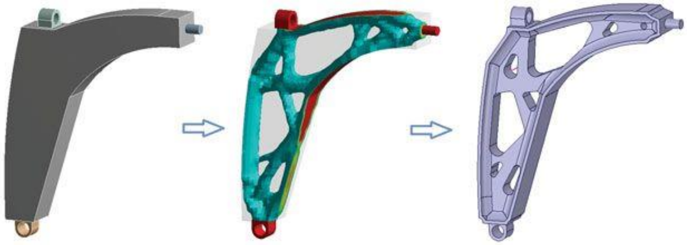
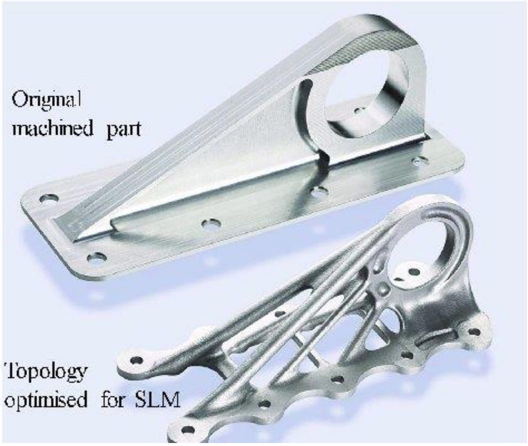
MAEG5160: Design for Additive Manufacturing

Lecture 22: Post-processing and Future of AM





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Lecture 22: Post-processing and Future of AM

All Additive manufacturing (AM) technologies require post-processing to produce parts that are ready for use. This post-processing can range from support material removal, to surface quality improvement, to colouring and painting, and to aging for polymer parts and heat-treatment for metal parts. Throughout the AM industry there is a vast amount of tacit knowledge in the area of post-processing but there, currently, exists very little documentation on the various post-processing methods for different AM technologies and materials. This leads to time being wasted by companies having to individually learn and develop post-processing methods. The overall process flow of additive manufacturing includes pre-processing and post-processing, and is presented in the following table. Note that the steps can vary, sometimes greatly, depending on the application, material, AM system being used, and specific requirements of the parts.

Metal powder-bed fusion	Polymer powder-bed fusion	Material extrusion	Vat photopoly-merization	Binder jetting
Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary	Check quality of files and repair if necessary
Prepare print-job in software by arranging parts on build platform and generate support material	Prepare print-job in software by arranging parts on build platform	Prepare print-job in software by arranging parts on build platform and generate support material	Prepare print-job in software by arranging parts on build platform and generate support material	Prepare print-job in software by arranging parts on build platform
Clean AM system	Clean AM system	Clean AM system	Clean AM system	Clean AM system
Preheat build chamber	Preheat build chamber	Preheat build chamber		Preheat build chamber
Print	Print	Print	Print	Print
Remove build plate from build chamber	Find and remove parts from powder bed	Remove parts from build chamber	Drain and/or recycle unused material as applicable	Find and remove parts from powder bed
Remove loose powder and recycle	Recycle remaining powder	Remove support material	Remove parts from build chamber	Recycle remaining powder
Thermal stress relief	Media-blast parts to remove surface powder	Surface finish: sand, vapor smooth, paint, etc.	Remove support material	Air-blast parts to remove surface powder
Remove parts from build plate	Surface finish: tumble, sand, dye, paint, etc.	Inspect	Post-cure in UV chamber	Bake parts as necessary
Hot isostatic pressing	Inspect		Surface finish: sand, vapor smooth, paint, etc.	Strengthen with infiltration
Remove support structures			Inspect	Surface finish, sand, paint, etc.
Heat treat				Inspect
Surface machining, shot-peening, abrasive flow machining, etc.				
Inspect				

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1. Support Material Removal

1.1 Polymer

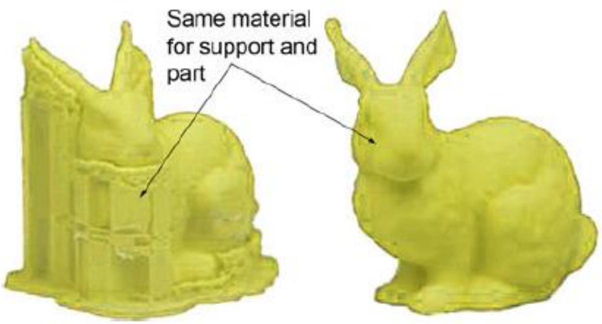
Material Extrusion

There are 3 main forms of support material used in material extrusion technologies:

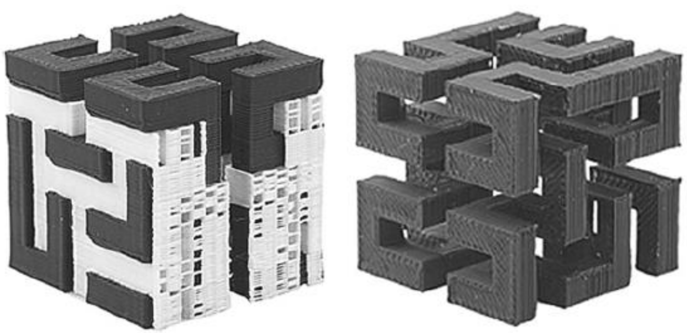
• The same polymer as the printed part is used as support: With these systems, a lower density version of the same polymer as the part polymer is used as support material. The support also makes only point contact with the part. The support material for these system is removed through mechanical force using hand tools. This form of support material is most commonly found on desktop 3D printers (left).

• Break-away support material: This support material is a different polymer to that of the part. The support material for these system is removed through mechanical force using hand tools (mid).

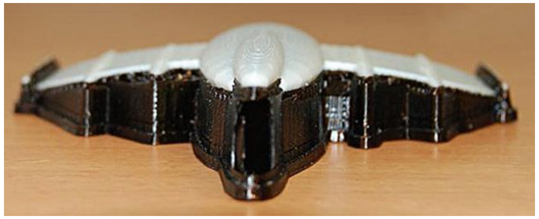
• Soluble support: This support can be dissolved using an appropriate solvent. It can, however, take several hours to dissolve, particularly if there is support material in long narrow pipes into which the solvent can only dissolve small amounts at a time. This support is the best to use if the part has fragile features that would, otherwise be damaged if removed mechanically (right).



Part printed with the same support material as the part



Part printed with break-away support material



Part printed with soluble support material

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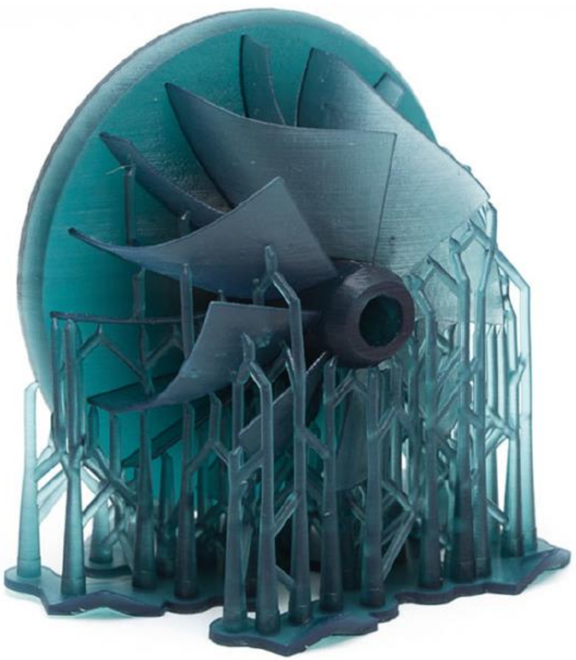
Vat Photopolymerisation

Vat photopolymerisation systems use the same polymer for the support as is used for the printed part: With these systems, the support material generally takes the form of a 'tree' in which the tree branches are what make contact with the part and support it. The support also makes only point contact with the part. The support material for these systems is removed through mechanical force using hand tools.

