



Level 7 – Design for Industry 4.0

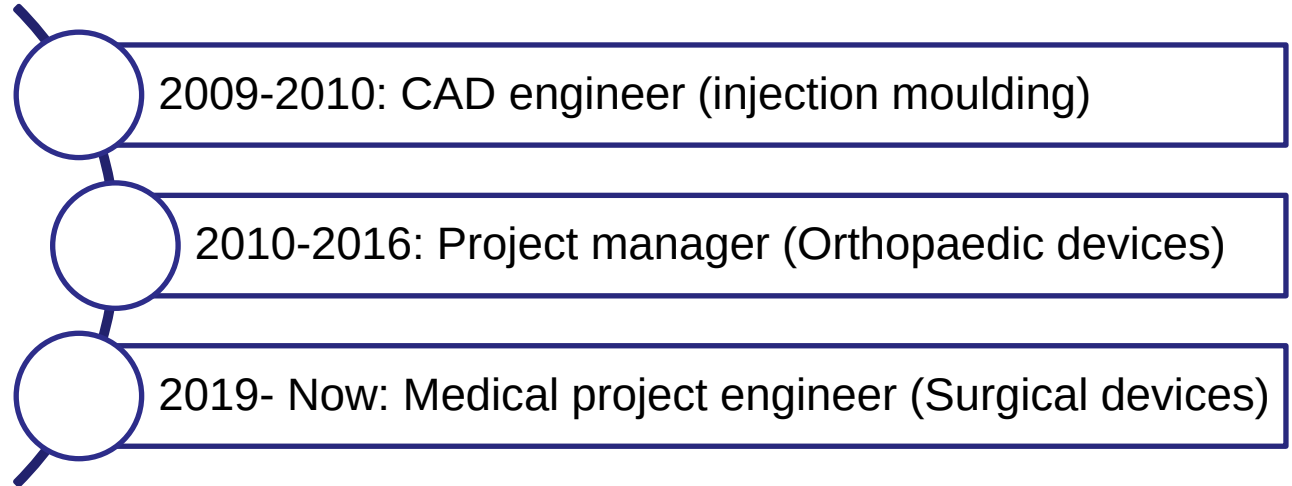
Design for Additive Manufacture (DfAM)

About me...

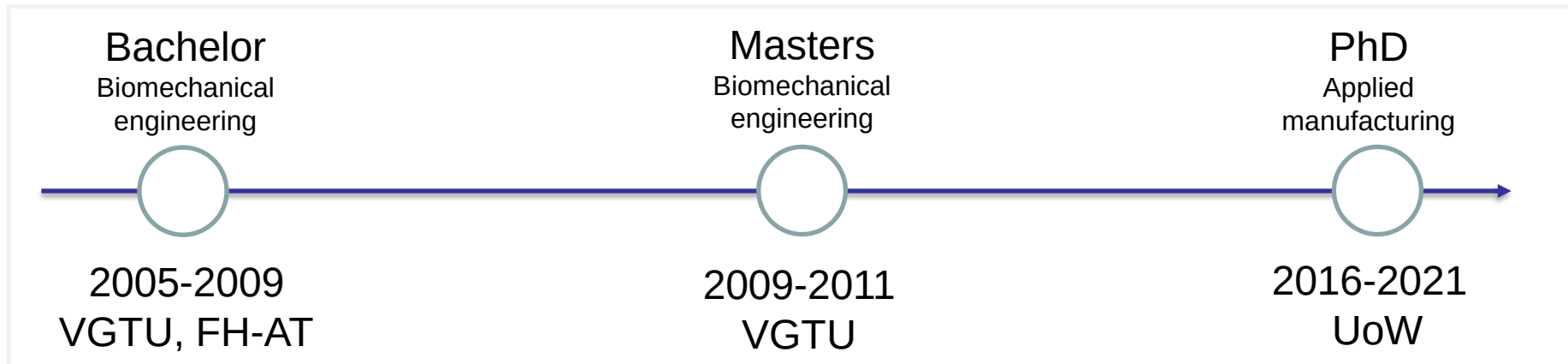


Ilja Asanovic, PhD

Professional experience



Education



Centre of advanced Batch Manufacture (CBM Wales)



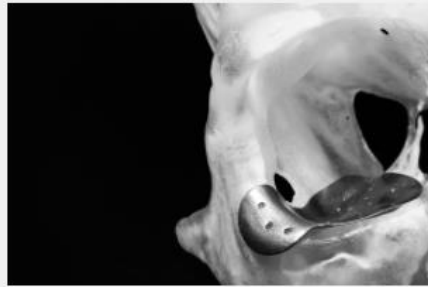
 <https://www.cbmwales.co.uk/>

 UWTSD, IQ Building, Kings Rd, SA18EW

Services



New Product Development
More Information 



Bespoke Medical Devices
More Information 



3D Printing & Scanning
More Information 



Prototype and Production
More Information 

ARCAM Q10



Vacuum casting



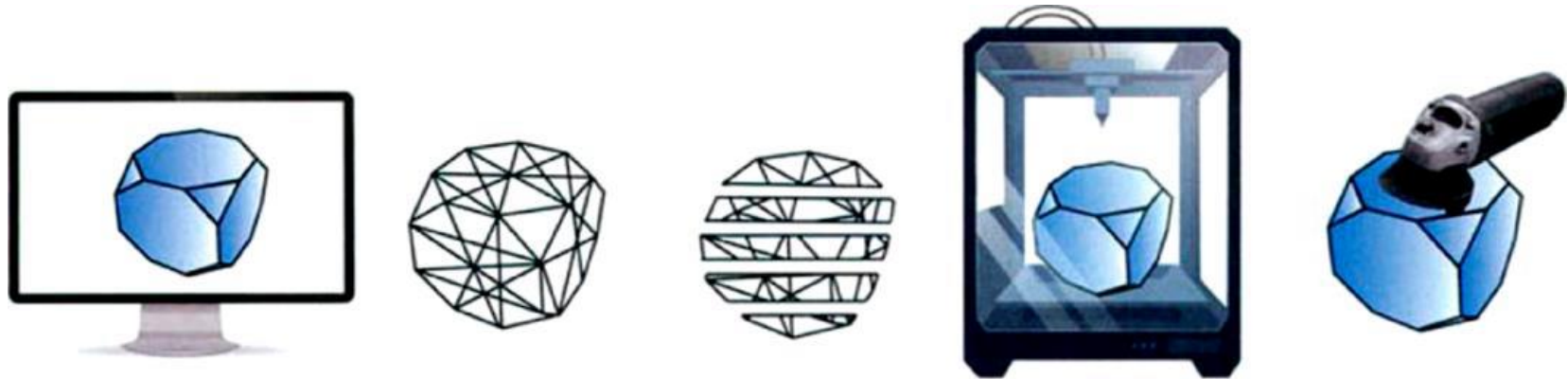
Optical 3d scanner



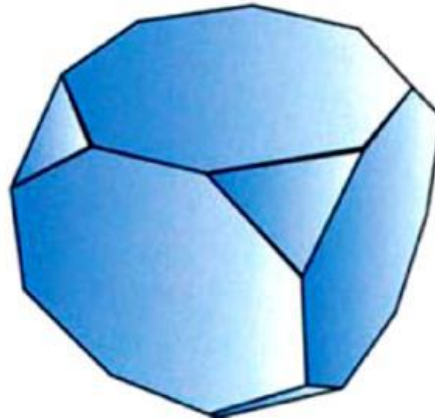
Stereolithography (SLA)

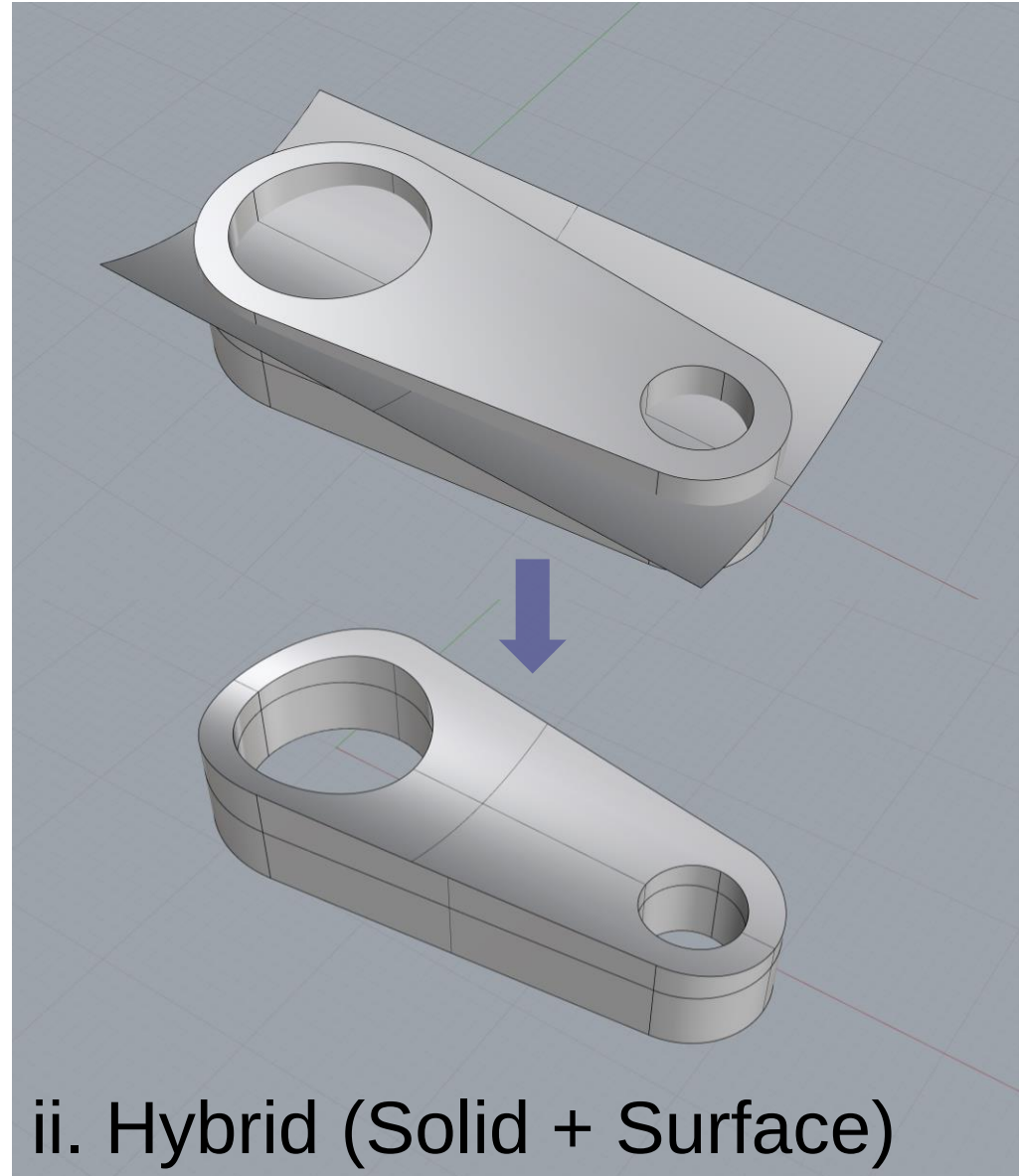
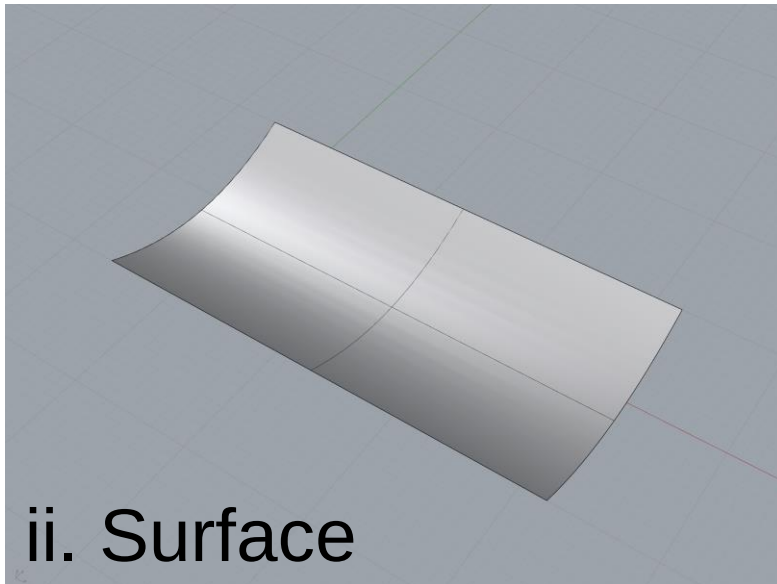
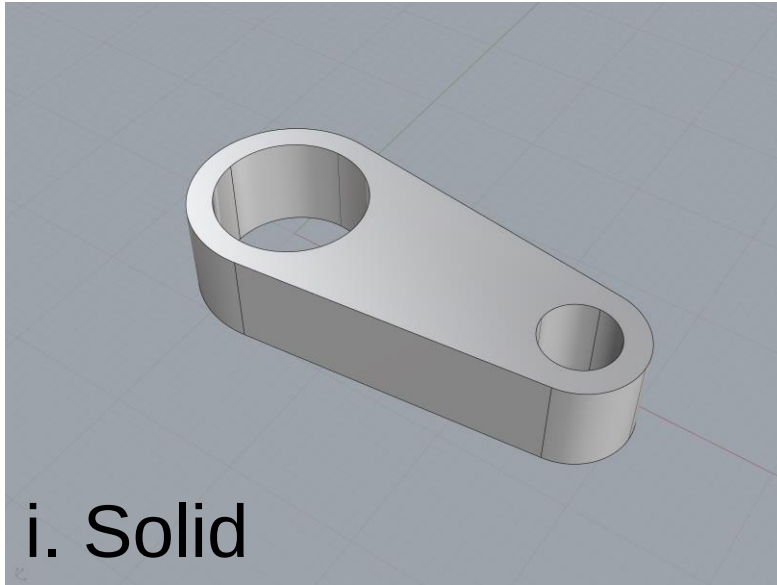


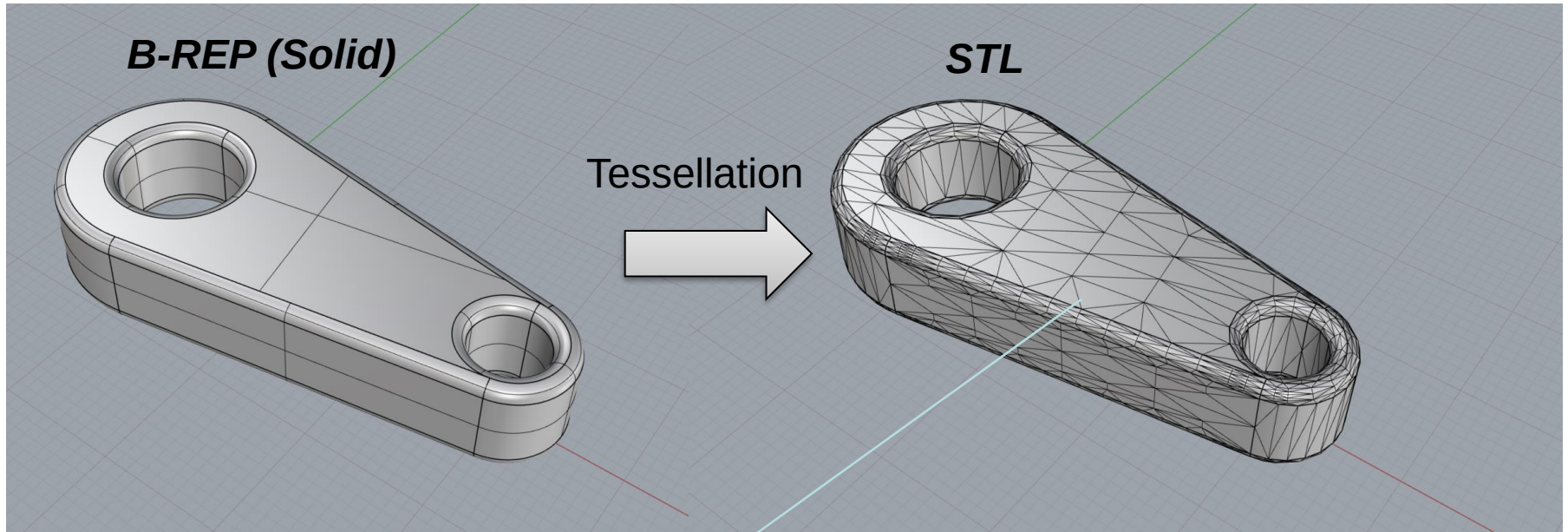
Additive Manufacture (AM) process flow



1	2	3	4	5
CAD-based 3D model	.STL file	Sliced layers	AM system	End part finishing

