LUT

Lappeenranta

University of Technology

Design in AM, DfAM

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LUT University
Research Group of Laser Materials Processing

Background

- Research in laser materials processing since 1985
- First own laser 1986
- Research was focused to laser welding, laser cladding, laser surface treatment etc. in 1980´s and 1990´s
- Many domestic actors in field of laser processing have their roots in LUT Laser
- Personnel: 4 research scientists, 2 research assistants, 2 Master Thesis workers and 1 laboratory technician
- Turn-over c. 1.0 M€/year
- Master Theses c. 6 pcs/year
- Doctoral Theses 1 pcs/year
- Publications c. 15 pcs/year
- Citations > 300/year

Additive manufacturing (AM)

- Research in monitoring of AM since 2009
- Device for metallic AM (EOS M series) since 5/2011
- Research topics:
  - Process efficiency
  - Product design
  - Design of internal structures
  - Mechanical properties of material
  - Etc.
- Education in AM for M.Sc. students since 2013

Research in additive manufacturing
Academic

- Academic research since 2009 has focused on understanding of laser beam and (metal) material interaction.
- Aim is to:
  - enables use of new materials,
  - enhance process efficiency and process control and
  - increase industrial implementation of new applications in AM.
- Topics in academic research have also been in:
  - printability of products,
  - costs in AM,
  - sustainability in AM and
  - how to avoid bottle necks, such as support structures, in industrial implementation.

Research in additive manufacturing
Academic

- First projects in LUT in field of AM were dealing with manufacturing of small-scale devices for chemical industry (so called micro reactors).
- Later, industrial projects have been in area of:
  - additive manufacturing of ceramics,
  - joining products done with AM as part of larger constructions,
  - techno-economic aspects of AM,
  - Etc.

Research in additive manufacturing
Industrial

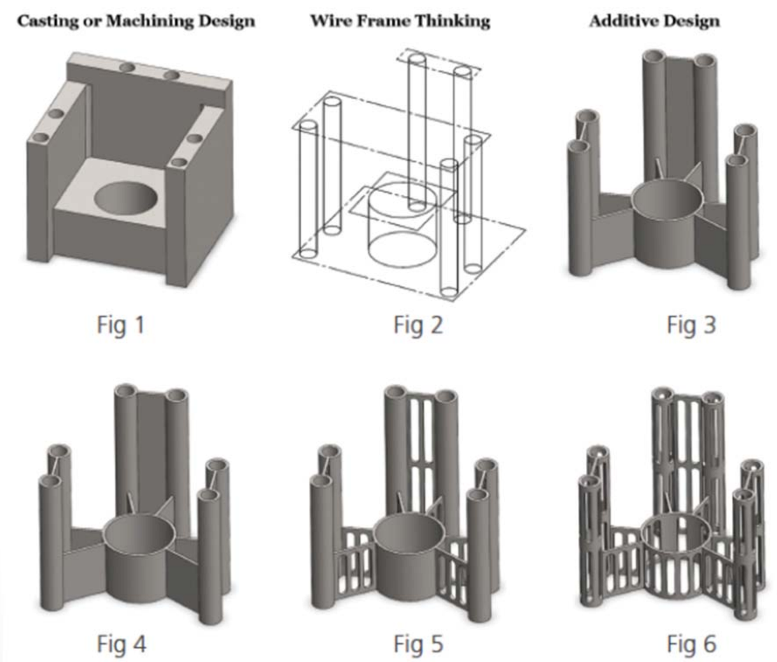
- LUT has carried out eight (8) large projects in field of industrial additive manufacturing in 2009-2018 and these projects are worth of ~3.7 M€.
- There has been:
  - six Business Finland (previously TEKES) projects,
  - one European Union 7th framework project and
  - one Academy of Finland project.
- There are going on at the moment:
  - one Business Finland project (NewArea),
  - one ERDF project Metal 3D Innovations (Me3DI) and
  - one project funded by Strategic Research Council of Finland.

Education in additive manufacturing
Master's degree

- Education in additive manufacturing started in beginning of 2013.
- One aim of education of additive manufacturing at LUT is to enhance know-how of additive manufacturing, especially in metallic AM, and bring new technology specialists and adopters to Finland.
- LUT has two independent courses about additive manufacturing (tot. 8 credits, c. 80 students/year) and three other courses where AM is in minor role (tot. 15 credits, c. 75 students/year).

AM Design, introduction

- Design for manufacturing and assembly has typically meant that designers should tailor their designs to eliminate manufacturing difficulties and minimize manufacturing, assembly, and logistics costs.
- **Designers need to adopt a new way of thinking.**



Design ENGINEERING

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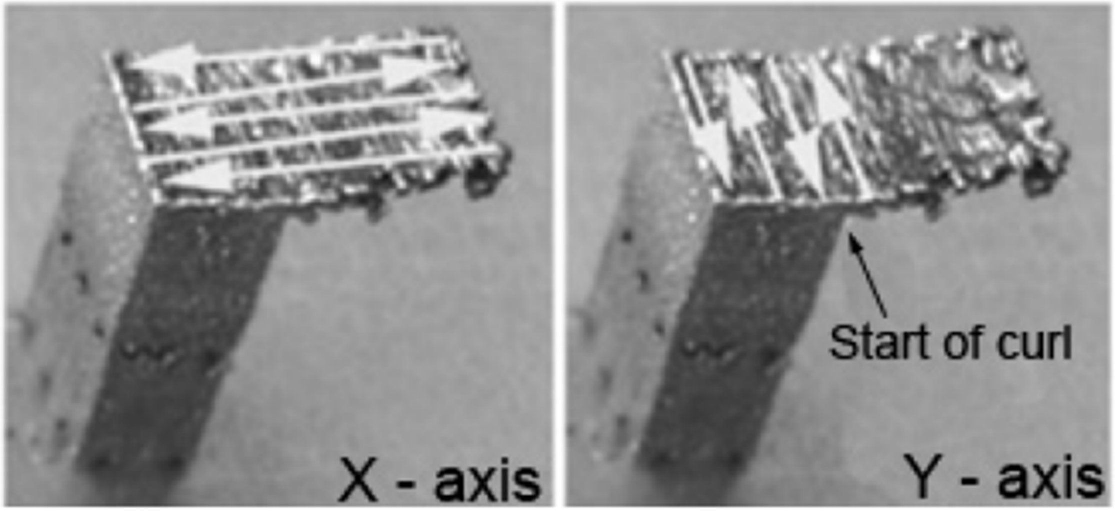
AM Design, introduction

- AM offers unique advantages: customization, improvement in product performance, multifunctionality, and lower overall manufacturing costs
- These slides are about powder bed fusion (PBF) of metallic materials because it is the most difficult process to control. Design for polymers follows similar rules.

AM Design, introduction

- There exists a gap in the available knowledge, in that there is very little design experience informing AM part creation.
- Designers are unaware of the limitations and possibilities of the AM process and often design parts to be made using incompatible design rules from familiar manufacturing processes such as casting, milling and injection moulding.
- This has been recognized as a barrier to the growth of AM and in particular PBF (Wohlers, 2009).

Curl and dross, effect of scan direction



Source: Thomas D. The Development of Design Rules for Selective Laser Melting. PhD-Thesis. University of Wales Institute; 2009

DfAM Essentials

- AM gives us unlimited freedom to design anything we want, right?
- Well, not quite.

- AM technologies have their capabilities and their limitations.
- In these slides some of DfAM aspects are looked more closely.
- Feature size, surface finish, overhanging features, minimizing supports, and avoiding component distortion are considered.

Source: Marc Saunders, Renishaw

Benefits of AM

- Internal and external complexity
- Potential to reduce number of parts
- Absence of tooling
- Ability to vary wall sections to achieve optimum strength

WITHIN

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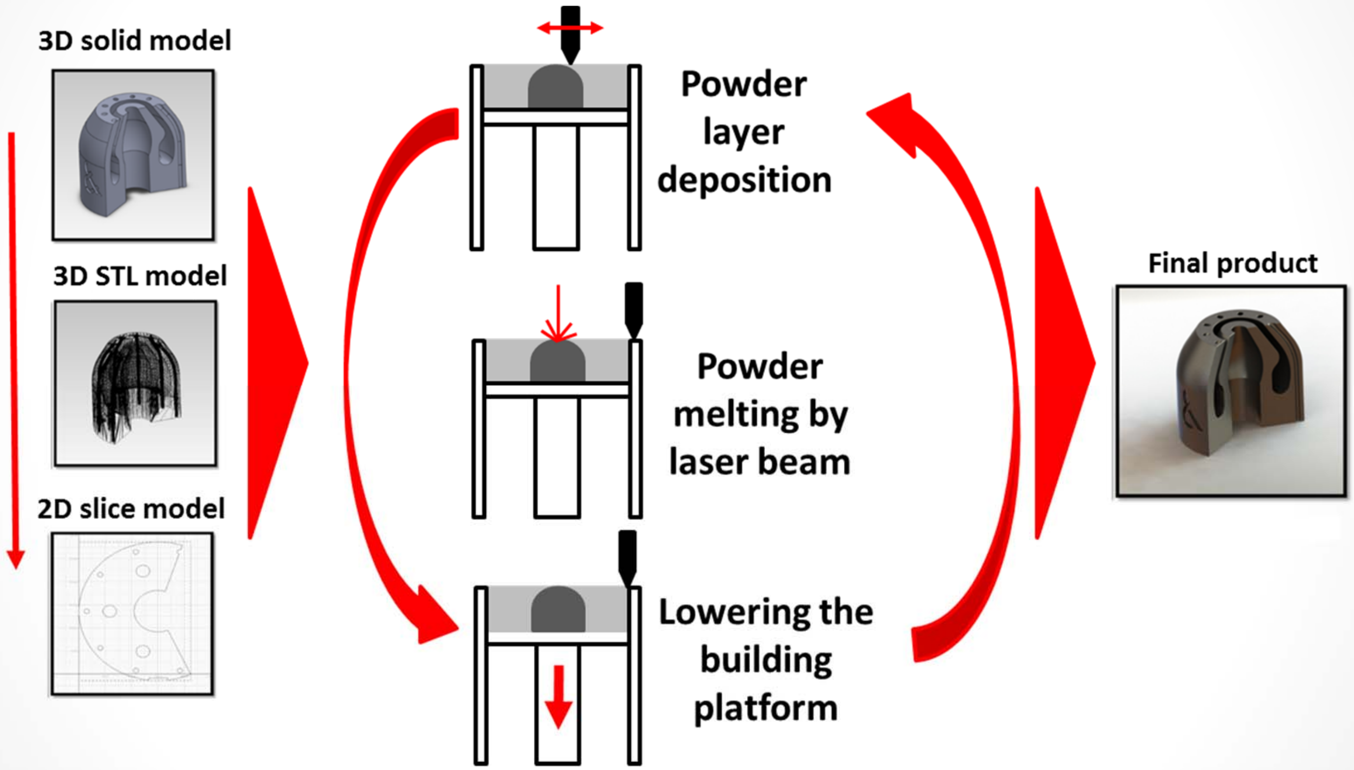
Principle of powder bed fusion

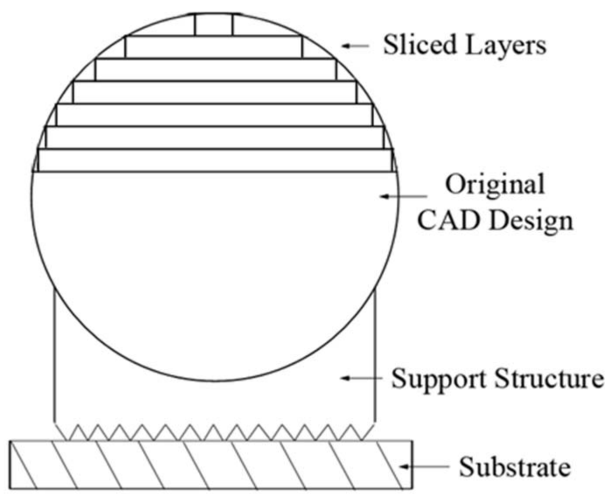


Design basics

- AM parts are built from sliced 3D data
- 3D models can be made with any program that can save the modeled part in a triangulated file format, most often .STL. E.g. Solidworks, Rhinoceros, 3DS Max etc.