Most vat photopolymerisation systems will require the part to be fully cured in a UV oven, or ambient sunlight, after it is removed from the printer. It is, generally, best to remove the support, and sand the part, while it is in between the two stages, and the material is still slightly soft so easier to remove.



Support material on vat photopolymerisation part

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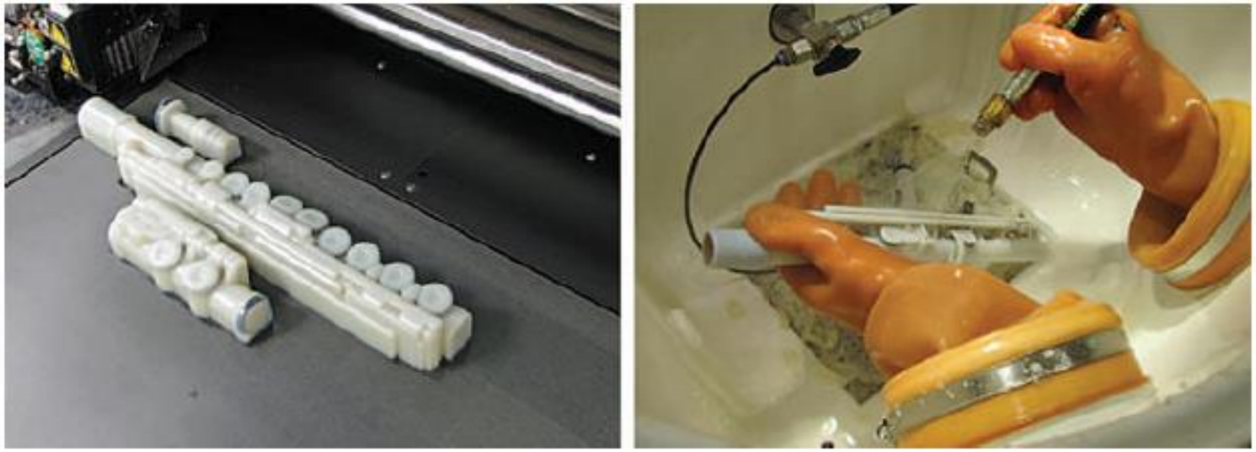
Material Jetting

Material jetting systems use a wax-like material as support material. Depending on the system, this support material can be washed off with a water jetting system, or melted off with heat.



Material jetting parts with water-blastable wax support material

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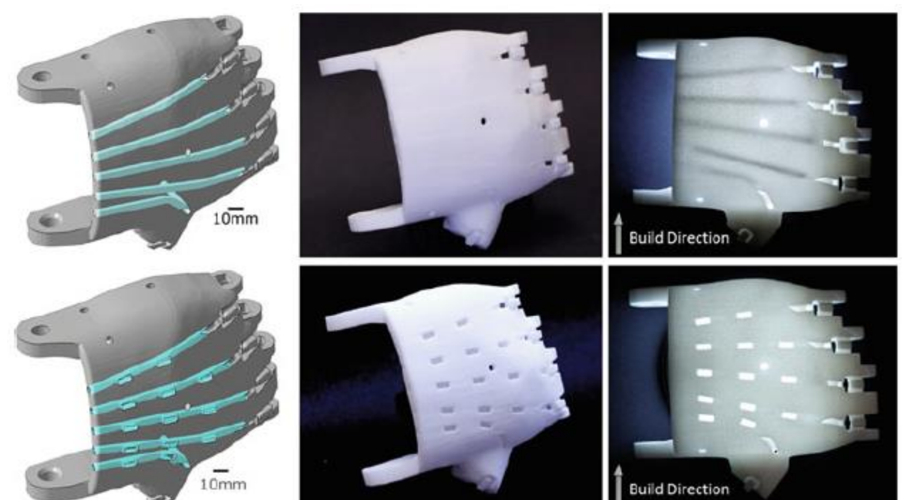
Powder Bed Fusion

Polymer powder bed fusion technologies are one of the few processes that do not require support material as the unmelted powder that surrounds the melted powder acts as support. When the printing process is finished and cooled, the parts are dug out of the powder 'cake' and blasted with air and sand (or powder) to clean off the part. The process is akin to an archaeologist digging parts out of a dig site (although the powder bed fusion powder is substantially easier to remove that it would be to remove clay or dirt from an archaeological dig site).

When sand-blasting, care should be taken not to get too close to the sand blasting nozzle, otherwise the sand can slightly 'burn' the part and leave brown marks behind. Laser sintered parts are particularly susceptible to this because they are usually made from white powder. If coloured powder or fusing agent is being used, such as in the multi jet fusion process which produces dark grey parts, this is much less of an issue. By blasting the part with the polyamide powder itself, instead of sand, this problem can be avoided, but the parts may take fractionally longer to clean because the polyamide powder is less abrasive than sand.

Because unsintered polymer powder gets 'caked' together during the printing process, powder can be hard to remove from long thin tubes or holes. A useful trick for making this easier is to leave cleanout holes along the length of the tubes for powder removal. The powder can then easily be blown out of the pipes with an air gun.

Powder bed fusion parts being removed from the powder 'cake'



Part designed with cleanout holes to make depowdering of the part easier

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1.2 Metal

Support material removal for metal parts can be challenging and require substantial amounts of time. This is why it is so important to design metal parts for AM to reduce the amount of support material required. To repeat a point made earlier, printing in metal is not easy! It requires considerable work before and after the part is printed, as well as a good understanding of the printing process itself. The bracelets below, for example, make a nice bit of marketing for what metal AM is capable of. But it is not until one understands the work behind them, however, that one understands just how hard it can sometimes be to justify the economics of AM.

Aluminium bracelets printed as single assemblies with moving parts

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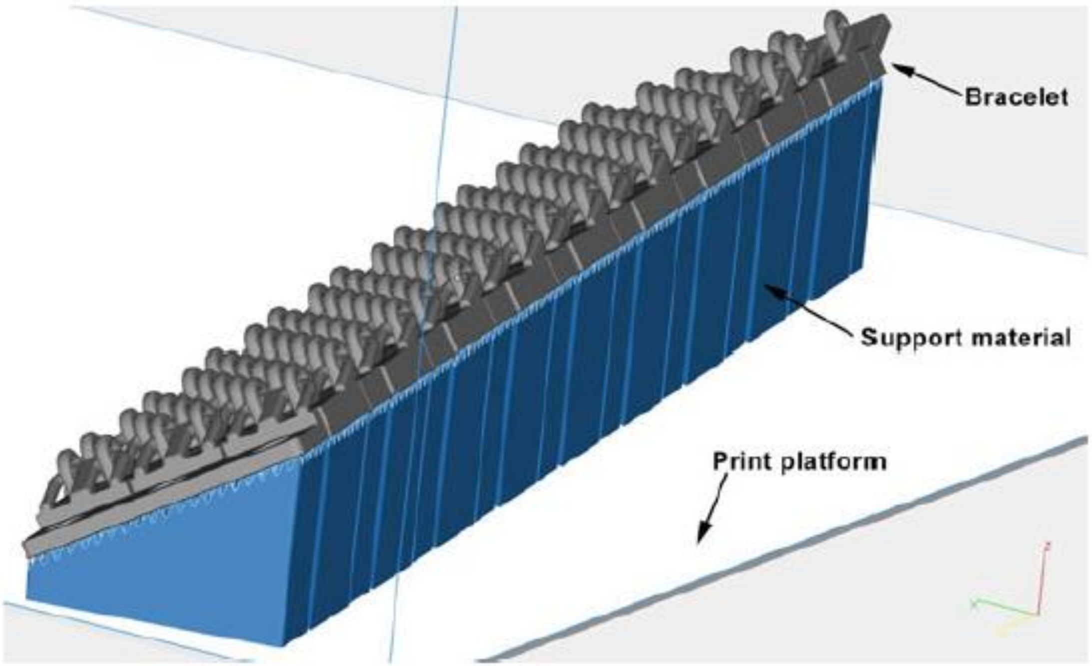
The time to print one of the above bracelets is around 10 h per bracelet. The reason for this relatively long print time is that the bracelets are printed at an angle of 45° to improve the bottom face surface finish and reduce the risk of stress cracks but this, unfortunately, increases the total build height and, therefore, the print time. If they are printed horizontally, the print time per bracelet would drop to approximately 3 h.



