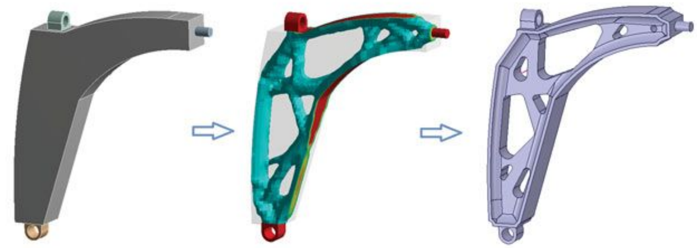
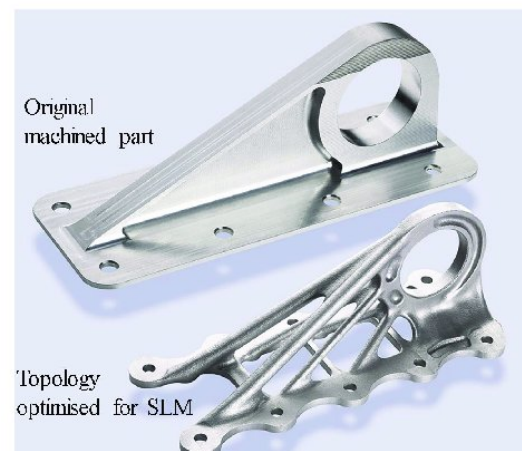
香港中文大學
The Chinese University of Hong Kong

MAEG5160: Design for Additive Manufacturing

Lecture 3: Design for metal AM





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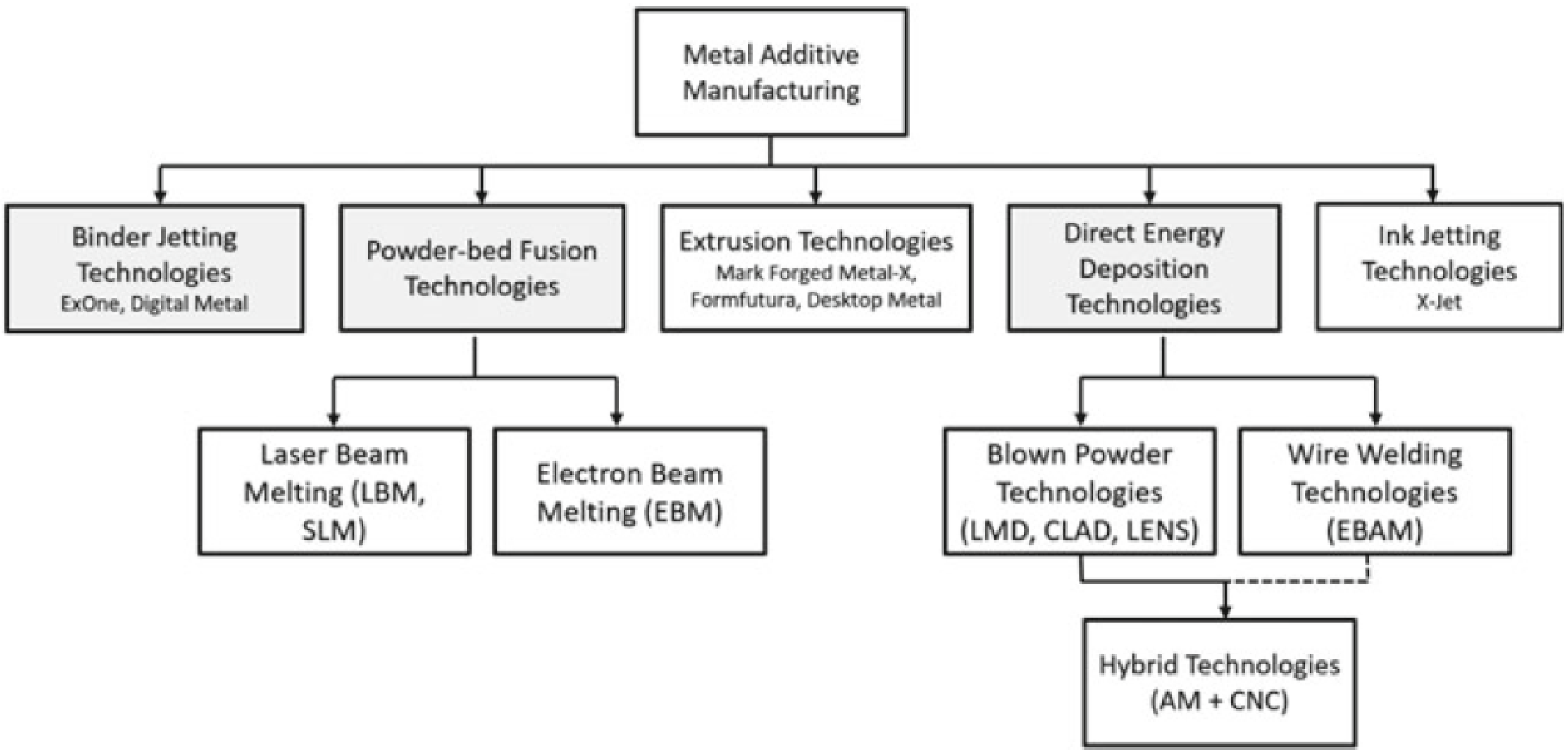
Design for metal AM: Process details



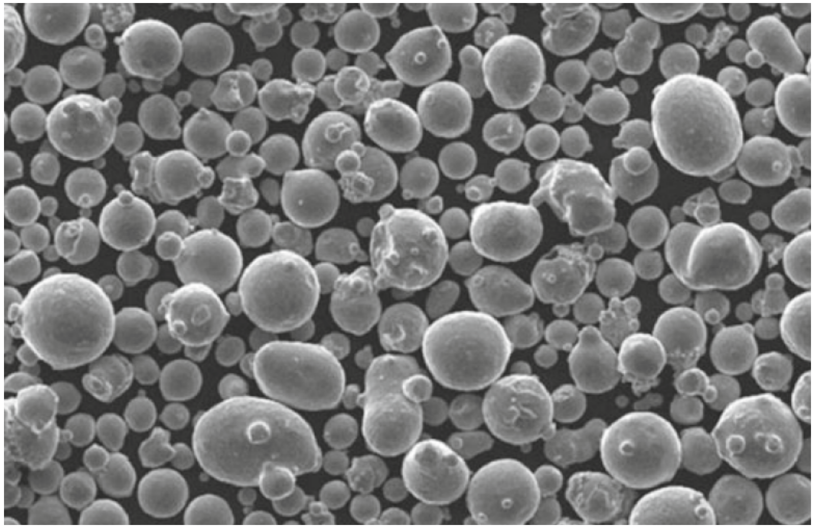
Metal AM process: a more detailed classification

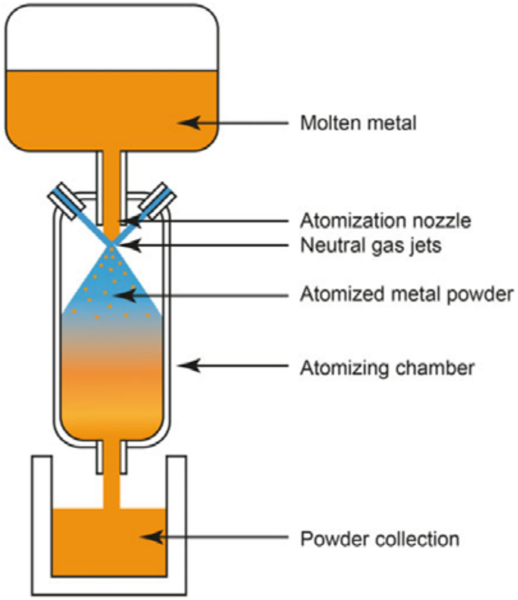
Design for metal AM: Process details

1. Metal Powder Production and Characteristics

Metal AM powder is, most commonly, made through a gas atomization process. There are a number of different atomisation processes including gas atomisation, vacuum induction melting gas atomisation, plasma atomisation, centrifugal atomisation, and water atomisation. Most of these atomization processes produce:

- A spherical powder shape
- A good powder density, thanks to the spherical shape and particle size distribution
- A good reproducibility of particle size distribution





Gas atomisation process and resultant powder

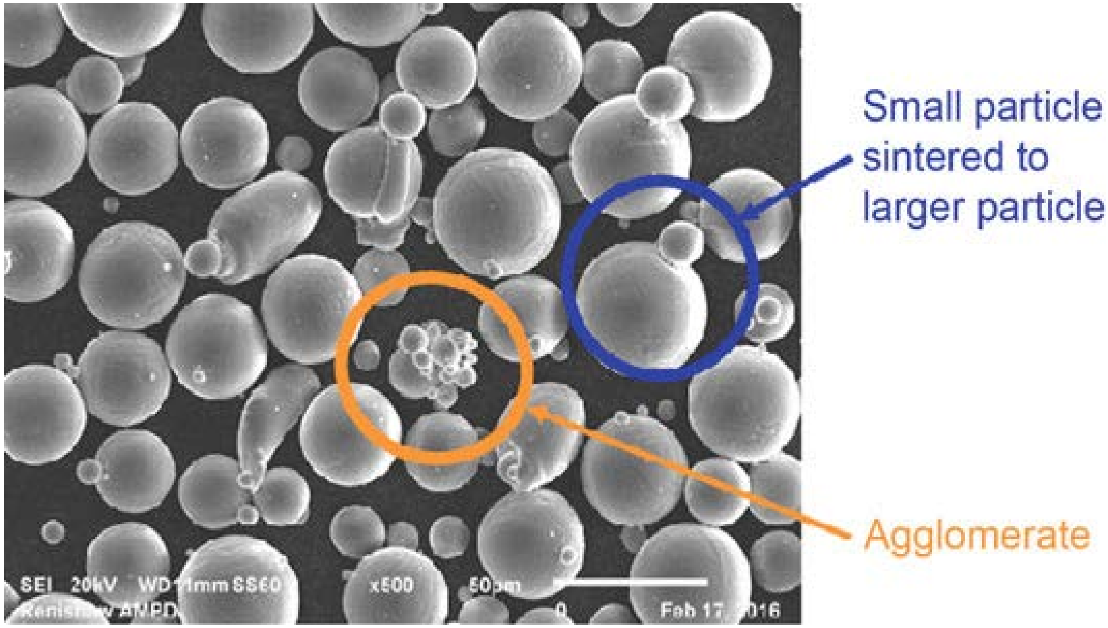
Design for metal AM: Process details

Typical defects to be controlled and minimized in powder are:

• Irregular powder shapes such as elongated particles, which may cause the powder to be harder to spread evenly.

