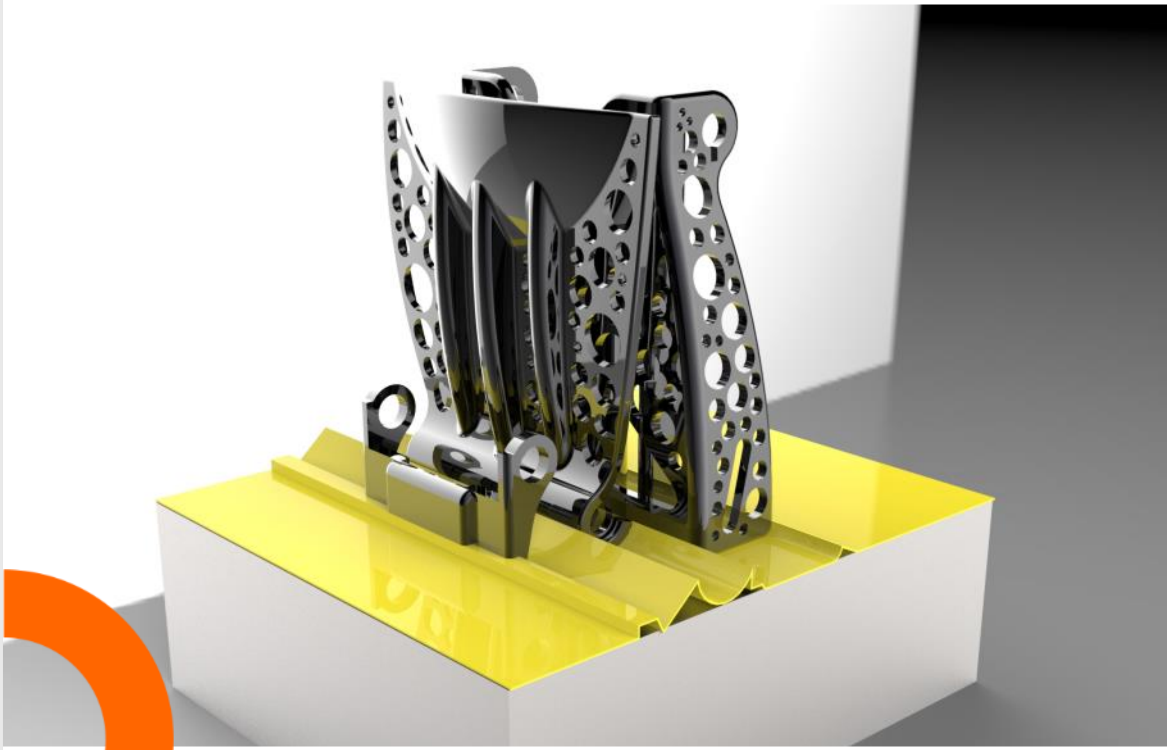


3D printing for manufacture:
a basic design guide

Crucible

Contents

Introduction

'3D printing' is the media-friendly name given to a range of technologies that build parts using layers of material to create a three dimensional object.

Building parts one layer at time means that 3D printed components do not need moulds or tooling, so conventional 'design for manufacture' (DfM) issues like draft angles and undercuts don't apply. This has led to the misconception that 3D printing isn't subject to any design limitations.

Although this may be true for prototyping, the use of 3D printing in manufacture means that it will be subject to the same demands to minimise time and cost as any other process.

Whilst 3D printing does not involve tooling, it does use a considerable amount of time and power, both in the production of parts and their finishing. These inputs need to be minimised to make the most efficient, and profitable, use of 3D printing as a manufacturing technology.

In this paper, we look at the most appropriate 3D printing technologies for manufactured parts. We will also explain the basic principles of the technologies. Finally, we will look at the advantages and limitations of the different technologies and examine the design rules that can help you create manufactured parts that minimise time, cost and waste.

We hope you find it useful.

3D printing fundamentals

Each new layer may require some support

Although the term '3D printing' tends to trivialise a range of complex production technologies, it is, in principle, an accurate description.

If you imagine that you could choose the thickness of the ink that your office printer places on each page you print, and that you could keep printing onto one area so that it got thicker, that is the principle on which most 3D printing technologies operate.

Some techniques use a layer of powder or resin that is solidified by UV light or a laser; some extrude very thin layers of molten material from a nozzle; but they all build parts by using data from CAD files to construct the geometry one layer at a time. The layers range from 0.015mm to 0.1mm in thickness, depending on the process. The thickness of the layers (the thinner the better) affects part quality, cost and the amount of finishing that the part needs once it is removed from the machine.

The other major implication of building a part one layer at a time is that, as the geometry builds upwards, any downward-facing surface will require some support, as the material will often be more fluid than solid at this point in the process (see left).

Most processes involve a support structure that is built as part of the model, like miniature scaffolding. This can be easily removed in some cases, but others will require it to be machined away once the part is built. This can involve considerable additional time and cost.

Issues like support removal, and other types of 'post processing', affect the economic viability of 3D printing as a production technology. Minimising the need for these additional operations is the key to making 3D printed parts as economically efficient as possible.

3D printing processes for manufacture

A great 3D printed product - Freedom of Creation's Lily lamp

Of the 20 or so technologies that come under the general banner of '3D printing' only a few are currently suitable for the production of manufactured parts. This is because many 3D printing processes use materials that were designed for prototyping, not production, so cannot withstand the rigours of day to day use.