Design basics

- The layers of all AM parts are created by slicing CAD data with specialist software
  - layers from 16 μm up to 200 μm (depending on 3d printing method used)
  - staircase effect, thinner layer → smoother quality



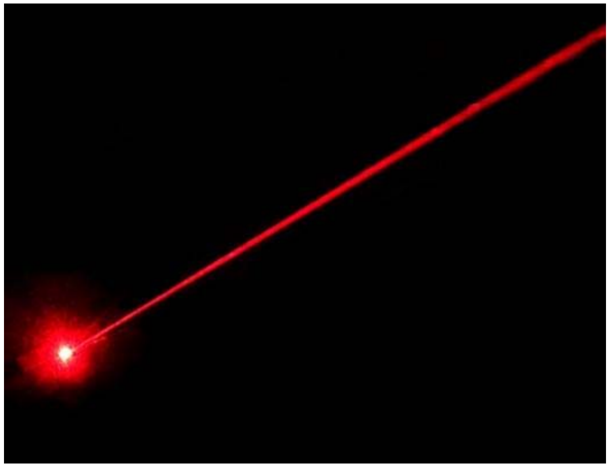
Feature size

- In machining processes, the size of detail feature that can be produced is limited by choice of cutting tool.
- Usually multiple tools are needed to create parts.

Source: Marc Saunders, Renishaw, www.mfgnewsweb.com

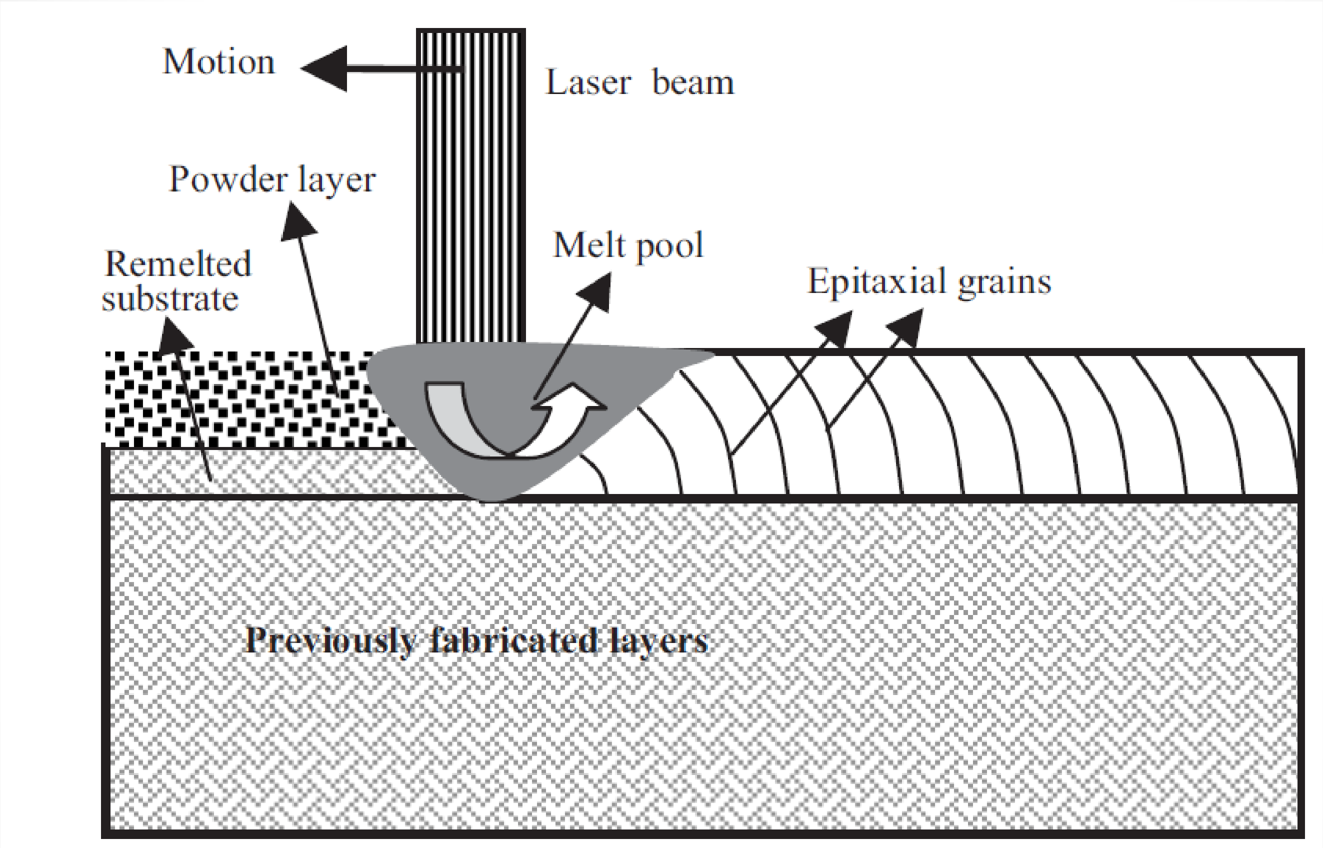
Feature size

- In AM, tool size is the spot size of your laser.
- Laser spot heats the powder to create a weld pool, which cools into a solid structure once the laser energy is removed.
- The size of the laser spot, along with laser power and modulation, controls the size of the weld pool and the size of the structure that can be built.



Source: Marc Saunders, Renishaw, www.discovercircuits.com

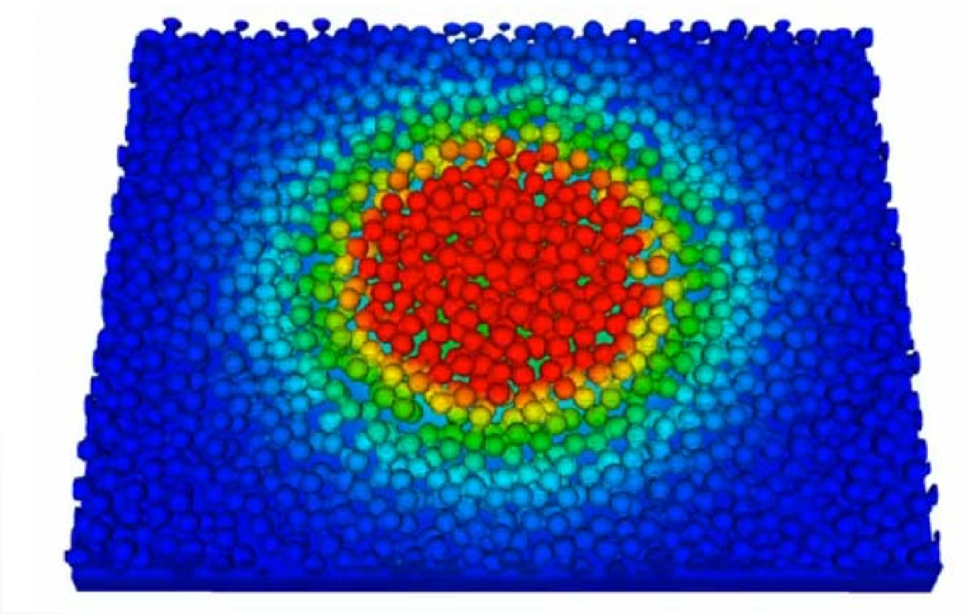
Full melting



S. Das, Advanced Engineering Materials, 2003, p.701-720

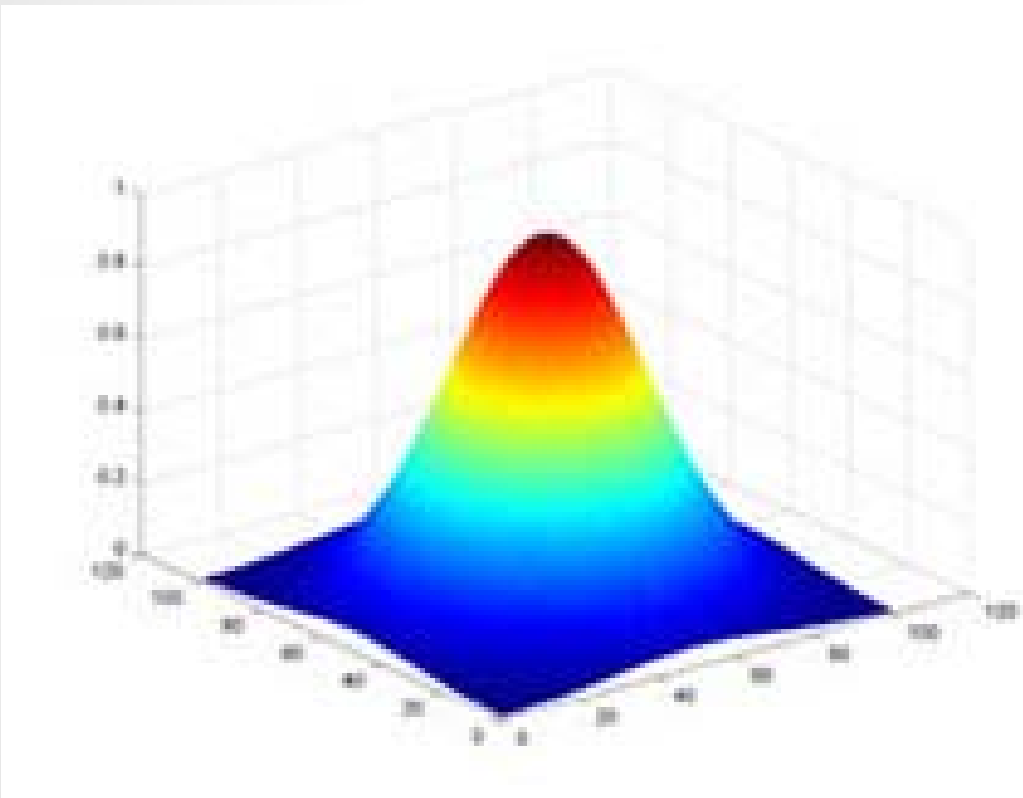
Feature size

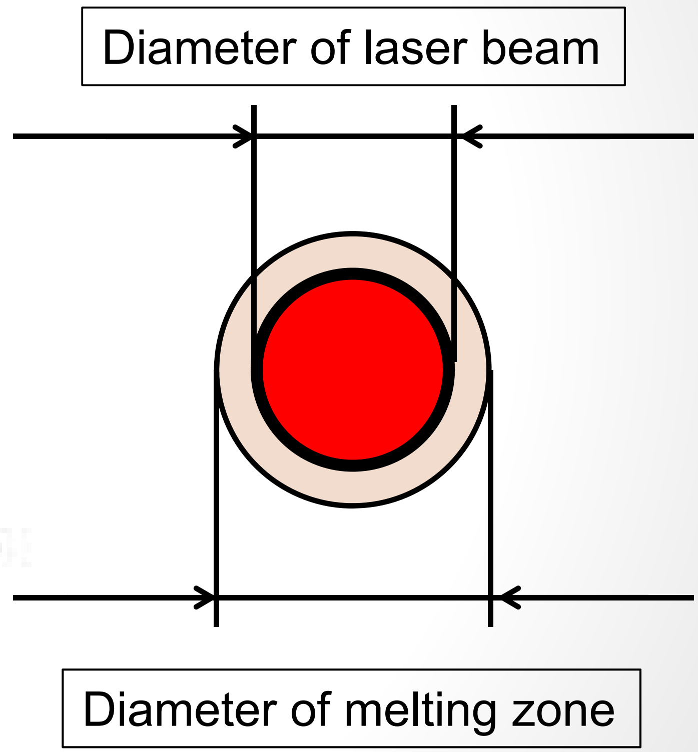
- The minimum producible feature size is generally somewhat larger than the spot size.