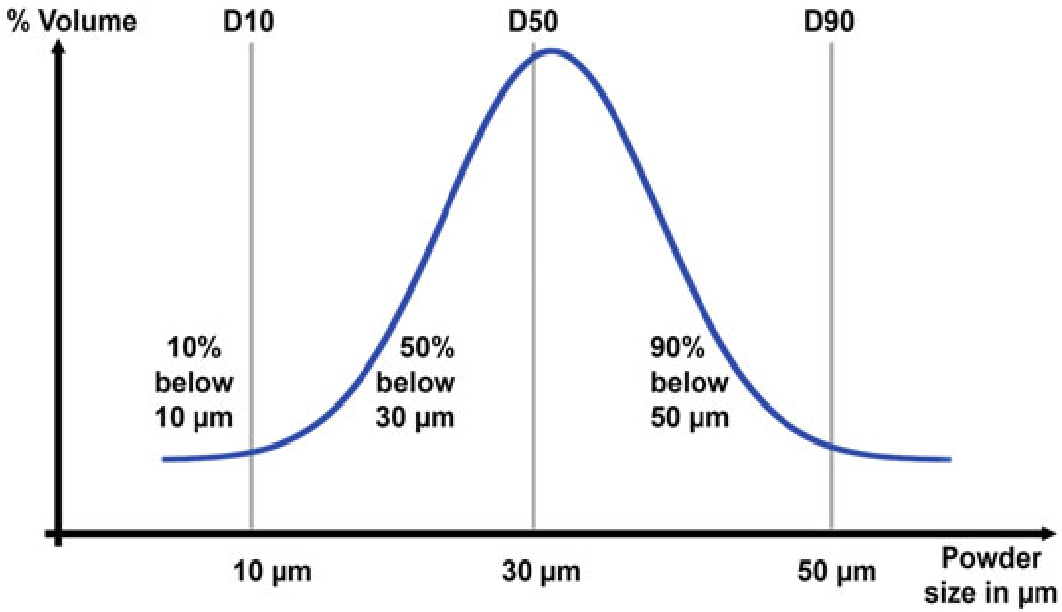
• Satellites which are small powder grains stuck on the surface of bigger grains, which will make it harder to spread or leave 'streaks' in the layer.

• Hollow powder particles, with open or closed porosity. These can explode during the melting process, or can entrap gas in the part which may produce parts with undesirable results.



Design for metal AM: Process details

For powder-bed fusion the powder size most commonly used is between 30 and 40 µm, with a bell-curve distribution with some large and some smaller particles. Some systems that allow for very thin layer thicknesses may require smaller particle sizes. Some materials, such as aluminium, for example, may have a slightly larger powder size distribution than, say, steel or titanium. Larger powder sizes of between 50 and 100–150 µm are commonly used for EBM and DED technologies. The reason a mixed powder size distribution is desirable is so that the smaller particles fit between the larger ones, and allow a denser layer of powder to be spread. If all the particles are exactly of the same size, this will leave gaps between the spread powder particles, which will cause it to collapse, or shrink, more during the meting process.



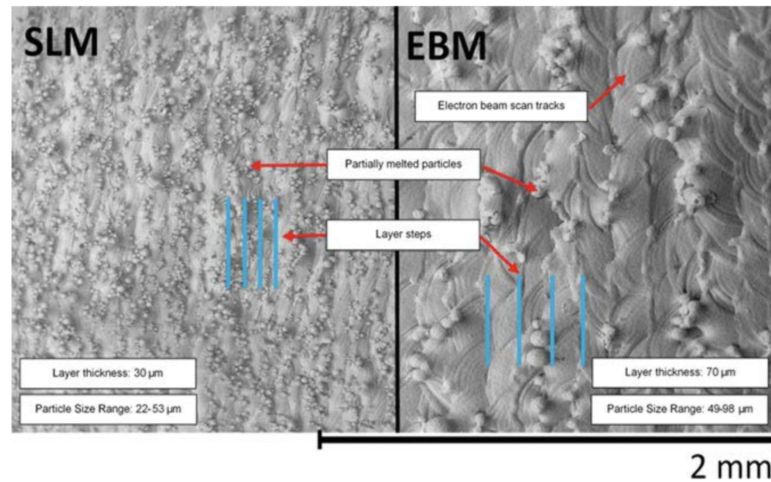
Design for metal AM: Process details

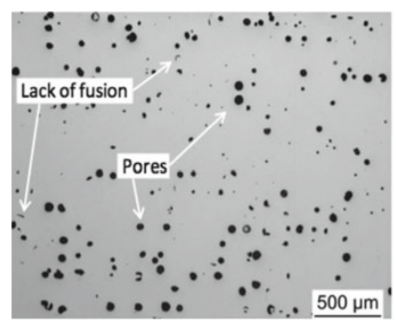
2. Final Part Production and Characteristics

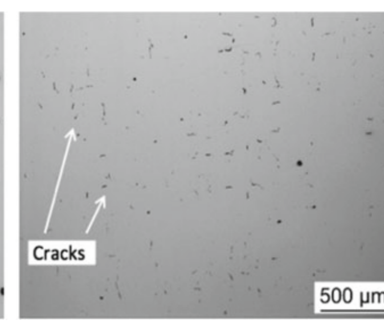
	Mechanical properties	Surface finish
Sand cast	AM superior	AM superior
Investment cast	AM superior	AM inferior
Wrought or forged	AM inferior	AM inferior

Common defects in AM parts:

- *Unmolten powder particles.*
- *Lacks of fusion.*
- *Pores.*
- *Cracks.*
- *Inclusions.*
- *Residual stresses.*
- *Poor surface roughness.*

