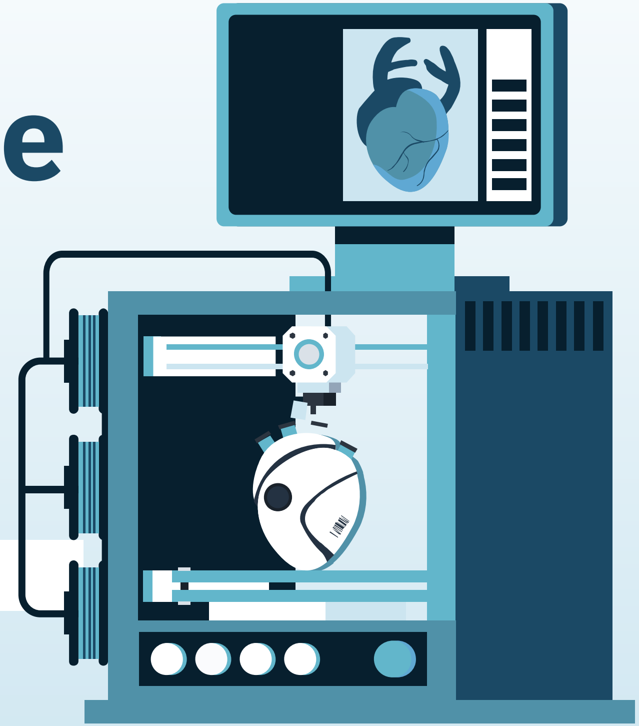
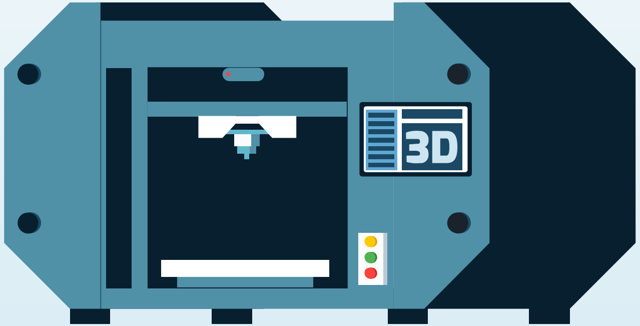
ME-413

# Design for Additive Manufacturing, rules to follow



Tania Rosset, Lucie Mc Cormack, Joshua Levy-Baron, Jolan Fath




# DfAM

Design for additive manufacturing

# Table of contents

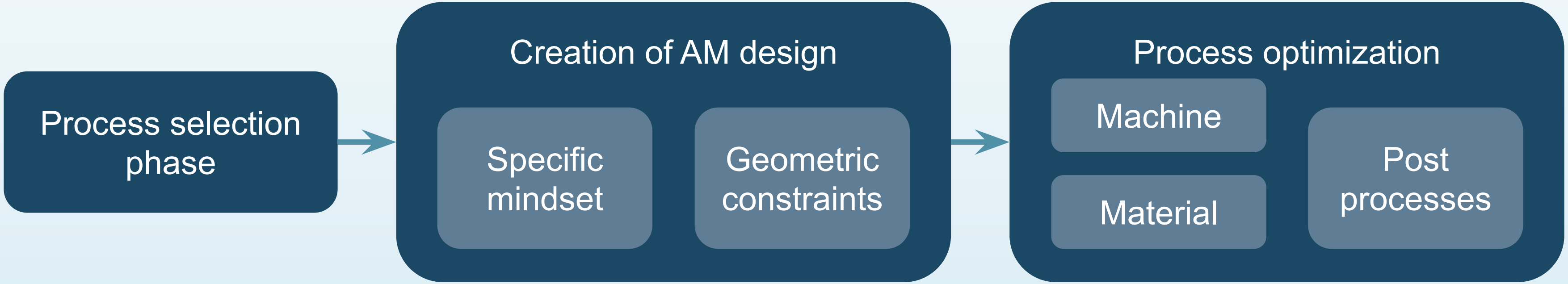


# 01

# Design Specifications

Lucie's part

# The DfAM process



# Process selection

Between traditional manufacturing and AM



## Cost of AM

Linked directly to the AM process

- **Material**
- **Process**
- **Labor**
- **Design phase**

Indirectly linked

- **Post-processing**
- **Computation cost**
- **Risk cost**

## Technical suitability

- **Adapted to application**
- **Adapted to material**

Will it improve the final part ?

- **Customization ability**
- **Internal channels**
- **Consolidation**
- **Light-weighting designs**

## Other factors

- **Sustainability**
- **Ease of access**
- **Rapidity**

⇨ **Always keep COSTS and SUITABILITY in mind when using DfAM**

# AM mindset

Its specificities

## Traditional Mindset → SHIFT → AM Mindset

### Traditional Mindset

**Subtractive**

"progressive material removal"

**Replicative**

"material addition/deformation in/on a shape tool"

- tooling dependency
- high setup costs for prototyping
- design constraints
- complexity penalties
- material waste

### AM Mindset

**Additive**

"Material addition without use of shape tool"

- Internal features
- Complex geometries
- Efficient material use
- Consolidation
- Customization
- On-demand production

DOESN'T FOLLOW TRADITIONAL LIMITATIONS & RULES

**⇨ Must SHIFT your mindset completely and REDESIGN**

# AM mindset

## Specific to part and functionality consolidation

Original design
(16 parts)

S. Yang et al. *Journal of Manufacturing processes* - 2015

Final design
(1 part)



⇨ **IDENTIFY opportunities to CONSOLIDATE parts**

# Light-Weight designs

AM => place material precisely where it is structurally and functionally essential

AM lightweighting strategies:

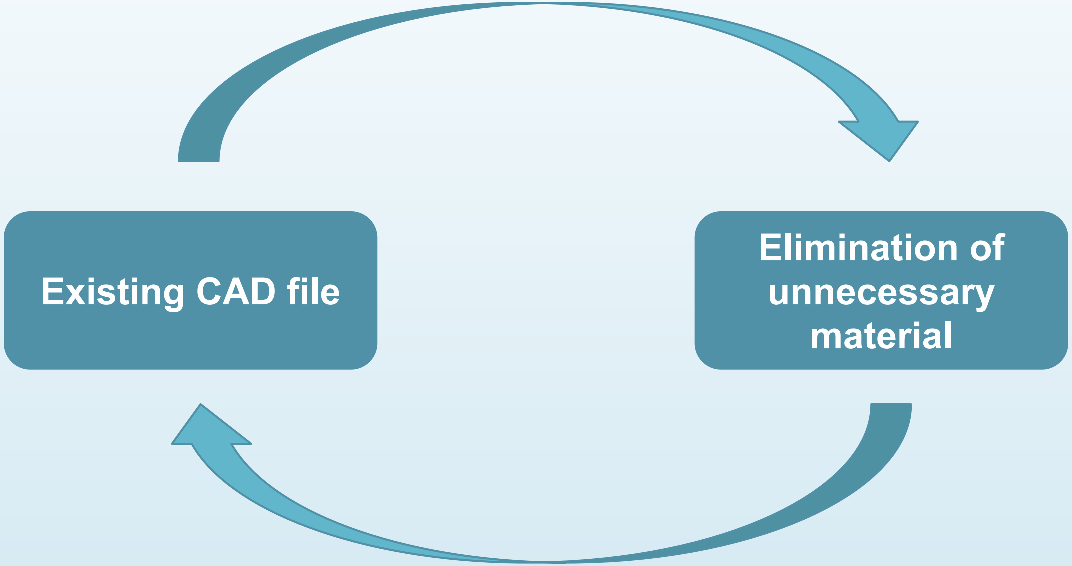
| | |
|---|---|
| **Topology Optimization** | **Generative Design** |
| **Lattice Structures** | **Part Infill** |



⇨ **Keep in mind computational demands of the strategies**

# Topology optimization

## Principle




<u>Iterative</u> process until optimal shape

<u>Objectives</u>

- Optimize material usage
- Maintain or Enhance structural properties
- Respect specific constraints
  - Volume
  - Force
  - Process

# Topology optimization

## Process steps

**1. Set the objective**

- Minimizing weight
- Maximizing stiffness
- Optimize strength-to-weight ratio

**2. Define the constraints**

- Physical properties
  - Max allowable stress
  - Max allowable displacement
- Design space
  - Max size of build (area & volume)