Bracelet print orientation for best surface finish

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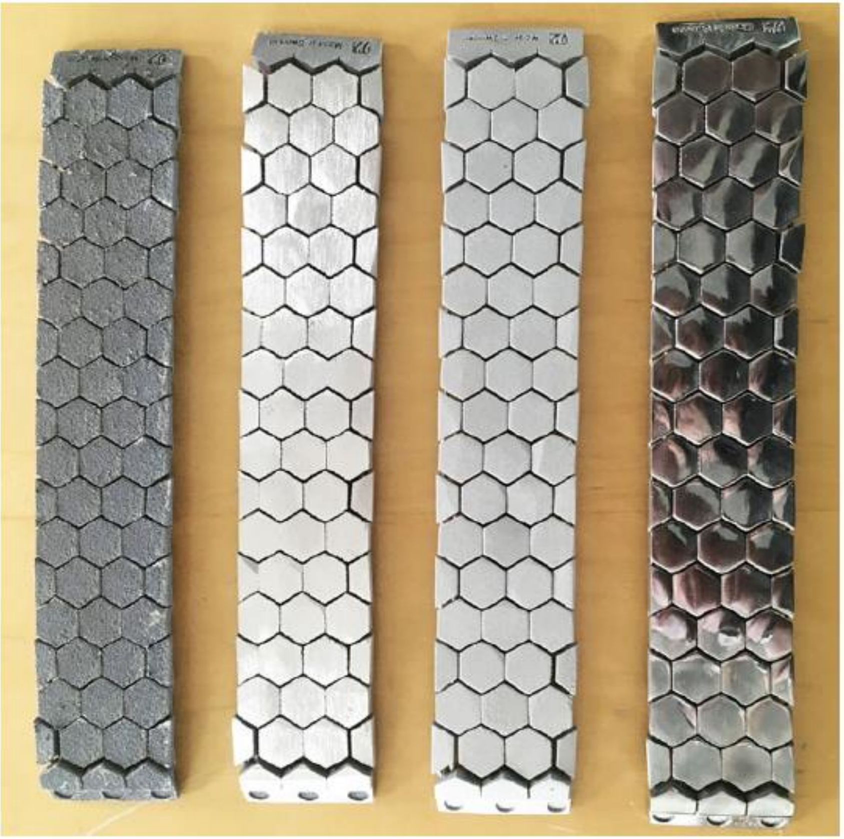
The table below shows the time to take the bracelets through the various postprocessing steps it must go through before being of an acceptable quality.

After the print has finished

With metal AM the entire part comes out of the machine welded to the build plate. The first step is to heat treat the part to remove residual stresses, otherwise the part will distort when removed from the platform. This is discussed in greater detail in the section on heat treatment.

Remove from build platform and remove supports	Linish surface with belt sander	Media-blast with glass beads	Polish
30 minutes	30 minutes	5 minutes	4~5 hours



Progression of different post-processing steps for bracelet

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Removing the part from the platform

After heat treatment, the first step is to cut the part off the build plate. This is generally done with wire cutting (wire Electrical Discharge Machining, or EDM) or with a saw.

It is for this reason that, when setting up a print job, the part is usually positioned either 2 or 5 mm above the build plate. If one is removing the part with wire EDM, 2 mm is required to account for the EDM wire thickness and, if one is using a saw, then 5 mm is needed to account for the thickness of the saw blade.

Task	Time (h)
File preparation	2.5
Machine preparation	2
Printing	9
Machine cleaning	2
Stress relief	3
Cooling	30
Removal from build plate	15
Support removal	4
Surface treatment (filing, sanding, shot-peening)	4

Aluminium guitar still welded to build plate after coming out of the printer, having the loose powder vacuumed away, and being heat treated

Aluminium guitar being cut off the build plate with a saw

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In general, it is faster to remove the part with a saw, but it is more precise to use wire EDM. Wire EDM also has the advantage that it can be used to improve the quality of the bottom surface of the part while it is cutting. Or it can be used to surface the top face of the build plate so it can be re-used with minimal effort, whereas using a saw will require the top face of the build plate to be machined flat.

Another consideration, however, in the choice between using a saw or wire EDM is whether there is any loose powder trapped inside the part. As wire EDM uses a dielectric liquid as part of the cutting process, if a part has any internal channels, for example, that are still filled with powder, then the liquid is likely to infiltrate the powder inside the part, turning it into a paste, and making it very difficult to remove. So, if wire EDM is being used, it is best to ensure that all loose powder from inside the part has been removed before beginning the EDM process.

Removing the support material

Then begins the often arduous task of removing support material. If a part is well designed, and only has support material on the bottom, then it can quickly be removed through wire EDM, cutting, or grinding. In most cases however, the rest of the support material will need to be removed by hand, and this can be a time consuming process. The support material for metal AM parts is removed through mechanical force using hand tools. Considerable force is sometimes required to break away the support material.

Support material that must be removed from aluminium guitar

AM manufactured aluminium guitar

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2. Polymer Surface Treatments

2.1 Vapour Smoothing

Vapour treatment is a way of smoothing the surface of a print with a solvent that can dissolve the material of the print. This is done by vaporizing the solvent, and letting the vapour dissolve the outer surface of the part enough to make the layer lines disappear. For ABS acetone is used as a solvent and chloroform can be used for PLA. **Great care should be taken when working with these chemicals**.

By heating the fluid, a vapour with little drops of the solvent will be formed. This will slowly settle on the print and start to dissolve the outer layer of plastic. When timed correctly, you are able to get a very smoothly finished print, similar to an injection molded part. It should be noted, however, that, as you are dissolving the outer surface of the part, dimensional accuracies will be affected by this process.

The simplest way to achieve vapour smoothing is to use a jar, with a bit of the solvent in the bottom of the jar, and suspend your part above the solvent. Even just doing this in ambient temperature will work, as the solvent will slowly evaporate and coat the part and dissolve its outer layer. Using a hot plate, or the 3D printer's heated bed, will greatly accelerate the process.

Acetone vapour smoothed ABS parts

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Timing of vapour treatment is critical, as the longer the part is left in the vapour, the more the plastic surface will be melted. The melting can also keep occurring for several minutes after the part is removed from the vapour. Exact timing is hard to specify, as it very much depends on the brand of ABS or PLA being used and the geometry of the part. The correct timing is best established through some timed trials of test parts.

The advantage of using a vapour, as compared to just dipping the print in the solvent, is that the solvent is equally distributed over the print. This will give a more consistent result. Material extrusion processes are also somewhat porous, so dipping a part can soak the solvent into the part so it will keep melting the part long after it has been removed from the liquid solvent. Using fluids such as acetone and chloroform is risky; make sure to only use this process if you know how to work with these materials!