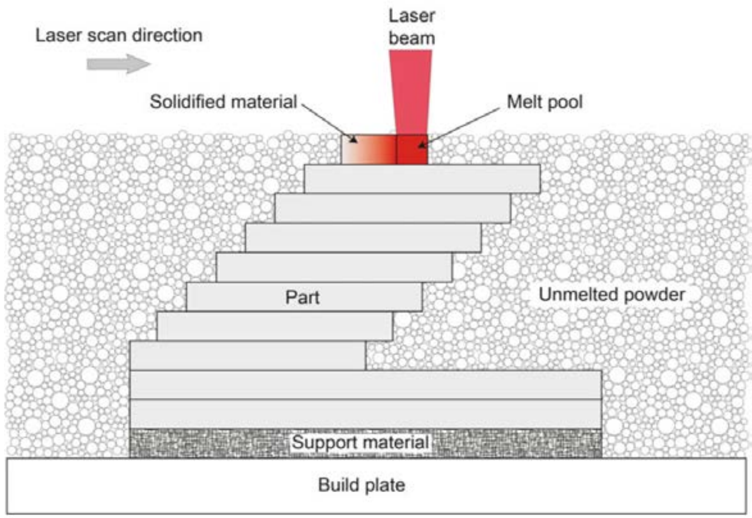




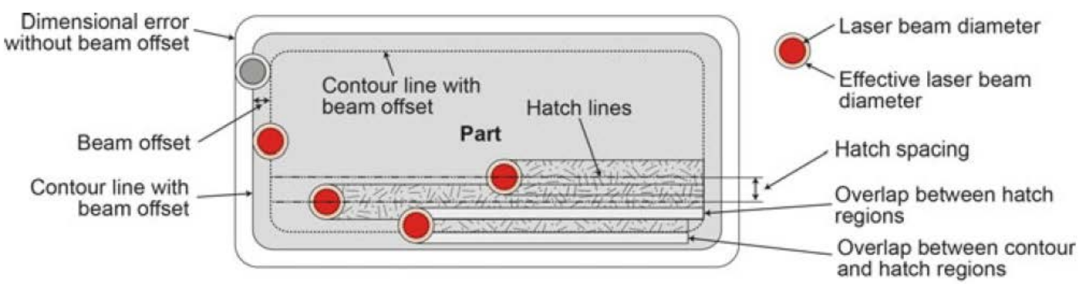


Design for metal AM: Process details

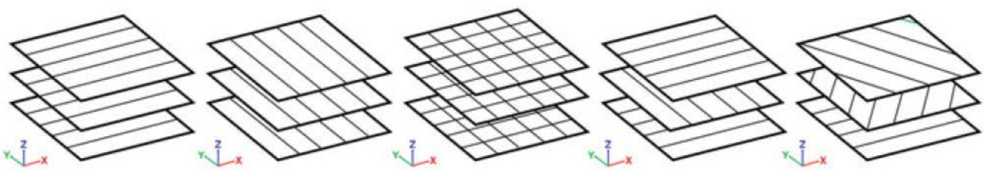
3. Powder bed metal AM process



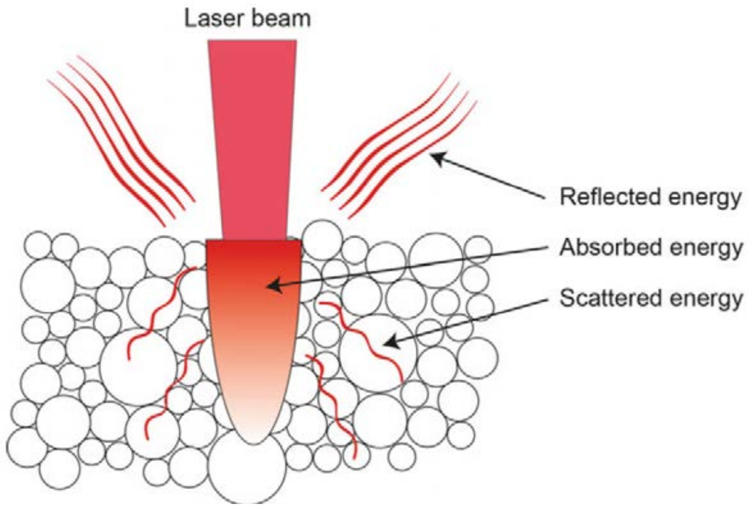
Overall powder bed metal AM build process



Cross section details



Different energy beam scanning strategy

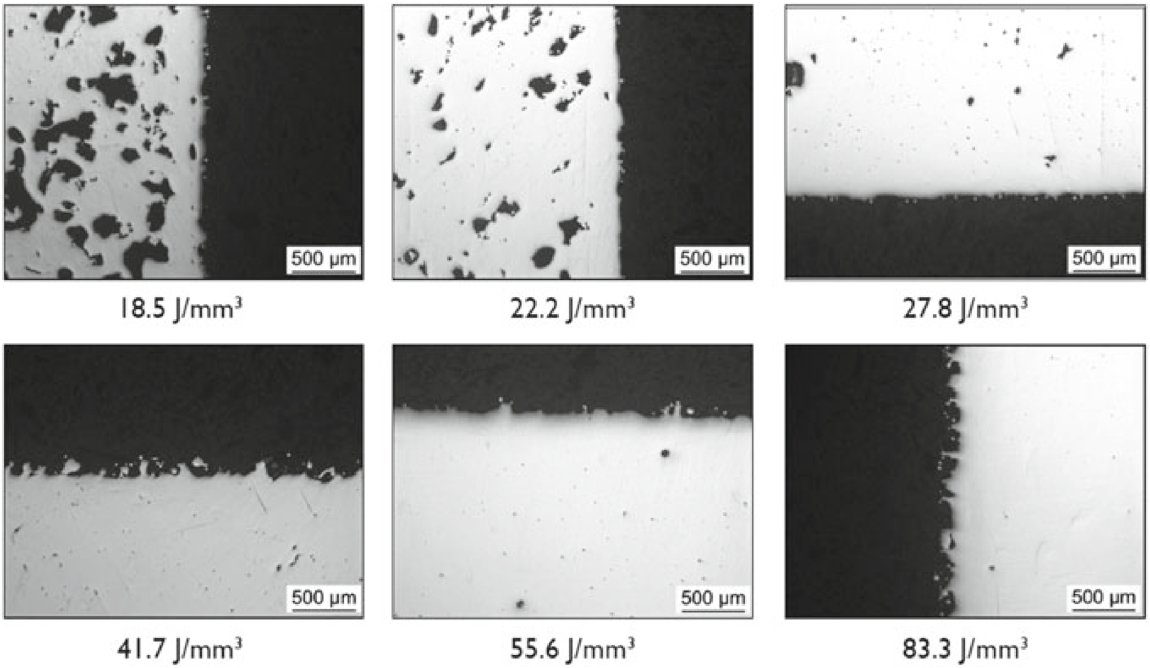


Effect of powder on energy beam absorption

There are also various scanning strategies that can be used in order to minimize the stress in each layer of the part so as to minimize part distortion. A common scanning strategy, for example, is to rotate the scan pattern for each successive layer by 67°. This avoids consecutive layers having exactly overlapping scan patterns, which could increase residual stress in the part.

Design for metal AM: Process details

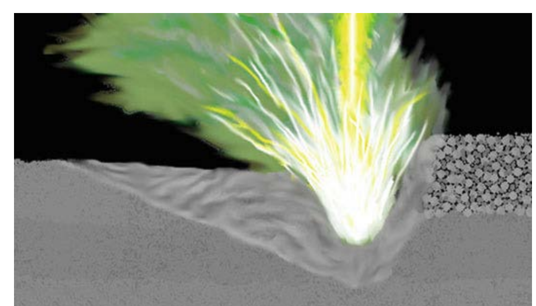
3. Powder bed metal AM process – energy density



$$E = \frac{P}{v \cdot h \cdot t}$$

E = energy density
P = Power (W)
v = Scanning speed (mm/s)
h = hatch spacing (mm)
t = layer thickness (mm)

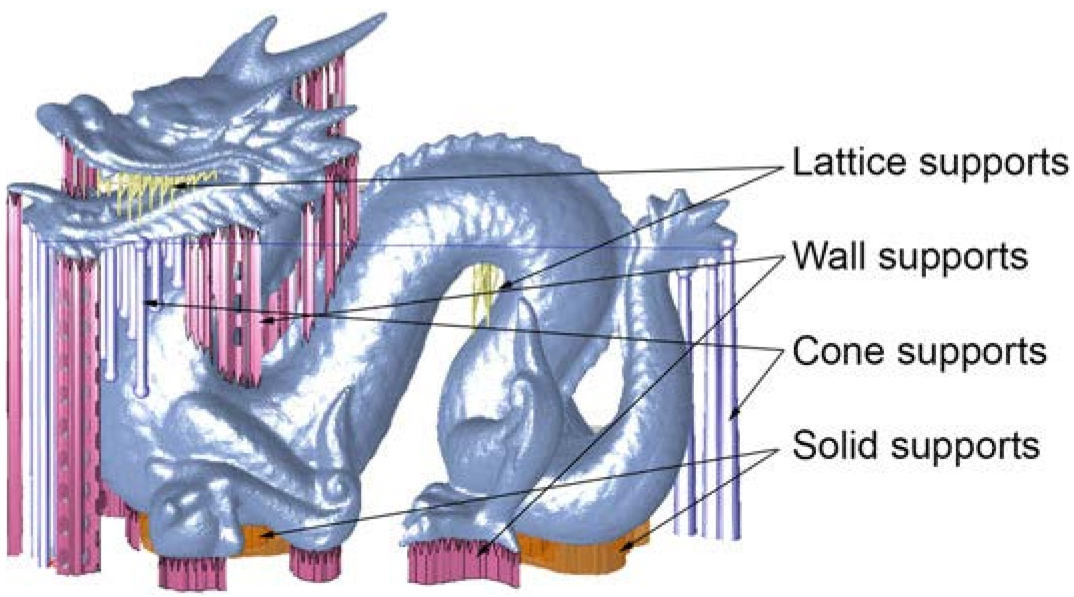
In the example below, using Ti6Al4 V as the material, energy densities above 40 J/mm3 are needed to obtain parts with 99.7–99.9% relative density. As the energy density increases beyond that, part density continues to improve but surface roughness gets worse. This is because the increased energy causes the molten material to be violently agitated, which results in a rougher surface. At an energy density of 30 J/ mm3, however, the part is slightly less dense (but generally still better than 99% dense) but the part has both improved surface quality and minimized defects at the borders.



Design for metal AM: Process details

4. Overhang and support material

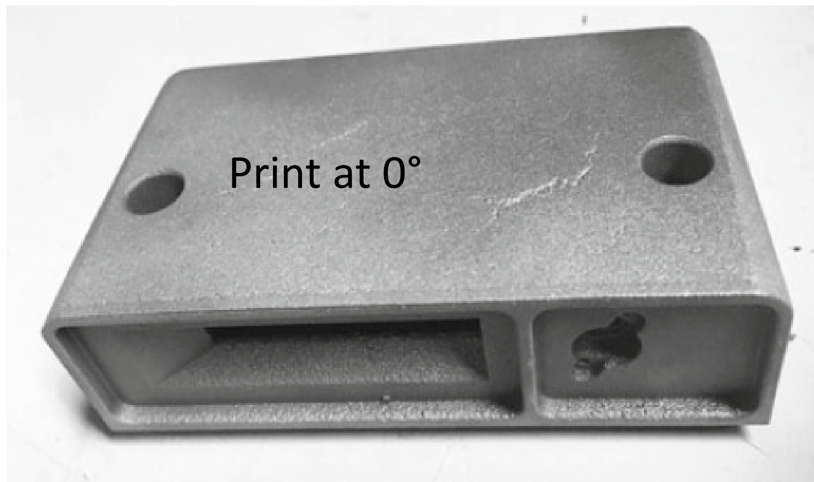
In metal AM, support structures have several functions:
- support the part in case of overhangs.
- strengthen and fix the part to the building platform.
- conduct excess heat away.
- prevent warping or complete build failure.
- Prevent the melt-pool from sinking down into lose powder.
- Resist the mechanical force of the powder spreading mechanism on the part.

