Integrating Metal 3D Printing & Flexible Post Processing

Deliverable 5.6.2 – Online Design Guide

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1. Introduction

Additive manufacturing (AM), more commonly known as '3D printing', is an umbrella term to describe various technologies that manufacture 3D objects through the addition of material layers. Although this layered process do not need moulds or tooling, it is subject to a separate set of design limitations, depending on the material being used.

One of the key aspects of building layer-upon-layer is that most vertically increasing shapes would require support structures on the down-facing surfaces to:

- Support the weight and shape of the part, since the material is not fully solid at this process phase.
- In particular for metal builds, aid with heat dissipation and restrict distortion due to residual stresses generated during the build.

The support structures are varied depending on part geometry and material, ranging from intricate lattice structures to solid blocks. Some of these structures can be easily removed, while others require extensive time and cost to machine away. In addition, depending on the layer thickness when manufacturing the part, the surface may require further processing to achieve the final finish.

The aim of this project is to optimise these post-process steps, both in terms of cost and time, which in turn will significantly improve the viability of AM as a production technology.

2. Deliverable 5.6.2 – Online Design Guide

The key objective of this deliverable is to provide guidance on how to design parts for the entire AM process, including the build and post-process phases. This document will remain live and continue to accommodate findings from this project.

The current chapter delivers a set of guidelines that would help to optimise design for AM parts at the build phase. These guidelines were developed for the SAVING project, funded by the Technology Strategy Board. The document developed by Crucible, one of the project partners of the SAVING project, can be found here.

3. Introduction to DMLS

DMLS is an AM process in which parts are built up in layers of metal powder which are melted together using a high power laser.

When compared to more traditional manufacturing processes, DMLS offers many benefits to a designer:

– The process is ideal for the creation of highly complex parts with internal channels, which would be difficult or even impossible to create in any other way.
– Additional tooling is not required to vary the level of component complexity.
– The ability to optimise a parts geometry beyond the capability of any other manufacturing process. For example, weight can be reduced while maintaining optimum strength through varying wall thickness, lattice structures and internal coring.
– The option to combine multiple parts of a component at the building process.

Whilst DMLS parts do not have to adhere to conventional design rules, the process does have its own constraints. An extensive amount of set-up and post-process is required to achieve a functioning finished part, which includes adding support structures to downward-facing surfaces and then machining them post build to obtain the final part.

3.1. Process Overview

Figure 1 provides an overview of the DMLS process:

1) A recoating blade, or 'recoater', deposits a layer of powder (0.02 - 0.06 mm) onto a build platform. A laser guided by mirrors melts the first layer of the part, fusing it to the build platform.
2) The build platform lowers by one layer at the same time as the powder reservoir rises slightly, and the recoater evenly distributes a powder dosage over the build area.
3) The laser then melts the next layer of the part, fusing it to the layer below.
4) Steps 2 and 3 repeat over and over, gradually building up the part.
5) Once the last layer has been built the un-sintered powder can be removed, revealing the part attached to the platform.