- Acetone vapours can cause irritation or muscle weakness and are highly flammable, so keep it away from fire.
- The vapours released by chloroform can be irritating to the eyes/skin or respiratory tract. They may also cause dizziness.
- Always dispose the leftover solvents in a chemical box.

2.2 Tumbling

Tumbling, also known as rumbling, is a type of mass finishing manufacturing process used to deburr, radius, descale, burnish, clean, and brighten AM parts. This process is applicable to most AM technologies.

In this batch-type operation, specially shaped pellets of media and the AM parts are placed into the tub of a tumbler and rotated or vibrated. There are many types of tumbling systems including vibratory tumbling, rotary tumbling, barrel finishing, centrifugal barrel finishing, etc. The movement action causes the media to rub against the AM parts, which gradually wares down the part surface and yields the desired result. Depending on the application, this can be either a dry or wet process.

Tumbling is a time dependent process where the longer the parts are left in the tumbler, the more worn (smooth) the parts will be come. Typical tumbling times, for LS parts, range from 3 to 6 h depending on the abrasive medium used. It should be noted that tumbling is an abrasive process, so part accuracy can be affected as the parts are, effectively, being worn. Sharp corners will also become slightly rounded.

Examples of tumbled AM parts

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2.3 Dying

Dying is a particularly good technique for applying colour to powder bed fusion polymer parts. Almost any synthetic material clothes dyes, or leather dyes, can be used. In most cases, it is just a matter of following the instructions for each particular type of dye.

The hue of colour largely depends of how long the parts are left in the dye. For most synthetic clothes dyes, it takes about 45 min to achieve a good colour with the dye bath at between 80 and 100 °C (176–212 °F) stirring continuously. The longer the part stays in the dye, the darker it gets. It is also important to constantly stir the dye, otherwise the parts end up with patches of darker and lighter colour on them.

Example of dyed part sample colour swatch

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2.4 Painting

Painting applies equally to all AM technologies and is one of the most common surface treatment processes for polymer AM parts. The process is very much the same as for any other form of painting.

The surface must first be prepared as much as possible by sanding. As with any other form of surface preparation for printing, one often starts with a relatively coarse grit san paper, around 120, and then moves up to gradually finer sand paper going through 240, 400 and then 800 grit papers. As many coats of sanding primer as is necessary to achieve a smooth surface are then applied, with sanding operation between each coat. The better the surface is prepared, the better the final results will be. In some cases, if the surface finish of the part is very rough, or has a very pronounced 'stair-step' effect, it can be quicker to apply a coat of automotive body filler to the part, and sand that down before applying a few coats of sanding primer.

Once the surface is smooth, the final colour is applied, again often requiring several coats, and is followed by a few coats of clear-coat both to protect the part, and to give it the appropriate desired level of glossiness.

Acrylic automotive paints generally produce excellent results. Some AM technologies, such as most material extrusion technologies will require more sanding and primer coats than others to achieve a smooth surface finish. Using matt, or stain, clear-coat as the final layer is a good technique to replicate the surface finish of many injection-molded components. Gloss clear-coats can, of course, also be used, but may require extra cutting and polishing, with standard automotive compounds, to achieve a mirror-smooth finish.

Example of painted powder bed fusion process parts. But the same process applies to any other AM technology

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2.5 Using Textures

Applying 3-dimensional textures, such has leather, shark skin, woven pattern, etc. to the surface of a part can, surprisingly, hide much of the stair-stepping effect that is very clearly visible without the texture. Even on very gently curving parts, texture can make the stair-stepping disappear almost completely. This technique works particularly well on polymer powder bed fusion parts.

There are now several software packages (Materialise 3-matic, Z-Brush, etc.) that allow true 3D textures to be added to the surface of a part, but care must be taken that the file size does not become too large to handle particularly if it needs to be converted into an STL file.

Texturing the curved surface of a part almost entirely eliminates the stair-step effect.
The left part clearly shows stair-stepping, whereas the textured parts do not

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2.6 Sand Blasting

Abrasive sand or media blasting is the operation of forcibly propelling a stream of sand against a surface under high pressure to smooth a rough surface, roughen a smooth surface, shape a surface, or remove surface contaminants. In the context of additive manufacturing, it is mainly used for powder bed fusion as a technique for removing the powder that is stuck to the surface of the part.

As sand-blasting is an abrasive process, care should be taken not to get too close to the sand blasting nozzle, otherwise the sand can slightly ‘burn’ the part and leave brown marks behind. A general recommendation is to keep the part approximately 30 cm (12”) from the sand blasting nozzle. In many cases, the sand can be replaced by used polyamide powder. By blasting with the polyamide powder itself, the burn problem that can occur with sand can be avoided, but the parts take fractionally longer to clean.

2.7 Machining

In many cases if an engineering quality surface finish or accuracy is required, then manual or CNC machining may be the only way to achieve this. The machining process is exactly the same as for any other polymer machining, except that greater care, or slower machining speeds, may be required for some of the AM processes with higher degrees of anisotropy (weakness between the layers), such as those from material extrusion technologies.

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2.8 Metalizing

All conventional polymer metalizing techniques that are used for conventional plastic parts can also be applied to AM parts. These include electroless plating or electroplating, and vacuum metalizing or PVD. If electroplating is used, or any other process that requires the part to be conductive, then a conductive paint must first be applied to the part.

Metalizing can produce parts that genuinely look and feel like metal parts, as they are genuinely coated with metal, except that they are noticeably lighter than their metal counterparts.

Artwork of sound waves converted to 3D, by artist James Charlton, printed in gypsum with binder jetting, painted with conductive paint, and electroplated in antique silver

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2.9 Wrapping

Wrapping a part consists of covering it with a stretchable polymer film. This technique is commonly used in the automotive industry, but can be used with AM parts, assuming the part is not too complex. Wraps can be textured to add a 3D effect to the part.
The only preparation that needs to be taken before wrapping is to endure that the material surface is smooth enough for any stair-stepping not to show through the wrap material, and that the surface is clean and dry so that the wrap can adhere to the surface.

2.10 Hydrographics

Hydrographics, also known as hydro dipping, immersion printing, or water transfer printing, is a method of applying printed designs to three-dimensional surfaces. The pattern or image to be applied is first printed onto a soluble PVA film which is placed onto the surface of a water tank which dissolve the film and leaves the images ink floating on the surface of the water. The part is then carefully lowered onto the ink layer floating on the surface of the water and pushed into the water to transfer the image ink onto the part.

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3. Metal Surface Treatments

The surface finish of metal AM parts is often too rough for some applications, so it is necessary to improve it. Surface roughness is determined by the AM process used, particle size of the material, layer thickness, build orientation, and the presence of supports.

It can be difficult to specify part roughness achievable with metal AM, particularly as the top, bottom, angled, and vertical surfaces each have a substantially different roughness. Laser-based powder bed fusion processes commonly produce as-built parts with a surface finish of about 7–15 μm (300–600 μin.) Ra on the top-facing and vertical surfaces. With Arcam's EBM process, the surface finish can be 20–25 μm (800–1000 μin.) Ra. Down-facing surfaces, and surfaces where support material is attached can, however, be substantially rougher, and on the bottom horizontal surfaces, where support material is usually attached Ra values as rough as 1000 μm can often be measured.

A variety of processes can help reduce the surface roughness of metal AM parts. Some involve mechanical action (e.g., machining, shot peening, and tumbling), while others involve chemicals combined with some type of mechanical action (e.g., electro-polishing). Each method must be evaluated based on how well it works, how much material is removed, cost, and the level of finish required.