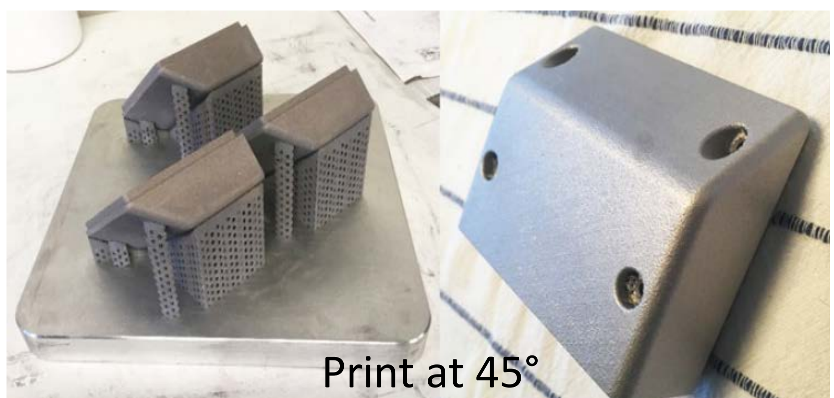


Support generation is almost an engineering art~ many software offer support generation capability as a starting guess

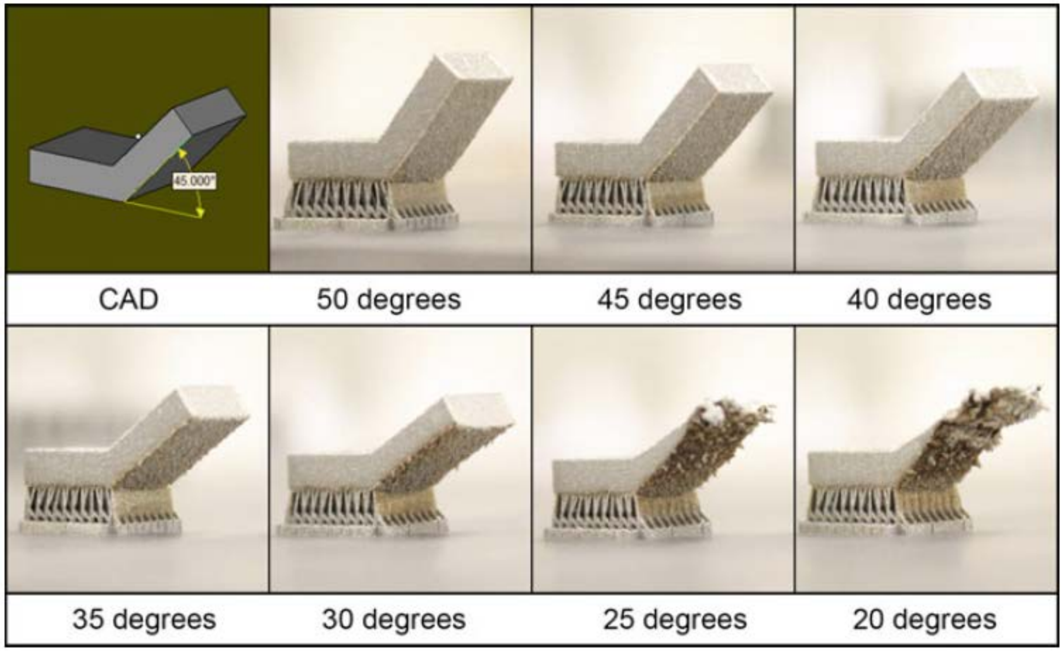
Design for metal AM: Process details

Parts with large horizontal areas of material will, in general, require much stronger supports than the rest of the part. This is because the sudden change in cross section to a large molten sheet of material will cause substantial residual stress and will, in all likelihood, cause cracks in the part if the support is not very strong and dense.

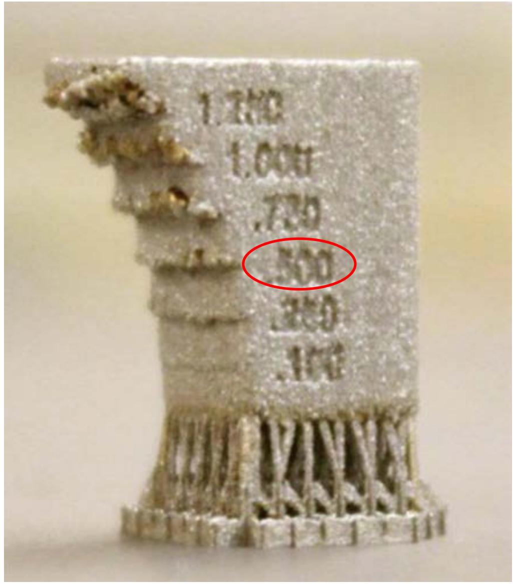




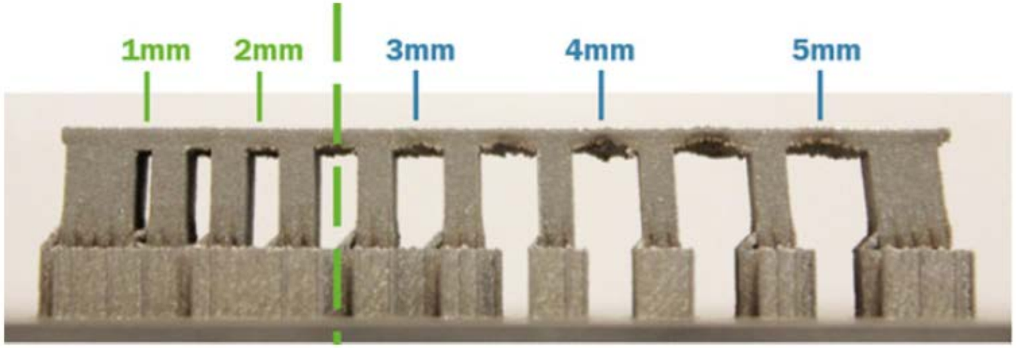
Design for metal AM: Process details



A general rule of thumb for angles that do not require support material are angles greater than 45° from horizontal.



In general, any design with an overhang greater than 0.5 mm will require additional support to prevent damage to the part.



The maximum allowable unsupported distance for the powder bed fusion process is around 2 mm.

Design for metal AM: Process details

4. Design to reduce residual stresses

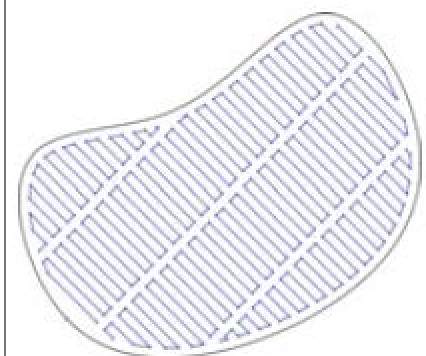
There are a number of relatively simple design techniques that can be employed to minimize residual stress. These include:

- Get rid of areas of uneven thickness. Large masses of material are the single biggest, but easily avoidable, source of residual stress.
- Try to avoid large changes in cross-section. This may, sometimes, mean having to print your component at an orientation other than horizontal.
- Pre-heat the build plate.
- Heat the build chamber.

