M.Tech
Digital Manufacturing

BITS Pilani
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Guest Faculty

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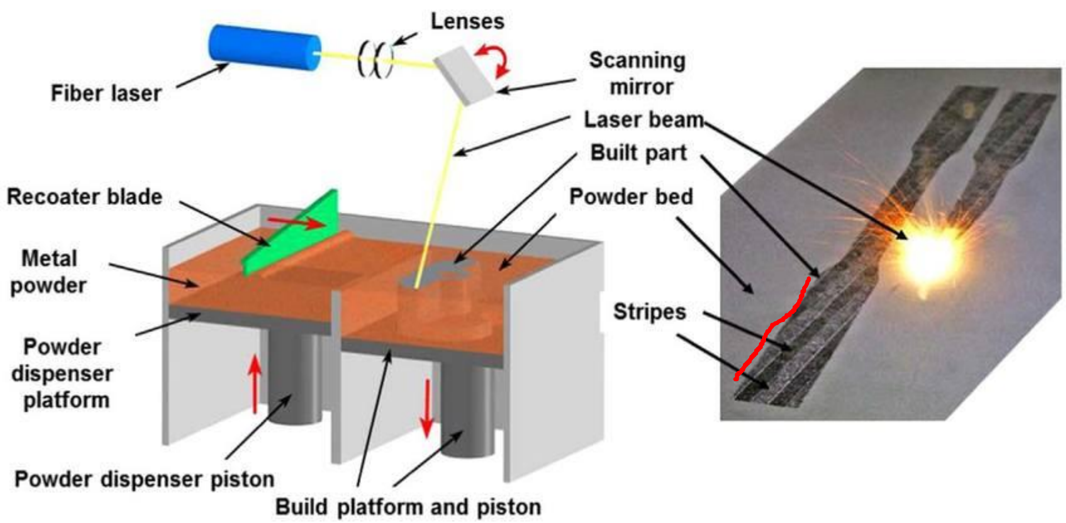
DMZG521- Design for Additive Manufacturing
Session 11 & Lecture 21-22

Process factors in PBF and DED

- Process Factors
  - Laser related
    - Power
    - Spot size
    - Wavelength
    - Beam Type
  - Scan Related
    - Scan Speed
    - Hatch Spacing
    - Scan strategy
  - Powder related
    - Powder size
    - Powder morphology
    - Powder Bed density
    - Layer thickness
    - Material properties
    - Powder flow rate
  - Temperature related
    - Powder bed temperature
    - Powder feeder temperature — DED
    - Temperature uniformity

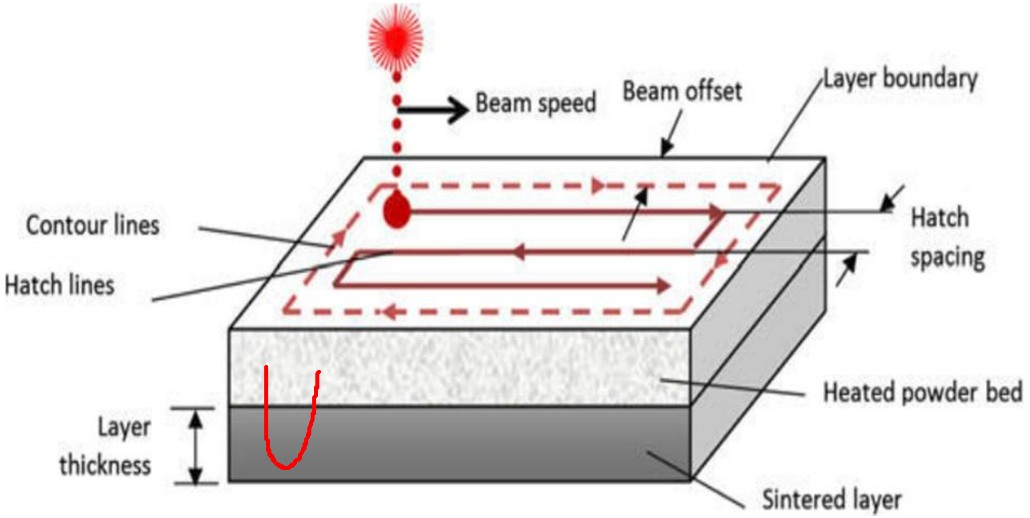
Laser power

- The current laser has a maximum output power of 400W.
- 1 kW lasers are also available on certain machines
- Laser power α melting point of material
- Laser power determines the density of the part



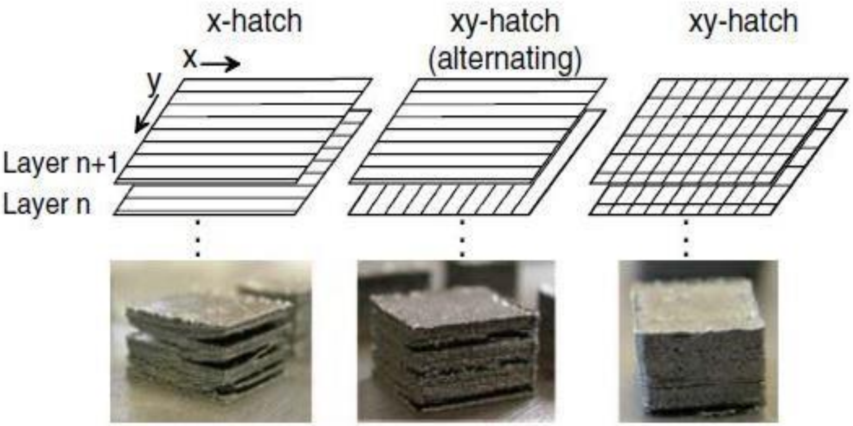
Energy density

- The melt pool formation and other part characteristics are determined by the total amount of applied energy
- $E_A = P / (h \times t \times U)$
- P is laser power, U is scan velocity, t is the layer thickness and h is the scan spacing (hatch spacing)

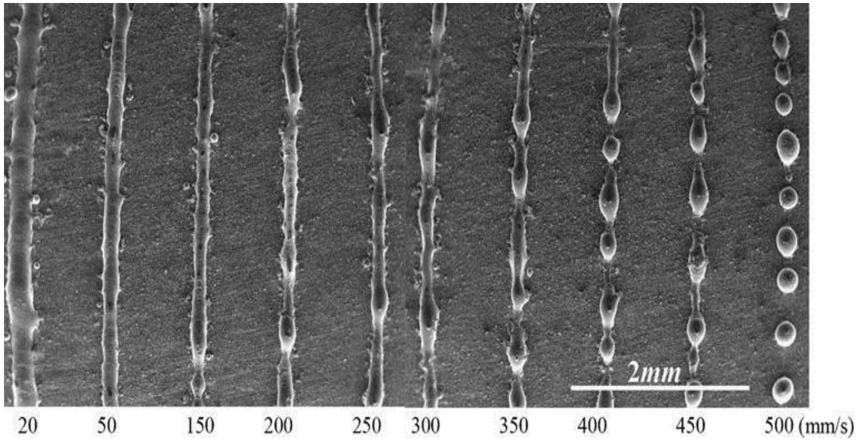


Process parameters in PBF process
Senthilkumaran et al. (2009)

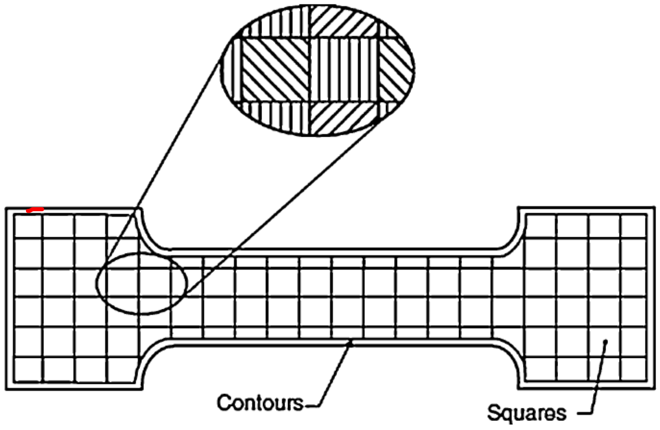
Scan Speed & Hatch Pattern



Effect of scanning pattern on delamination
(Zaeh et al., 2009)

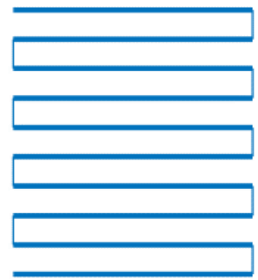


Balling defects of single scan tracks under different scan speeds
(Li et al., 2012)