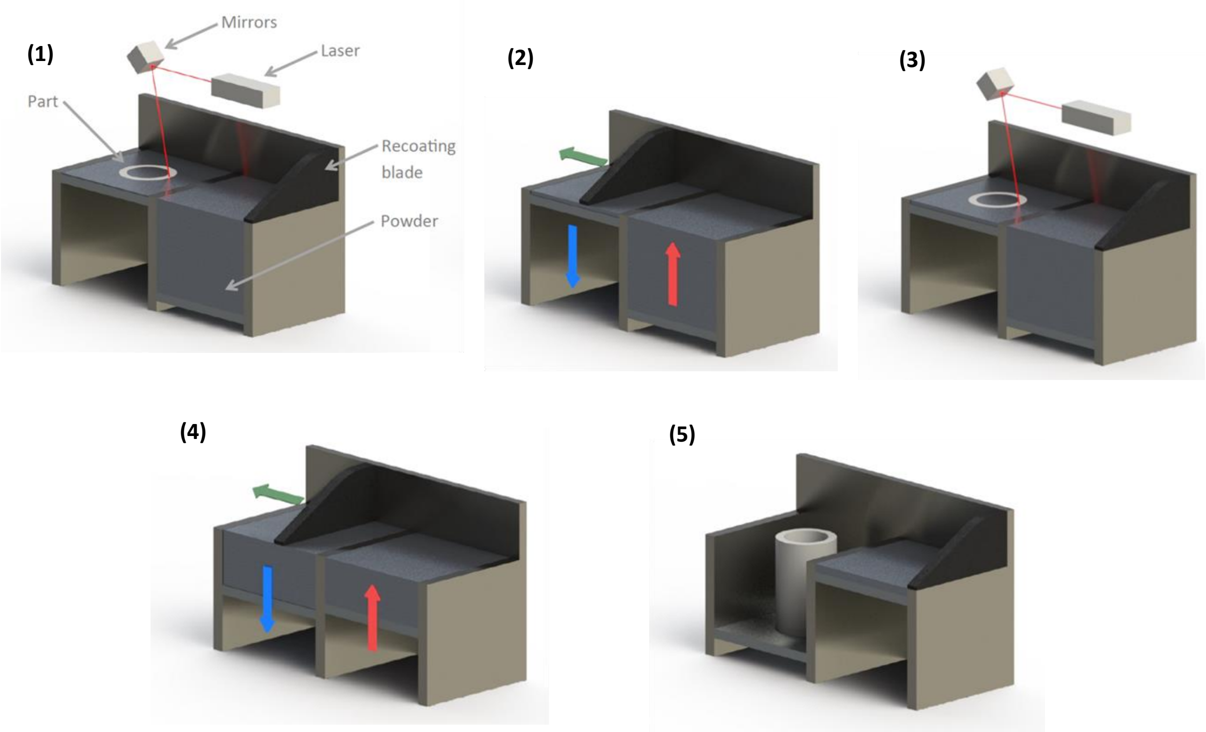

Figure 1: DMLS process summary: (1) Recoating blade deposits material, a mirror guided laser then melts the first layer of the part on to the build platform; (2) Build platform then lowers as the powder reservoir raises, and the recoating blade deposits new layer of powder over build area; (3) The laser then melts the next layer of the part, which forms on to the layer below; (4) Steps 2 and 3 are repeated until the part is complete; (5) After the final layer has been built, the un-sintered powder is removed and the part is left attached on the platform.

3.2. Materials

A wide variety of materials can be used in DMLS, including Aluminium (AlSi10Mg), Cobalt Chrome Alloy (Co28Cr6Mo), Nickel Alloy (In718), Maraging Steel (1.2709), Stainless Steel (316L and 15-5PH), Commercially Pure Titanium (TiCP) and Titanium Alloy (Ti6Al4V). The different materials are suitable for different applications, as listed in Table 1.

Table 1: DMLS materials and their typical applications.

Material Group	Typical Applications
Aluminium (AlSi10Mg)	Aluminium AlSi10Mg is a typical casting alloy used for parts with thin walls and complex geometry. It offers good strength, hardness and dynamic properties and is therefore also used for parts that are subject to high loads. Parts in Aluminium AlSi10Mg are ideal for applications which require a combination of good thermal properties and low weight.
Cobalt Chrome Alloy (Co28Cr6Mo)	Cobalt Chrome Alloy Co28Cr6Mo produces parts in a cobalt-chrome-molybdenum based super-alloy. Co28Cr6Mo is a class of super-alloy, and is characterised by having excellent mechanical properties (strength, hardness etc.), corrosion and temperature resistance. Such alloys are commonly used in biomedical applications such as dental and medical implants and also for high-temperature engineering applications such as in aero engines.

Table 1 continued.

Material Group	Typical Applications
Nickel Alloy (In718)	Nickel Alloy In718 is a heat resistant alloy which is precipitation-hardened. It is characterized by having good tensile, fatigue, creep and rupture strength at temperatures up to 700°C. In718 also has outstanding corrosion resistance in various corrosive environments. This material is ideal for many high temperature applications such as gas turbine parts, instrumentation parts, power and process industry parts etc.
Maraging Steel (1.2709)	Maraging Steel (1.2709) is characterised by having very good mechanical properties, and being easily heat-treatable using a simple thermal age-hardening process to obtain excellent hardness and strength. Ideal for many tooling applications such as tools for injection moulding, die casting of light metal alloys, punching, and extrusion. It is also good for high performance industrial and engineering parts, for example aerospace and motor racing applications.
316L Stainless Steel	316L Stainless Steel is characterised by having higher corrosion resistance and mechanical properties than the more common 304 alloy, and can be used over a wide temperature range down to cryogenic temperatures. 316L Stainless Steel is widely used in a variety of food processing, medical, aerospace, oil and gas, and other engineering applications requiring high strength and corrosion resistance.
15-5PH Stainless Steel	15-5PH Stainless Steel is characterised by having very good corrosion resistance and mechanical properties, especially in the precipitation hardened state. This type of steel is widely used in metal prototypes and a variety of medical, aerospace and other engineering applications requiring high hardness, strength and corrosion resistance.
Commercially Pure Titanium (TiCP)	Commercially pure titanium, a well-known light metal, is characterised by ductility and corrosion resistance combined with low specific weight and biocompatibility. This material is ideal for many high-performance engineering applications, for example for aerospace, the chemical industry, offshore applications and production of biomedical implants.
Titanium Alloy (Ti6Al4V)	Ti6Al4V is a light alloy characterised by having excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility. Ti6Al4V is ideal for many high-performance engineering applications, for example in aerospace and motor racing, and also for the production of biomedical implants.