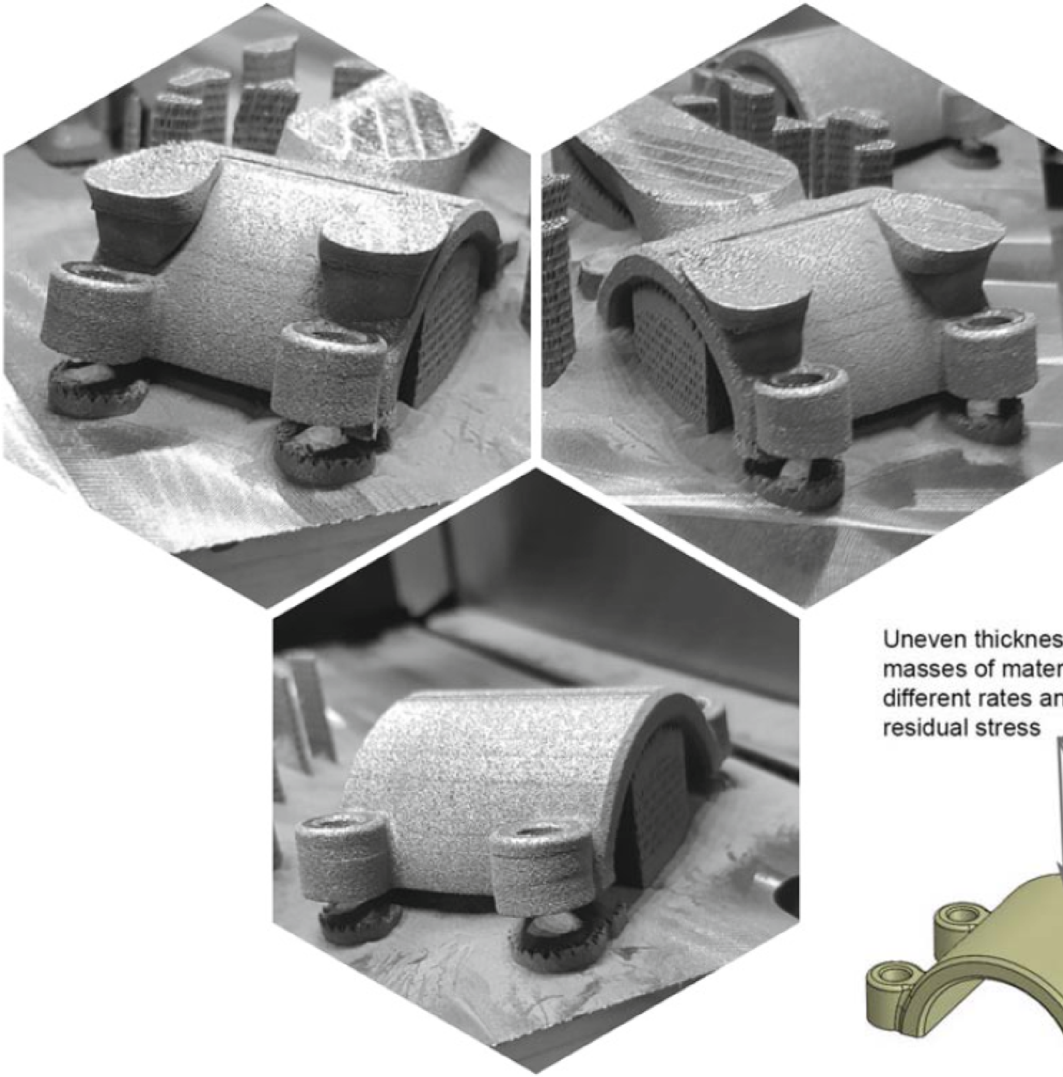
Design for metal AM: Process details

If large masses of material are completely unavoidable (which is rare), use different laser hatch parameter settings to minimize the build-up of residual stress.

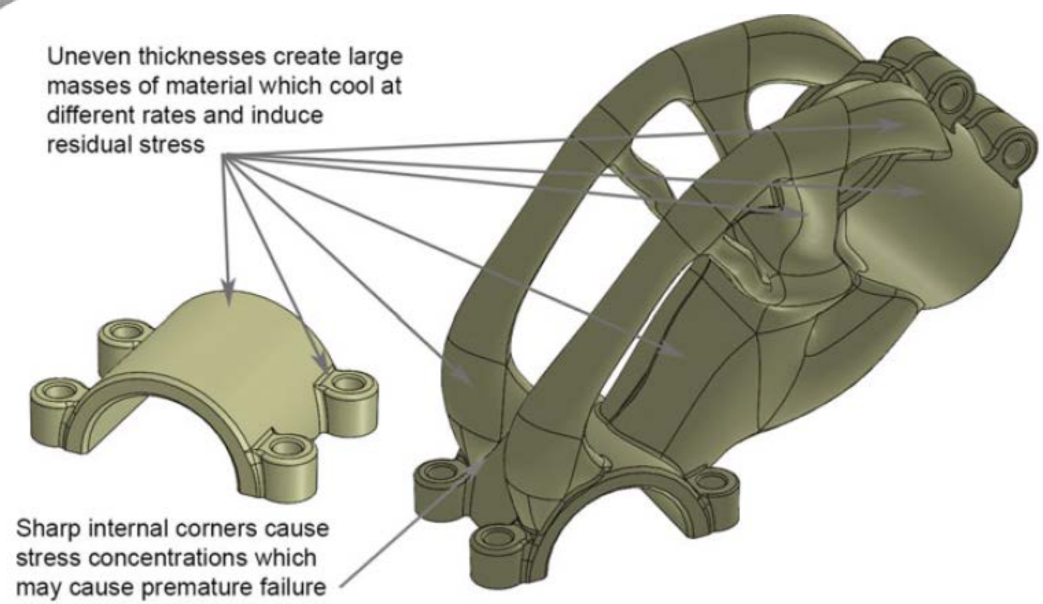
- Smaller chess-board hatch patterns will, for example, create less residual stress than bigger ones, or than large scan areas. But they will slow down the build process a bit.
- Rotate each hatch scan, usually by 67°, for each layer.

		
Meander hatch pattern High build rate Higher residual stress Suitable for small/thin parts	**Stripe hatch pattern** Medium build rate Medium residual stress Suitable for large parts	**Chessboard hatch pattern** Slow build rate Lower residual stress Suitable for large parts

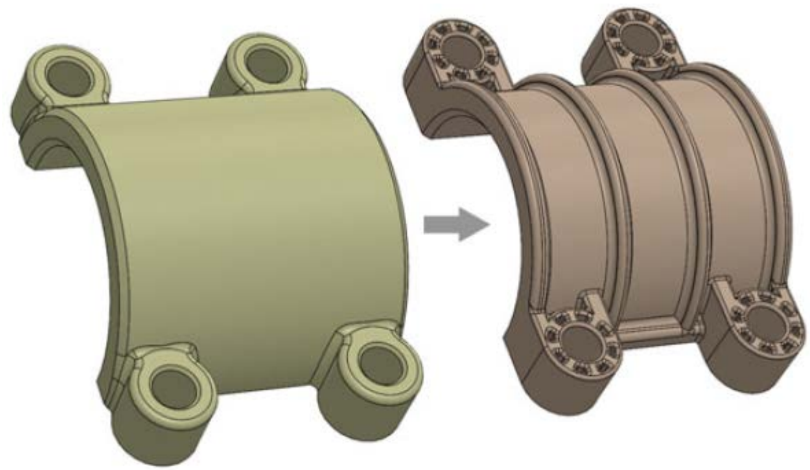
Design for metal AM: Process details



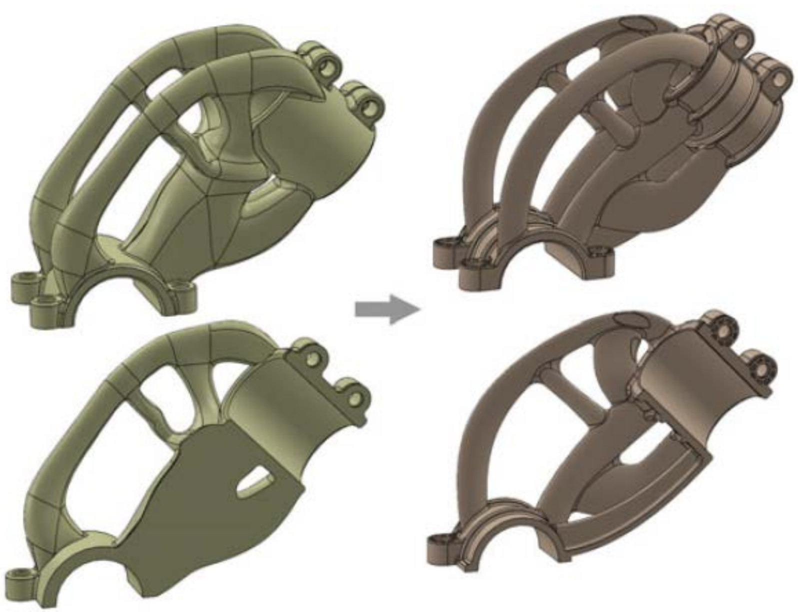
Bracket and clamp design, an example to redesign to reduce residual stresses

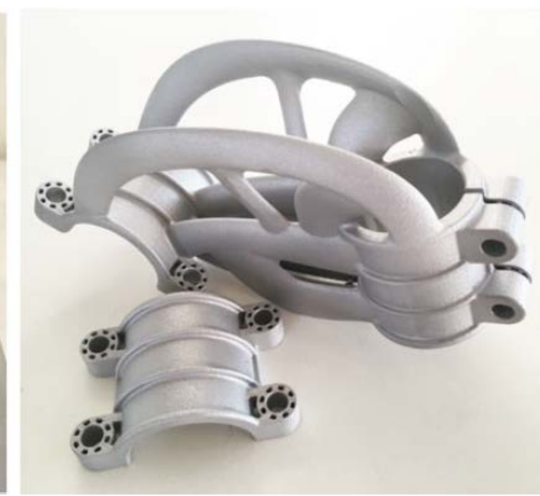


Design for metal AM: Process details



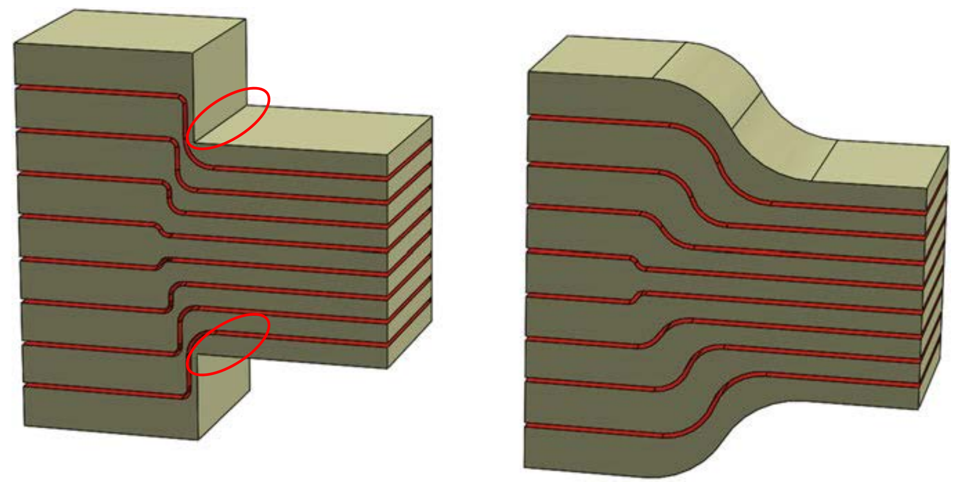
Redesign of small clamp. The new design has an even wall thickness and no areas where stress can build up. It also weighs 25% less than the original