Source: Marc Saunders, Renishaw

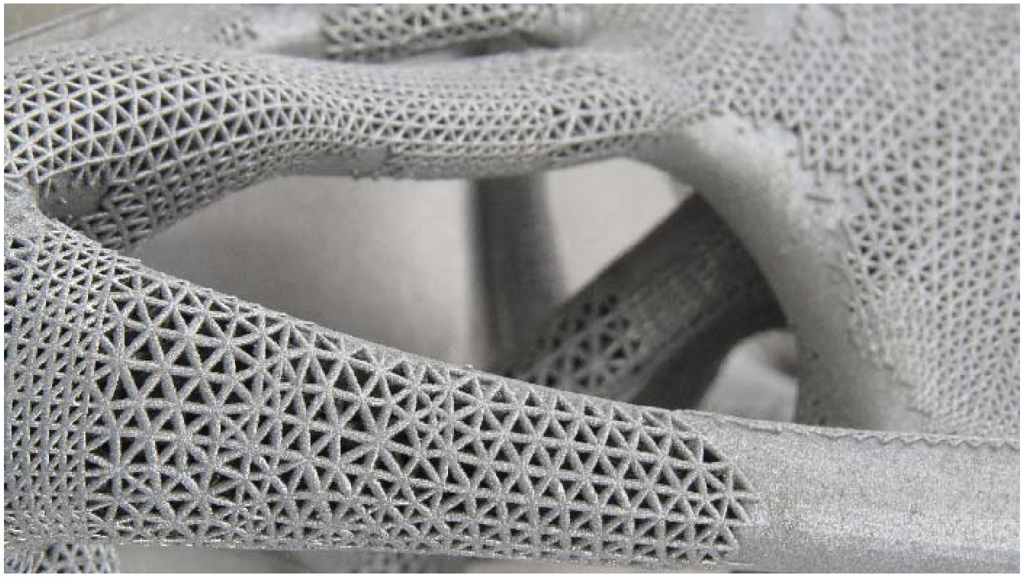
Beam properties





Feature size

- For example, with 70 µm laser spot, lattices with strut dimension of 140 µm can be built.
- Wall thickness of 200 µm can be achieved with same spot size.



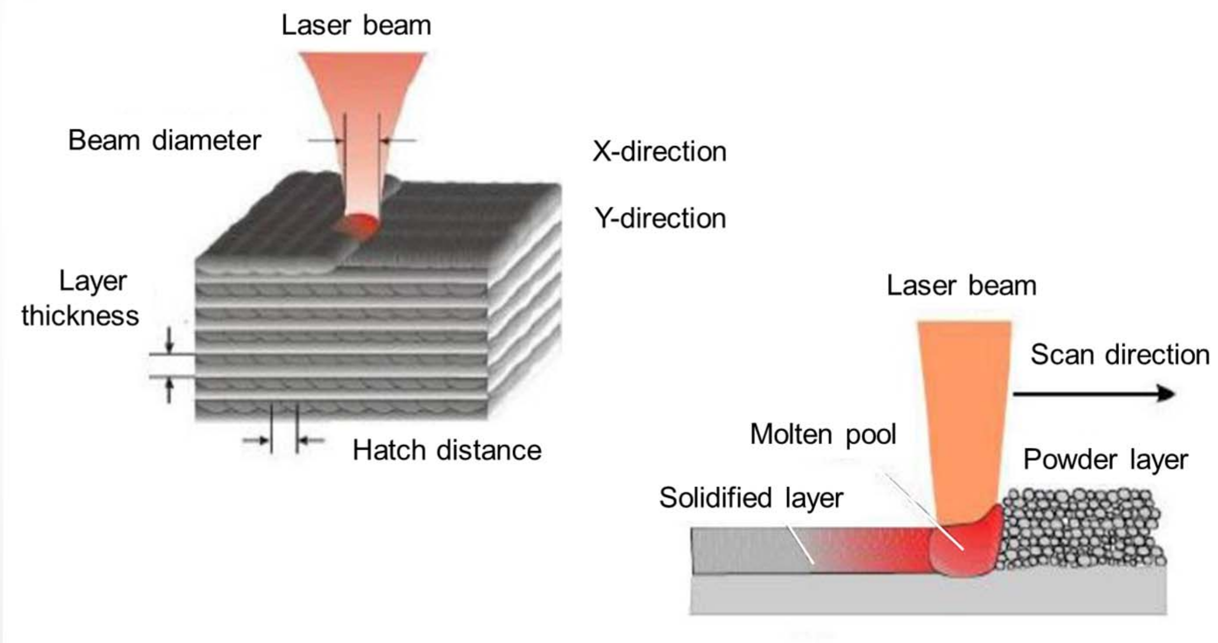
Source: Marc Saunders, Renishaw

Design basics

- The most straightforward geometry to build is a vertical ‘extrusion’ from the build platform, where each layer is similar to the one beneath it

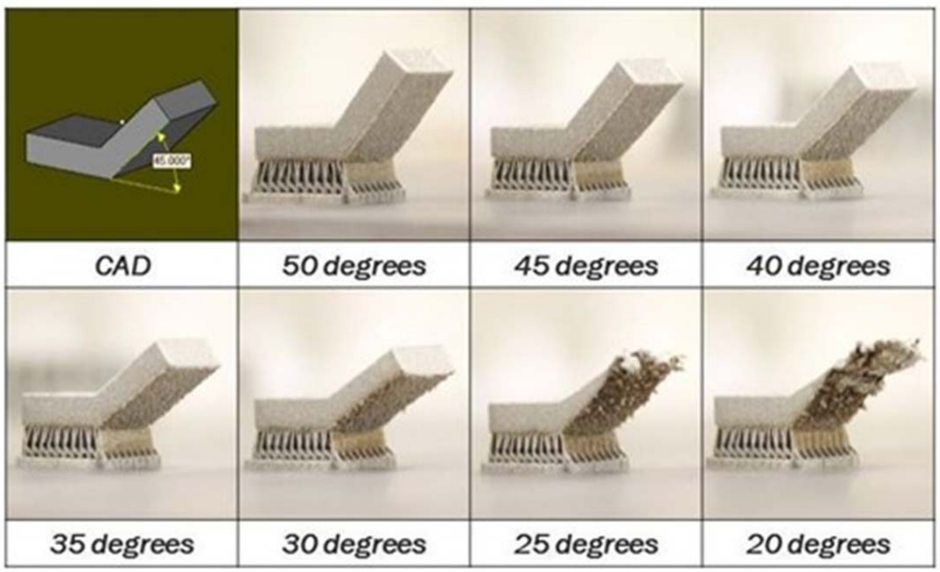
Overhangs

- In powder-bed processes, where shapes are built up layer by layer, the way these layers relate to each other is important.
- As each layer is melted, it relies on the layer below to provide both physical support and a path to conduct heat away.



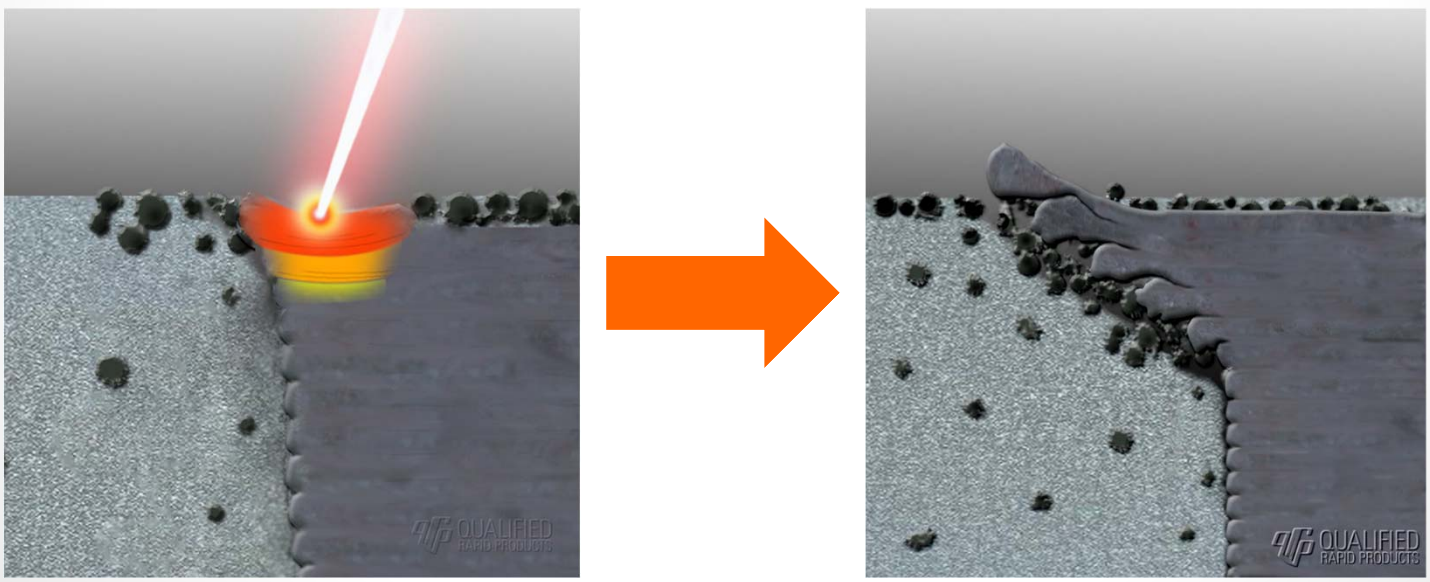
Overhangs

- When the laser is melting powder in an area where the layer below is solid metal, then heat flows from the weld pool down into the structure below, partially re-melting it and creating a strong weld.
- The weld pool will also solidify quickly once the laser source is removed as the heat is conducted away effectively.



