification of AM processes

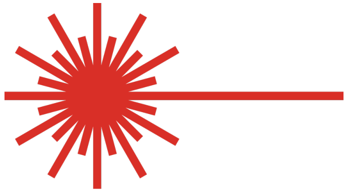
Raw Material	Process Principle			
Powder 	Laser fusion/sintering 	Electron beam melting 	Binder Jetting 	Laser + Powder 
Liquid 	Laser polymerization 	Light projection polymerization 	Material Jetting 	
Filament/Wire 	Fused deposition 	Electron + Wire 		
Sheet/Foil 	Ultrasonic bonding 	Laser lamination 		

ASTM categories for AM

Raw Material	Process Principle

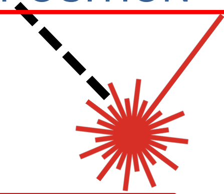
Powder

POWDER BED FUSION



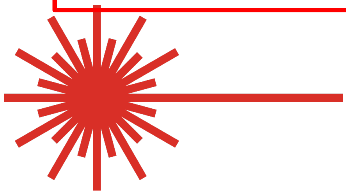
BINDER JETTING

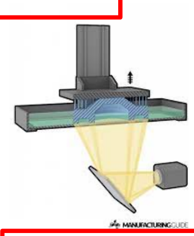
DIRECT ENERGY DEPOSITION



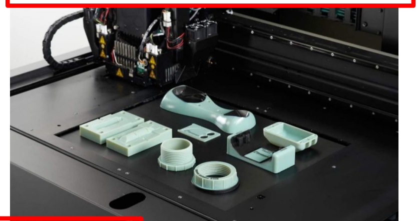
Liquid

VAT PHOTOPOLYMERIZATION



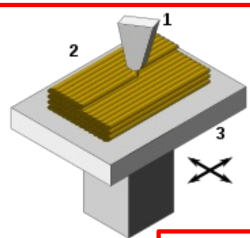


MATERIAL JETTING

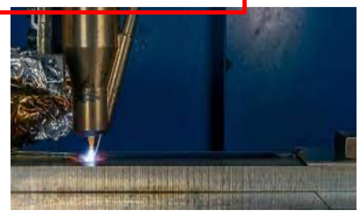


Filament/Wire

MATERIAL EXTRUSION

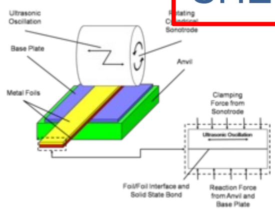


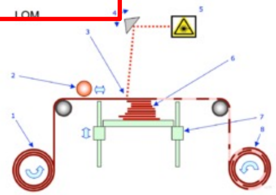
DIRECT ENERGY DEPOSITION



Sheet/Foil

SHEET LAMINATION





Images – Wikimedia Commons, Beamler

Generic AM process

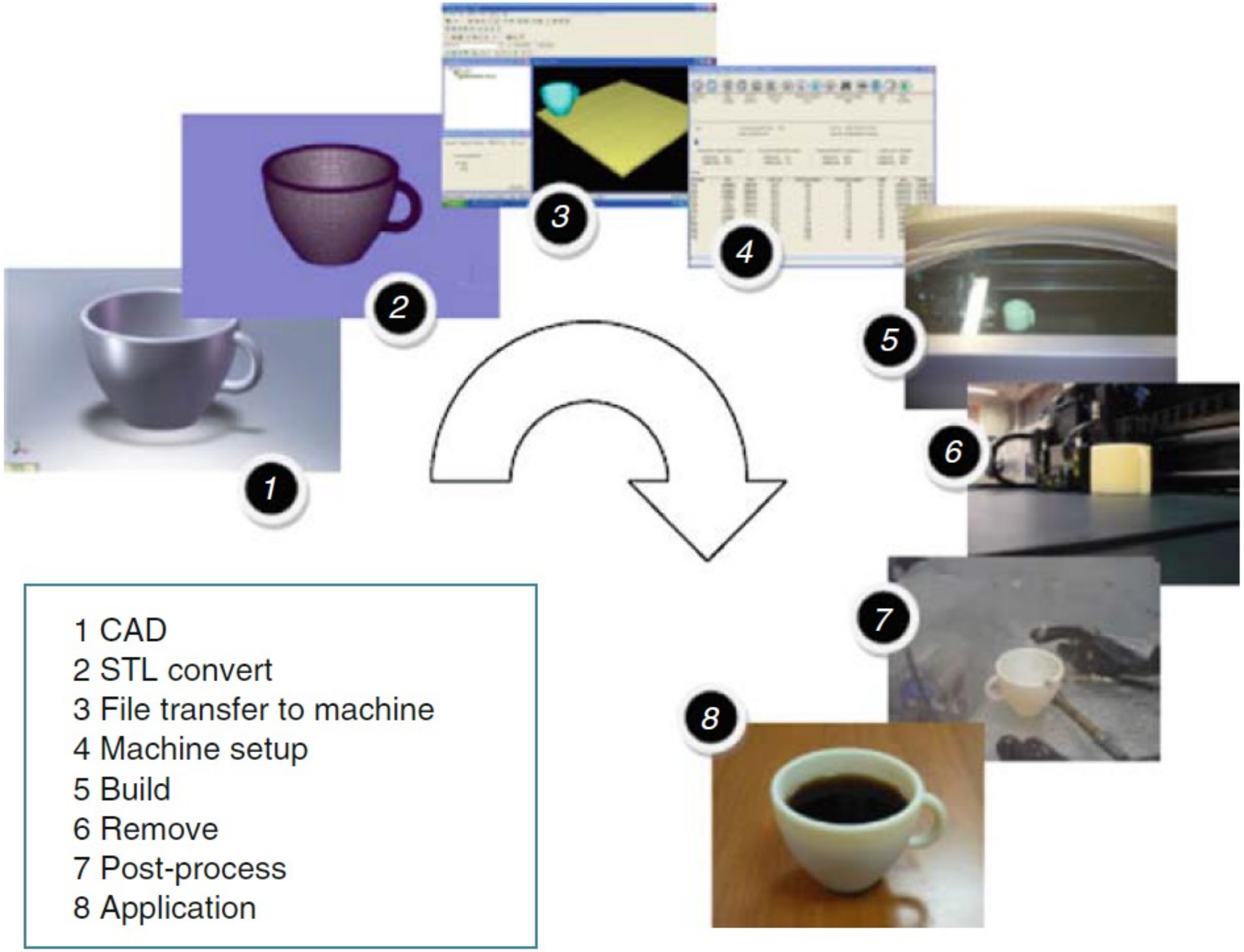
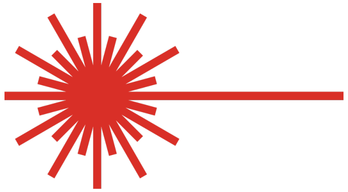
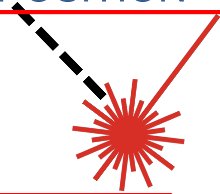
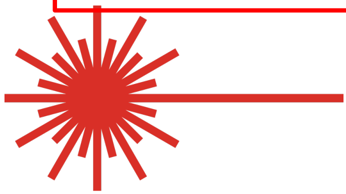
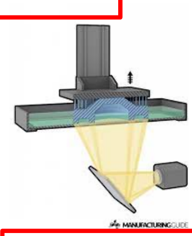
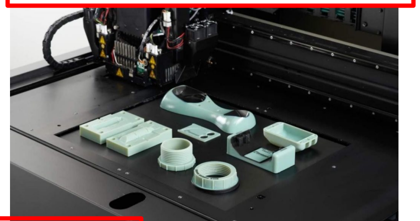
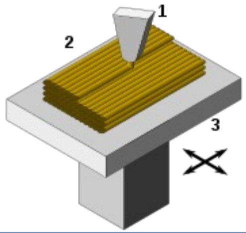
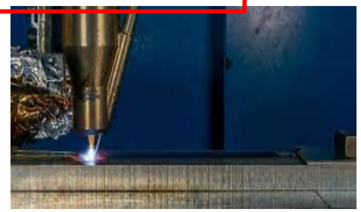


Image – Additive Manufacturing Technologies, I. Gibson

Generic AM process

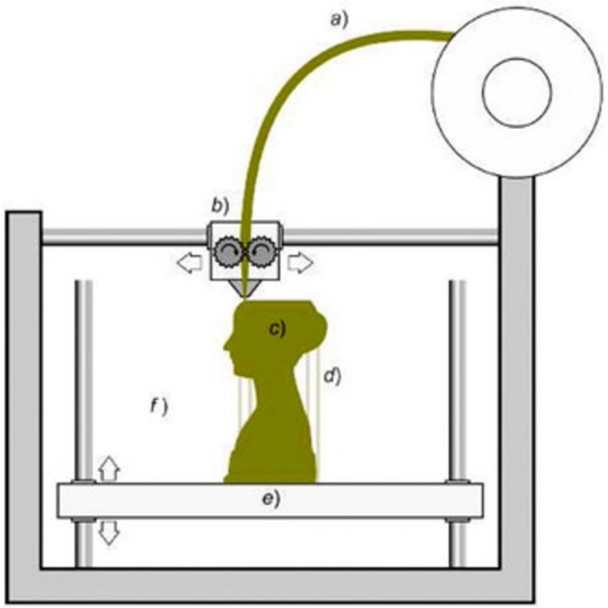
1. **CAD** – 3D solid or surface representation. Reverse engineering (laser scanning) also possible.
2. **.STL file** – Describes external closed surfaces of the CAD model and is the basis for slicing
3. **File transfer to machine** – Also includes manipulation like size, position and orientation
4. **Machine setup** – Build parameter setup (energy source, layer thickness, scan strategy *etc.*)
5. **Build** – Automated. Some superficial monitoring needed.
6. **Removal**
7. **Postprocessing** – Cleaning, support removal, heat treatment *etc.*
8. **Application** – Surface finish, assembly

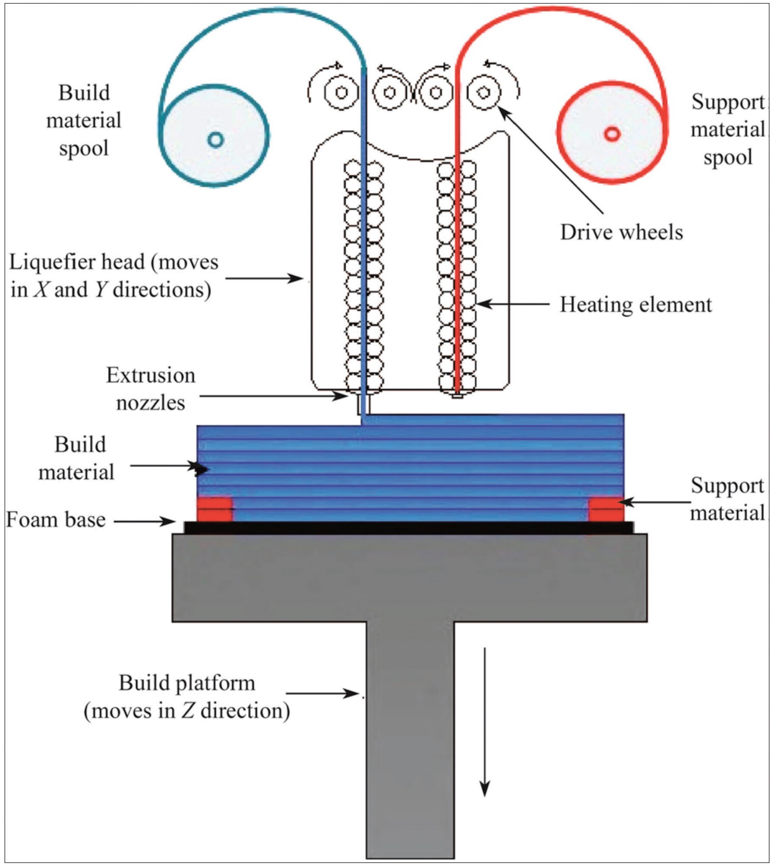
ASTM categories for AM

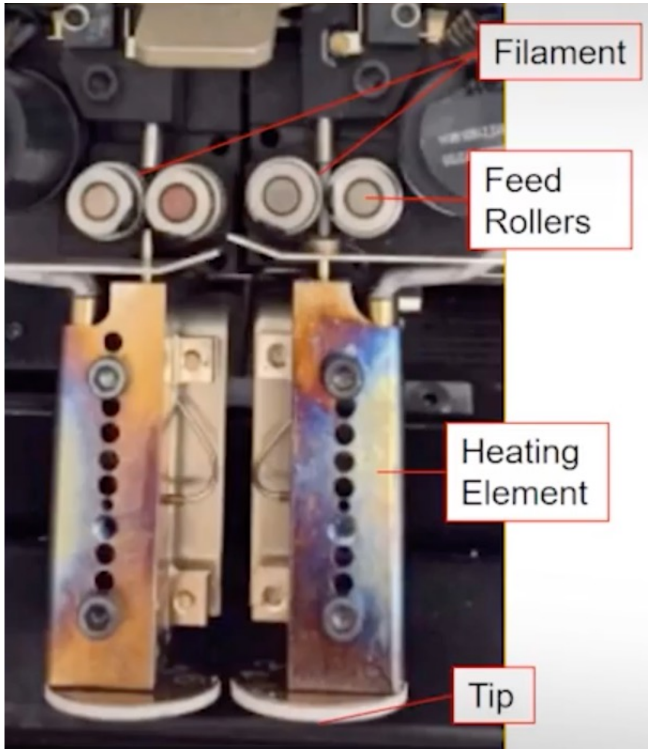
Raw Material	Process Principle
Powder 	POWDER BED FUSION   BINDER JETTING  DIRECT ENERGY DEPOSITION 
Liquid 	VAT PHOTOPOLYMERIZATION   MATERIAL JETTING 
Filament/Wire 	MATERIAL EXTRUSION  DIRECT ENERGY DEPOSITION  

Material extrusion (FDM)

A thermoplastic filament is extruded through a nozzle assembly and heated to its softening temperature.

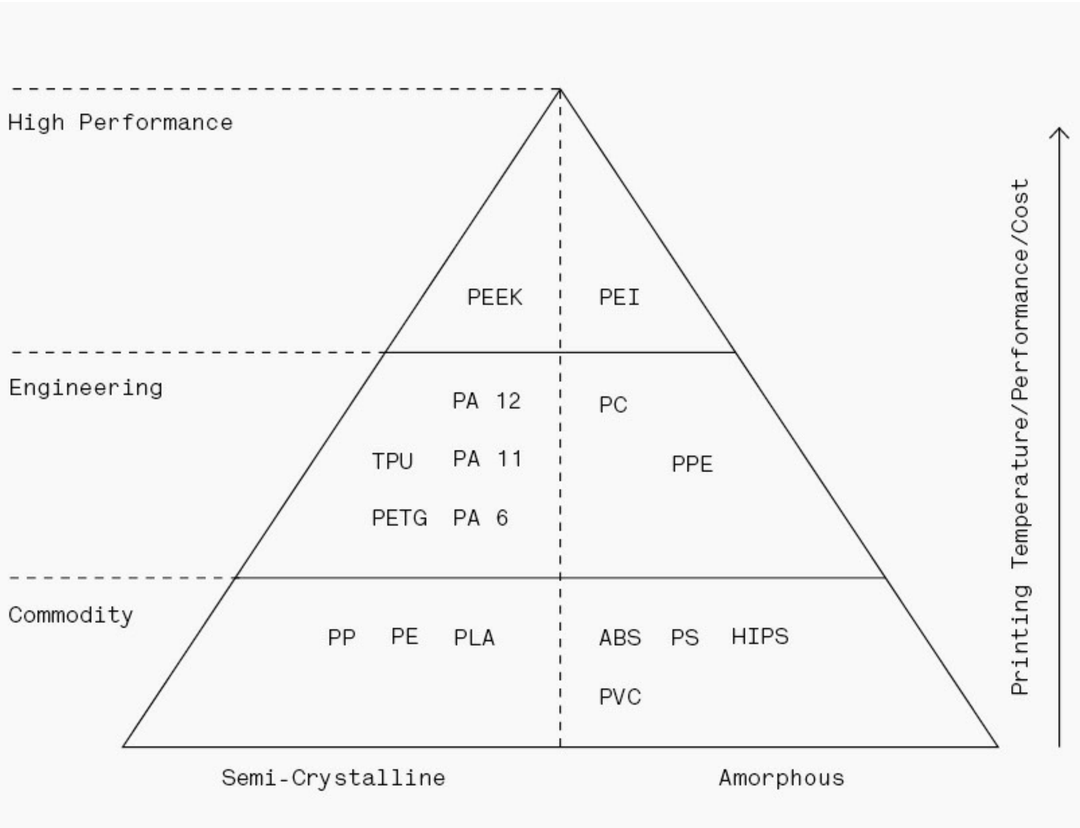






Computer Graphics Forum, Volume: 36 (1),
Mohamed, O.A. et al., Adv. Manuf., 2015

Material extrusion

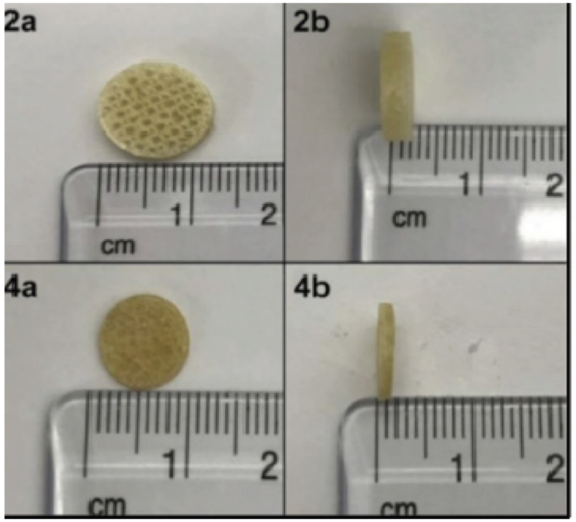


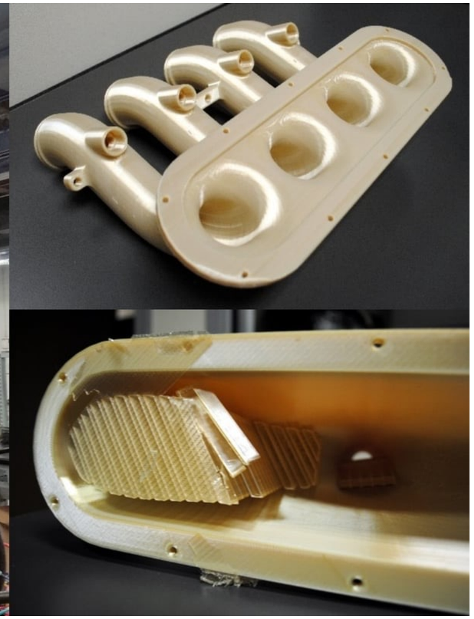
[Materials]