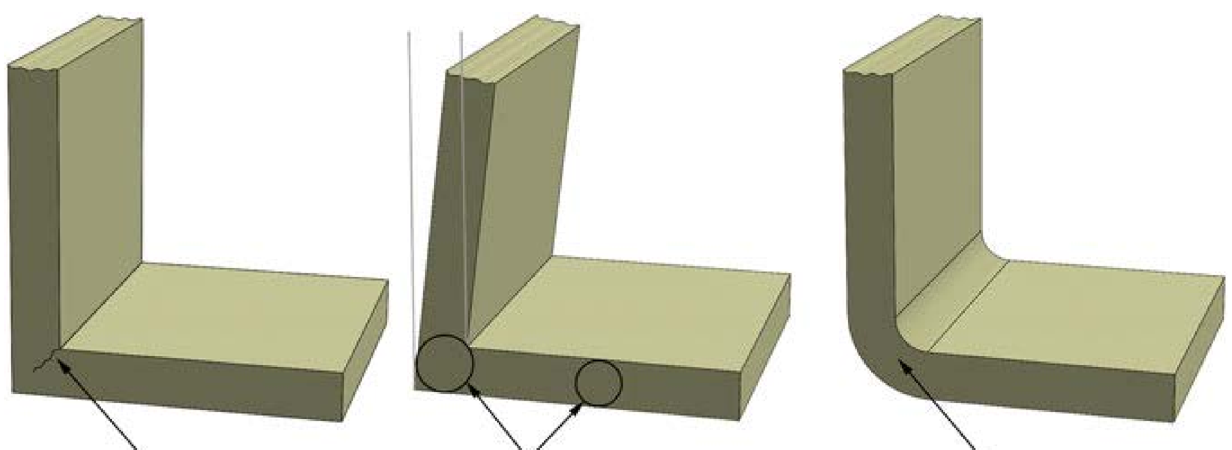




Redesign of main bracket from originally topology optimized bracket. New bracket has relatively even wall thicknesses everywhere. The new design weighs 47% of the original bracket

Design for metal AM: Process details





Stress concentration crack

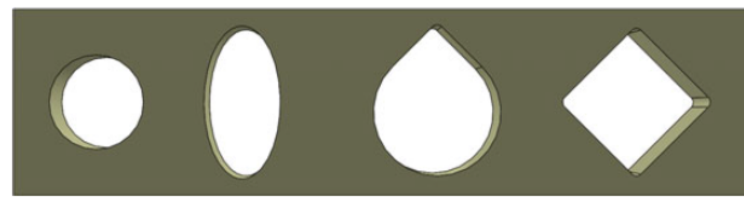
Uneven thickness at corner so risk of residual stress and deformation

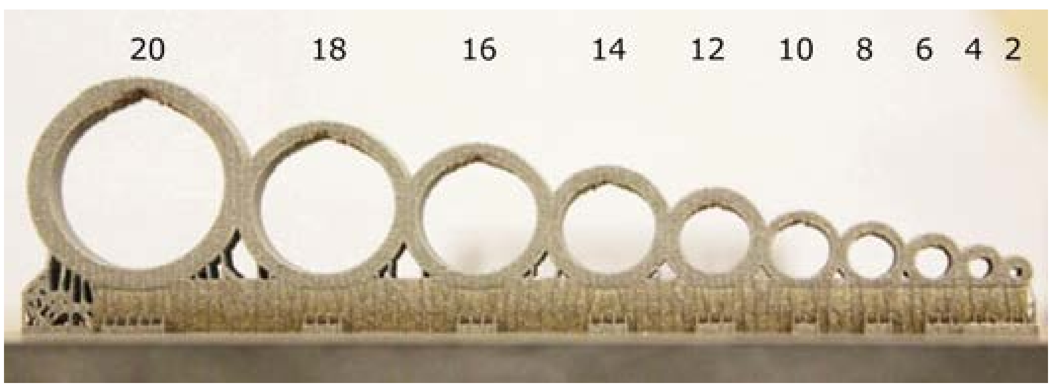
Filleted corner reduces risk of stress concentration and residual stress

Design for metal AM: Process details

5. Horizontal Holes

In metal AM, horizontal holes (or holes angled below the minimum support angle) over a certain diameter will require support material inside the hole. Though this is not necessarily a problem, it should be remembered that it is always harder to remove support material from inside the part than from outside the part. For long holes or pipes that are not perfectly straight, in particular, the support can be hard to remove from inside the pipe. As a general guideline, holes below a diameter of 8 mm can be printed without supports. If larger holes are required, the most common technique is to change the hole from a circular to a shape that can be printed without the need for support material. These shapes commonly include ellipses, teardrops, and diamonds.

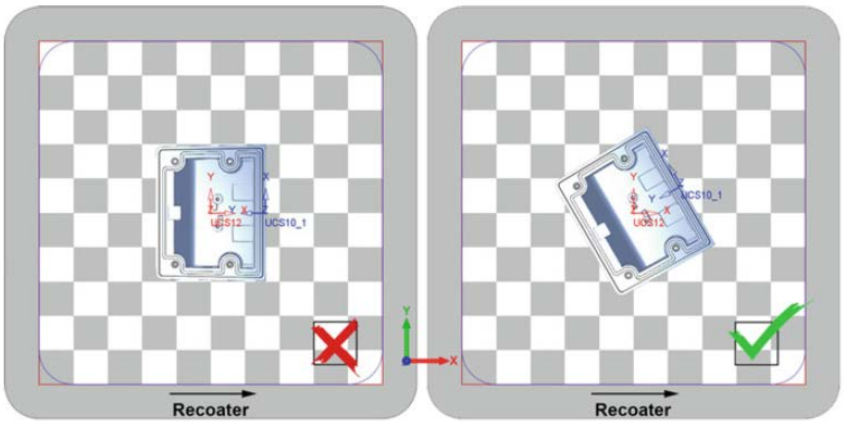




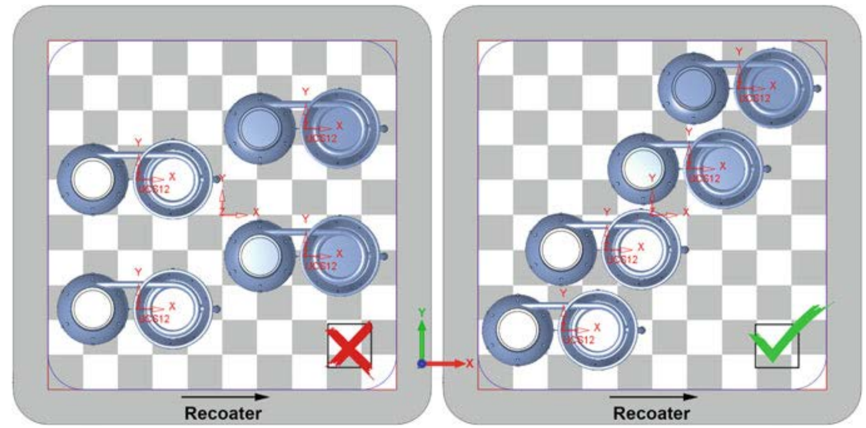
Round holes can, generally, be built without support up to a diameter of around 8mm. Holes larger than this will require supports. Note that this diameter varies based on the machine and material used.	Elliptical holes, when the height of the ellipse is twice the width, can be printed to about 25mm tall, depending on the system being used.	Teardrop shaped holes can be printed to almost any diameter providing the top angle is no less than the minimum support angle. It is good practice to fillet the top of the teardrop to avoid a stress concentration.	Diamond shaped holes can be printed to almost any size. It is good practice to fillet the corners of the hole to avoid stress concentrations in the corners.