Boundary conditions
  - Forces applied to structure
  - Fixed parts of structure

# Topology optimization

## Process steps

**3. Run algorithm**

Iterative process

**4. Refine design**

Iterative designs until optimal configuration -> complex shaped

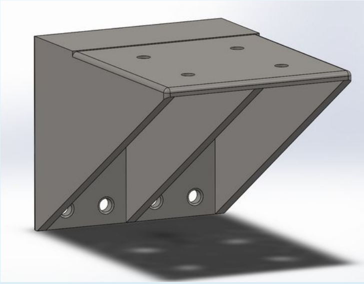
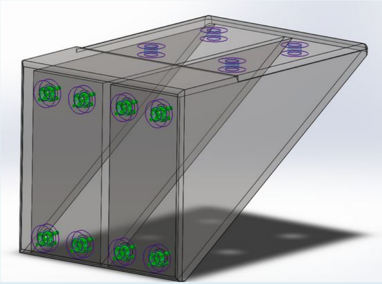
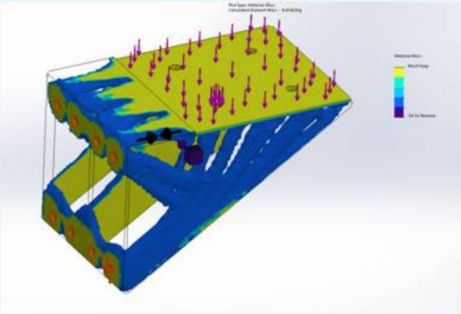
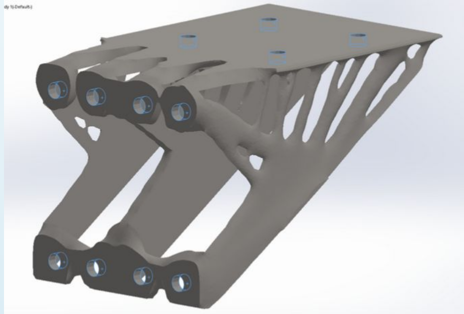
**5. Post-analysis**

Check if design respects manufacturing considerations
- Use of support structures
- Influence of build direction
- Restrict to viable geometries

# Topology optimization

## Process steps

1. Set objectives
2. Define constraints
3. Run algorithms
4. Refine design
5. Post analysis

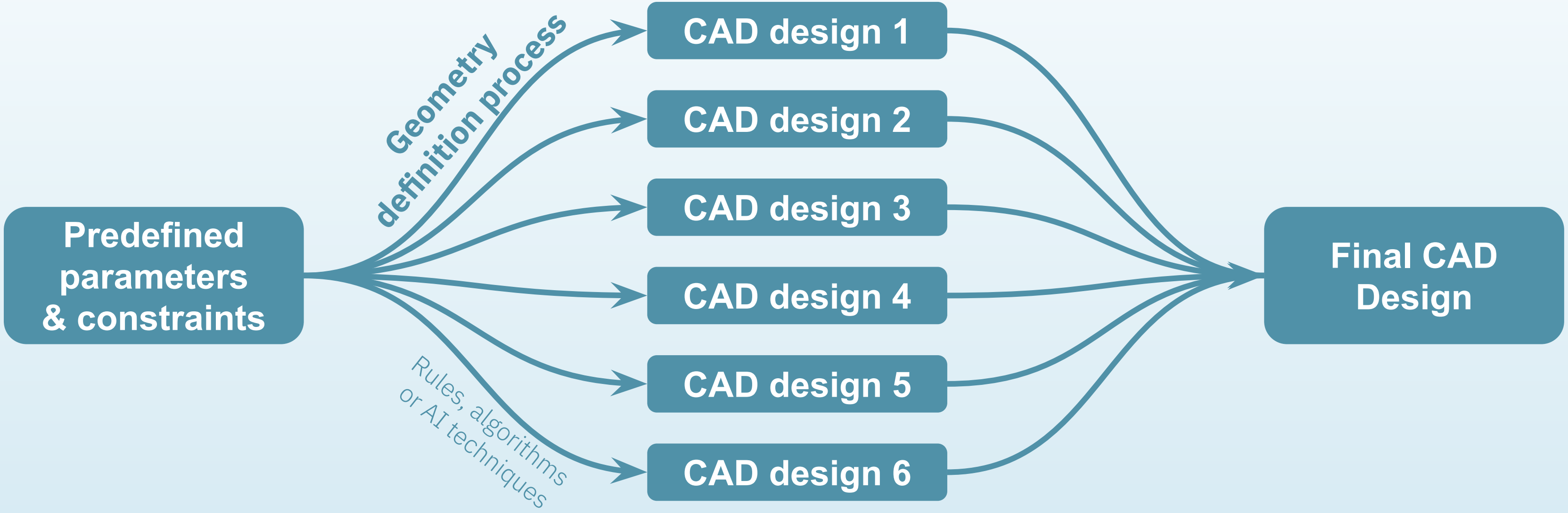
Website: engineersrule.com
https://www.engineersrule.com/performing-topology-optimization-step-step-guide/

Process still under development and research
Complexity of mathematical models makes it difficult to include more parameters

**FOLLOW all the steps, rely on your KNOWLEDGE for post-analysis/refinement**

# Generative Design

## Principle



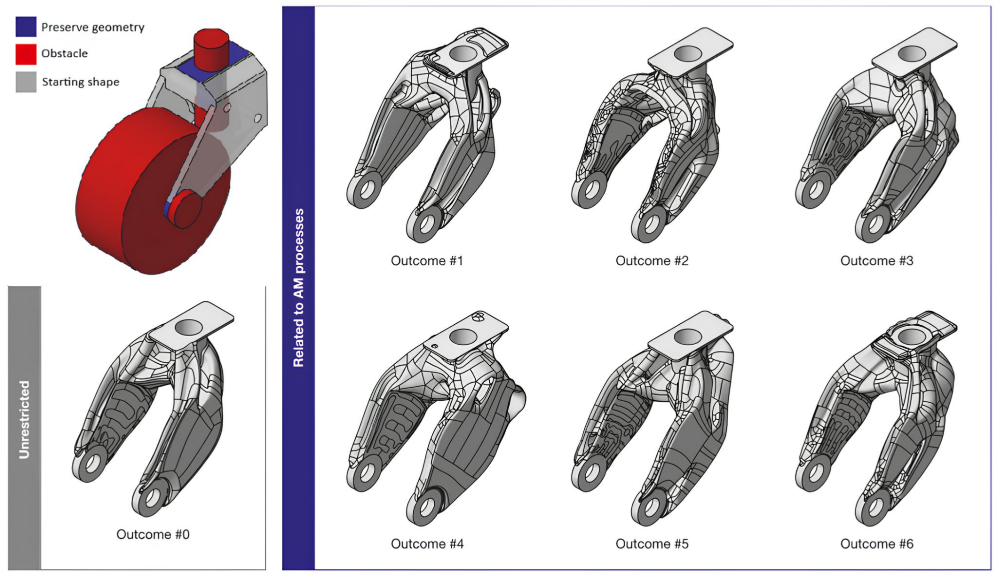
# Generative Design

## Process steps and example

1. Set
- constraints
- parameters
- performance criteria

2. Generate Designs

3. **CHOICE of Design**




AN. Pilagatti et al. *Procedia CIRP* - 2022

# Generative Design

Example

**3. CHOICE of Design**

3.1 Sort the designs according to **weight**

3.2 **Rank them** for each relevant **criteria**

3.3 **Choose** based on this ranking and **designer knowledge**

!!! Even most promising solution will need to be subject to redesign / refinement !!!