Manufacturers

- Stratasys
- Ultimaker
- Wasp
- Prusa
- Lulzbot
- Formlab

Material extrusion





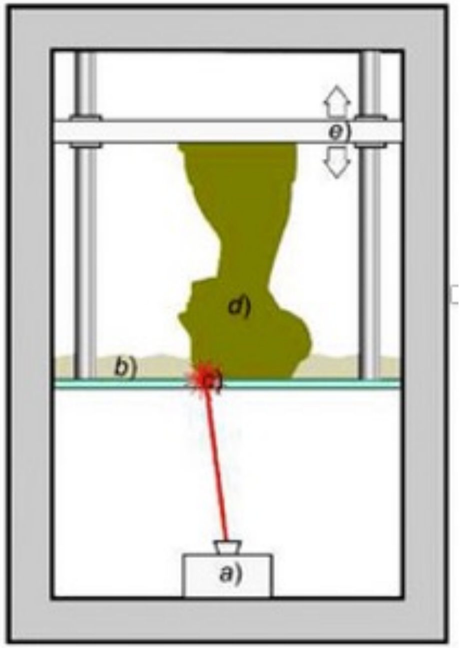
Images – All3DP.com, ASM handbook vol. 24, Solanki, N.G. et al., J. Pharm. Sci., 2018

FDM @ IITR

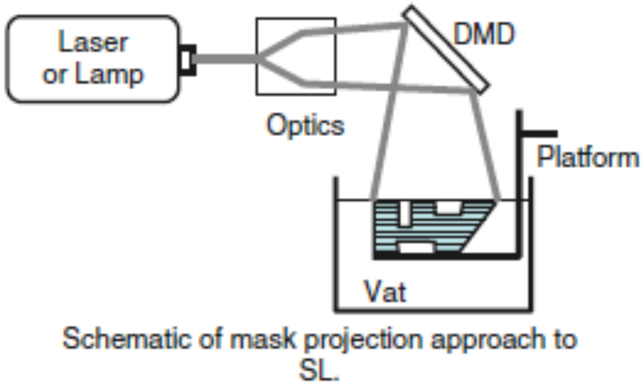
Wasp.com

Vat Photopolymerization (VP)

Light cures a photopolymer bath (vat) into a solid



Stereolithography (SLA)

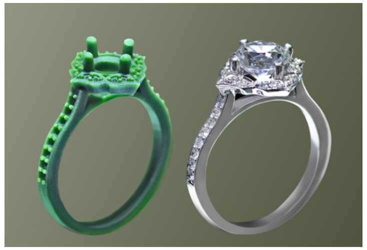


Digital Light Processing (DLP)

Digital Light Synthesis (DLS)

Vat Photopolymerization (VP)

- High Resolution
- Surface finish
- Clear parts possible
- UV degradation (limits life)
- Limited performance (brittle)



Images – 3D printing handbook, desktop metal

Vat Photopolymerization (VP)

Manufacturers

SLA
- 3D systems
- FormLabs

DLP
- Envsion Tec (now Desktop Metal)

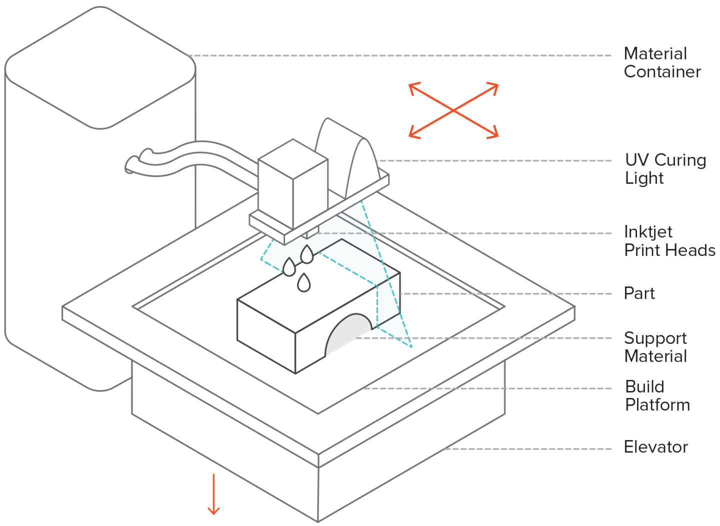
DLS
- Carbon

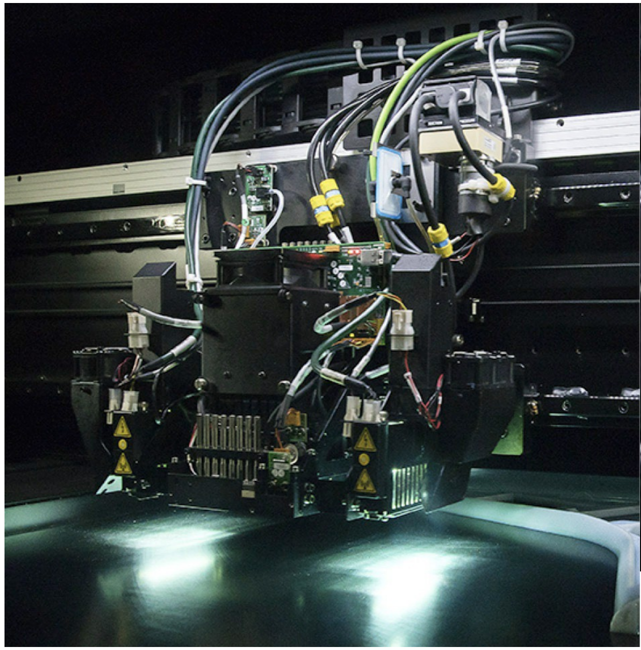
Materials

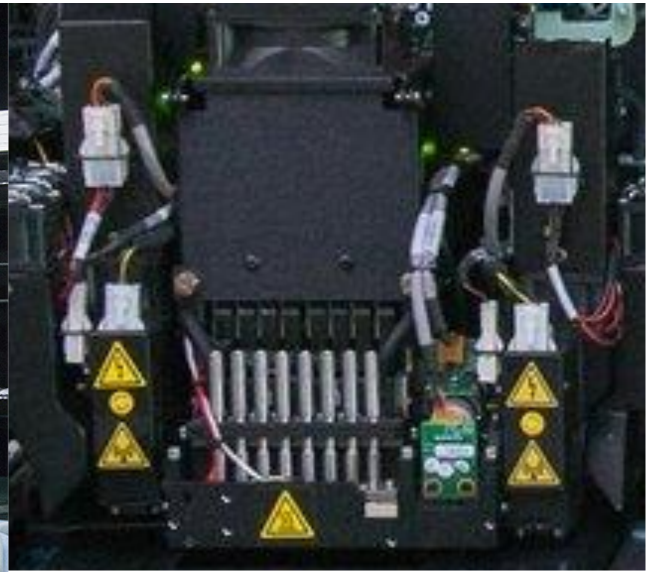
Class	Key characteristics
Standard	• Smooth surface finish • Brittle
Transient	• Clear
Tough/Durable	• ABS-like or PP-like
High Temperature	• Useful for injection molding & thermoforming tooling
Dental	• Biocompatible • Abrasion resistant • High cost
Flexible	• Rubber-like
Ceramic precursors	• Print is followed by pyrolysis

Material Jetting

Liquid is jetted and light (or heat) is used to cure material

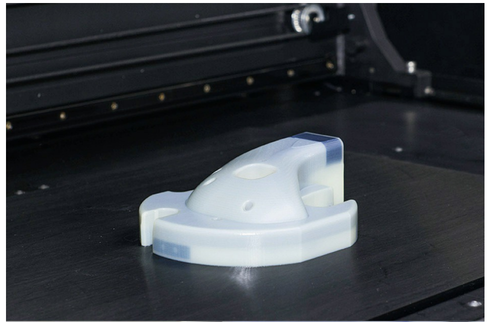


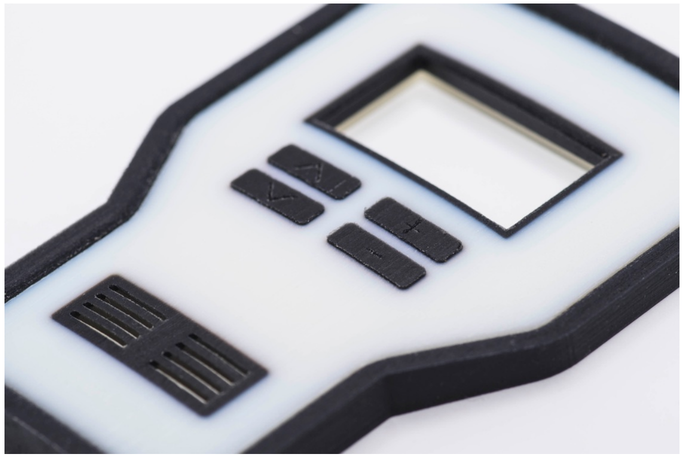




Material jetting parts

- Multi-color
- Multi-material
- Fine resolution
- Dissolvable supports





Material Jetting

Manufacturers

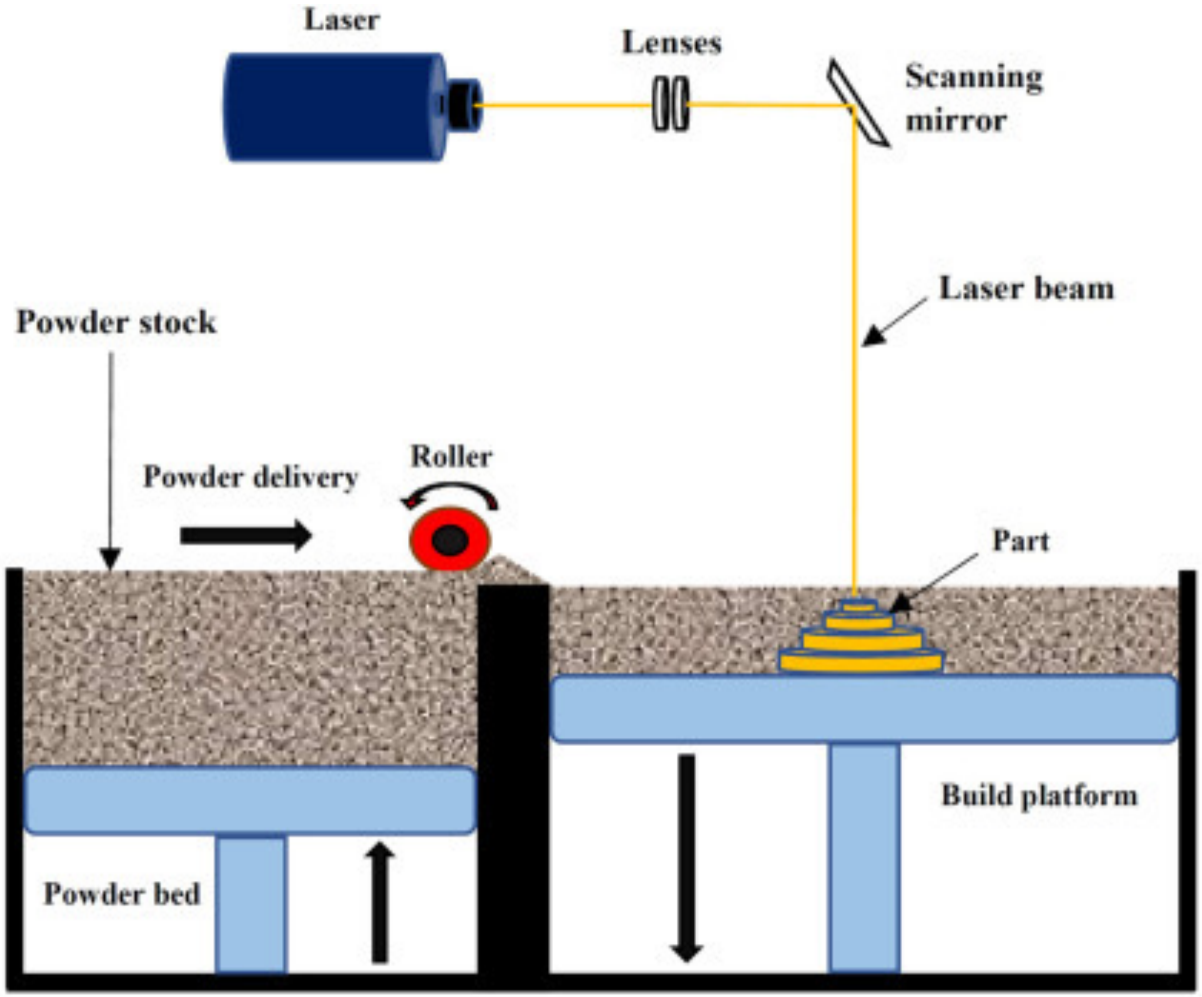
Material Jetting

- 3D Systems
- Stratatys

Materials

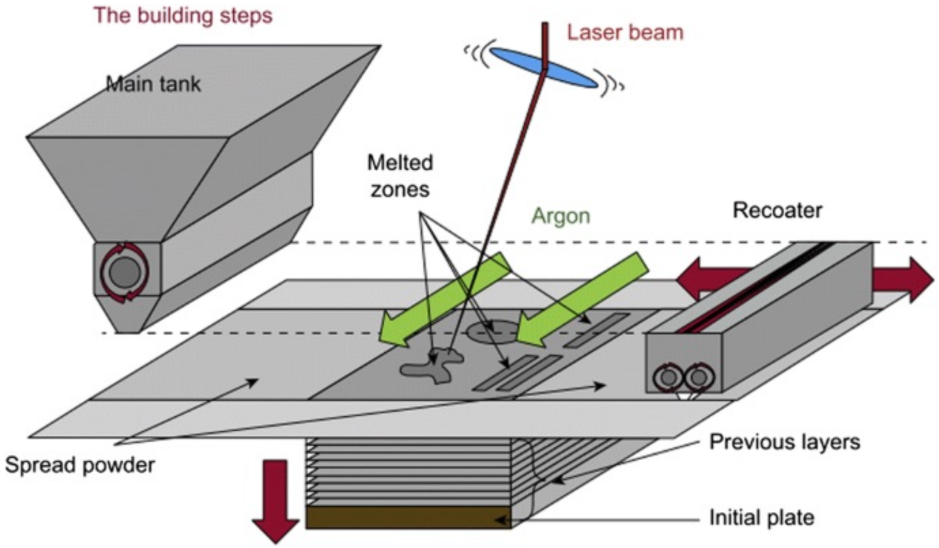
Class	Key characteristics
Standard	• Rigid opaque plastic • Simulates injection molded parts • Brittle
Flexible	• Wide range, can be modified • Customizable store hardness • Poor elongation and stretch
Tough/Durable	• ABS-like or PP-like • Brittle
Bio-compatible	• Short term biocompatibility • Sterilizable

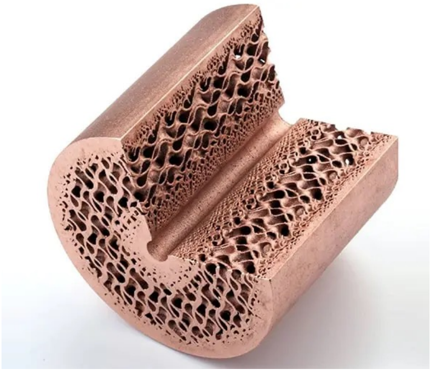
Powder Bed Fusion

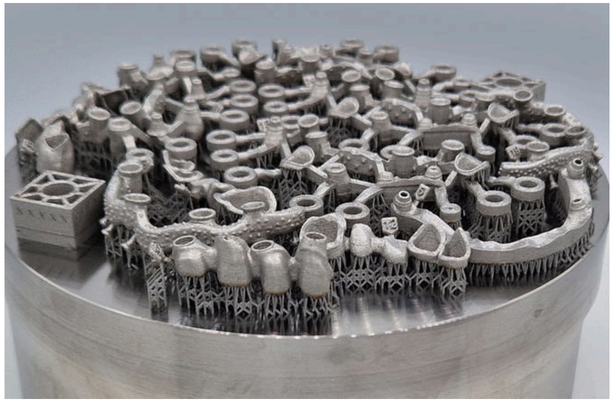


Nugroho *et al.*, Chapter 4 - 3D printing composite materials: A comprehensive review, Editor(s): It-Meng Low, Yu Dong, Composite Materials, Elsevier.