3.3. Machines

Figure 2 summarises the various DMLS machines in use at 3T-am.

EOS M270	EOS M280	EOS M290	EOS M400
Build Volume (Dimensions include build platform)**:**			
X: 250 mm	X: 250 mm	X: 250 mm	X: 400 mm
Y: 250 mm	Y: 250 mm	Y: 250 mm	Y: 400 mm
Z: 215 mm	Z: 325 mm	Z: 325 mm	Z: 400 mm

Figure 2: DMLS machines in use at 3T-am.

3.4. Build Plates

When designing a part that will go to the very limit of the available build volume it is important to consider the bolt holes in the corners of the build plates used to fix them into the machine (see Figure 3). Parts cannot be built over these areas of the platform.

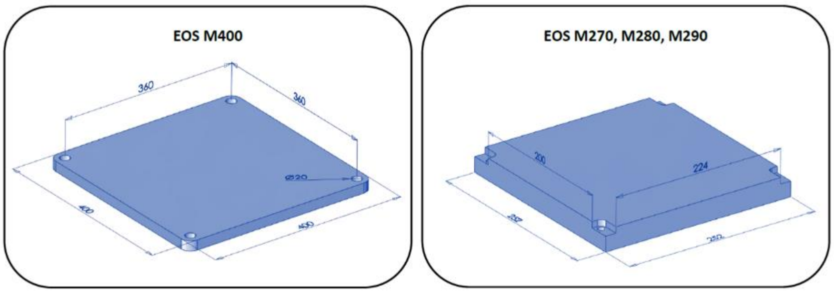

Figure 3: Build platform dimensions of the various EOS DMLS machines in use at 3T-am.

3.5. Post Processing

Following production, almost all parts go through a set of post-build processes that include heat treatment, removal of support structures, blasting, machining and polishing (as required).

3.6. Heat Treatment

The build is heat treated (material dependent) before any parts are removed to:

– Relieve stress, and
– Age harden.

3.7. Wire Cutting

Electrical Discharge Machining (EDM), also known as 'wire-cutting', is used to remove the parts from the build platform (Figure 4). This process can also be used to define the geometry of the finished part.

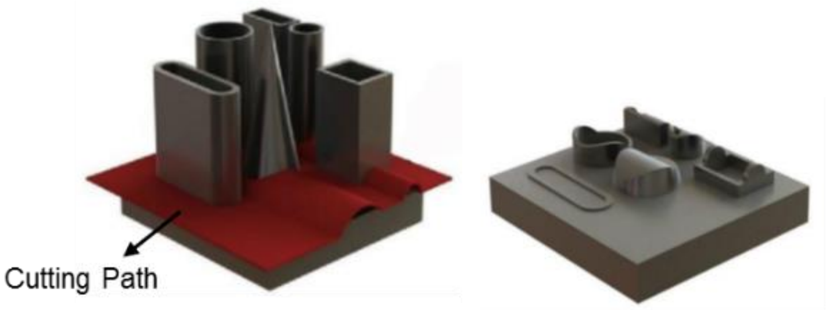

Figure 4: Example of finished part removal from platform.

The remaining material on the platform is machined away to prepare the platform for another build.

3.8. Support Removal

In many cases the wire cutting process is used to remove most or all of the support on a part. In cases where the supports cannot be removed by this process, they are either machined or carefully removed by a technician with hand and power tools.