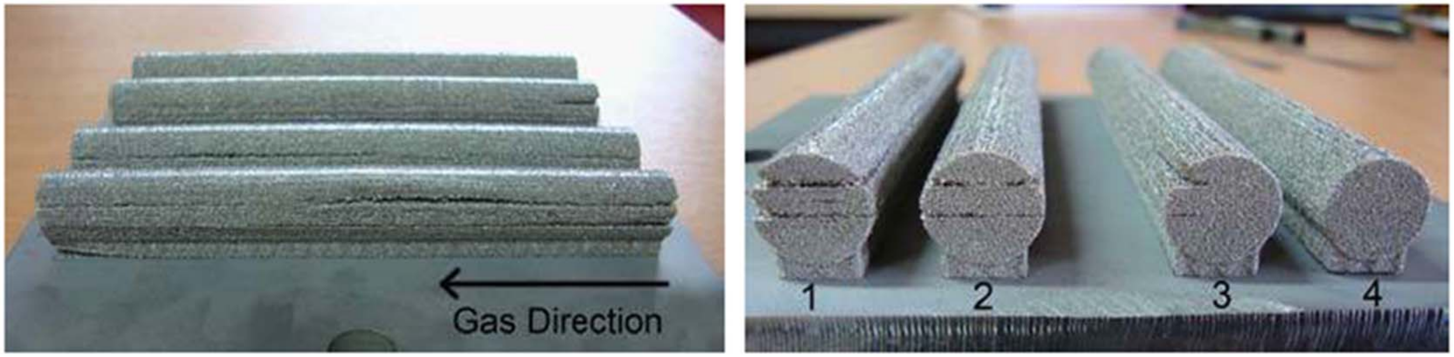
Overhangs

- Where component features overhang, then at least part of the zone below the weld pool will consist of un-melted powder.
- Powder is less dense than solid metal, so unsupported thin layers of newly welded metal can sag.
- Un-melted powder is also far less thermally conductive than solid metal, and so heat from the melt pool is in molten state longer.



Overhangs

- Delamination



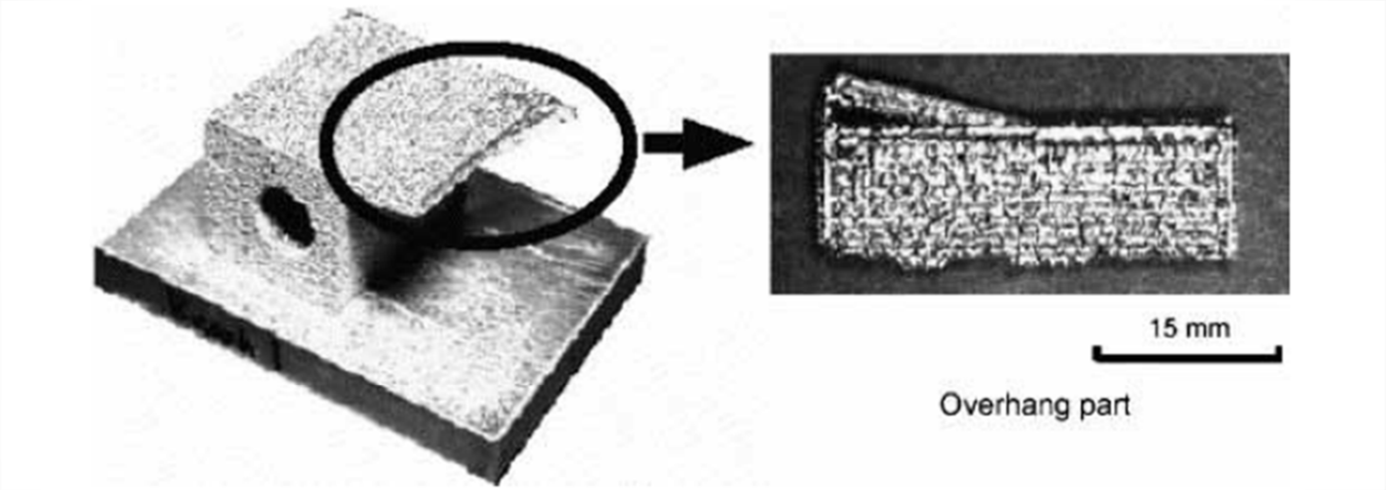
(a) (b)

Notes: (a) Front; (b) right view

Source: S. Dadbakhsh L. Hao N. Sewell, (2012),"Effect of selective laser melting layout on the quality of stainless steel parts", Rapid Prototyping Journal, Vol. 18 Iss 3 pp. 241 - 249

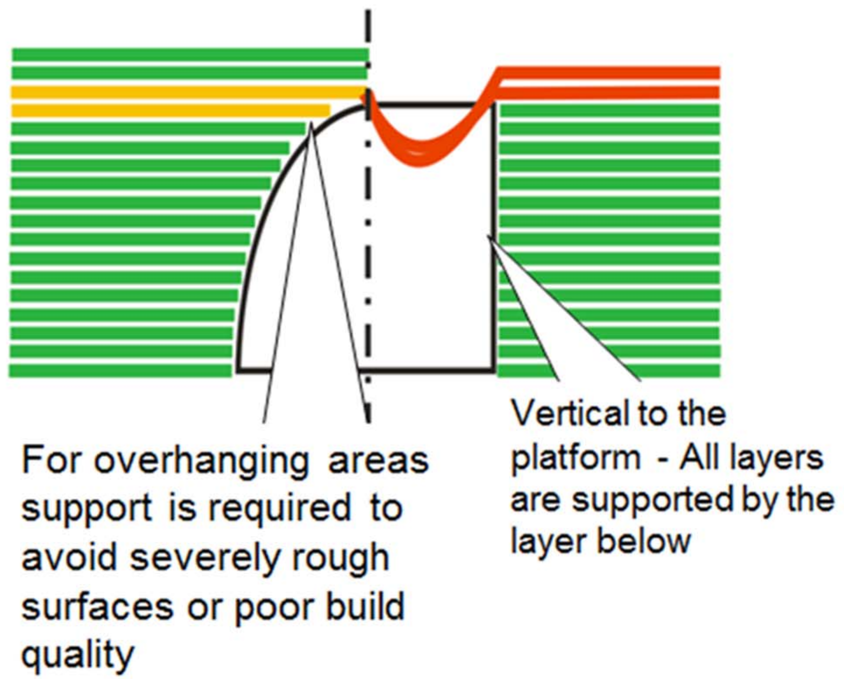
Overhangs

- Delamination and curl



Source: Kozo Osakada, Masanori Shiomi. 2006 Flexible manufacturing of metallic products by selective laser melting of powder. International Journal of Machine Tools and Manufacture. Volume 46, Issue 11. September 2006

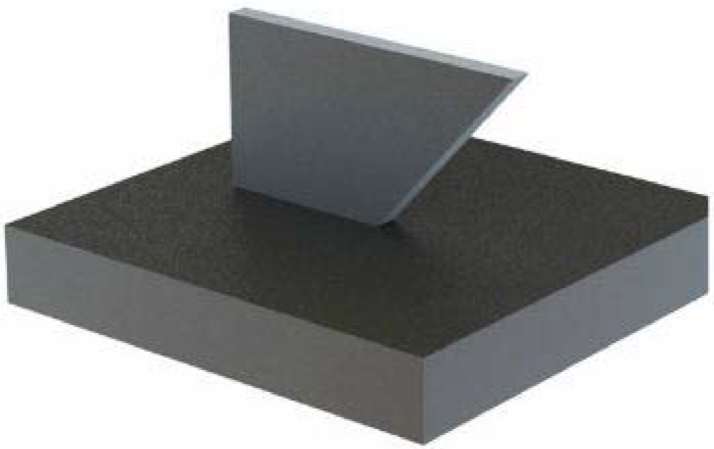
Overhangs



Source: Marc Saunders, Renishaw

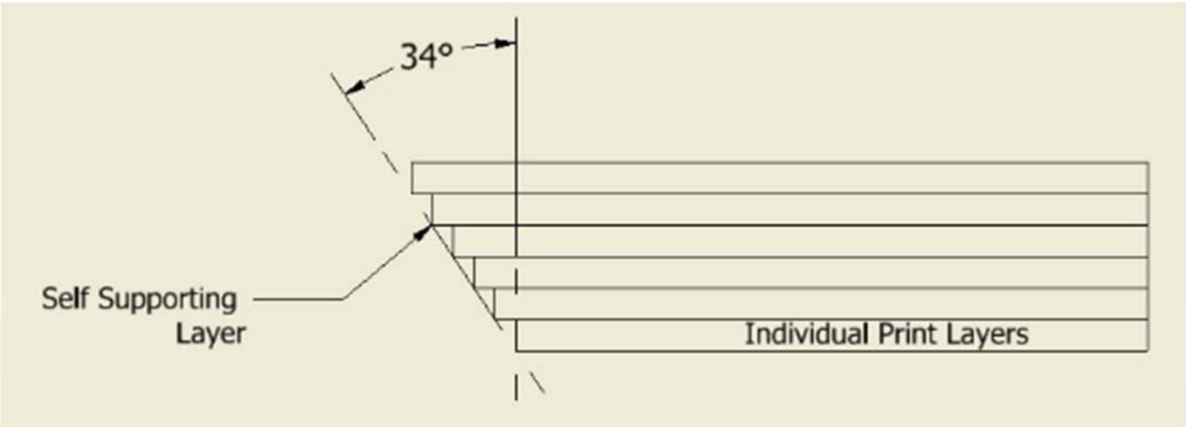
Design basics, angled structures

- Powder material in part building does not provide support for angled parts, so any angled surfaces should ideally be self-supporting.



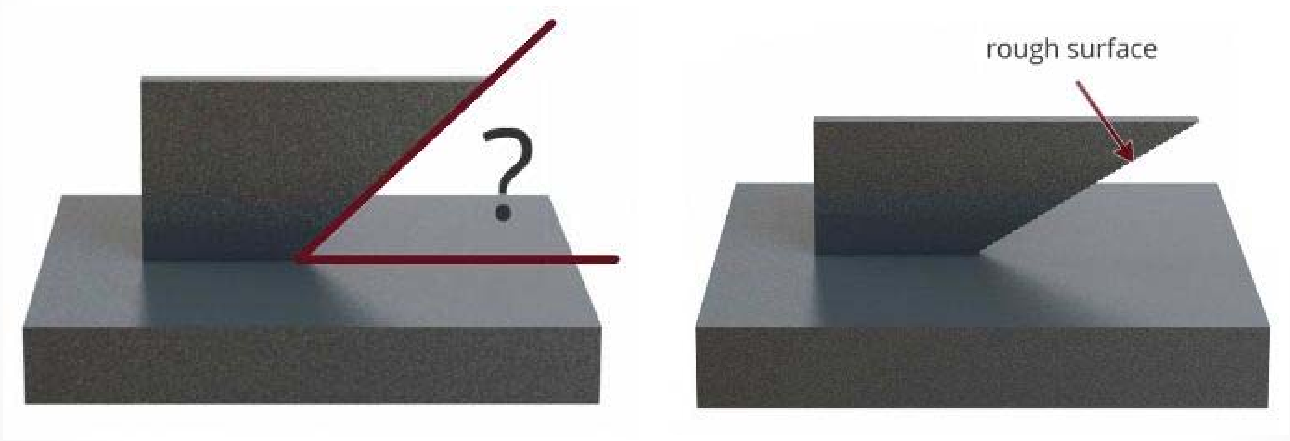
Design basics, angled structures

- Absolute minimum angles that will be self-supporting are approximately:
  - Stainless steel 30 degrees
  - Inconels 45 degrees
  - Titanium 20-30 degrees
  - Aluminium 45 degrees
  - Cobalt Chrome 30 degrees



Design basics, angled structures

- If the angle is near to needing supports, downward facing surface will become rough and will need considerable post-processing.