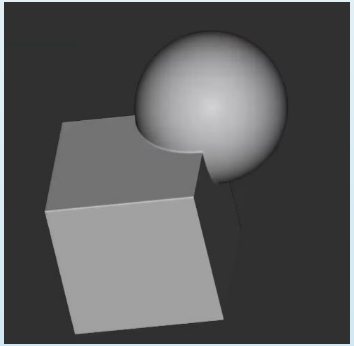
# Lattice Structures

## Principle

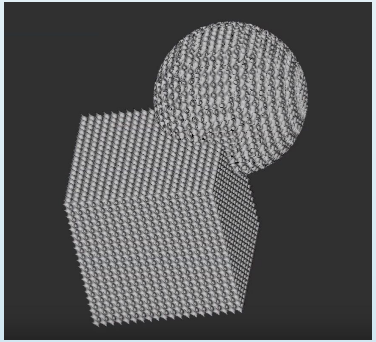
"Geometric arrangement composed of connective links between vertices (points) creating a functional structure" ISO/ASTM 52900:2021

**Existing CAD solid volume** → Lattice algorithm → **Porous lattice/network volume**

**Unit cell** → **Cell Network**



Website - nTop.com



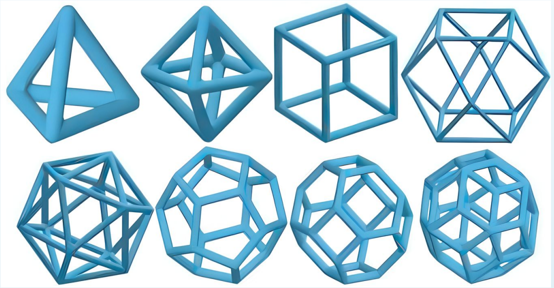
Website - nTop.com

# Lattice Structures

Types of lattices - examples

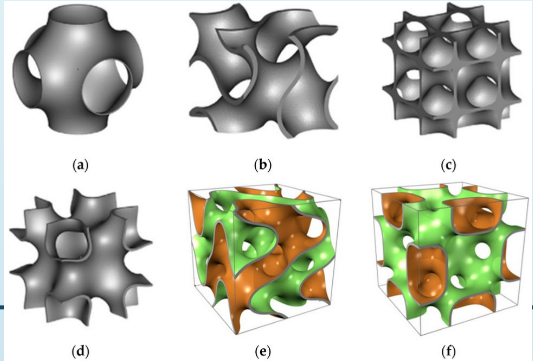
## Unit cells

Wire -frame



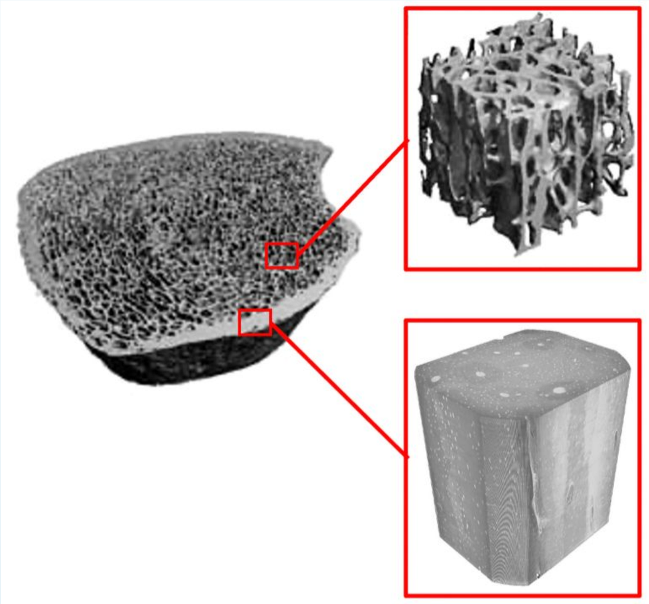
C. Pan et al. *Applied Sciences* - 2020

Algo Generated




C. Pan et al. *Applied Sciences* - 2020

## End volumes



M. McGregor et al. *Additive manufacturing 47* - 2021

# Lattice Structures

## Objectives - Purpose

- **Lighter design**
- **Improved**
  - Compression
  - Energy absorption
  - Impact protection
  - Adhesion
  - Integration (eg. bone prosthesis)
  - Thermal conduction

\+ **Possibility of creating Auxetics parts (ν<0)**

**!!! Intense computational demand and rendering !!!**


©Constellium exposition part

⇨ **CHOOSE lattice according to needs, VERIFY its influence, KNOW: rendering ≠ reality**

# Part infills

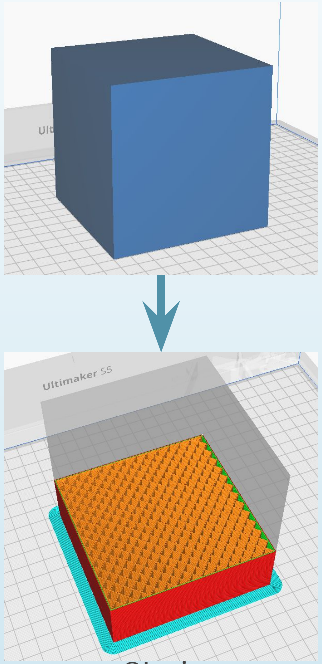
## Principle

**Internal Structure of 3D-printed objects**

- **Reduced**
  - Material consumption
  - Print time
  - Weight

- **Action**
  - Provide Basic internal support
  - Prevent warping

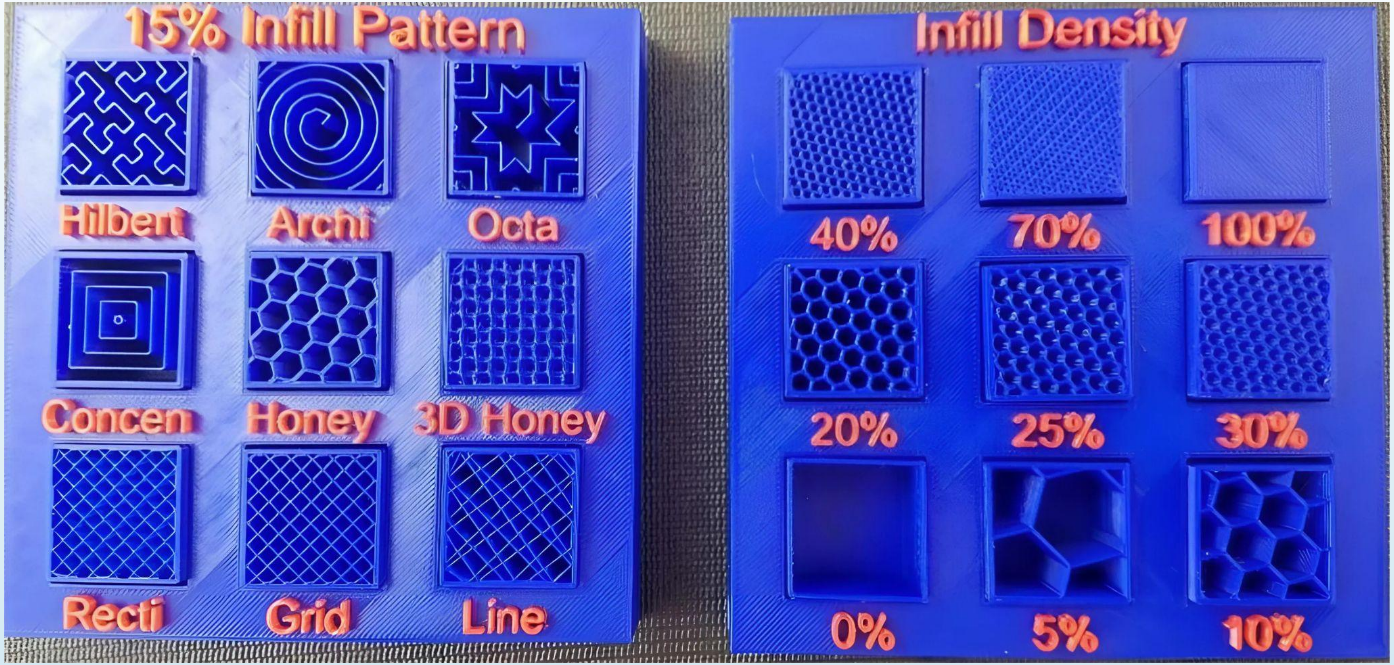
**!!! not usually optimized for the design !!!**




@Lucie

# Part infills

Types of infill patterns




MQ. Tanveer et al. *Materials Today: Proceedings* - 2022

02

# Geometric Constraints

Tania’s part

# Subdivision of the geometric constraints content

Walls and layers

Holes design

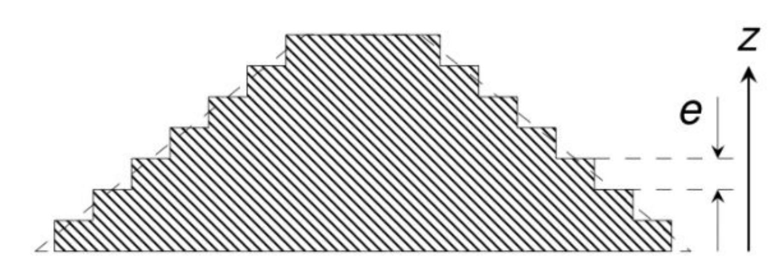
Support

Global sizes

# Sizing walls

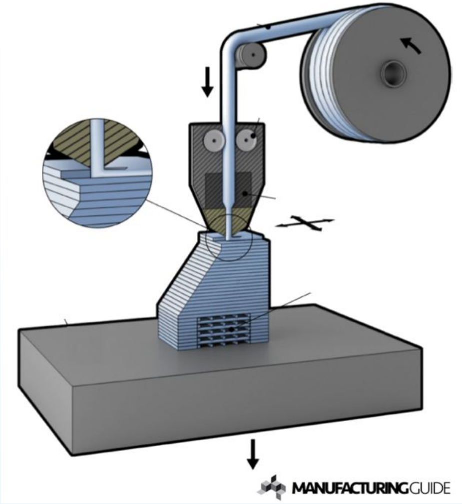
- <u>Wall thickness should be an integer multiple of extrusion width :</u> Nozzle extrusion width of 0.4 mm, thickness of 0.8 or 1.2 mm recommended !