3.9. Abrasive Blasting

Abrasive blasting involves propelling a stream of pressurised fluid (typically air or water) containing abrasive material (often called the media) to either smoothen a rough surface or roughen a smooth surface. This process has several variants, including bead blasting, sand blasting, wet blasting, and shot blasting.

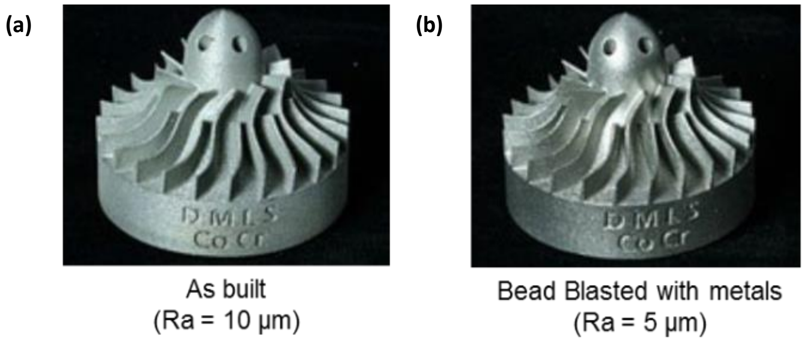

Figure 5: Example of surface finish (a) as built and (b) after blasting, which smoothened the surface throughout.

Once the support structure has been removed from the built part, the part is blasted with abrasive medium to remove the residues. As shown in Figure 5, this process helps to give the surface a homogenous appearance.

3.10. Machining

Machining a part post-build can be used to create further detail within the part which otherwise would have required extensive support structure. In addition, post machining can be used to achieve tighter tolerances on critical features.

3.11. Hand Finishing / Polishing

Alongside aesthetics, polishing a part before other surface treatments can also prevent corrosion and surface contamination. Although this is a common requirement for components used in aerospace and automotive applications, the highly polished surface is frequently essential in medical application to maintain hygienic conditions and prevent contamination.

Using a combination of manual, mechanical and electrochemical techniques, dedicated hand-finishing experts process parts to ensure all areas meet agreed tolerance requirements.

Figure 6: Example of a hand-finished surface.

4. Design Guide

The design considerations for 3D printing varies depending on the manufacturing process. Due to volume restrictions on the 3D printing process and the complexity of post-processing parts, the design guide focusses on increasing build efficiency and reducing post-process steps required. This document will focus on the design parameters of Powder-Bed technology.

4.1. Part Orientation

When designing a part optimised for metal AM one of the first things to consider is the orientation in which the part will be built – there are several factors that influence this decision.

4.2. Quantity

As shown in Figure 7, the quantity of part(s) and therefore the part density on the platform is one of the key components to consider when determining the build orientation:

- **One off Production:** Orientating the part to achieve a smaller height will help reduce build time and component cost.
- **Batch / Production Runs:** When building several of the same part, choosing an orientation that will allow several to be built on the same platform will help reduce the unit cost.

(a) One off Production **(b) Batch Production**

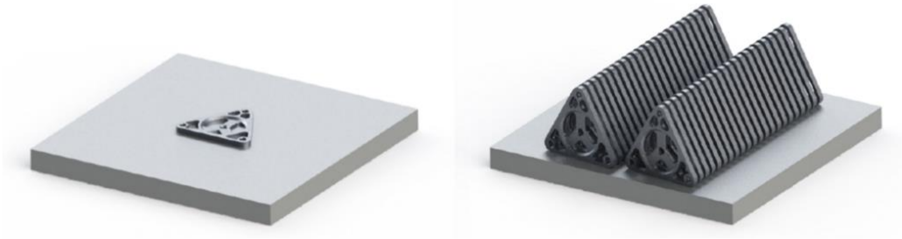

Figure 7: Part orientation is dependent on the quantity of parts.

4.3. Minimising Support Structure

When designing for metal AM the ultimate goal should be to produce a geometry which is completely self-supporting (i.e. requires no additional support structure). This may not always be possible but choosing an orientation for the part which requires the least amount of additional support will help to reduce material costs and the amount of post processing the part requires.

4.4. Part Recoating

As the process involves drawing a blade over the newly built surface to recoat it with powder, the top of the built part frequently connects with the blade. As a part builds up, the forces applied to it by the recoater blade becomes greater. This can cause damage to the part or build failure.

