An introduction to **3D printing (Additive Manufacturing)** in Engineering

Lecturer: Reza Hedayati, PhD

Department of Aerospace Structures and Materials (ASM)
Faculty of Aerospace Engineering
Delft University of Technology (TU Delft)

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1

Introduction: What is Additive Manufacturing (AM)?

Question

Polling

?

- How many of you know what is additive manufacturing?
- How many of you have previous experience with additive manufacturing?
- How many see themselves working with additive manufacturing in near future?

Reza Hedayati, PhD – rezahedayati@gmail.com

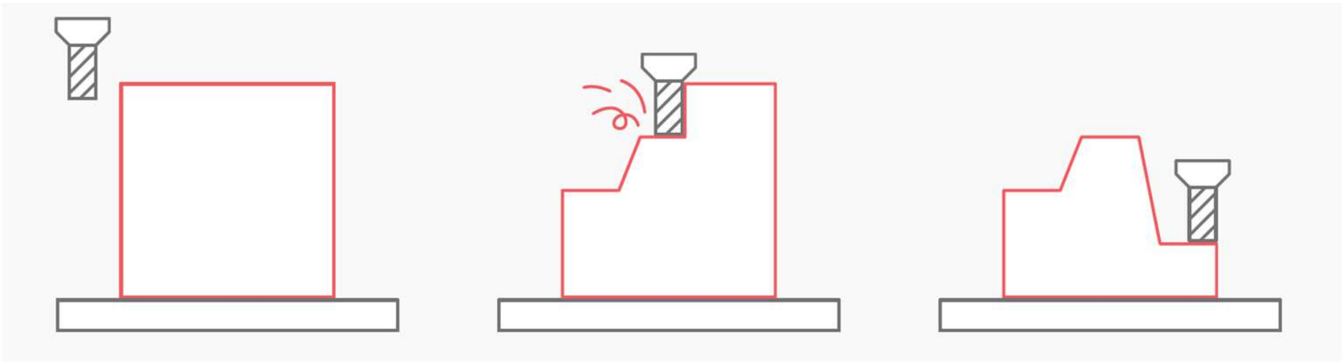
Definition

Additive manufacturing is the ‘process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies’

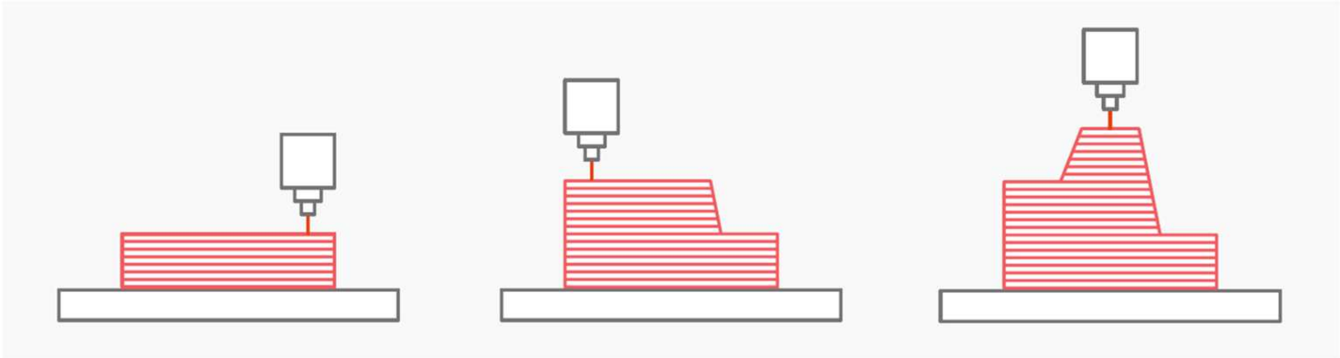
ASTM F2792 – 10

Subtractive vs Additive manufacturing

Subtractive manufacturing (removing material by milling)



Additive manufacturing



Deposition mostly in the form of filament, powder, and resin

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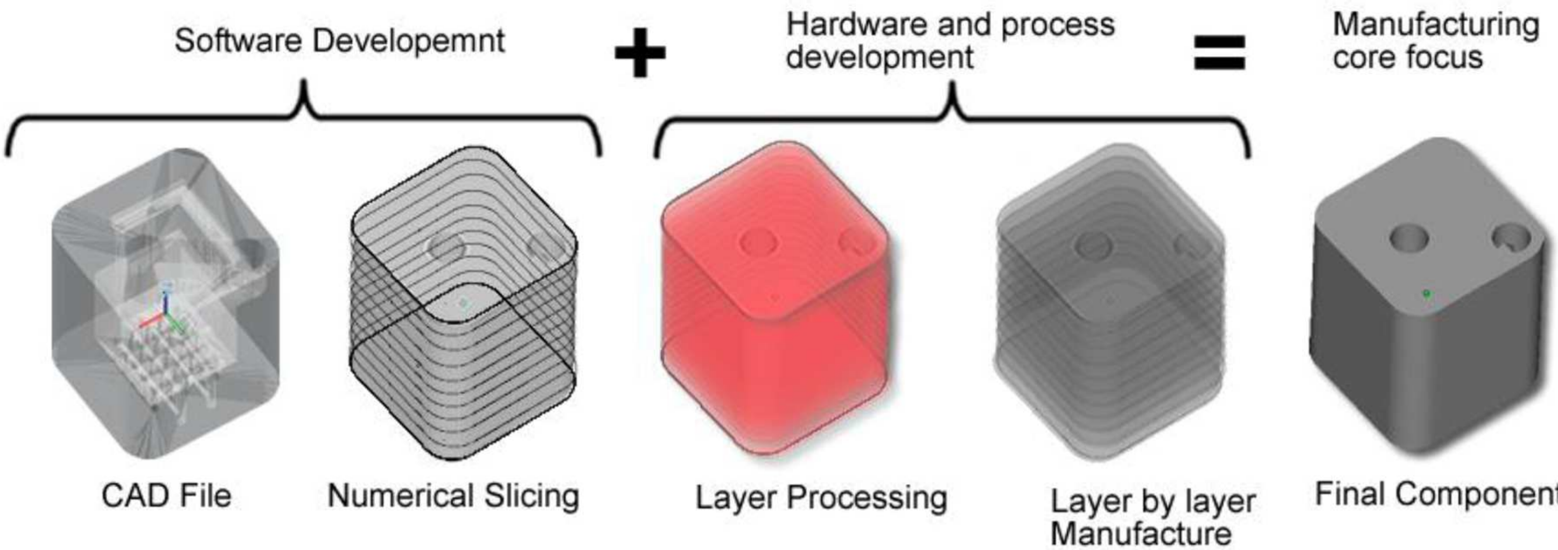
(https://www.3dhubs.com/knowledge-base/3d-printing-vs-cnc-machining)

Subtractive vs Additive manufacturing

Watch online

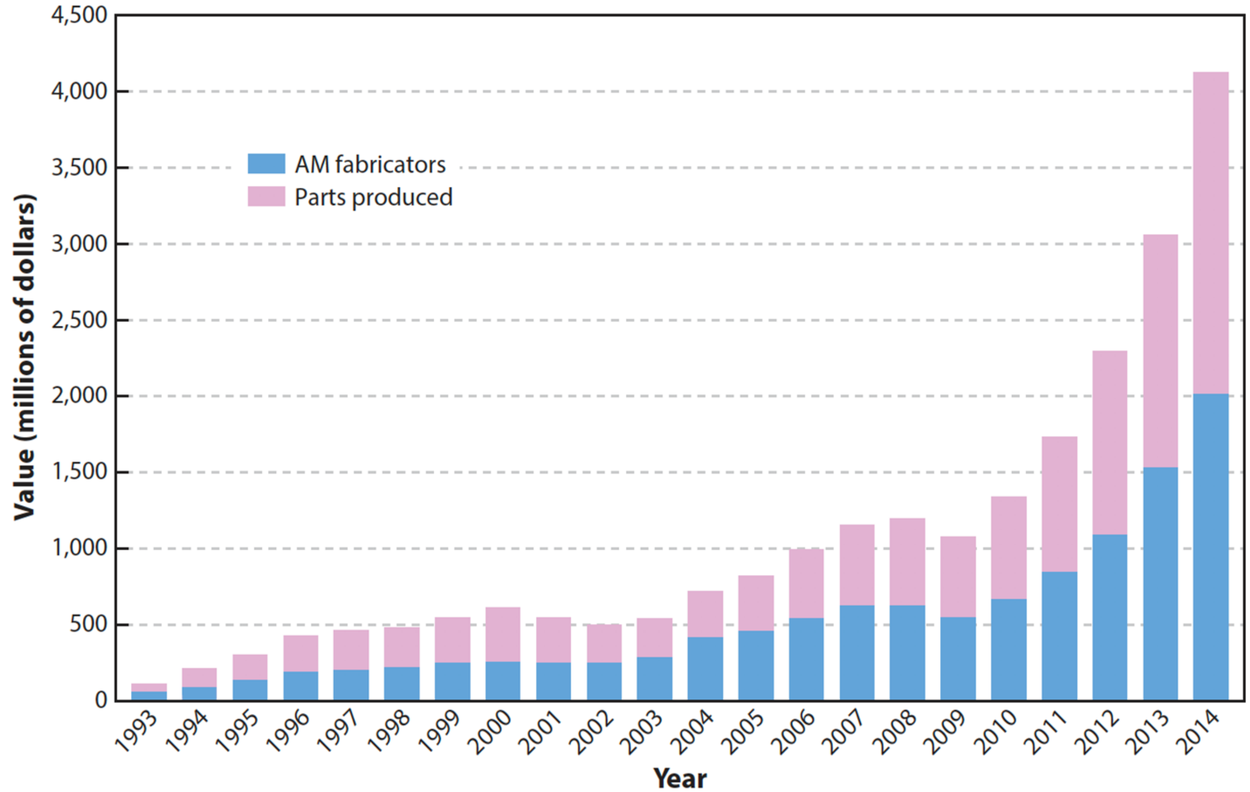
https://www.youtube.com/watch?v=zhSIMnW4Rd0

How it works?



(Sidambe, 2014)

Rise of additive manufacturing in 2000s



2014: the value of production industry and parts produced was over $4.2 B

Growth of AM worldwide from 1993 to 2014 in terms of the value of AM fabricators (lower bars) and parts produced (upper bars).

(Bourell, 2016)

Question

Open-ended question

?

- Why is there a growing rise in additive manufacturing?