Powder Bed Fusion







prostheses, crowns, partial frames, and bridges

Laser Additive Manufacturing *Materials, Design, Technologies, and Applications* (book), metal-am.com, Hyperganic, primaadditive.com

Selective Laser Sintering (SLS) – Polymer

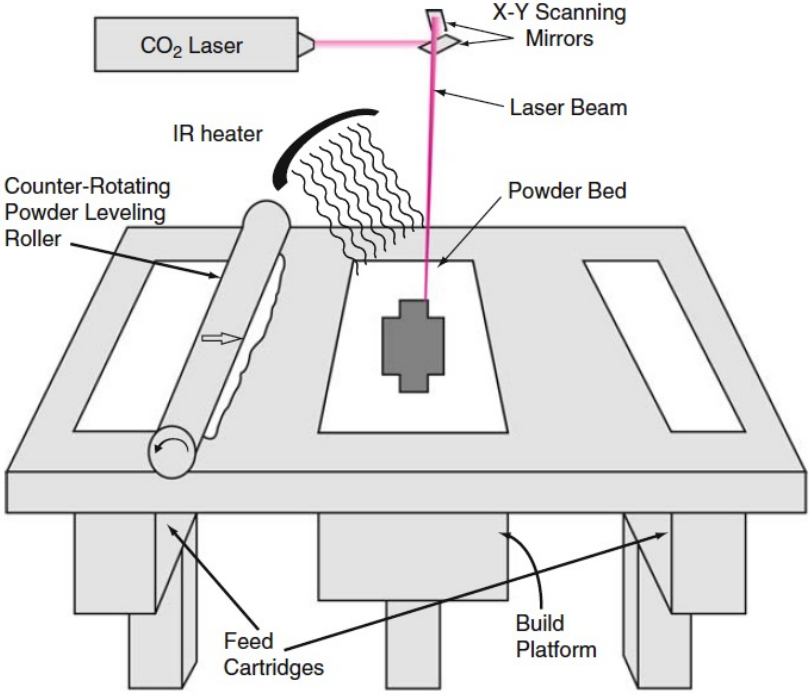
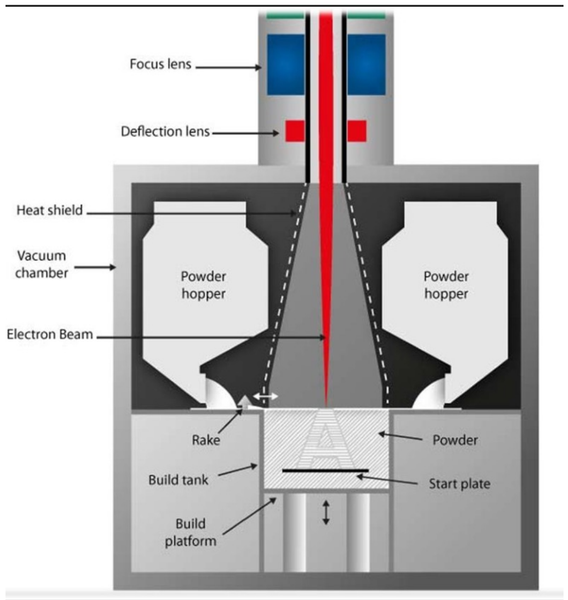
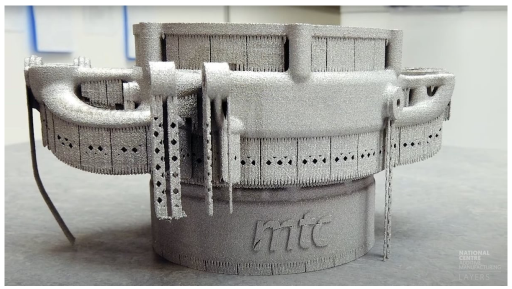


Image – Additive Manufacturing Technologies, I. Gibson, EOS, 3D printing handbook, Mbworld.org

Electron beam melting





- Superior mechanical properties
- Can process high-temperature, crack-prone and reflective alloys
- Poor surface finish, less resolution

Image – Arcam, Autodesk, all3dp.com, 3D printing handbook

Manufacturers & Materials

Manufacturers

Metal (Laser)

- EOS
- Concept laser (now GE)
- Renishaw
- SLM
- 3D systems
- Additive industries
- Add up
- Intech (*Indian*)

Metal (EB)

- Arcam (now GE)
- Polymer
- EOS
- 3D systems
- Form labs

Materials

Metal (Laser)

Non-Reactive alloys

- Steels (316L, 17-4PH), Stellite, Inconel, Bronze, precious metals

Reactive

- Ti-6Al-4V, AlSi10Mg

Metal (EB)

- Ti-6Al-4V, Inconel 718, CoCrW

Polymer (Laser)

- Nylon12
- Alumide
- Nylon glass-filled

Binder Jetting

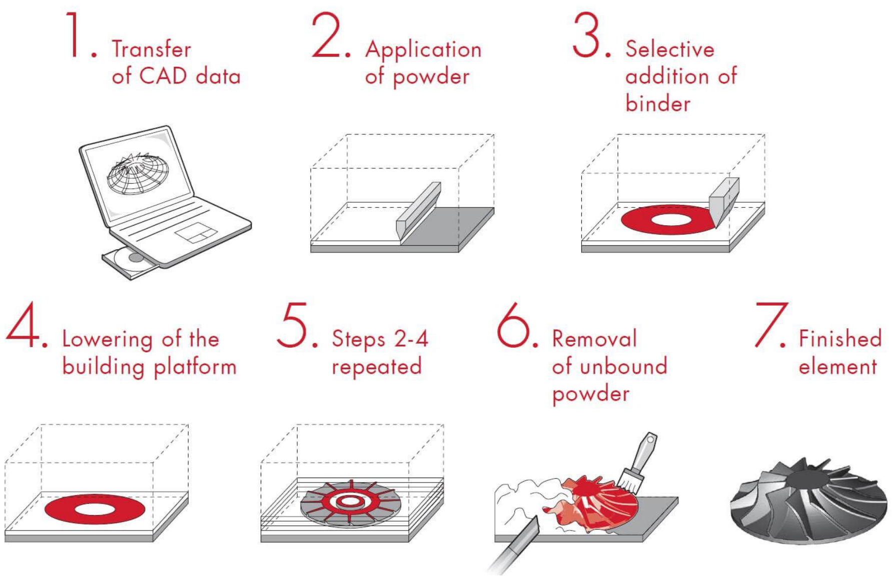


Image – HP, ExOne, all3dp.com, 3D printing handbook, voxeljet

Manufacturers & Materials

Manufacturers

- 3D systems
- Digital metal
- ExOne
- HP

Metals

- Inconel alloy (sintered)
- Tungsten carbide (sintered)
- SS (sintered)
- SS-bronze matrix (infiltrated)

Materials

- Sandstone
- Silica sand

Direct Energy Deposition (DED)

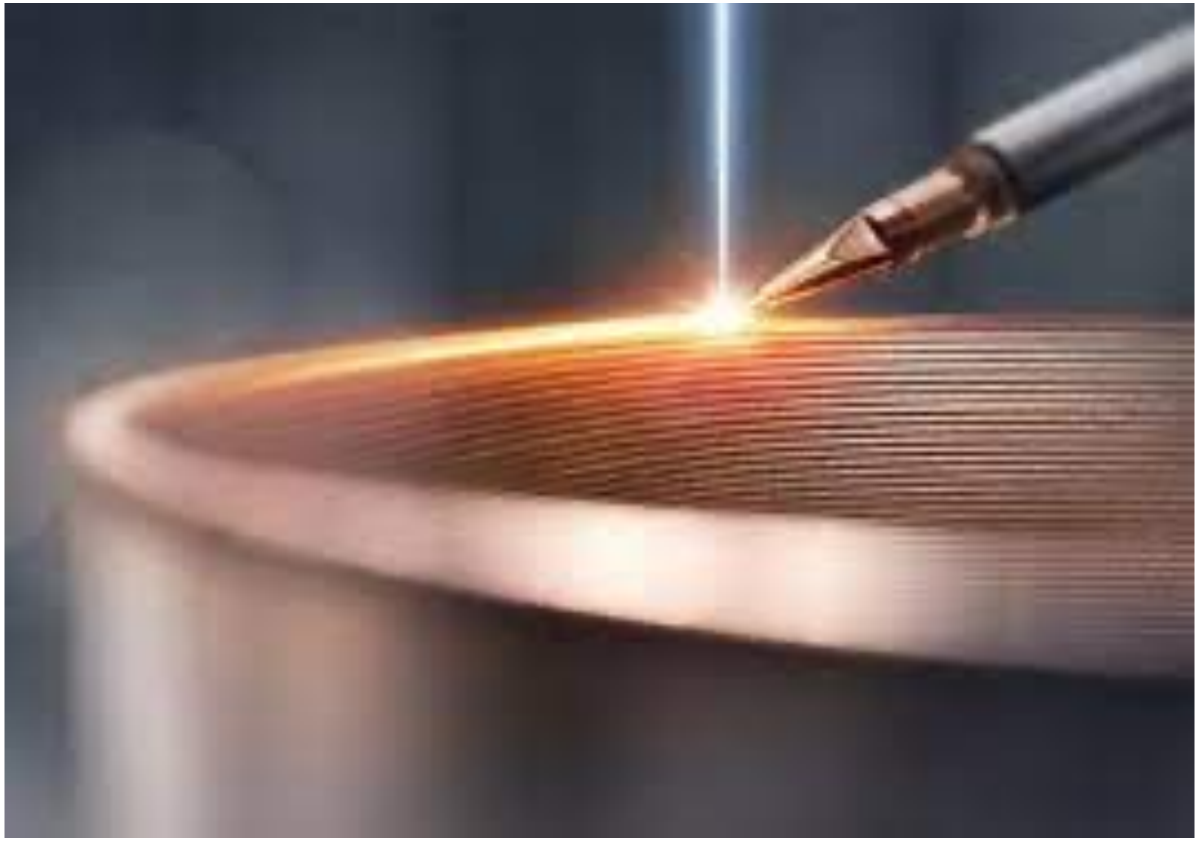
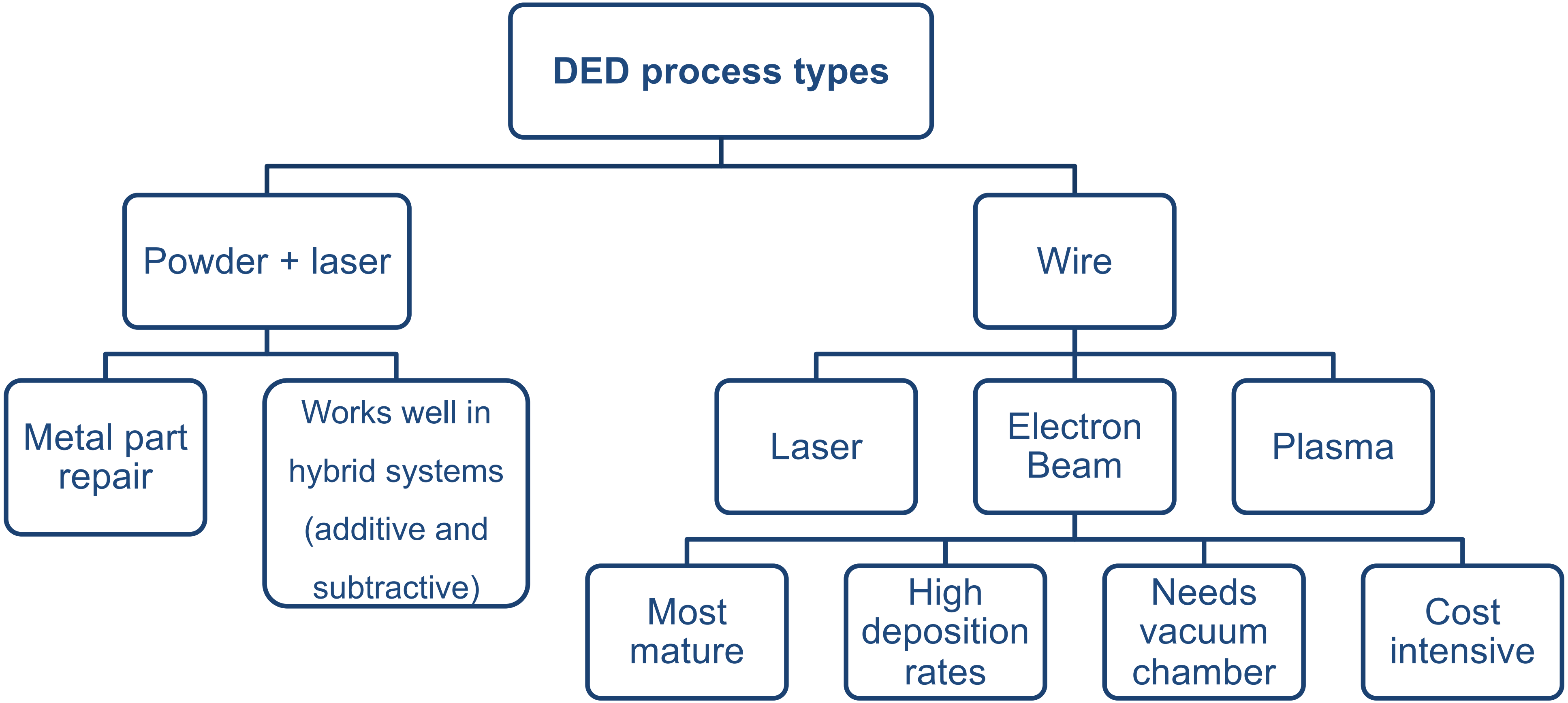


Image – pro-beam.com

DED


DED process types
Powder + laser
Wire
Metal part repair
Works well in hybrid systems (additive and subtractive)
Laser
Electron Beam
Plasma
Most mature
High deposition rates
Needs vacuum chamber
Cost intensive

Manufacturers & Materials

Manufacturers

Laser-blown powder deposition

- Optomec
- DM3D

Wire feed deposition

EB

- Sciaky

Laser

- GKN Aerospace

Plasma

- Norsk Titanium
- Cranfield University

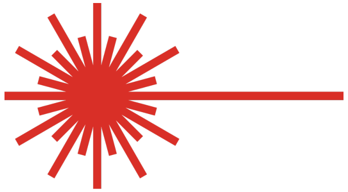
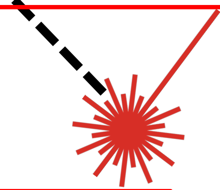
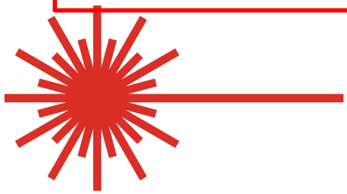
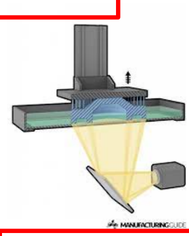
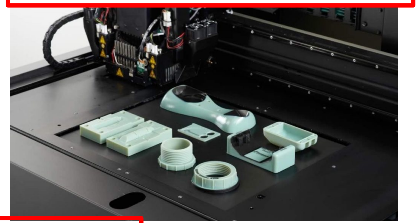
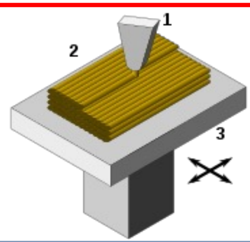
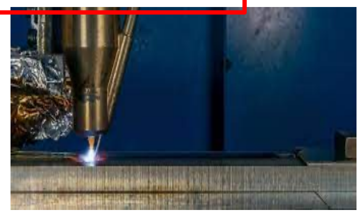
Materials

- Al alloys, 1100, 2xxx, 4043, 5xxx series
- Ti & its alloys
- Co alloys
- Ta
- Inconel 625, 718, 600
- Ni & Cu-Ni alloys
- W
- Nb
- Mo
- Zirconium alloy

Video/animations

- Fused deposition modeling
- Stereolithography
- Laser powder bed fusion - metal 3D printing
- Material jetting (PolyJet)
- Selective laser sintering

Recap

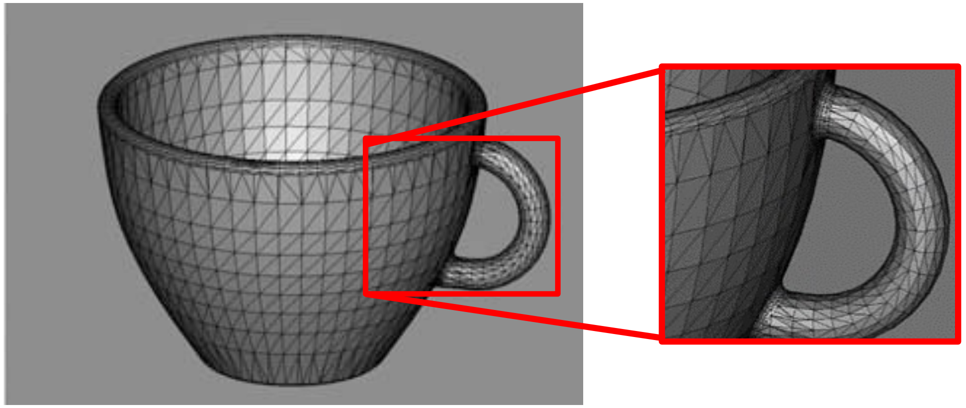
Raw Material	Process Principle
Powder 	POWDER BED FUSION   BINDER JETTING  DIRECT ENERGY DEPOSITION 
Liquid 	VAT PHOTOPOLYMERIZATION   MATERIAL JETTING 
Filament/Wire 	MATERIAL EXTRUSION  DIRECT ENERGY DEPOSITION  