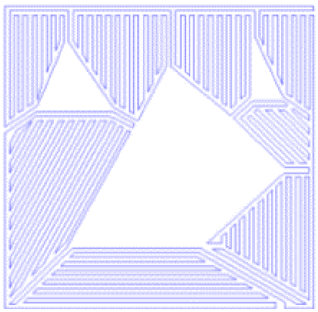
Scan Strategy

Raster

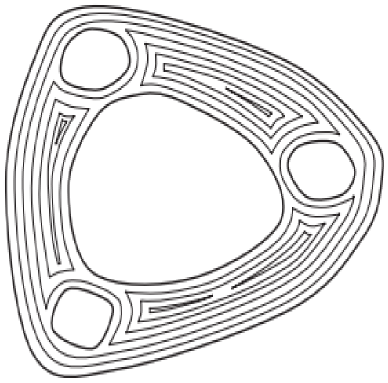


Zig-Zag

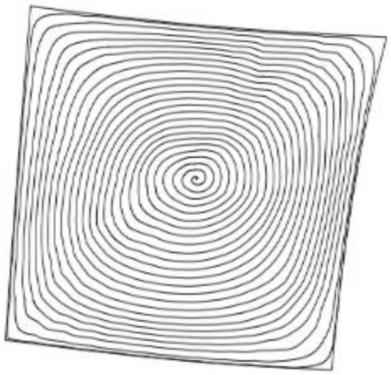
Hybrid



Continuous



Contour



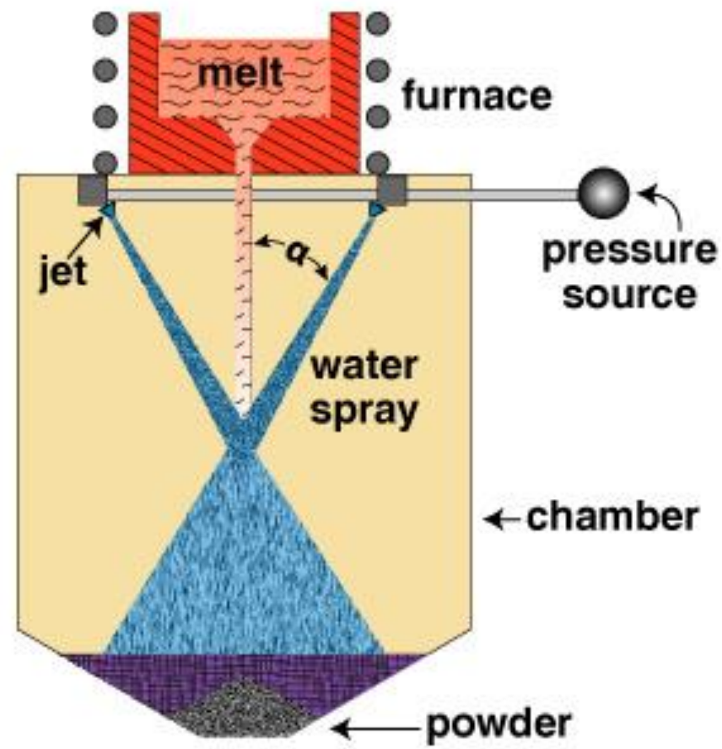
Spiral

Powder related parameters

- Particle shape
- Size
- Distribution
- Powder bed density
- Layer thickness
- Material properties

Powder manufacturing techniques

- Solid-State Reduction
- Atomization
- Electrolysis
- Chemical



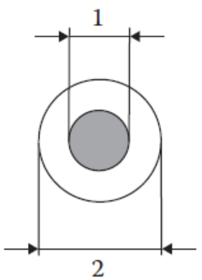
The water atomization process, where a molten metal stream is disintegrated by multiple water jets. The angle determines the atomization efficiency.
(Source: *Fundamentals of Powder Metallurgy*)

Powder spreading

Source: altair
https://www.youtube.com/watch?v=x7jxg26vY20&list=PL4DHAcvLtNm4YkgwU_MSI8mcb5S99Sr8P&index=9

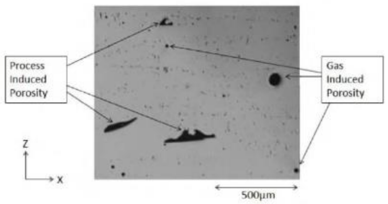
Thumb rule for process parameters in PBF

- Study the wettability and viscosity of the powder material
- Consider the different forces like buoyancy force, gravity force and convective force
- Spot size = 2 X diameter of beam
- Layer thickness = 3 X average size of powder particle



1 Diameter of the laser beam
2 Diameter of the curing zone

Defects in metal AM process



Process induced porosity and gas induced porosity in Inconel 718 part processed by EBM *(Sames et al., 2014)*

Cracking

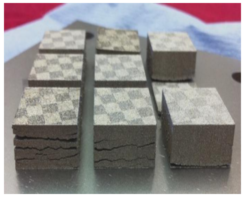
Porosity

Distortion

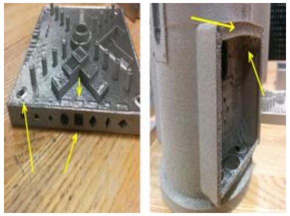
Defects

Balling

Delamination



Cracking due to thermal stresses (SLM)
(Kempen et al., 2013)



EBM-printed Ti–6Al–4V parts with defects
(Sames et al., 2016)

Melt ball formation occurs due to improper process control (EBM).
(Kahnert et al., 2007)

Delamination occurs due to residual stresses.
(Kahnert et al., 2007)

DEFECTS IN METAL AM PROCESS - Cracking

TYPES OF CRACK FORMATION
- Solidification cracks,
- Grain boundary cracks and
- Volumetric defects or voids

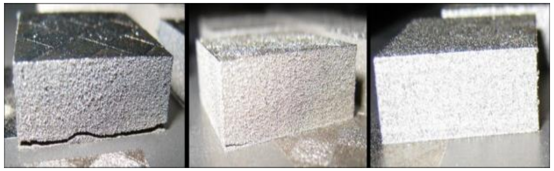
[Alexander McNutt, 2015]

CONTROL MEASURES

•Preheating the substrate which means reducing the temperature gradient.
[*K. Kempen et al., 2013*]

PROCESS PARAMETERS

•Highly influenced by laser power and scanning speed.
•Less influenced by laser spot diameter and deposit dilution
•Tool path patterns.
•High energy and temperature.
[W. J. Sames, 2016]



Parts fabricated without Preheating and Preheating substrate
(Kempen et al., 2013)

RESULTS
- Poor mechanical strength of the part.

DEFECTS IN METAL AM PROCESS - Delamination

- Delamination is the separation of adjacent layers within parts due to incomplete melting between layers.
- Delamination are macroscopic and cannot be repaired by post-processing. *[Sames et al., 2016]*

REASONS:

- Improper heat transfer between layers.
- Lack of fusion between deposited layers.

PROCESS PARAMETERS

- Scan speed
- Laser power
- Layer thickness
- Scanning strategy

[M. F. Zah and S. Lutzmann, 2010]

Delamination betweenlayers
(Kahnert et al., 2007)

DEFECTS IN METAL AM PROCESS - Distortion

REASONS

•Operating temperature of the AM process.
•Increase in dwell time between the layers increases accumulation of residual stress.
•Material.
[Peter Mercelis , J.P. Kruth, 2006], [Erik R. Denlinger, 2015]

RESULTS

•Distortion of part geometry and affect mechanical property.
•Possible lack-of fusion or delamination.
•Propagation of cracks.
•Cause changes in grain structure.
[J.P. Kruth et al., 2004]

CONTROL MEASURES

- Heating of the substrate.
- Using different scan patterns.
- Annnealing

[L. N. Carter et al., 2012]

IN-PROCESS MEASUREMENTS

•Optical measurement system.
- Digital image *correlation [Ocelik et al., 2009]*.

•LVDT setup *[Plati et al., 2006]*
•Laser displacement sensor *[Erik R. Denlinger et al., 2015].*

POST PROCESS MEASUREMENTS

- CMM and Hole drilling method *[Erik R. Denlinger et al., 2015].*
- Crack Compliance Method [*Peter Mercelis et al., 2006*]
- X-ray diffraction.

DEFECTS IN METAL AM PROCESS - Porosity

TYPES OF POROSITY DEFECTS

•Gas-induced Porosity

- It occurs when air or gas gets trapped inside the powder particles while production.

•Process- induced porosity

- when the applied energy is not sufficient for complete melting or spatter ejection occurs.

[Kobryn et al., 2000]

CAUSES

•Different tool path strategies.

•Powder quality (size, shape, surface morphology, composition and amount of internal porosity).

[Sames et al., 2016]

RESULTS

•Leads to micro cracks which lead to failure of components as the crack propagates further.

•Causes lack of fusion between particles.

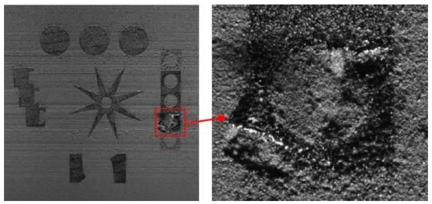
PROCESS PARAMETERS

- Laser scan speed
- Laser power

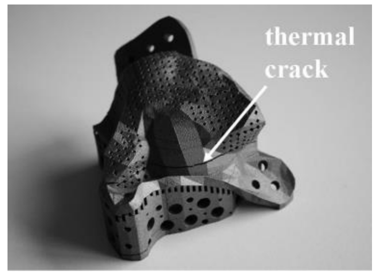
PREVENTIVE MEASURES

- Hot Isostatic Pressing (HIP) to close the pores.

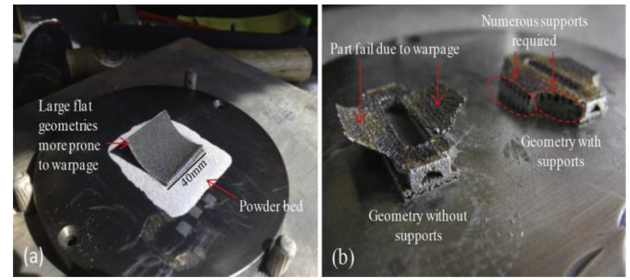
Defects in SLM/SLSprocess



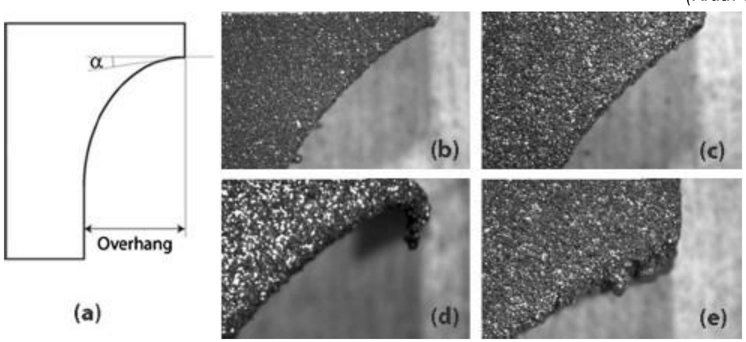
Defect caused due to recoater blade damage
(Kleszczynski et al., 2012)



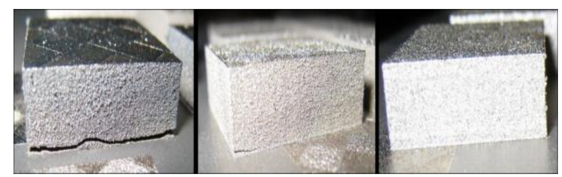
Selective laser melted part with cracks induced by thermal stresses.
(Kruth et al., 2012)