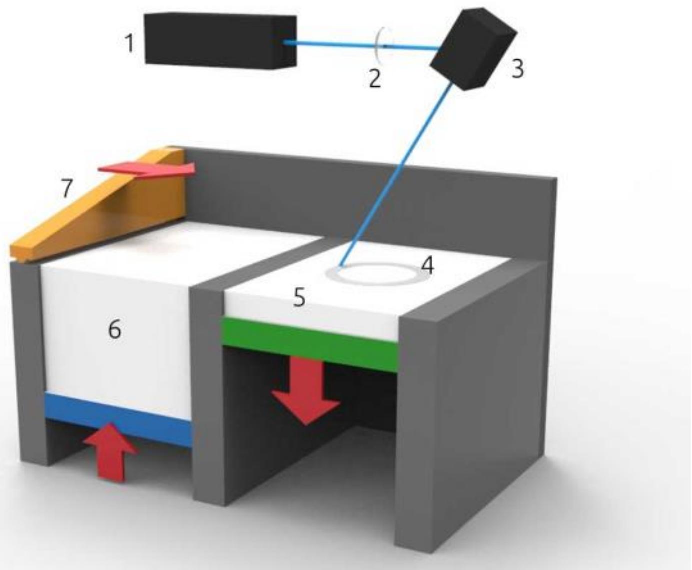
The technologies described in the following pages represent the main 3D printing systems that are suitable for producing useable parts. This is very much a moving target, and new processes are being developed and improved all the time.

3D printed products are still a relatively specialised and costly market sector. Commercial 3D printing systems are expensive, and the build chambers are relatively small, so individual part costs tend to be high. Some processes do however allow for complex 'nesting' of the build chamber, which can dramatically reduce costs. For example, the 'Lily' lampshade (left) was designed to have a small version made inside the large one within the build chamber, doubling the efficiency of the overall part volume.

However, the most challenging issue for 3D printed products remains that of finish. Most processes deliver a part with a rough surface. Some products, like the Lily lamp (left) use this as an integral feature of the design. If a more conventional finish is needed, considerable work, and cost, may be needed to achieve an acceptable appearance.

Introducing Selective Laser Sintering (SLS)

Co2 laser - 1
Optics - 2
Mirrors - 3
Part being built - 4
Build chamber - 5
Supply chamber - 6
Recoating roller - 7



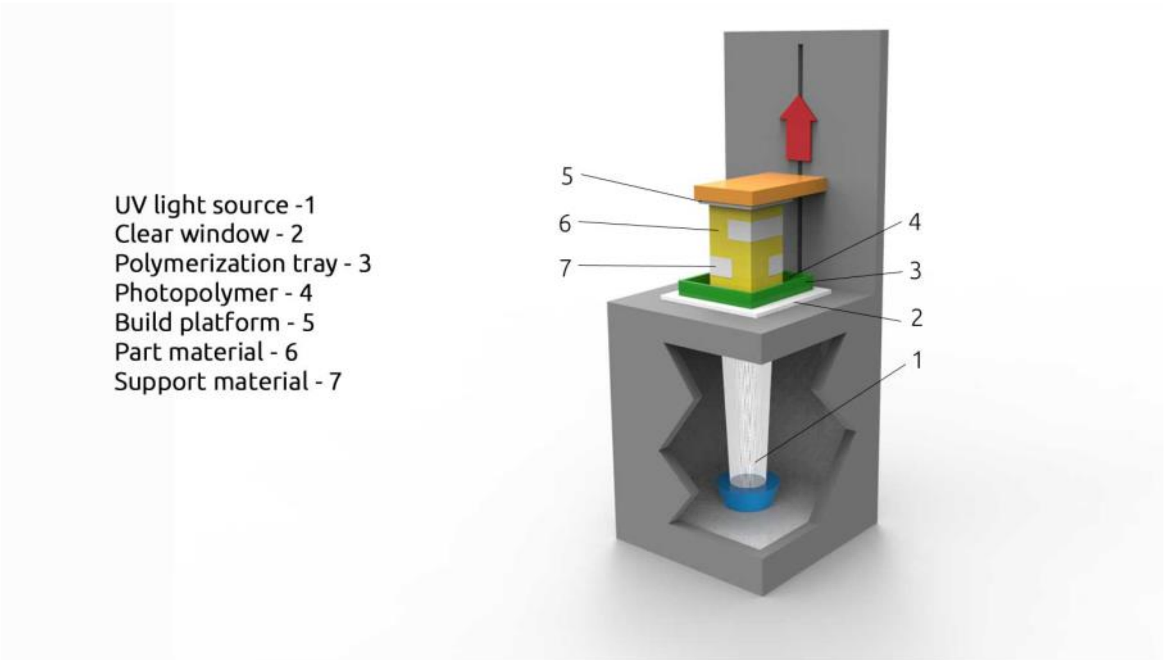
Selective Laser Sintering (SLS) uses layers of thermoplastic powder to create parts.

Each layer of powder is applied from the supply chamber to the build chamber by a recoating roller, where it is fused to the one beneath it by laser. The build chamber then drops by one layer, the supply chamber rises by one layer and the process begins again.

As each layer (0.05 - 0.2mm) is applied, the part sits in a chamber of mostly reusable powder that supports the partially built parts. This removes the need for support structures which minimises the need for post processing.

The materials used in SLS have good mechanical properties for making functional parts.

Introducing Digital Light Processing (DLP)