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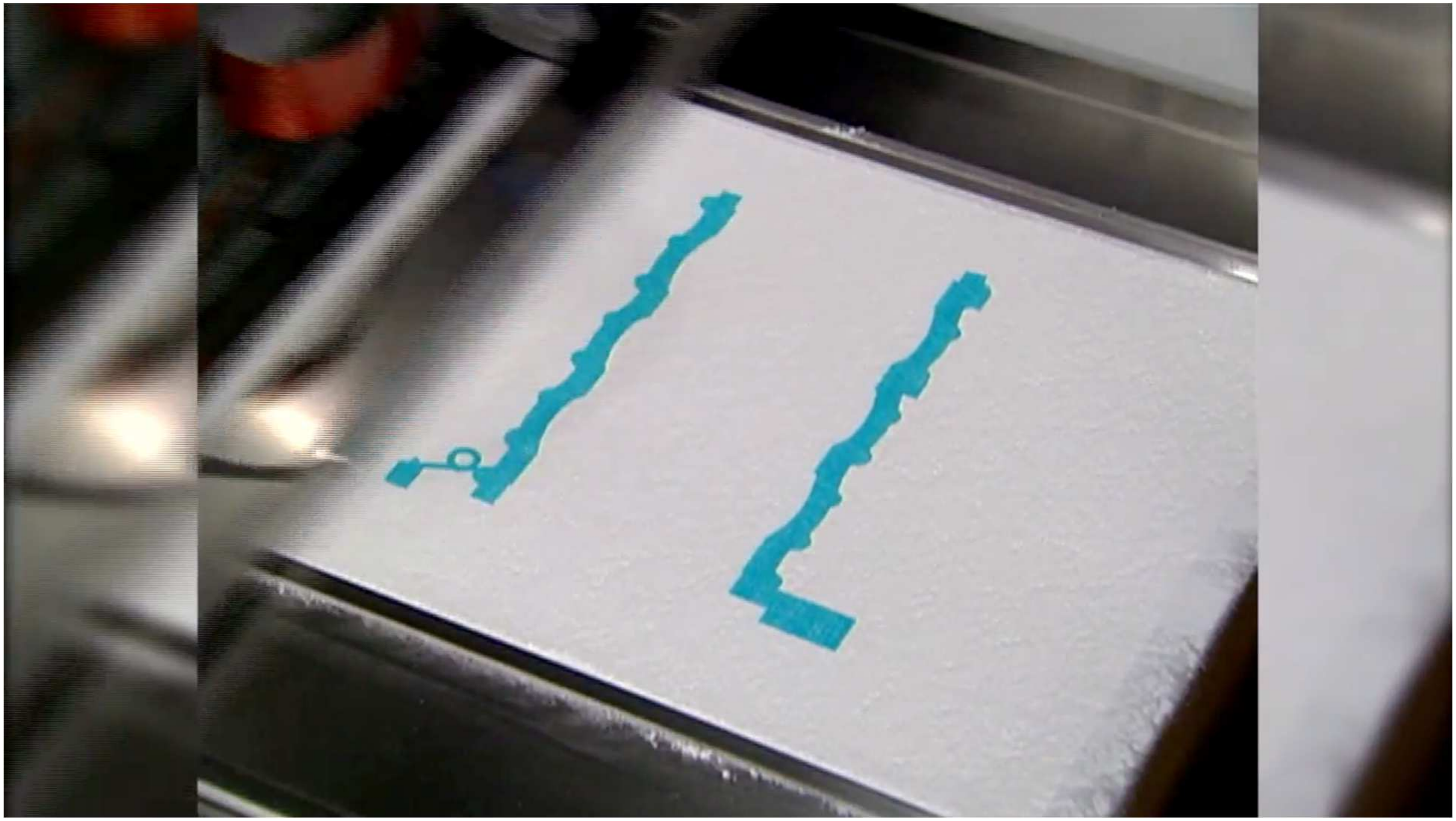
Rise of additive manufacturing in 2000s

- Many relevant patents are expired
- Widespread use of CAD/CAM programs in academia/industry
- Increase in the library of printable materials

2

Overview and advantages of AM techniques

Overview of AM techniques



Watch online

https://www.youtube.com/watch?v=Ev-MM9cGKiQ

Overview of AM techniques

Material extrusion	FDM, FFF	An object is built by selectively depositing melted material in a pre-determined path layer-by-layer.
Photopolymerization	SLA	An object is created by selectively curing a polymer resin layer-by-layer using an ultraviolet (UV) laser beam
Powder bed fusion	SLS, SLM	A laser selectively sinters the particles of a polymer/metal/ceramic powder, fusing them together and building a part layer-by-layer.
Binder jetting	3DP	A binder is selectively deposited onto the powder bed
Material jetting	Objet	a printhead dispenses droplets of a photosensitive material that solidifies under ultraviolet (UV) light
Direct energy deposition	LENS	Focused thermal energy is used to fuse powder bed selectively
Sheet lamination	LOM	Sheets are cut selectively and then bond together to form an object

(3dhubs.com)

Advantages of Additive manufacturing

- It is easy to change or revise versions of a product
- Reduction of waste production
- Possibility of fast production of a replacement part
- Some shape are only possible to manufacture using AM

Advantages of Additive manufacturing

Think-pair-share

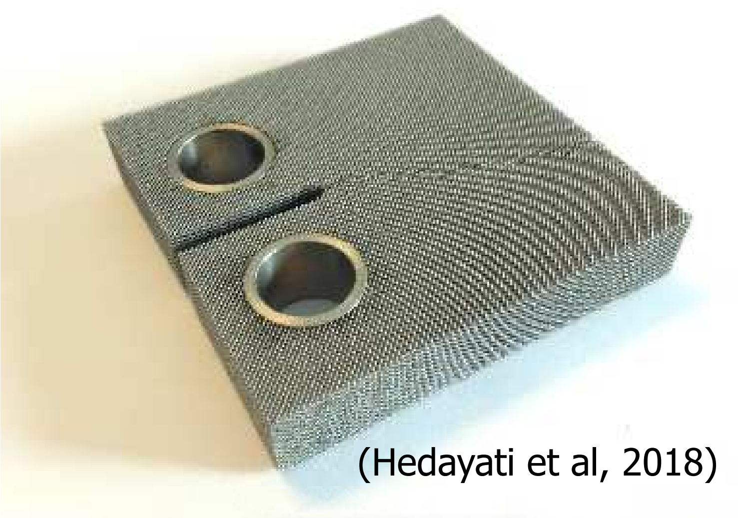
?

Try to think of some examples of geometries that are only possible to be made using AM

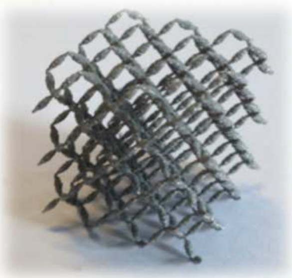
3 min

Advantages of Additive manufacturing

An example: Rationally-designed porous materials

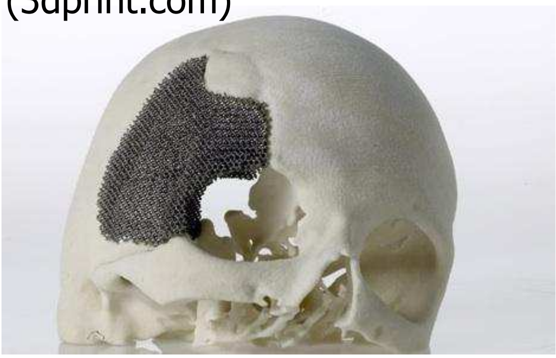


(Hedayati et al, 2018)

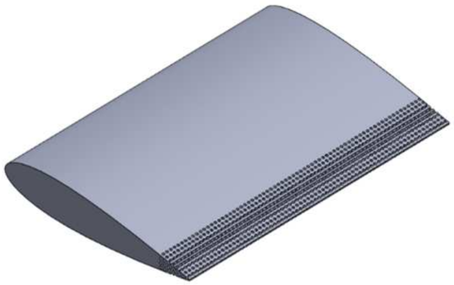


Applications:

(3dprint.com)



Biomedical implants



Aerospace

Chemical filtering

Another example: Porsche metal exhaust

FIGURE [2] /
Porsche turbo exhaust manifold printed by MIMO Technik in Inconel 625 with a 1-mm wall

(https://lightweightingworld.com/automotive-applications-embracing-metal-additive-manufacturing/)

3

Costs of AM technologies

Conventional vs Additive manufacturing

Often large compared with that for traditional manufacturing processes

No tooling

Equipment cost C_C is large. Coupled with the low production rate, the equipment cost term often dominates the part cost for service parts

Quite high

Cost of a manufactured part

$$C_p = \text{material cost} + \text{tooling cost} + \text{equipment cost} + \text{overhead cost}$$

$$C_p = \left(\frac{P_m \rho V}{1-f}\right) + \frac{C_T N_T}{n} + \frac{1}{\dot{n}}\left[\frac{C_C}{L t_{wo}}\right] + \frac{\dot{C}_{oh}}{\dot{n}}.$$

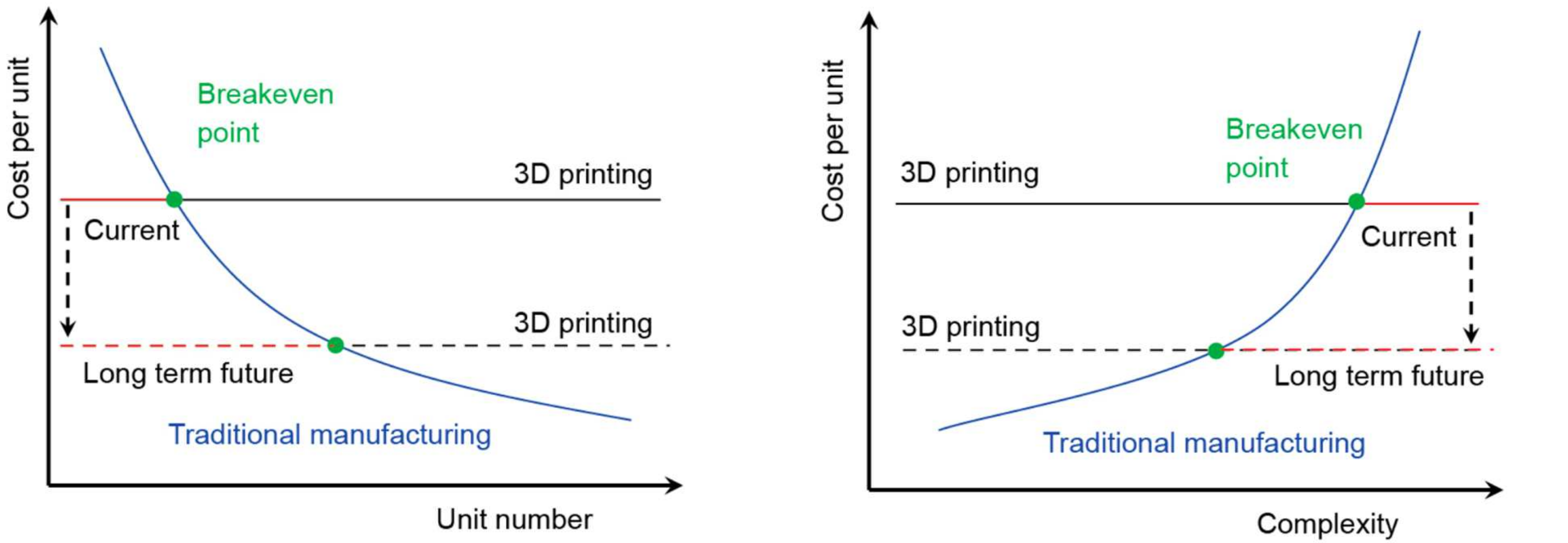
High contribution to AM costs. Reason: $\dot{n}$ is generally very low

P_m: material cost on a mass basis,
ρ: material density,
V: part volume,
f: fraction of material scrapped during manufacturing,
C_T: cost for (dedicated) tooling,
N_T: the number of complete tool sets needed for the production run,

n: the number of identical parts desired,
$\dot{n}$: the rate at which parts are manufactured (the production rate),
C_C: the cost of (permanent, nondedicated) equipment,
L: the time load (the fraction of the total time during which parts are being produced),
t_{wo}: the write-off time (the lifetime of the equipment),
$\dot{C}_{oh}$: the overhead cost

(Bourell, 2016)

Cost of conventional vs Additive manufacturing



AM is the optimum option for low production number and highly complex geometries

(Ma et al. 2018)