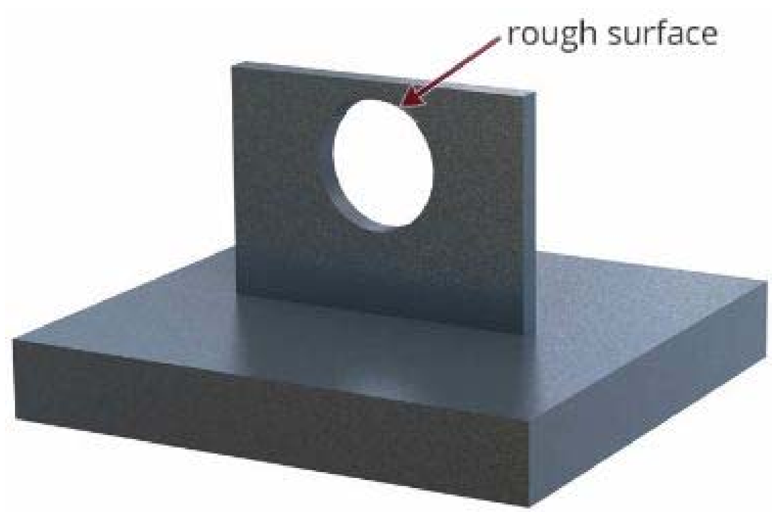


Design basics, holes

- Horizontal holes of less than 6 mm diameter are possible to manufacture without support structures.

Design basics, holes

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



Design basics, holes

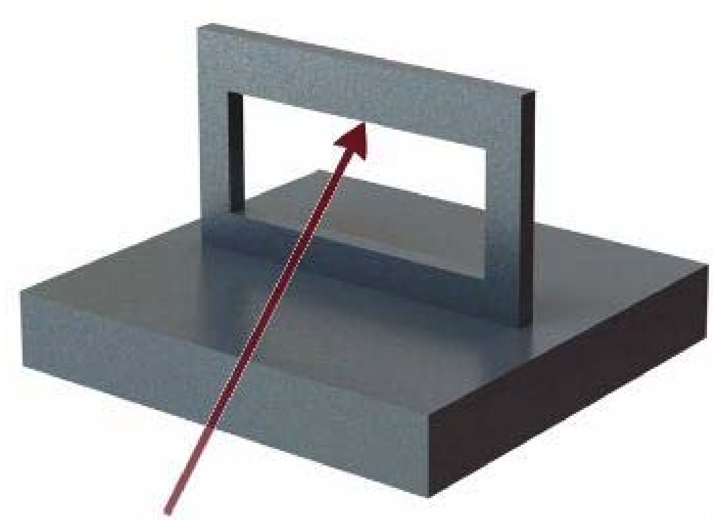
- Larger holes require support structures to be added in the centre to prevent the part from collapsing or becoming distorted during the build process. These supports need to be removed by wire cutting or machining.

Design basics, holes

- If the hole has an angled or arched upper area it will probably not need any supports.

Design basics, overhangs

- All overhangs need supports



Design basics, overhangs

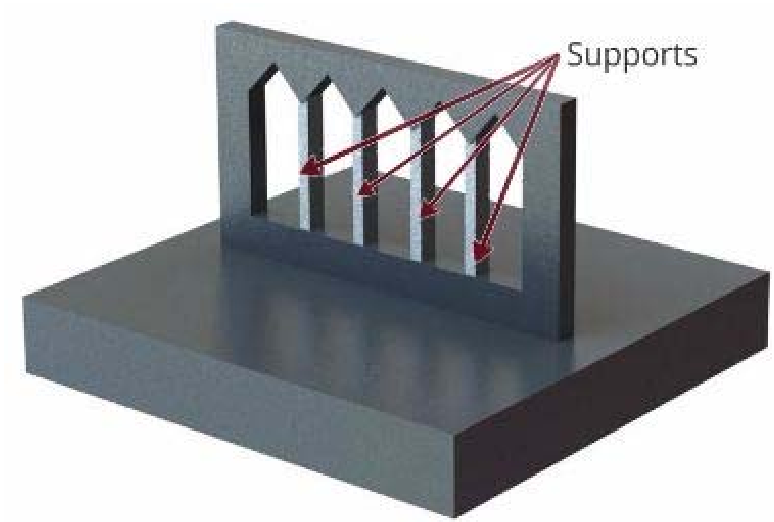
- Most simple support structure just fills the hole that creates a overhang.

Design basics, overhangs

- An offset support structure can be used that will be easier to remove. In this case the support is attached by only one side to the part

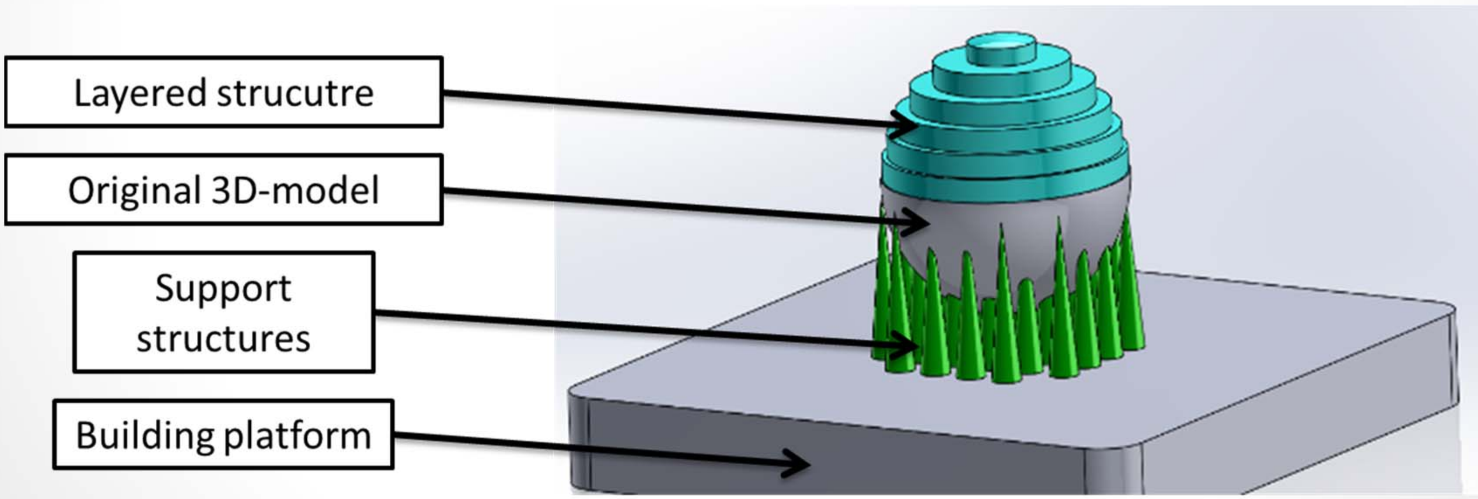
Design basics, overhangs

- If the top surface can be made of a series of angles which are self-supporting, the supports can be minimized



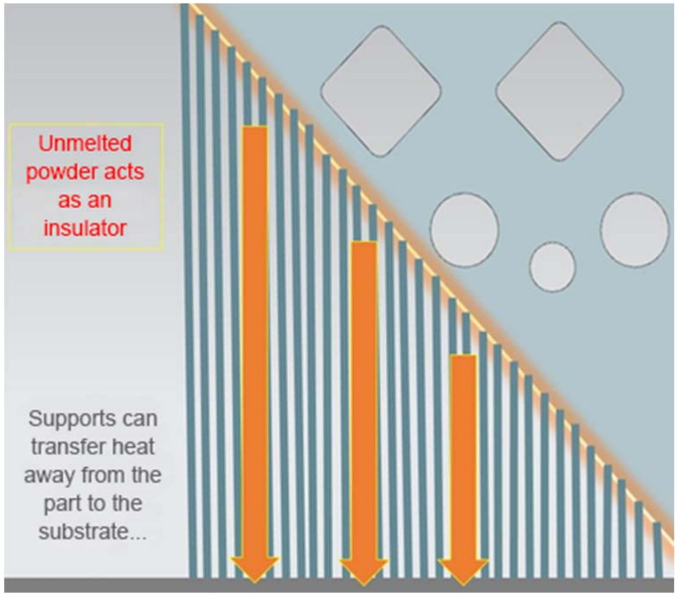
Support structures

- Supports are small, scaffold-like structures beneath - and sometimes partly within - the part to be built which anchor the part to the platform.



Support structures

- Support structures are needed in metal PBF to:
  1. Anchor the parts to a substrate to prevent movement and to support newly melted surface, particularly downward facing surfaces and shallow angles
  2. Prevent new geometry from deforming
  3. Dissipate heat away