4.5. Lead In / Stability

When choosing a Z-axis orientation for the part, it is important to ensure there are no surfaces parallel to the recoating blade, as the blade will tend to bounce off of this parallel wall causing shifts in the part or in worst cases a build crash (Figure 8 a). By turning the part at least 5 degrees from parallel with the blade reduces the contact point with the blade to a significantly smaller surface, allowing it to pass over smoothly (Figure 8 b). Despite the rotated angle, it is still important that the geometry exposed is rigid enough to withstand the recoater blade passing over it (Figure 8 c), and whenever possible, aligned along the direction of travel of the recoater blade (Figure 8 d).

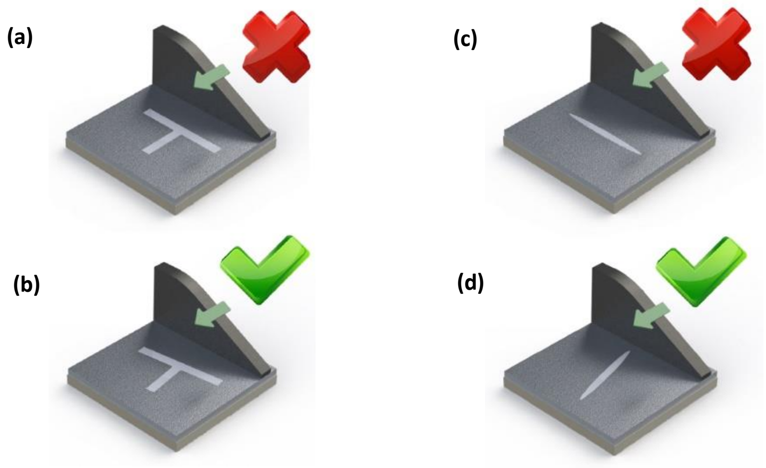

Figure 8: (a) Flat surfaces parallel to the recoater blade can cause shift lines or build crashes, (b) rotating the flat surface at least 5 degrees from parallel with the blade will improve buildability, (c) whenever possible, long thin parts should be aligned along the direction of travel of the recoater blade, as shown in (d).

4.6. Part Strength (8:1 Ratio)

Whilst the effects of the forces from the recoater blade will be minimised by choosing the best build position and orientation, any part designed for metal AM should be inherently stiff so as to allow for a stable and reliable building process.

A good rule to achieve a stable part is to ensure the ratio between the cross-section and the height is no more than 8:1 (Figure 9 a), as exceeding this ratio might damage the part alongside adjacent parts

(Figure 9 b). These issues can be prevented by bridging the vertical sections at frequent intervals to form a more rigid structure (Figure 9 c). Arching the horizontal bridges will ensure they are self-supporting and avoid the need for additional support structures.