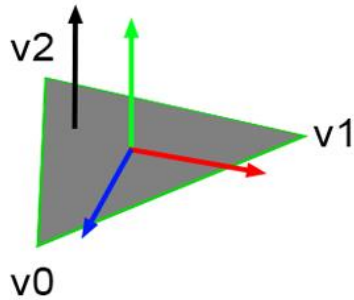






STL file format

Face Normal



```
facet normal nx ny nz
  outer loop
    vertex vx1 vy1 vz1
    vertex vx2 vy2 vz2
    vertex vx3 vy3 vz3
  endloop
endfacet
```

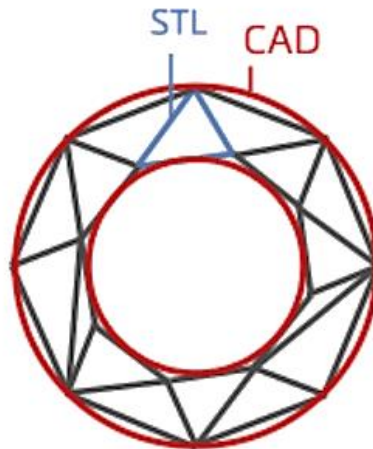
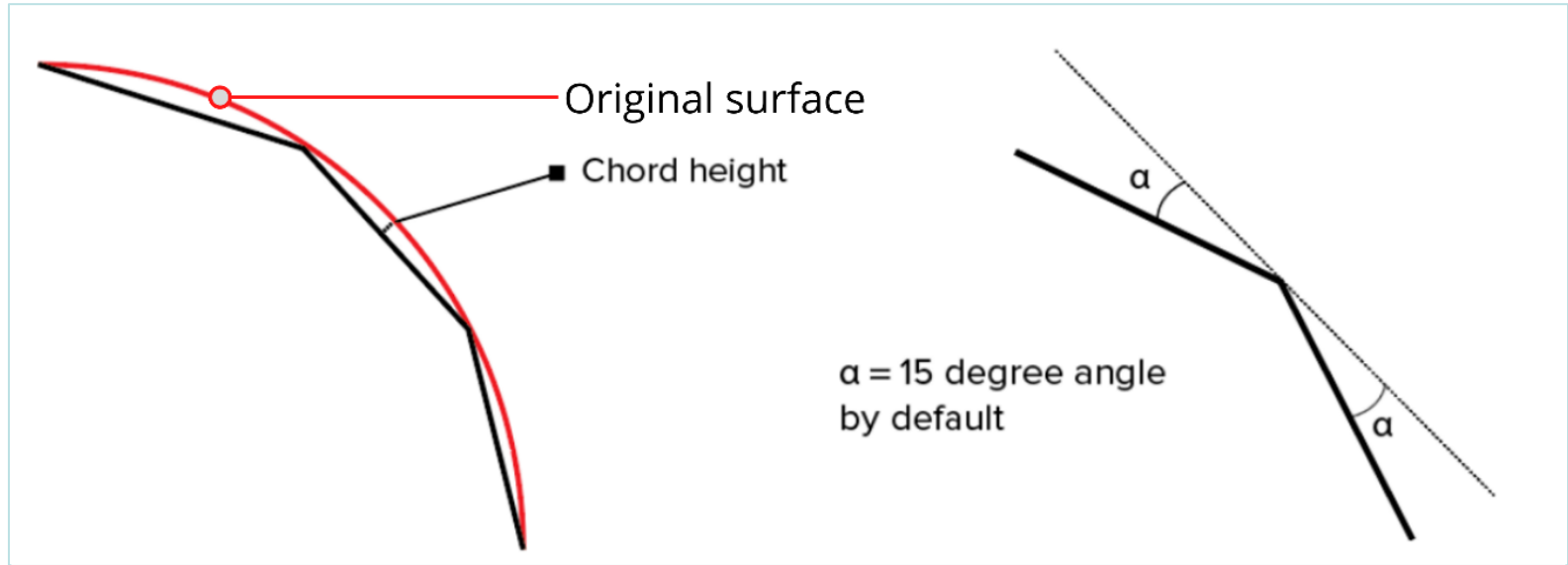
Emerging AM file formats

Additive
Manufacture File
AMF



STL
2.0

STL file (Geometry approximation)



STL file (Geometry approximation)



SOLIDWORKS file
6434 faces



5000 faces

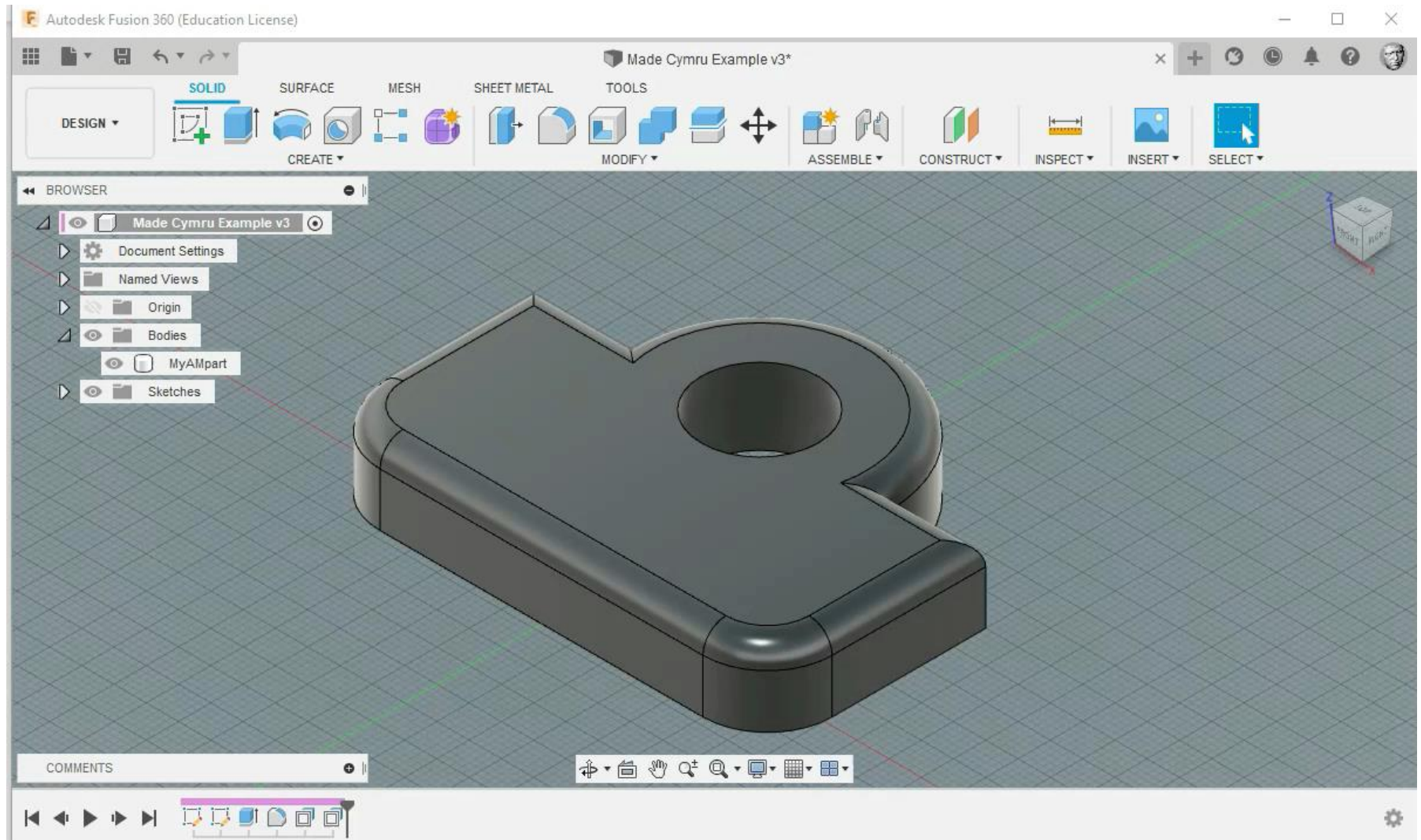


3000 faces

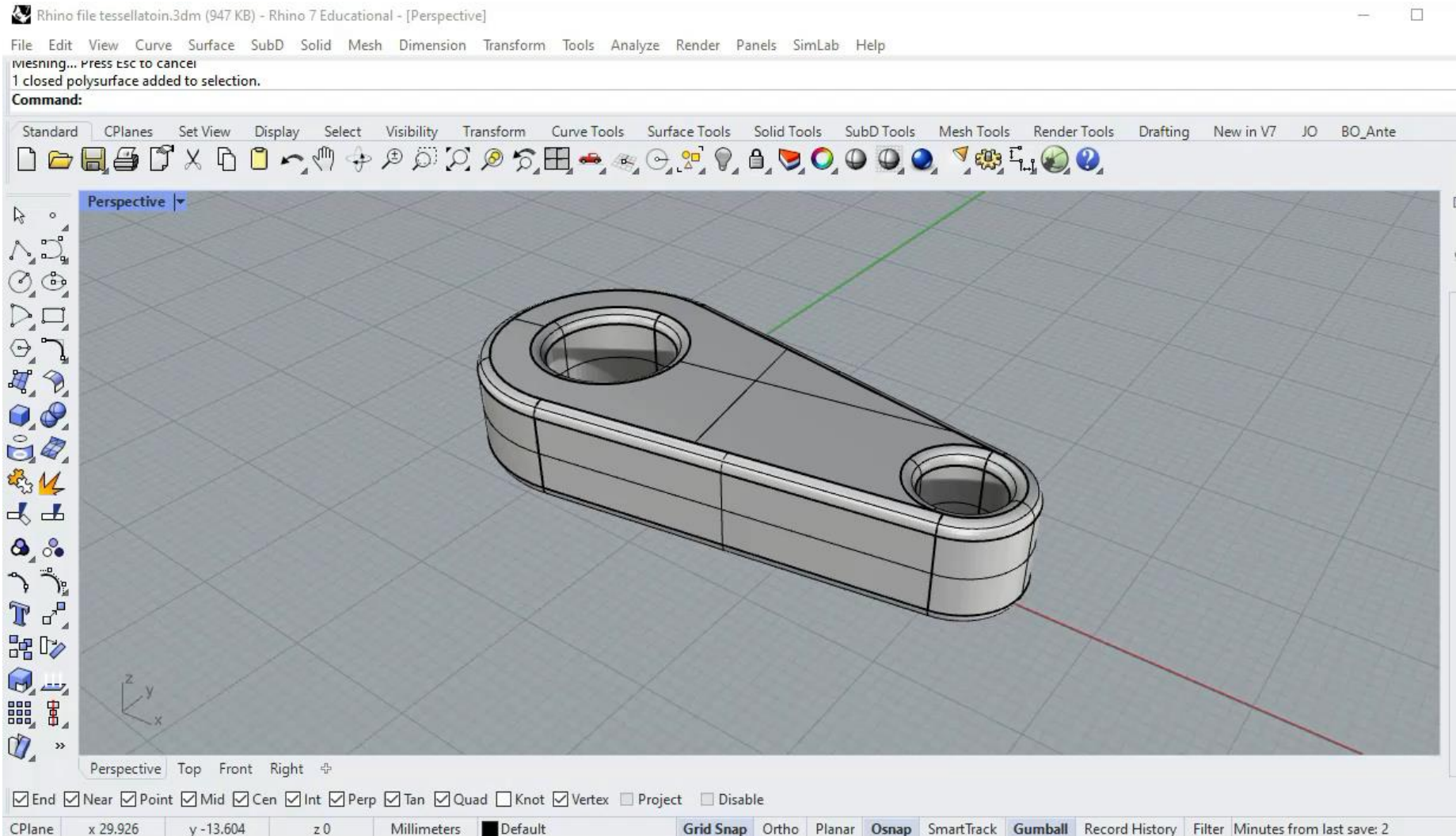


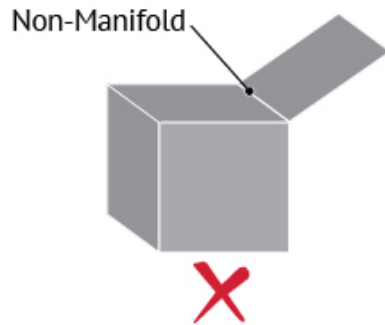
1500 faces

STL file (Tessellation “Save As...” example, Fusion 360)

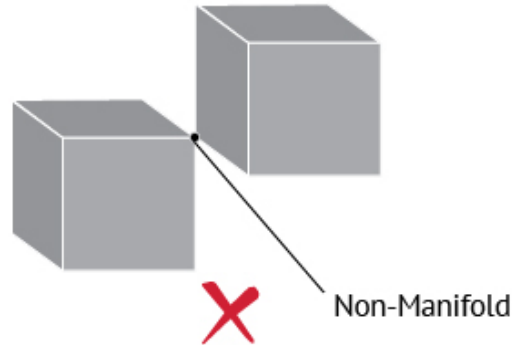


STL file (Meshing, Rhinoceros 3D)