Support structures

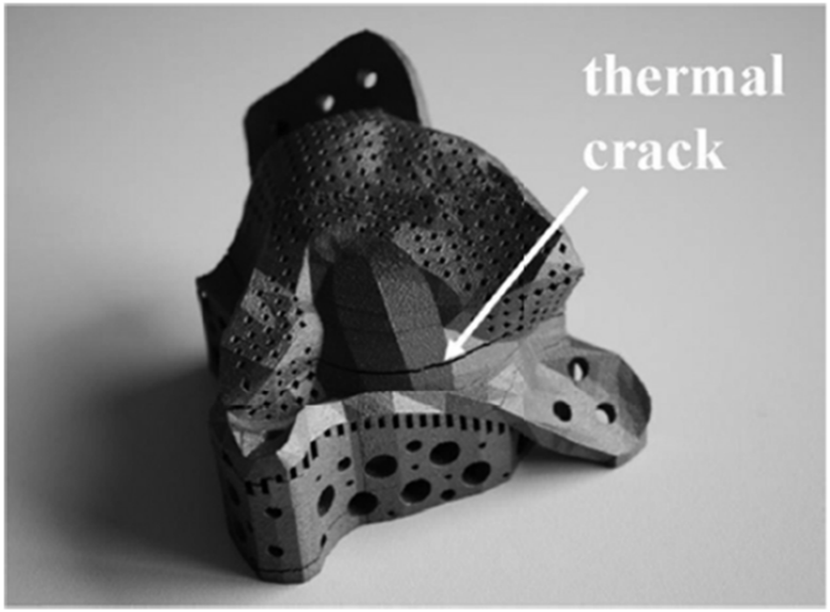
Nacelle hinge

Supports

Fuel injector part

Support structures

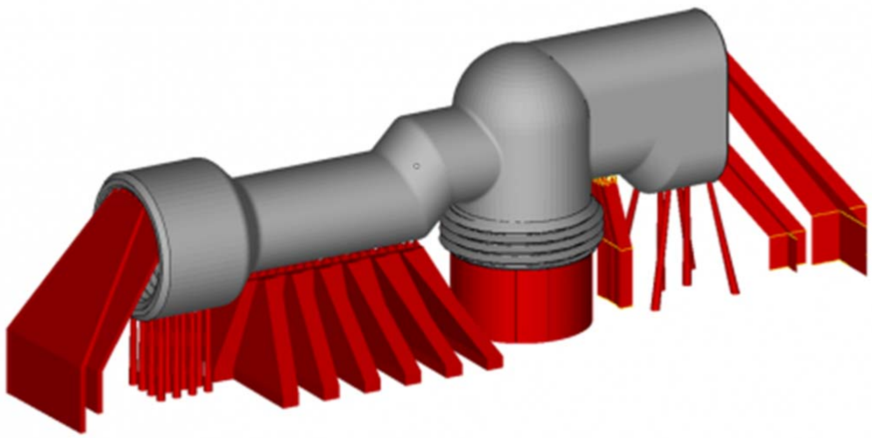
- Thermal crack



Source: Kruth et al. 2002 / Master Thesis_Xiaoyun Li

Support structures

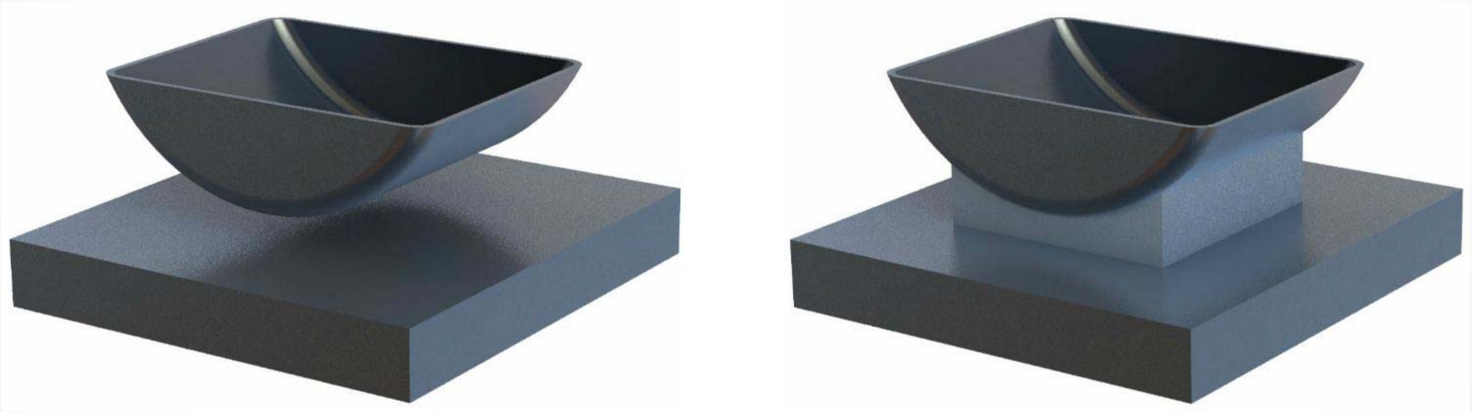
- Supports are ’a necessary evil’ in PBF of metals. Good design minimizes the use of them because they are difficult to remove and use a lot of energy in building process
- Out of all AM processes, PBF of metals has the most difficult supports to remove as they are dense metal



3D model with support structures shown in red. Supports were made with Magics software by Materialise

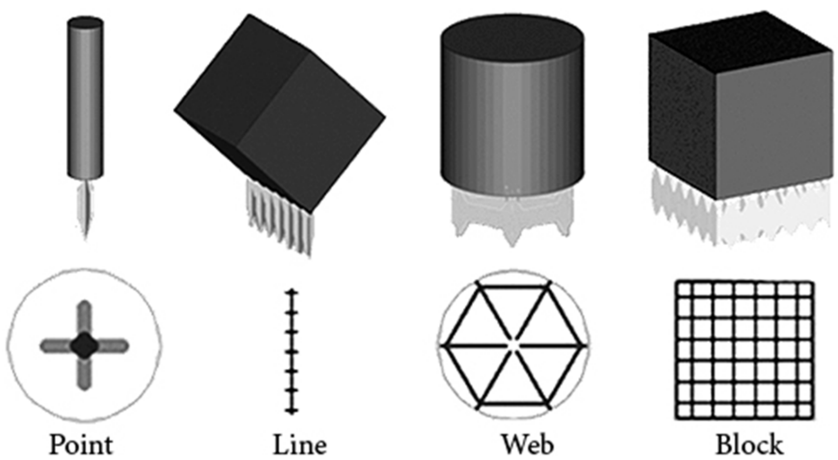
Support structures, curved surfaces

- Support structure is formed under the part and afterwards removed by wire cutting or machining.
- Note the angle between the curved surface and building platform.



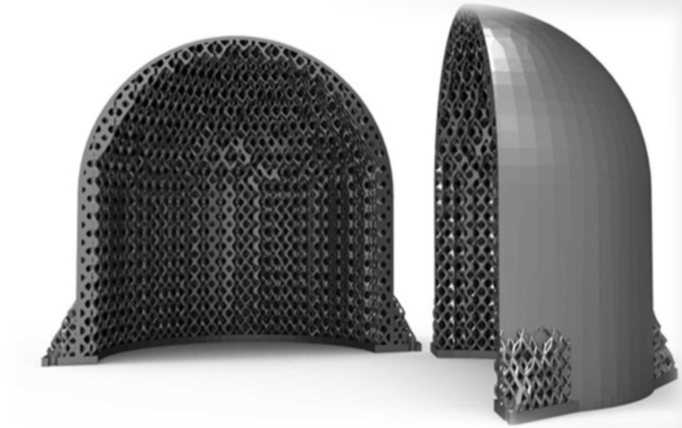
Support types, examples

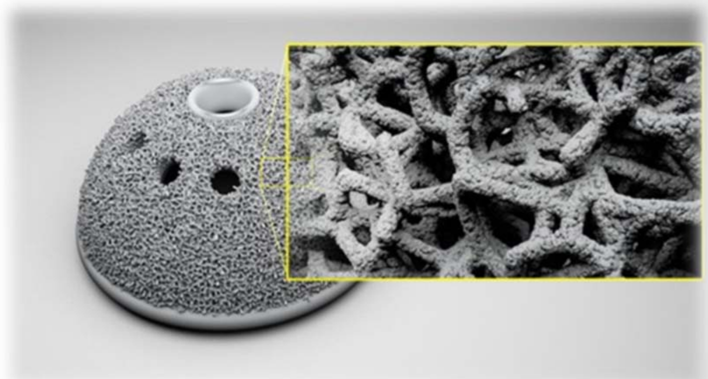
- Most commonly used support structures are thin, scaffold-like structures with small pointed teeth for minimizing the amount of part contact so that they can be broken away from the part easily using hand tools.



Support structures, example of 3D lattice

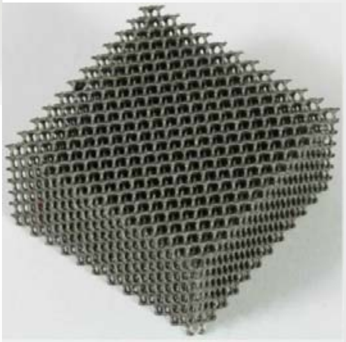
- Standard supports are based on extruded lattices inside a closed skin.
- 3D lattices are a litte more sophisticated.
- Made up of repeated structures that occupy a low fraction of the volume that makes up the part. They use less material and take less time to build than conventional lattice supports.



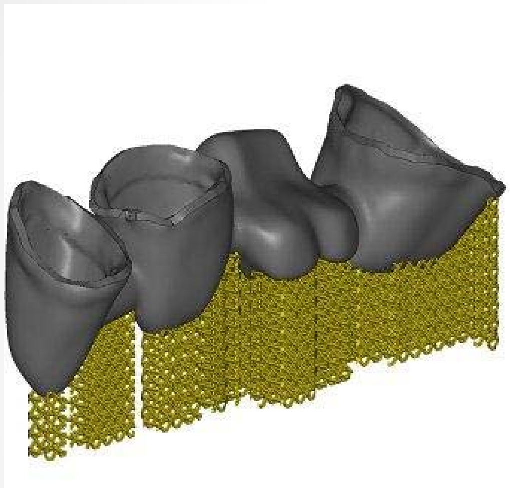


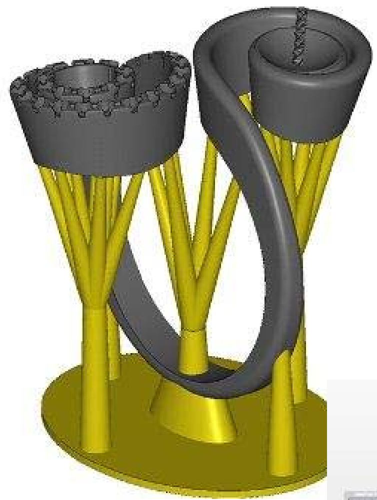
Support structures, example of 3D lattice

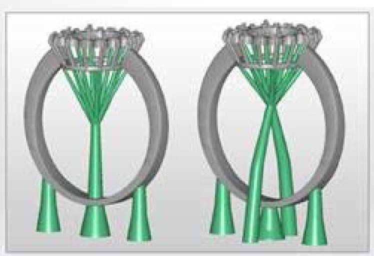
- Open nature of the lattice allows easy removal of surplus powder → easier to remove the part and platform from the build chamber
- Only few specialized CAD tools exist to easily make these kind of structures.