AM process chain

1. Solid model (CAD model)

AM process chain

2. Tessellation



.stl file

STereoLithography file (3D systems)

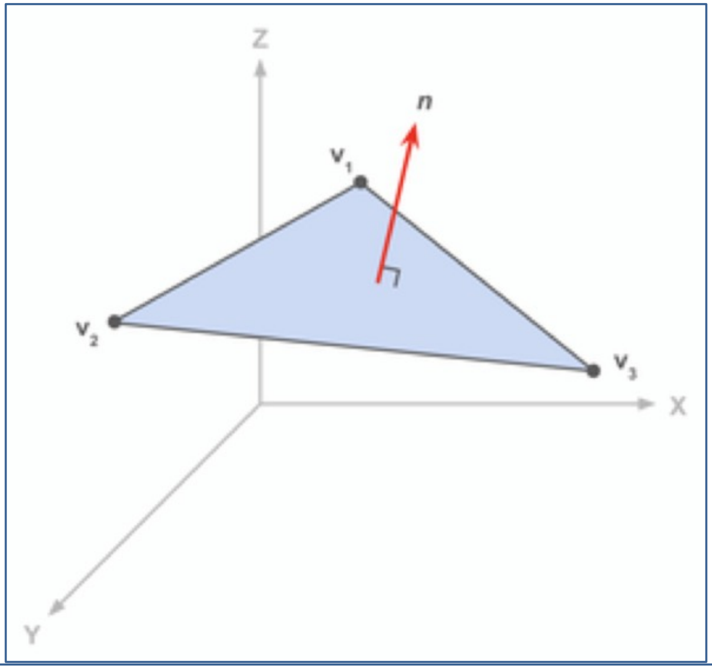
Standard Tessellation Language

Standard Triangle Language

Most common representation of CAD geometry

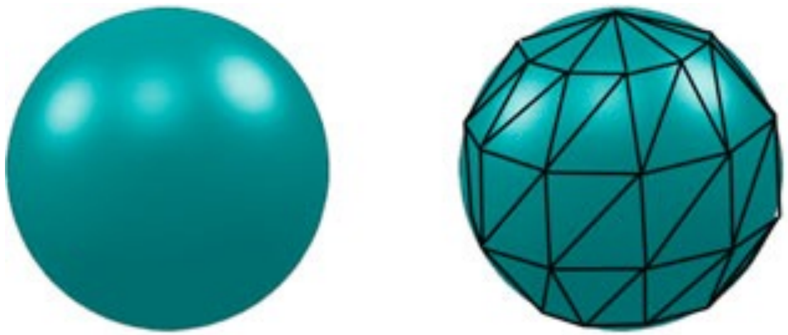
Triangles (mesh) approximates the continuous surfaces of a 3D CAD model

AM process chain

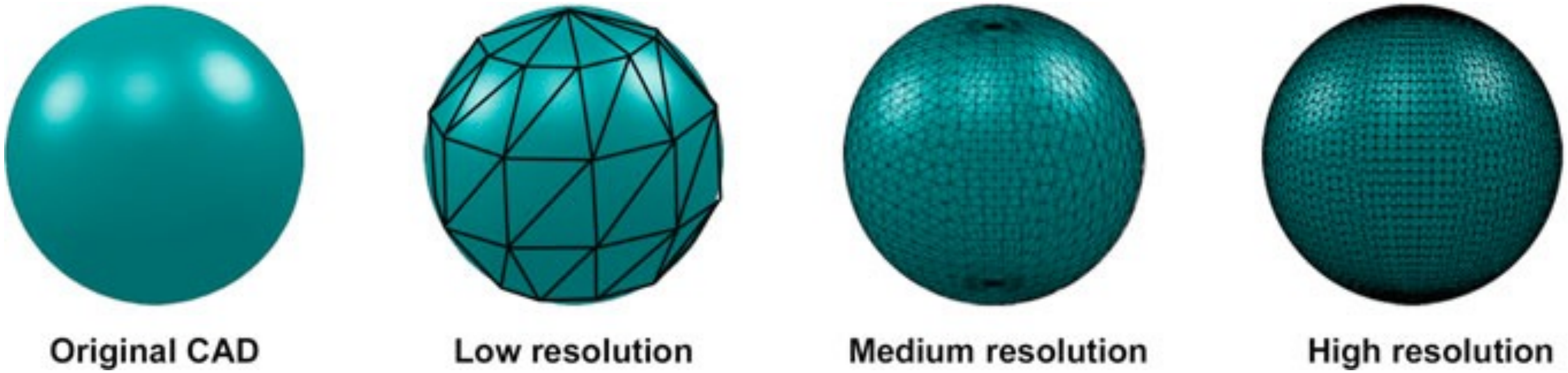


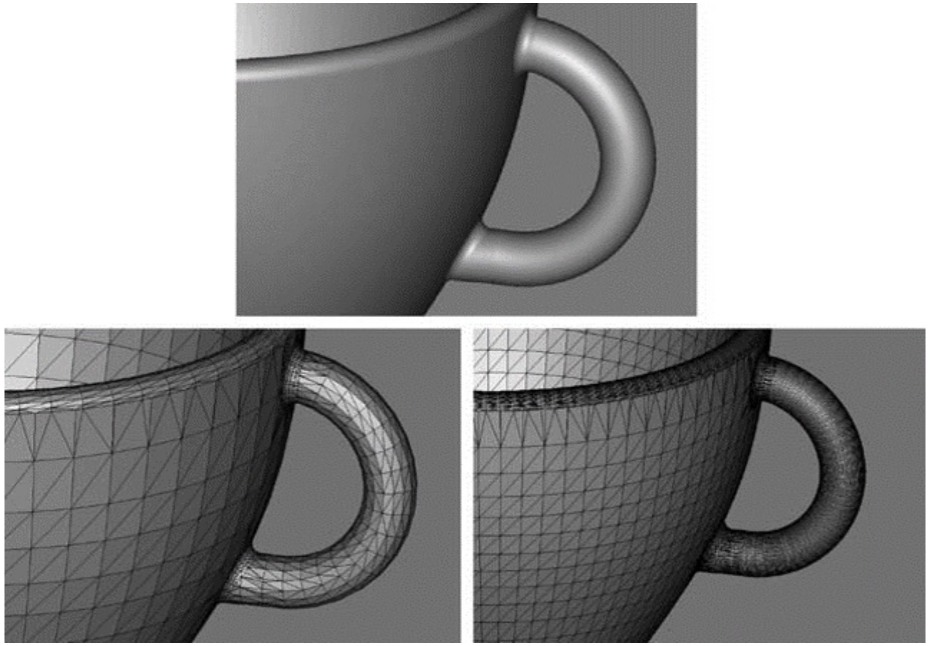
Each triangle in an STL file is represented by a set of three vertex points and a normal vector

```
facet normal ni nj nk
outer loop
vertex v1x v1y v1z
vertex v2x v2y v2z
vertex v3x v3y v3z
endloop
endfacet
```

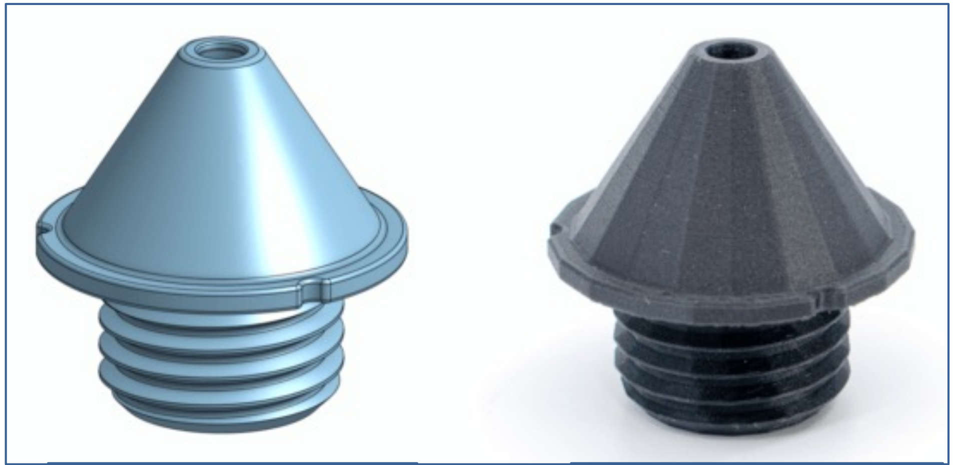


AM process chain



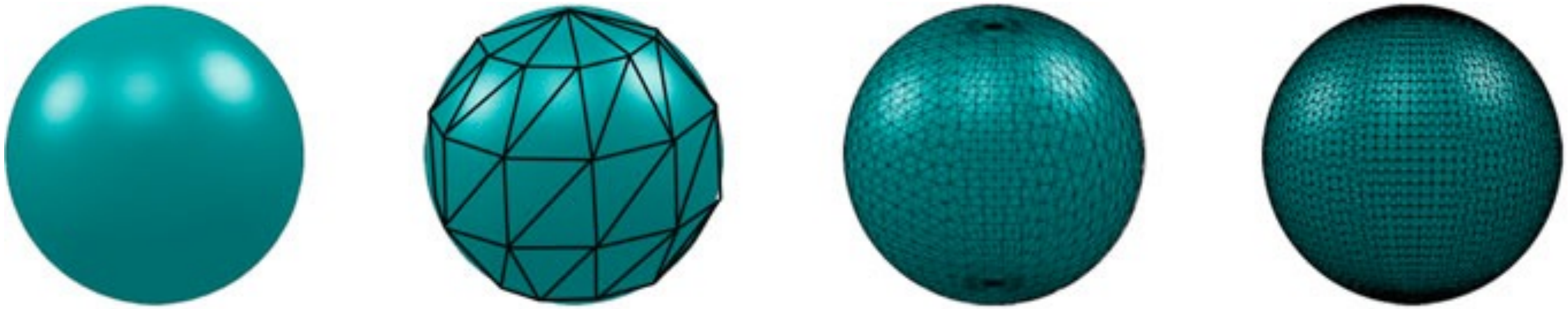


AM process chain



CAD geometry

3D printed part



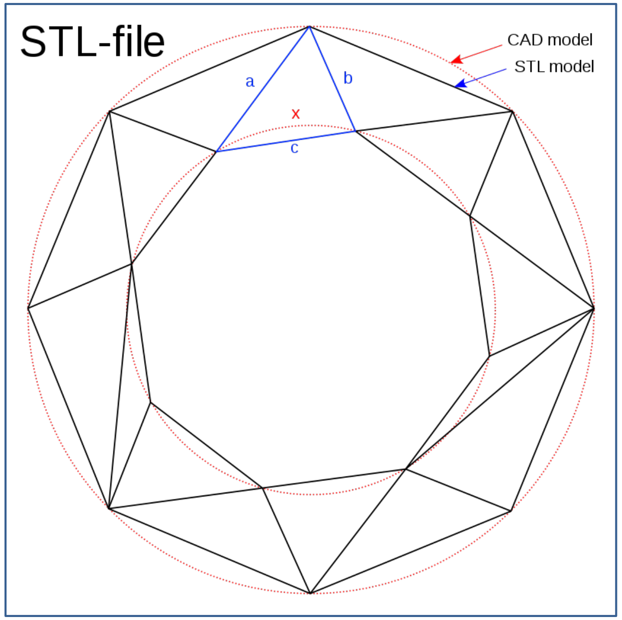
Original CAD

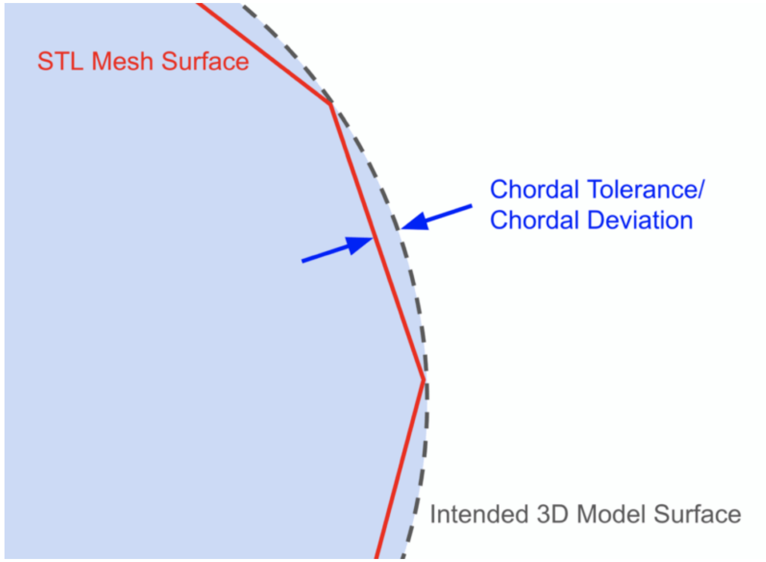
Low resolution

Medium resolution

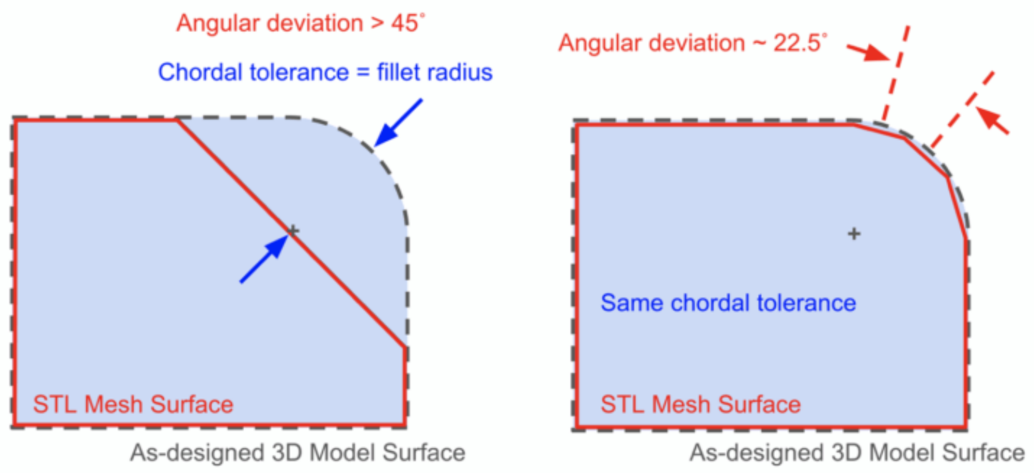
High resolution

AM process chain





AM process chain



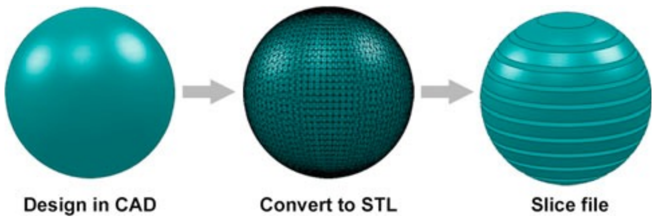
AM process chain

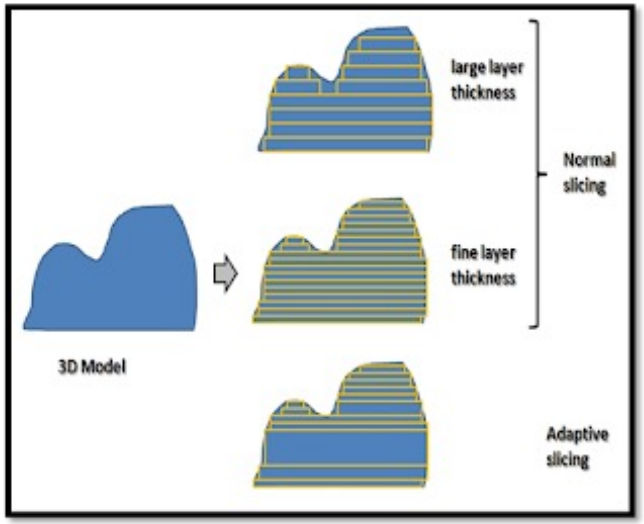
3. Slicing

STL file is prepared for 3D printing

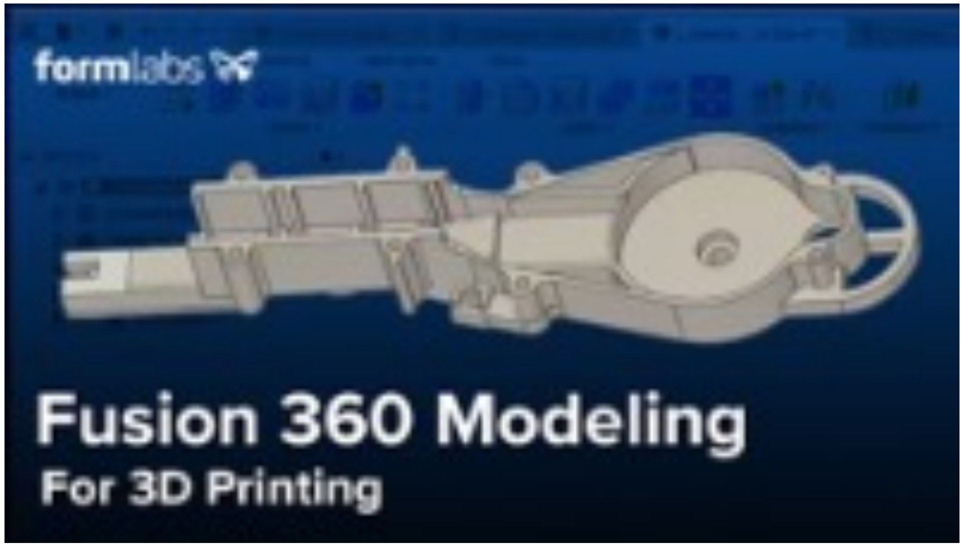
Define layer thickness

- Thinner layer leads to better resolution and improves surface roughness
- Parts take longer time