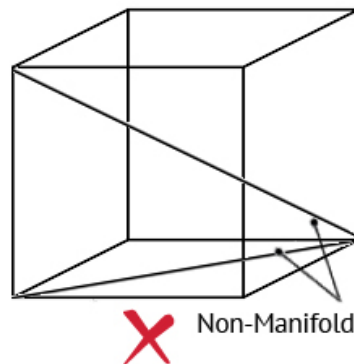
1. Three faces sharing one edge



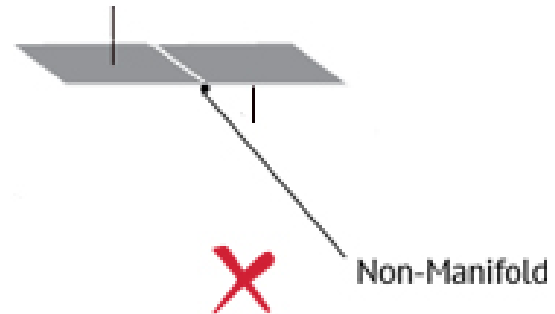
2. Multiple faces sharing one vertex



3. Hollow "zero volume" objects

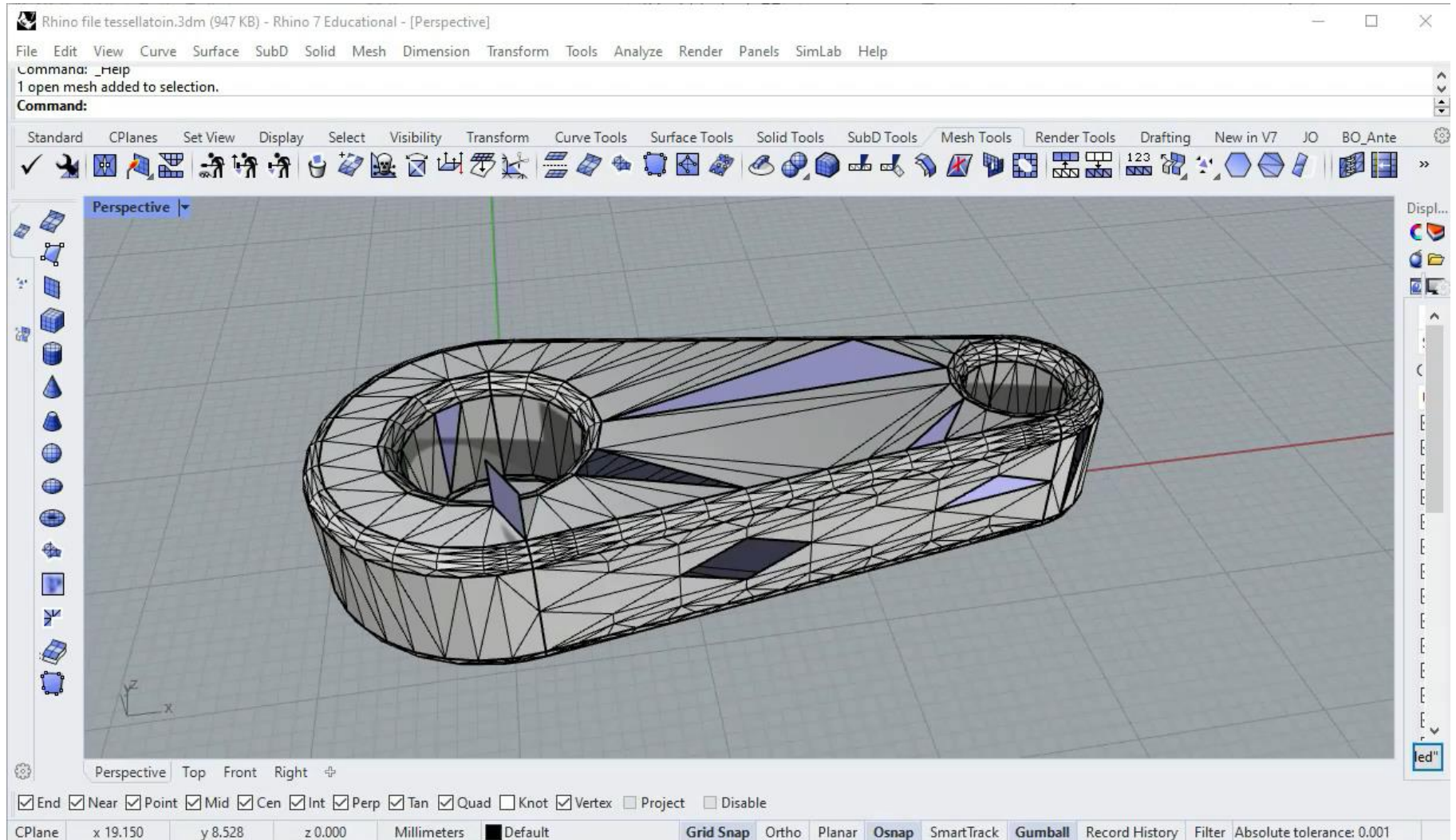


4. Internal faces

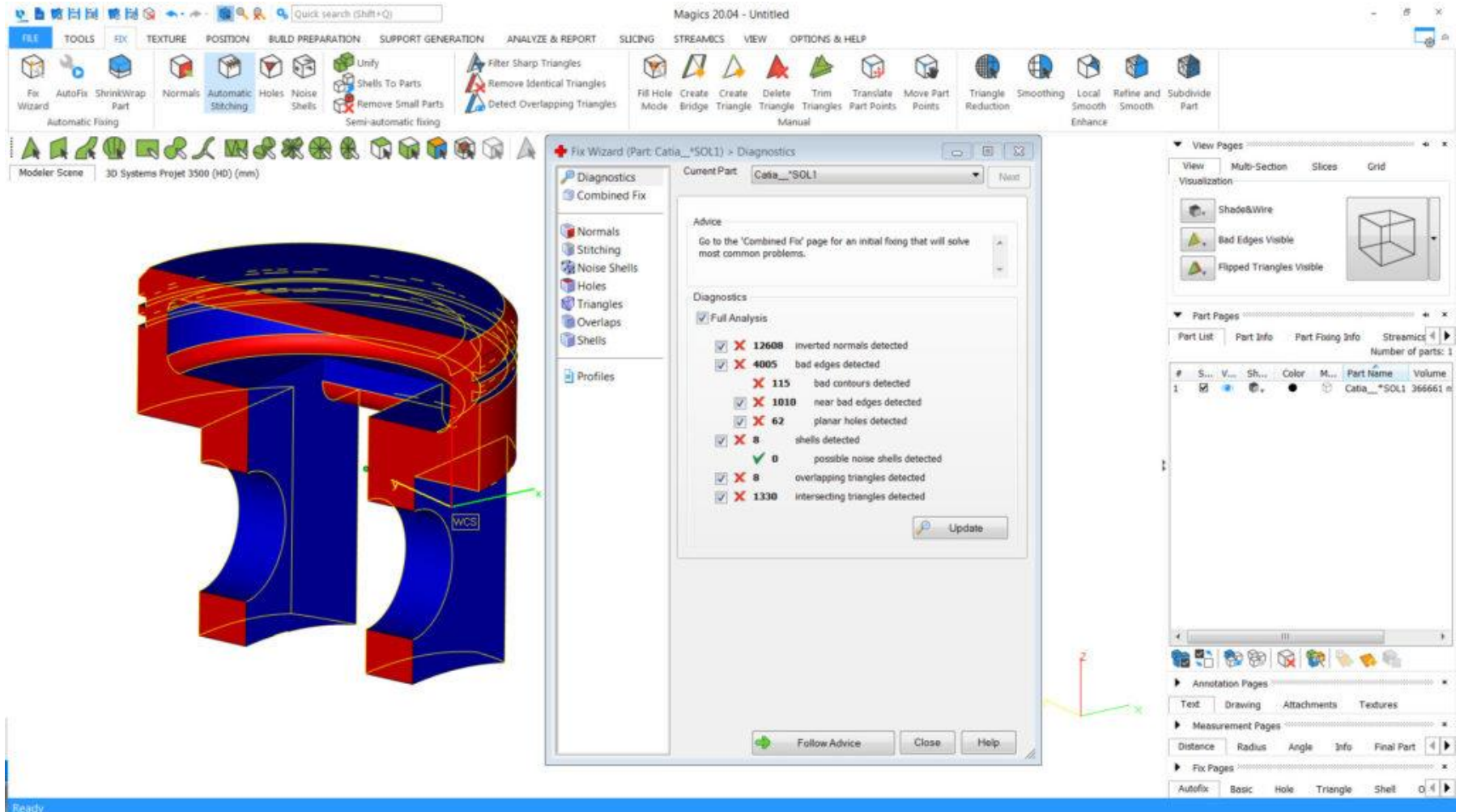


5. Inverted normals

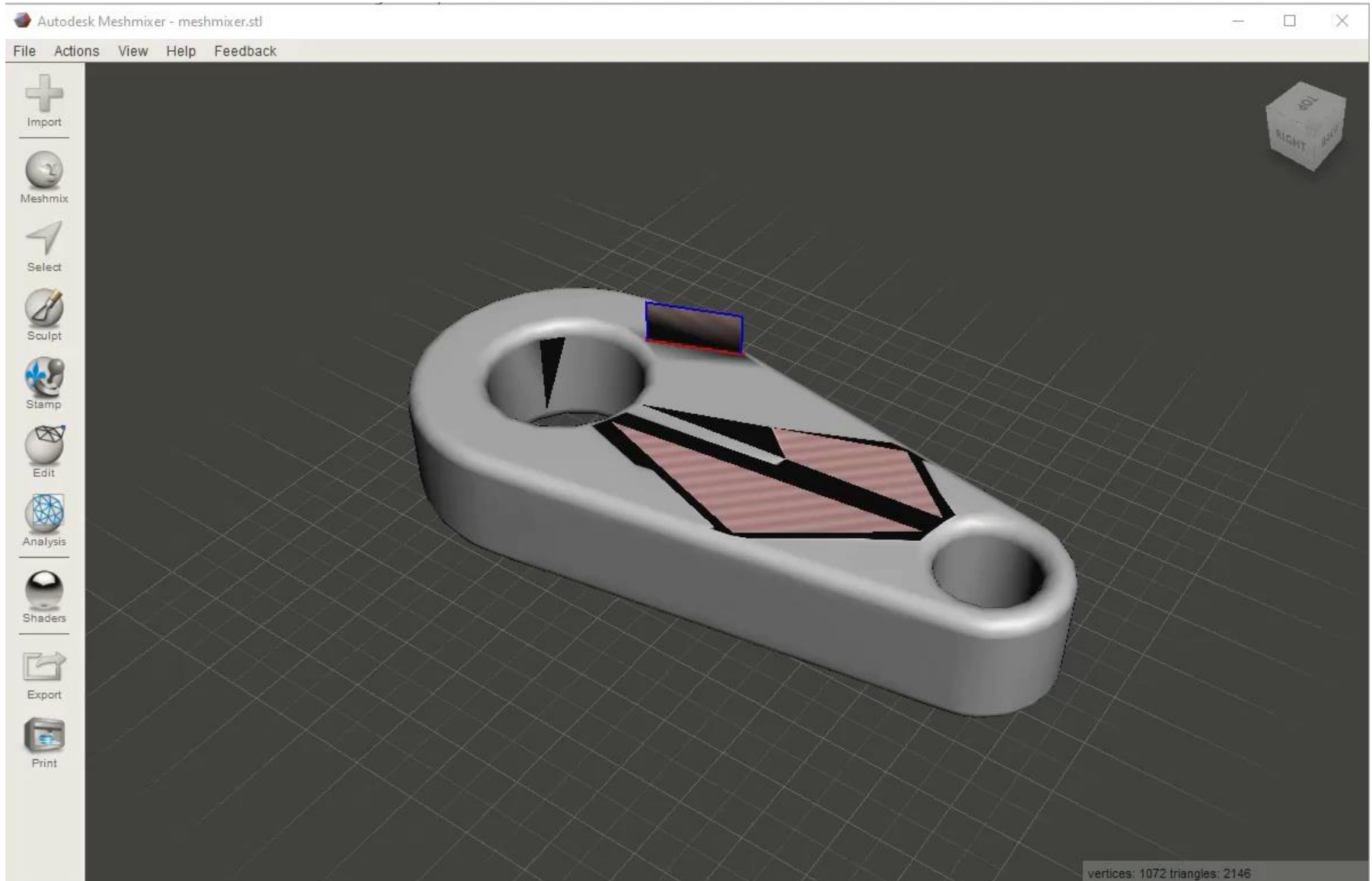
STL file. Fixing tessellation errors (Rhino 3D)



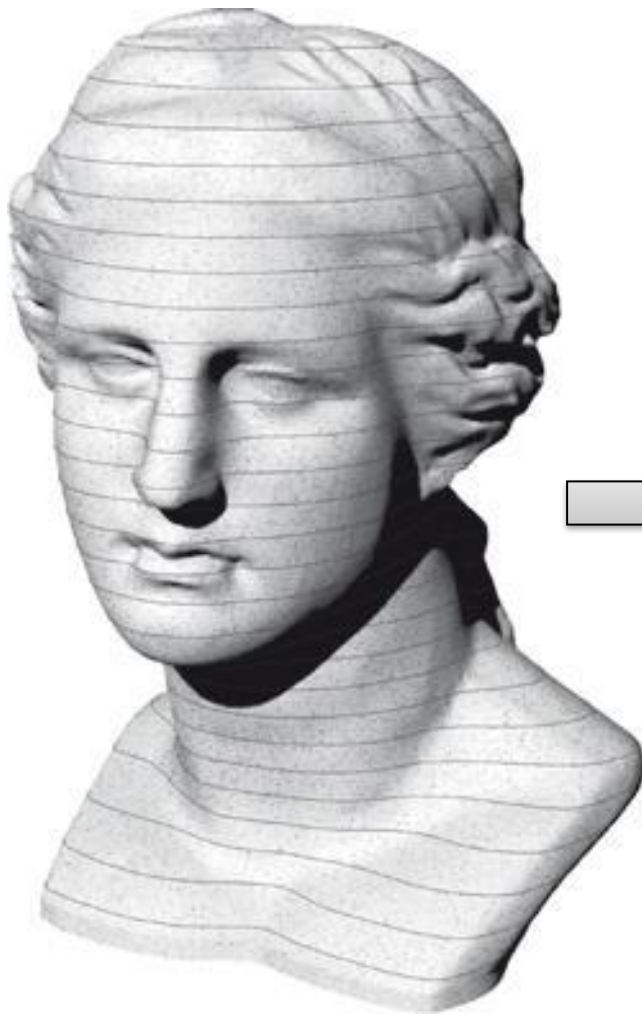
STL file. Fixing tessellation errors (Materialise Magics)



STL file. Fixing tessellation errors (Autodesk MeshMixer)



STL file slicing

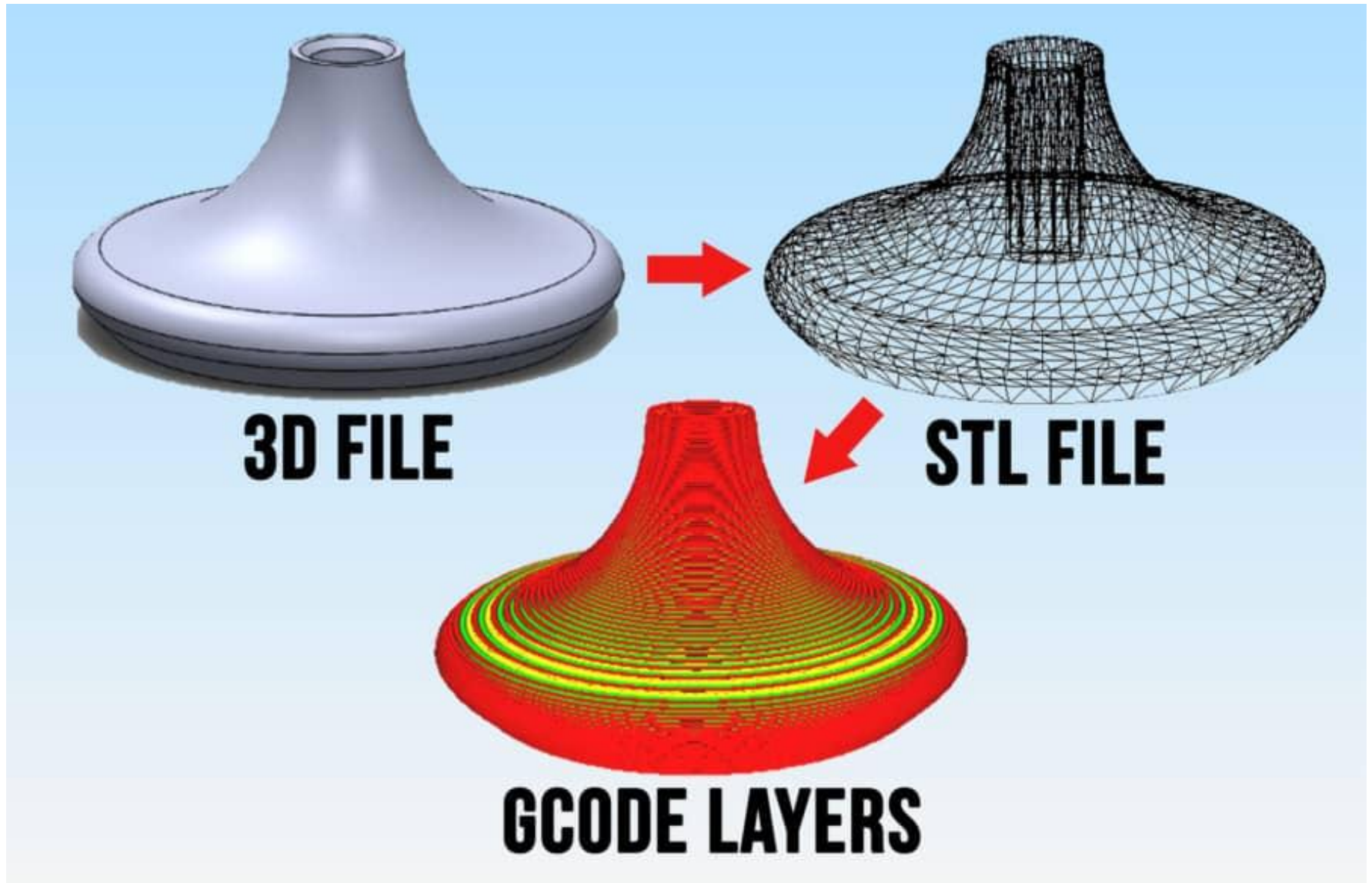


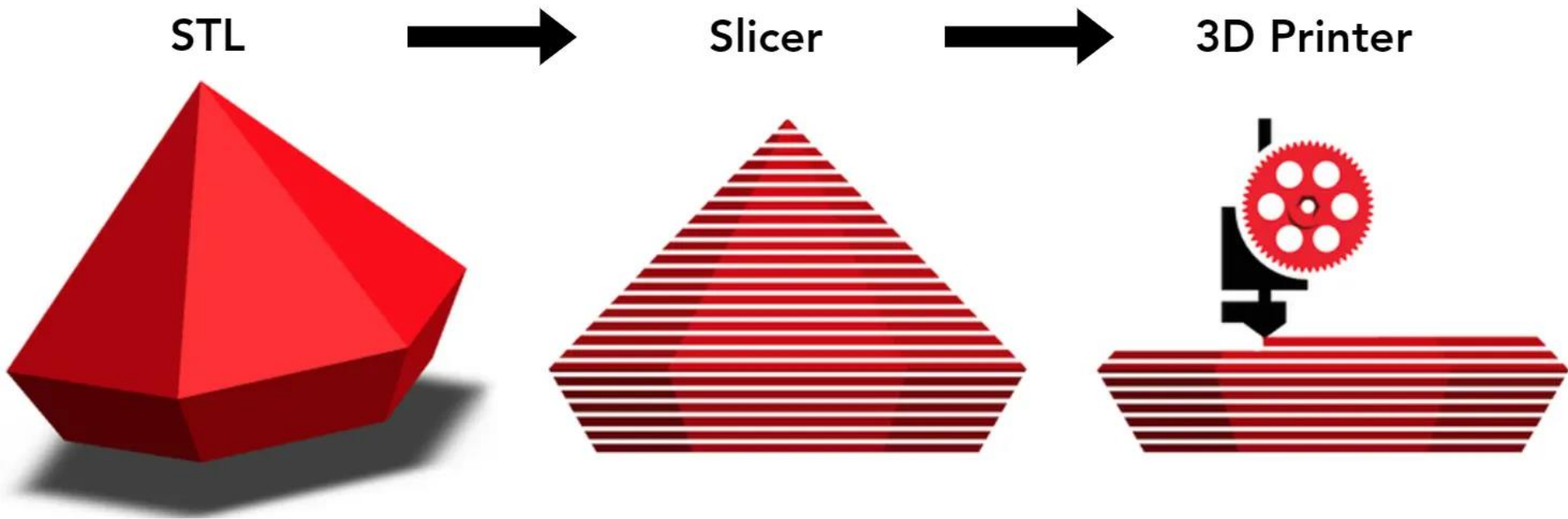
3D STL file



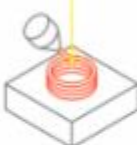
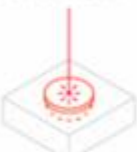
2D sliced data