4

Extrusion processes

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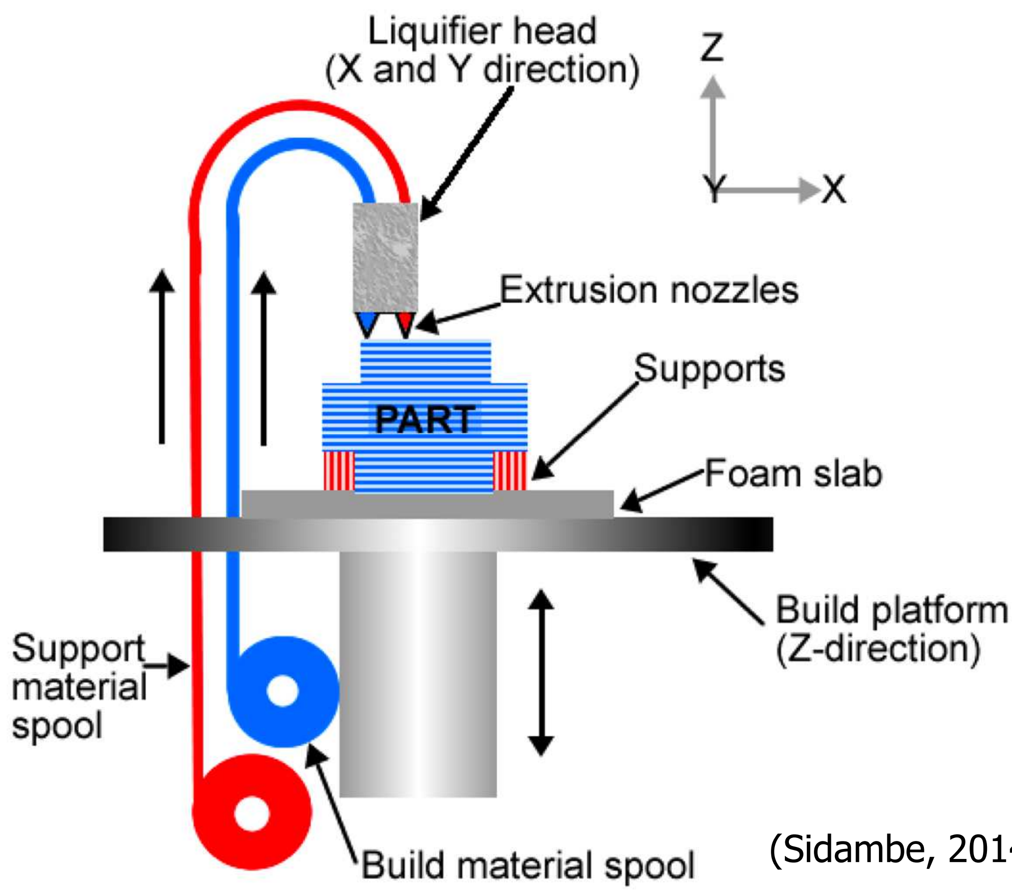
Fused deposition modeling (FDM)

An object is built by selectively depositing melted material in a pre-determined path layer-by-layer. The materials used are thermoplastic polymers and come in a filament form.



(Sidambe, 2014)

(Varotsis, 2018)

Fused deposition modeling (FDM)

Watch online ▶ https://www.youtube.com/watch?v=WHO6G67GJbM&t=41s

Fused deposition modeling - Clones

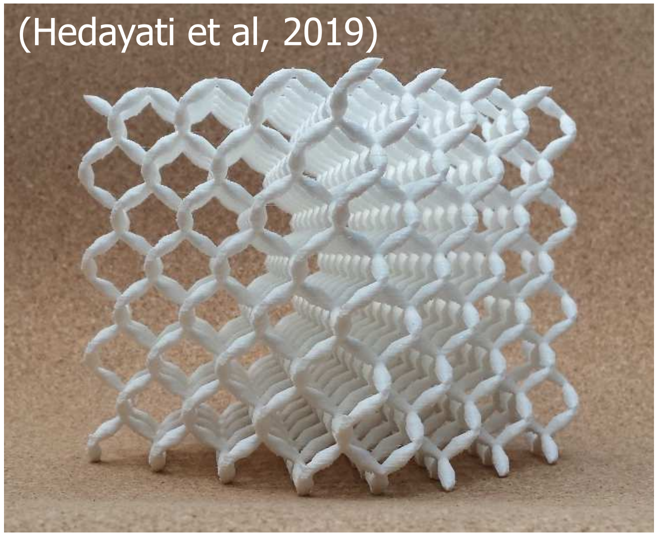
Ultimaker 3

Makerbot 5th Gen

Cube 3 (3D Systems)

Zotrax M300

Fused deposition modeling (FDM)



Pentamode metamaterial

(makepartsfast.com)

Aircraft duct

Example of parts additively manufactured by FDM technology

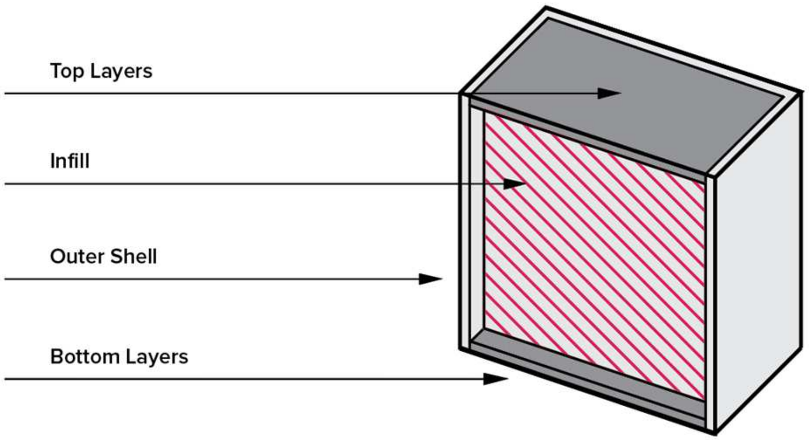
Materials for FDM

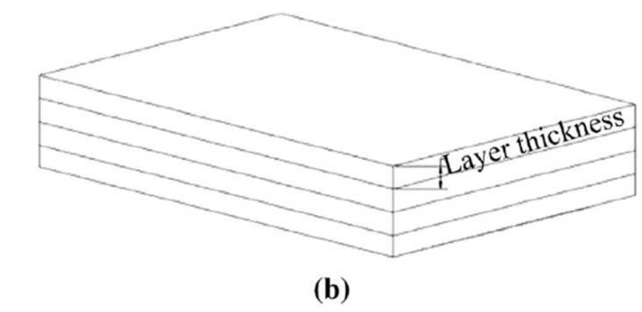
- PLA (PolyLactic Acid)
- ABS (Acrylonitrile butadiene styrene)
- Nylon
- PC (Polycarbonate Thermoplastic)
- ASA (Acrylic Styrene Acrylonitrile)

	Image	Description	Colors Available	Tensile Strength	Tensile Modulus	Tensile Elongation
ABS-M30 Datasheet		Strong, functional, smooth parts with good feature detail		5,200 psi (36 MPa)	350,000 psi (2,400 MPa)	4%
ABS-ESD7 Datasheet		Strong thermoplastic with static dissipative properties		5,200 psi (36 MPa)	350,000 psi (2,400 MPa)	3%
ABSi Datasheet		Superior strength; translucent in nature.	T T T	5,400 psi (37 MPa)	277,700 psi (1,920 MPa)	4.4%
ABS-M30i Datasheet		Bio-compatible (ISO 10993; USP Class VI), Gamma & EtO sterilizable ABS material for medical and pharmaceutical		5,200 psi (36 MPa)	350,000 psi (2,400 MPa)	4%
ASA Datasheet	NOW AVAILABLE	Production-grade thermoplastic; UV-stable and color-fast; especially suited for outdoor commercial and infrastructure end-use parts		Ultimate (XY): 4,720 psi (33 MPa) Ultimate (Z): 4,300 psi (30 MPa)	(XY): 291,000 psi (2,010 MPa) (Z): 283,000 psi (1,950 MPa)	Break (XY): 9% Break (Z): 3%
PC Datasheet		Accurate, durable, strong, stable; suitable for functional testing; imaging & RF transparent		9,800 psi (68 MPa)	330,000 psi (2,300 MPa)	5%
PC-ISO Datasheet		Bio-compatible (ISO 10993; USP Class VI), Gamma & EtO sterilizable, imaging & RF transparent, strong and rigid material		8,300 psi (57 MPa)	289,800 psi (2,000 MPa)	4%
PC-ABS Datasheet		Superior strength, heat resistance, flexibility; widely used		5,900 psi (41 MPa)	278,000 psi (1,900 MPa)	6%
ULTEM 9085 Datasheet		Flame retardant (FAR 25.853; UL 94 V-0) high-performance thermoplastic		10,400 psi (71.6 MPa)	322,000 psi (2,200 MPa)	6%
Nylon 12 Datasheet	NOW AVAILABLE	With higher elongation at break and good impact strength, Nylon 12 is the “toughest” FDM material		7,700 psi (53 MPa)	190,000 psi (1,310 MPa)	9.5%

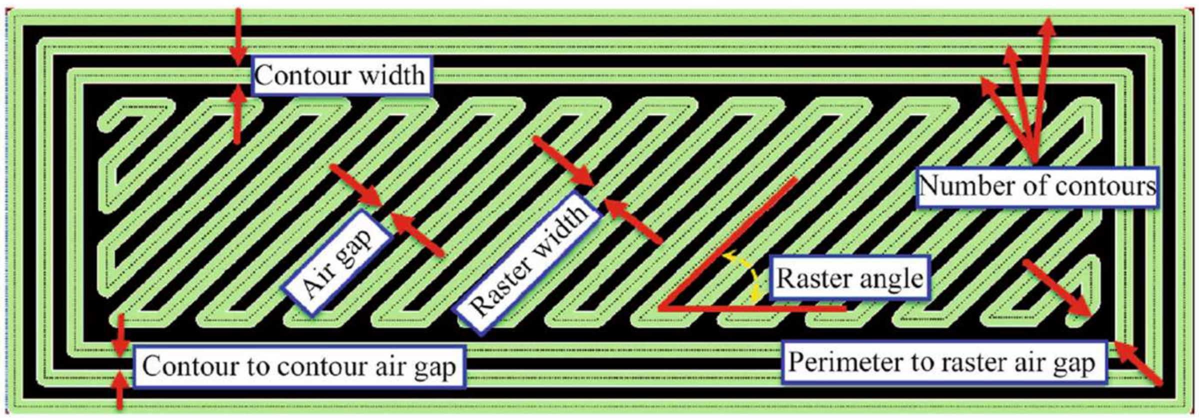
Stratasys materials for FDM

Discretization and toolpath effects





Layer thickness



FDM tool path parameters

(Cain, 2019); (Mohammed et al, 2015)

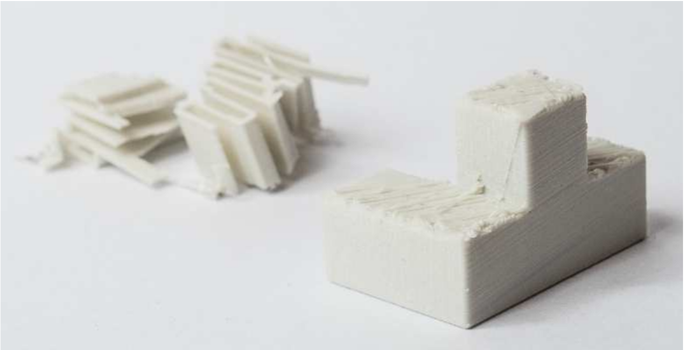
FDM parameters – Support structure

Rule of thumb: use support for bridging wider than 5 mm

Support structures for letters Y, H, and T

There is a lot of sagging due to lack of support structures

Downside of support structures

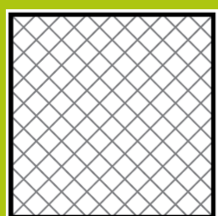


(Cain, 201

FDM parameters – Infill percentage

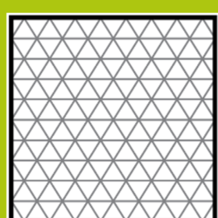
20% 50% 75%

- For prototypes in which shape/form is important, default 20% infill is sufficient
- If the part is to experience mechanical load, higher infill percentages are required

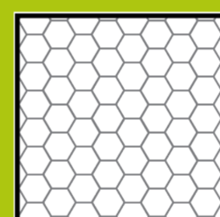


Rectangular
- Standard infill
- Strength in all directions and reasonably fast
- Least amount of bridging.