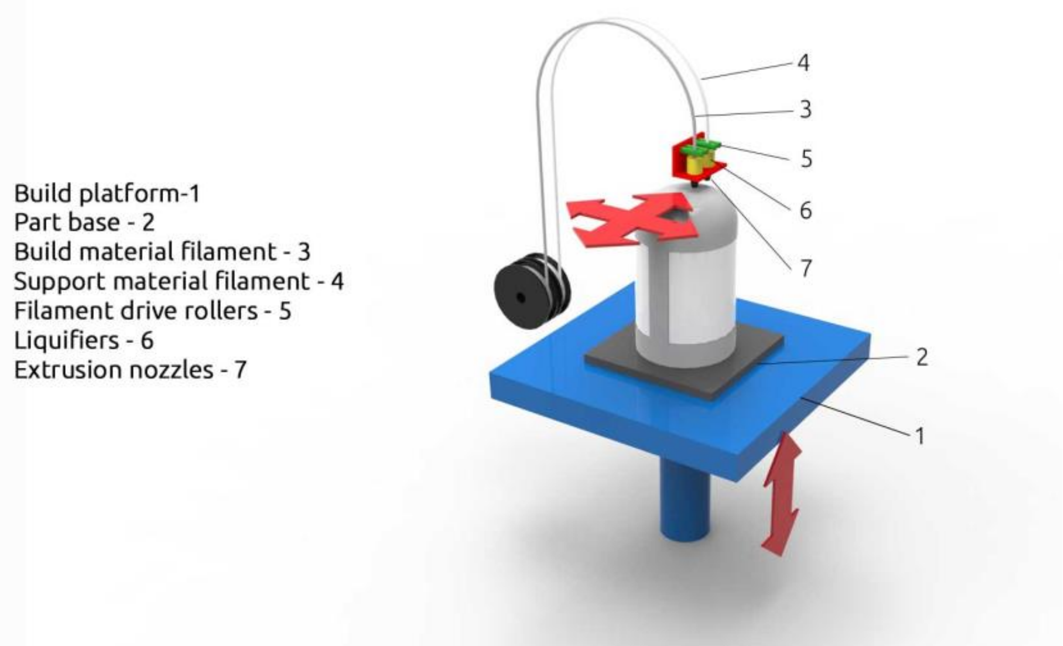


Developed by EnvisionTEC, DLP 3D printers use acrylic photo-curable polymer cured by UV light. Strictly speaking, the system works on individual voxels, or volumetric pixels, rather than layers, which means that parts straight from the machine are considerably smoother than conventional layer -based systems.

The process is also considerably quicker than Stereolithography and other similar systems. DLP parts build upside down, with the model suspended below the build platform.

Support material is added to assist the production of overhanging areas (see 7 above). This can be removed quickly, and does not have a major impact on post-processing time.

Introducing Fused Deposition Modelling (FDM)

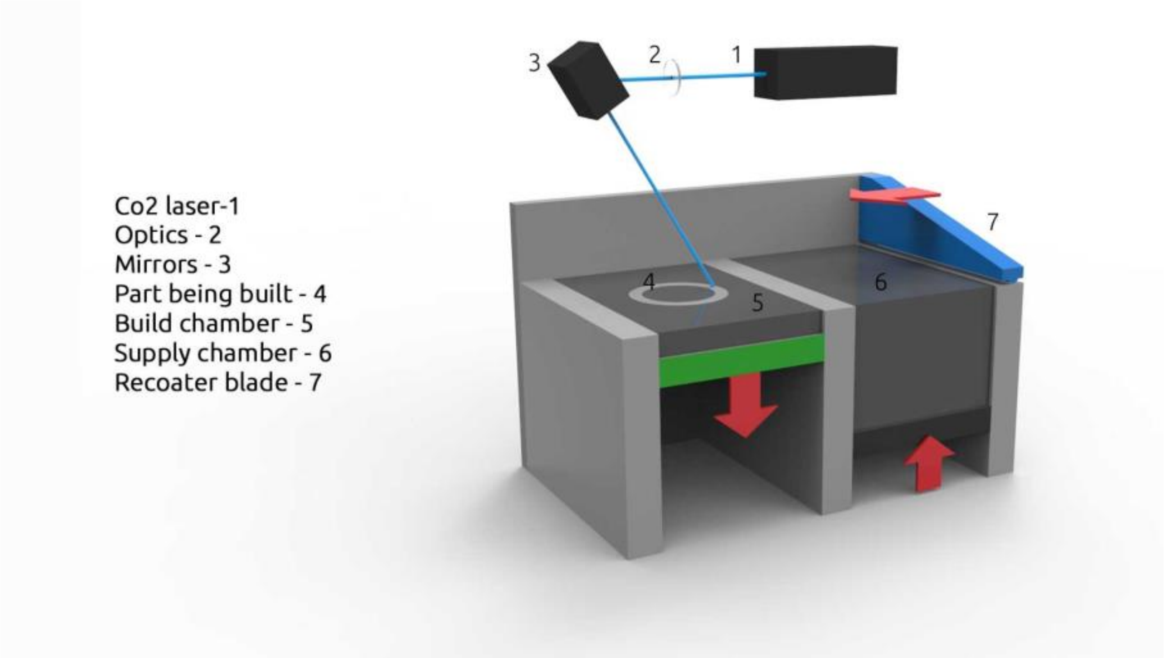


One of the most popular 3D printing systems, FDM uses a similar method to conventional printing, a printer head that moves in the X and Y axes, to lay down a thin layer of molten polymer. The build platform moves up and down in the Z axis to enable depth to be added to the part.

The process uses thin plastic filaments drawn through rollers to provide the material for the part and any supporting structures that may be needed. These are then liquefied in heated collars (6, above) and extruded out to form the part.

The support material can either be broken off after the part is built or, depending on the system, dissolved in a water filled tank.

Introducing Direct Metal Laser Sintering (DMLS)



DMLS is similar to SLS, but uses various types of metal powder melted by laser to build up the layers of the part. Far higher temperatures are involved, and the process requires considerable set up and post finishing work to create useable parts.

The process is based on laying down layers of fused metal powder onto a rigid steel build plate. Support structures are needed for all downward facing surfaces or those at a small angle to the horizontal. As the supports must be made from the same material as the part, these have to be removed by machining, which can take a considerable amount of time.

Design considerations for 3D printing

3D printed parts obey different rules to conventional parts (image from 3TRPD)

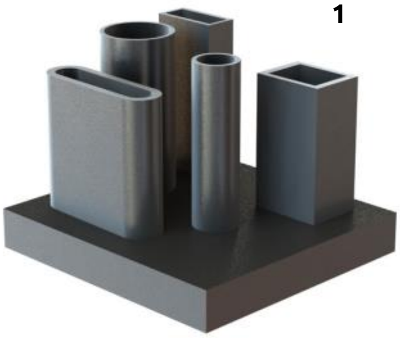
The design rules for 3D printing are very different from conventional ones, and they vary for each process. Most of them relate to minimising the cost of post processing and making the build process as efficient as possible.