Fusion 360 Autodesk



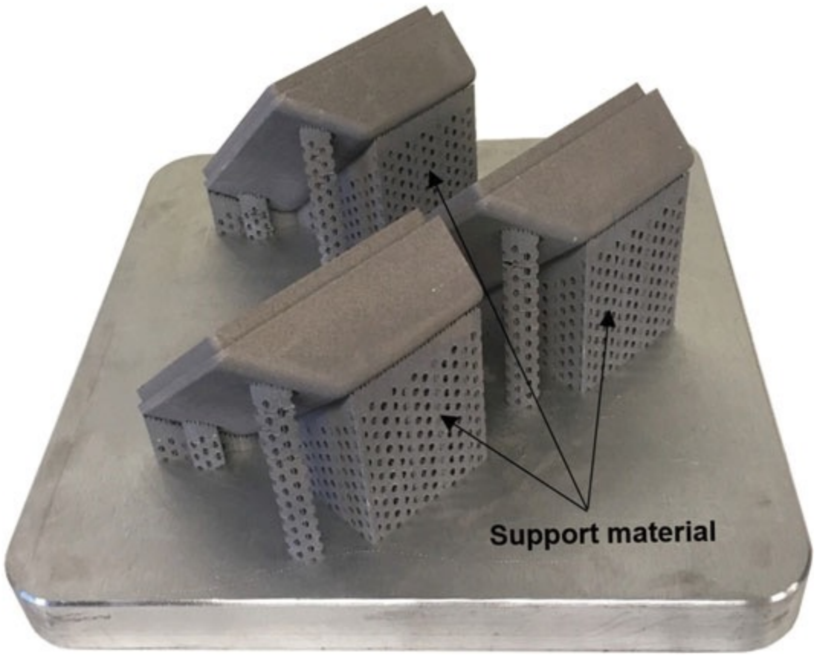
TED talk

.

[What if 3D printing was 100x faster? | Joseph DeSimone]

AM process chain

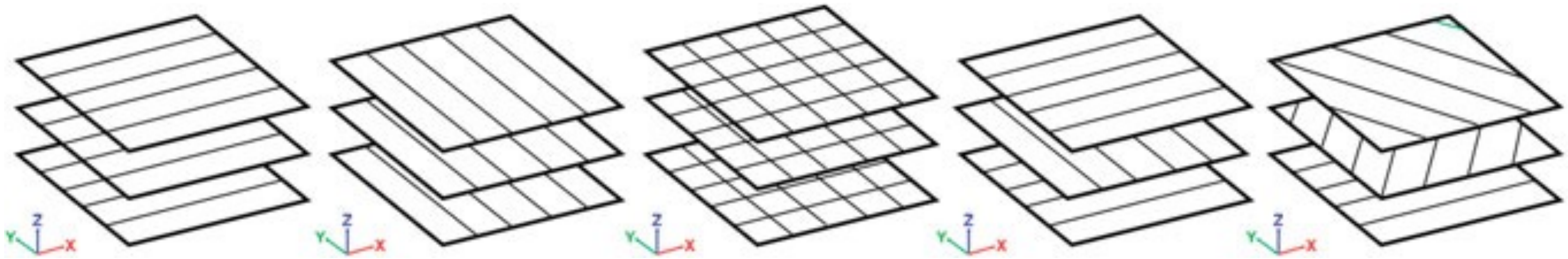
4. Support



- Stability against gravity (phase transition)
- Counter residual stresses
- Thermal management

AM process chain

5. Toolpath

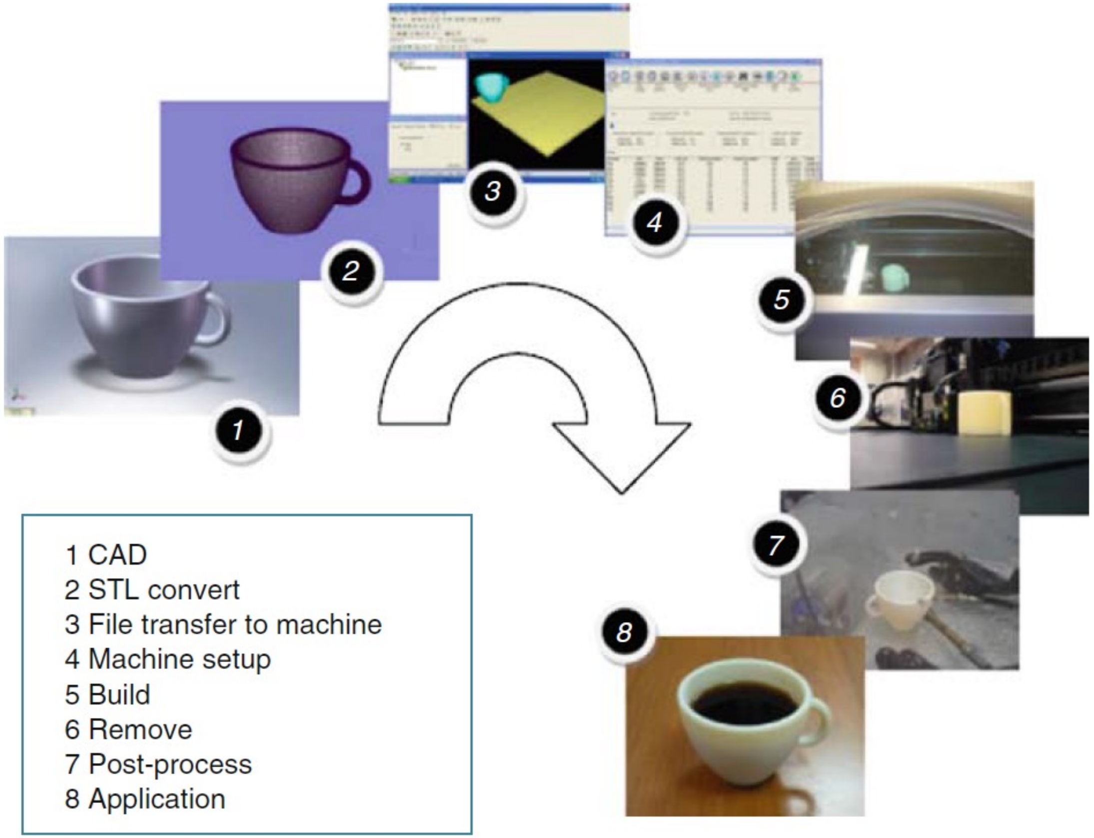


Examples of different energy beam scanning strategies

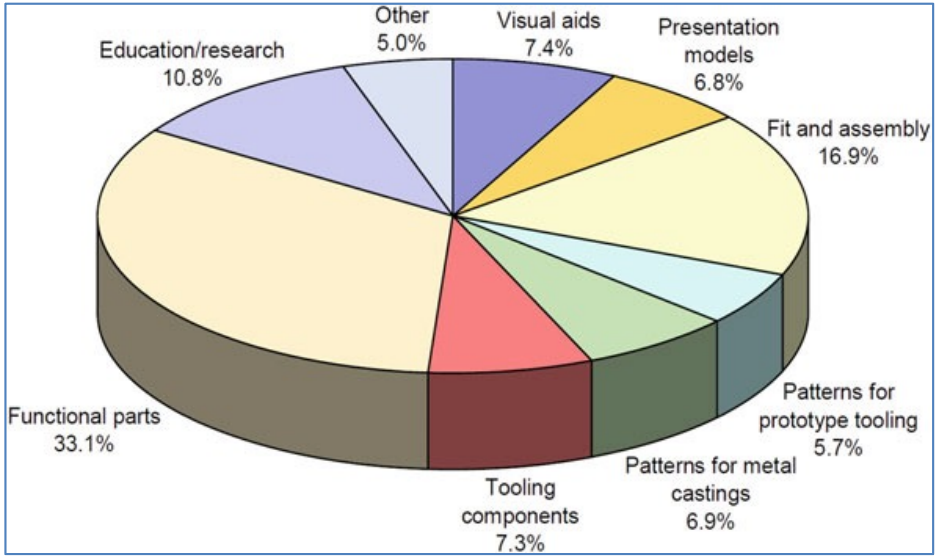
Process → Structure → Property

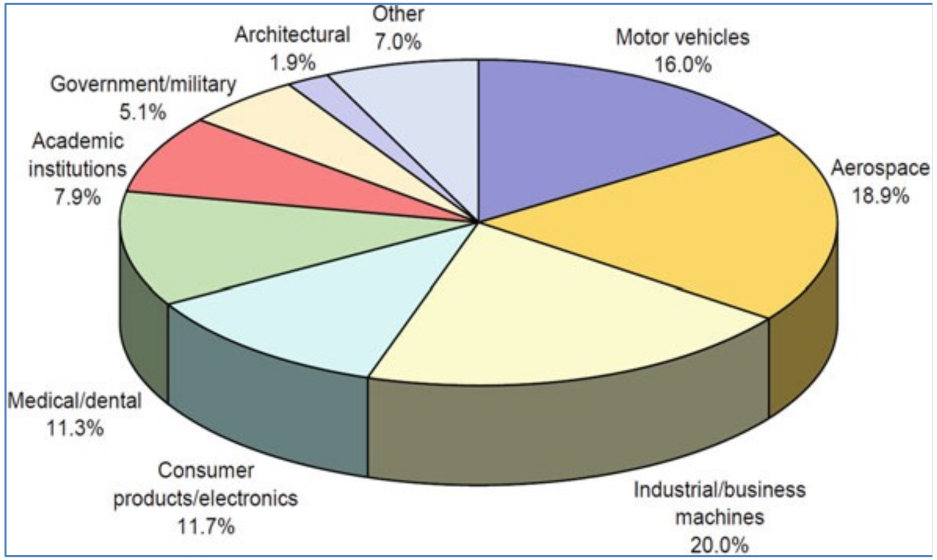
AM process chain

6. Printing
7. Postprocessing



Usage of 3D printing





Application areas that AM is currently being used for

Industries using additive manufacturing

Wohlers Associates

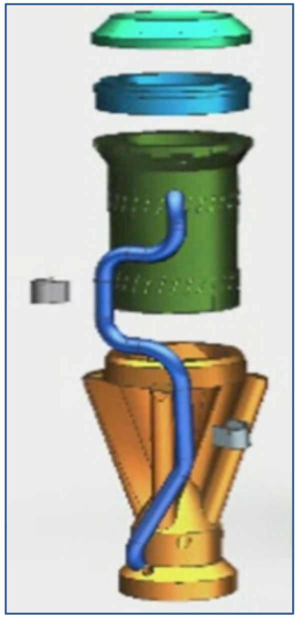
Advantages of 3D printing

AM as a viable production method should bring added value to a product

- Either by reducing life cycle costs of the product or,
- By enabling a higher price to be charged

Advantages of 3D printing

1. Part complexity



Conventionally manufactured gas turbine burner

13 parts joined together
Lead time – 26 weeks
Mass – 4.5 kg

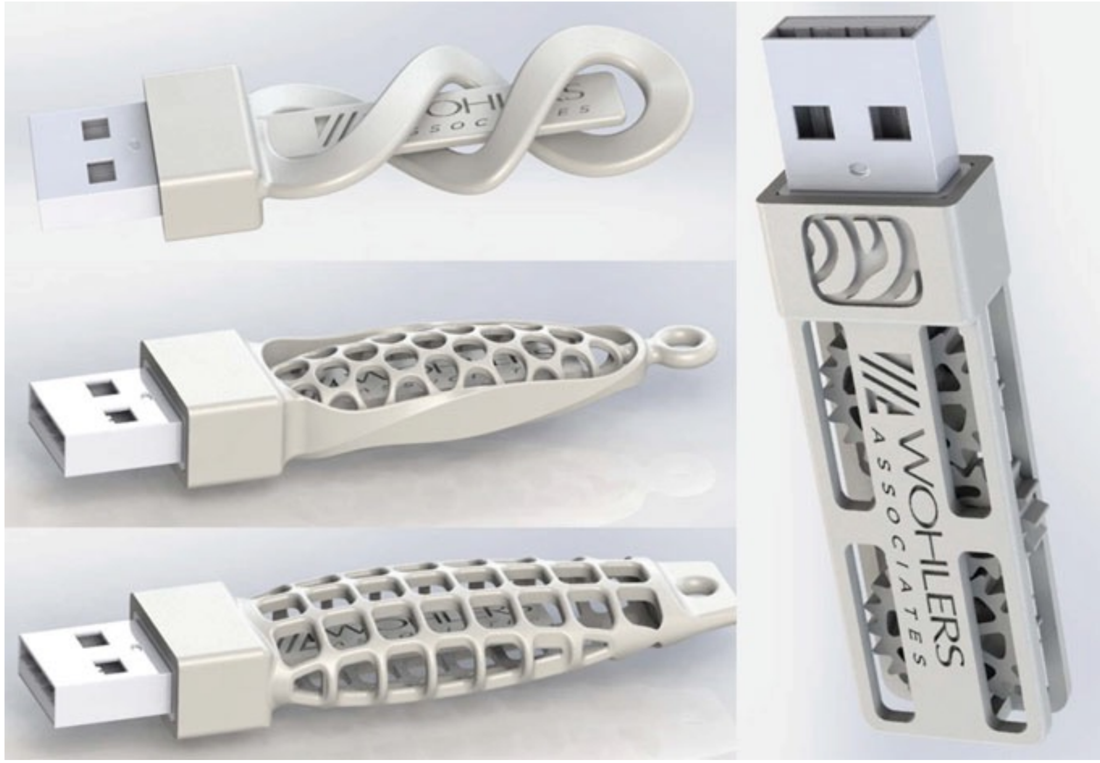
Additive manufactured gas turbine burner

1 single part
Lead time – 3 weeks
Mass – 3.5 kg

Courtesy – Siemens

Advantages of 3D printing

1. Part complexity



The more geometrically complex the part is, the more suitable it is for AM

Advantages of 3D printing

2. Instant assemblies

Foldable guitar stand manufactured as a single component using polymer powder bed fusion (**interlocked movable parts**)

Single component, ready-to-use

Advantages of 3D printing

3. Part consolidation

AM of entire drone is possible using two components

Advantages of 3D printing

4. Mass customization

Individually customized prosthetic

Completely different components are possible in a production run

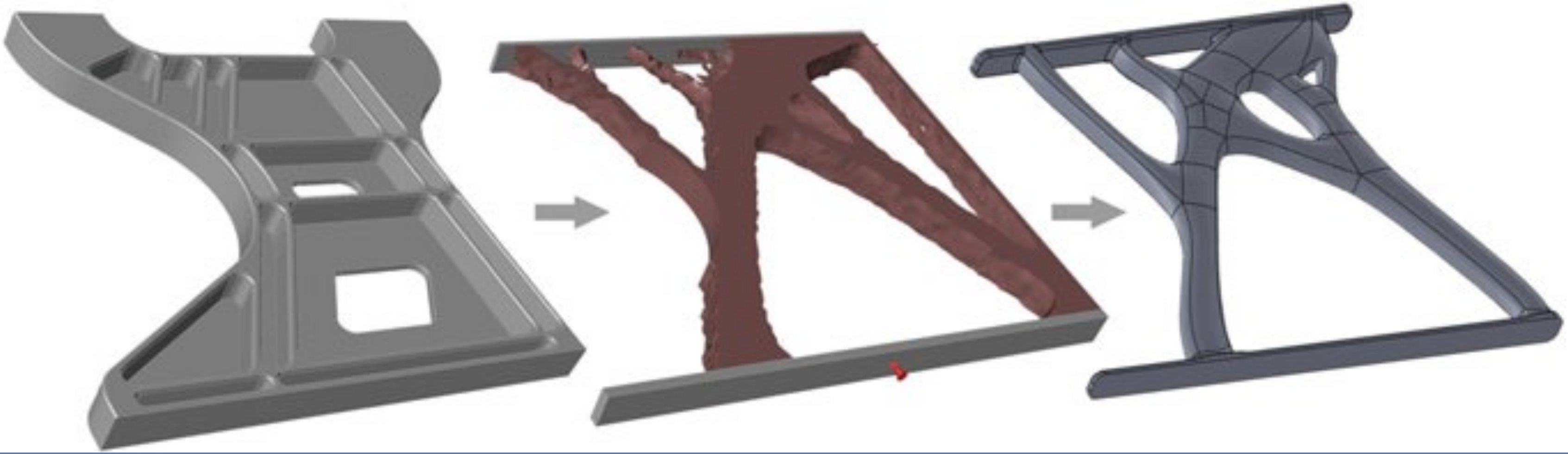
Advantages of 3D printing

5. Freedom of design

Almost anything the designer imagines can be made precisely as the designer conceives