Wiggle
- Allows the model to be soft, to twist, or to compress.
- Good choice with a soft rubbery material or softer nylon.



Triangular
- When strength is needed in the direction of the walls.
- Take a little longer to print.



Honeycomb
- Quick to print
- Very strong, providing strength in all directions.

(Cain, 2019)

FDM parameters – Shell thickness

- Increasing shell thickness increases strength without having to increase the amount of material used for infill.
- Increasing shell thickness is often necessary if post-processing methods such as sanding or chemical smoothing are required as they reduce the thickness of the surface.
- Any increase in the number of shells also increase the amount of time and material (increasing overall cost)
- Shells typically consist of a specified number of nozzle diameters. It is always good to design shells to be a multiple of nozzle diameter to prevent voids.

Multiple nozzle-diameter thickness

2 nozzle-diameter thickness

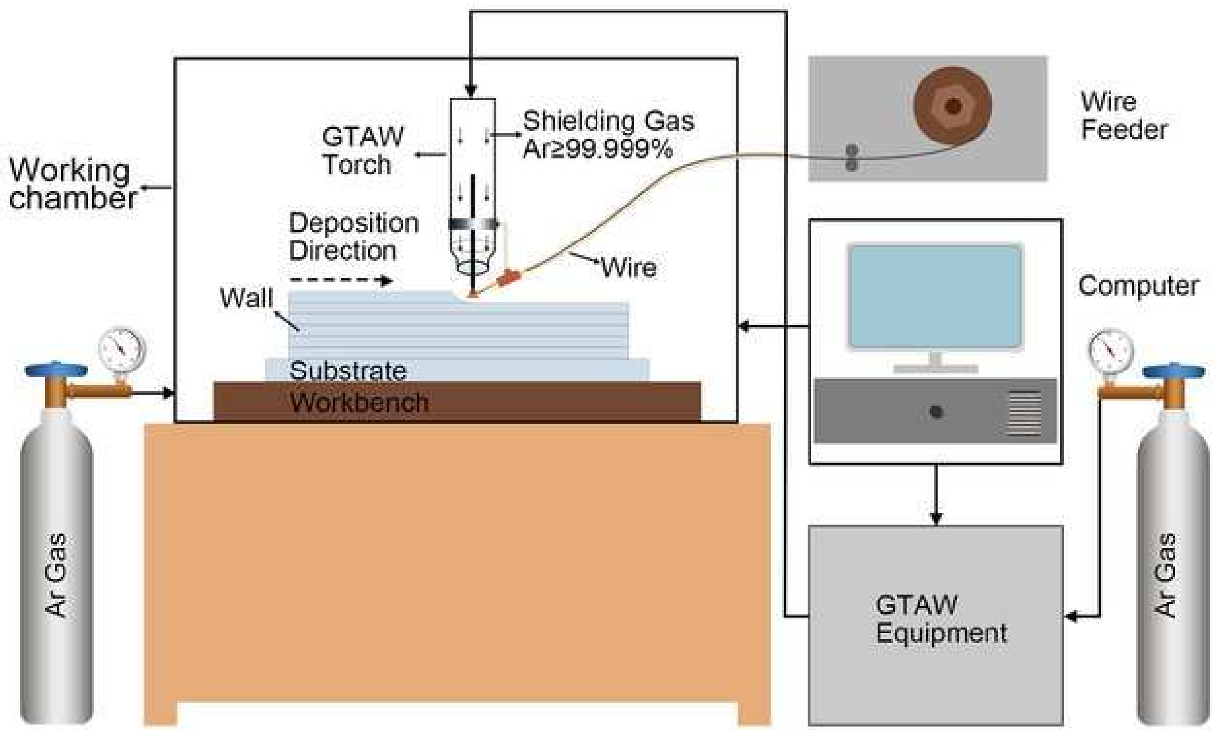
(Cain, 2019)

Laser deposition technology (LDT)

TU Delft Watch online https://www.youtube.com/watch?v=d2foaRi4nxM&t=119s

Wire + ARC Additive manufacturing (WAAM)

- Combination of an electric arc as heat source and wire as feedstock
- Potential to fabricate large metal components with low cost and short production lead time



(Guo et al, 2016)

Wire + ARC Additive manufacturing (WAAM)

Watch online

https://www.youtube.com/watch?v=aktUXbCVq

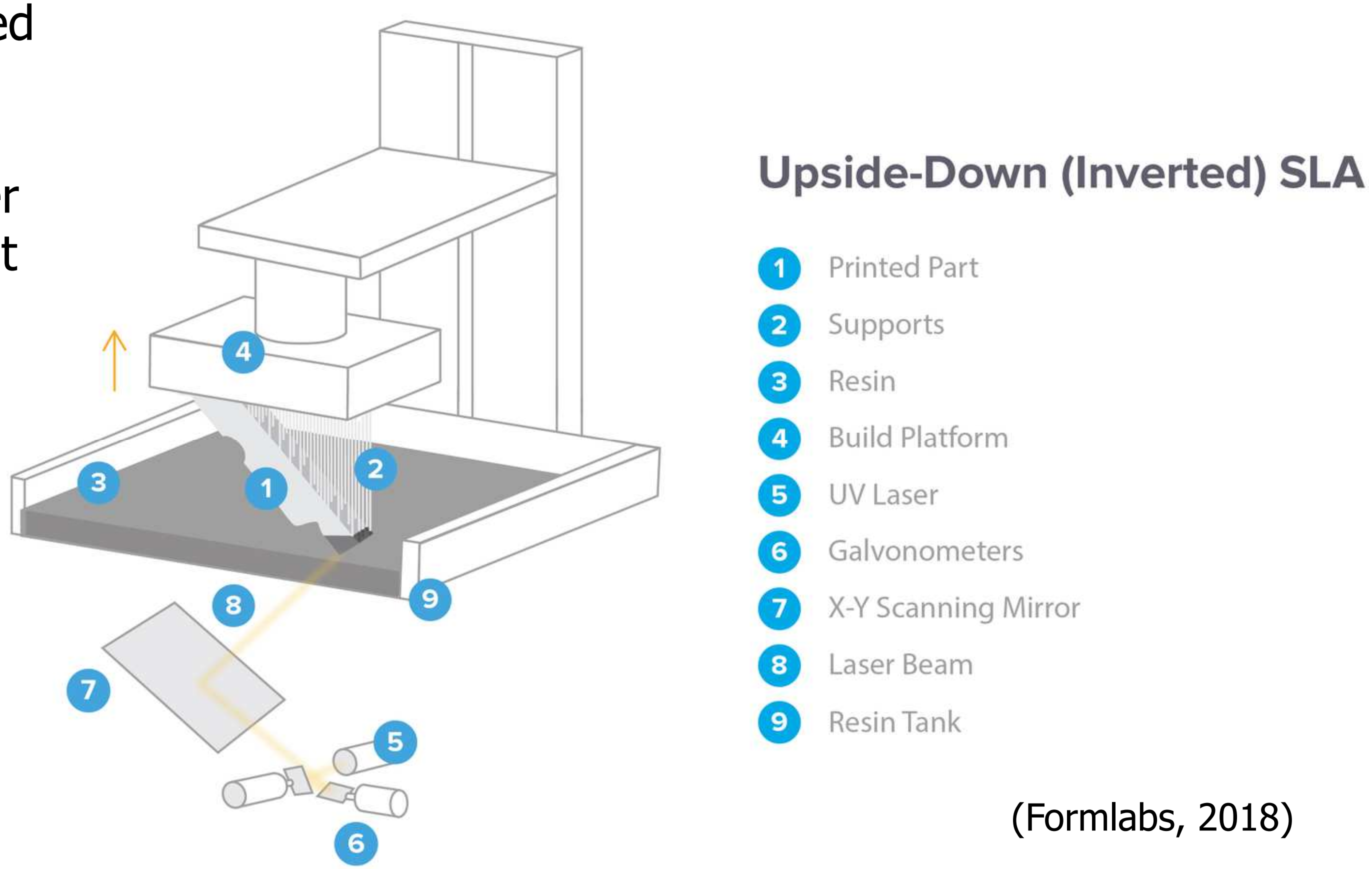
5

Photopolymerization

Reza Hedayati, PhD – rezahedayati@gmail.com

Stereolithography (SLA)

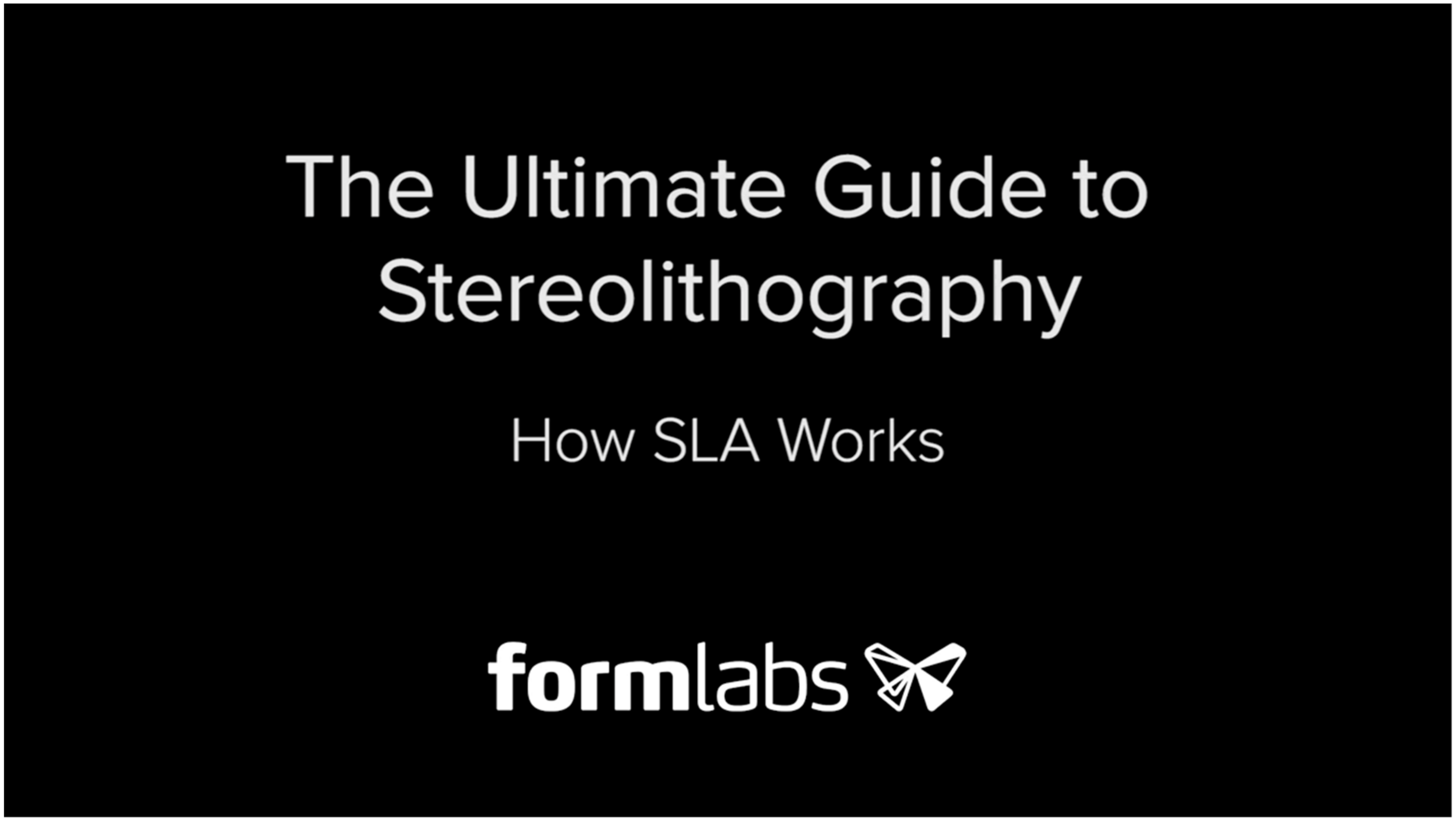
An object is created by selectively curing a polymer resin layer-by-layer using an ultraviolet (UV) laser beam