- Impossible to create a wall thickness **smaller** than the nozzle size.



E.Boillat - Chapter 2: Liquid based processes - EPFL

- **Inclined wall or finition : Resolution is limited by a stair effect**



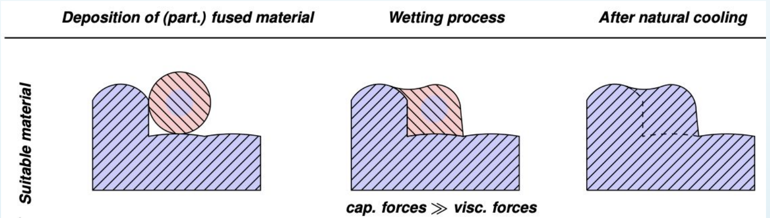
Fused Deposition Modeling - manufacturingguide.com

| Thin walls | Thick walls |
|---|---|
| More fragile | More material |
| More flexible | Longer printing time |

# Part quality

- Wall thickness depends on the **machine's resolution** (laser and nozzle)

## Laser Powder Bed Fusion

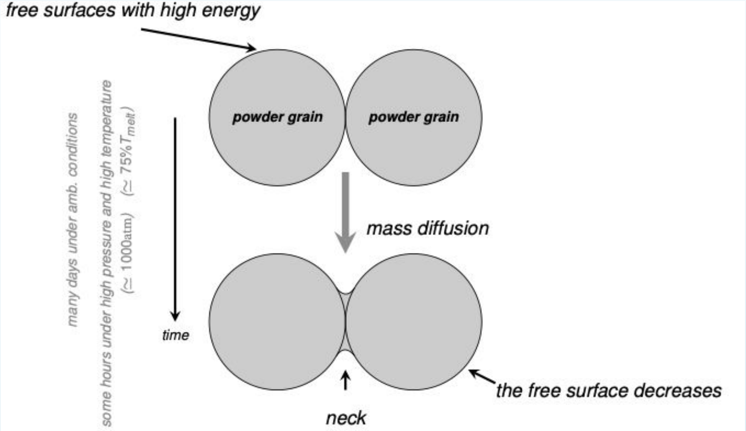



E.Boillat - Chapter 3: Extrusion processes - EPFL

- **Fully melts** the powder
- **Metal powder** or high perf polymer

-> LPBF : **high-strength** and more details
-> SLS : lower part density but more **flexibility**

## Selective Laser Sintering



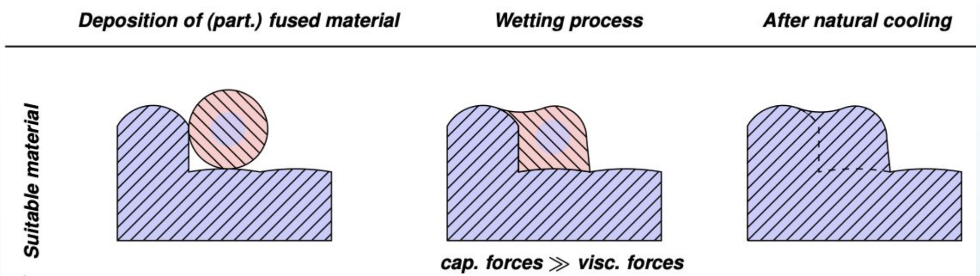

E.Boillat - Chapter 2: Liquid based processes - EPFL

- Heat the powder particles just enough to fuse them at their surfaces (**sintering**)
- Mostly used with **polymer powder**

# Layer thickness

- Layer thickness is influenced by the **particle size** of the powder or resin being used.
- The layer height **must always be thicker than the largest particle** size to avoid defects (lumping, poor fusion).
- **Material's properties** set practical limitations on how thin the layers can be.

- The case for many methods : SLS, SLM, binder jetting, SLA, DLP




E.Boillat - Chapter 3: Extrusion processes - EPFL

The ideal layer thickness depends on the specific AM **technology and material** being used.

# Layer thickness

## Positivity of thin layers (for SLS or FDM)

- Stronger parts, improves **micro-hardness** and tensile strength.
- Better **load bearing** capabilities
- **Less risk** of defects (warping, cracking)

- BUT **longer print times**

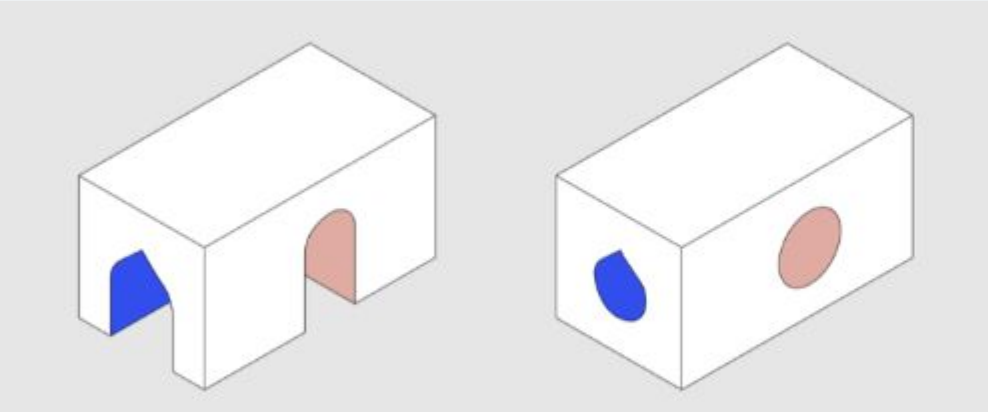
=> SLS typically use layer thicknesses between 50 µm and 150 µm to find a **balance between detail and print speed**.

*For most processes, the above formula only* ***underestimates*** *the fab. time. An accurate computation of the fabrication time of a part by an additive process also involves a term proportional to the construction height of the part :*

$$\text{fab. time} \simeq \frac{\text{volume}}{MCR} + \frac{\text{height}}{e} \times \frac{\tau_{layer}}{N}. \qquad (1)$$

*where e is the layer thickness and* $\tau_{\text{layer}}$ *the* ***time to prepare a layer****: the ratio height/e represents the total number of layers. Note that the layering time can be* ***mutualized*** *between the N parts built in the same batch.*

# Sizing holes



Design for additive manufacturing - aon3d.com

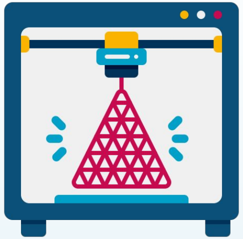
Horizontal holes:

- Additional supports (next slides)
- Tear-drop shape (requires design modifications)

- Orientation : Vertical better than horizontal (no supports and tighter tolerances)
- Size : depends on printer resolution (ex : 1.5 mm is too small, won’t materialize)
- Proximity with other features : to maintain part strength and avoid interference