Z-Axis





AM manufacturing processes

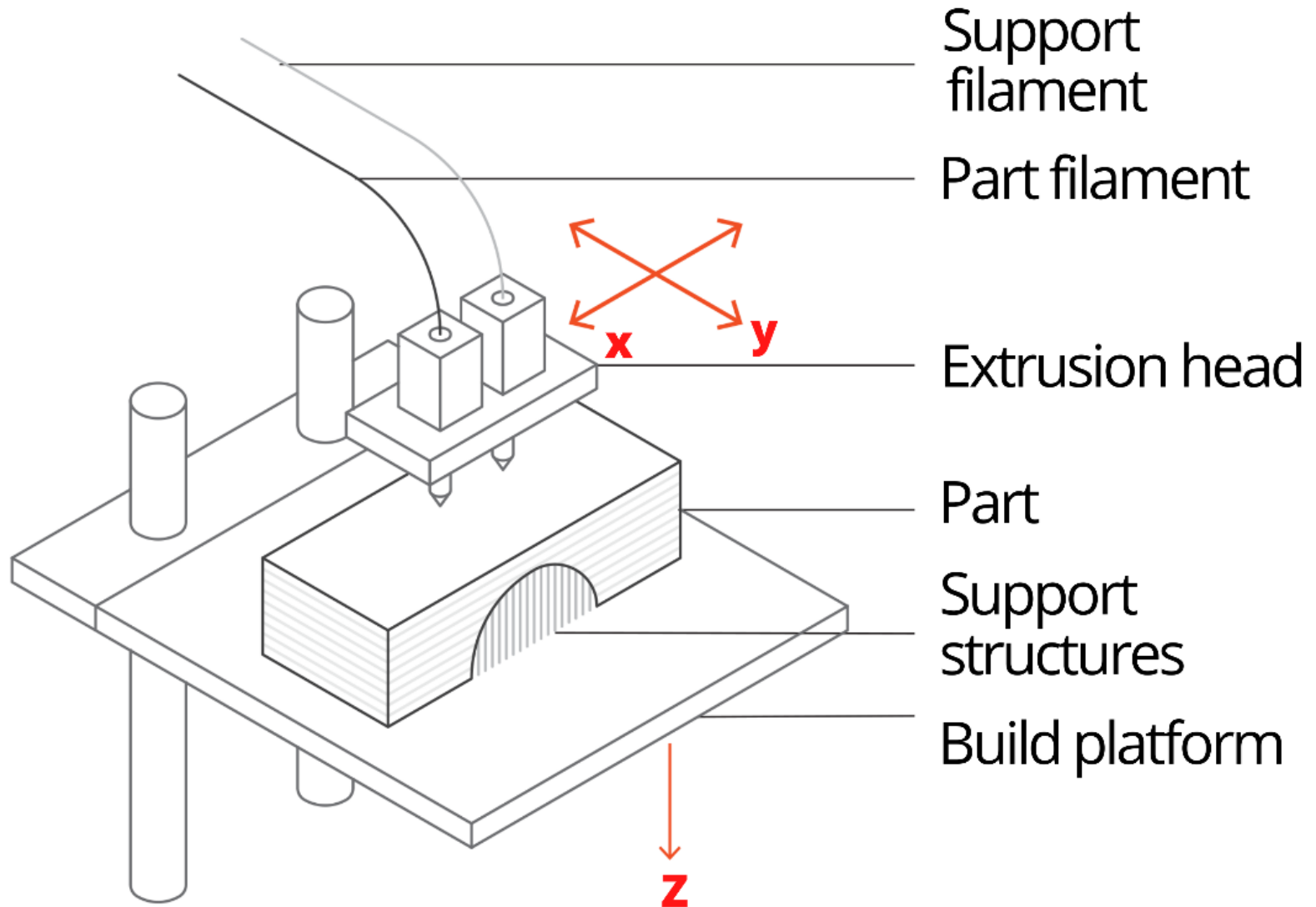
Process	Description	Technologies	Process	Description	Technologies
Material Extrusion 	Material is selectively dispensed through a nozzle or orifice.	Fused Filament Fabrication (FFF), more commonly referred to as Fused Deposition Modeling (FDM)	Binder Jetting 	A liquid bonding agent selectively binds regions of a powder bed.	Binder Jetting (BJ)
Vat Polymerization 	A liquid photopolymer in a vat is selectively cured by light-activated polymerization.	Stereolithography (SLA), Direct Light Processing (DLP)	Direct Energy Deposition 	Focused thermal energy is used to fuse materials by melting as they are being deposited.	Laser Engineering Net Shaping (LENS), Laser-Based Metal Deposition (LBMD)
Powder Bed Fusion 	Thermal energy selectively fuses regions of a powder bed.	Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Electron Beam Melting (EBM)	Sheet Lamination 	Sheets of material are bonded to form a part.	Ultrasonic Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM)
Material Jetting 	Droplets of material are selectively deposited and cured on a build plate.	Material Jetting (MJ), Drop On Demand (DOD)			

Design Rules for AM – quick overview

DESIGN RULES FOR 3D PRINTING

	Supported Walls	Unsupported Walls	Support & Overhangs	Embossed & Engraved Details	Horizontal Bridges	Holes	Connecting /Moving Parts	Escape Holes	Minimum Features	Pin Diameter	Tolerance
	Walls that are connected to the rest of the print on at least two sides.	Unsupported walls are connected to the rest of the print on less than two sides.	The maximum angle a wall can be printed at without requiring support.	Features on the model that are raised or recessed below the model surface.	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between two moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.	The expected tolerance (dimensional accuracy) of a specific technology.
Fused Deposition Modeling	0.8 mm	0.8 mm	45°	0.6 mm wide & 2 mm high	10 mm	Ø2 mm	0.5 mm		2 mm	3 mm	±0.5% (lower limit ±0.5 mm)
Stereo-lithography	0.5 mm	1 mm	support always required	0.4 mm wide & high		Ø0.5 mm	0.5 mm	4 mm	0.2 mm	0.5 mm	±0.5% (lower limit ±0.15 mm)
Selective Laser Sintering	0.7 mm			1 mm wide & high		Ø1.5 mm	0.3 mm for moving parts & 0.1 mm for connections	5 mm	0.8 mm	0.8 mm	±0.3% (lower limit ±0.3 mm)
Material Jetting	1 mm	1 mm	support always required	0.5 mm wide & high		Ø0.5 mm	0.2 mm		0.5 mm	0.5 mm	±0.1 mm
Binder Jetting	2 mm	3 mm		0.5 mm wide & high		Ø1.5 mm		5 mm	2 mm	2 mm	±0.2 mm for metal & ±0.3 mm for sand
Direct Metal Laser Sintering	0.4 mm	0.5 mm	support always required	0.1 mm wide & high	2 mm	Ø1.5 mm		5 mm	0.6 mm	1 mm	±0.1 mm

Design Rules for AM. Material Extrusion

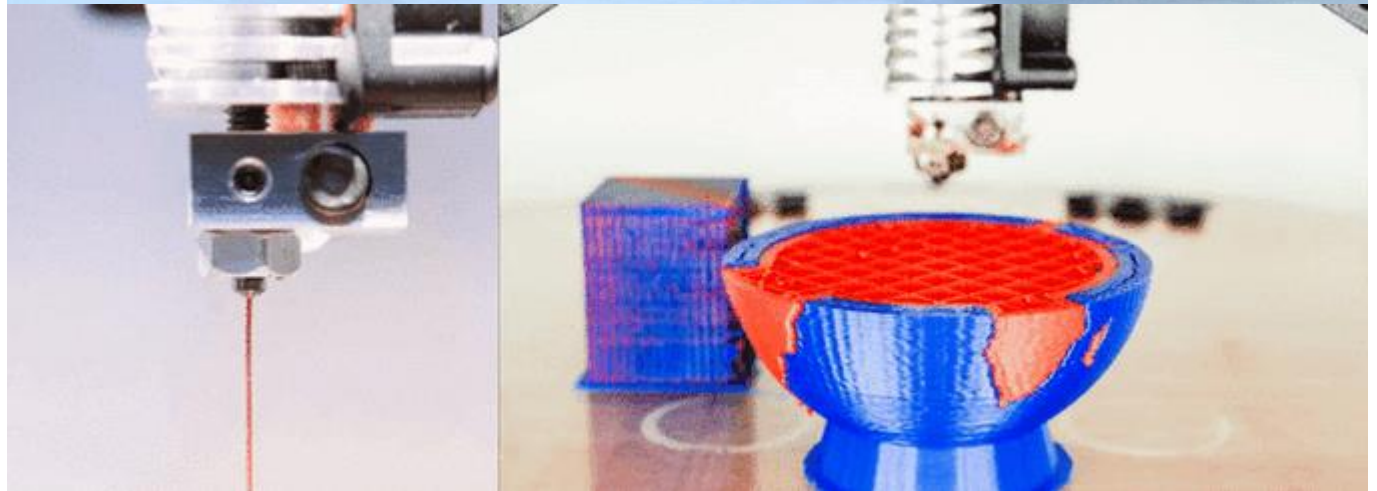


Design Rules for AM. Material Extrusion

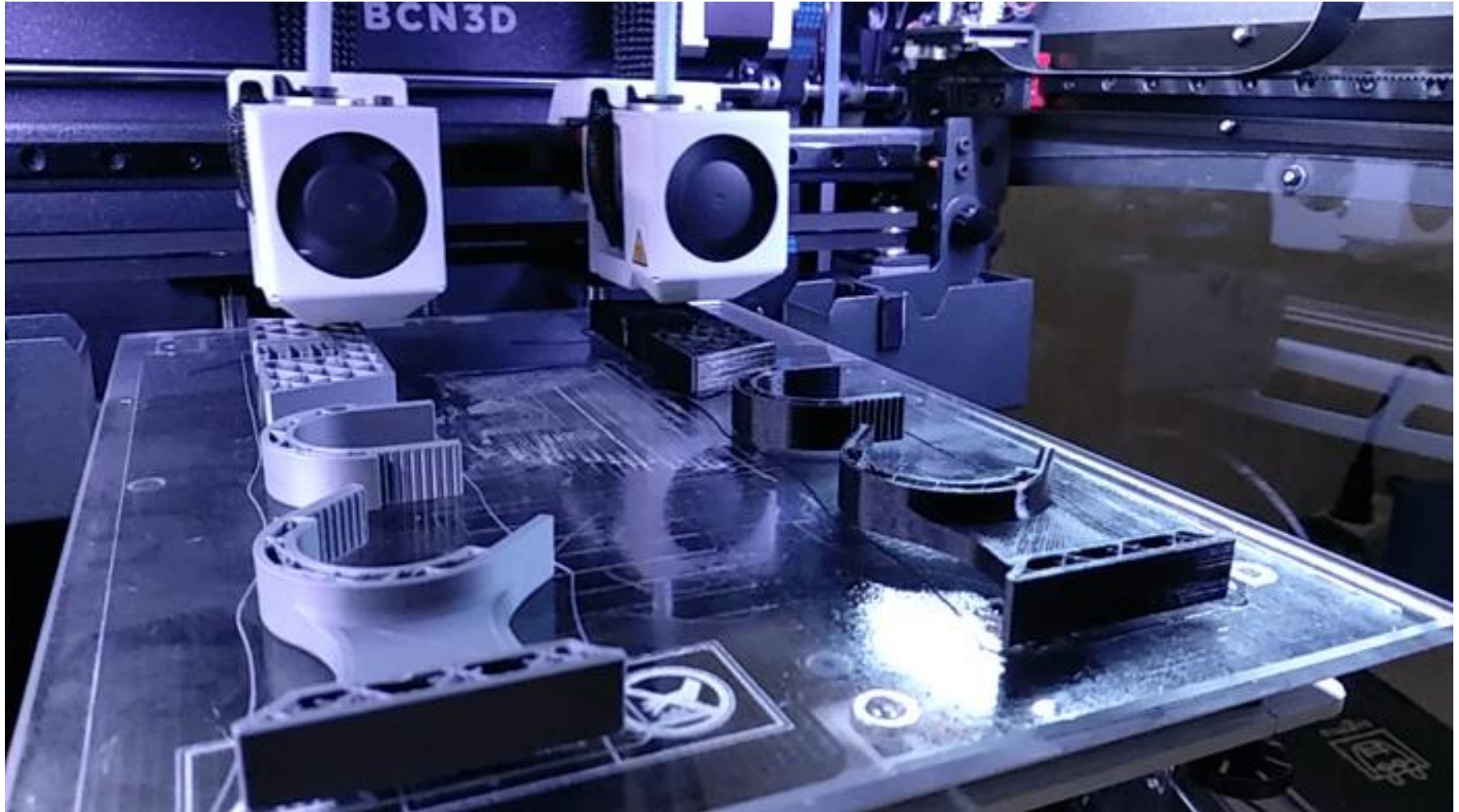
Single
extruder



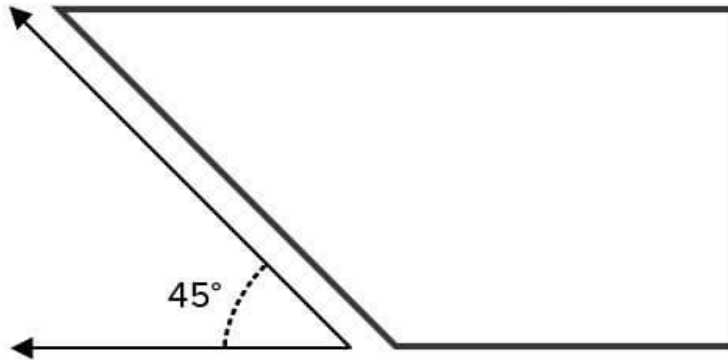
Dual
extruder



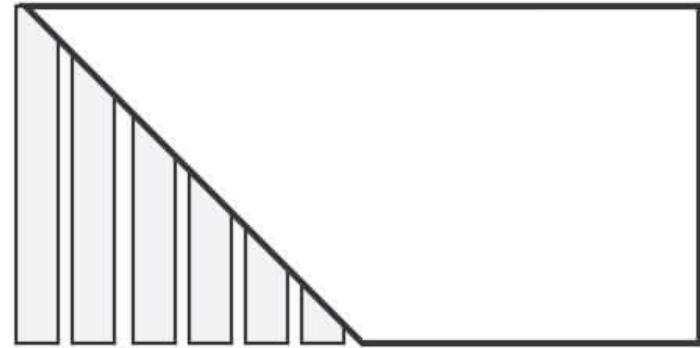
Design Rules for AM. Multi-head material extrusion