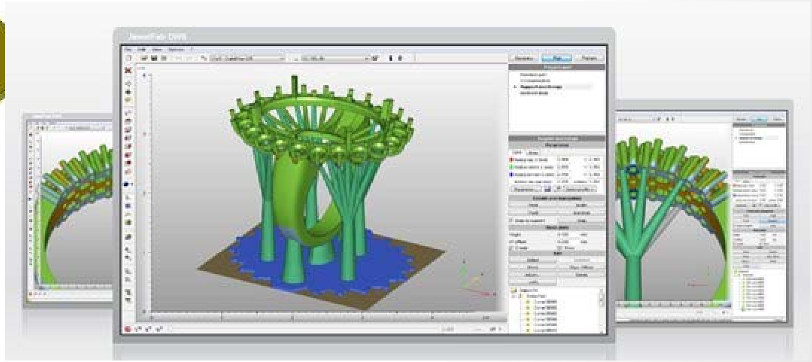
Support structures, examples



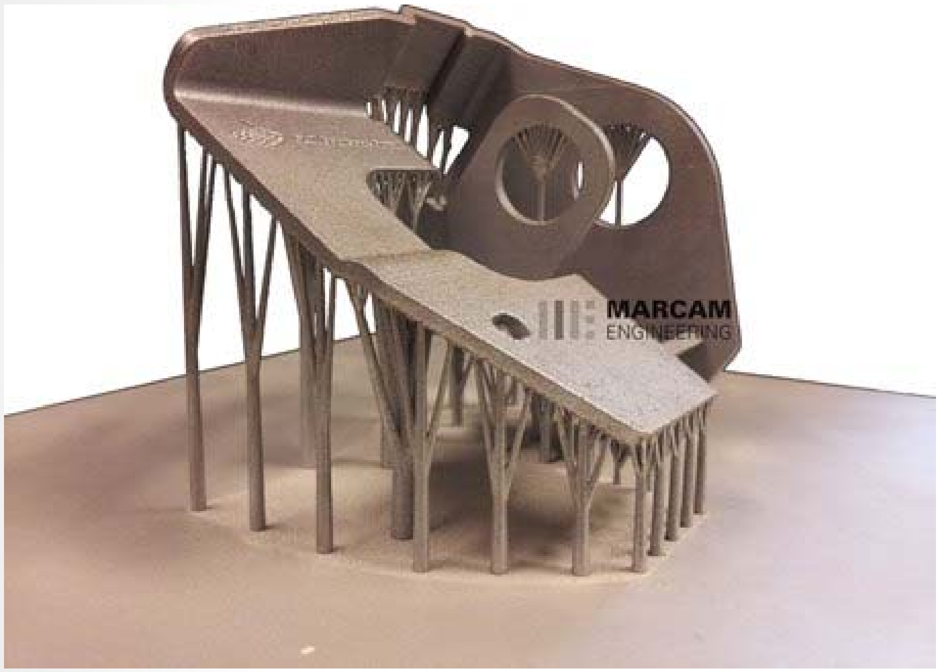


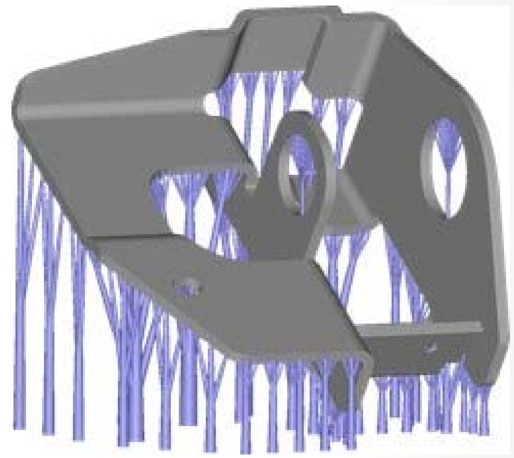


Solution 1 Solution 2

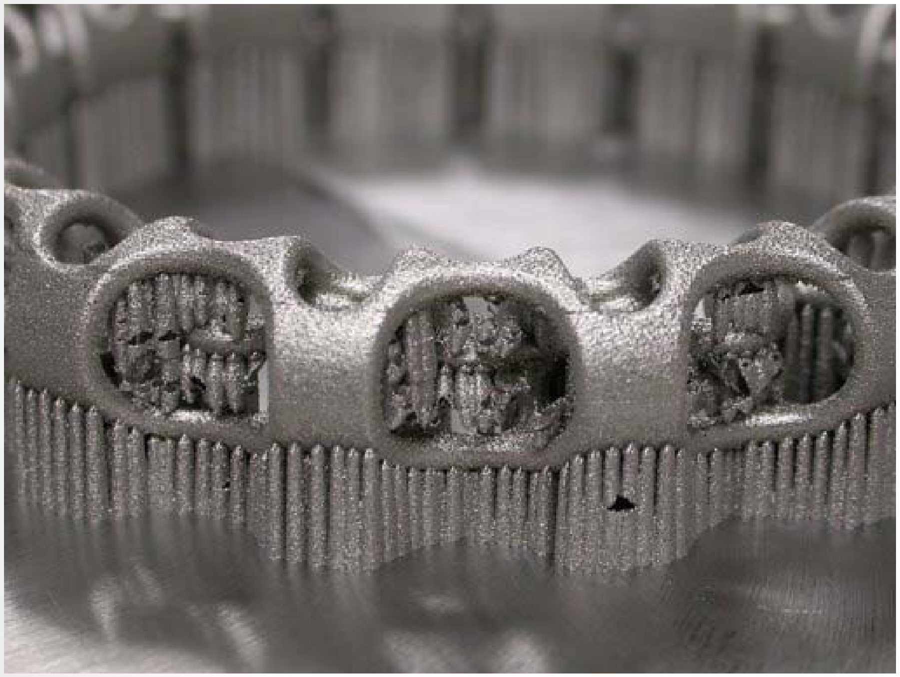


Support structures, examples

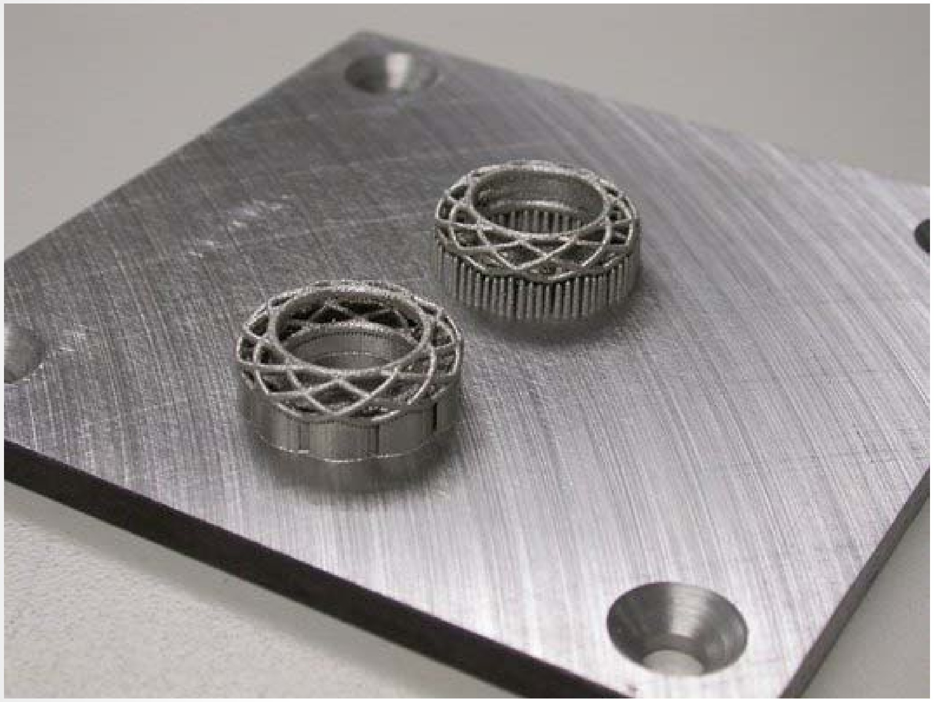




Support structures, examples



Support structures, examples



Removal of supports

- Supports can be very light, tubular forms, or heavy sections supporting large downward facing surfaces
- They are usually removed by wire cutting or sawing, or otherwise machined off by CNC equipment or manually
- Best designed supports are those most easily removed

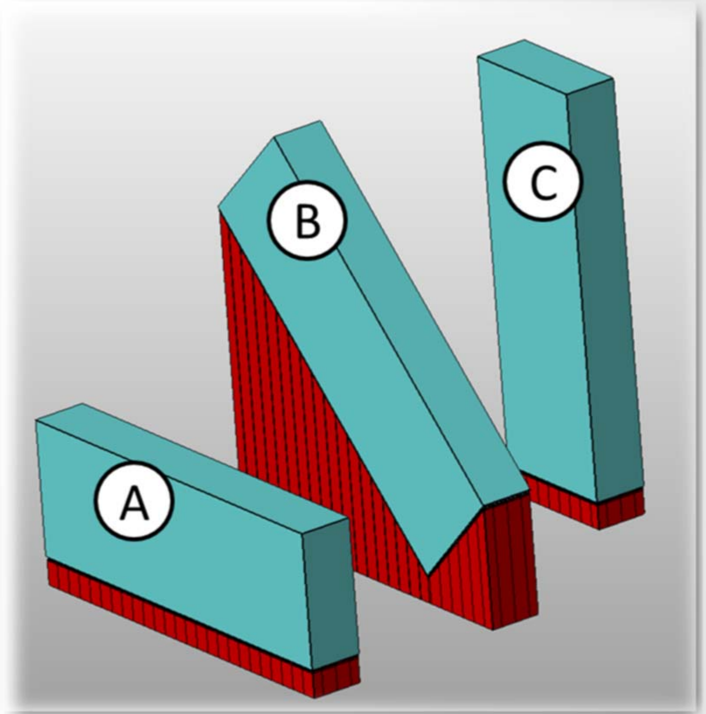
Minimizing supports

- Supports are effectively waste and have to be removed after the build is complete.
- Supports enable the AM process to succeed, but add complexity and cost further down the process line.

Minimizing supports

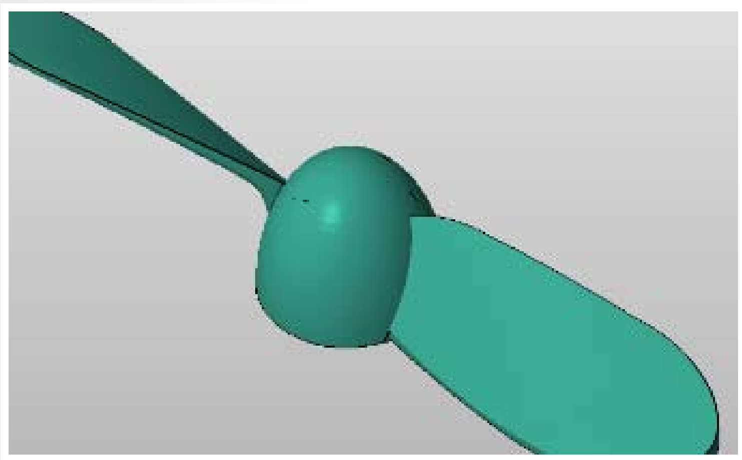
- Certain workpieces might need certain positioning into building platform:

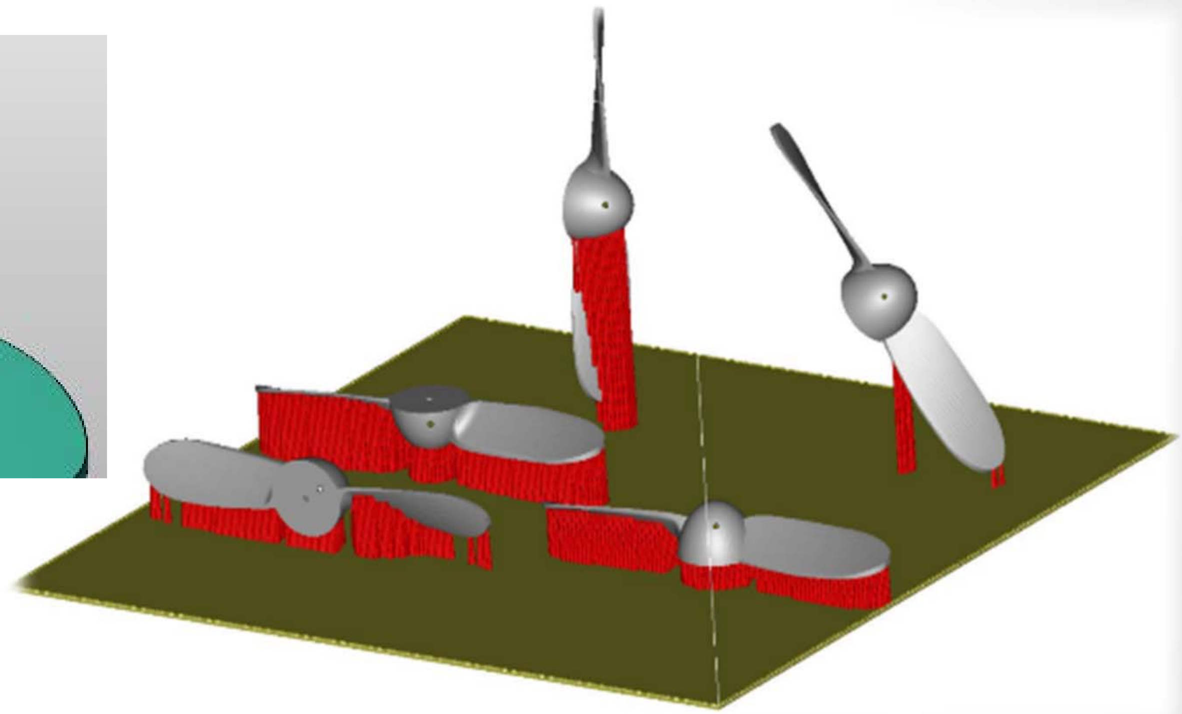
A. Fastest fabrication, but possibly worst quality, most cheapest way
B. Compromise solution
C. Slowest and most expensive fabrication but best quality