Design for metal AM: Process details

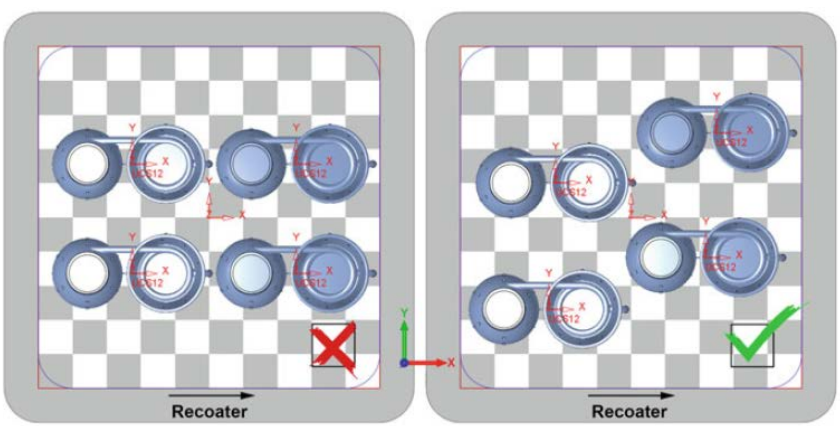
6. General Part Positioning Guideline (if possible)



Avoid parts parallel to the recoater blade

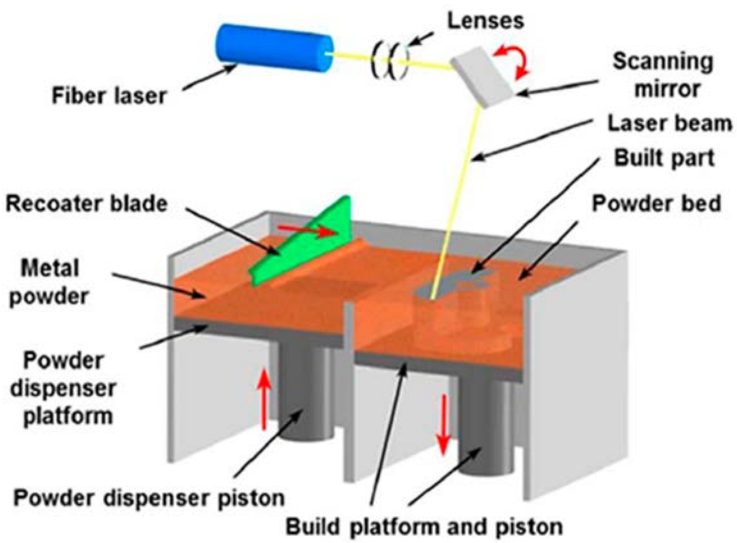


Avoid multiple parts hitting the recoater blade at the same time

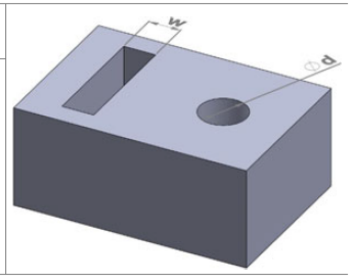


Avoid parts lined up directly behind each other

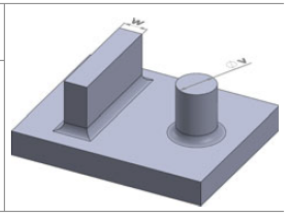
Design for metal AM: Laser Powder Bed Fusion



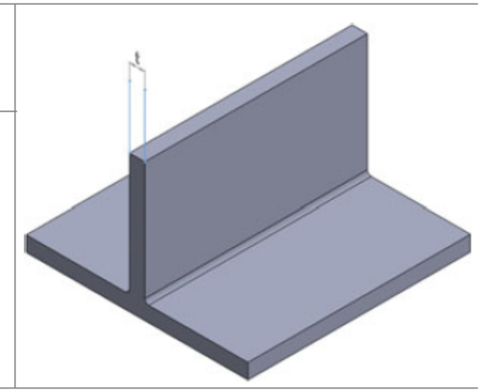
Minimum width for slot (w)	Minimum diameter for circular hole (d)
0.5 mm (0.02 in.)	0.5 mm (0.02 in.)



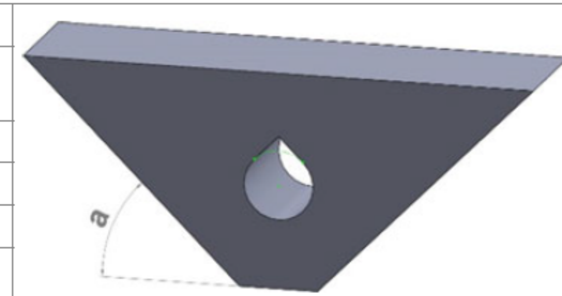
Minimum width for boss (w)	Minimum diameter for circular pin (d)
0.5 mm (0.02 in.)	0.5 mm (0.02 in.)



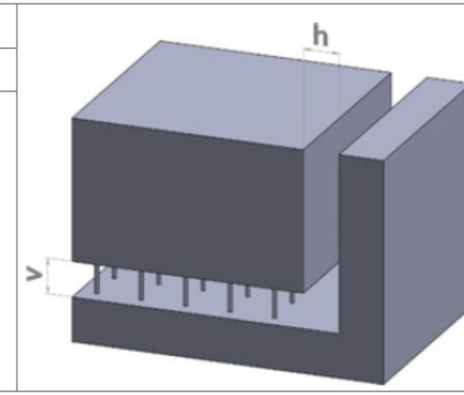
Minimum wall thickness (t)	Recommended minimum wall thickness (t)
0.3 mm (0.016 in.)	1 mm (0.039 in.)



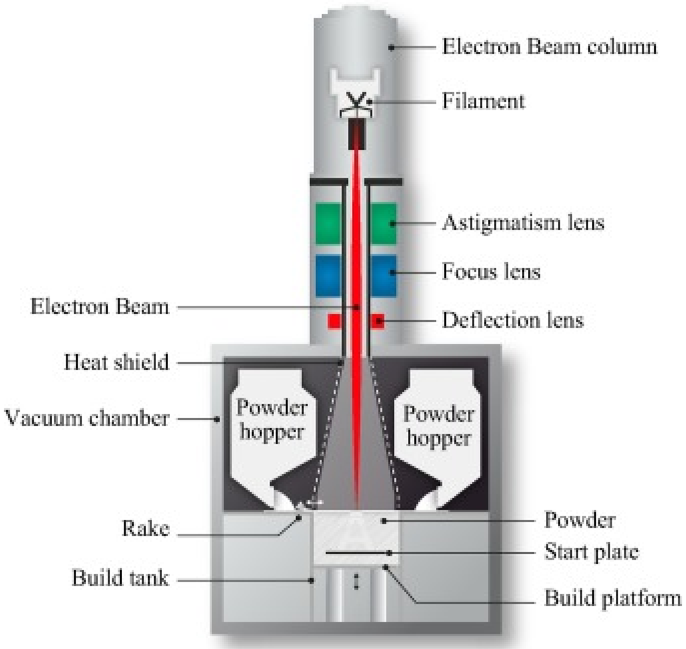
Maximum overhang angle (a)	
DMLS stainless steel	60°
DMLS Inconel	45°
DMLS titanium	60°
DMLS aluminium	45°
DMLS cobalt chrome	60°



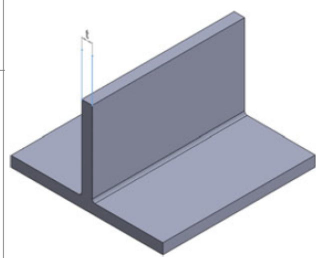
Minimum clearance	
Horizontal (h)	Vertical (v)
0.2 mm (0.079 in.)	Adequate access to facilitate the removal of support material



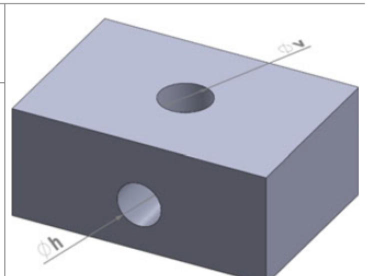
Design for metal AM: Electron Beam Melting

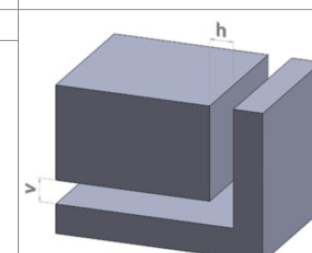


Feature type	Laser powder bed fusion	EBM
Orientation	Upskins/verticals smoother, downskins rougher	Upskins smoother, Vertical/Downskins rougher
Support angle	Bottom edge and surfaces ~45° or less from platform need support	Bottom edge and horizontals or areas vulnerable to over melting and need support
Wall thickness	Minimum 0.3–0.5 mm	Minimum 0.6–1.0 mm
Details	Small details should be oriented upwards to avoid the need for supports/rougher surface textures	
Holes/tubes	>0.5 mm ø vertical; <8 mm ø horizontal without support	>0.5–2.0 mm ø can build but powder removal may be difficult
Machining stock	0.1–0.5 mm to be added to machining surfaces	0.5–2.0 mm to be added to machining surfaces
Clearance	>0.15 mm for assemblies; >1.0 mm between parts	>1.0 mm between parts removal of powder must be considered

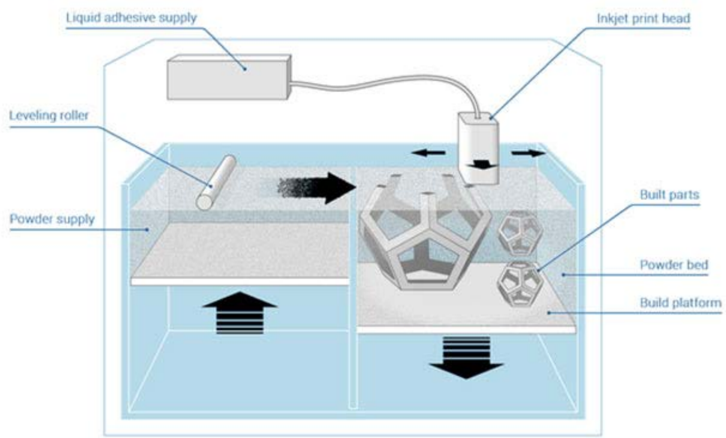
Minimum wall thickness (t)	Recommended minimum wall thickness (t)	
0.6 mm (0.032 in.)	1 mm (0.039 in.)	