(a) Warpage of part without supports and (b) with and without supports for different geometry.
(Vora et al., 2015)

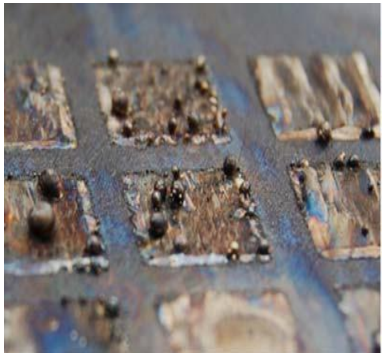


(a) Concave radii. Titanium: (b) overhang of 9 mm, (d) overhang of 15 mm. Aluminum: (c) overhang of 9 mm,
(e) overhang of 15 mm.
(Calignano, 2014)

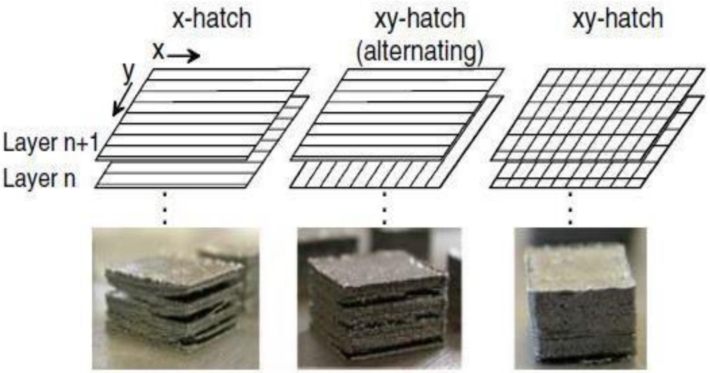


Parts fabricated without Preheating and Preheating substrate
(Kempen et al., 2013)

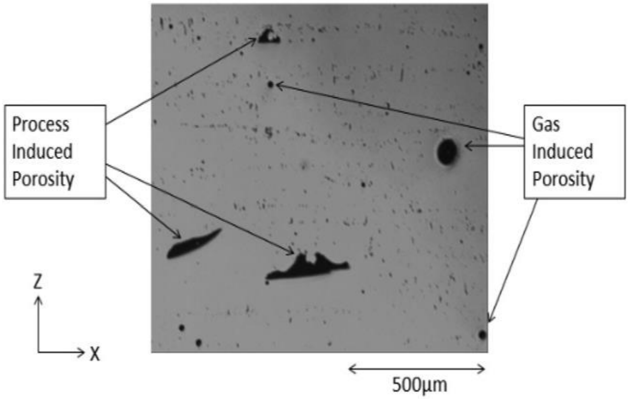
Defects in EBM process



Melt ball formation occurs due to improper process control
(Kahnert et al., 2007)

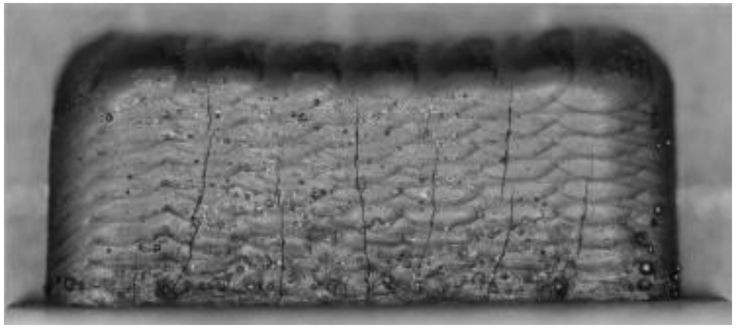


Effect of scanning pattern on delamination
(Zaeh et al., 2009)

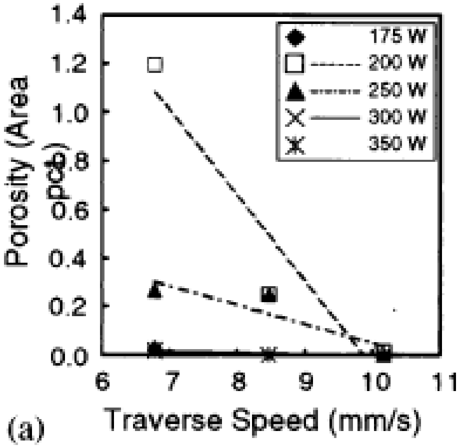


Process induced porosity vs. gas induced porosity for the GA - Vertical sample (EBM – IN 718)
(*Sames et al., 2014****)***

Defects in DMD process



Crack formation in laser deposited CM247LC nickel super alloy
(Mcnutt et al., 2015)

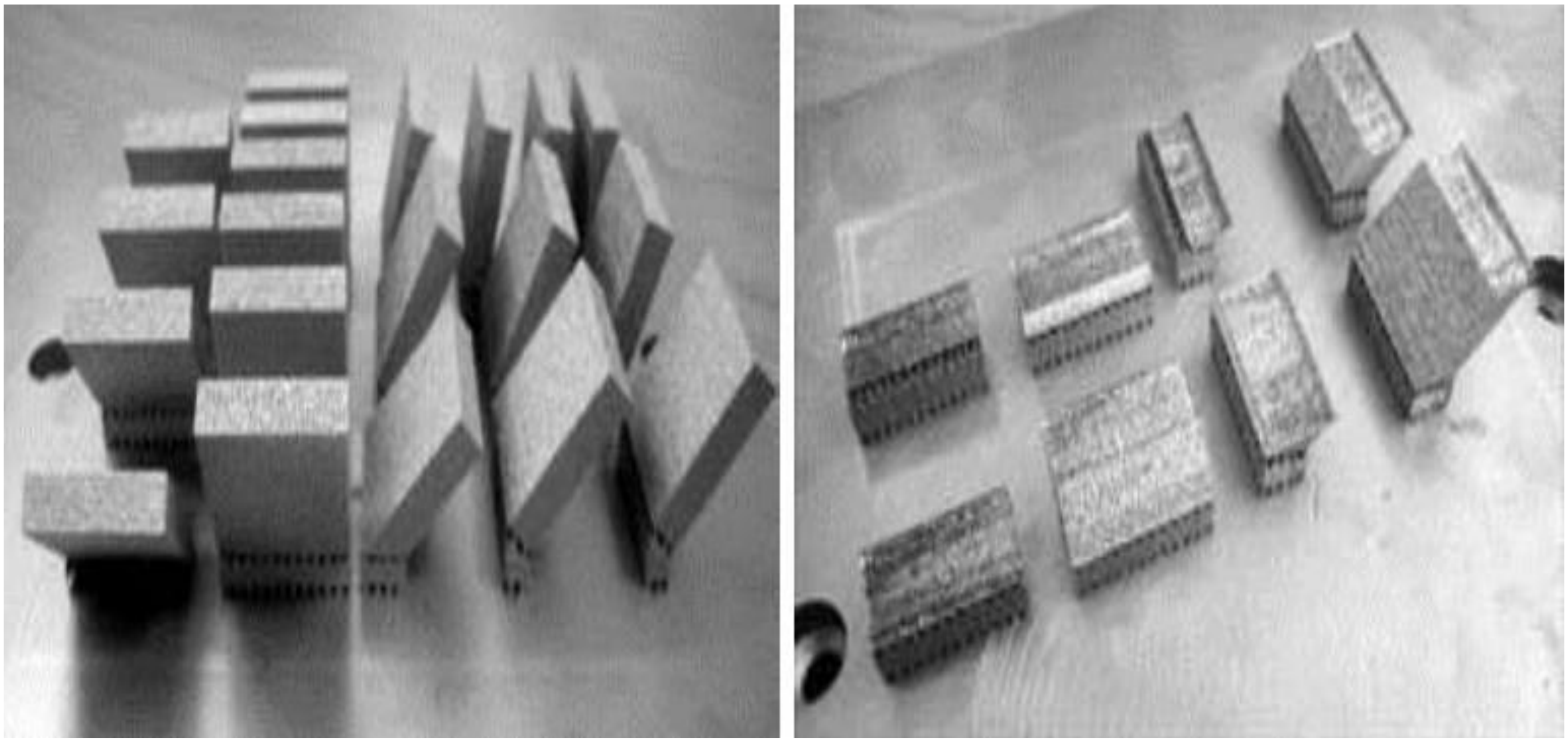


Porosity as a function of traverse speed for laser-deposited Ti-6Al-4V parts.
(Kobryn et al., 2000)

Classification of defects

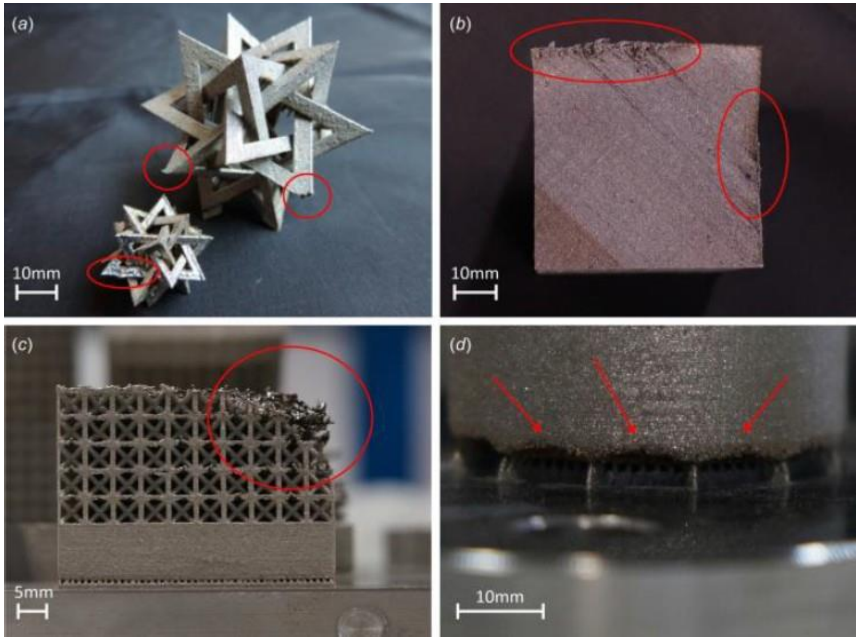
- **Classification of defects based on**
  - Geometry of the part, orientation and supports
  - Improper process control
  - Material
  - Physical phenomenon