Design Rules for AM. Supports



Overhang of less than 45 degrees
No support is needed



Overhang of more than 45 degrees
Support is needed



Design Rules for AM. Material Extrusion: Supports





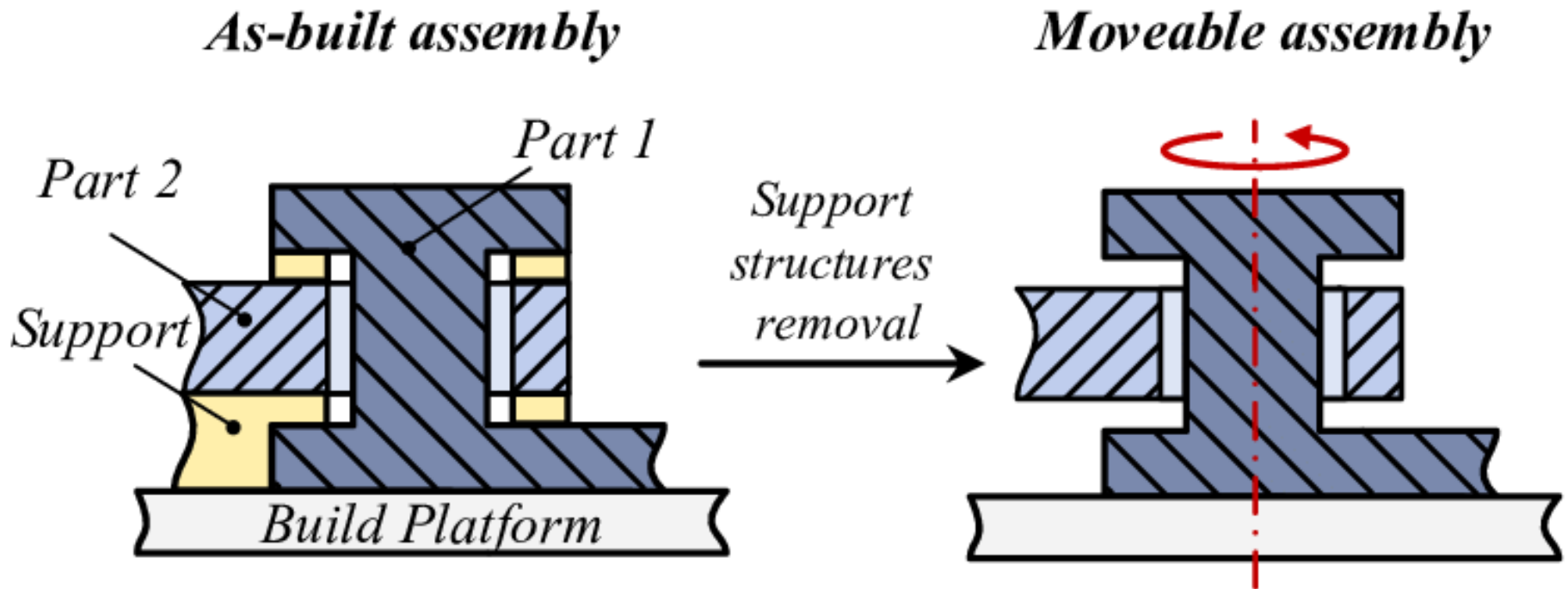


Design Rules for AM. Material Extrusion: Self-supporting

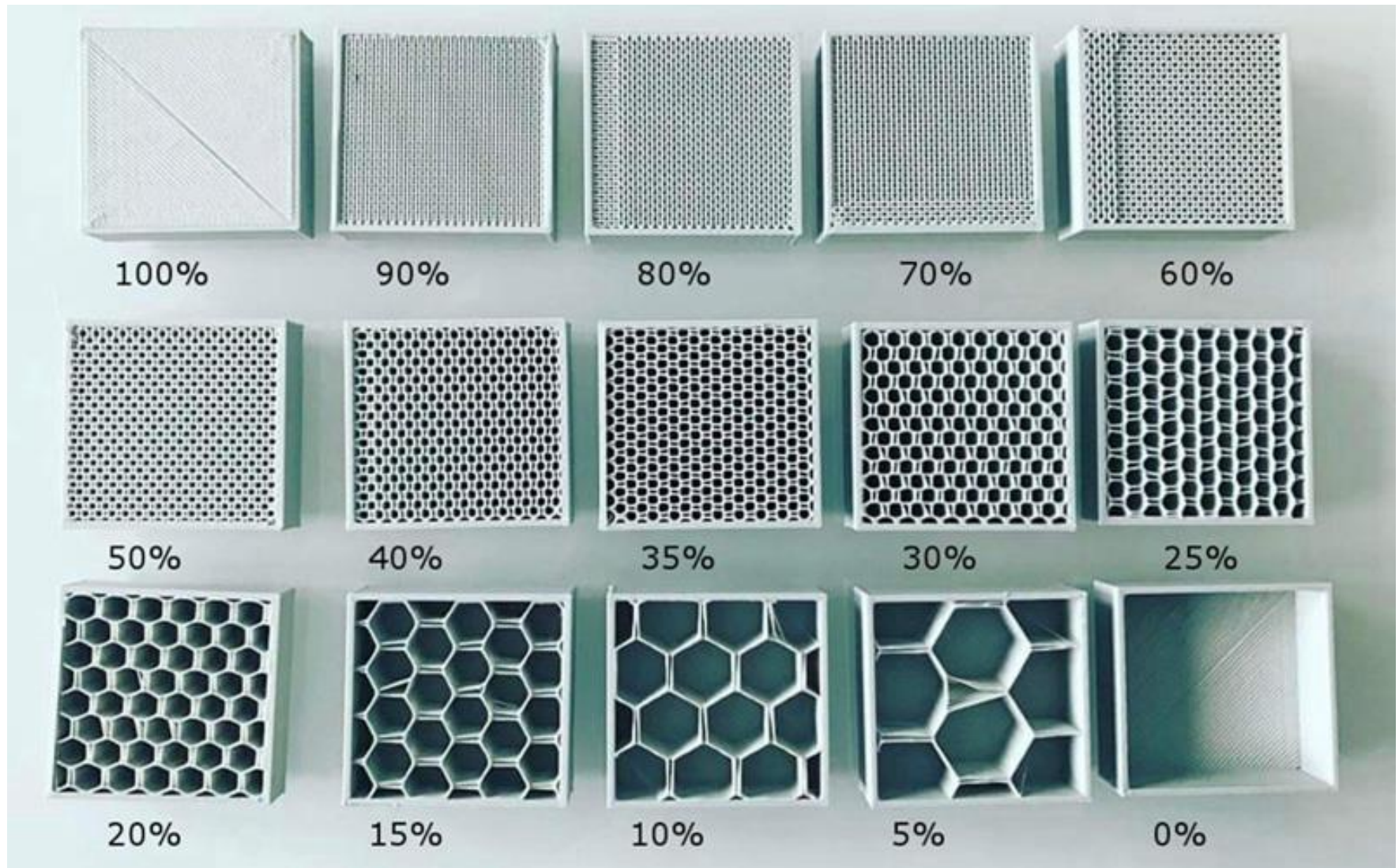


Design Rules for AM. Material Extrusion

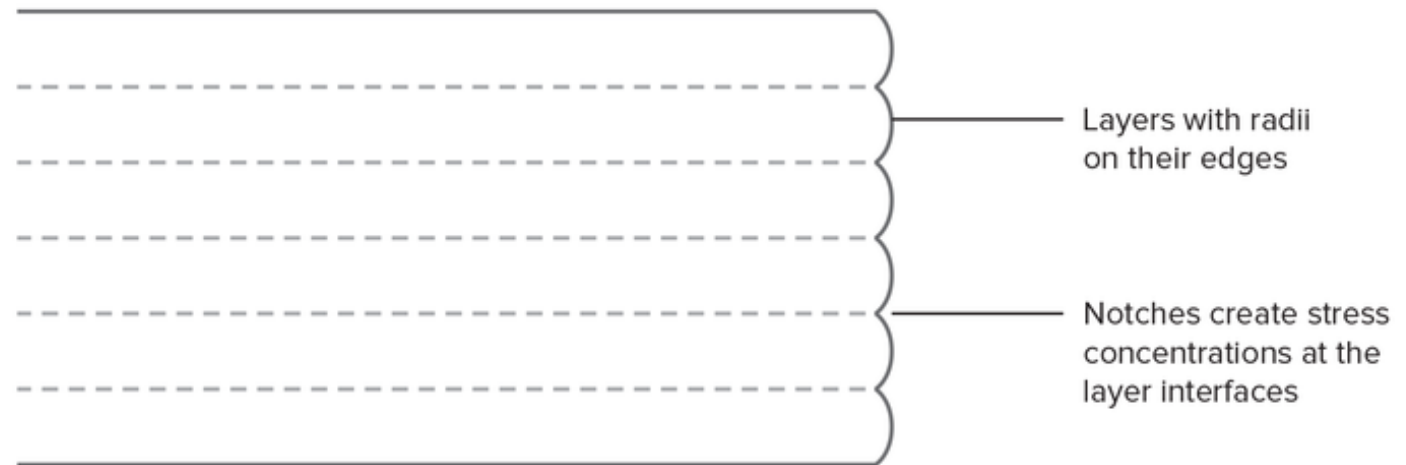
Feature	Description
	Wall thickness. A part needs to be designed with a minimal wall thickness of 1 mm. The walls of larger parts need at least 1.2mm thickness. Thick walls are not advisable since they use more material and there is a risk of deforming the part. Thick walls may be filled with sparse structures (infill) to eliminate deformation and to save filament.
	Internal support. Any model with an interior section below 45 degrees must be supported.
	Interlocking or moving parts. Parts that are printed together should have a minimum clearance of 0.4 mm.
	Embossed and engraved details. A minimum line thickness of 1 mm and a depth of 0.3 mm for engraved text or surface details. A minimum line thickness of 2.5 mm and a depth of 0.5 mm for embossed text or surface details.



Design Rules for AM. Material Extrusion: Infill

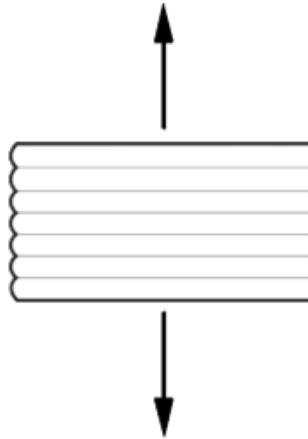


Design Rules for AM. Material Extrusion: Part orientation

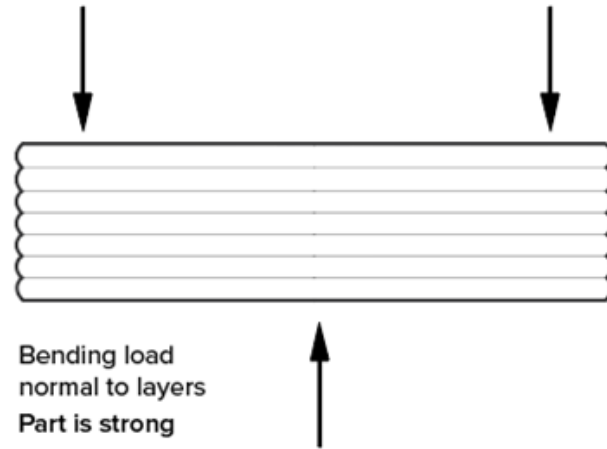


Design Rules for AM. Material Extrusion: Part orientation

Tension load
normal to layers
Part is weak



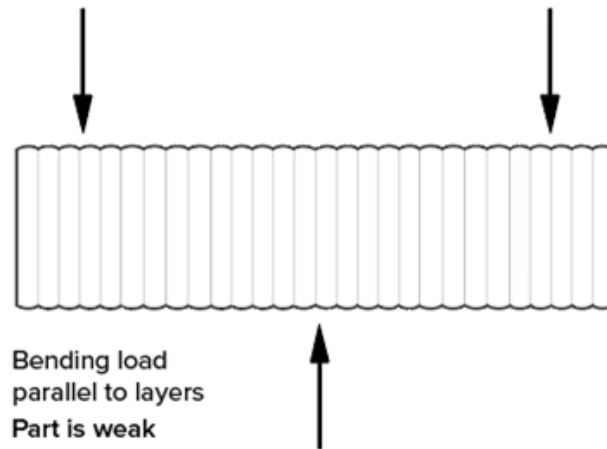
Bending load
normal to layers
Part is strong