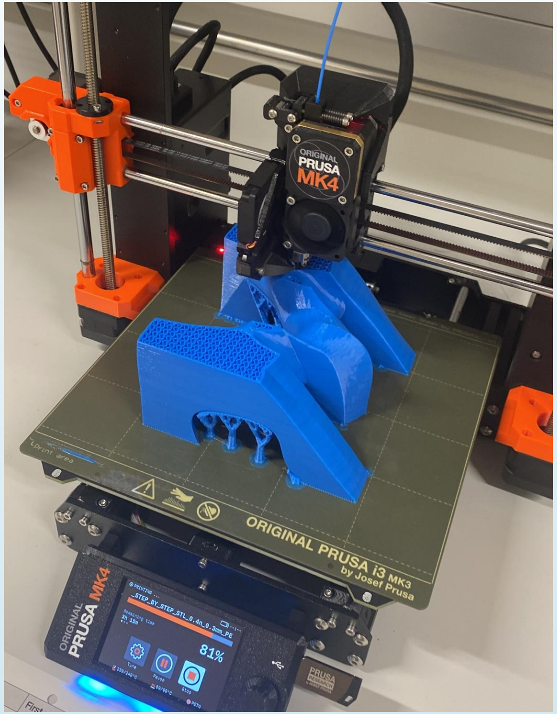
→ impact not only the visual of the part but also the structural strength
→ need to be thought about to avoid print failure

# Supports



## Definition and use :

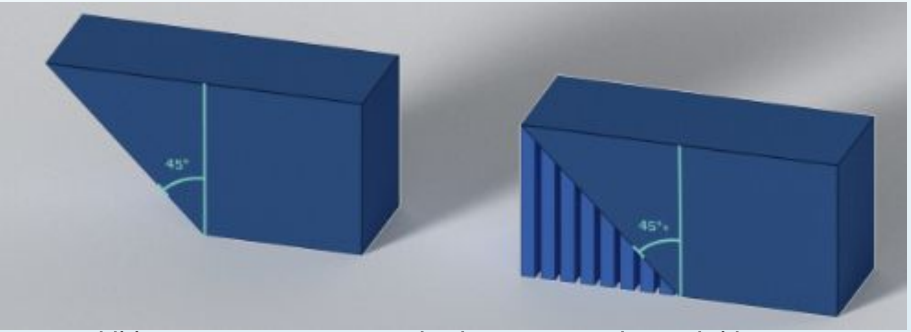
- An **added component** -> provides support to overhanging sections of a part when printing.
- Necessary when dealing with overhangs, bridge structures, or hollow sections in relatively simple designs -> **preventing collapse** !
- In more complex or irregular structures, -> used to **maintain stability**.
- After the printing, these supports are typically **removed**.




@Tania & Josh (& Ly)

# Supports

## 45° rule

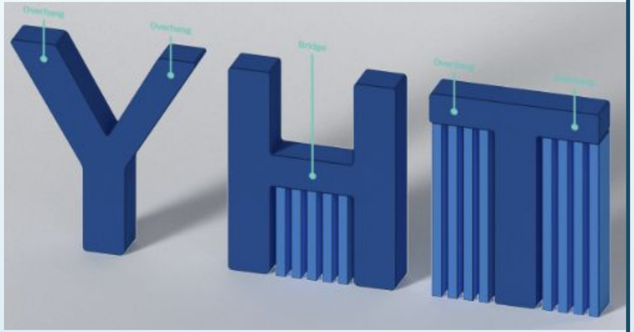



Additive Support structures : Why they matter and … - sybridge.com

- Overhangs greater than 45° typically **require supports**.

- The complexity of the design and the material properties will dictate the necessity of supports.

## ’YHT’ principle

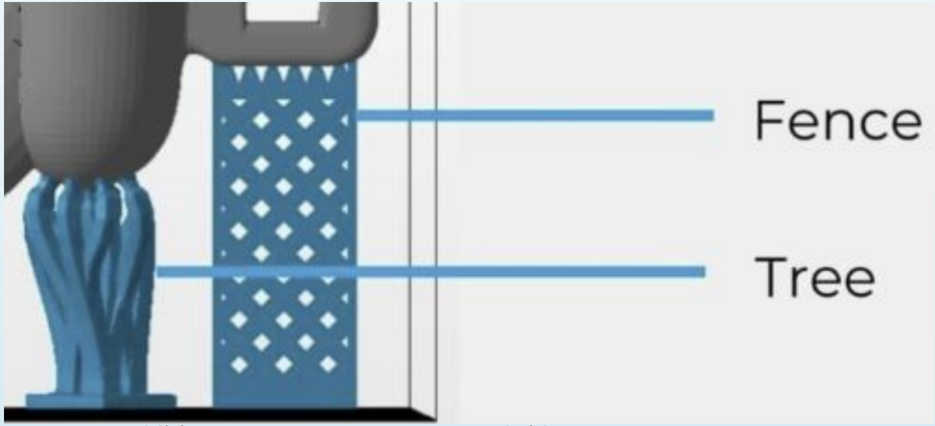


Additive support structures : … - sybridge.com

- <u>Y :</u> arms that may require support at their **junction**.
- <u>H :</u> the crossbar can cause a need for supports **beneath** it.
- <u>T :</u> the need for support at the **intersection** of its components.

# Supports

## Fence VS Tree




Additive support structures : ... - sybridge.com

- **Different shapes and designs** depending on geometries and process.
- Broadly categorized into **two main types**: trees and fences.

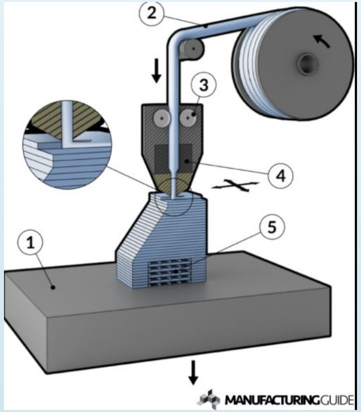
- <u>Tree supports</u> : resemble branches
  - Ideal for angled or **complex** surfaces.
  - More **difficult** to remove

- <u>Fence supports :</u> resemble walls
  - Often featuring a lattice structure
  - Printed **perpendicular** to the surface
  - **Easier** to remove

# Supports

Examples

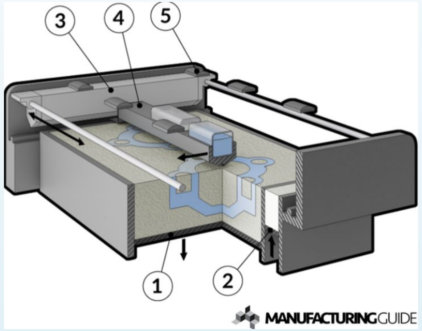
## Fused Deposition Modeling (FDM)



Fused Deposition Modelling (FDM) - manufacturingguide.com

- **Break-away or dissolvable supports**
  - High-Impact Polystyrene (HIPS)
  - Polyvinyl Alcohol (PVA)
- Really easily be removed after printing **without damaging** the part.

## Multi Jet Fusion (MJF)



Multi Jet Fusion (MJF) - manufacturingguide.com

- No supports ! Use a powder bed to print parts
- **The powder itself provides support** during the build process.
- Allows for **greater design flexibility.**

# Global sizes

## Metal Big Area Additive Manufacturing

- **Larger** build volumes = lower resolution
- Larger **deposition rates**
- Post-processing for finer details

**Example of machine technical data :**
Direct Light Processing

## Fused Deposition Modelling

- **Smaller** build volumes = constraints parts dimensions
- Could need to **separate** the part in segments
- Other **challenges** : layer adhesion, anisotropy for big builds

*Envisiontec™*


source: Envisiontec™

| Material | Application |
|---|---|
| Standard resin | prototyping, master models (vacuum casting) |
| Thermofusible resin | lost patterns (investment casting) |
| Charged resin | mold cavity |

Equipment (type, dimensions)

| Build volume, $mm^3$ | Low Precision (LP Mode) | High Precision (HP Mode) |
|---|---|---|
| | $120 \times 90 \times 230$ | $60 \times 45 \times 230$ |

Performances — DLP beamer with $1400 \times 1050$ pixels

| Mode | x-y resol. | layer thick. | build speed | layering time |
|---|---|---|---|---|
| LP | 86 $\mu m$ | 50 $\mu m$ | n.a. $(\infty)^2$ | $< 10$ s |
| HP | 43 $\mu m$ | 25 $\mu m$ | n.a. $(\infty)^2$ | $< 10$ s |

[2] the build time is not sensitive to part volume but only to part height: fab.time $= \frac{height}{e} \frac{\tau_{layer}}{N}$ with $e$ : layer thickness, $N$ : batch size.