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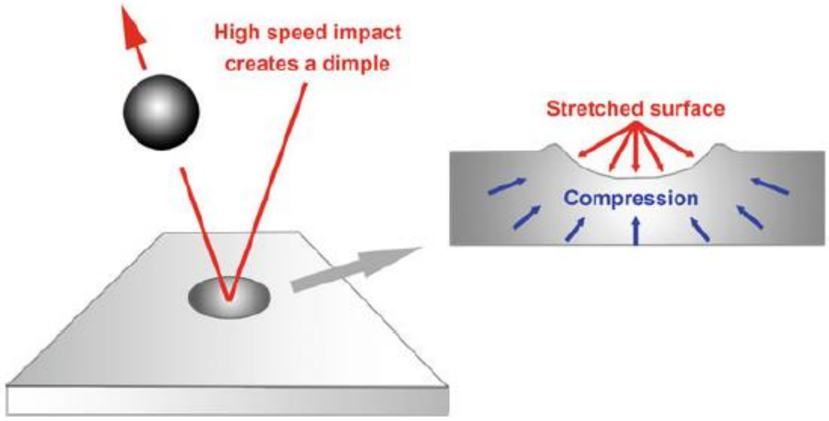
3.1 Shot-Peening

Most metal AM parts are subjected to media-blasting (usually with sand or glass beads) as the first post-processing step after the support material has been removed from the part. This process helps to clean the part as well as remove any residual powder that is still attached to the part.

Shot-peening is a process, similar to sand-blasting, that uses compressed air to shoot small spherical particles against the part. Whereas sand-blasting is an abrasive processes that remove material from the surface, shot-peening flattens all the peaks of the rough surface that protrudes from the part, and has a micro-forging effect on the part which, not only smooths the surface, but can also strengthen the part.

Common media for shot-peening includes glass beads and steel ball-bearings. Most metal AM parts are subjected to shot-peening as the first post-processing process after the support material has been removed from the part.

Shot-peening has a micro-forging effect that can strengthen the surface of a part



3.2 Plasma Cleaning and Ion Beam Cleaning

Plasma cleaning is the process of removing matter from the surface of an object through the use of an ionized gas called plasma. This is generally performed in a vacuum chamber utilizing gases such as argon and oxygen, as well as mixtures such as air and hydrogen/nitrogen. The plasma is created by using high frequency voltages (typically kHz to MHz) to ionise the low pressure gas (typically around 1/1000 atmospheric pressure), although atmospheric pressure plasmas are now also common.

Ion-beam cleaning technology can be used for finish cleaning of the surface of AM parts with accelerated ion beams with energy of up to 1500 eV from molecular particles, adsorbed gases such as argon, polymer fragments, and water vapours.

3.3 Painting

For painting metal AM parts, refer to the section on painting AM polymer parts, as the same principles apply. The only difference is that you may need to use a sanding primer that is suitable for metal.

Additionally, powder coating is possible with metal parts. Powder coating works by electrostatically depositing a dry powder on the surface of the part. The powder is then cured in an oven to allow the powder to melt and form a polymer skin on the product. Powder coating typically results in more durable coatings than wet painting.

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3.4 Machining and Grinding

With metal AM, in general, the down-skin (the surface that is on the bottom surfaces of the part) and any areas that make contact with support material can have a rough surface finish. The top surfaces can also have patterns on it that are left behind by different laser hatching strategies. These surfaces must often be improved through filing, grinding or sanding.

If better surface finishes than those provided straight off the AM system are required, such as those required for a gasket to seal, or engineering accuracies, such as those required to press-fit a bearing, then the part must be machined as a secondary operation. Machining an AM part is no different from machining any other metal part. It gets clamped into the mill or lathe and is machined using the same speeds and feeds as for the conventional material.

Some ways to improve the machining of AM parts includes:

- Don't forget to add some extra material to those surfaces that will require machining. Usually around 0.5 mm extra material is enough.
- Add fixtures and mounting points to the part to make it much quicker to mount into the CNC machine. Often, what takes the longest in this secondary operation, is the time it takes to mount the part in the CNC machine. The cutting is often just a finishing cut in which around 0.5 mm of material is removed from the surfaces where high accuracy or good surface finishes are required. So any features that can make the part faster to mount into the CNC machine, and set the machine origin, will reduce the time needed for the overall operation.
- Counterintuitively, make the surfaces where you need the best surface finish those where you put the support material, as these surfaces are the ones that are likely to need to be machined anyway.

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3.5 Abrasive Flow Machining

Abrasive flow machining, or extrude hone, is a technique for polishing internal channels by pumping an abrasive paste through the internal channels in the part. The abrasive particles in the media grind away rather than shear off the unwanted material.

The rate of material removal depends on the following factors:

- Media flow rate
- Viscosity
- Abrasive particle size
- Abrasive concentration
- Particle density
- Particle hardness
- Workpiece hardness.

3.6 Anodizing

Anodizing is used to produce protective and decorative oxide layers on aluminium, improving corrosion protection and wear resistance. Different colours can be created by dying or electrolytic colouring.

Aluminium AM parts can be anodized in exactly the same way as conventional aluminium parts. With AM parts, however, you may have more freedom to design in better hanging points for when the part is hung in the anodizing bath.

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3.7 Plasma Spraying

Plasma spray is a thermal spray coating process used to produce a high quality coating by a combination of high temperature, high energy heat source, a relatively inert spraying medium, usually argon, and high particle velocities. Plasma is the term used to describe gas which has been raised to such a high temperature that it ionizes and becomes electrically conductive.

The utilisation of plasma spray coating technology allows the spraying of almost any metallic or ceramic on to a large range of materials with exceptional bond strength, while minimising distortion of the substrate.

Plasma spraying can be used to improve:

- corrosion protection
- wear resistance
- heat and oxidation resistance
- temperature management
- electrical resistivity and conductivity.

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3.8 Plating and PVD

Electroplating can be applied to AM parts in the same way as it can be applied to conventionally manufactured parts. Electroplating is also known as electrodeposition because the process involves depositing a thin layer of metal onto the surface of a work piece, which is referred to as the substrate. An electric current is used to cause the desired reaction.

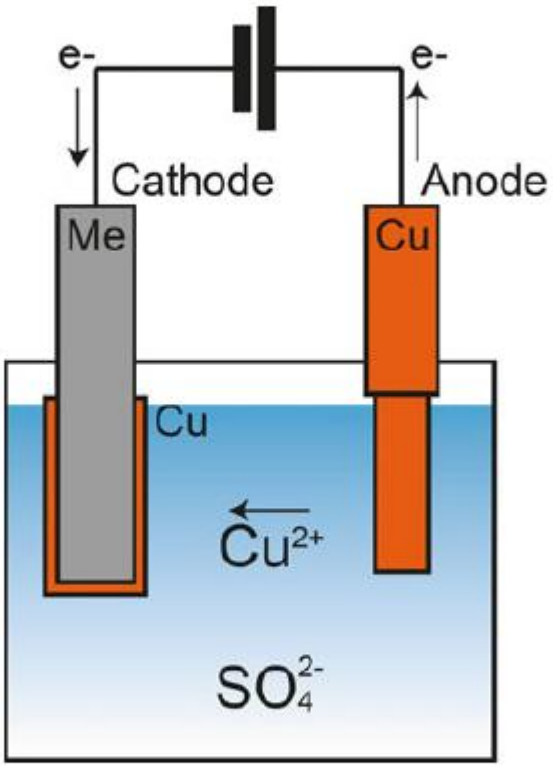
How electroplating works if a layer of, say, nickel is to be electroplated onto a metal AM part to improve the appearance of the piece: The plating metal (nickel) is connected to the anode (positively charged electrode) of the electrical circuit, while the AM part is placed at the cathode (negatively charged electrode). Both are immersed in a specially developed electrolytic solution (bath). At this point, a DC current is supplied to the anode, which oxidizes the metal atoms in the nickel and dissolves them into the bath. The dissolved nickel ions are attracted to the cathode and deposited (plated) onto the AM part.