Advantages of 3D printing

6. Light-weighting

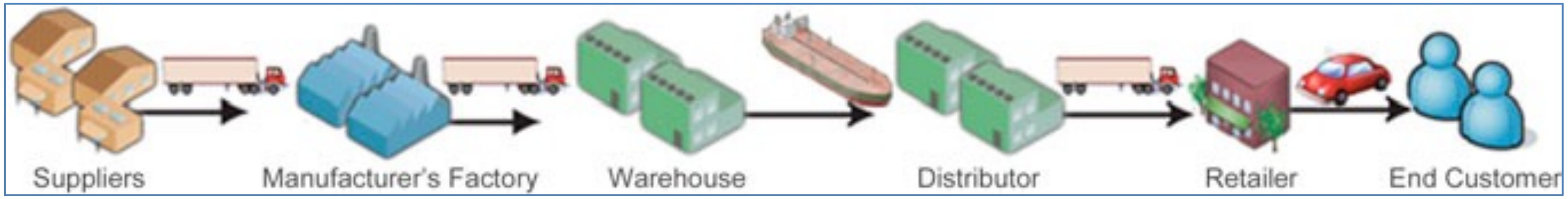


CNC-machined aircraft seat frame (left), rough topology optimized version (centre), and finished design (right)

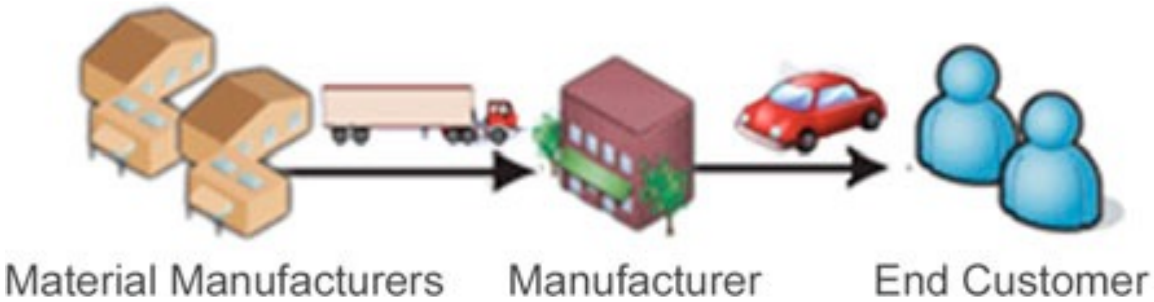
Topology optimization

Advantages of 3D printing

7. On-demand manufacturing



Supply chain today



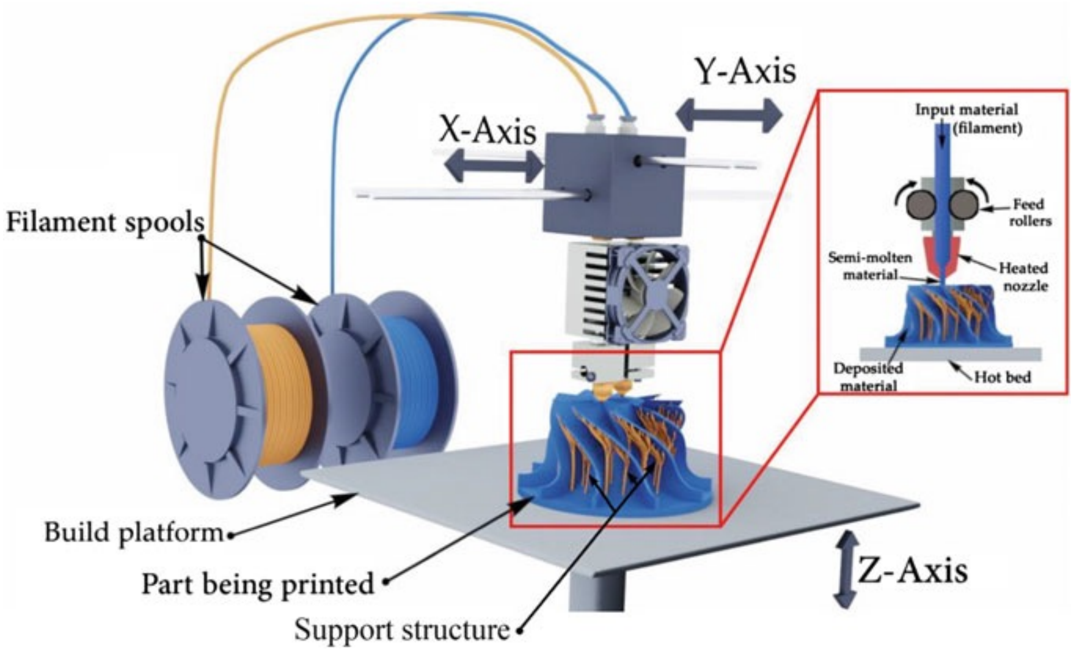
Supply chain of tomorrow

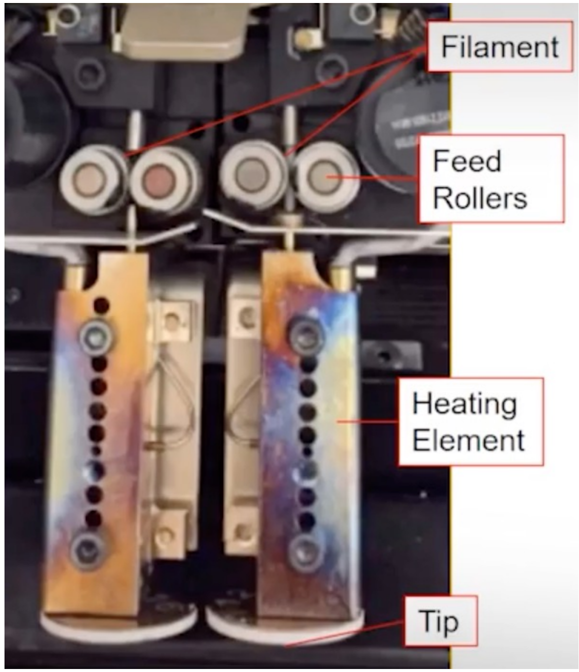
Material Extrusion

Material Extrusion

- FDM (Fused Deposition Modeling) is the most popular material extrusion-based AM method

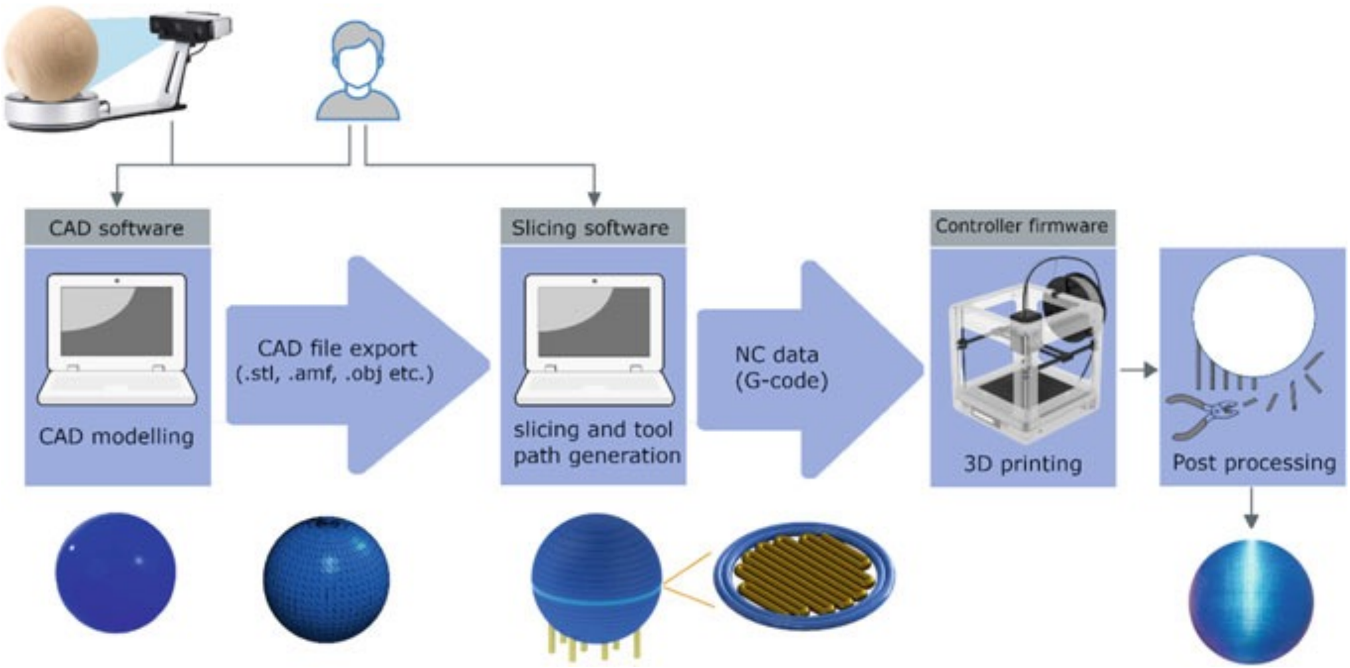
- Raw material – Filament of thermoplastic polymers





FDM

- Filament is extruded through a nozzle and heated to its softening temperature
- Preprocessing → production → postprocessing



Process flow of FDM

FDM

SLICING PARAMETERS

- LAYER THICKNESS
- FLOW RATE
- DEPOSITION SPEED
- INFILL PERCENTEGE
- RASTER ANGLE
- RASTER PATTERN
- CONTOUR WIDTH
- AIR GAPS
- NOZZLE DIAMETER
- TOP & BOTTOM WIDTH

BUILDING ORIENTATION

- HORIZONTAL
- VERTICAL
- LATERAL
- OTHERS

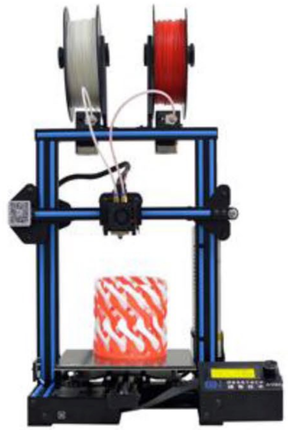
TEMPERATURE CONDITION

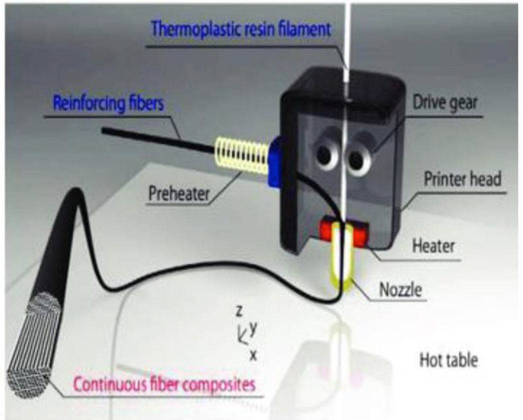
- ENVIRONMENTAL TEMPERATURE
- EXTRUSION TEMPERATURE
- BED (or) PLATFORM TEMPERATURE

Important process parameters of FDM

FDM

- Extrusion heads
  - Single head
  - Dual head
  - In-nozzle impregnation





Single Head Method

Printing single materials like polymer, reinforced material, composite filament

Dual Head Method

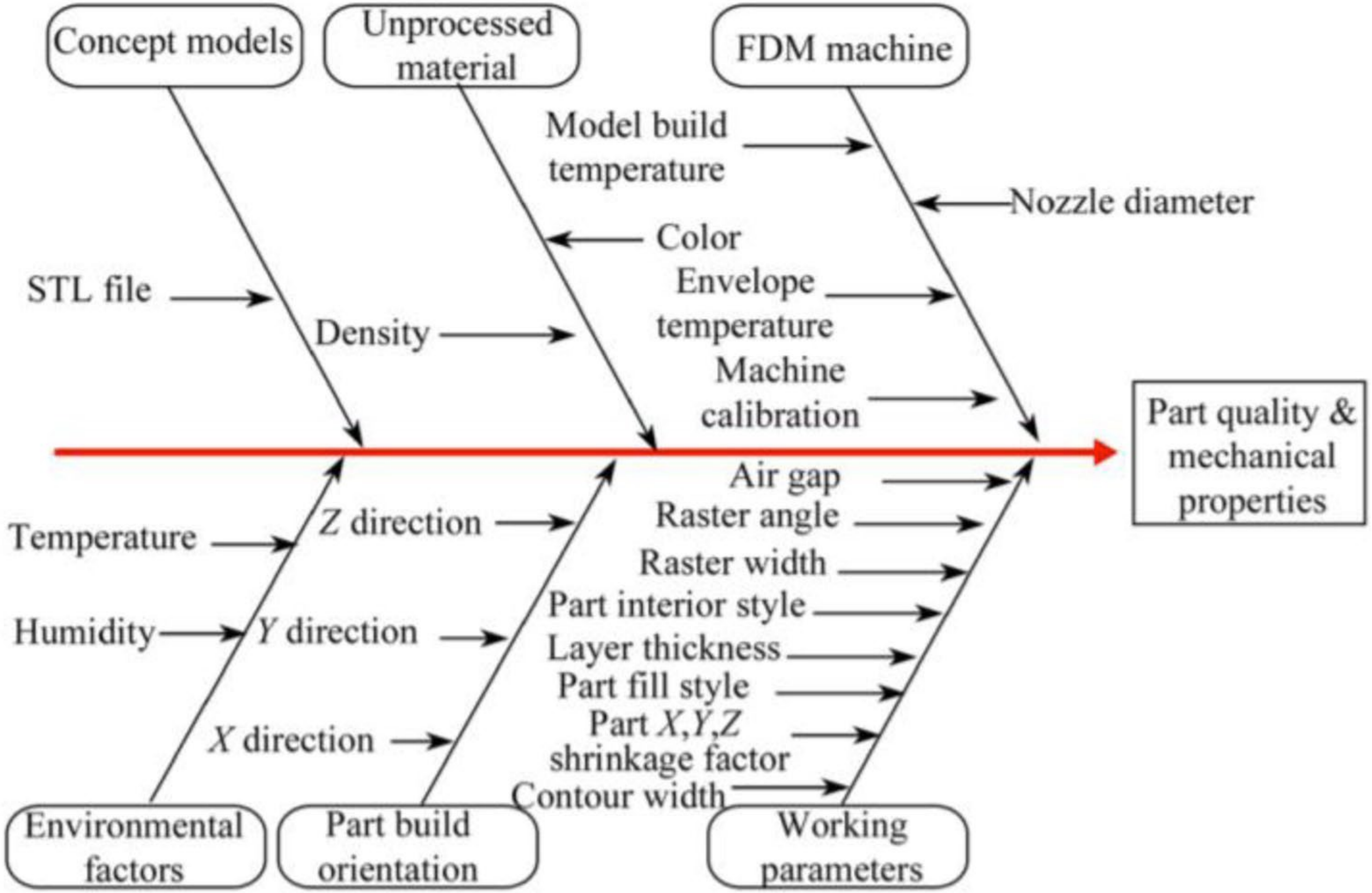
Printing of layered composites (alternative printing of two materials)

In-Nozzle Impregnation Method

Fibers are directly feeding into the nozzle head to form composite in nozzle

FDM

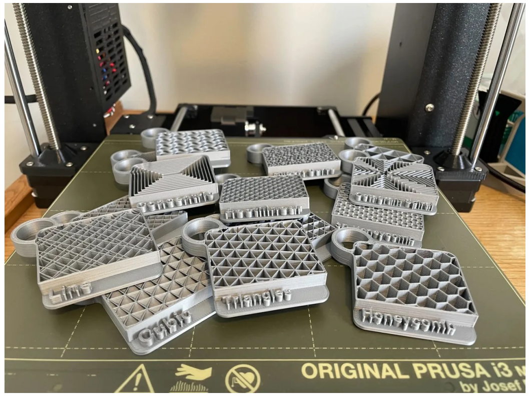
Parameters of FDM

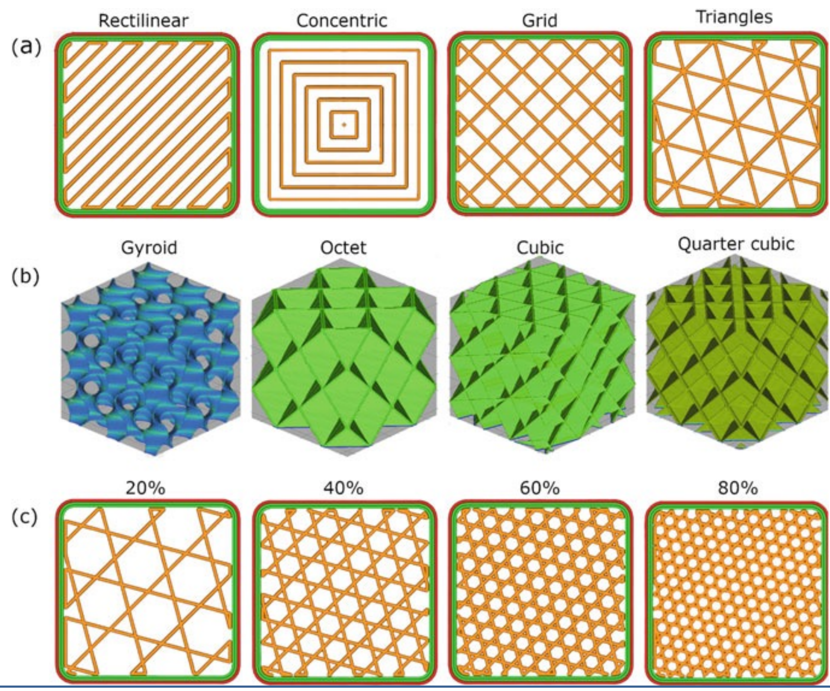


Fishbone diagram of FDM

FDM – parameters

1. Infill pattern

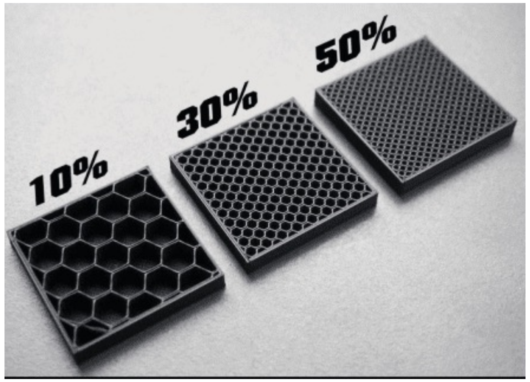




Commonly found infill types in open software, a 2D infill patterns, b 3D infill patterns, and c various infill density for tri-hexagon/stars pattern