# Summary

## Walls and layers

- Machine resolution (laser, nozzle)
- Printing time
- Materials property

## Holes

- Size
- Proximity
- Orientation -> Need of support

## Supports

- Needed or not ? (rules)
- Shapes of supports

## Global sizes

- Part volume vs build volume
- Machine limitations

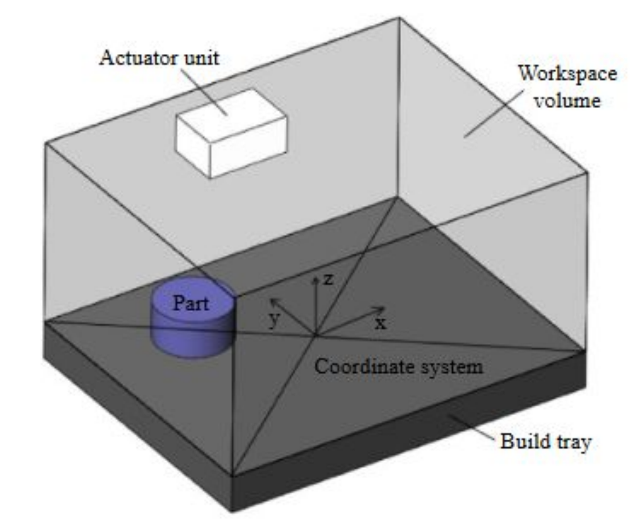
**Many elements to take into consideration when designing your part !**

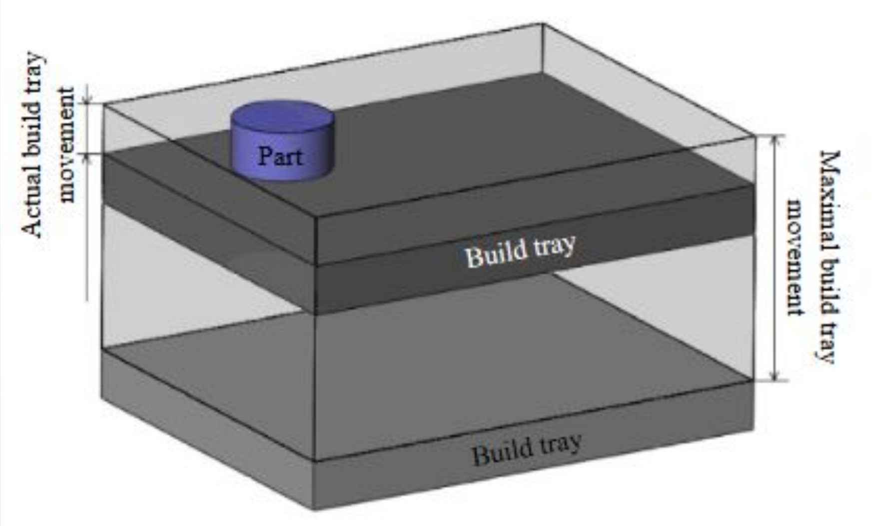
# 03

# Machine limitations

Josh’s part

# General AM machine schematics




*T.Brajlih et al., Rapid Prototyping Journal, 2009*

# 2 build volume architectures

## Open build volume

Stargate 4th, Relativity Space - 3dnatives.com

Original Prusa MK4S - a-printer.ch

## Enclosed build volume

Form 3+ - formlabs.com

Formup 350 - addupsolutions.com

# Open Build Volume Machines

Most widely adopted architecture for consumer grade machines

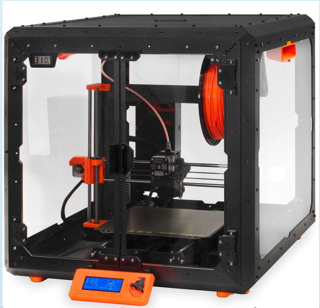
## Advantages

- Cheaper
- More easily built and maintained
- Facilitated monitoring
- Improved cooling

## Disadvantages

- Temperature fluctuations
- Limited materials
- Noise level
- Safety
- Dust and Contaminants
- Fume emissions

*Original Prusa MK4S - a-printer.ch*



*Original Prusa Enclosure - a-printer.ch*

Architecture incompatible with processes that require precise environmental control like SLA, PBF, High-temp FDM, or Titanium DED (inert env.)

# Enclosed Build Volume Machines

## Advantages

- Temperature stability
- Material compatibility
- Fume containment
- Protection from external environment
- Noise reduction

## Disadvantages

- Higher cost
- Reduced accessibility
- Bulkiness
- Increased cooling complexity
- Ventilation requirements
- More intricate assembly

Incompatible with processes that require large spaces (like large-scale DED), airflow and/or external equipment

# Splitting a Part for printing

Ideally, the part should be split before the design knowing the available workspace area

If design is already over, here are some steps for efficiently splitting a part :

- Use CAD or slicer software (the more comfortable the user the better)
- Determine split location, prioritize splitting along **flat surfaces,** or in **hidden areas**

*!! Make sure to avoid compromising structural integrity of the part !!*

- Add alignment features

*!! Pre Existing part features may be used to ensure alignment !!*

- Add adhesion/fastening features for assembly
- After manufacture, pre-process for assembly (cleaning, sanding)
- Post-process the part to achieve the desired finish

# Speed & Accuracy

Speed and accuracy are two sides of the same coin, there is a trade-off between one and the other

**Speed**

**Depends on :**
- Layer height
- Geometrical complexity
- Material
- Machine capabilities

↓

**Production quantity/Throughput**

**Accuracy**

**Depends on :**
- Layer height
- Geometrical complexity
- Material
- Machine capabilities

↓

**Product quality/details**

# Differences between the design and the final printed part

## Layer-by-layer

- Dimensional distortion
- Surface roughness
- Anisotropy

=> STL files, approximate the model's geometry (small triangles) -> **loss of details** affecting precision

## Powder melting (metal)

- Distortions
- Warping
- Build failures

=> heating and cooling cycles introduce **thermal stresses**

@ Tania & Josh

Other mistakes like bad holes sizing or dimensional failures can also happen.

# Defects in AM

AM remains plagued with various types of defects

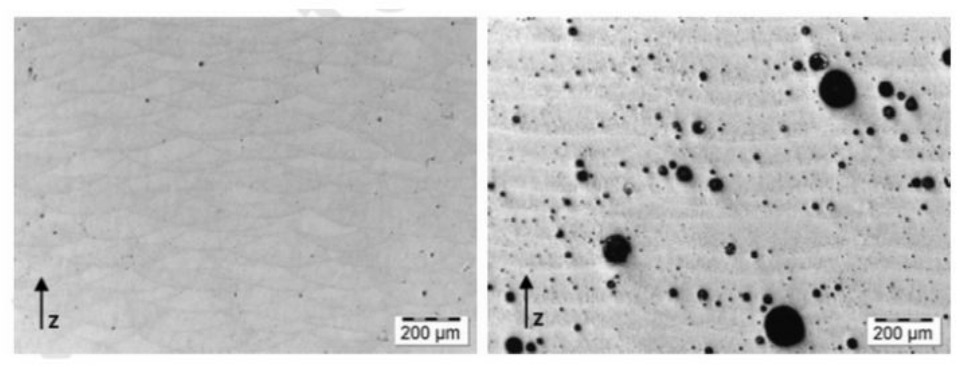
- Layer Shifting
- Warping
- Elephant foot
- Bed adherence
- Layer misalignment
- Inconsistent material flow
- Porosity
- Layer adhesion
- Internal blockage
- Ghosting

# Porosity

Inconsistent material density in the product

Can lead to structural and surface defects, and an overall change in the properties of the product

Affects mainly powder based methods, other Defects can have similar symptoms for other processes

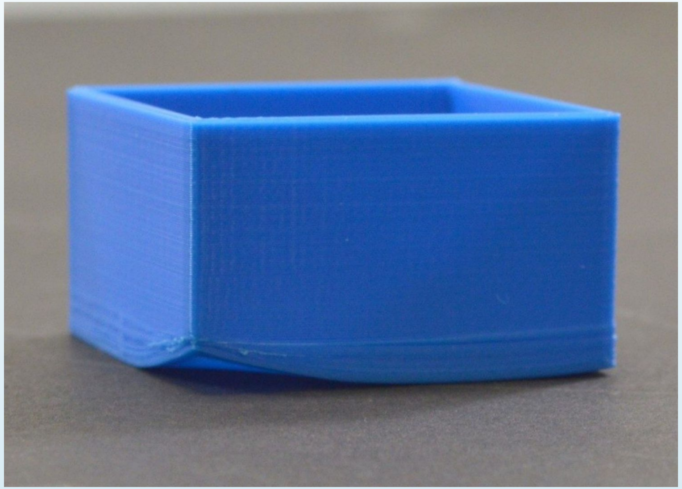



Reducing hydrogen pores formation in AlSi10Mg... - insidemetaladditivemanufacturing.com