Defects based on geometry of the part, supports and orientation



Successfully built parts with orientation of 45⁰ and 90 ⁰ (left) and Failed part builds with orientation of 25⁰ and 40⁰ (right)
(*Thomas et al., 2008*)

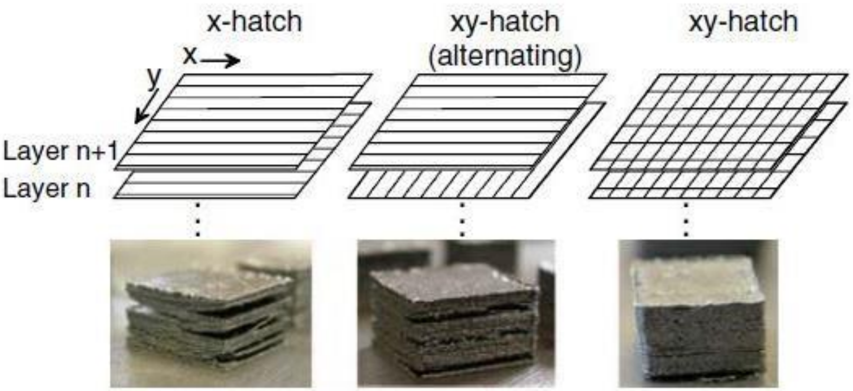
Defects based on geometry of the part, supports and orientation



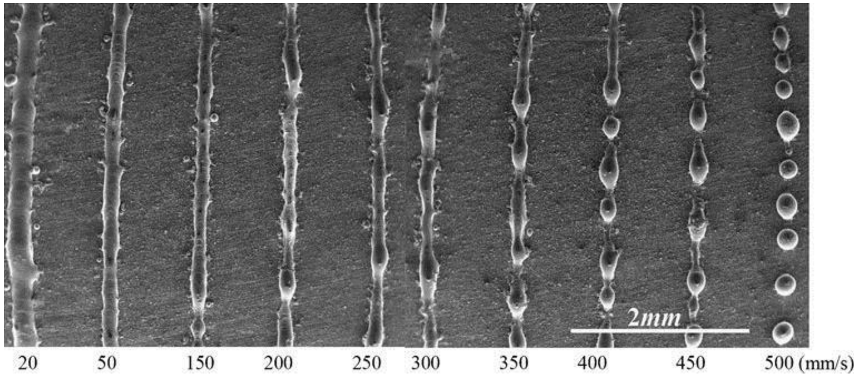
Geometrical Defects in metal AM parts due to (a) Sharp corners (b) poor contour (c) lattice structures and (d) support interface with the part.

(Craeghs et al., 2011)

Defects based on Improper process control

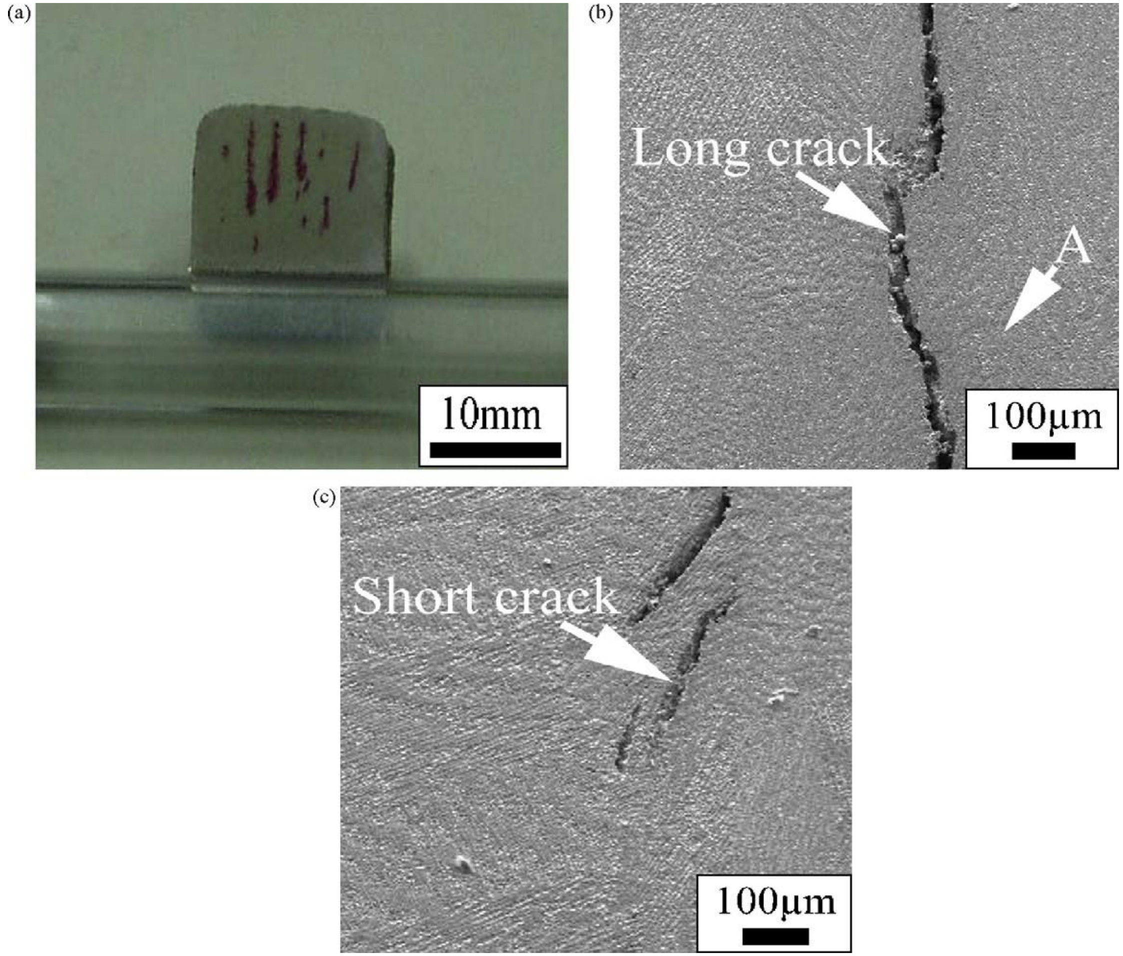


Effect of scanning pattern on delamination
(Zaeh et al., 2009)



Balling defects of single scan tracks under different scan speeds
(Li et al., 2012)

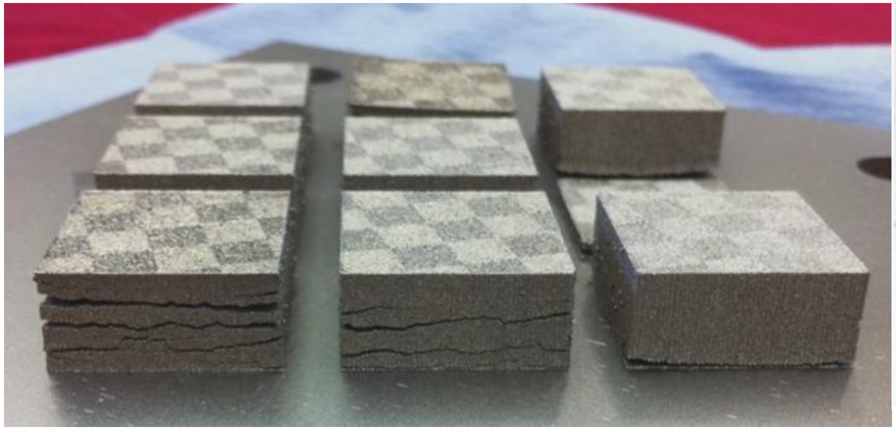
Defects based on Material



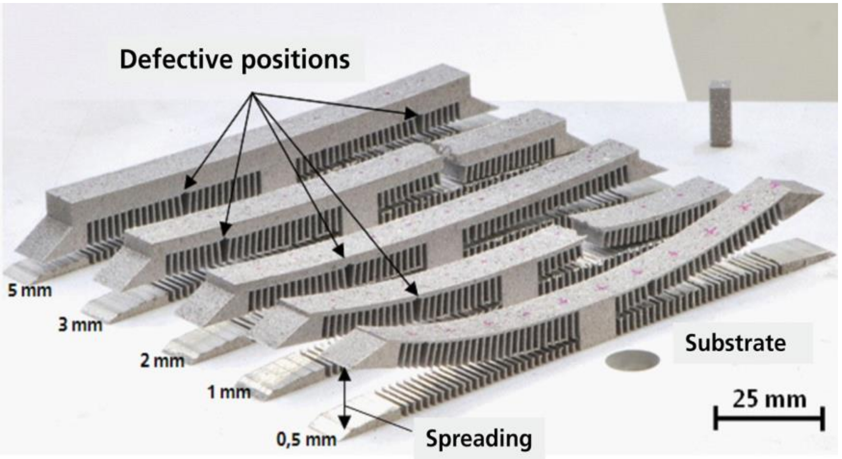
Cracks in LSFed Rene88DT sample: (a) overall view of the cracks distribution in the transverse section of the sample; (b) the long crack (3–10mm); (c) the short crack (100–300m).

(Zhao et al. 2009)

Defects based on physical phenomenon



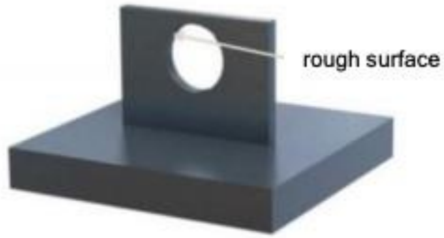
Cracking due to thermal stresses
(Kempen et al., 2013)



Spreading and defective positions at twin cantilevers with different bar thicknesses after separating the supports
(Buchbinder et al., 2014)

Design considerations

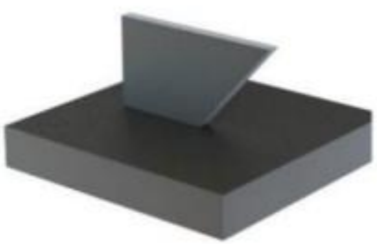
Small holes can be accommodated easily. Holes of less than 6mm diameter are ideal.