Minimizing supports

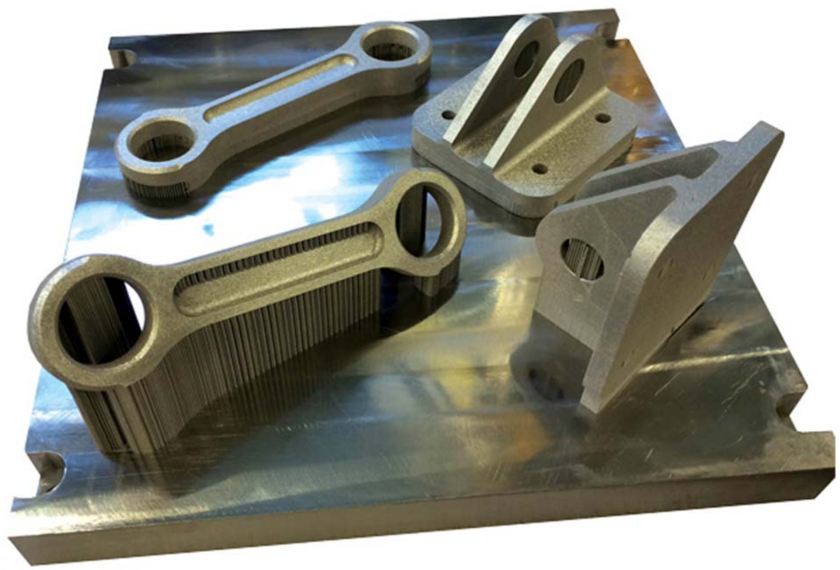
- Depending on position of workpieces on building platform, support structures can be very different.





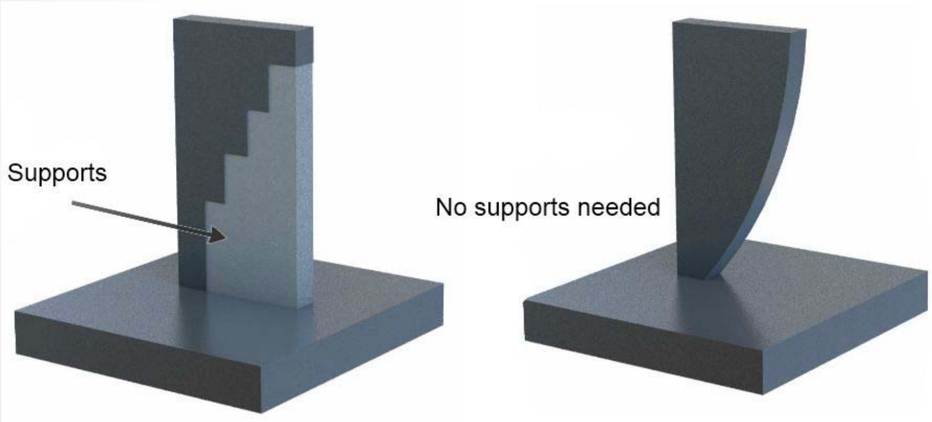
Minimizing supports

- Key part of the DfAM process is to define how to build the part with the minimum of supports.
- It can be done by eliminating overhangs by angling the part, and by modifying the design of overhanging features such as holes, slots and channels.



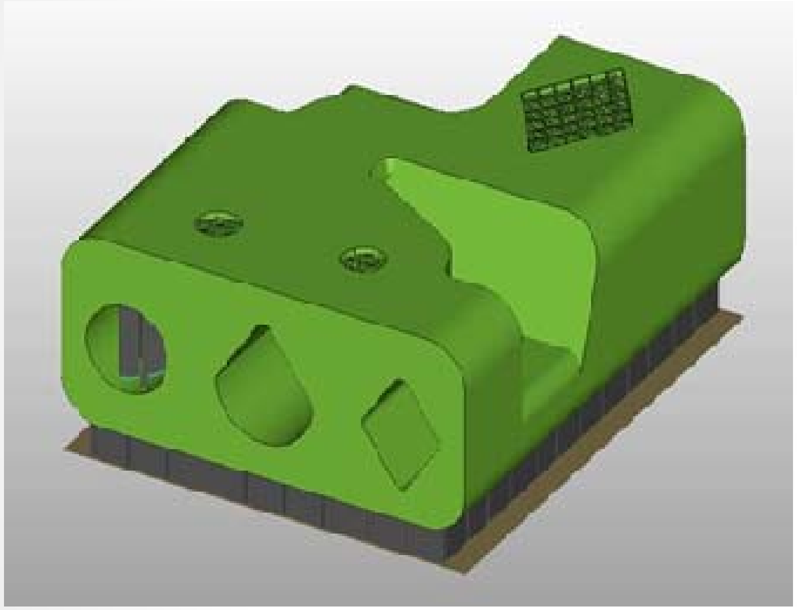
Minimizing supports

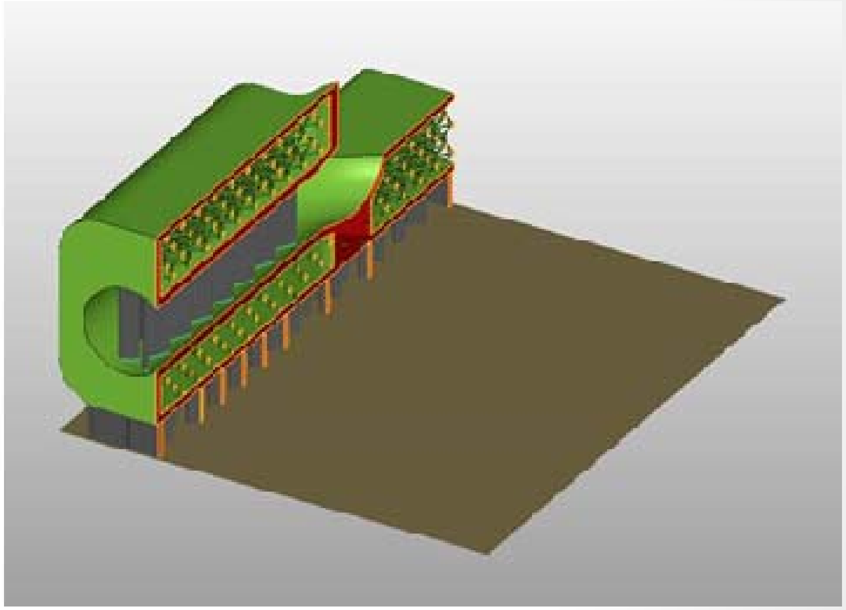
- Ideally parts should be designed so that no supports at all are needed. In reality this is rarely possible.
- Support structures are almost always formed from fine lattices, to minimize build time and removal effort.



Geometry modified to simple curve that can be built without supports

Minimizing supports

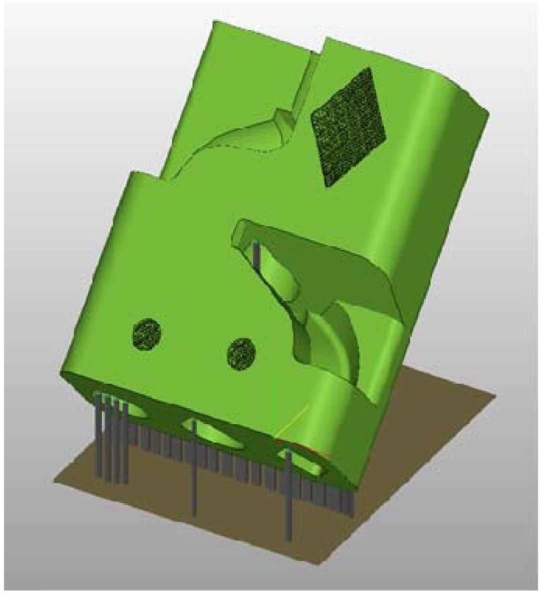


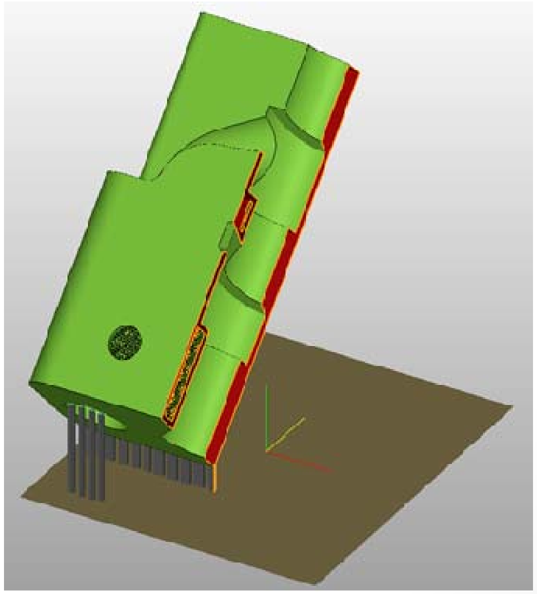


Source: Marc Saunders, Renishaw

Minimizing supports

- Other way to eliminate supports is to orientate the part so that it needs less or none supports.
- This can lead to increased build time





Source: Marc Saunders, Renishaw

Support software

- Support software demo:
  - https://www.youtube.com/watch?v=6tlrCpwAV4M

Further reading/useful links

- http://canadamakes.ca/app/ - General and design info about AM
- https://etda.libraries.psu.edu/catalog/21832 - Thesis about design guidelines
- https://sffsymposium.engr.utexas.edu/Manuscripts/2012/2012-70-Seepersad.pdf - A designer’s guide for dimensioning and tolerancing SLS parts
- https://www.linkedin.com/pulse/design-metal-am-beginners-guide-marc-saunders/ - Beginner´s guide to DfAM
- https://www.linkedin.com/pulse/can-you-build-am-parts-without-supports-marc-saunders/ - About need of supports

Thank you for your attention!

Any questions?

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