Caused by uneven material quality, uneven flow of material through the nozzle, non-optimal energy delivery

# Warping

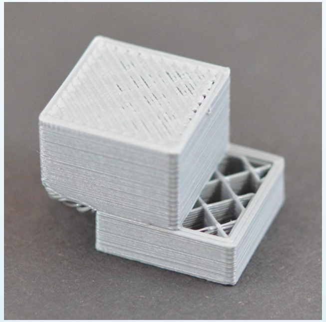
Thermal stresses cause the part to bend
Results in a modified part geometry and wasted material



Jakk - Additive-X.com

Caused by an uneven cooling of the part, causing the part to deform under the inner thermal stresses. Can be remediated through a heating element in the build platform, or an enclosure for temperature control

# Surface defects



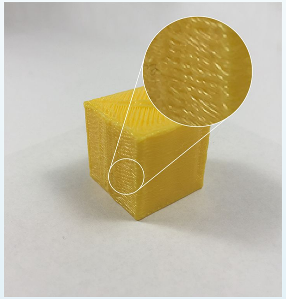
Layer Shifting - simplify3d.com

## Layer shifting

<u>Causes</u> : Excessive speed, obstruction on nozzle path, issues with mechanical drive

## Inconsistent Extrusion :

<u>Causes</u> : Clogged nozzle, Incorrect parameters ( Temperature, Material type)



Inconsistent extrusion - realvisiononline.com

Smashed First Layer - matterhackers.com

## Elephant’s Foot

<u>Causes</u> : Unlevel Printing surface Machine parameters incorrect (extrusion rate, layer height)

## Layer Separation

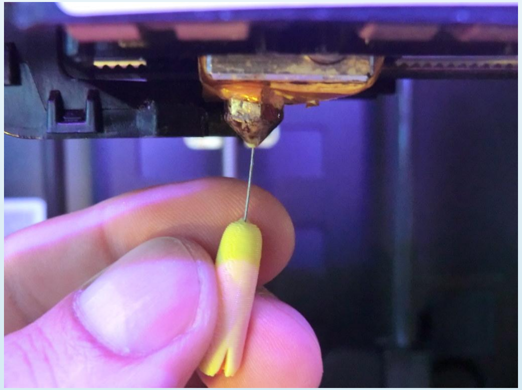
<u>Causes</u> : Incorrect parameters (Temperature, Overcooling), Excessive Speed

Layer Separation - matterhackers.com

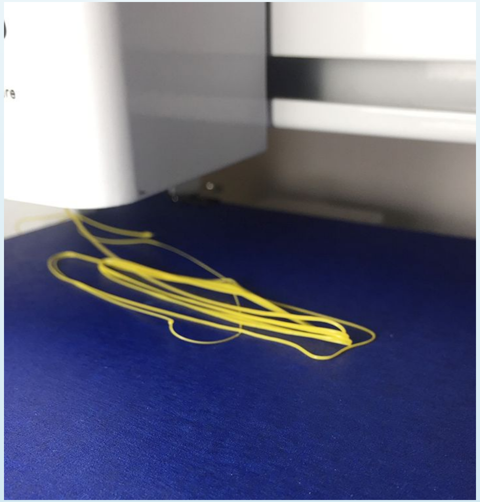
# The importance of maintenance

## Regular light maintenance

Cleaning and visual inspection of machine, calibration as often as required, comes at little to no material cost



Matthew - additive-x.com

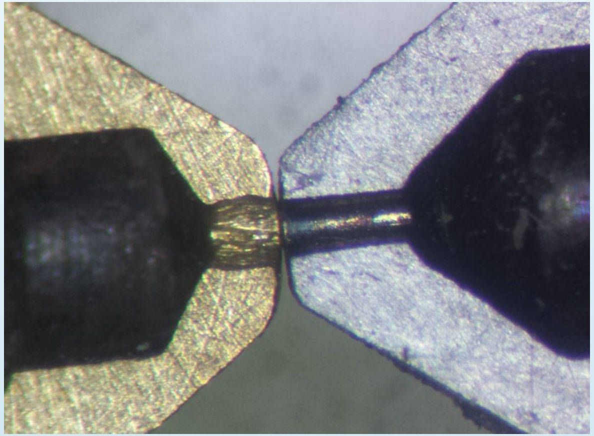


Viola - realvisiononline.com

# The importance of maintenance

## Heavy periodical maintenance

Periodically, more often for violent processes (DED), replacement of critical components, inspection of mechanical components (adjusting, tightening, greasing), may include extensive disassembly



e3d-online.com

04

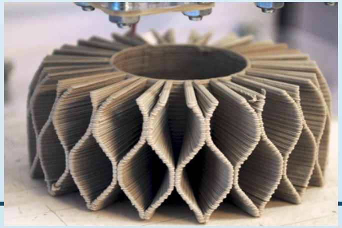
# Material specifications

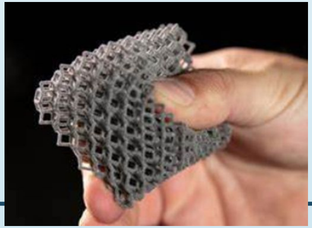
Jolan’s part

# Most used materials in AMD

| Metals | Ceramics | Polymers |
|---|---|---|
| Stainless Steel (SS) | Zirconia ($ZrO_2$) | Polylactic Acid (PLA) |
| Aluminum (Al) | Alumina ($Al_2O_3$) | Nylon (Polyamide, PA) |
| Titanium (Ti) | Silicon Carbide (SiC) | Polyethylene (PE) |
| Inconel (Ni-Cr alloy) | Silicon Nitride ($Si_3N_4$) | Polypropylene (PP) |
| Cobalt-Chromium | Boron Carbide ($B_4C$) | TPU |
| Copper (Cu) | Hydroxyapatite | PETG |
| Magnesium (Mg) | Glass-Ceramics | PEEK |
| Nickel (Ni) | Mullite | ABS |


https://prototypehubs.com/3d-printing/


https://www.ponoko.com/


https://3dprintingindustry.com/

# Mechanical properties

**Metals**

- High strength to weight ratio (Titanium)
- High tensile strength
- Good corrosion resistance (Stainless Steel)
- Good fracture toughness

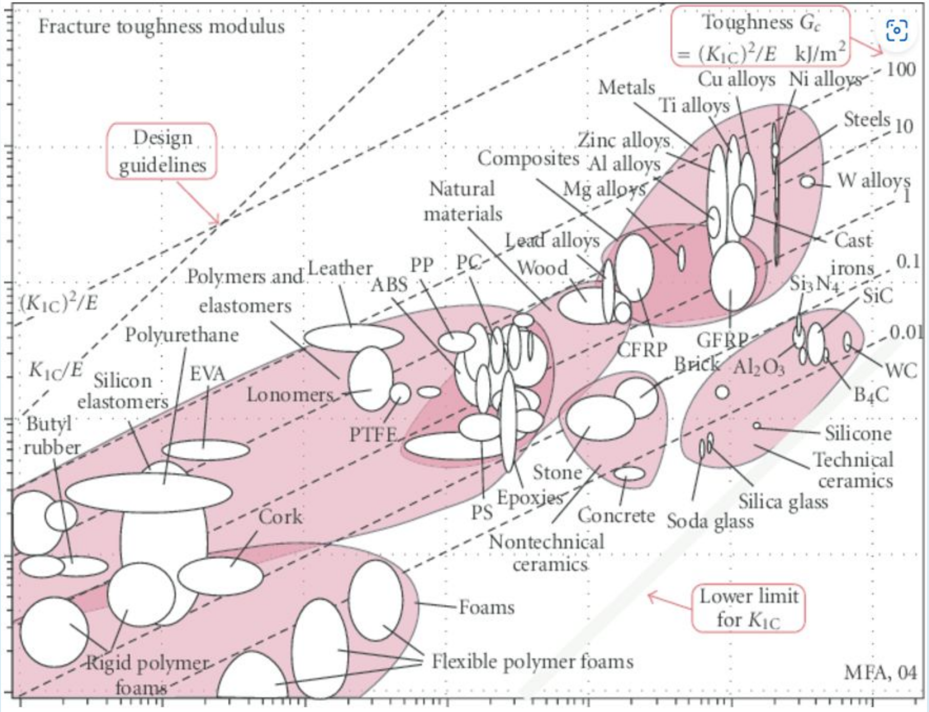
**Ceramics**

- High hardness
- High compressive strength
- High corrosion resistance
- Their brittleness limits mechanical flexibility