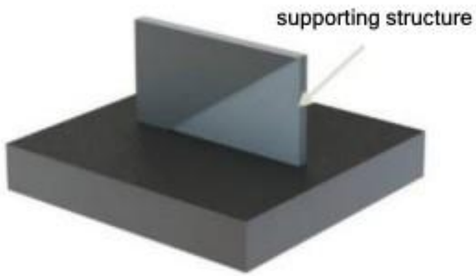
Larger circular holes will result in a roughened surface at the top which may need post-machining.

Large holes will require support structures to be added in the centre to prevent the part collapsing or becoming distorted during the build process. These supports will need to be removed by wire cutting or machining.

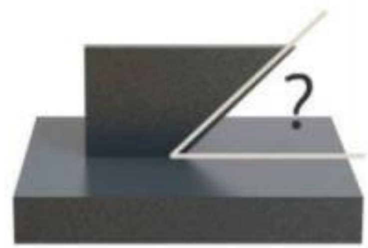
If the hole has an angled or arched upper area it will probably not require any supports. This is one of the features of DMLS that can have a significant impact on the design process.



The powder in the build chamber does not provide any support to the part as it builds, so any angled surfaces will ideally be self-supporting.

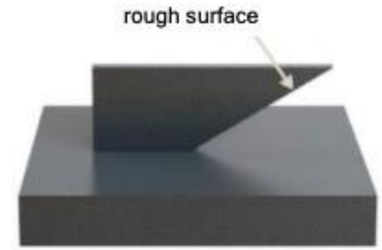


If the angle is too acute, the surface will need a supporting structure built in as part of the model. This supporting structure will then need to be removed by machining or wire cutting, increasing energy use.

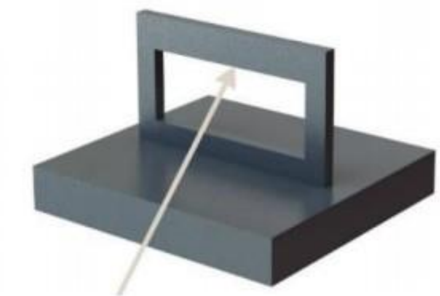


The minimum angles that will be self supporting are approximately:

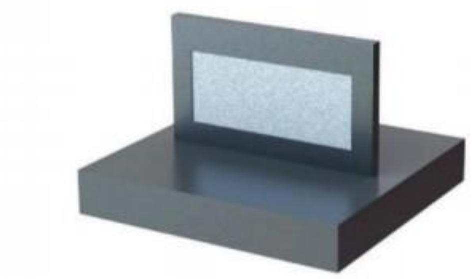
- Stainless steels: 30 degrees
- Inconels: 45 degrees
- Titanium: 20-30 degrees
- Aluminium: 45 degrees
- Cobalt Chrome: 30 degrees



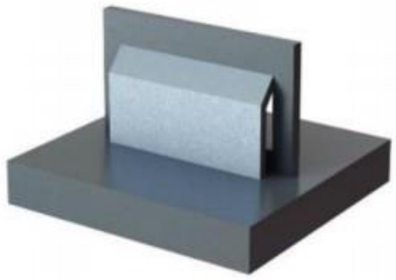
If the angle is near the point where it needs supports, the downward facing surface will become rough and may require considerable post-finishing.



Any downward facing surface will require support. Support structures will need to be removed by wire cutting or machining, which will increase the energy and waste involved in the process.

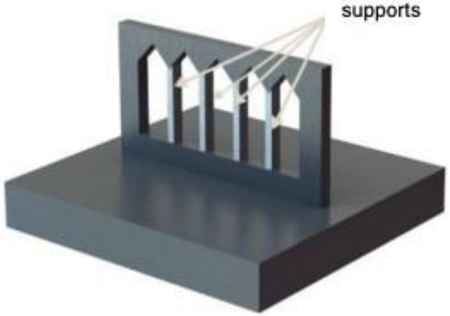


The most simple support structure will fill the hole that creates the downward facing surface. This can be removed by wire cutting or machining.



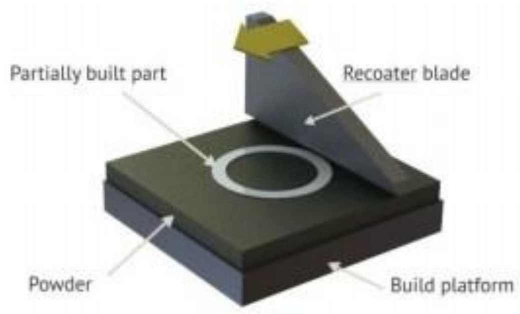
An offset support structure can be used that will be easier to remove. In this case, the base of the support will be cut when the part is removed from the base by wire cutting, leaving one edge to be cut in order to remove the rest of the support.

An alternative to this approach will be to turn the part through 45 degrees to make all the surfaces angled and remove the need for supports. Orientation is a major issue in finding the most efficient build method - please see item 3 in Other Issues for more details on the limits and possible pitfalls of using angled edges like the ones shown above...



If the top surface of the hole can be made of a series of angles (which are self supporting) the supports can be minimised to the base of each angled surface.

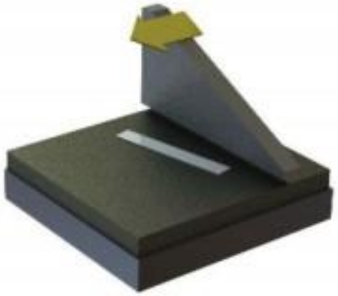
If the hole is simply for weight reduction or cooling, for example, it can be modified as a series of semi-circular topped slots which will not require supports. However, the 'pillars' between the holes need to be self-supporting.



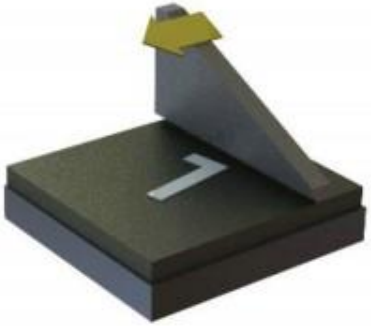
As the re-coater blade passes over the part, depositing another layer of powder, it can touch the layer below, sometimes with force. The orientation of the part is, therefore, important. The ideal geometry is a circular profile which provides a smooth lead in for the blade, and

An open 'U' or similar shape is also ideal, as the lead in for the blade is again rounded, and the basic profile will be strong as it builds, resisting the force of the recoating blade.

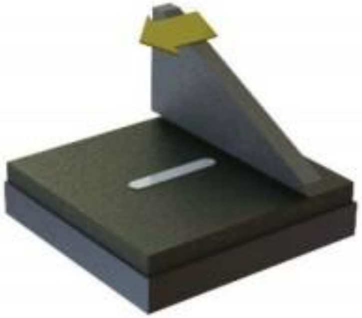
The 'worst case' geometry would be a thin section parallel to the re-coater blade. The blade will tend to 'bounce' off the parallel wall, and the section itself will not resist the force of the blade as it builds.



Any flat surfaces need to be at least 5 degrees from parallel with the blade to allow the blade to touch the part at a point, not a face.



In addition to touching the part at an angle, it helps if the geometry is inherently stiff, which will resist bending forces as the re-coater blade passes over the part.



Long, thinner parts with rounded ends will build well, as they also provide a smooth lead in for the blade and are inherently stiff. However, all these issues need to be considered in parallel with the other limits (build angles, etc) mentioned elsewhere in this section.

As the re-coater blade passes over the part, more force will be applied to the geometry as it gets taller. As a rule of thumb, the ratio between the section and the height should be no more than 8:1.

The exact proportions will always depend on the specific geometry, but if the section gets too high, there is a danger that the re-coater blade will bend the part, and possibly damage itself in the process, terminating the build sequence.

To prevent these problems, vertical sections need to be bridged at certain points. The best method of achieving this will be to use 'arches' to avoid the creation of downward facing flat surfaces.

Even a part that will be strong when it is finished may need some support during the build process. This triangular section will be very weak as the build gets close to the apex.

This kind of structure may need a simple support structure up the middle to provide some rigidity before the part is completed.

If the reason for the open structure is simply weight reduction, it may be easier to perforate it with holes (ideally less than 6mm in dia) that will reduce weight, but not require any supports.

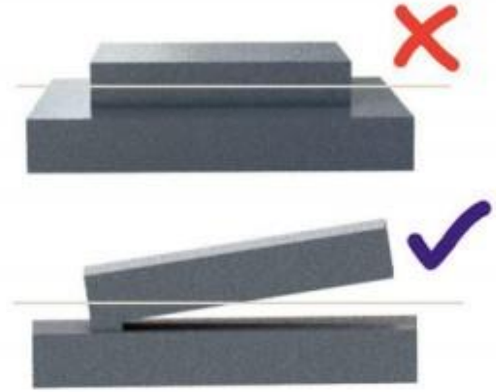
A conventional 'rat trap' bicycle pedal (left) has a large number of surfaces. If it is built in the horizontal plane, the large number of downward facing surfaces will require a significant amount of support (right). A large number of these can be offset, which will reduce the removal time, but building the part would require a considerable amount of energy.

If the geometry is modified to reduce the number of downward facing surfaces (mainly by putting in a number of 45 degree angled surfaces) the amount of supports needed is reduced significantly (right).

However, by changing the orientation of the part to vertical, the number of supports needed is dramatically reduced.

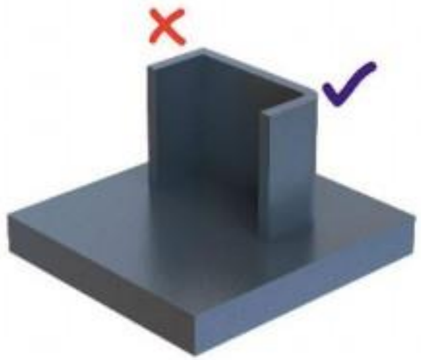
This vertical orientation, combined with design changes to the pedal, would allow designs to be produced that require no supports at all.