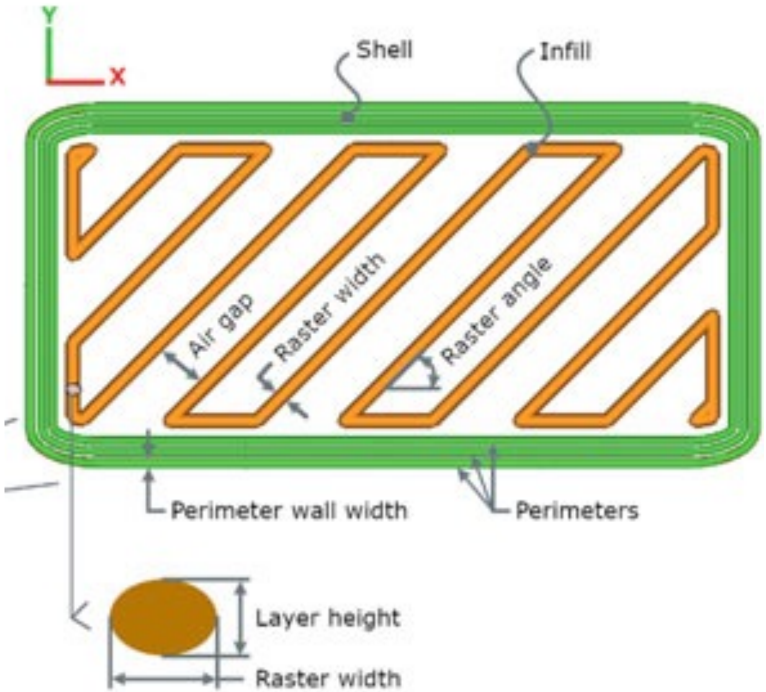
FDM – parameters

2. Infill density



3. Raster angle

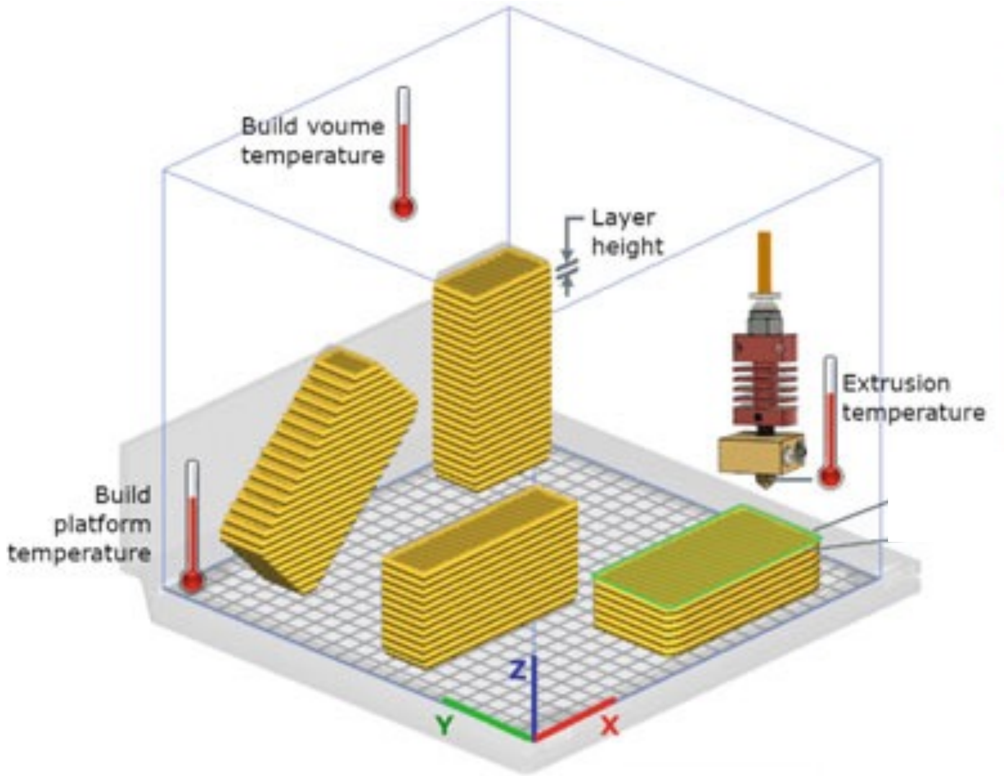
4. Raster width



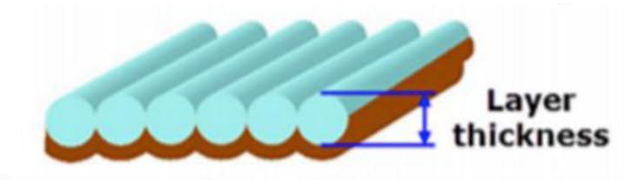
5. Air gap

FDM – parameters

6. Build orientation



7. Layer thickness



c) Layer thickness

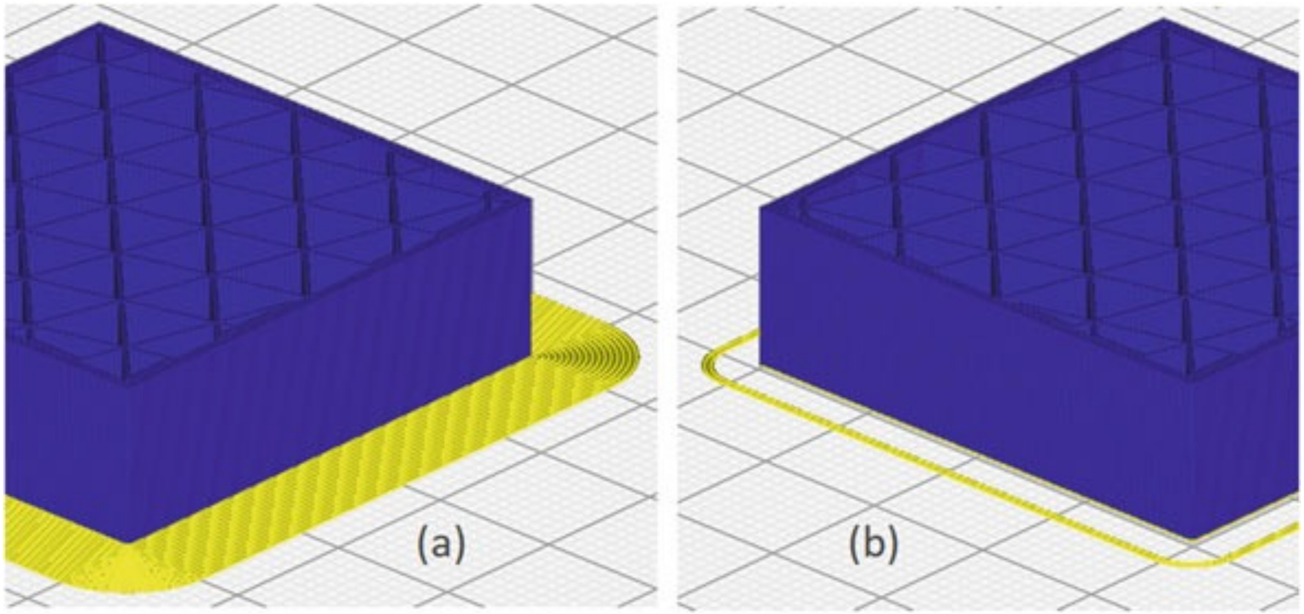
FDM – parameters

8. Printing speed

9. Operating temperature

FDM – parameters

10. Skirt and brim



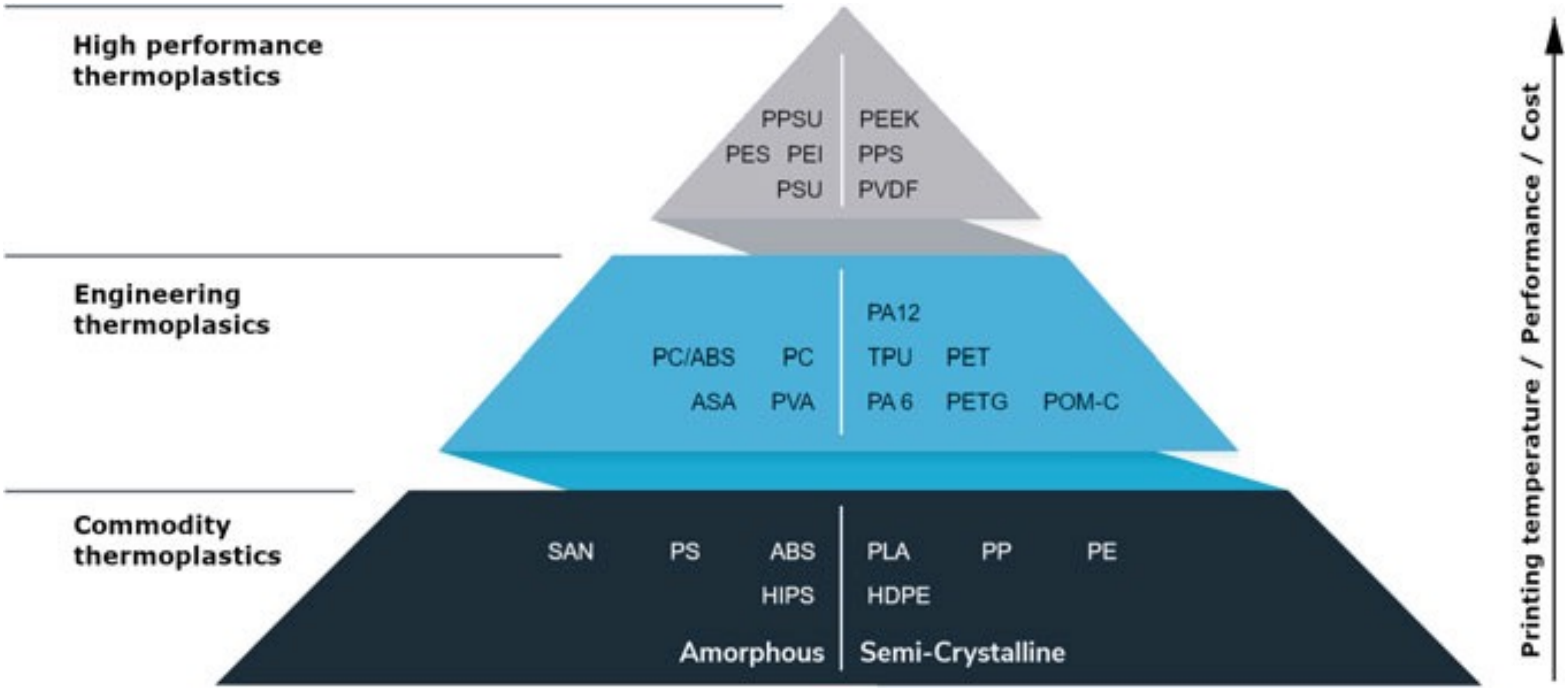
FDM printed part (blue) with a Brim (yellow) and b skirt (yellow)

FDM – Processing parameters correlation

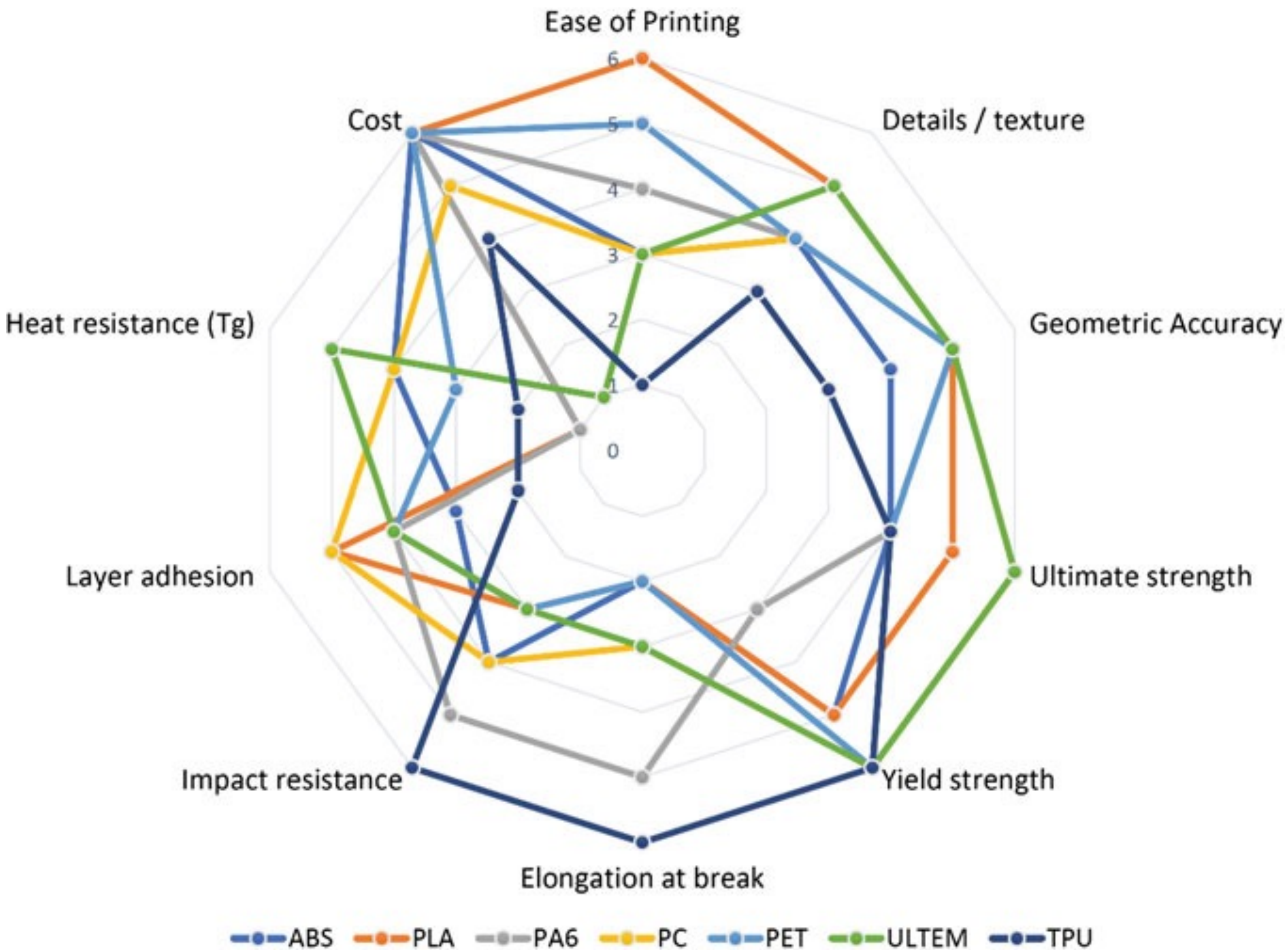
- Layer thickness, build orientation, raster angle, infill pattern, infill density and air gap are the key parameters having significant effect on mechanical properties of FDM printed parts
- Tensile strength is increased with rise in infill density and perimeters
- Build time is found minimum at higher layer thickness, low infill density, zero raster angle and build orientation having minimum support structure

Processing-structure-property relationships in FDM are complex, nonlinear and poorly understood

FDM – filament materials



FDM – filament materials

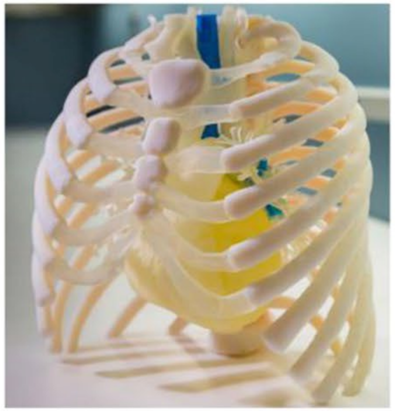


Spider web diagram – Ranking of FDM AM of various polymers

FDM – Applications

(a)