Unlike other production processes, 3D printing involves the use of a finite build chamber or platform. By packing as much as possible into each 'build' the individual part costs can be dramatically reduced and this can have a serious impact on design considerations.

Post processing is the big issue. An injection moulded part comes off the machine ready to use, whereas a DMLS part has to removed from its construction base by wire erosion; have the supports machined off; machined to make sure critical surfaces are correct; and then have the surface prepared for painting or plating.

Before we look at the issues for each process, there is one issue that affects most of them...

A word or two about layers and supports...



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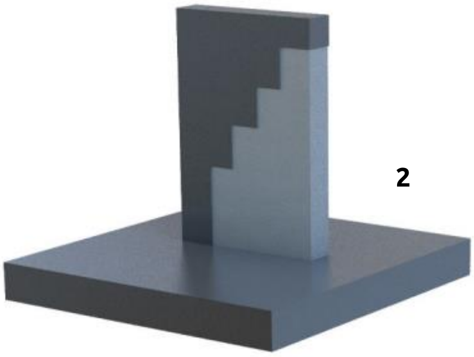
As discussed, most 3D printing processes require some supports to be built into the model, so let's look at this important general issue first.

Why are supports needed?

With most 3D printing processes, each layer is soft when it is first built. If it is applied to a solid base, that is fine, but if it is not fully supported from below, it might collapse or become distorted. In image 1, the part geometry goes vertically upwards with each layer building on the last. This does not require supports.



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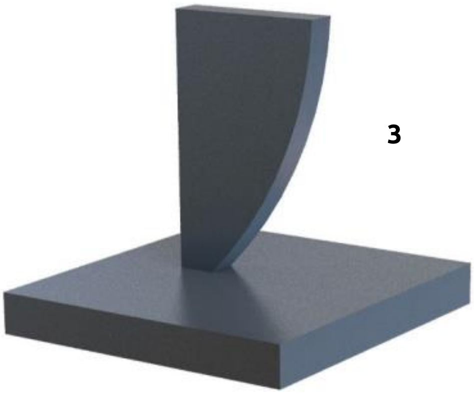
In image 2, however, the downward facing surfaces of the dark grey material needs supporting by the light grey material as it builds upwards, or the 'steps' would otherwise distort or collapse.

Why are supports important?

Because they have to be removed when the part is finished, and this takes time and costs money. Sometimes steps are inevitable. However if they can be designed out, or the part orientation changed to make them unnecessary, it will reduce your costs - and minimise waste.



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For example, the same geometry that is used in image 2 could be made by using a gentle curve (image 3). For some processes, this removal of the downward facing flat surfaces would be enough to eliminate the need for supports.

Design considerations for Selective Laser Sintering (SLS)

Front end for Smart car made from several SLS parts bonded together

How useable are SLS parts?

SLS parts are very durable and have excellent mechanical properties. The surface finish is like fine sandpaper, and nylon parts tend to absorb moisture. Accuracy is very good, and bearing surfaces tend to 'work harden' in use with little wear. The prototype front end for a Smart car (left), that Crucible designed, was unpainted SLS and showed no wear or damage after several thousand miles of test driving.

Which materials can I use?

The most common material is polyamide (nylon) which can be used in either standard or modified form, with glass or aluminium added to the powder. Other fillers can be used to enable living hinges to be built and create materials that can be useable in temperatures of up to 184°C. Elastomeric materials can also be used to create gaskets, seals and other flexible parts. SLS parts do not require supports during the build process, as the geometry is supported by the bed of powder that the parts sit in.

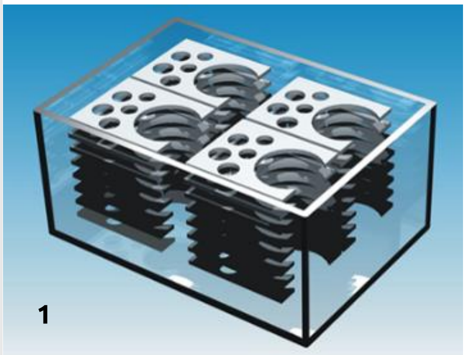
Layer thicknesses range from 0.05mm to 0. 2mm.

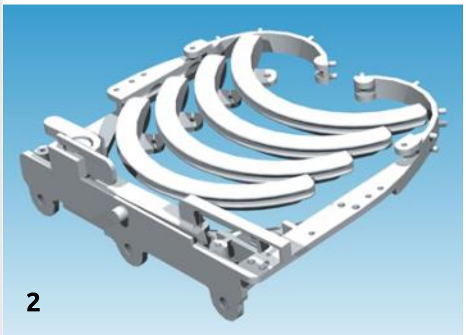
How large can the parts be?

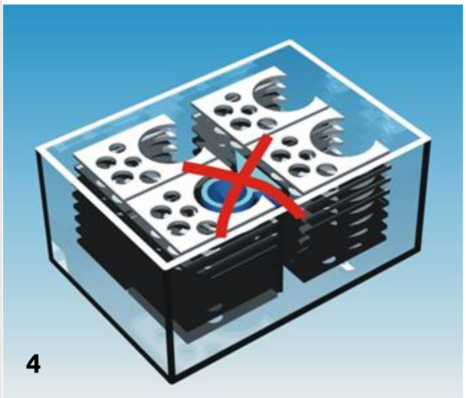
The largest SLS machines can build parts up 700mm x 380mm x 600mm, and parts can be joined together to make larger items (see image).

How difficult is surface finishing?

Difficult. The surface can be rolled in abrasive powder (similar to the lapidary machines used to polish pebbles) or bead blasted to make it smoother, but nylon is hard to rub down to a smooth surface capable of taking a good paint finish. Allow a cost almost equivalent to the part itself to get a good cosmetic surface.