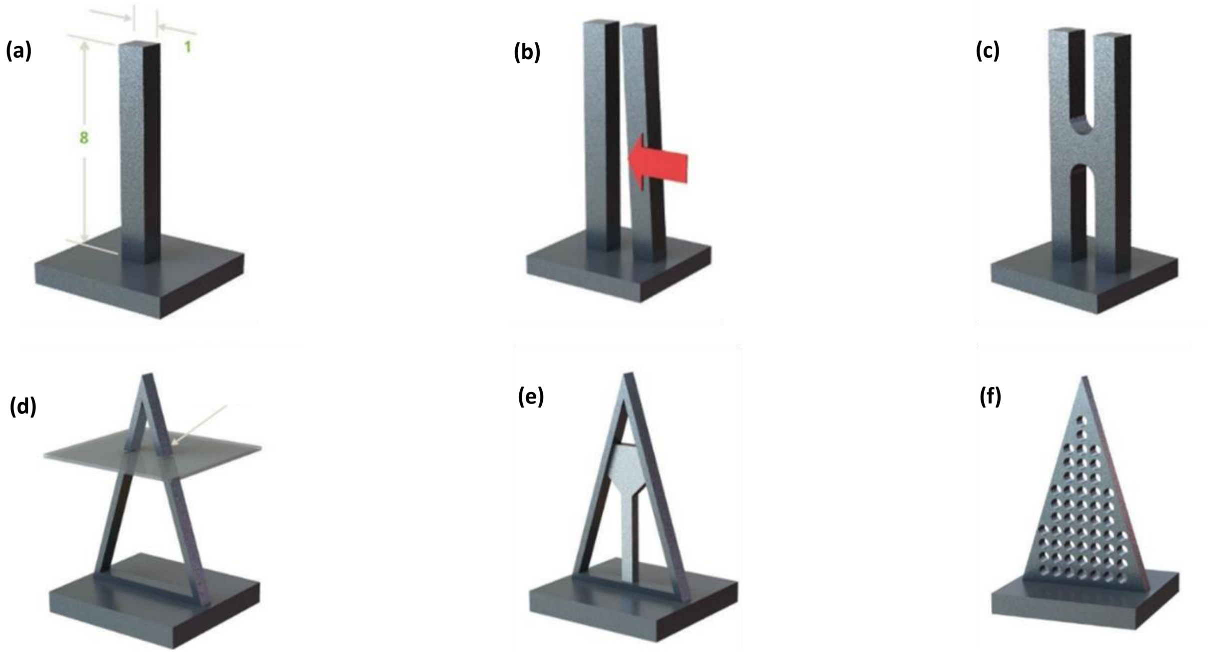

Figure 9: (a) Height to width ratio of 8:1 is optimal for part stability; (b) parts that are higher than this ratio may get damaged during recoating, damage adjacent parts and/or cause build crashes; (c) frequent horizontal bridges can strengthen the part during build; (d) some geometry may be strong on completion, but require additional support during the build process; (e) simple support structure can sometimes strengthen a part throughout the build process; (f) a slight re-design (introduction of perforated surface in this case) may provide adequate support and maintain the reduced weight whilst minimising support structure requirements.

Although some parts may be strong on completion, it might still be necessary to support its geometry during the building process. For example, the triangular structure shown in Figure 9(d) will be very weak as the build approaches the apex. Thus, dragging a dynamic section through the CAD model can help to ensure that the part has good rigidity at every stage of the build.

The introduction of a simple support structure might be sufficient to strengthen the part throughout the build process (Figure 9 e), whilst the introduction of a perforated sheet would circumvent the support removal step (Figure 9 f). Thus, it is often worth considering how the part could be re-designed to avoid any areas of weakness, while maintaining the design benefits offered by AM.

4.7. Support Structure

Although all design guides advise on minimising support structures due to build and post-process time/costs, supports play a critical role in the DMLS process:

- Support structures act as a heatsink, allowing effective energy dissipation;
- They can be used to improve structure rigidity during the build process;
- While allowing the part to be connected to the build-platform, they provide cutting clearance for part separation;
- Support structures can also prevent parts from distorting due to internal stresses.

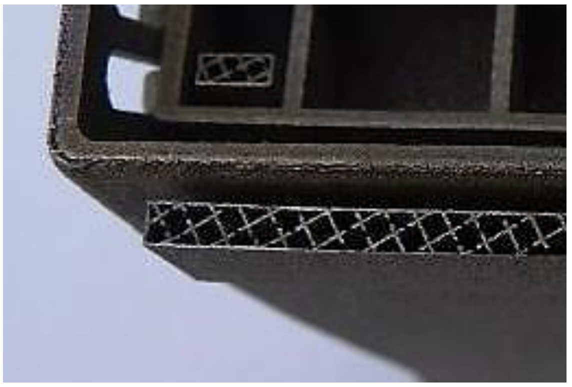

Figure 10: Hollow support structure built from fine lattices, and as a result minimising additional build time and material cost.

4.8. Angles Surfaces

Unlike polymers, metal powder in the build chamber does not provide any support to layers being built above it. Depending on the material, some angled surfaces, despite having downward facing surfaces, are self-supporting. Support structures will be required, however, if the angle is too acute. Furthermore, if support structures are required near the angle, the downward facing surface may require significant amount of post-processing to reduce the surface roughness.

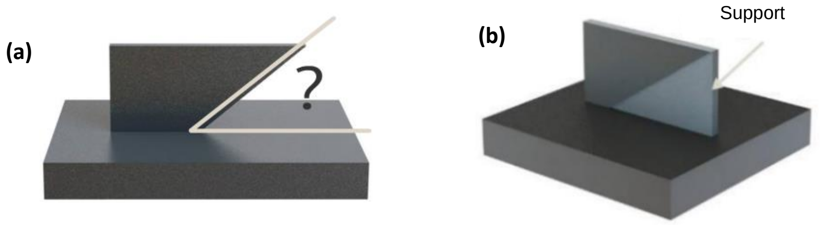

Figure 11: (a) depending on the material, some angles are self-supporting; but (b) support structures are required if the angle is too acute.