(Formlabs, 2018)

(Varotsis, 2018)

Stereolithography (SLA)



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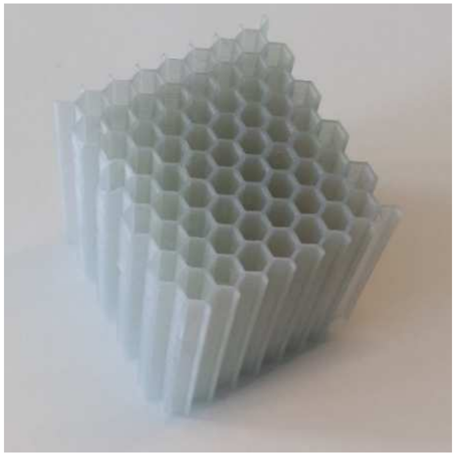
Watch online https://www.youtube.com/watch?v=8a2xNaAkvLo

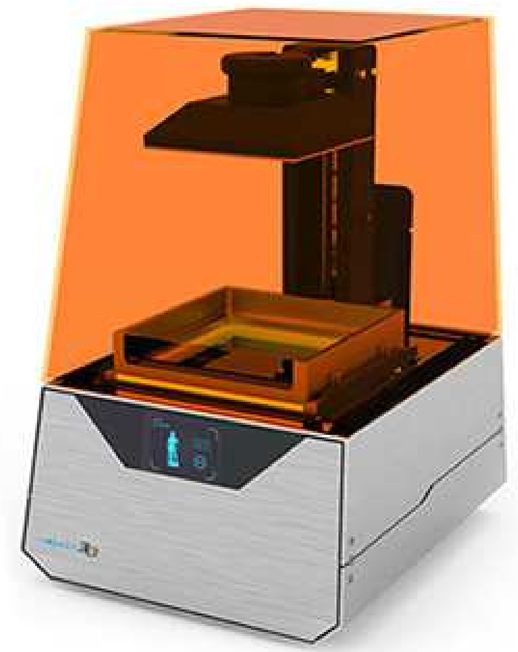
Stereolithography (SLA)



Examples of parts manufactured by SLA technique.

Stereolithography - Clones

Formlabs



Dazz 3D

FDM vs SLA

Materials

	FDM	SLA
Material types	PLA, ABS, PC, Nylon, ASA Exchangeable between different printers	Each company produces resins of its own. Resins usually not exchangeable between different printers
Colors	A large range of options	Limited (for example, Formlabs only provides black, white, grey and clear)
Use of material		There are options of choosing more durable or highly specialized materials for industrial or medical use

(Grieser, 2018)

FDM vs SLA

Smoothness

	FDM	SLA
Factors influencing resolution	• Nozzle size • Precision of XY movement of nozzle • Precision of Z movement of build plate • Weight of upper layers might squeeze the lower layers	• Optical spot size either of the laser or the projector (which is very small) • Low force is applied on the model
Result	Relatively rough surface finish	Much smoother surface finish

(Formlabs.com)

(Grieser, 2018)

Question

?

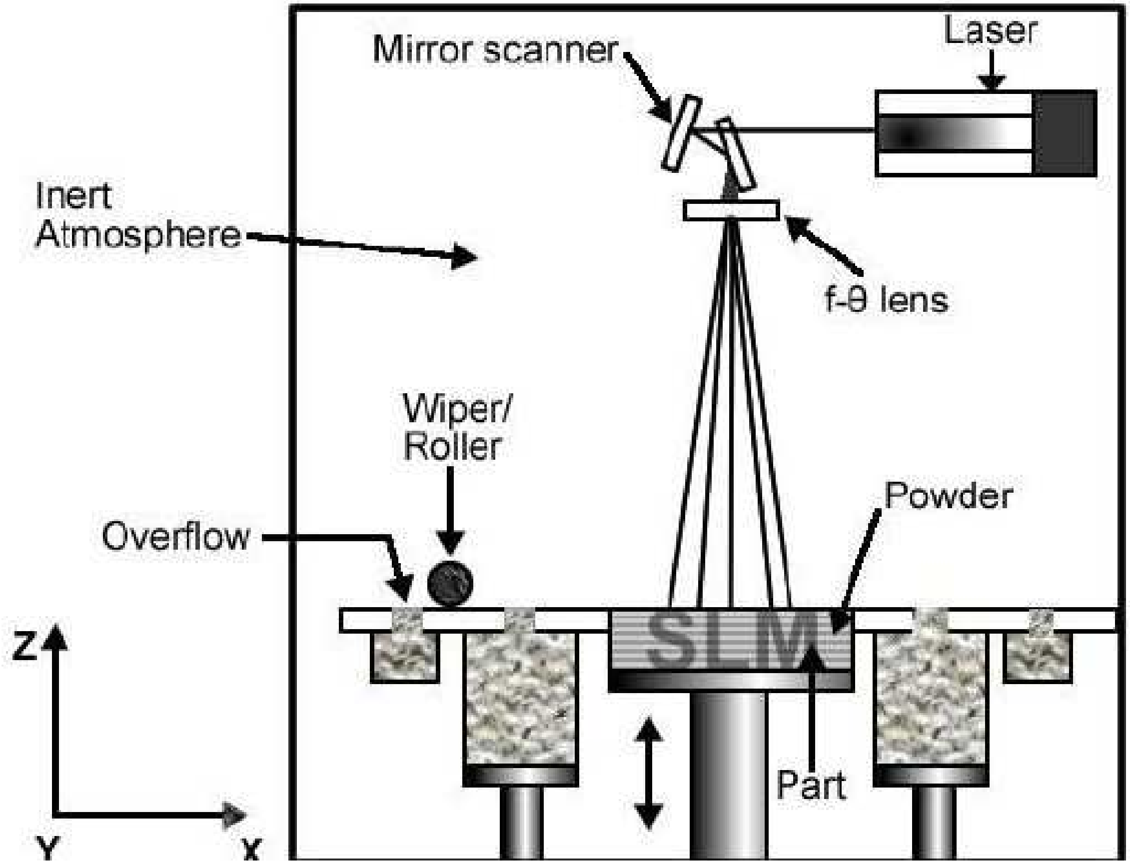
- Does anyone have any interesting experience with AM (particularly FDM and SLA) they want to share with class?

6

Powder bed fusion

Selective laser melting (SLM)

A high power-density laser to melt and fuse metallic powders together

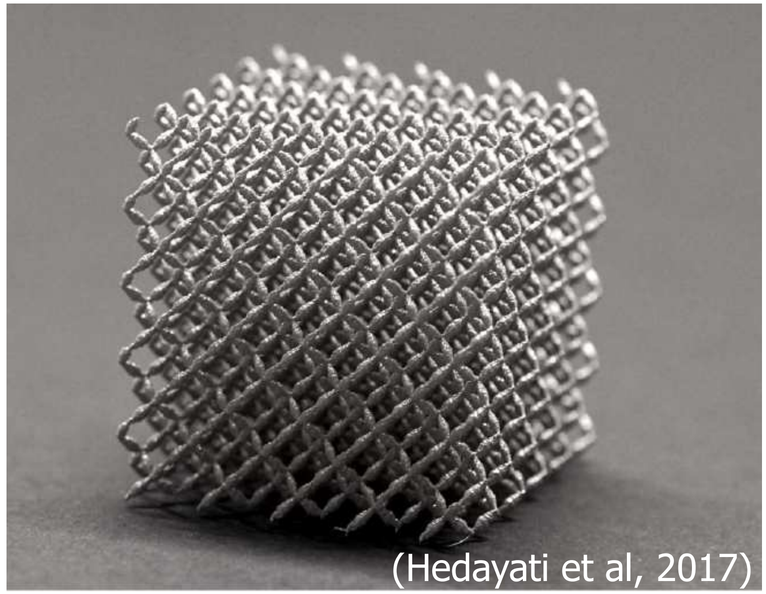


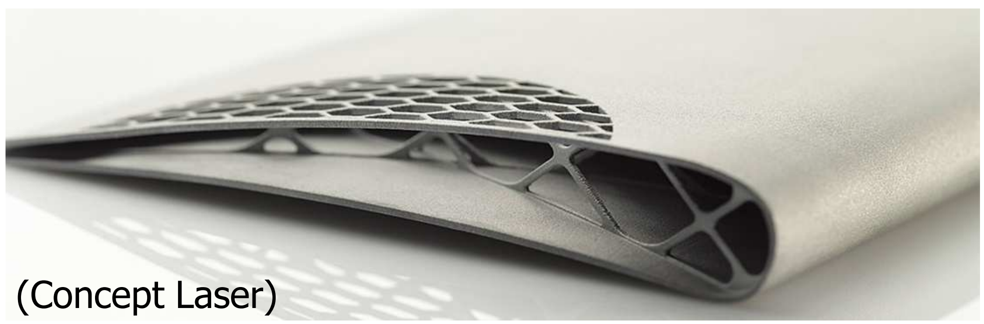
(Sidambe, 2014)

Selective laser melting (SLM)

Watch online https://www.youtube.com/watch?v=da5IsmZZ-tw

Selective laser melting (SLM)





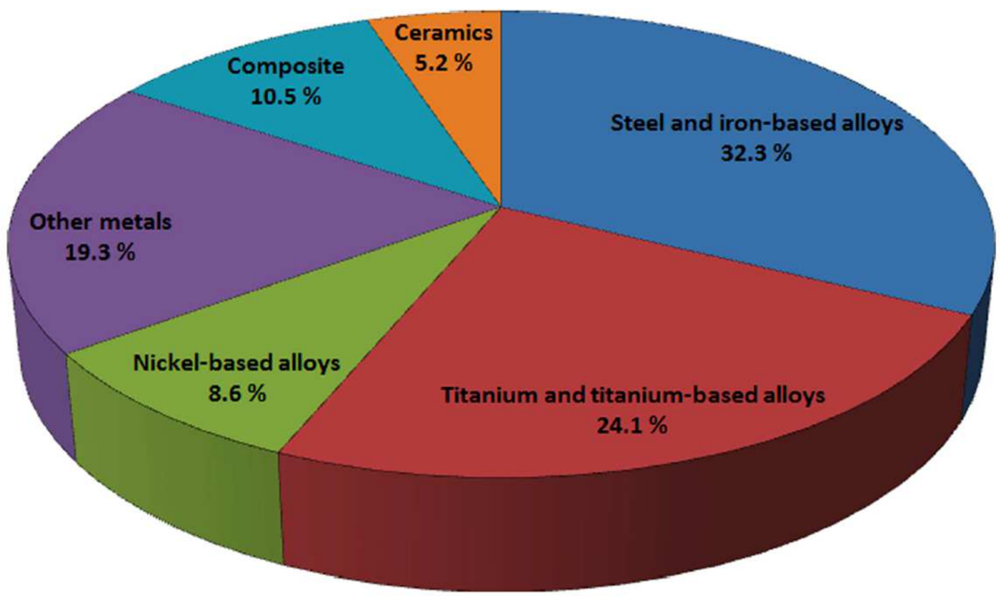
Examples of parts manufactured by powder bed fusion technologies: (a) pentamode metamaterial, and (b) topology-optimized airfoil.