Most commonly, however, plating is done with several layers of different metals. The first layer of plating is often done with copper, as it is relatively easy to polish to a highly smooth surface. The copper layer is then plated with a subsequent layer such as nickel, chrome, silver, etc.

Factors that impact the final plating result include:

- the chemical composition and temperature of the bath;
- the voltage level of the electric current;
- the distance between the anode and the cathode;
- the electrical current application's length of time.

As with anodizing, with AM parts, you have more freedom to design in better hanging points for when the part is hung in the electroplating bath.



electroplating process

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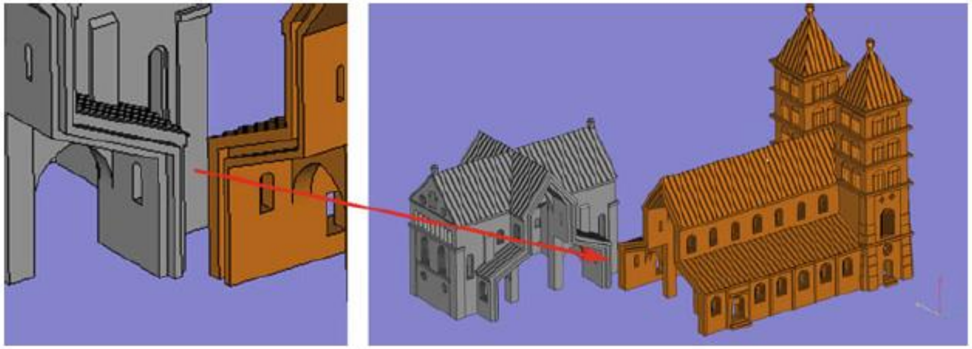
4. Gluing and Welding AM Parts

It is common to need parts that are larger than can be produced on many AM systems. In these cases, the parts must be printed in several smaller pieces and then joined together. The most common way of doing this is by gluing them together. This applies equally to polymer and to metal parts.

With the majority of Am processes and materials, most commonly available epoxy glues will work. With some AM materials, cyanoacrylate glues (superglue) can also be used. With some metal, there are speciality adhesives on the market that may provide better glue joint properties. And, for metal parts, the separate parts can also be welded together.

For parts in ABS, applying a thin coat of acetone to the faces to be glued, and then pushing them together can form a very strong welded plastic bond. The acetone will dissolve the surface layer and allow the pieces to be joined without glue. If parts do need to be glued or welded together, it is strongly recommended that male/female joints be added to the parts so that things line up nicely. This simple design change can greatly accelerate, and improve the quality, of the parts when they are glued together.



Always include some kind of male/female joint between parts that need to be glued together

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5. Heat Treatment and Aging

5.1 Residual Stress Relief

Stress relieving is strongly adviced on all AM metal products in order to minimize residual stresses in the structure, and thereby reducing the risk of dimensional changes during further manufacturing or final use of the component. With AM, this stress relieving is done as the first post-processing step after the build platform is removed from the machine. It happens while the parts are still attached to the build plate by their support material.

Stress relieving does not change the material's structure and does not significantly affect its hardness. The stress relieving temperature, for steel parts, for example, is normally between 550 and 650 °C, and the parts are heated slowly over about one to two hours. Soaking time is then several hours, and varies depending on the size/mass of the part. A general rule-of-thumb is to soak for 1 h per 25 mm of material thickness. After the soaking time the components should be cooled down slowly in the furnace, to about 300 °C, and then can finish cooling in air. A slow cooling speed is important to avoid tensions being reintroduced into the part by temperature differences in different areas of the material. This is especially important when stress relieving larger components. For stainless steels, a higher temperature solution heat treatment is normally necessary than for steel. Temperatures and times vary greatly from metal to metal and part to part. But the general principle is relatively straight forward: The idea is to evenly heat the part, and let it soak until the entire part, both thick sections and thin sections, have reached a temperature equilibrium. After that, the idea is to slowly cool down the part, so that the thick sections and thin sections cool down at exactly the same rate. If the thin sections were to cool down quicker than the thick sections, for example, then residual stress would be reintroduced into the part. If necessary, stress relieving can be performed in a furnace with protective gas to protect surfaces from oxidation. In extreme conditions, vacuum furnaces can be used.

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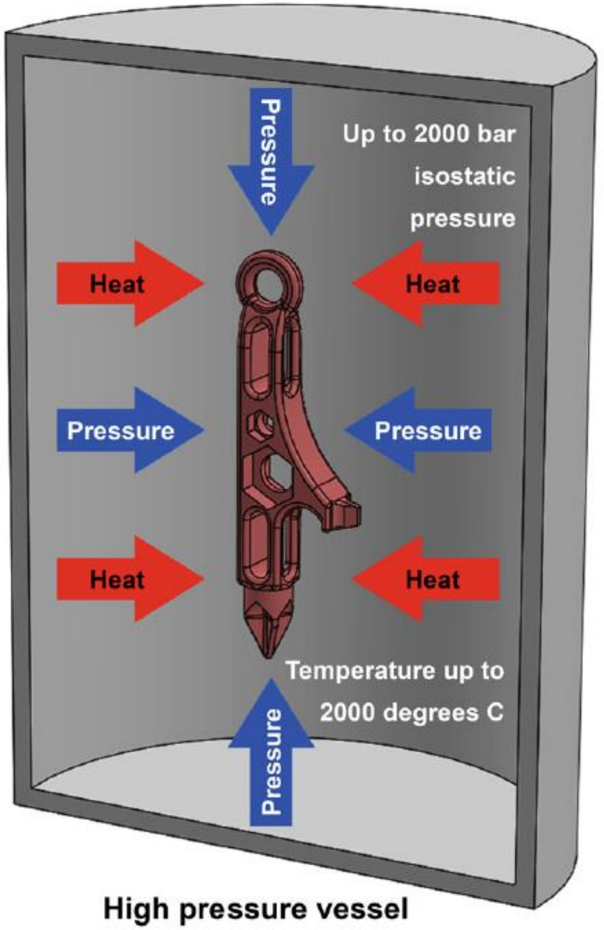
5.2 Hot Isostatic Pressing (HIP)

Hot isostatic pressing (HIP) is a form of heat treatment that uses high pressure to improve material properties. That pressure is applied by an inert gas, usually argon. Time at elevated temperature and pressure allows plastic deformation, creep and diffusion to occur. AM parts for critical applications are HIPed to eliminate internal microporosities, thereby improving mechanical properties by removing defects. It also improves the material's mechanical properties and workability. Metal parts that have been HIPed can reach metallurgical properties similar to wrought or forged parts.

The HIP process subjects a component to elevated temperature and gas pressure in a high pressure containment vessel. The pressurizing gas most widely used is argon (inert gas is used, so that the material does not react chemically). The chamber is heated, causing the pressure inside the vessel to increase. Pressure is applied to the material from all directions (hence the term "isostatic").

Simply put, HIP involves squeezing the part equally from all directions under high temperature in order to improve its properties. The pressure and temperature will eliminate most of the porosities or surface micro-cracks. Because the part is being squeezed equally from all directions, including any internal faces that are accessible to the gas, the process has relatively little effect on the dimensions of the part (though this must, of course, be verified for each particular application).

The HIP process



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The Future of Additive Manufacturing

Additive manufacturing is developing very rapidly. Every few months we see new technologies, new materials, new software, and new AM products coming to market.

It is of great importance to those with an interest in AM to keep abreast of some of the upcoming developments as they will, without doubt, affect how we develop future products.