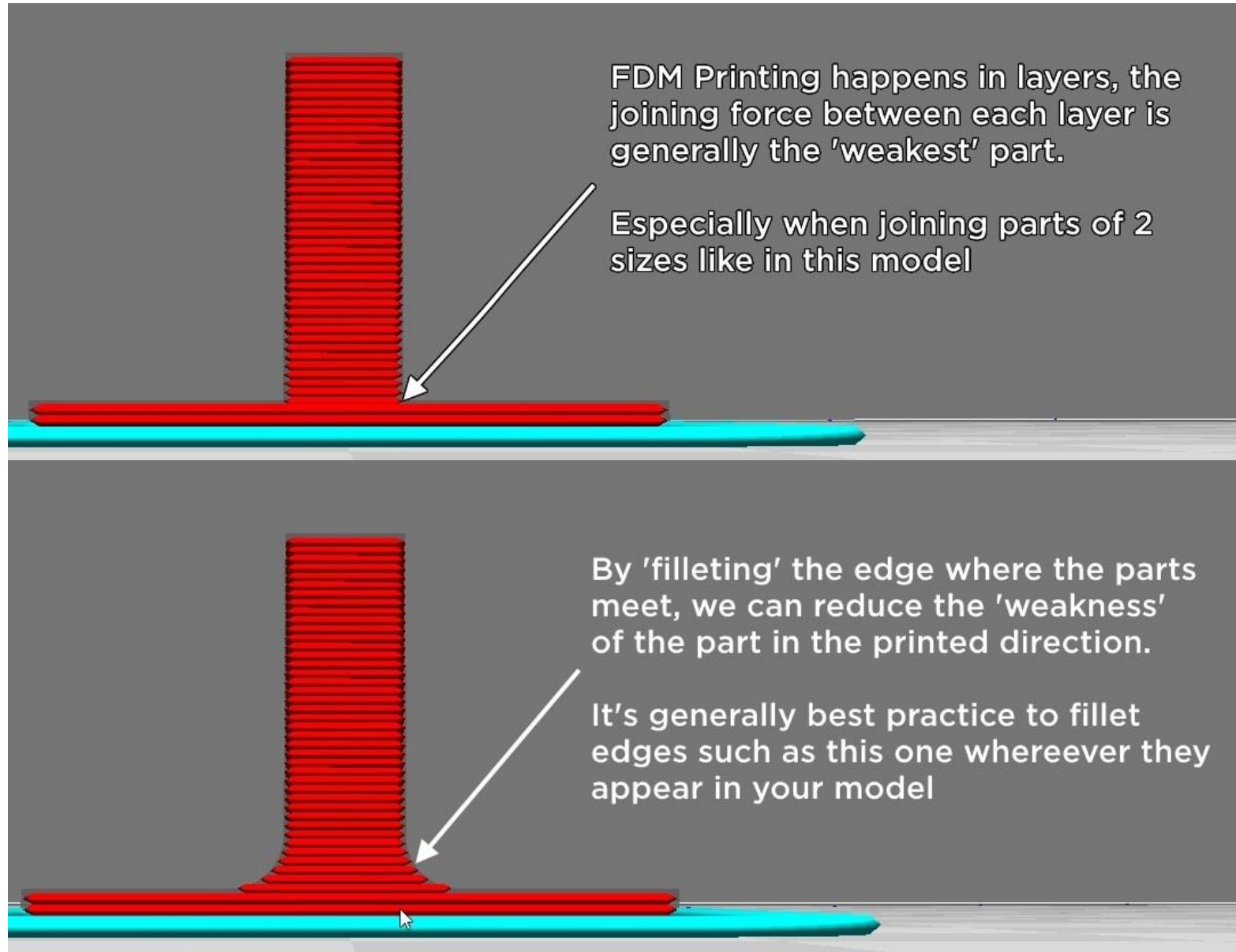


Tension load
parallel to layers
Part is strong

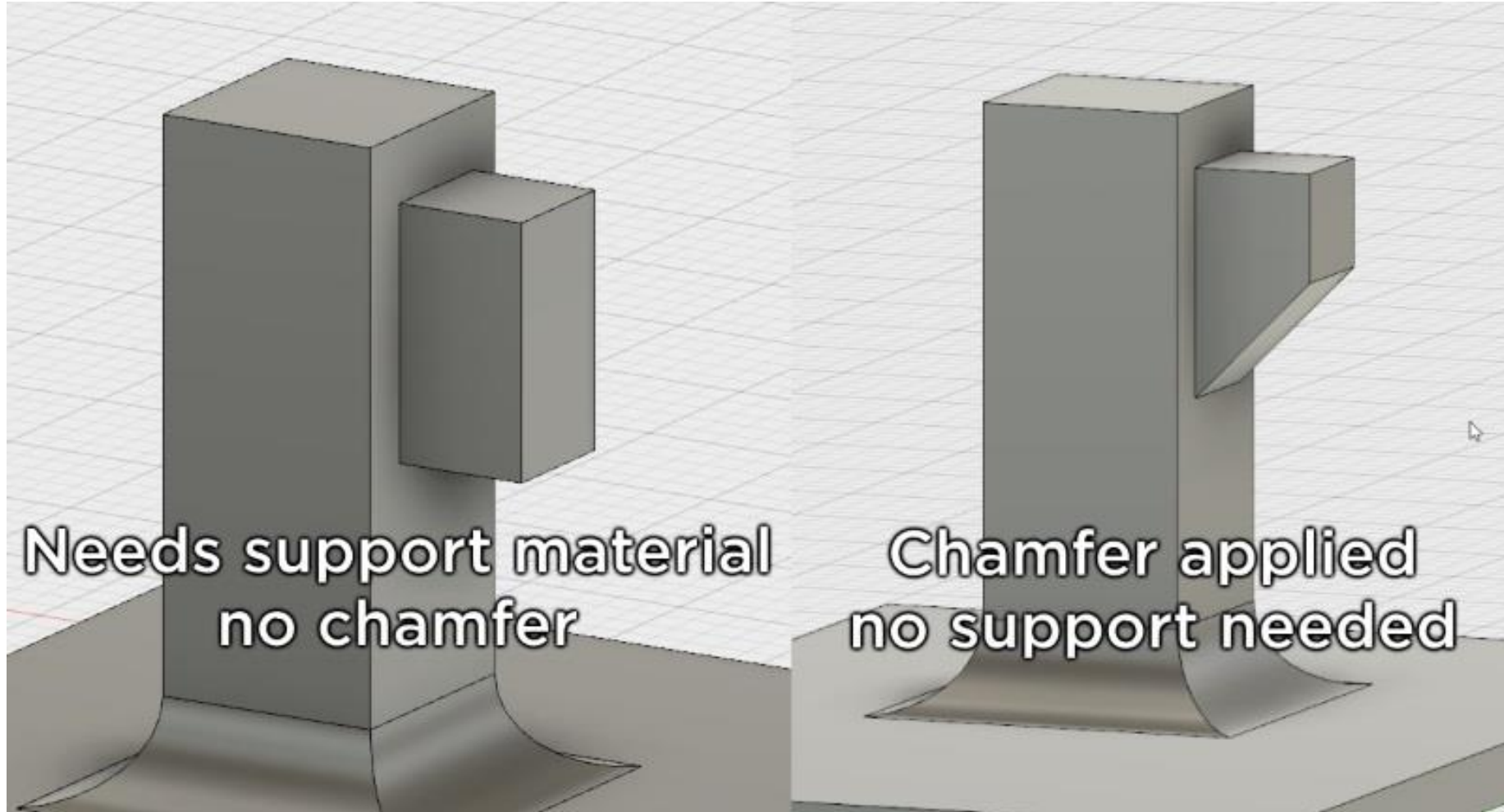


Bending load
parallel to layers
Part is weak





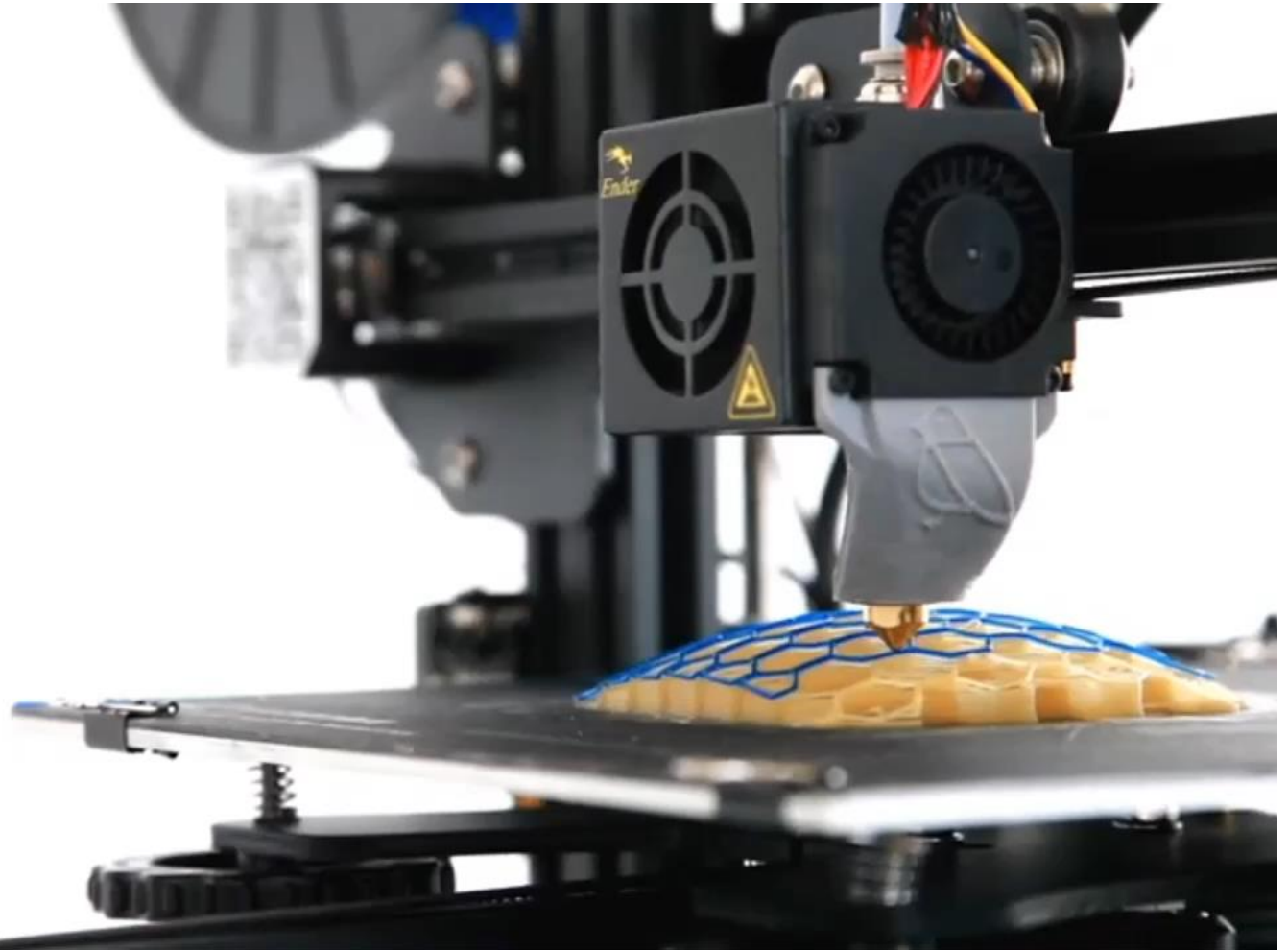
Design Rules for AM. Material Extrusion: Part orientation



Design Rules for AM. Material Extrusion: “Conveyor” FDM **MADE**



Design Rules for AM. Material Extrusion: Non-planar FDM **MADE**



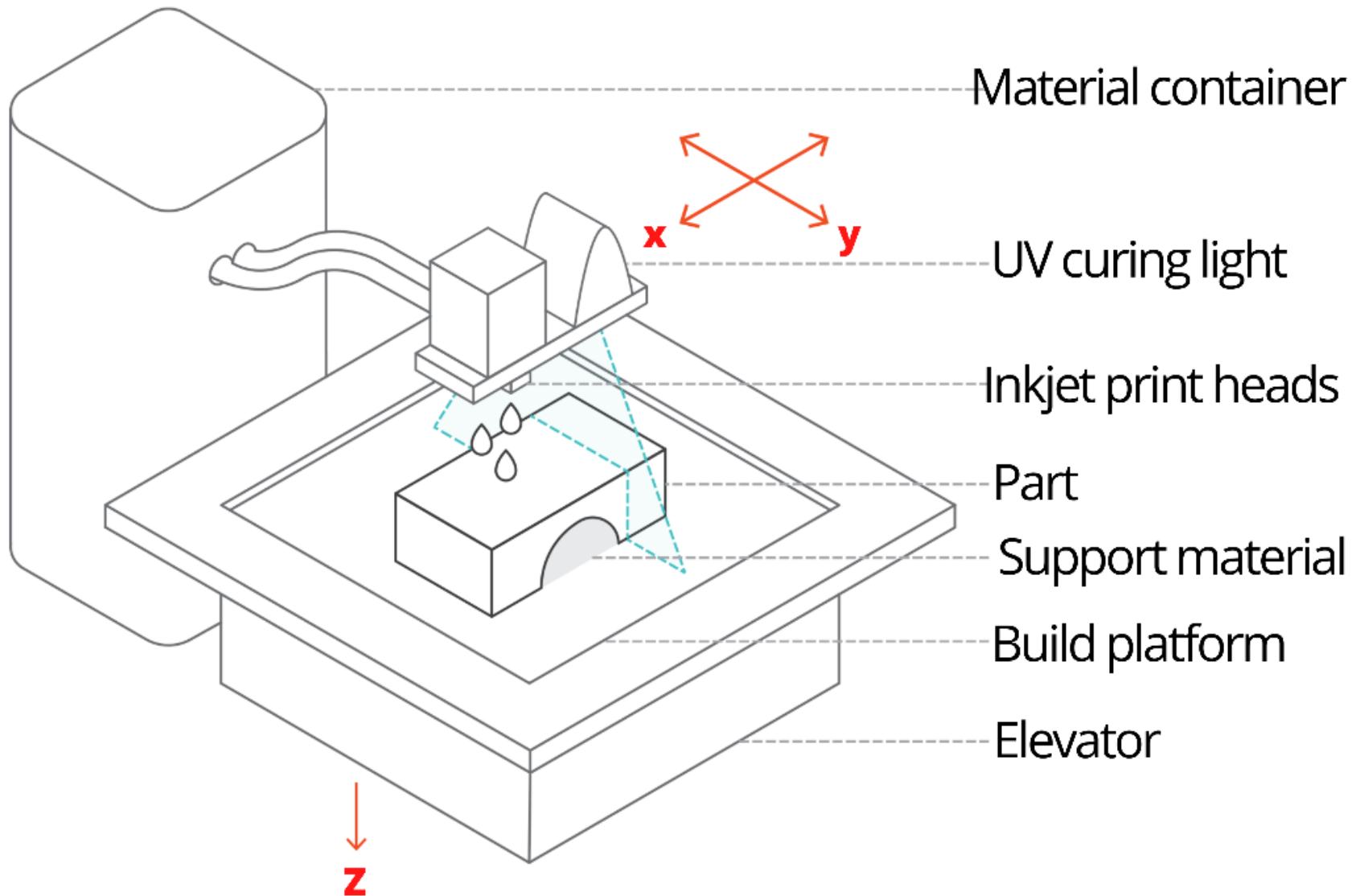
Advantages:

- FDM is the most cost-effective way of producing custom thermoplastic parts and prototypes;
- a wide range of thermoplastic materials is available, suitable for both prototyping and functional applications.

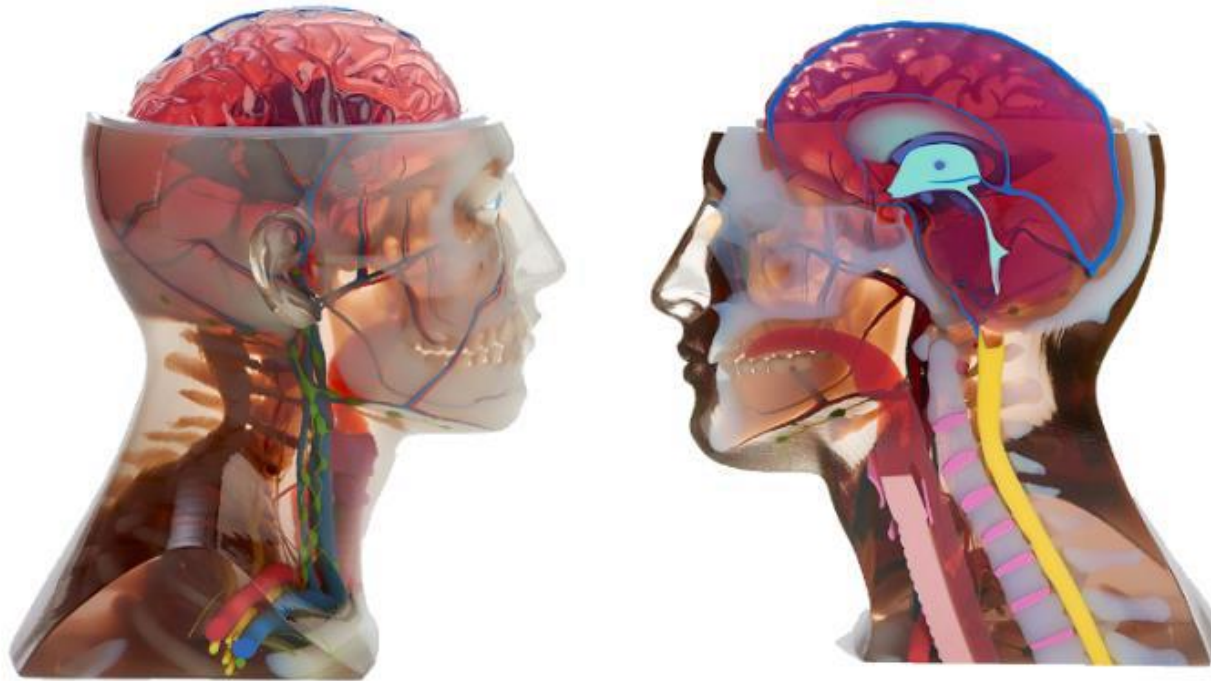
Disadvantages:

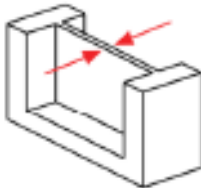
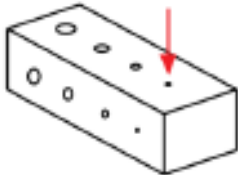
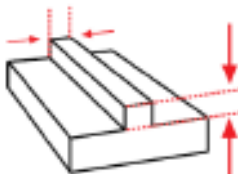
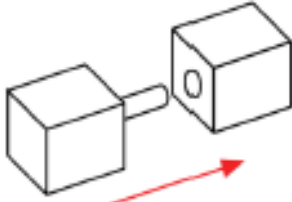
- FDM parts are likely to have visible layer lines, so post processing is required for a smooth finish. FDM parts can be finished using various post-processing methods, such as sanding and polishing, priming and painting, cold welding, vapour smoothing, epoxy coating and metal plating;
- the layer adhesion mechanism makes FDM parts inherently anisotropic.

