PRINTING BY THE RULES

The additive manufacturing (AM) of high-quality products requires knowledge of the 3D-printing process and the related design guidelines. Allthough AM has been around for some years, many engineers still lack this knowledge. Therefore, Fontys University of Applied Sciences sets great store by training of engineers, education of engineering students and knowledge sharing on this topic. As an appetiser, this article offers a beginner's course.

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AM has most definitely been a hype in recent years and is now producing relevant applications; see Figure 1 and other articles in this issue. Nevertheless, many engineers have not familiarised themselves with AM's 'unique selling points':

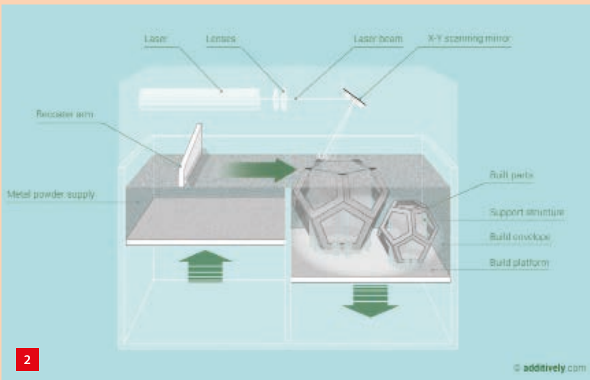
- customisation of parts and products (for example, for medical applications and spare parts);
- freedom of design (complex features that cannot be conventionally machined);
- mass reduction and stiffness optimisation (using topology optimisation: putting material only where it will add value);
- integration of functions (potentially leading to new design principles);
- specific material properties (of optical surfaces, for example).

One of the barriers for adopting AM may be the lack of knowledge of the appropriate design guidelines. At the ObjeXlab of Fontys University of Applied Sciences, these AM design rules are the subject of research and knowledge sharing, through research projects, education and training. The focus is on the design guidelines for two popular AM technologies, i.e. SLM and FDM.

1 *Conventional design of a steel-cast bracket (left) and the corresponding topology-optimised design of the titanium AM-made bracket (right), printed on an EOS machine. Source: Airbus Group Innovations*

FDM and SLM

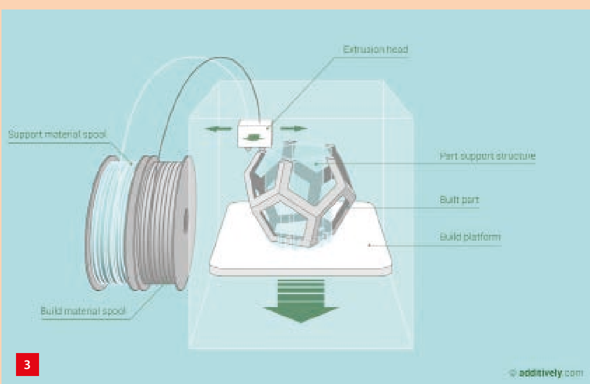
Two popular AM technologies are SLM (selective laser melting) and FDM (fused deposition modelling), for metals and plastics, respectively. With SLM (selective laser melting, see Figure 2) a metal powder is distributed equally in a thin layer over a build platform (powder bed), by means of a roller or a squeegee. Typical layer thickness is around 25-100 µm. An (X,Y)-controlled laser beam melts together the powder particles in the build layer (and with the layer below). After building a slice of the component, the platform will sink by one layer thickness and a new layer of powder will be applied over the previous one.



2 *Selective laser melting (SLM) printing principle.*

The powder bed can be heated to reduce excessive temperature differences between the particles that should be joined together and the superfluous particles. Also, the atmosphere inside the machine should be low in oxygen content to reduce unwanted oxidation. This can be achieved by applying a nitrogen or argon atmosphere or by means of evacuation (electron beam melting). After the component has been built, the unused powder should be removed (after cooling the component down to room temperature), the part has to be separated from the build plate and mechanical stress has to be relieved. The density will be 99-100% and sintering is not necessary.

With FDM (Figure 3) a plastic wire (filament) is fed into a heated extruder where the solid plastic is weakened and pressed through a nozzle. This nozzle is moved in the horizontal plane by means of a software-controlled gantry. The movement path of the nozzle corresponds to the slice outline of the layer to be built. Below this nozzle is a build platform which is lowered each time a layer of the object has been built.

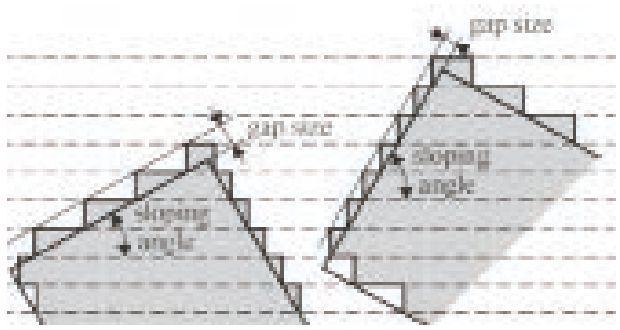


3 *Fused deposition modelling (FDM) printing principle.*

SLM design rules

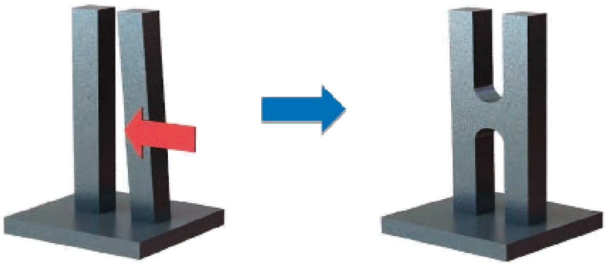
Some important SLM process parameters are layer thickness (vertical pitch), laser power, scan velocity and distance between print tracks (hatch distance). The printing resolution is determined by the interplay between these parameters and the powder composition (type and size distribution). For a high-resolution print, low laser power, low scan velocity and low layer thickness are required, whereas a high building speed requires high laser power, high scan velocity and a thick powder layer.