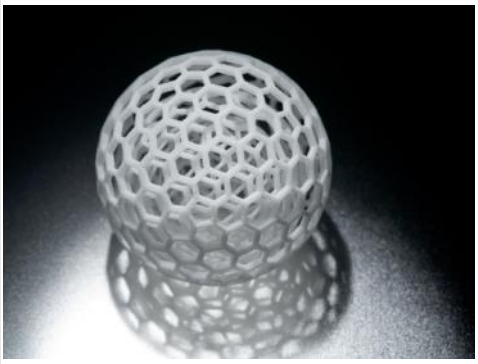




What are the main design rules?

- Ensure wall sections do not drop below 1mm.
- When working with small diameter pins or shafts, remember that the diameter may deviate by up to 0.3mm. This could be significant if you are developing a mechanism.
- The accuracy of holes in the parts will be seriously affected by the wall thickness. The thicker the wall section, the less accurate the hole will be. Generally, it is best to avoid holes smaller than 1mm diameter in parts with a 2.0 – 5.00mm wall section.
- If you are developing a mechanism to be made as an assembly in SLS, always leave at least 0.6mm between the individual parts. This prevents them binding together during the build process.
- Make your parts as two dimensional as possible. The key to an environmentally and economically efficient build, particularly in a production context, is getting as many parts into the chamber as possible. This will be helped if the parts can be layered to make maximum use of the chamber volume (1).
- Alternatively, nest the parts inside each other (2).
- Consider the orientation of the part. SLS lays down layers of material which will be visible and may introduce weakness in thin parts. The orientation of the part may also have an affect on the build chamber efficiency (3).
- Avoid 'build fodder'. When using SLS for manufacture, do not place one-off prototype parts into spaces that might be available. This may introduce distortions into the thermal efficiency of the build chamber which will distort the parts (4).

- Consider section consistency. Some commentators suggest that wall section issues that affect mouldings do not apply to ALM parts, but this is not the case. Very thick wall sections create large concentrations of heat during the build process that can affect cooling performance and distort parts. Large heat concentrations can also affect adjacent parts in the build. Overall, it should be considered that maintaining consistent wall sections is good design practice, whatever production process is used.



- Take full advantage of the technology. The layer-based process used in SLS enables otherwise impossible geometries to be created (see left). The possibilities offered by this technology are considerable, including the production of complete assemblies as one 'part', including hinges and other moving components. Close tolerances on the moving parts are not possible, however. Joints are ok, bearings are not.
- Other benefits offered by SLS are:
  - Complex edges that would be undercuts in a moulding
  - Snap details to aid assembly
  - Sprung sections for holding other parts in place.
- Aesthetically, SLS allows the creation of any form that can be thought of and modelled using a CAD system

Design considerations for Digital Light Processing (DLP)

DLP is particularly suitable for small, precise parts

How useable are DLP parts?

DLP is widely used to create small, precise parts that require customisation, such as parts for hearing aids. They are as durable as the equivalent moulding would be.

Which materials can I use?

Over ten resins are available to create parts with different properties, from transparent to coloured opaque and soft materials. Medical grade polymers are available, and wax-like materials are suitable for patterns for casting. Depending on the material used, resolution can be as fine as 0.015mm. This, plus the curing of individual voxels, rather than layers, results in parts with no visible stepping.

For more information, go to www.envisiontec.com

How large can the parts be?

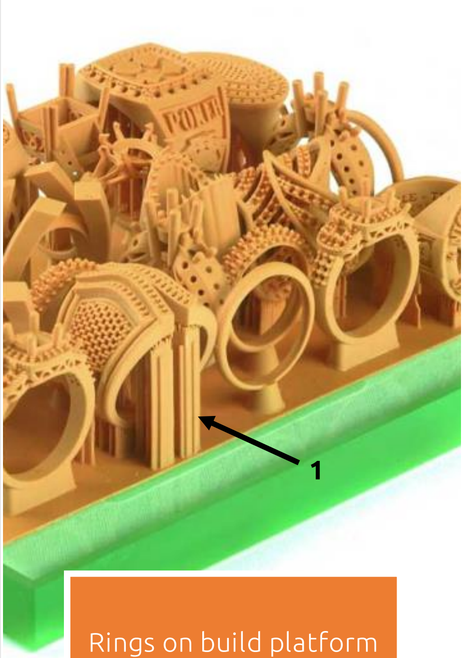
This is the main limitation of the DLP process. The highest precision machines (with the best surface finish) currently build parts up to a maximum size of 160mm x 100mm x 160mm. This means that the process is ideally suited to small parts like hearing aid shells (left).

How difficult is surface finishing?

Quite simple, due to the naturally smooth surface of the finished parts. Most parts will have support structures built in to avoid distortion during building, but these are quite easy to remove mechanically. Unlike most other 3D printing processes, parts can be made in the final colour, making this similar to low volume moulding.

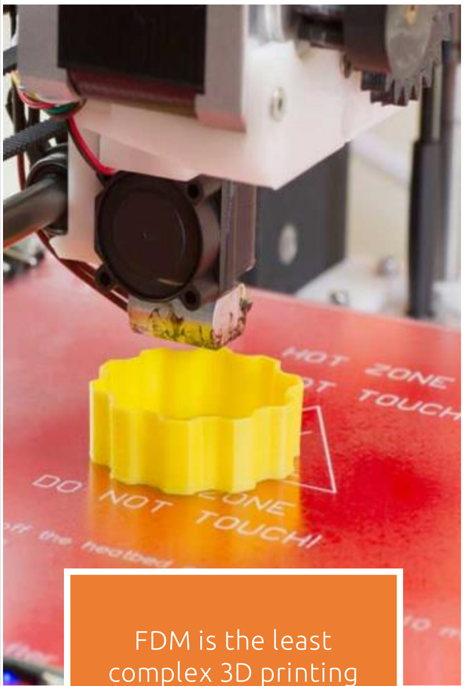
What are the main design rules?