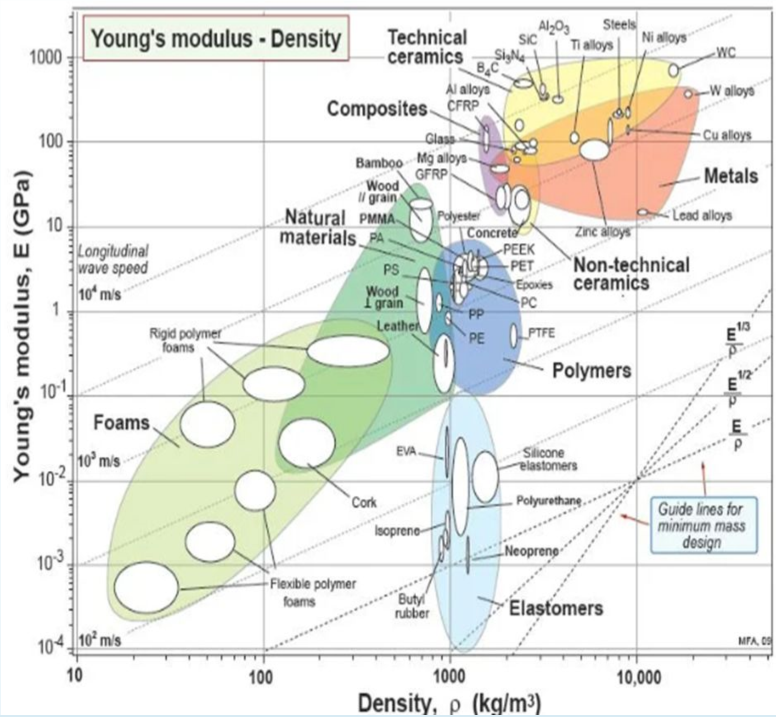
**Polymers**

- Lightweight
- Good impact resistance (ABS)
- Biodegradable (PLA)
- Good tensile strength and flexibility (Nylon)
- Good toughness (Polycarbonate) compared to glass

# Mechanical properties




Fehim Findik et al. J ISRN Mechanical Engineering - 2011




Rémi Merindol et al. Hal Theses - 2014

# Thermal and Electrical Properties

| Metals | Ceramics | Polymers |
| --- | --- | --- |
| High thermal conductivity<br>High electrical conductivity | Low to moderate thermal conductivity<br>Very low electrical conductivity | Low thermal conductivity<br>Mostly isolating for electrical conductivity |
| | Certain ceramic materials can be modified to exhibit semiconducting properties (SiC) | Modifications to improve the electrical conductivity of polymers (metallic fiber or powder added). |

# Print orientation on mechanical properties

Metals

Ceramics

Polymers

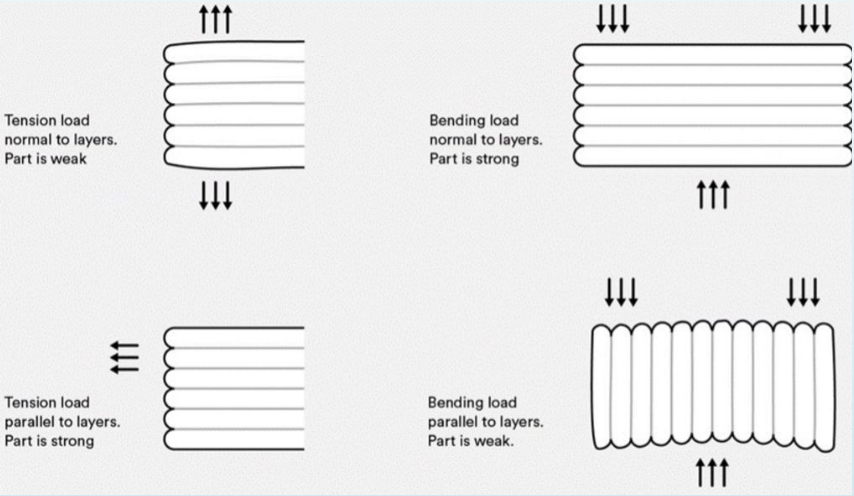
Vertical orientation

Horizontal orientation

Improved compressive strength

Improved tensile strength

Post processing




https://www.protolabs.com/

# 05 Post processing

Jolan’s part

# Post Processing for Metals

### CNC Machining and Grinding

Removes imperfections, allowing tighter tolerances

### Support Removal

CNC or EDM to preserve structural integrity

### Heat Treatments

Relieve stresses and modify hardness.

### Surface Treatments

Improve surface hardness and fatigue resistance

### Hot Isostatic Pressing (HIP)

To eliminate porosity, enhancing density and strength

### Deburring and Polishing

Removing sharp edges or residual burrs from machining.

### Laser and Plasma Treatments

Improve surface hardness without affecting the core, offering durability for wear-prone parts.

# Post Processing for Ceramics

**Sintering**

Densifying ceramics, reducing porosity, and enhancing mechanical properties.

**Support Removal**

Manual tools or innovative soluble supports

**Chemical Treatments**

To improve surface smoothness

**Surface Finishing**

Grinding, polishing, and advanced laser polishing

**Hot Isostatic Pressing (HIP)**

To reduce porosity and enhance toughness (post sintering)

**Ultrasonic Machining**

To shape ceramics delicately, reducing risk of fractures

**Polymer and Metal Infiltration**

Reinforces ceramics by filling microstructures, improving strength, and resistance

# Post Processing for Polymers

**Support Removal**

Careful manual support removal

**Annealing**

Improves strength and dimensional stability (semi crystalline)

**Painting and Coating**

Adds aesthetic appeal, UV resistance, and durability

**UV Curing**

To solidify the surface and enhance durability (resin based)

**Welding and Bonding**

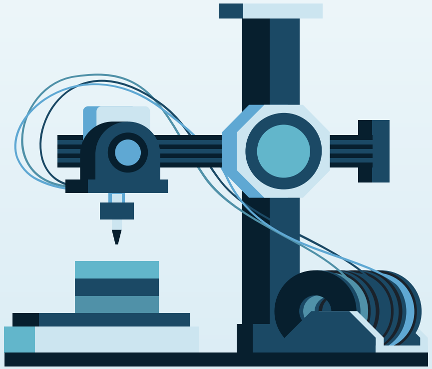
Plastic welding and UV bonding create strong assemblies

**Surface Finishing**

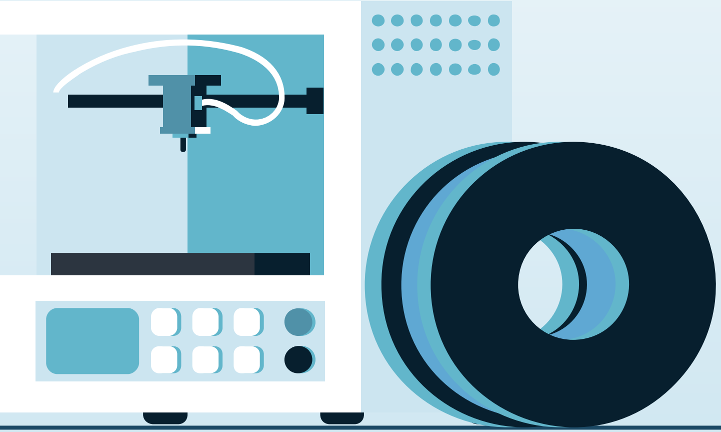
To enhance surface quality (very used for ABS)

# Conclusion

- Keep costs and technical suitability in mind when choosing AM
- Shift your mindset from traditional to additive
- Follow every steps of the process
- Rely on your previous knowledge
- Be careful of the computation demands
- If you use powder, take in consideration the particle size
- See what kind of supports you need and what is available
- Search what are the resolution limitation of your AM method
- Think about your printing time and if that is a problem for you
- Look at materials
- Be careful of the post processing needed



Our theme is rules to follow but we realized that it was recommendations more than rules, it is things to think about



Thank you for listening !