Selective laser melting (SLM)

Materials

Usually metals

- copper,
- aluminum,
- stainless steel,
- tool steel,
- cobalt chrome,
- titanium and
- Tungsten
- Ceramics

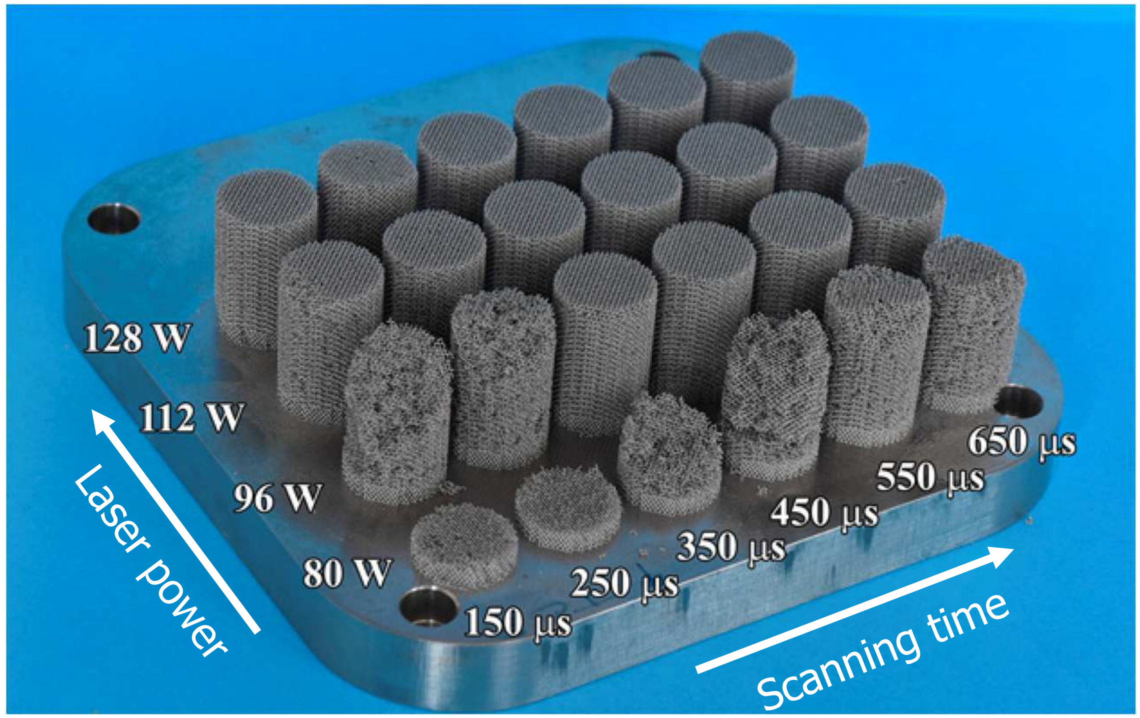


(Yap et al, 2015)

Selective laser melting (SLM)

Critical process parameters

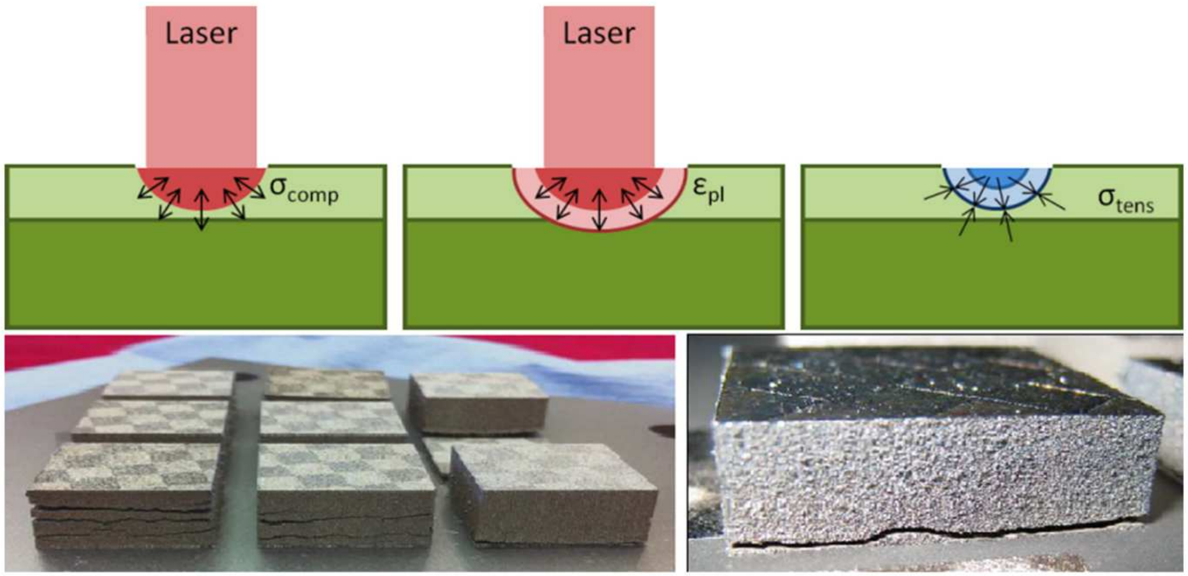
- Laser power
- Scanning speed
- Patterning technique
- Powder size
- Layer height
- Powder bed uniformity



(Ahmadi et al., 2017)

Selective laser melting (SLM)

Thermal fluctuations



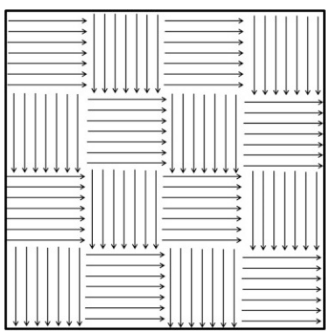
(Yap et al, 2015)

Temperature gradient creates residual stress. This can lead to crack formation and delamination of parts.

Selective laser melting (SLM)

Solutions to residual stress resulting from thermal fluctuations

- **Heat treatment:** The part is heated in a muffle furnace and is kept at the temperature for some time (for example one hour) to relieve stress.
- **Rescanning of laser:** Residual stress may be relieved by heating the newly formed part. To heat the top surface, a laser scan process with the same laser beam as forming is carried out after making each layer.
- **Heating of powder bed:** A higher cooling speed may cause a larger residual stress. To reduce the cooling speed in SLM process, the powder bed temperature is raised by heating the base plate.
- **Sectoral scanning**: This strategy breaks down a layer into small square grids and neighboring grids are scanned perpendicular to one another



(Sing et al, 2016)

Sectoral scanning

(Shiomi et al, 2004)

Selective laser melting (SLM)

Heat treatment

- SLM Ti6Al4V parts show out-of-equilibrium fine acicular martensitic structure ($\acute{\alpha}$ phase) due to high solidification rate.
- 2-hour heat treatment of Ti-6Al-4V parts transforms the fine martensitic structure into a mixture of α and β phases where α phase is present as needles.
- Changing the microstructure of Ti-6Al-4V from α' phase to equiaxed $\alpha+\beta$ increases the static and fatigue strengths and leads to higher ductility.

(Huang et al, 2015)

Selective laser melting (SLM)

Heat treatment

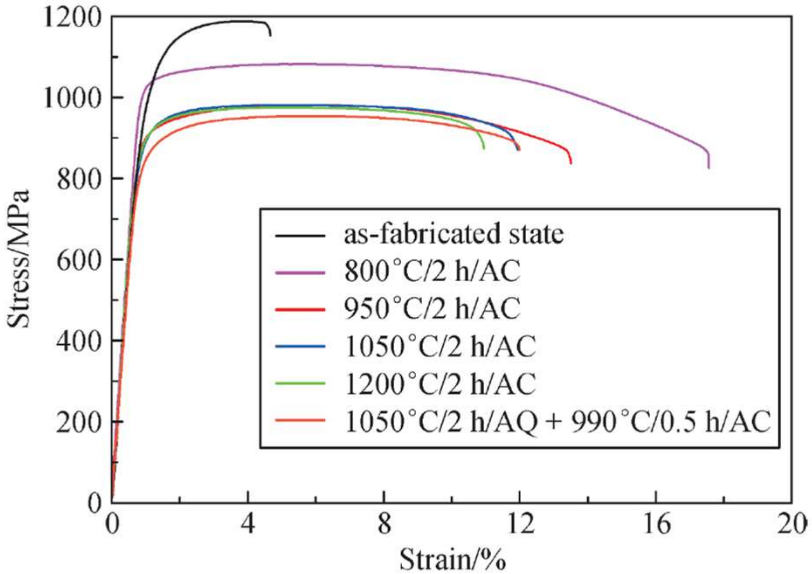


Table: Mechanical properties of SLM Ti-6Al-4V after different heat treatment strategies

No.	T /°C	t /h	Cooling mode	UTS /MPa	YS /MPa	BE /%
1				1191±6	970±6	5.37±1.39
2	800	2	AC	1073±9	1010±11	17.05±1.14
3	950	2	AC	984±5	893±3	14.15±1.49
4	1050	1	AC	988±8	869±4	13.34±0.67
5	1200	1	AC	988±8	878±7	11.25±1.25
6	1050	1	WQ			
		followed by		962±12	838±6	11.96±0.07
	990	0.5	AC			

Note: Treatment one (No.1) is noted for the un-heat-treated as-fabricated material; WQ = water quenching; AC = air cooling; UTS = ultimate tensile strength; YS = yield strength; BE = breaking elongation.

(Huang et al, 2015)

Question

Think-pair-share

?

- Regardless of material, can you think of some geometries which can only be manufactured by some of the techniques FDM, SLM, and SLA and not with others?

Reza Hedayati, PhD – rezahedayati@gmail.com

Question

(rajgurusteel.co.in)

Hollow sphere

Possible:
FDM, Reverse SLA

Material trapped inside:
SLM and SLA
(they would need window for discharging trapped material inside)

Other geometries?