The minimum angles that will be self-supporting are approximately:

- Stainless Steels - 30°
- Inconels - 55°
- Titanium - 30°
- Aluminium - 45°
- Cobalt Chrome - 30°

4.9. Downward Facing Surfaces: Cut-Outs

All geometries with downward facing surfaces will require support structures, which will subsequently require removal and surface finishing. There are various approaches to deal with downward facing surfaces:

- Simply remove the feature and build a solid section instead. The feature can be reintroduced during post-processing (Figure 12 b). This option adds build time, material cost and post-process costs.
- Introduce an offset support structure that will enable the feature to be built into the part, significantly reducing machining time to remove it (Figure 12 c). Only one edge would require machining to remove the support structure.
- There is often a build orientation that can reduce or eliminate all horizontal downward facing surfaces (Figure 12 d).
- If the part design can accommodate, it can be beneficial to consider how the cut-out will be supported. For example, introducing angles on downward facing surfaces can significantly reduce the amount of support structures required (Figure 12 e).

  It is also beneficial to evaluate the purpose of the cut-out. If it is simply for weight reduction or cooling, a self-supporting structure that offers comparable performance might be advantageous both in terms of post-production cost as well as time (Figure 12 f).

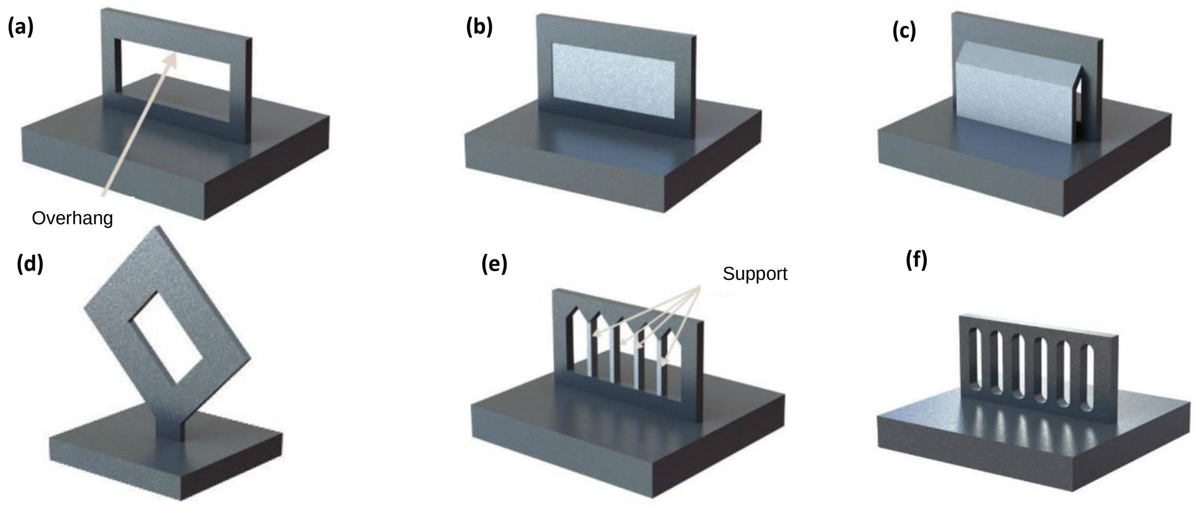

Figure 12: (a) Cut-outs with horizontal downward facing surfaces, as shown in this example, can be dealt with using various approaches; (b) the cut-out can be filled with support structures that will require machining and finishing post-production; (c) an offset support can be introduced, which will only require removal from one of the part surfaces; (d) the part can be re-orientated to remove almost all horizontal downward facing surfaces. In this example, rotating the part by 45° results in all the downward facing surfaces being angled and self-supporting; (e) introducing angles to the horizontal downward facing surface, that is, changing the profile from flat to a series of 'v's will only require columns to support the surface; (f) depending on the purpose of the cut-out, re-designing the shape to include columns with oval slots will remove the need for supports altogether.

4.10. Downward Facing Surfaces: Overhangs

Horizontal overhanging surfaces present the same challenge as downwards facing surfaces in cut-outs, and thus, can be dealt with using similar approaches:

– These surfaces can be supported straight down to the build platform. This, however, will increase material cost, build time and post-process time and cost (Figure 13 a).
– An angled support extending from the surface to the main part is a more efficient solution, both in terms of time and cost (Figure 13 b).
– If the part design can accommodate, the best solution would be to re-design the part to include angled downward facing surfaces that are self-supporting (Figure 13 c).