If one examines where the bulk of research and development effort is being put today, it is, by far, focused on speed: Developing machines that are faster to eventually meet the need for the increased changes in volumes required by industry. There is also much research in new materials that are specifically designed for AM. This is both to have materials with better mechanical properties and to have materials that can be processed faster by the machines.

Another area of growth is in larger machines. The largest metal machines today, for example, have build volumes of around 500mm×500mm×500 mm. But developments are underway, using a number of the different AM technologies discussed in this book, to develop systems with much larger build volumes. Some other area of upcoming development that are of interest are discussed below.

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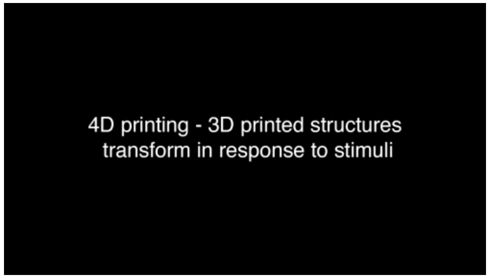
1. Functionally Graded Materials

A particularly interesting area of materials growth is in functionally graded materials, smart material and multi-materials. Functionally graded materials are materials that change properties throughout a part. The functionality gradient can occur either because the actual material changes across the spectrum of the part, or because the geometry changes within the part.

Smart materials are materials that can change properties in response to an external stimulus, and multi-materials are related to printers that can print in several different materials at the same time to better meet the needs of products that are made up of multiple materials.

The new materials present tremendous potential to develop new smart products with improved functionalities. These materials are so new, however, that we don’t quite know what to do with them yet, so novel applications will need to be developed at the same time that the materials are being developed.



Classification of different types of functionally graded materials, ranging from transitions between different materials to structural geometry changes within the material

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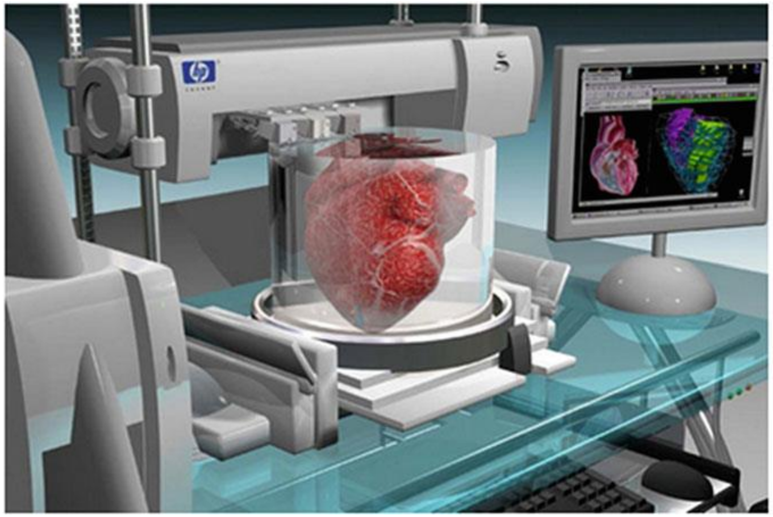
13.2 Bioprinting

Tissue engineering and, ultimately, the printing of entire organs or body parts, is an active area of research worldwide. Researchers are currently able to bioprint a number of animal organs, human tracheas, heart valves, and bladders for humans that are engineered out of the patients own stem cells.

There are, currently two main techniques used for bioprinting. The first 3D prints a biodegradable polymer scaffold and seeds it with the patients stem cells. Over the incubation period, as the cells grow into what they are supposed to grow into, the polymer is degrading at the same rate that the cells are growing so that, by the time the cells have grown, all the polymer has been replaced by living cells. The other techniques is similar, but uses a hydrogel to suspend the stem cells in, and then print the mixture of hydrogel and stem cells (usually with extrusion or inkjet systems) into the right configuration. They then incubate them and, again, the cells gradually replace the hydrogel as they grow into what they are supposed to.

The whole area of tissue engineering and bioprinting are still in their relative infancy, and it may be a few years before we see the ability to print more complex organs such as livers and hearts. But the potential it has for human health and wellbeing is tremendous, which makes it a truly valuable area of research. It is important to understand that additive manufacturing is only a very small part of tissue engineering and bioprinting research. It relies as much on other disciplines including medicine, biology, software, etc. as it does on AM. It is also an area that will need the parallel development of a whole new branch of research into ethical and the social implications of such technologies.



Bioprinting may, one day, give the ability to print entire replacement organs

3. Construction Applications

Work is going on at many universities and companies around the world to develop technologies capable of printing entire buildings and houses. The vast majority of the efforts in this area use a material extrusion based process in which concrete is extruded out of a nozzle and deposited. The concrete material can contain a variety of fillers, polystyrene, or fibers to reinforce it.

It has been predicted that, once the various house printing technologies have been fully developed, it will be possible to print an entire house within the timespan of only a few days. This includes not only the concrete structure, but all the amenities that form part of a functional house. It will be possible to order a house online, modify it to suits one's own design preferences, have the house printing machine trucked and installed on the construction site, and begin printing the house. A few days later and the house will be ready to move into.

As a reality check, however, one must remember that the already well established pre-cast method of building houses, in which sections of the house are pre-cast in a factory, and then assembled on site can do the same thing if one ignores the supply chain aspects that add time to the build. But these would apply equally to 3D printed houses.

Printing houses: the University of Southern California's Contour Crafting system

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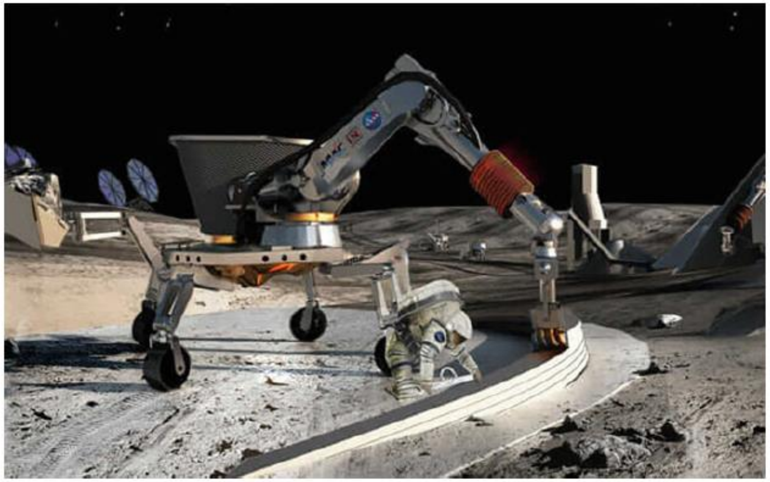
To date, the vast majority of 'printed houses' have been relatively simple structures that would be possible to pre-cast more cost-effectively, which means that additive manufacturing has added little value to the end product. So, if 3D printed houses are to take off beyond just being a cool application of the technology, greater input from architects may be needed so as to design architectural structures that would not be possible to pre-cast. And applications need to be found in which AM allows buildings to be printed in a way, or in a context, that would otherwise not be possible. Otherwise additive manufacturing will add relatively little value to the construction business.

There are, however, some future areas of applications for the technologies that could be of great interest. One, in particular, is in printing space habitats. As exploration of the solar system continues, 3D printing could be a viable technology to mine raw materials from the planet being explored, and use that raw material to print habitats on the planet. This would alleviate the inefficient and very expensive challenge of sending up construction materials into space by rocket.



Printing habitats in space

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4. Printed Electronics

From a product development point of view, conductive AM and printed electronics have the potential to truly change how we design products. Today, almost all electromechanical products are designed around rectangular flat circuit boards, so most products are largely rectangular in shape. Imagine no longer having this constraint, with more freedom of design afforded by curved electronics and eliminating the need for wires.