(b)



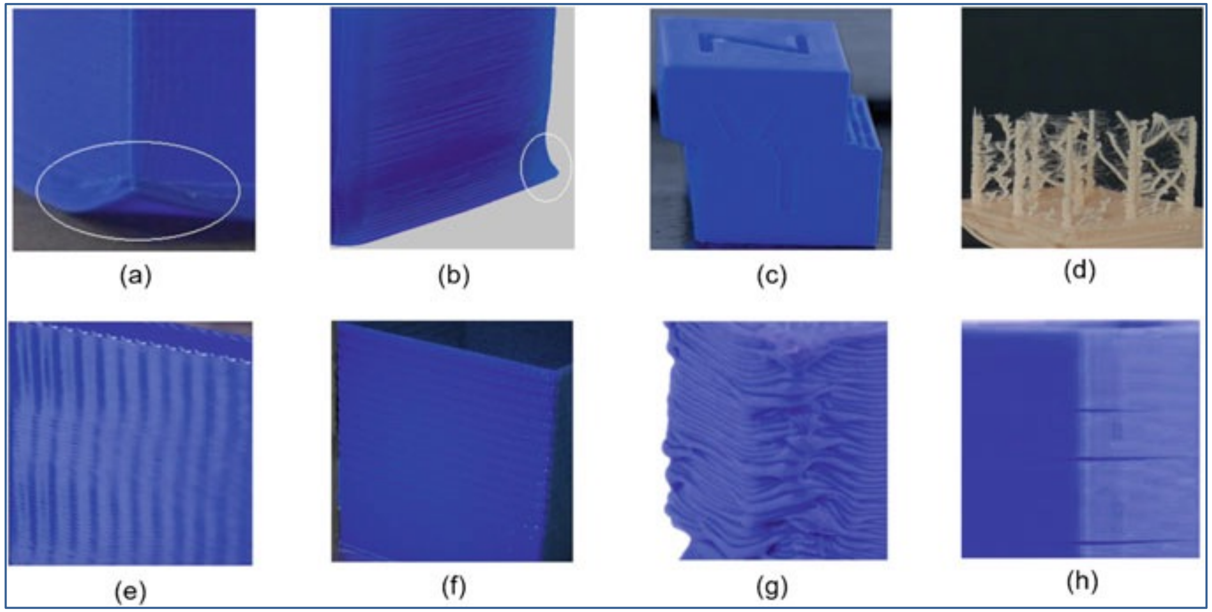
(c)

(d)

a Evektor aircraft components and FDM printed duct adapter. **b** FDM-printed electric circuit with LED **c** FDM-printed Ribcage. **d** FDM concrete printing process and the first FDM printed house by WinSun company in 2014

FDM - defects

a) Non-uniform thermal contraction
b) Close proximity of the printing nozzle to the build plate
c) Servo motors with open-loop control system
d) Retraction settings and extruder temperature
e) Printer head vibrations and/or loose machine components
f) Inconsistent extrusion (clogged nozzle/abnormal temperature variations), mechanical issues
g) Overheating
h) Poor bonding between the layers



Defects in FDM printed parts, **a** warping, **b** elephant's foot, **c** layer shifting, **d** stringing, **e** ringing, **f** z-wobble, **g** curling, and **h** layer separation

FDM - Advantages

• Compare to other major 3D printing methods, FDM is more affordable, accessible and cost-effective. Due to these reasons it is most used 3DP technology and best suited for beginners.
• FDM printer is relatively simple to operate and maintain.
• The process is relatively clean, safe and doesn't require the use of harsh chemicals.
• Feedstock materials are very diverse, readily available and affordable.
• Broad range of thermoplastic materials and exotic filaments can be printed with no or relatively few alterations on any FDM printer.
• Design of FDM printer can be scaled easily compare to other 3DP technology.

They are available in size that can fit on a desktop to size of large wardrobe.

FDM - Limitations

- The major limitation of FDM is part strength and anisotropy. Parts build by FDM are not fully dense and z-axis anisotropy arises as inter-layer bonding is not as strong as intra-layer bonding.
- Surface quality (including volumetric error, shape deviation and surface finish) of FDM is not as good as other major 3D printing methods.
- High detail prints are hard to achieve.
- Unsuitable for thin-walled products. As per thumb rule, recommended minimum wall thickness for horizontal/vertical wall is 1 mm, while curved and slant wall will require more thickness.
- FDM is primarily limited to thermoplastics based pure- and composite-materials.
    - Metal and ceramic material printing is possible by using thermoplastics based metal/ceramic reinforced filament, but it requires secondary sintering operation and resultant part will not be fully dense.

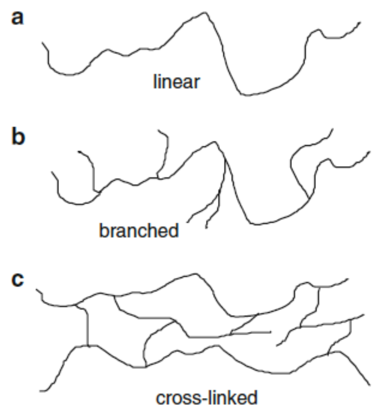
Stereolithography

Vat photopolymerization (VP)

- Also known as Stereolithography (SL) and Stereography.
- Earliest form of AM (80’s)
- All AM processes which involve solidification of liquids (raw material) are based on photo-polymerization
- Components are produced by a localized photopolymerization process – (hardening/curing) by UV/visible light of a bath of liquid resins (monomers, photoinitiators)
- Parts are usually cured up to 80%. Post processing for full hardening.
- Photopolymers were invented in 60’s. Widely used in coating, printing, dentistry *etc.*
- Various VP technologies exist – arrangement of their components, such as light source, build platform, curing direction, and resin tank.

VP – Photopolymerization

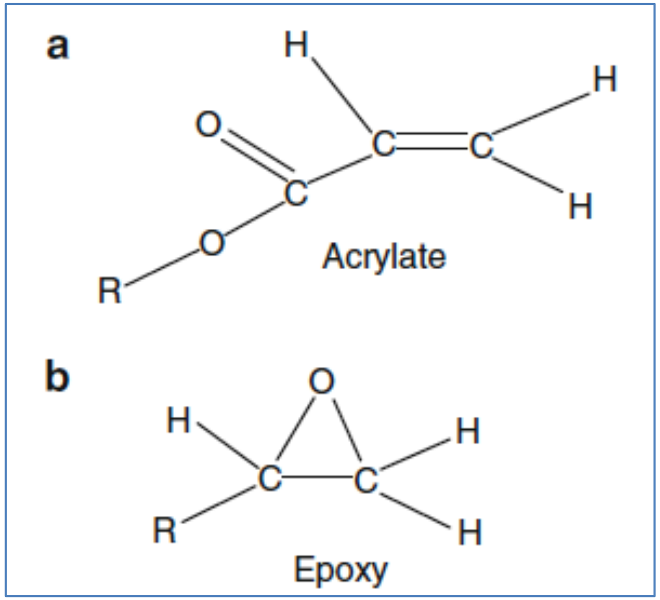
- Thermoplastic polymers (FDM) have a linear or branched molecular structure.
- In contrast, SL photopolymers (thermosetting polymer) are crosslinked, do not melt and exhibit much less creep and stress relaxation.
- SL photopolymers consists of photoinitiators, stabilizers, liquid monomers *etc.*
- Once the SL resin is irradiated with UV light, photoinitiators become reactive and react with the liquid monomer to form a polymer chain.
- Subsequent reactions occur to build polymer chain and cross linking occurs → strong covalent bond formation b/w polymer chains



Photopolymerization *contd…*

- Polymerization is the term used to describe the process of linking small molecules (monomers) into larger molecules (polymers) composed of many monomer units.
- The first SL resins were acrylates based.
  - Weak parts were produced due to shrinkage (5 – 20 %) and curling issues.
  - Curing of 46% only.
  - Partially cured layer undergoes additional crosslinking under laser irradiation, which leads to additional shrinkage and stresses.
  - Partially cured layer is not inhibited to atmospheric oxygen, *i.e,* extensive crosslinking.
- Later, epoxide based SL resins were invented.
  - More accurate, stronger and harder.
  - Lesser shrinkage (1–2 %).
  - Slow photospeed and brittleness of the cured parts.
  - Sensitive to humidity, which can inhibit polymerization.
- ***Most commercial SL resins are epoxides with some acrylate content.***

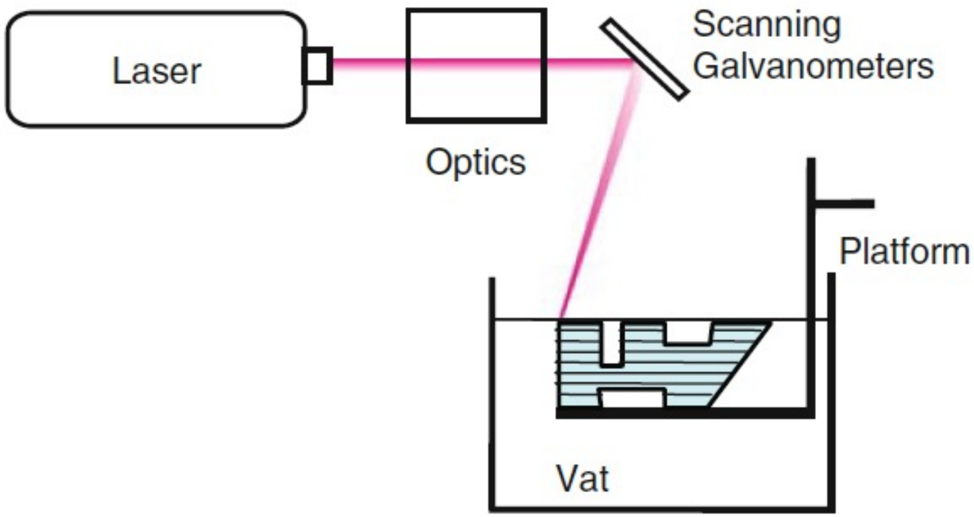
Photopolymerization *contd…*



Molecular structure of SL monomers

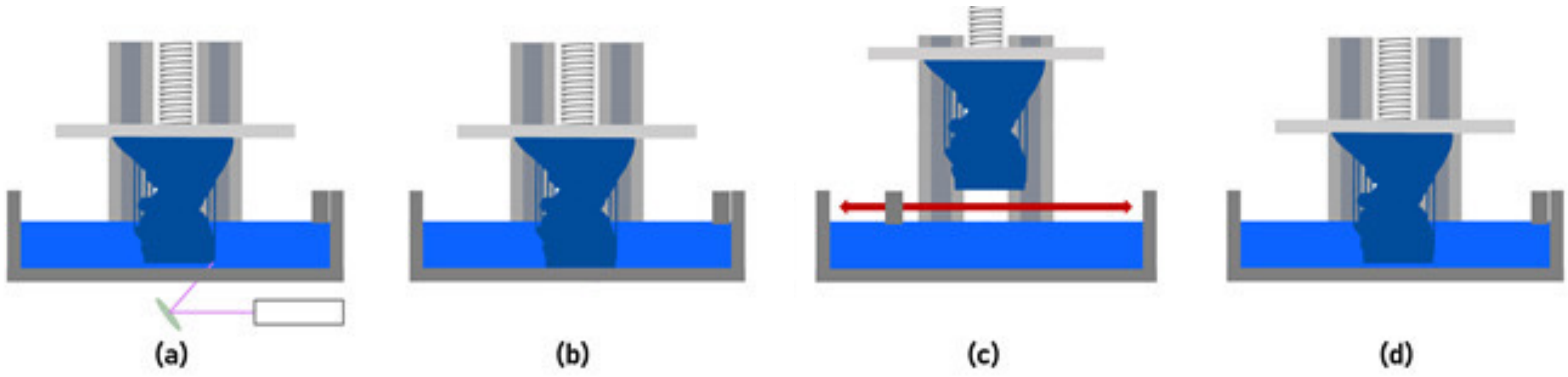
VP

- Point-by-point approach
  - A fine laser beam forms the contour of the respective cross section on the surface of a resin bath and generates locally the critical energy density that is required for the polymerization and thus the desired solidification.



Point-by-point scanning

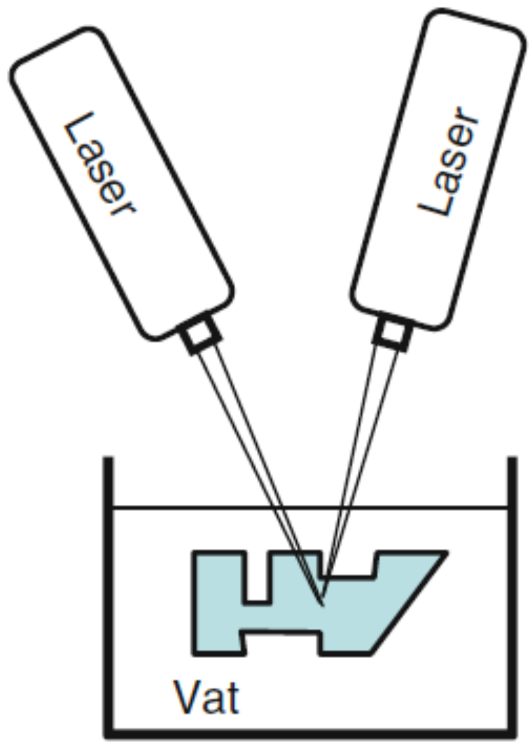
VP



SLA printer prints a layer between the build platform and the vat (a & b), raises the platform and resets the liquid using the sweeper (c), and then lowers the part back down to print another layer (d)

VP

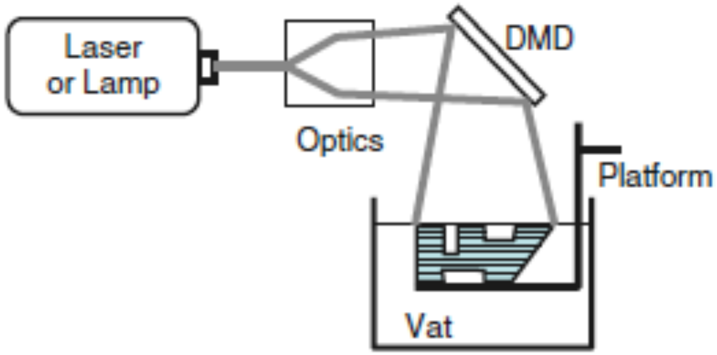
- Point-by-point approach
  - In the two photon approach, photopolymerization occurs at the intersection of two scanning laser beams. Femtosecond laser pulses with a very small spot size are used.
  - A very high resolution is possible (sub 100 nm!)



Two-photon approach

VP

- Mask projection
  - Or layer wise approaches, irradiate entire layers at one time
  - DMD (digital micromirror device), an array of several millions of mirrors can be controlled independently to produce mask patterns
  - Sub micrometer resolution is possible. Very fast.

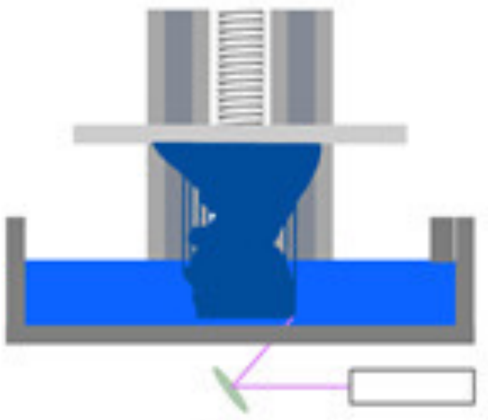


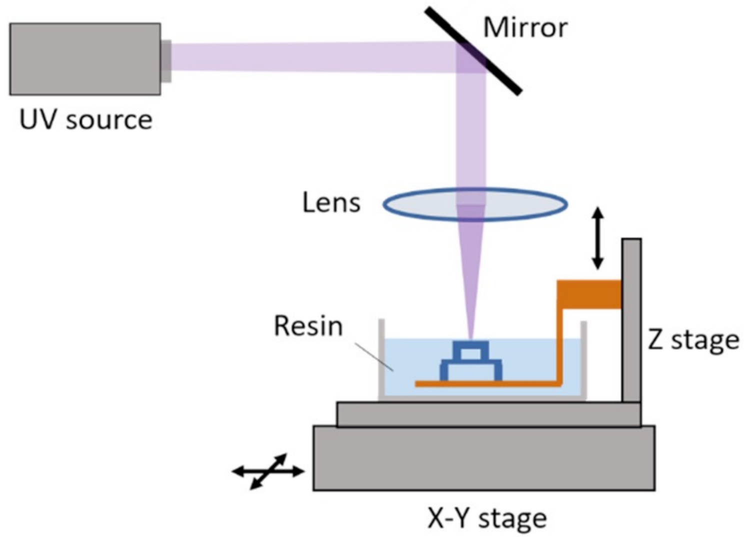
Schematic of mask projection approach to SL.

Digital Light Processing (DLP)

VP

1. Expose resin to UV light.
2. The cured part mechanically moved either to separate from the surface of resin vat (for bottom-up systems) or to lower into the resin (for top-down systems) for resin renewal.
3. Re-positioning.





Not a continuous process!

Printing speed is restricted to a few millimetres per hour

VP – CLIP

- CLIP (continuous liquid interface production)
  - Patented by Carbon.
  - Oxygen permeable window creates a thin oxygenated resin layer, where polymerization does not occur. **Incredible!**

Digital Light Synthesis (DLS)