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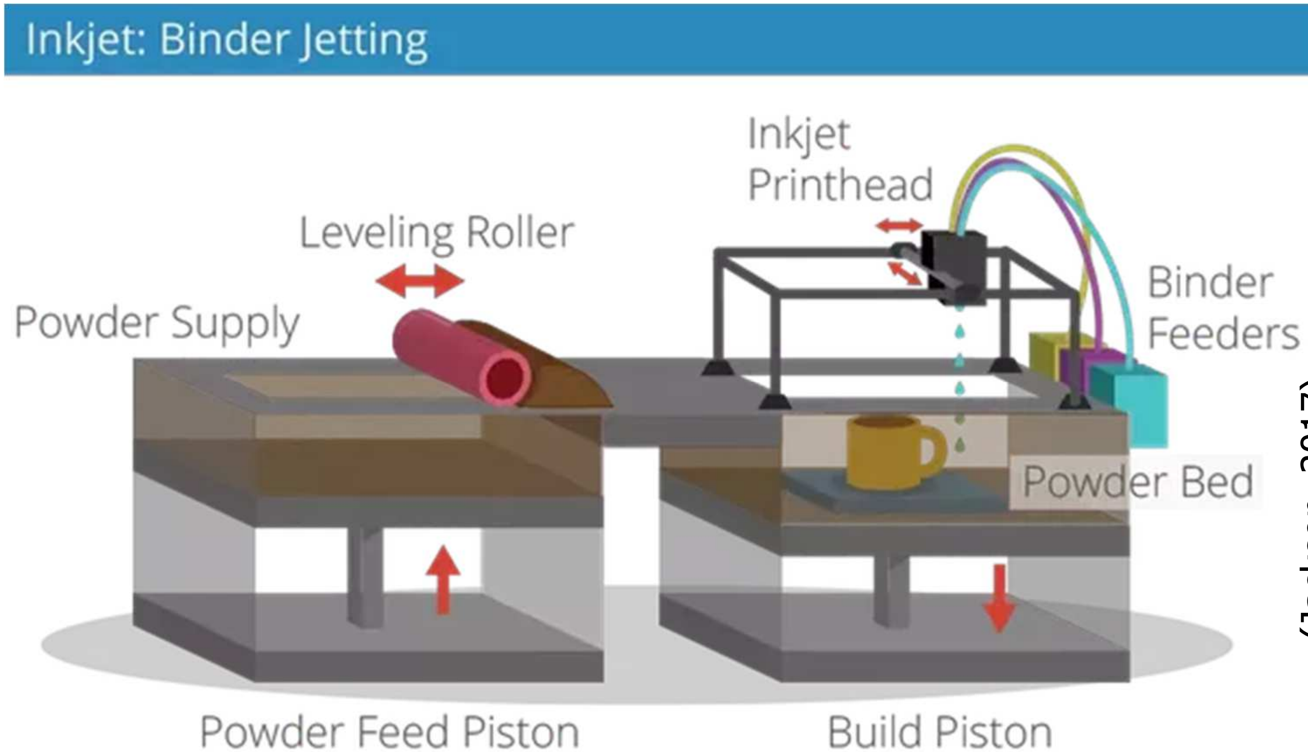
7

Binder jetting

Binder jetting



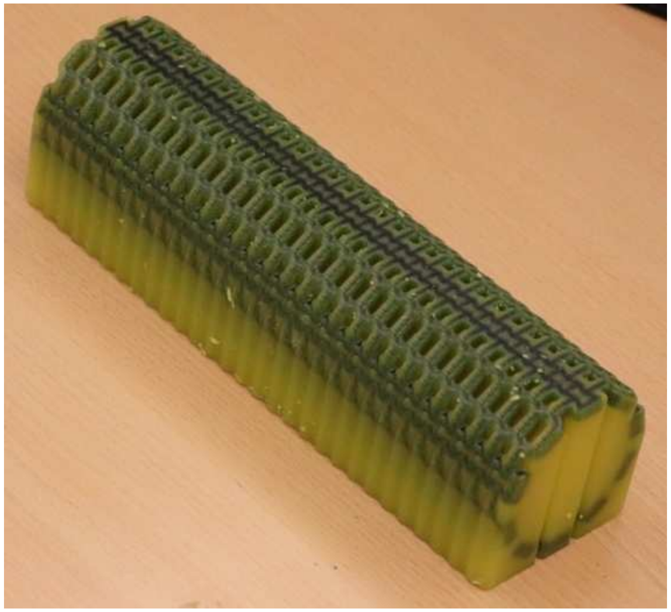
(Jackson, 2017)

A binder is selectively deposited onto the powder bed, bonding these areas together to form a solid part

Binder jetting

Reza Hedayati, PhD – rezahedayati@gmail.com

Binder jetting



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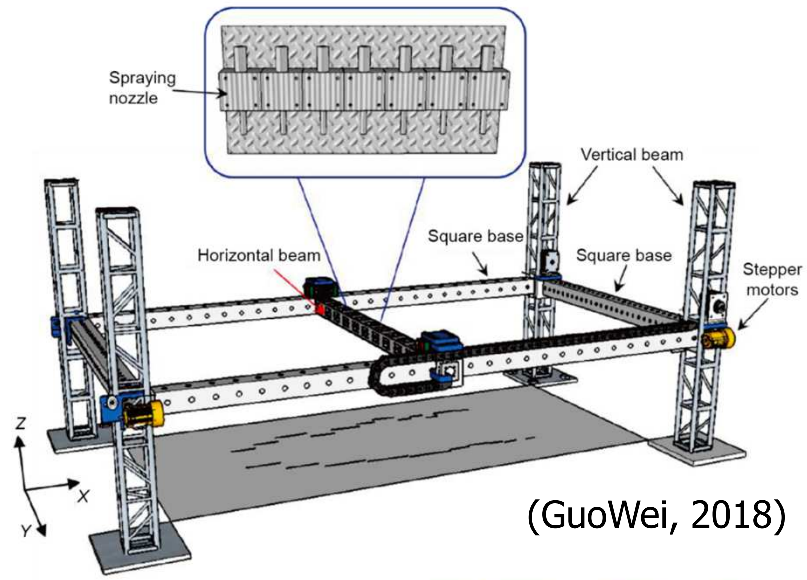
Binder jetting for construction field

D-shape printer

- Printer head installed with hundreds of spraying nozzles.
- The printer head is connected to the square base by a horizontal beam, which can freely move along X axis. The square base moves upwards (z-axis) through four stepper motors.
- During printing process, spraying nozzles selectively sprays a binding liquid on predefined areas of the sand layer.
- Once a layer has been printed, a horizontal beam also act as powder material spreader prior to subsequent layer deposition



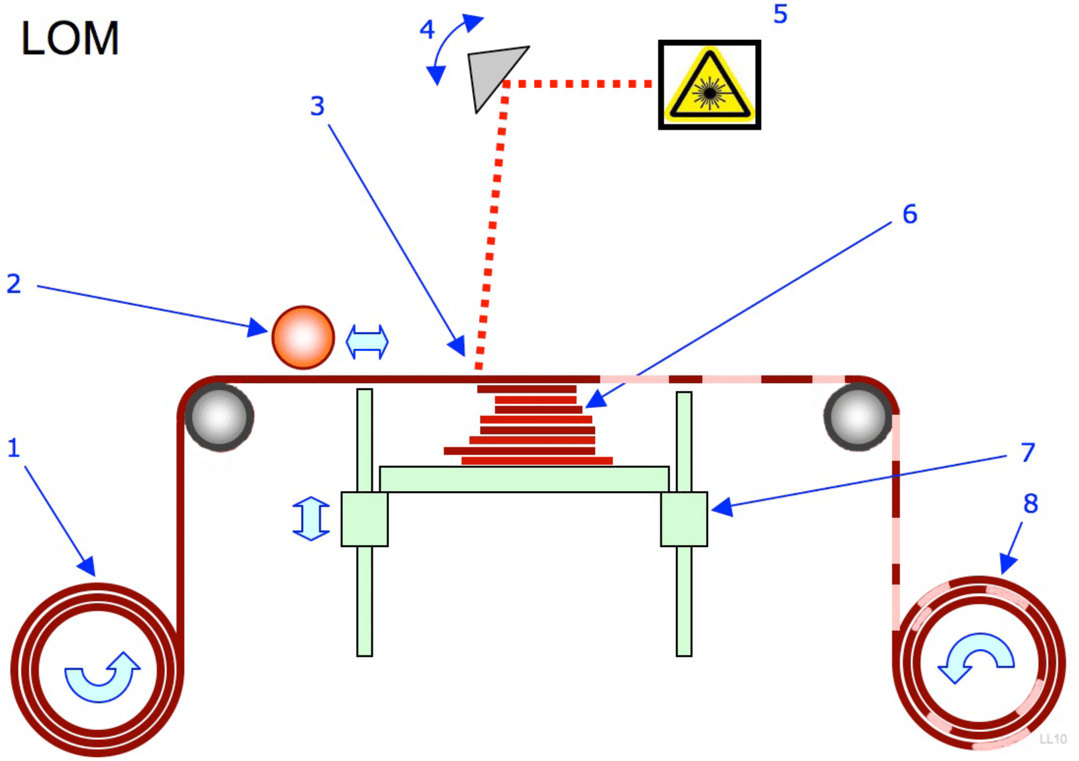
(GuoWei, 2018)

(GuoWei, 2018)