The level of readiness for the technology, today, is largely based around the ability to print wires integral to a polymer component, and printing circuit boards. Several companies have done substantial work in this area, including Voxel8, Nano Dimension, Optomec, and HP. This ability to print wires and circuit boards, alone, can already be of great benefit to product developers.

Printed thermometer with printed electronic circuits

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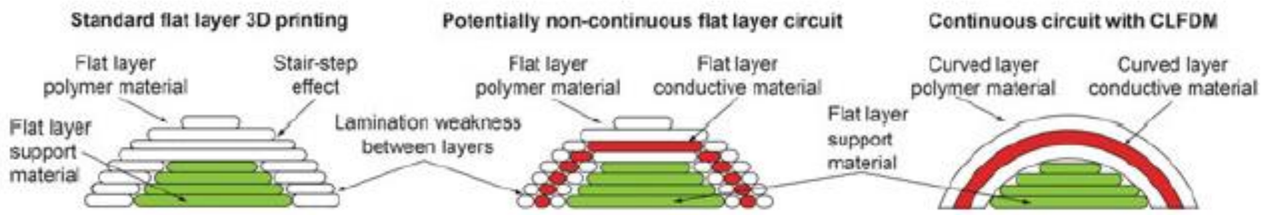
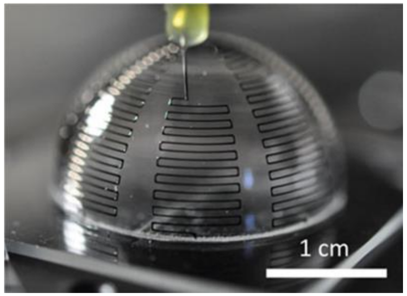
Some researchers have also proposed the idea of curved layer material extrusion as a way of eliminating the potential risk of discontinuous circuits in flat-layer applications. Much like the mechanical anisotropy caused by the joint between layers, with conductive 3D printing, the risk is that the conductivity between the layers may not be as good as the conductivity within the layer. The idea with curved layer FDM (CLFDM) is to, first, print all the support material, and then print the polymer material and conductive polymer material as curved layers on top of the support material.

This ensures that the conductive tracks that form the wires are continuous and have the same conductivity throughout the wire. Researchers have also successfully printed relatively simple components like transistors and capacitors. But, once we reach the level of being able to print more advanced electronics, such as integrated circuit, the product development industry will truly be revolutionized.





Curved layer material extrusion for 3D printed electronics

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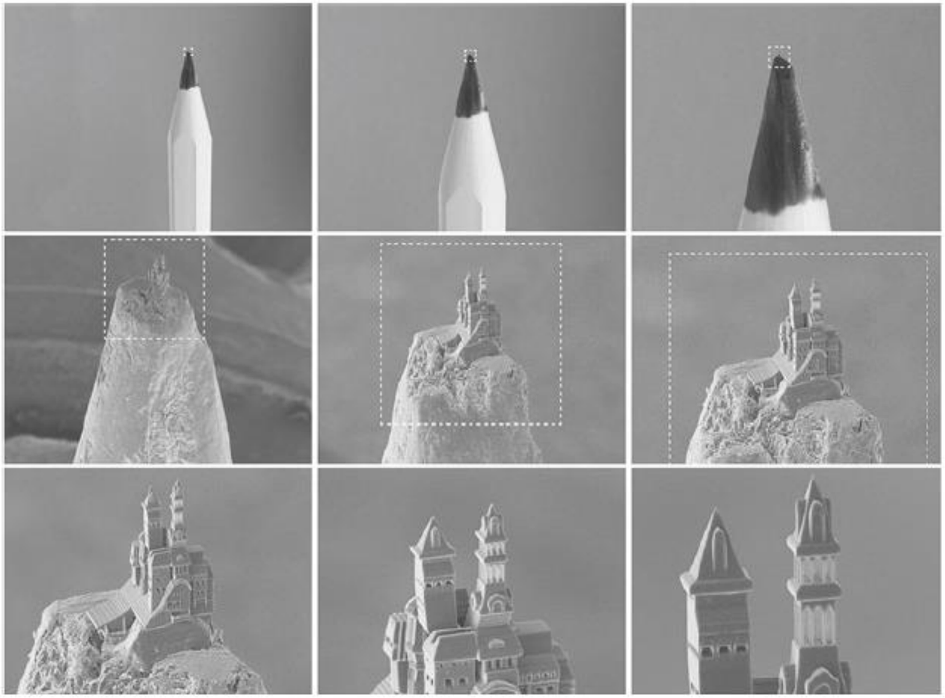
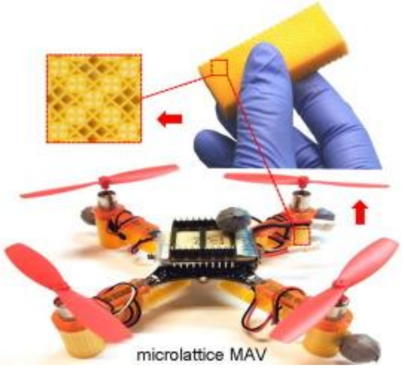
5. Nano Printing

Though we are not quite yet using additive manufacturing at a nano-scale, researchers have been coming very close to this. The pioneering work, in 2001, in femtosecond laser manufacturing of Prof. Satoshi Kawata, at Osaka University in Japan, for example has printed parts that are at the few microns scale. This includes parts, such as the nano-bull, which measure roughly one tenth of a human hair in size. Researchers at the Vienna Institute of Technology have also created a tiny Formula One race car, using two-photon lithography, which uses highly-focused light beams to manipulate then harden the resin molecules in exactly the right position. The 'two-photon' part of the name refers to how the resin only hardens when two photons hit it at the same time. The image is a great example of small scale printing and shows a printed cathedral at the very top of a pencil. This technology could, ultimately, mean the manufacture of nanobots that could, for example, be injected into the blood stream with the task of cleaning the blood stream of all undesirable molecules.



Nanoscale 3D printed structure of the Sutyagin house, or "Spitzen-Forschung" (holiday house) in Arkhangelsk, Russia, on the tip of a pencil, made with two-photon polymerization



6. Food Printers

There is now a whole new field of research concentrating on developing 3D printers capable of printing food. By far, the majority of the efforts in this area use material extrusion technologies to extrude food pastes in order to reconstitute facsimiles of food. So these machines are not so much ‘printing food’ as ‘printing with food’. Some others use binder jetting technology to bind powdered materials, such as sugar, together with an ink-jetted binder. One of the few efforts in true printing of food has been in printing meat, using bovine stem cells and a method similar to that described in the section on bioprinting above.

The Cornucopia project food printer

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Much of the 3D printed food, so far, has focused on printing geometrically complex, or customized, foods such as chocolates, pasta, sugar wedding cake toppers and candies, etc. Though this is, of course, interesting, one can question whether it adds enough value to the food to be worth the relatively slow print speed and, therefore, whether it is a cost-effective way of producing food.

An area where 3D printed food can, however, potentially add great value is on printing customized foods for people with dysphagia, or other chewing and swallowing disorders. There is potential, for example, for printing food with internal lattice structures that would rapidly dissolve when put in the mouth, or be easy to chew and swallow by the customer. So could one print a carrot that looks like a carrot, tastes like a carrot, but is easy for the customer to chew or swallow? Not only could it have the right texture and consistency for the customer, but it could also have its ingredients customized to meet the users' needs with, for example, extra vitamin B or calcium.

3D printing of Food for the elderly

Thank you for your attention