- Small parts may require some adjustment to wall thicknesses to obtain the desired result.
- Most parts will require some support structure (1). The design and location of the supports will depend on part orientation, size and wall thickness. Software like 'Magics' and some CAD programmes will create support structures automatically, but advice from experts in the process would be advisable to ensure the part is built as accurately as possible. It may take a few iterations of build orientation and support design before the best solution is found.
- Uncured resin may be trapped in enclosed volumes if a drain hole is not included in the geometry.



Rings on build platform with supports (image from EnvisionTEC)

Design considerations for Fused Deposition Modelling (FDM)



FDM is the least complex 3D printing technology

How useable are FDM parts?

The materials used in FDM parts are very close to conventional engineering polymers, so basic material suitability is not an issue. The main difference between an FDM part and a moulding is the fact that it is built up in layers, which means that the inherent strength of the part will be slightly lower in the 'Z' direction (vertically). Part layers are relatively large - between 0.13mm and 0.33mm. This can result in quite rough surface finishes prior to surface treatment.

Which materials can I use?

The process works well with several polymers, including ABS, polycarbonate and polyphenylsulfone. A range of coloured plastics can be used. Layer thicknesses range from 0.13mm to 0.33mm.

How large can the parts be?

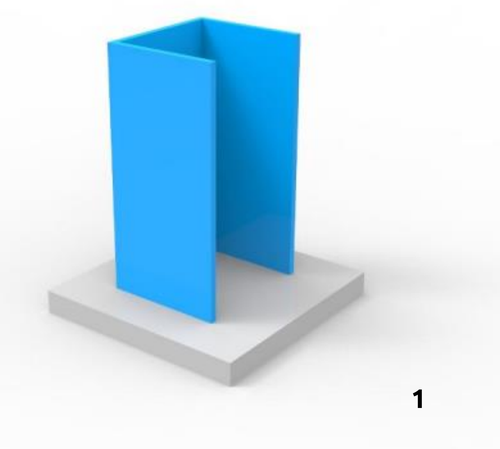
Parts up to 900mm x 600mm x 900mm can be built on the largest machines, although most of the commercially available FDM printers have considerably smaller build platforms.

How difficult is surface finishing?

Reasonably simple, as some systems allow for support structures to be removed in a tank of water, and the parts can be self coloured in a (limited) range of colours.

The stepped surface of FDM models can be considerably improved by using plastic pellet bead blasting or proprietary systems that smooth the surface of the parts. In conventional finishing terms, the materials are quite simple to work with, and easy to rub down and paint.

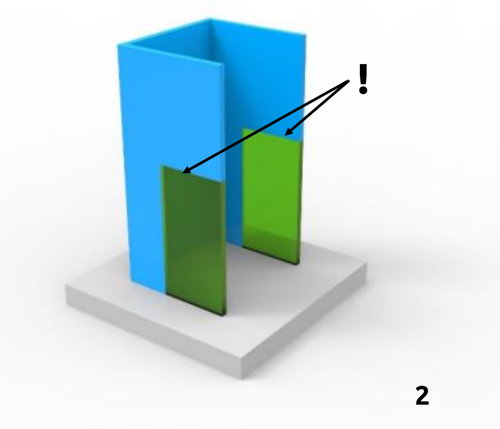
What are the main design rules?



1

- FDM parts that have downward facing horizontal surfaces will need supports, and these will need to be removed once the part is built, adding time and cost. So, if possible, design your part to avoid the need for supports, or possibly change its build angle to achieve the same result.

  In the examples on the left, the part in image 1 is a simple vertical build that does not require any supports - each new layer is directly on top of the previous one.



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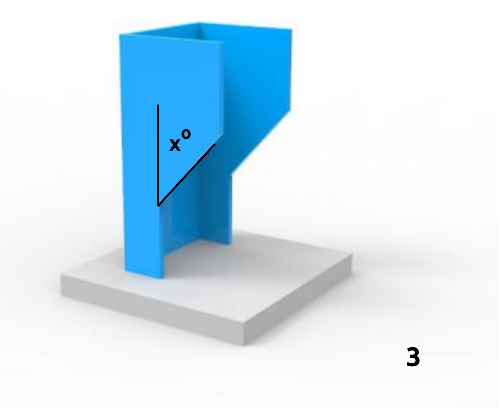
  In image 2, the example has horizontal downward facing surfaces (indicated by the exclamation mark) that need to be held up by the support material (shown in green). This support material will add time to the build process, as the machine has to switch materials, and it will also add time and complexity to the part finishing process.

  In image 3, the downward facing horizontal surfaces have been replaced by angled surfaces. FDM is capable of building faces as steps at an angle without supports, although the resulting surface will not be very smooth. The precise angle that the face can be built at (x°) will vary depending on the system and the material, but somewhere between 45° and 30° is a good starting point.

  This approach will impose limits on the design, in the same way that draft angles do, but will result in a more efficient, less costly and less wasteful product.



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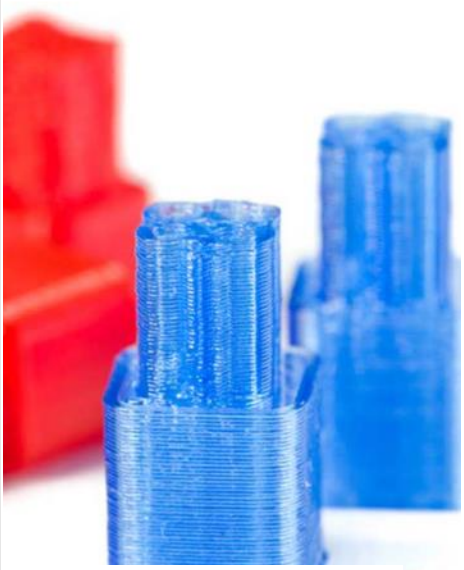


FDM parts showing layers prior to finishing

- Warping due to heat is not usually a problem with FDM parts, but may occur in thin wall sections. This should be prevented by using ribs, similar to those used in an injection moulding.
- Holes under 3mm in diameter should be drilled out to ensure their accuracy.
- Holes in for self tapping screws in fixing bosses should be slightly larger than for an equivalent injection moulded part (0.9 x the diameter of the screw thread, rather than the more normal 0.8 for ABS, for example). This will reduce the chances of the boss shearing off.
- Wall thicknesses are related to the layer thickness of the build process. For example, a part with 0.13mm layers could have a wall thickness of 0.5mm, whilst one with layers 0.33mm thick would have to use a minimum wall thickness of 0.8mm.
- If your model will include any text, 16pt bold face is the smallest font that should be used on top or bottom planes. 10 pt is the minimum size that should be used on vertical surfaces.