1. Avoid sharp edges. Very sharp edges cannot be built in DMLS, and it is better to design parts with minimum radii of approximately 0.5mm.

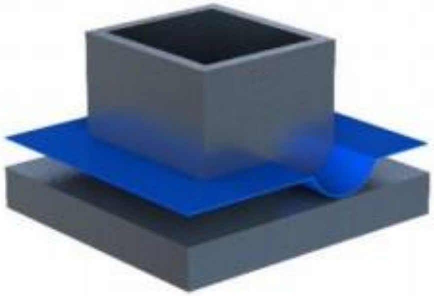


2. Avoid thick sections. The heat build up when creating very large horizontal sections can affect the build geometry, particularly when using titanium. A better approach is to angle the part to minimise the horizontal section at any one time.

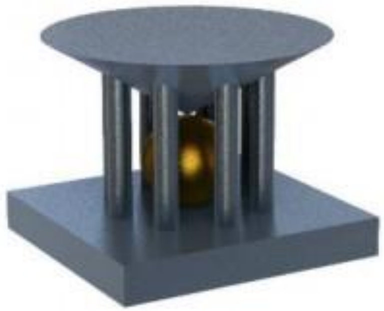
3. Avoid angles facing into the re-coater blade. Angled parts that lean into the path of the re-coater blade may cause the blade to collide with the part and terminate the build.



4. Avoid sharp edges. Sharp corners can act as 'stress raisers' in DMLS in the same way as they can in most processes. Always try to use radii on corners instead of sharp edges.



5. Use the wire cut removal path. The path used to wire cut the part from the base can be used as an integral part of the component design, rather than simply as a straight cut.



6. Build multiple parts. The nature of the DMLS process allows for multiple parts to be built 'in situ'. This can save considerable time and assembly cost for appropriate geometry.

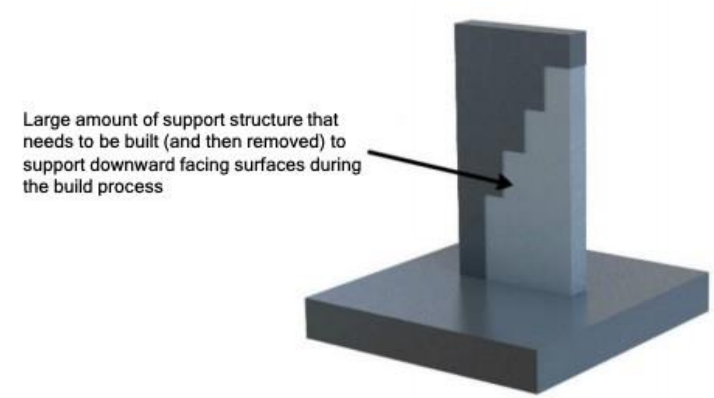
Support Structure

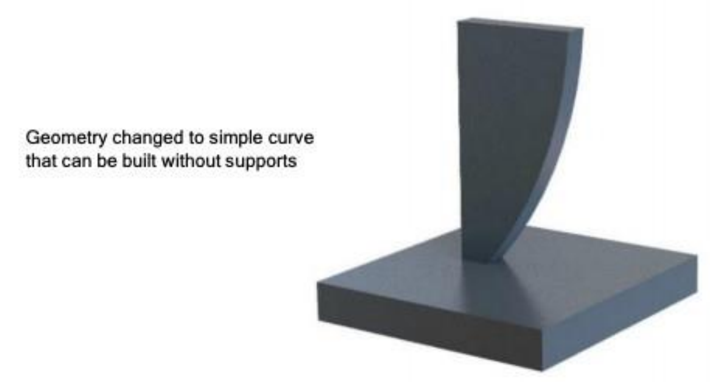
They support the newly melted surface, particularly on downward facing surfaces and shallow angles.

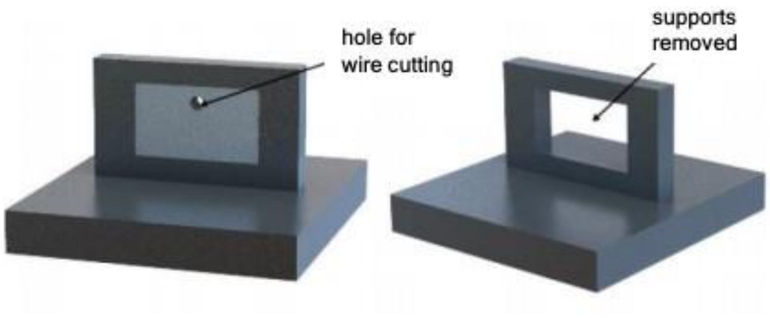
They can prevent the new geometry from deforming.

They dissipate heat away from the newly formed geometry, and

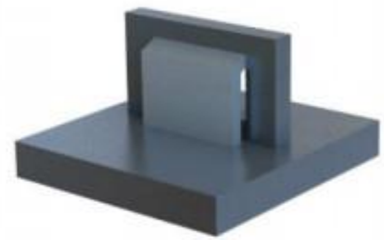
They provide temporary support for geometry that will be strong when complete, but that is weak during the build process. (see 'part strength during the build process').



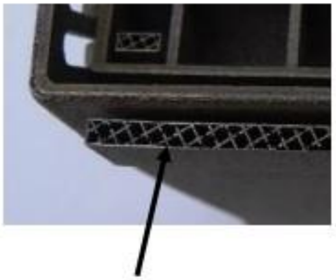




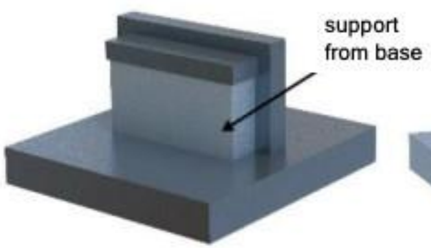
1. Simple fill in. The most simple form of support is to fill in the area that needs support, and then cut this out when the build is complete by wire cutting or machining. If the support area is to be removed with wire cutting, a small hole needs to be placed in the support area to allow the wire to be located.

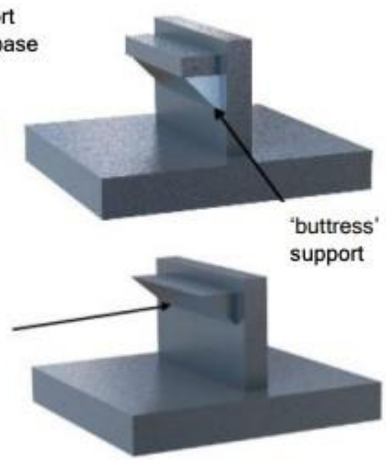


2. Offset supports. Offset supports require less machining. They rise vertically and then angle in to support specific surfaces. The base of the support is usually removed with the wire cut removal of the part, requiring only the supported surface to be machined.

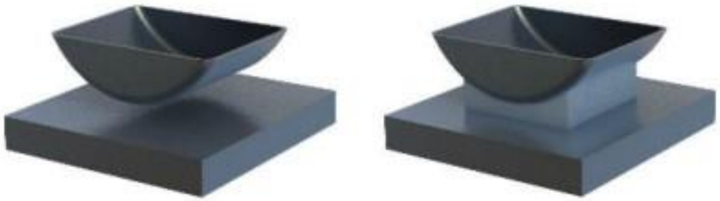


All support structures are formed from fine lattices, to minimise energy consumption and build time





3. Overhanging surfaces. Horizontal overhanging surfaces can be supported from the base, although this will require a considerable amount of material and energy. A better solution is to 'buttress' the surface from the main geometry at an angle. Better still, design the support into the geometry and remove the need for any additional work.



4. Supports for curved surfaces. Sometimes, it is necessary to support a downward facing curved surface to prevent the geometry failing or a very rough surface being formed. In this case, a support structure is formed under the part which is then removed by wire cutting or machining when the part is removed from the base.