Feature type	Laser powder bed fusion	EBM
Hollowing	0.3–0.5 mm min wall thickness, must add powder release hole	0.6–1.0 mm min wall thickness removal of caked powder must be considered
Screw threads	Should be built vertically, must be tapped/machined	Must be tapped/machined

Minimum diameter for circular horizontal hole (h)	Minimum diameter for circular vertical hole (v)	
0.5 mm (0.02 in.)	1 mm (0.04 in.)	

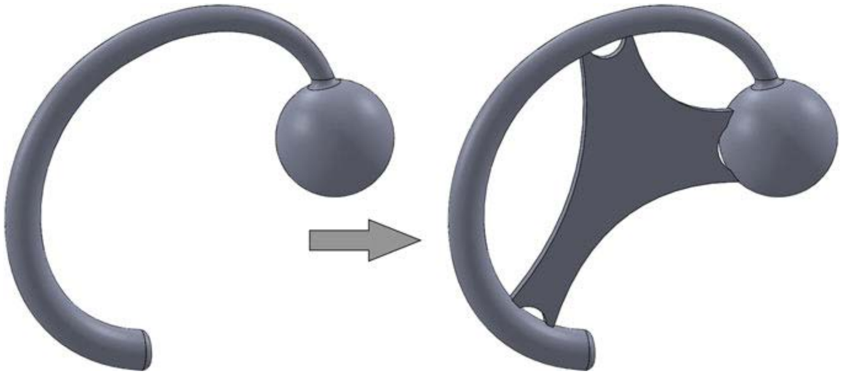
Minimum clearance		
horizontal (h)	vertical (v)	
1 mm (0.04 in.)	1 mm (0.04 in.)	

Design for metal AM: Metal binder jetting

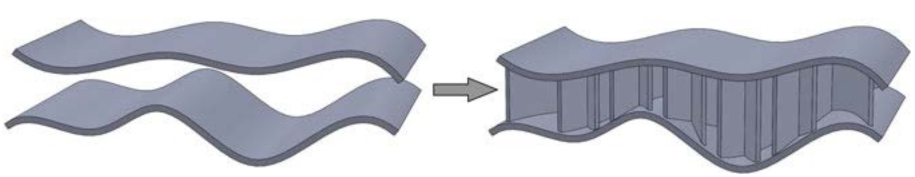


	Binder Jetting Stainless Steel 316 (sintered)	Binder Jetting Stainless Steel 316 (bronze infiltrated)	DMLS/SLM Stainless Steel 316L
Yield strength (MPa)	214	283	470
Elongation at break (%)	34	14.5	40
Modulus of elasticity (GPa)	165	135	180
Surface roughness without post-processing (µm)		Ra 15	Ra 15–50

Binder Jetting metal parts will typically have some internal porosity. Bronze infiltrated parts will typically be 90% dense. Sintered stainless steel parts will typically be 97% dense.



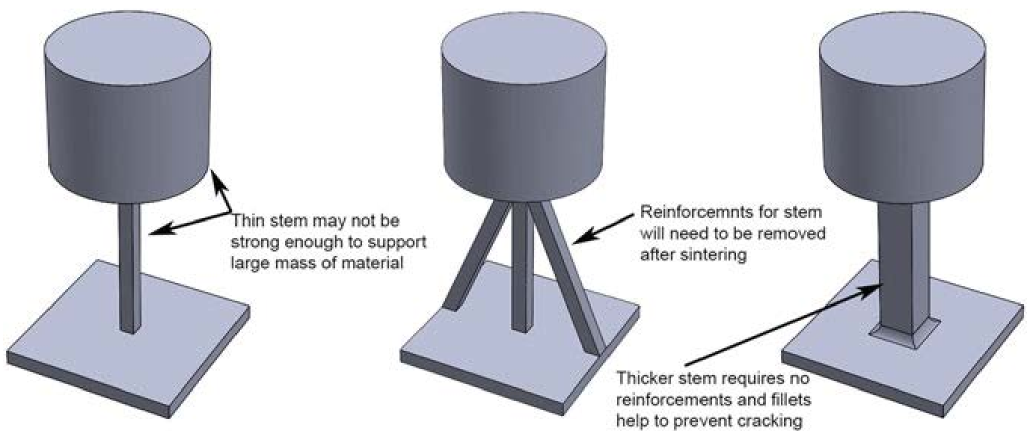
Making the part strong enough to handle in its green state

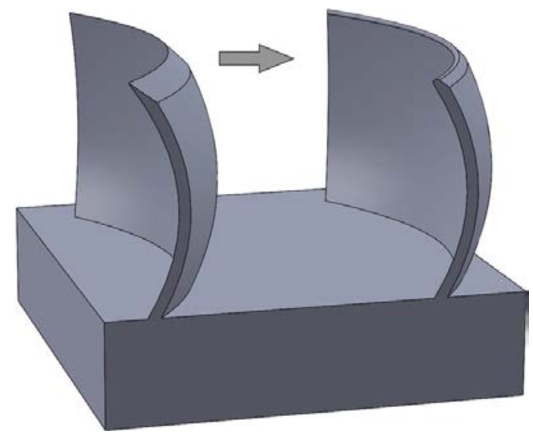


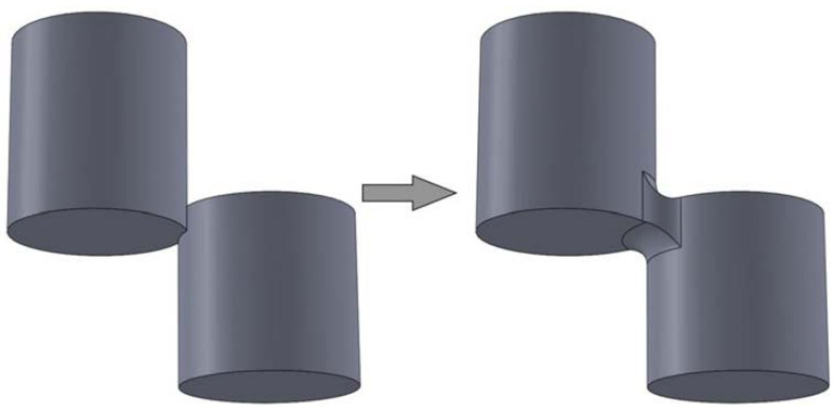
Avoid large surface area unsupported walls

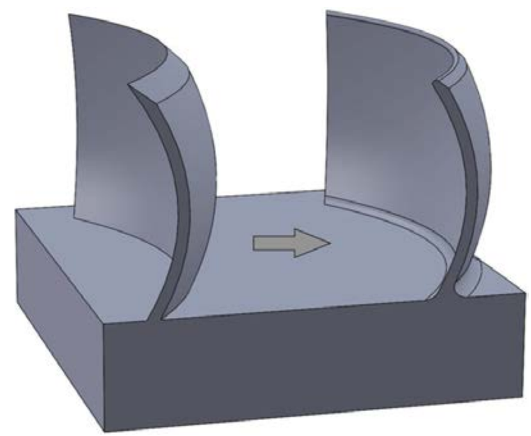
Design for metal AM: Metal binder jetting

The Most Important Design Rule for Metal Binder Jetting: Green parts are fragile. Everything in your design is influenced by this.



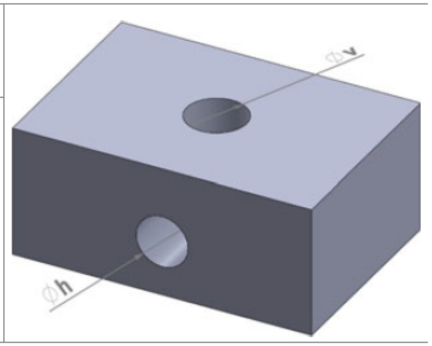




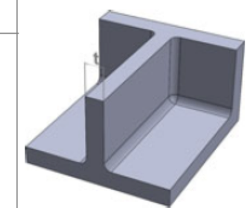


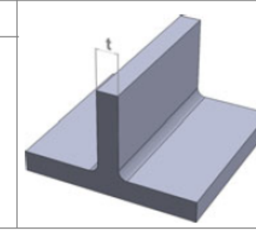
Design for metal AM: Metal binder jetting

Minimum diameter for circular horizontal hole (h)	Minimum diameter for circular vertical hole (v)
2 mm (0.078 in.)	(0.06 in.) 1.5 mm

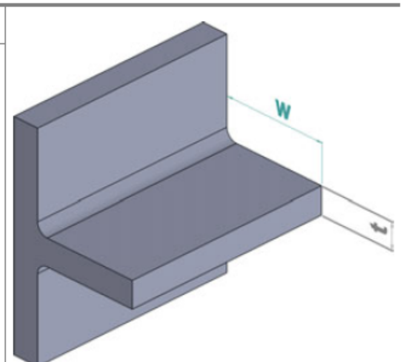


Build size	Minimum wall thickness
3–75 mm (0.125–3 in.)	1.0 mm (0.04 in.)
75–152 mm (3–6 in.)	1.5 mm (0.06 in.)
152–203 mm (6–8 in.)	2.0 mm (0.08 in.)
203–305 mm (8–12 in.)	3.2 mm (0.12 in.)





Minimum thickness (t)	
Thickness	>2 mm (0.08 in.)
Width	25 mm (1 in.)



Minimum diameter for salt-shaker hole (d)
5 mm (0.2 in.)

Thank you for your attention

and don’t forget ink (material) jetting, DED and extrusion ~