Design considerations for Direct Metal Laser Sintering (DMLS)

DMLS produces accurate, durable parts - at a price

How useable are DMLS parts?

DMLS parts are extremely strong and durable. The process delivers solid metal parts in a range of highly durable materials (see below). DMLS parts are now used as production parts in commercial aircraft, for example. Extremely complex geometry can be constructed, and if the process is used correctly, parts can be combined to improve durability and make a product more efficient.

Which materials can I use?

A range of metals can be used in DMLS, including titanium, stainless steel, aluminium, bronze, cobalt chromium and maraging steel.

Unlike SLS, where parts can be stacked on top of each other to make maximum use of the build chamber, DMLS parts can only occupy the space on the build platform. Any space above the part cannot be used.

The layer thickness is fine, from 0.02m to 0.1mm.

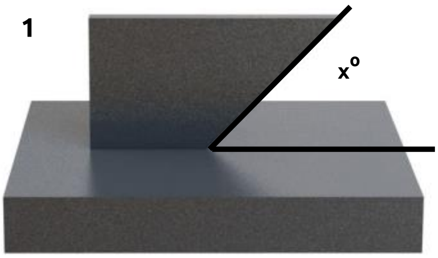
How large can the parts be?

Most machines have build chambers approximately 250mm x 250mm x 250mm, although some larger machines can build parts up to the size of a 500mm cube.

How difficult is surface finishing?

Complex and expensive. The parts need to be removed from the build platform using wire erosion, which is expensive and power intensive. The supports then need to be machined off, and the parts then have to be smoothed and polished.

1



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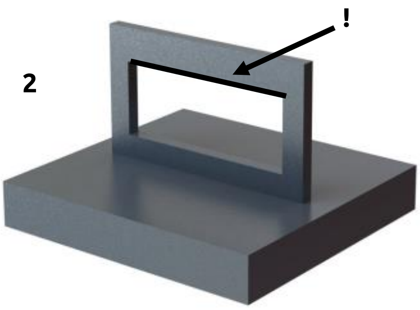

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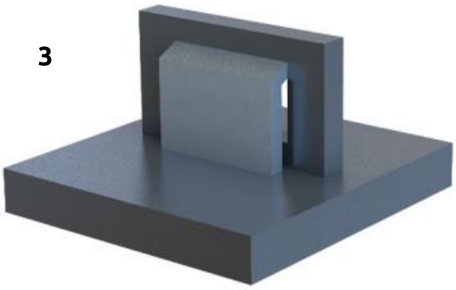

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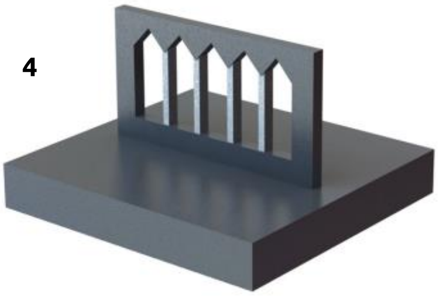


What are the main design rules?

- Support for downward facing surfaces is a major issue in DMLS part design. For a general introduction, see page 11. Because the support material in DMLS parts is made of the same material as the rest of the component, removal usually involves significant machine time.

  Like other processes (FDM - see page 18) DMLS can build surfaces at an angle without supports (1). The angle will differ with each material:

  - Stainless steel - 30°
  - Aluminium - 45°
  - Titanium - 30°
  - Cobalt chrome - 30°

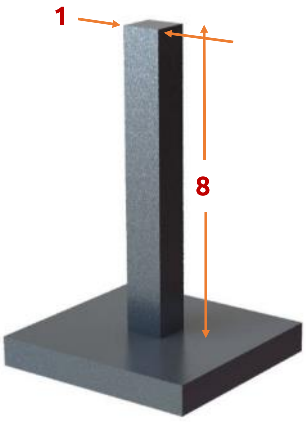
  Where downward facing surfaces are unavoidable (2), a support structure can be built from the side and angled inwards, minimising the amount of material that needs to be removed (shown in light grey) (3).

  Alternatively, the same opening can be divided into a number of smaller holes with angled tops that only need support at their lower points (4).

  Small holes can be built into a face without supports, but large round holes will require some support in the centre or the entire part may collapse or distort. A tear-drop shaped hole (which tapers to a point at the top) will not, however, require any support.

1

2



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- Another consideration for DMLS is the strength of the part as it builds. The process involves coating newly built surfaces with a layer of powder, and this is achieved by drawing a blade over the part. This blade can connect with the top surface, so any weak geometry may be damaged (1).

  The solution to this possible problem is to avoid long vertical openings by bridging them at frequent intervals (2).

  As a general rule, the vertical height of a section of geometry should not be more than 8 times the width of the part (3).

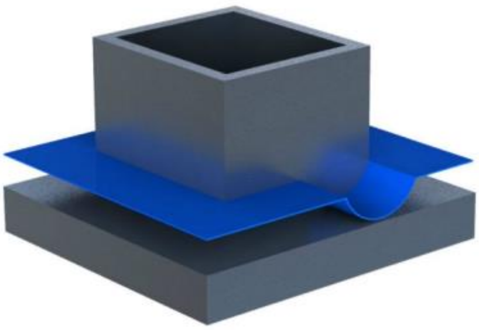
  It is good design practice to drag a dynamic section up through your CAD model as the design progresses. This will simulate the vertical building process and will allow you to see if there will be any weak areas during the build itself.