Post Processing

Removal of Supports

Heat Treatment

Post finishing operati
s

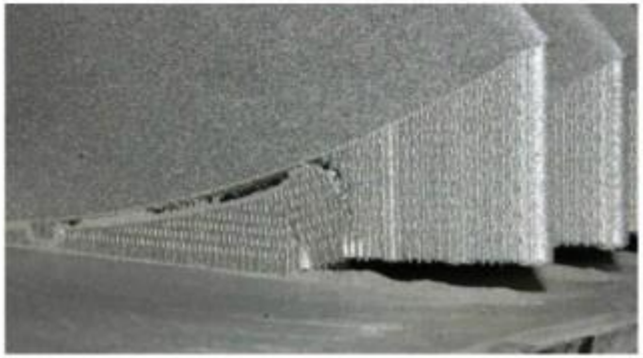
Problems with SLS build

Distortion

Warpage

Delamination

Porosity



Threads

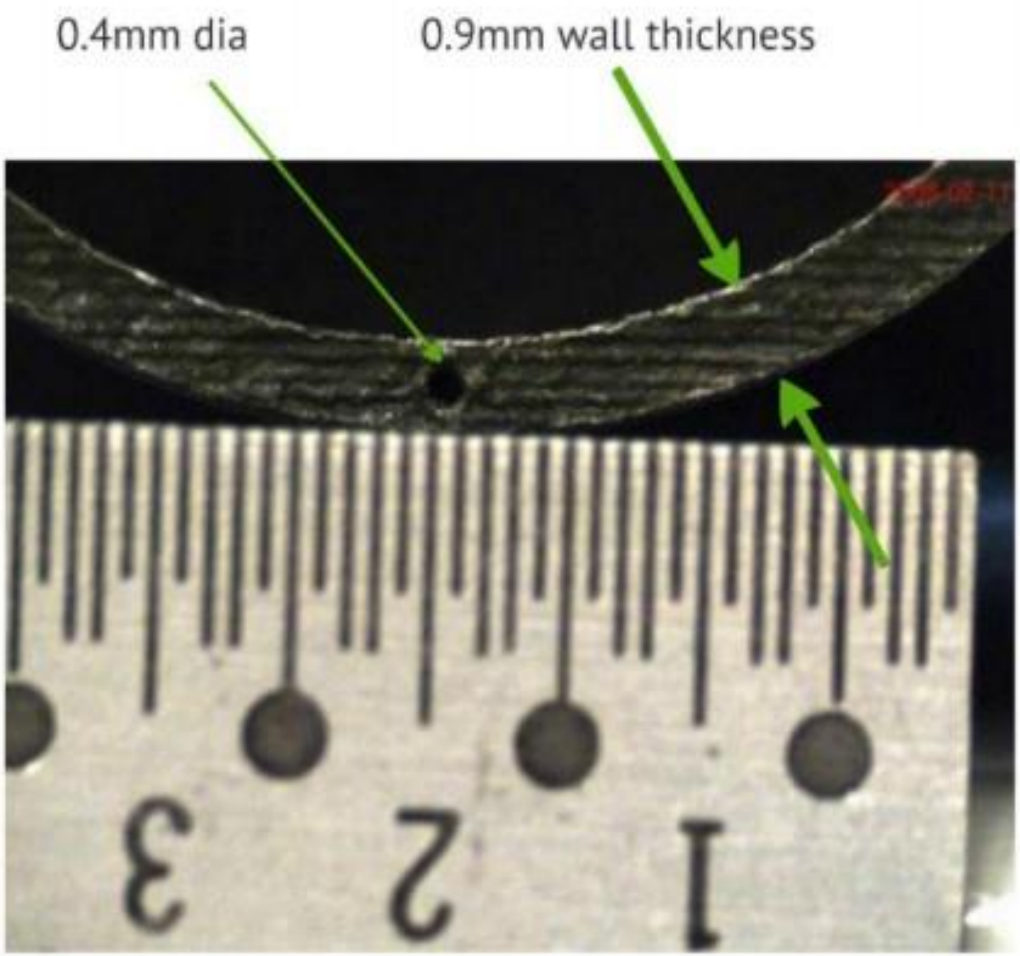
Threads can be formed directly into parts, depending on the size of the thread and the orientation. Threaded areas should always be vertical, and ideally have sufficient clearance around the thread to allow a tap or die to be used to ensure that it is clean.

Smaller threaded areas should be left off the CAD file, and post-machined (Drilled and tapped or thread milled).

Wall thickness

Wall thicknesses are somewhat material dependent, but as a rule of thumb, wall sections should not fall below 1mm.Very thin wall sections - or placing a thin section against a thick section - may result in significant distortion due to the very high temperatures involved in the process.

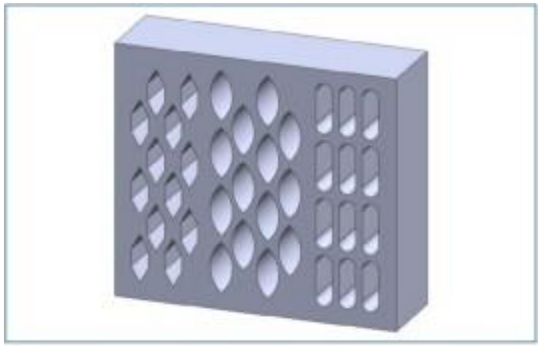
Fine detail is possible, however, particularly in the vertical plane. The illustration on the right shows a section of a pipe with a wall section of 0.9mm with a hole running through it of 0.4mm diameter.



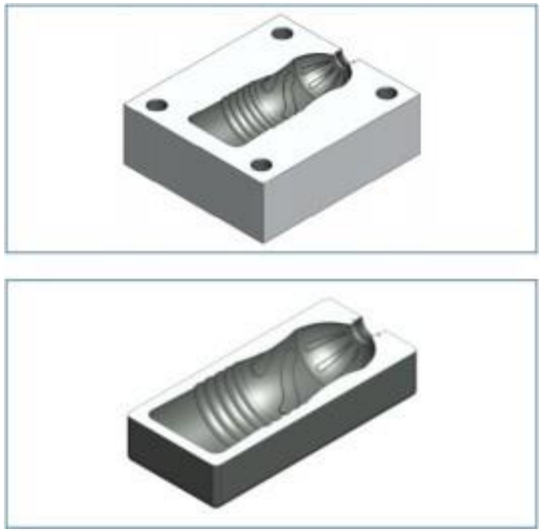
Design Rules

- Based on efficiency
- Based on weak layers
- Part oriention
- Considerations for the wire-erosion process that removes part from platform
- Creative with Design Freedom

Material Efficiency

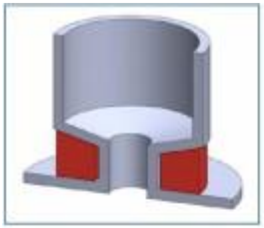


Example of self-supporting features

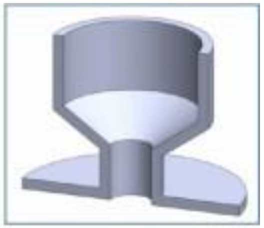


Design Guidelines

Add chamfers or fillets to overhanging geometry to make it self-supporting



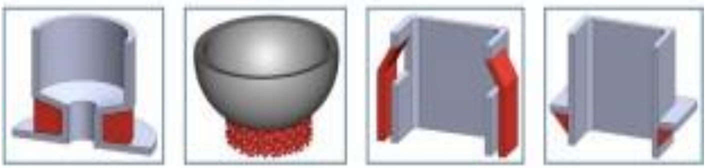
Angles <30°: non self-supporting



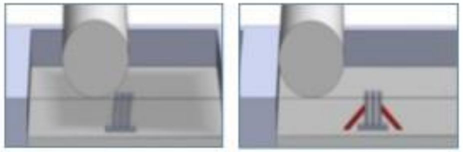
Angles 30°-45°: self-supporting with rough surface finish

Angles >45°: self-supporting with smooth surface finish

Design rules



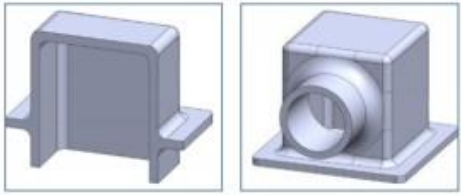
Fill Lattice Offset Gusset



Force from the roller may cause tall, narrow parts to shift in the build

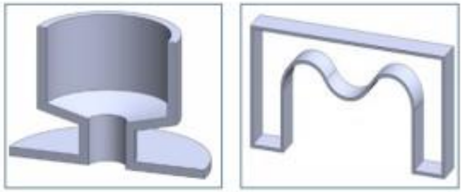
Support structures prevent parts from shifting in the build

Overhang geometry may require support structures to successfully build using DMLS:



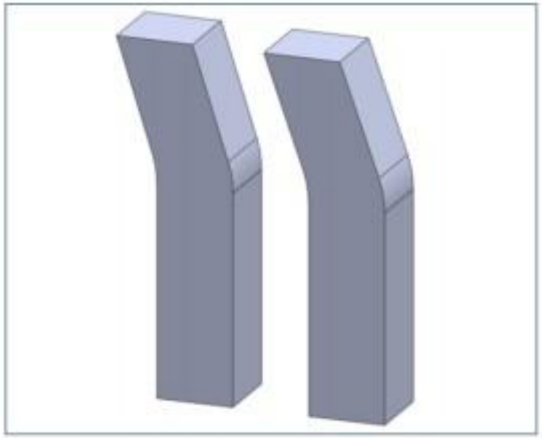
Horizontal surfaces

Large holes on the horizontal axis

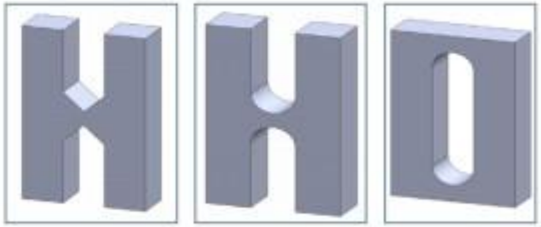


Angled surfaces <30°

Arches and overhangs



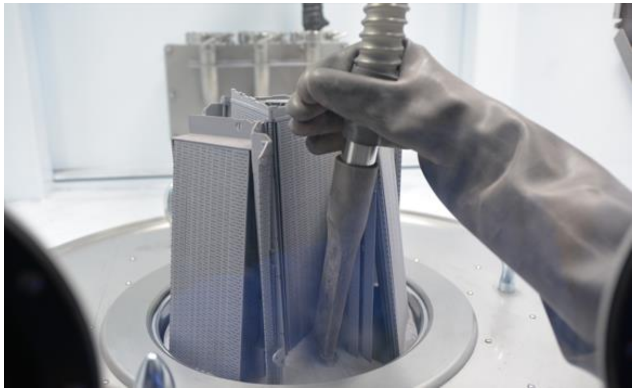
Example of warping on a tall, thin part without support structures

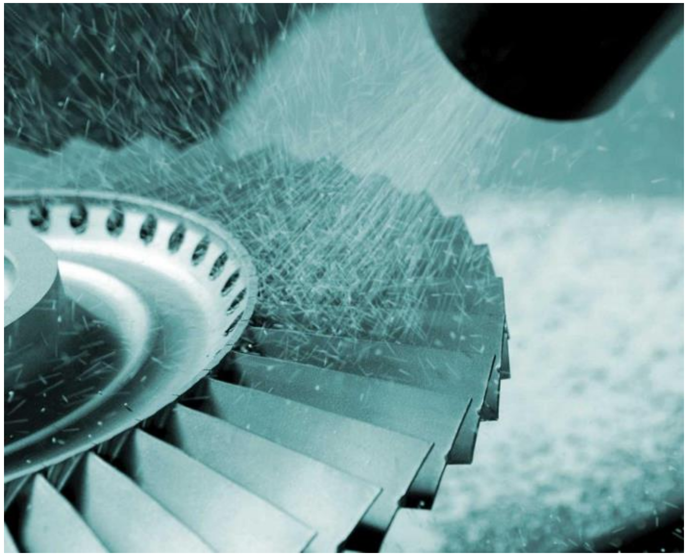


Examples of potential design improvements to prevent warping

Post processing

- Removal of part from the substrate
- Removing the unused powders
- Improving surface finish
- Heat treatment