Design Rules for AM. Material Jetting







Feature	Description
	Major supported walls. The minimum wall thickness for major supported walls is 1 mm.
	Hole size. For a hole to successfully print, the minimum diameter should be no smaller than 0.5 mm. Holes, whenever possible, should be oriented vertically, to maximize the circularity of the feature.
	Embossed and engraved details. To ensure small details are visible, the following rules apply: • Minimum depth of engraving 0.5 mm; • Minimum height of embossing 0.5 mm.
	Moving parts. Assembled parts, hinges and joints should have 0.15–0.2 mm clearance around all sides. This clearance must also be accessible in some way to allow for cleaning/removal of the support material that will build in the gap.

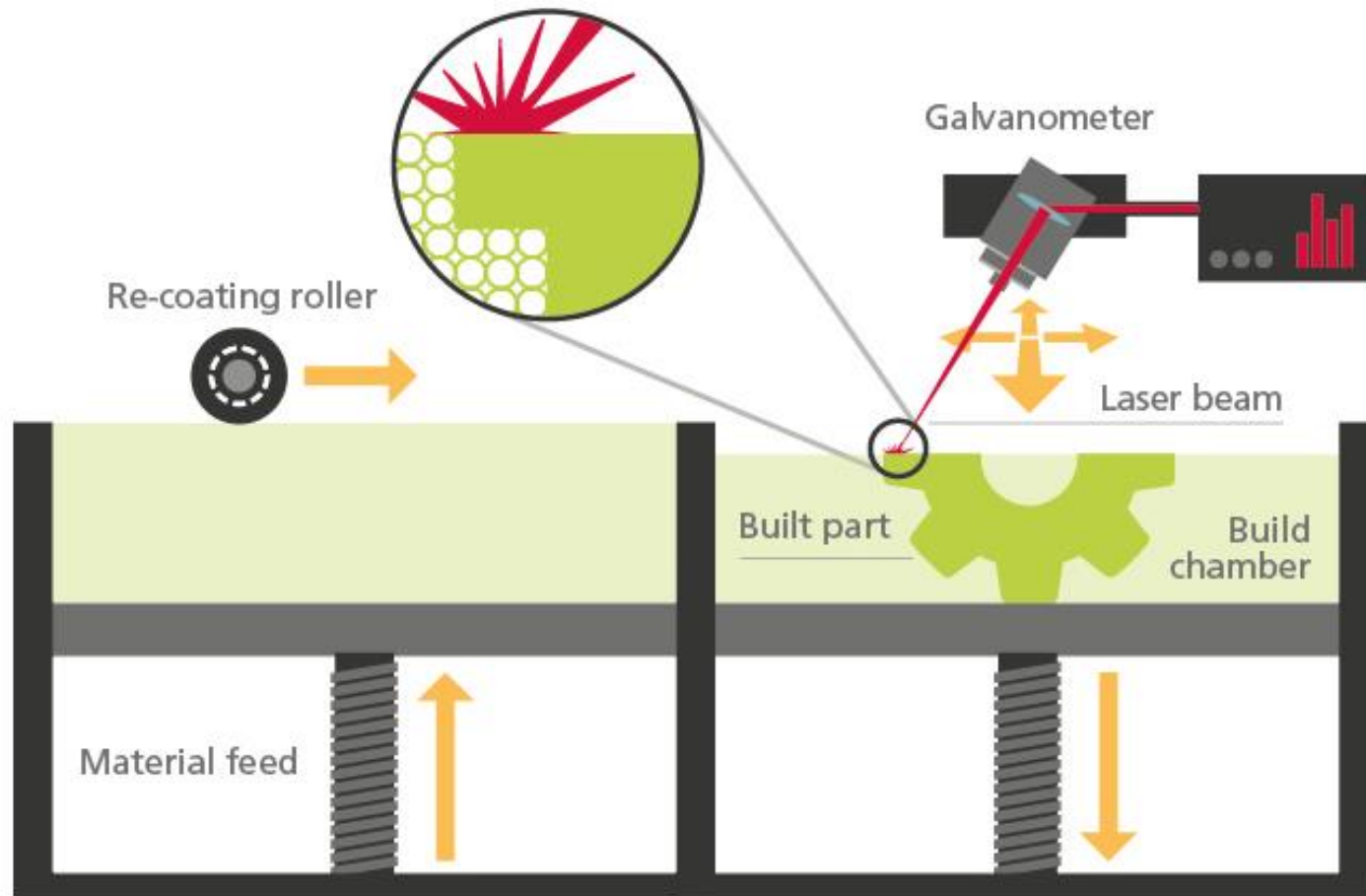
Advantages:

- the Material Jetting AM produces smooth parts with surfaces comparable to injection moulding and very high dimensional accuracy;
- parts created with the Material Jetting AM have homogeneous mechanical and thermal properties;
- the multi-material capabilities of the Material Jetting AM technology enable the creation of accurate visual and haptic prototypes.

Disadvantages:

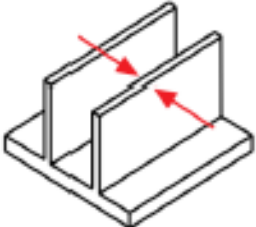
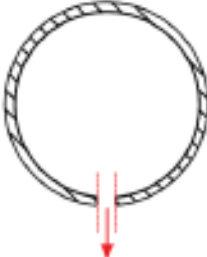
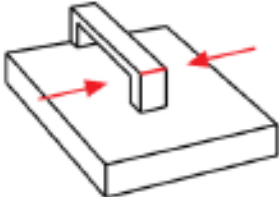
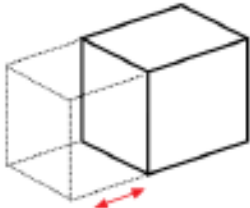
- parts fabricated via the Material Jetting AM technology are mainly suitable for non-functional prototypes, as they have poor mechanical properties (low elongation at break);
- Material Jetting materials are photosensitive, and their mechanical properties degrade over time;
- high costs of the technology and materials (approximately from \$300 to \$1000 per 1kg) may make the Material Jetting AM financially not viable for some applications.

Design Rules for AM. Powder Bed Fusion



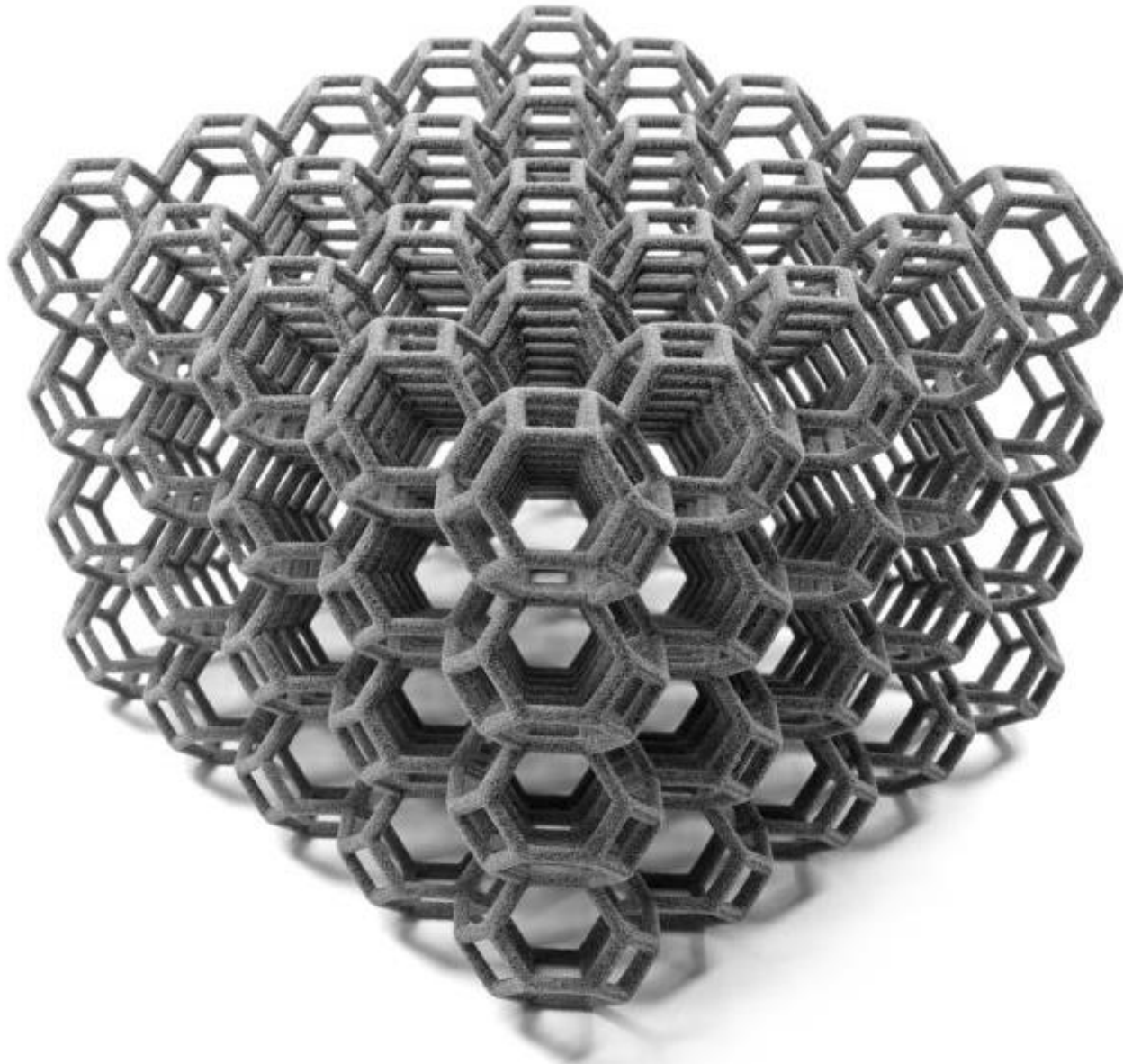




Feature	Description
	Wall thickness. The minimum wall thickness varies between 0.7 mm up to 2.0 mm.
	Escape holes. To save weight (and sometimes costs) SLS parts may be printed hollow. To remove unsintered powder after production, escape holes must be designed. Escape holes must be a minimum of 3.5 mm in diameter.
	Feature size (pins, protruding features etc.). A minimum size of 0.8 mm is recommended.
	Tolerances. Typical tolerance for SLS parts is ± 0.3 mm.

Design Rules for AM. Powder Bed Fusion







Advantages:

- SLS parts have good isotropic mechanical properties, making them ideal for functional parts and prototypes;
- SLS AM process requires no support structures, so designs with complex geometries can be easily produced.

Disadvantages:

- SLS parts have a grainy surface finish and internal porosity that may require post processing, if a smooth surface is required;
- large flat surfaces and small holes cannot be printed accurately with SLS, as they are susceptible to warping.



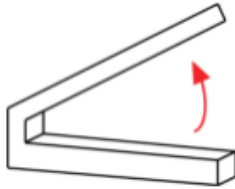
Multi Jet Fusion technology

GE ADDITIVE MANUFACTURING

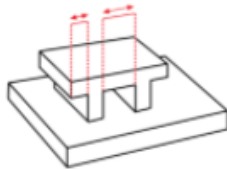
The EBM Process

The Future of Industrial Production

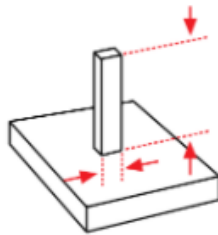




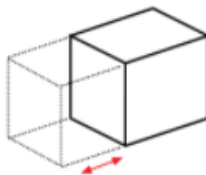
Overhanging Surfaces - The minimum angle where support material is not required on an overhanging surface is 45° relative to the horizontal in most cases. It is possible to reduce this angle further by optimizing the laser parameters.



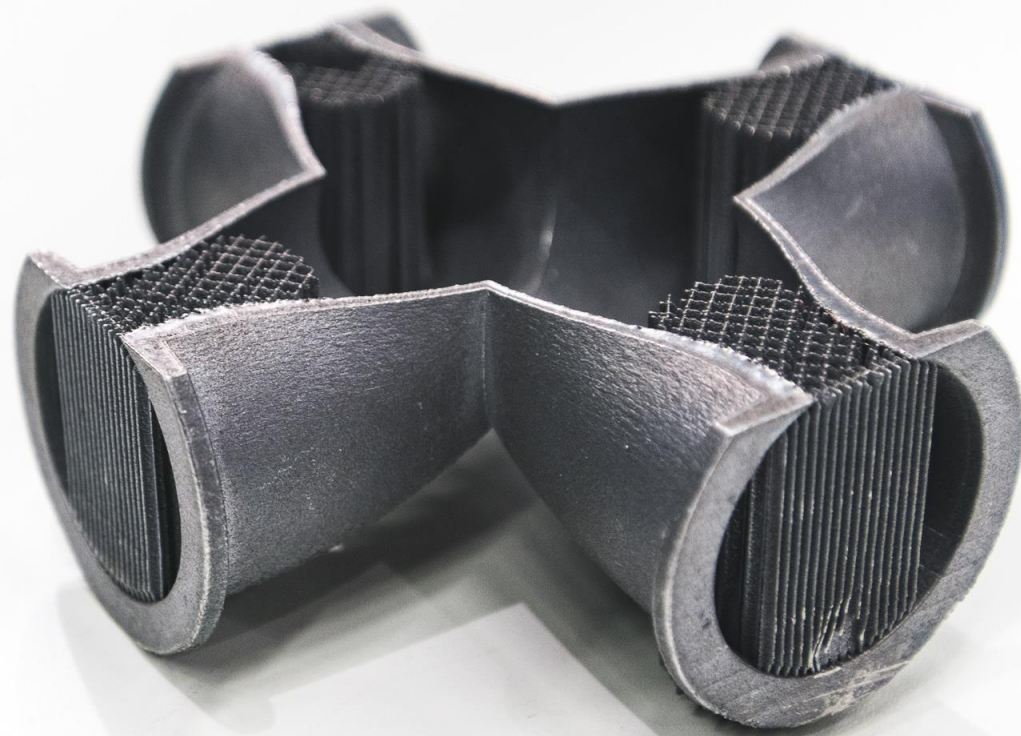
Unsupported Edges - The maximum length of a cantilever-style overhanging surface is 0.5 mm. An overhanging horizontal surface supported on both ends can be 1 mm long. These rules will apply to embossed and engraved features with unsupported surfaces as well.



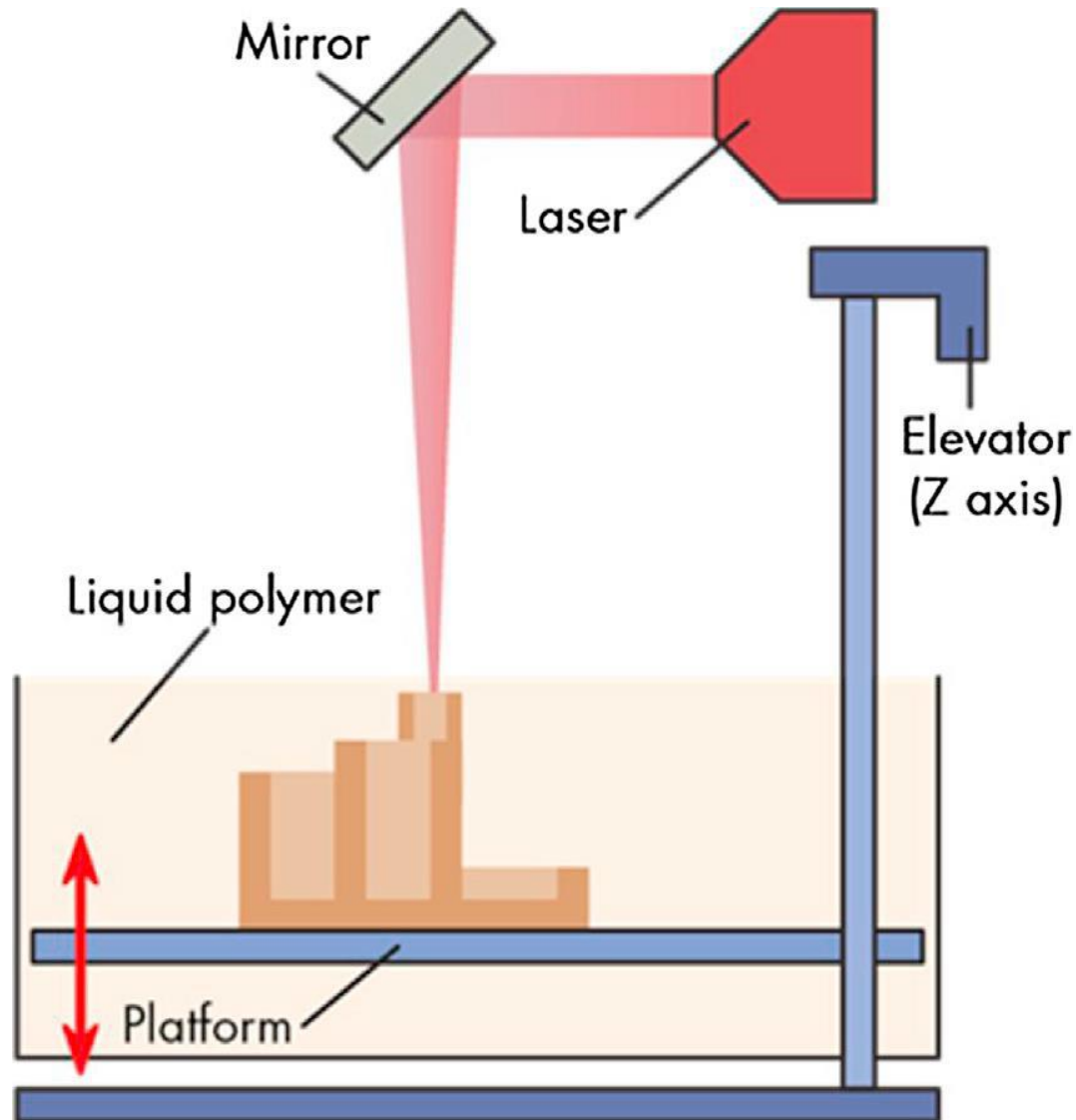
Aspect Ratio - The maximum ratio between the vertical print height and the part section is 8:1 to ensure stability of the printed part on the build plate.