8

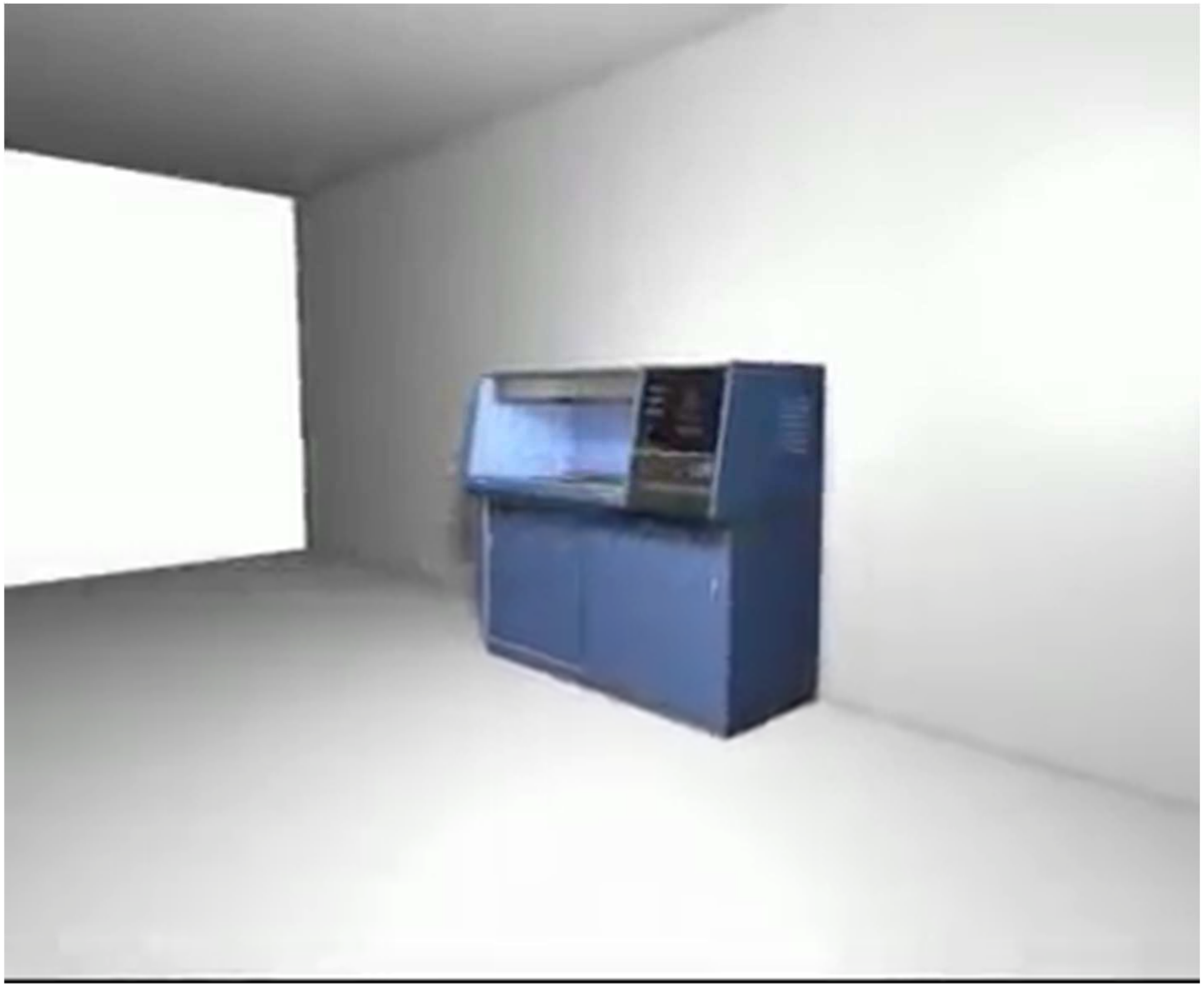
Laminated object processes

Layer laminated manufacturing (LLM)



(LaurensvanLieshout)

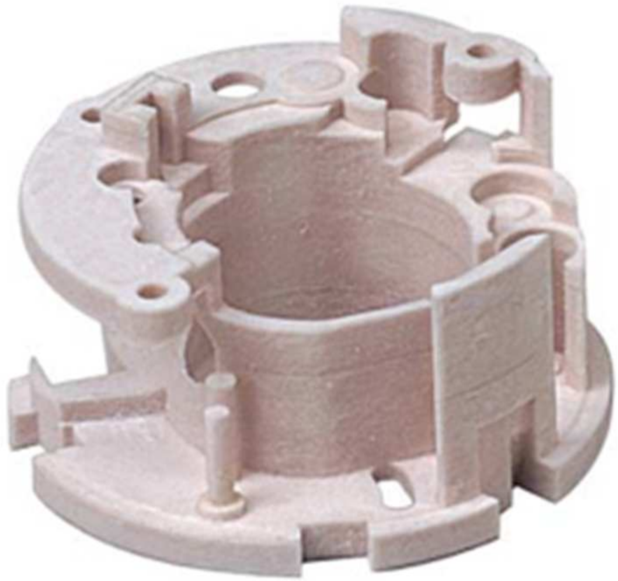
Layer laminated manufacturing (LLM)



Watch online https://www.youtube.com/watch?v=GUvnz0borAI

Layer laminated manufacturing (LLM)

(Inggo.com)



(Gebhardt, 2012)

9

Detailed comparison of different AM techniques

Detailed comparison of AM techniques

A summary of materials, application, benefits and drawbacks of the main methods of additive manufacturing

Methods	Materials	Applications	Benefits	Drawbacks	Resolution range (μm)
Fused deposition modelling	• Continuous filaments of thermoplastic polymers • Continuous fibre-reinforced polymers	• Rapid prototyping • Toys • Advanced composite parts	• Low cost • High speed • Simplicity	• Weak mechanical properties • Limited materials (only thermoplastics) • Layer-by-layer finish	50-200 μm
Powder bed fusion (SLS, SLM, 3DP)	• Compacted fine powders • Metals, alloys and limited polymers (SLS or SLM) ceramic and polymers (3DP)	• Biomedical • Electronics • Aerospace • Lightweight structures • (lattices) • Heat exchangers	• Fine resolution • High quality	• Slow printing • Expensive • High porosity in the binder method (3DP)	80-250 μm
Inkjet printing and contour crafting (binder jetting)	• A concentrated dispersion of particles in a liquid (ink or paste) • Ceramic, concrete and soil	• Biomedical • Large structures • Buildings	• Ability to print large structures • Quick printing	• Maintaining workability • Coarse resolution • Lack of adhesion between layers • Layer-by-layer finish	Inkjet: 5–200 μm Contour crafting: 25–40mm

(Ngo, 2018)

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Detailed comparison of AM techniques

A summary of materials, application, benefits and drawbacks of the main methods of additive manufacturing

Methods	Materials	Applications	Benefits	Drawbacks	Resolution range (µm)
Stereolithography	• A resin with photo-active monomers • Hybrid polymer-ceramics	• Biomedical • Prototyping	• Fine resolution • High quality	• Very limited materials • Slow printing • Expensive	10 µm
Direct energy deposition	• Metals and alloys in the form of powder or wire • Ceramics and polymers	• Aerospace • Retrofitting • Repair • Cladding • Biomedical	• Reduced manufacturing time and cost • Excellent mechanical properties • Controlled microstructure • Accurate composition control • Excellent for repair and retrofitting	• Low accuracy • Low surface quality • Need for a dense support structure • Limitation in printing complex shapes with fine details	250 µm
Laminated object manufacturing	• Polymer composites • Ceramics • Paper • Metal-filled tapes • Metal rolls	• Paper manufacturing • Foundry industries • Electronics • Smart structures	• Reduced tooling and • manufacturing time • A vast range of materials • Low cost • Excellent for manufacturing of larger structures	• Inferior surface quality and dimensional accuracy • Limitation in manufacturing of complex shapes	Depends on the thickness of the laminates

(Ngo, 2018)

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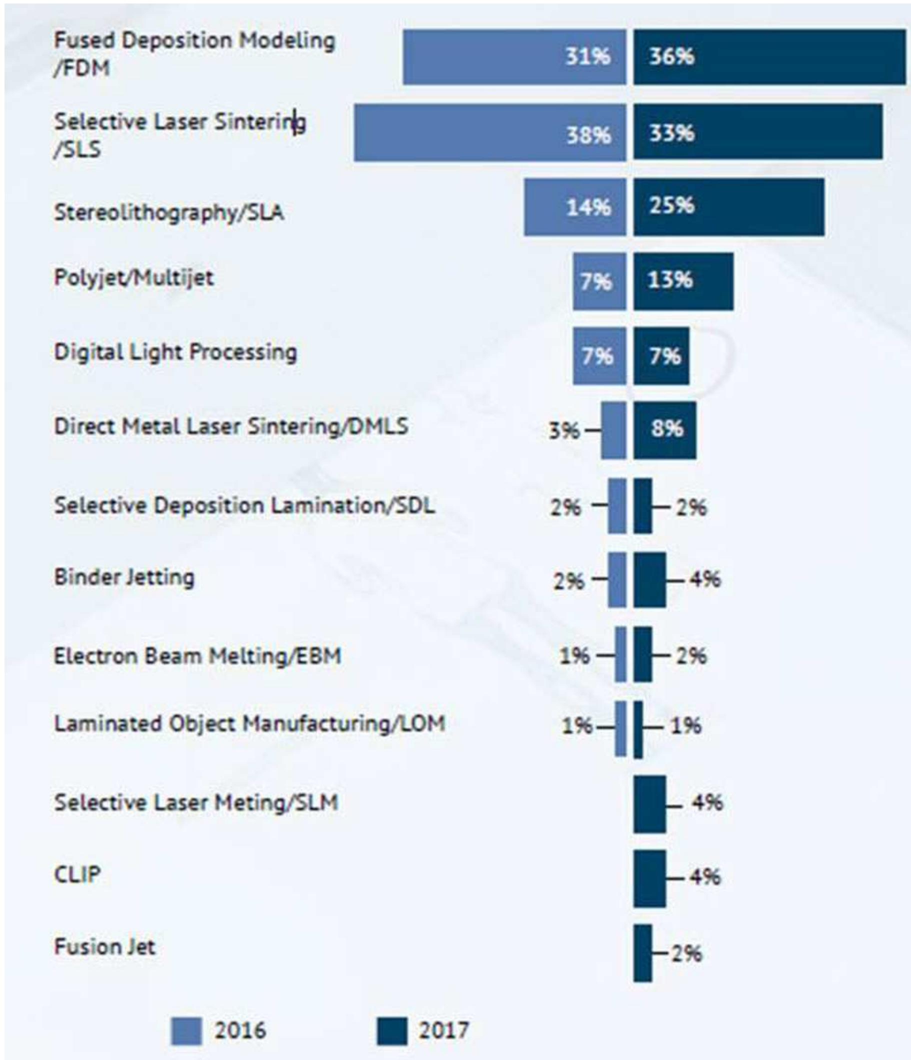
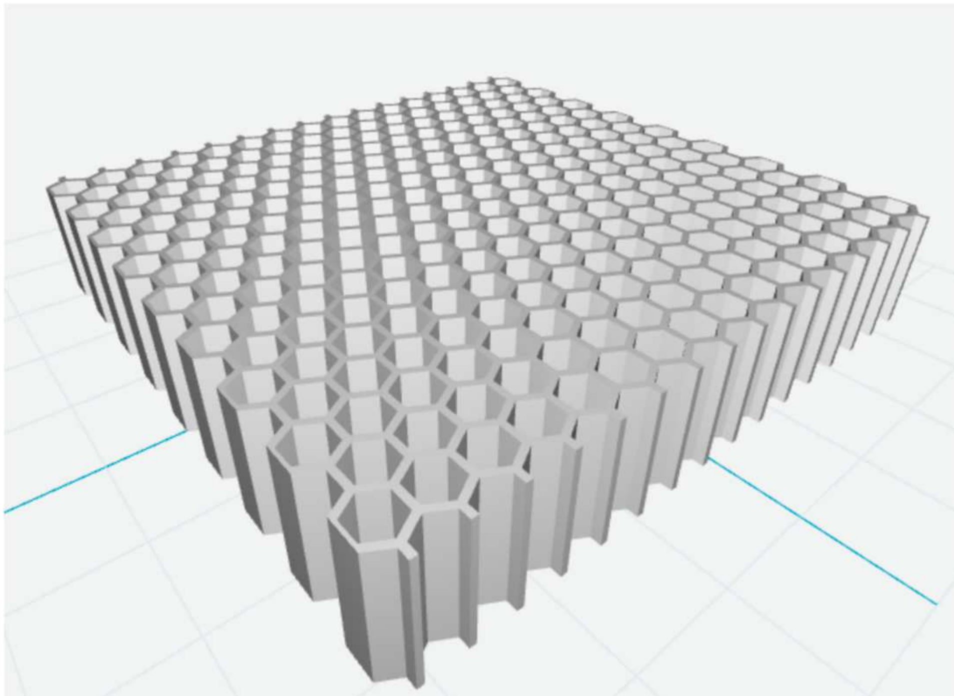
Ranking of popularity of AM techniques



https://blogs-images.forbes.com/louiscolumbus/files/2017/05/top-3d-printing-technologies.jpg

Comparison of costs

Example:



SLS (Polyamide): 86 €
Stereolithography (Gray resin): 272 €
SLM (Aluminum): 1066 €

Pricing: Materialise

Dimension: 135 mm x 135 mm x 25 mm

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