Purpose of Post processing

1. Support material removal
2. Surface texture improvements
3. Accuracy improvements
4. Aesthetic improvements
5. Preparation for use as a pattern
6. Property enhancements using non-thermal techniques
7. Property enhancements using thermal techniques

Support material removal

- Natural Support
- Synthetic support

Fig. 14.1 Automated powder removal using vibratory and vacuum assist in a ZCorp 450 machine (Courtesy Z Corporation)

Synthetic support

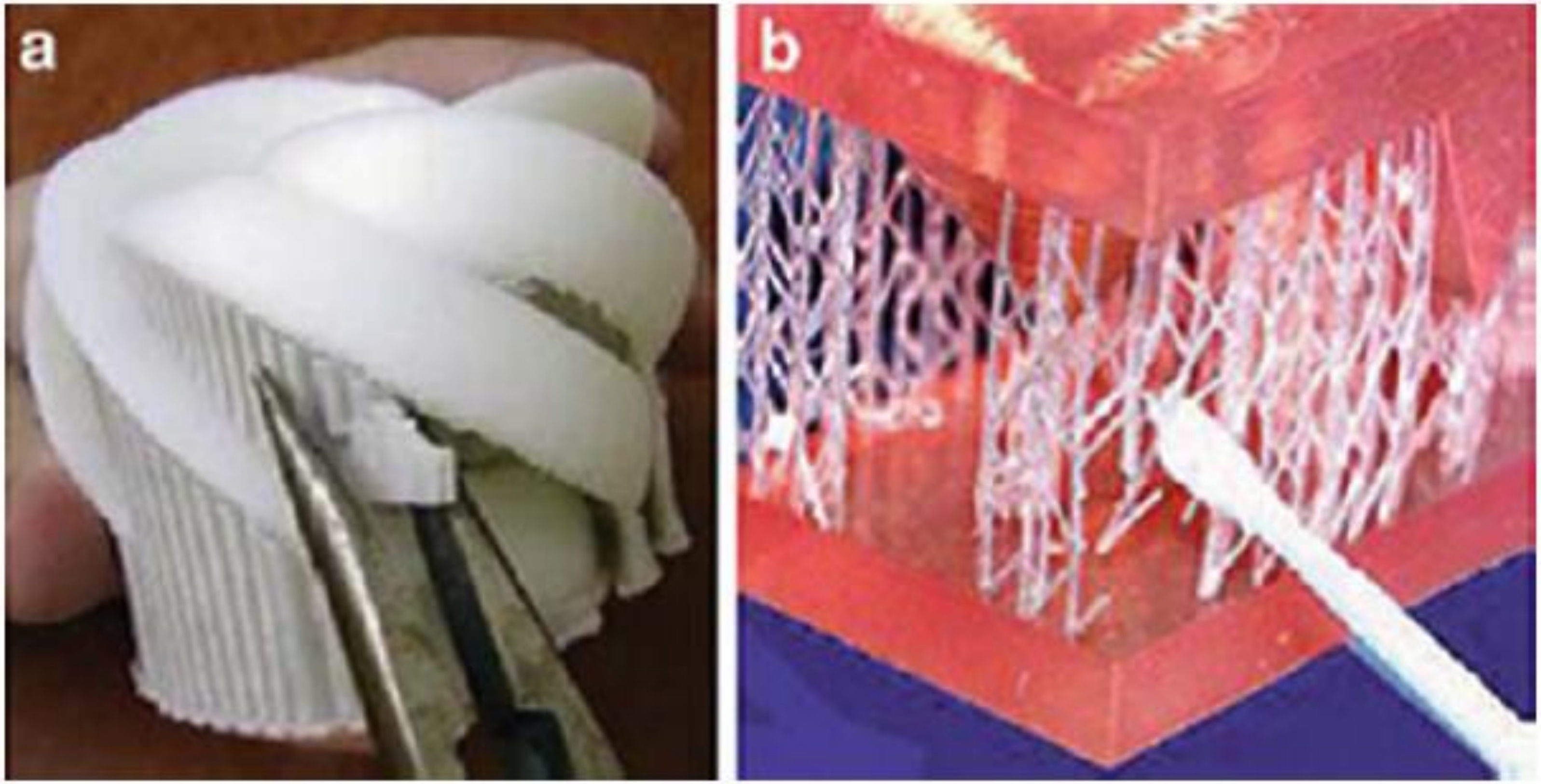
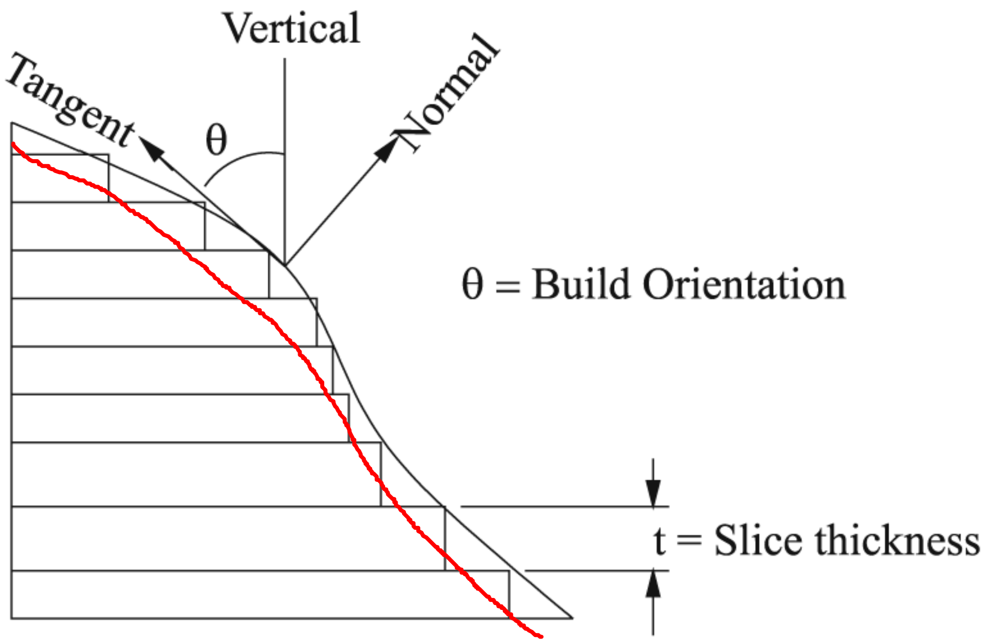


Fig. 14.4 Breakaway support removal for (**a**) an FDM part (courtesy of Jim Flowers) and (**b**) an SLA part (Courtesy Worldwide Guide to Rapid Prototyping web site. © Copyright Castle Island Co., All rights reserved. Photo provided by Cadem A.S., Turkey)

Accuracy improvements

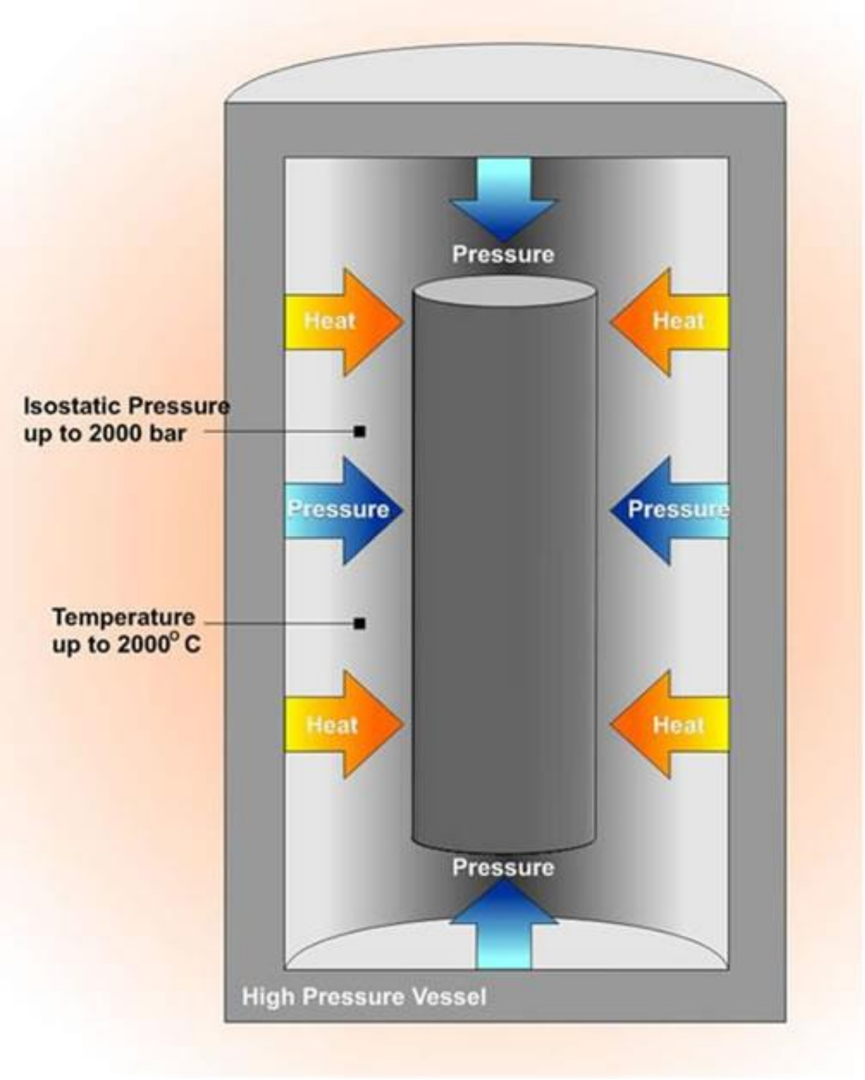
Process parameter selection

Shrinkage compensation



Property improvement

Hot Isostatic Pressing



innovate achieve lead

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End of Session 11