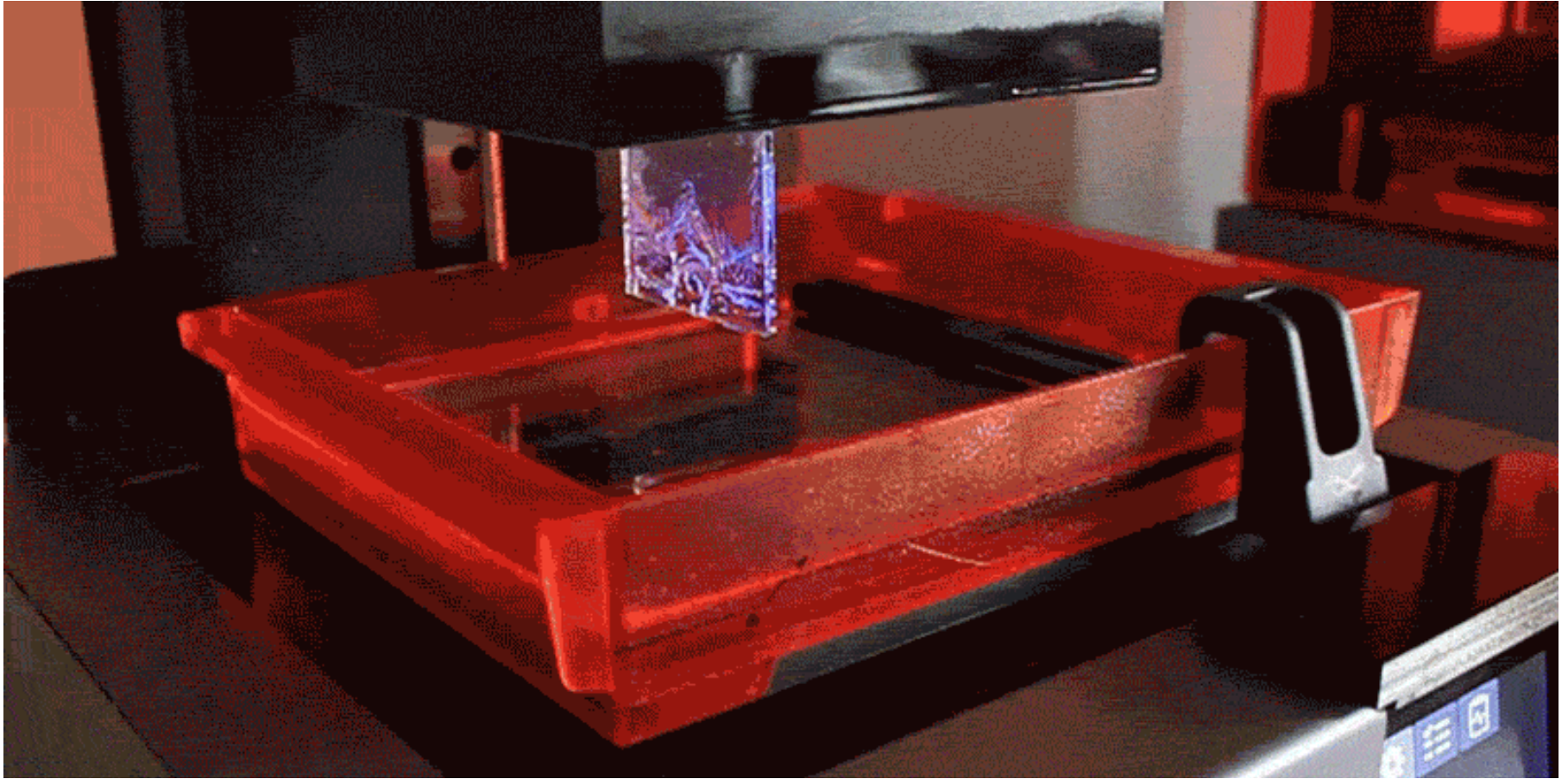


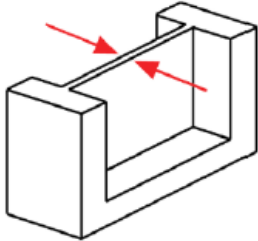
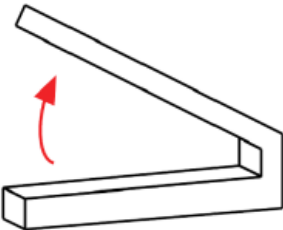
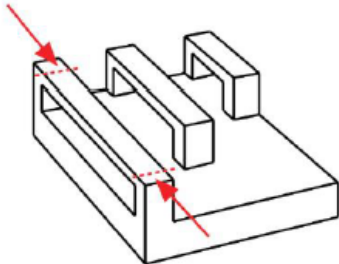
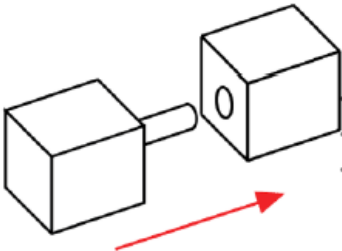
Tolerances - Part tolerance in the print direction is ± 1 -layer thickness. In the XY plane, the achievable tolerance is ± 0.127 mm

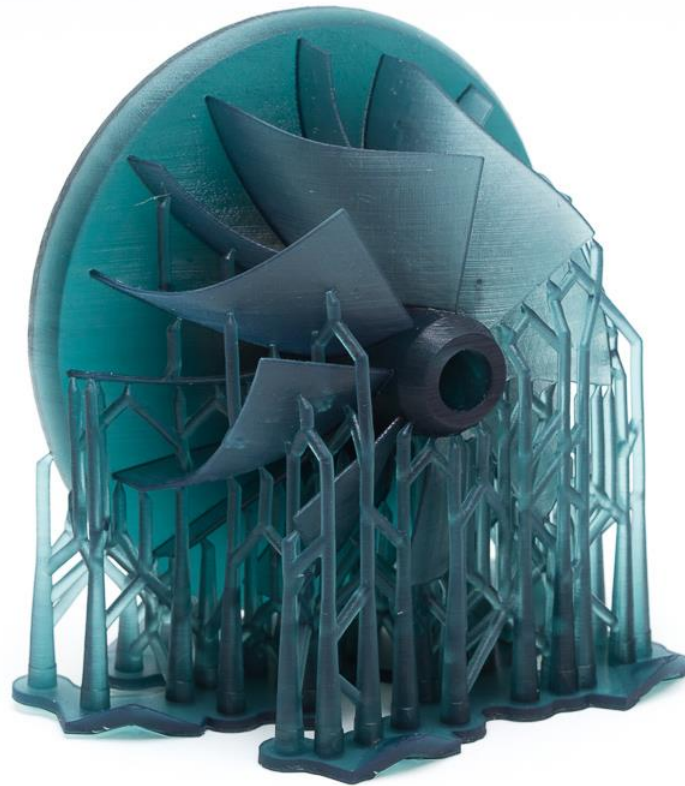


Design Rules for AM. Vat Photopolymerisation





Feature	Description
	Supported walls. Walls that are connected to other structures on at least two sides, so they have very little chance of warping. These should be designed at a minimum of 0.4 mm thick.
	Overhangs. Pose very little issue with SLA printing, unless the model is being printed without adequate internal and external support structures. Printing without supports often leads to warping of the print.
	Horizontal bridges. Bridges between two points on a model can be successfully printed, but the designer must keep in mind that wider bridges must be kept shorter (less than 21 mm) than thin bridges. Wider bridges have a greater Z-axis area of contact, increasing the chance of print failure during the peeling process.
	Connections: • 0.5 mm clearance between moving parts; • 0.2 mm clearance for assembly connections; • 0.1 mm clearance will give a push or snug fit.





Advantages:

- SLA can produce parts with very high dimensional accuracy and with intricate details;
- SLA parts have a very smooth surface finish, making them ideal for visual prototypes;
- Speciality SLA materials are available, such as clear, flexible, dental and castable resins.

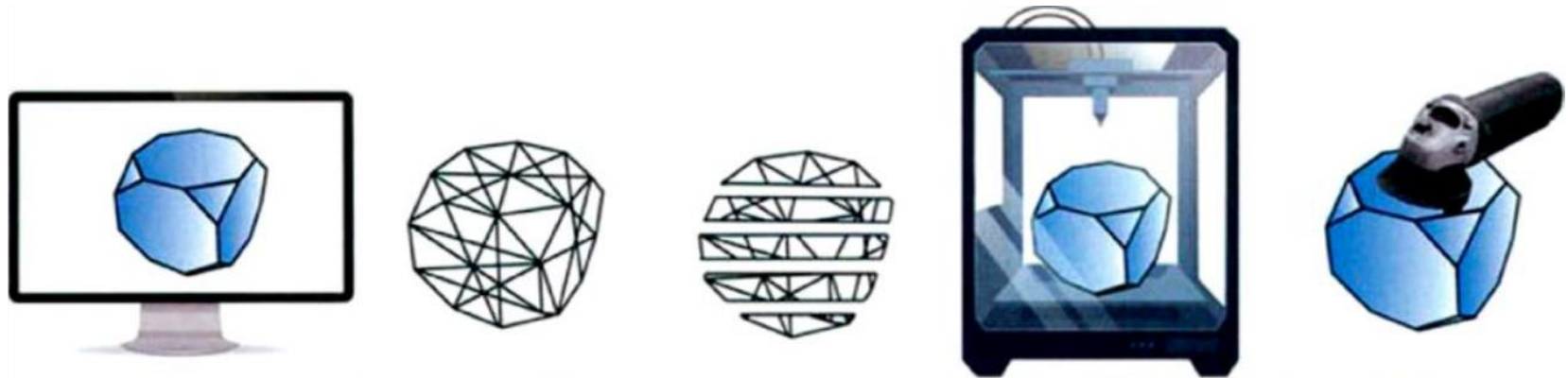
Disadvantages:

- SLA parts are generally brittle and not suitable for functional prototypes;
- the mechanical properties and visual appearance of SLA parts will degrade over time when the parts are exposed to sunlight;
- support structures are always required, and post-processing is necessary to remove the visual marks left on the SLA part.

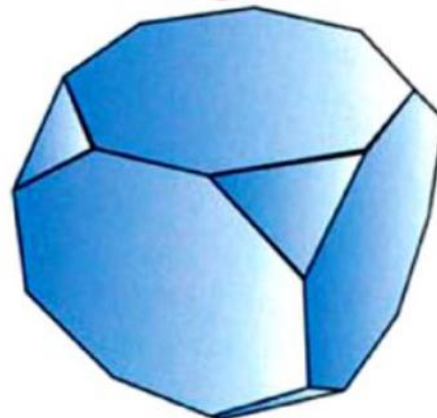
Design Rules for AM. Vat Photopolymerisation. Carbon 3D **MADE**



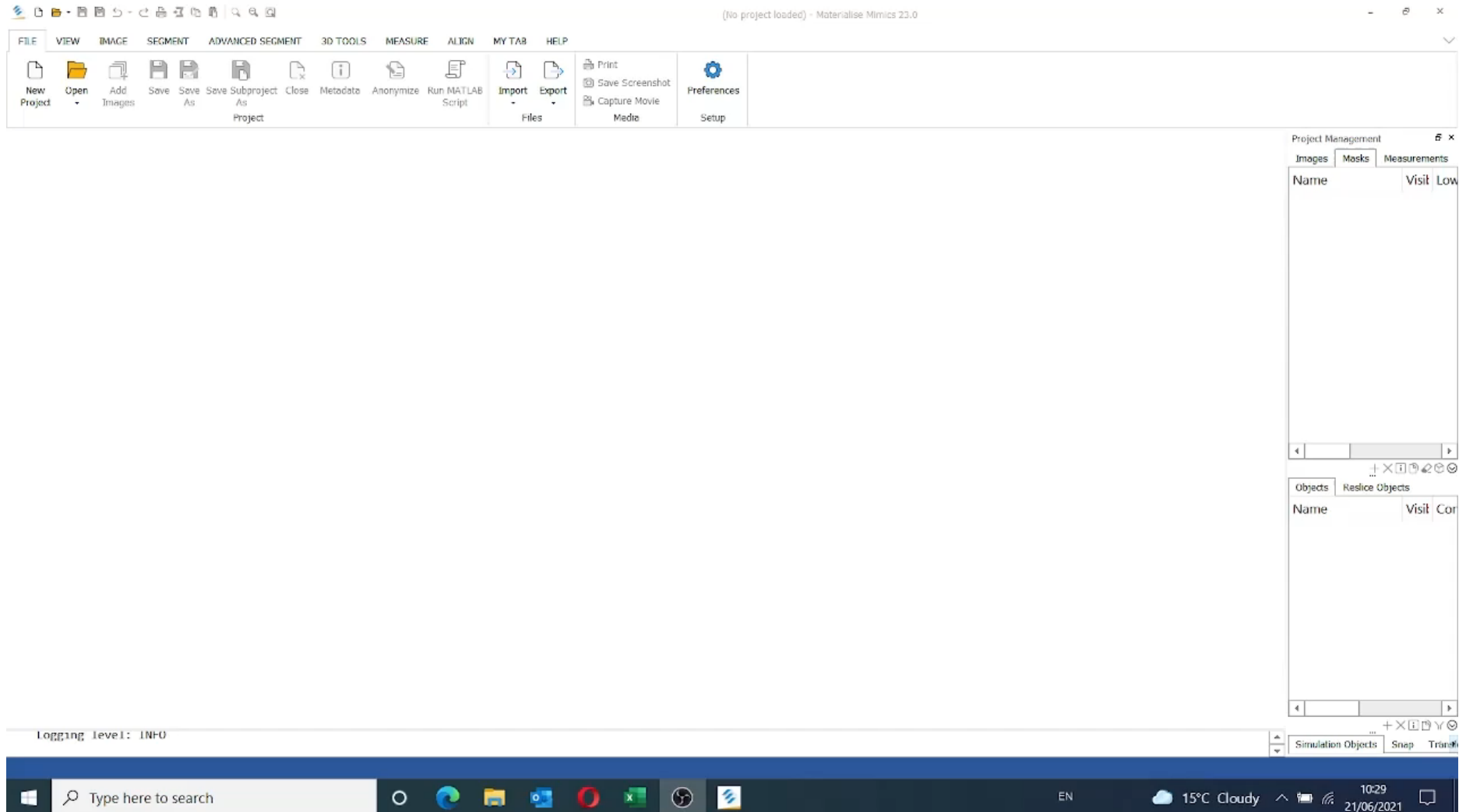
Case study – Spinal stabilisation system



1	2	3	4	5
CAD-based 3D model	.STL file	Sliced layers	AM system	End part finishing



Case study – Spinal stabilisation system



Questions?