- It is good to avoid any sharp edges in the design, particularly vertical points.

- Thick sections should be avoided as the heat build up in these areas could damage or distort the part as a whole. This is particularly true if thin areas are placed next to thick ones.

- If possible, avoid angled surfaces that point towards the recoating blade. This will increase the chances of the blade colliding with the part as new layers of powder are applied.

1



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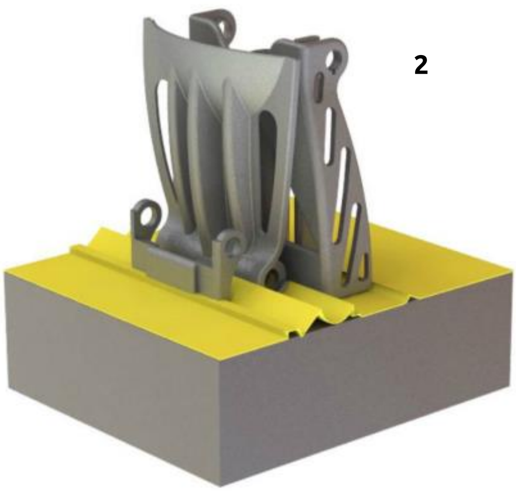


- The removal of the part from the build platform is another significant issue in the DMLS process as it involves wire erosion or Electrical Discharge Machining (EDM). In this process, discharges of electrical current take place between a wire electrode and the DMLS platform in a bath of dielectric liquid, causing material to be removed. It is slow and uses a considerable amount of power. Consequently, anything that can be done to make it more useful is a positive move.

  One way to do this is to include the cutting path (which is similar to a cheese wire) in the design of the part, as it will create a well defined surface (1).

  If the cutting path is considered as part of the design process, the components can be arranged on the build platform to minimise the need for supports and utilise the cutting path as part of the part construction (2).

- Where possible, design parts to be vertically oriented on the build platform (2) to make the most use of the space available.

- Finally, consider the finishing of your part when working on the detailed design. It is possible to polish even the most complex geometry with deep grooves and holes, but they should be avoided.

In summary

An example of analogue layer-based construction

3D printing is not free of design constraints - they are just completely different from conventional ones. If you intend to use 3D printing techniques for the production of useable parts, and you want to minimise your costs, there are a number of design issues to get to grips with.

These range from making the most efficient use of the build chamber or platform for your chosen process, to minimising the use of the supports that have to be removed.

Choosing the right process for your product will depend on many factors - size, required surface finish, strength and the function of the part. For example, large parts that won't be seen would probably be best produced in SLS, whilst small parts that need to look good might be better made using the DLP process.

Whichever process you use, we strongly advise talking to the potential supplier as early as possible in the design process. This is because the successful and economic design of parts made for manufacture using 3D printing are even more closely associated with their production process than conventional moulded components. Build platform size; the layout of the parts in the build; their orientation and the minimisation of supports could all have an impact on the design of the part.

So, when someone tells you that 3D printing has eliminated design for manufacture rules - please ignore them!

Mike Ayre. June 2014

Contacts and further information

Plunkett Associates
(www.plunkettassociates.co.uk).

Plunkett Associates cover all prototyping and manufacturing solutions, from CNC machining to injection mould tooling and all the additive layer based processes that fall under the popular heading of 3D printing. As it says on their website 'We get things made'.

3TRPD

www.3trpd.co.uk

3T specialise in SLS and DMLS, and are the experts when it comes to laser sintered parts.

EnvisionTEC

www.envisiontec.com

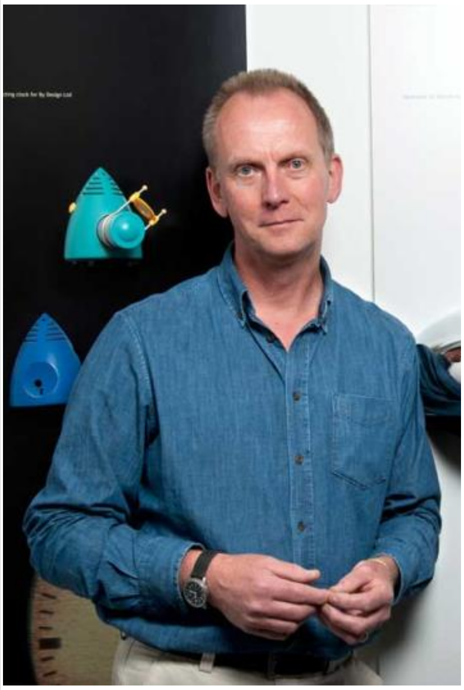
EnvisionTEC developed the first DLP systems and remain the experts.

Stratasys

www.stratsys.com

Stratasys produce some of the best, professional FDM machines.

About the author



Mike Ayre is the Managing Director of Crucible Industrial Design, an award winning industrial design consultancy with over twenty years of experience in product design and development.

Mike's early interest in creativity, design and science led him to complete a BA in Industrial Design. Several years later Mike was responsible for pioneering research into CAD systems and 3D computer modelling whilst he completed his MDes at the Royal College of Art. Having graduated Mike spent over ten years working on design projects in the third world. These projects required a profound understanding of the product's requirements, as well as detailed knowledge of production methods. This early training has given Mike a unique ability to evaluate practical requirements and identify appropriate materials and production methods.

Following work at a London based consultancy, Mike set up his own industrial design practice in 1990. Crucible Industrial Design works across all areas of product development, from low volume high value scientific instruments to high volume consumer goods.

Mike's authority in matters of industrial design are recognised across the industry. He has held positions as a part-time university lecturer and is a regularly published author of design related articles and also participates as a guest speaker at industry shows and events.