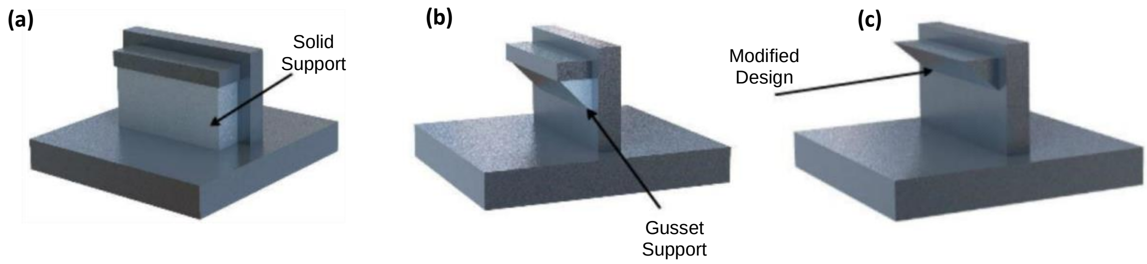

Figure 13: Downward facing surfaces (overhangs) can be supported using (a) solid support structure extending down to the build-platform; (b) angled support structure connected to the main part; and (c) re-design of part to remove the need for support altogether.

Holes

Small holes up to a maximum of **6 mm diameter** can be accommodated by the process without the requirement for support structure (Figure 14 a). Holes larger than 6 mm are more likely to have a very rough, low density surface at the top which may require post processing (Figure 14 b).

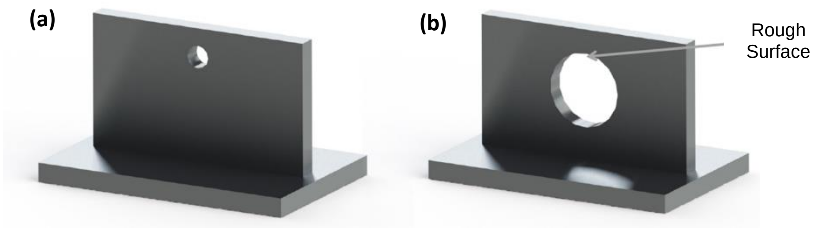

Figure 14: (a) Holes that are 6 mm or smaller can be accommodated without support structures; (b) holes that are bigger than 6 mm are likely to have rough downward facing surfaces, which might require further post-processing.

The addition of support structure into a larger hole will help to improve roundness and the surface finish of the downward facing surface. It will also prevent the hole from collapsing or distorting.

Alternatively, a teardrop shaped hole is very effective as it will not require any support structure but can still offer the same material reduction benefits.

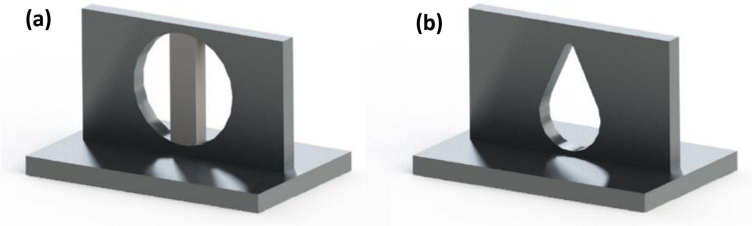

Figure 15: (a) Supported holes are likely to maintain better roundness, better surface finish and reduced likelihood of the shape distorting; (b) creating a self-supporting angle at the top may remove the need for supports altogether.

4.11. Aspects to Avoid

In addition to the design recommendations outlined above, there are some aspects of geometry that should be avoided when manufacturing via DMLS:

1. **Thick Sections on Horizontal Plane**
   It is best to avoid thick wall sections, especially on the horizontal plane. The accumulation of heat while building these sections may cause inhomogeneous shrinkage, which in turn can result in increased internal stresses and therefore potential for part to distort. A better approach is to re-orientate the part to reduce horizontal sections.
2. **Sharp Edges**
   It is best to avoid very sharp edges as they will not fully form through DMLS, and increase the potential for build issues as they collide with the recoater blade. A better approach is to apply radii of approximately 0.5 mm.
3. **Sharp Internal Corners**
   It is best to avoid sharp corners since they can act as stress concentration points, which can then lead to cracks in the part. A better approach is to apply minimum radii of approximately 0.5 mm.