Naturally, the resolution of the printing process influences the surface roughness, depending on the sloping angle of the surface under hand; this is called the staircase effect (Figure 4). The steeper the surface that is being printed, the smoother the result, depending on the layer thickness. The exact nature of the melting process also has its influence on the surface quality. For high-quality surfaces, remelting or other post-processing options are required.



4 *The staircase effect.*

A product-specific design parameter that has to be considered is the printing orientation of the product. Mechanical properties of SLM-printed products are, to a large extent, independent of the printing direction, but they do depend on the scan strategy. The orientation of the product with respect to the build plate (and hence the total processing set-up) can be selected in a trade-off between productivity (the number of parts stacked on the build plate for one printing run) versus the interaction of the squeegee with the product (the risk of damaging thin or thin-walled parts of the object). The squeegee movement has to be as much as possible in the 'stiff direction' of each part of the product. Stress relief considerations also play a role in determining the optimum printing orientation.
An alternative is to increase the stiffness by adding support structures, for example 'bridges' that connect vulnerable parts (Figure 5).



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Support structures are also required in the case of strongly overhanging structures (Figure 6) or in the case of thin-walled structures (transfer of surplus heat, see below). Of course, these support structures have to be avoided as much as possible, as their printing and removal afterwards takes up additional process time and introduces the risk of damaging the part. This may require modifications to the design. But tilting the design may also decrease the need for support.

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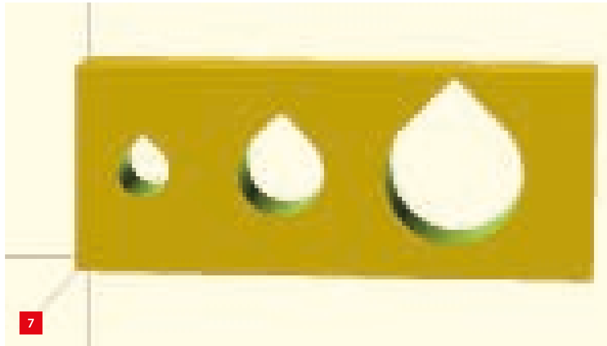
A special challenge in AM is the printing of holes. Their diameters should not be less than 2 mm, or powder will stick to the wall of the hole. In the case of very shallow holes (or vertical holes), smaller diameters can be achieved. From machining history, round holes are standard in any design. With drilling, the orientation of the hole is not relevant for the outcome, but with AM it definitely is. It is preferable to orient the part in such a way that a hole has to be built in the vertical direction. This is because when printing a hole in the horizontal direction, the lower and upper parts will be become rough due to the staircase effect – thermal and surface tension effects may also come into play – and the upper part may require a support structure.

When there is no definite need for a round hole, a droplet-like hole may be an alternative. The steeper surfaces at the top do not need a support. This is a typical example of the new possibilities unveiled by AM that cannot be achieved by conventional machining (drilling).



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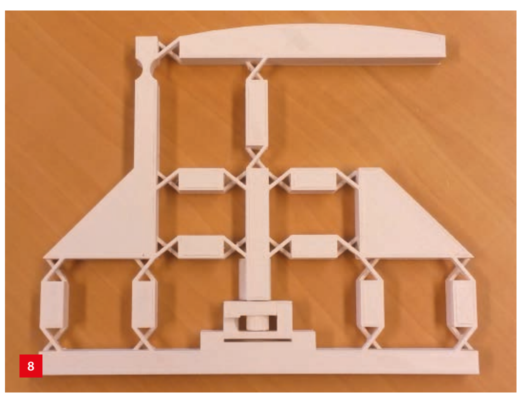
Thermal aspects play an important role in the printing process and must therefore be dealt with. The laser injects a lot of power into the part being printed. As the powder more or less behaves like a thermal insulator, all the heat has to dissipate via the product itself. In thin-walled structures, increasing cross-sections or adding internal grids within the product may therefore promote dissipation.

In the design the removal of support structures and superfluous powder after printing has to be accounted for. Relevant aspects include accessibility for external tools (such as – cheap – band saws or wire-erosion tools), 'vents' for removal of the powder, and preventing damage to the product at the support connection points.

Similarly, post-processing has to be taken into account in the design. For example, mounting options can be provided in the design. Ideally the build plate is used for mounting, but when necessary supports (for example, non-functional cross-connections) can be added for taking up clamping loads or relieving machining stresses and strains. A well-known procedure (also used with casting) for obtaining high-accuracy products is to print excess material that will be removed in a precise post-processing (e.g. machining) procedure.

FDM design rules

For high-tech applications of parts under mechanical load, metal printing using SLM for example appears to be the prime candidate, but with the 'simple' FDM technology 'serious' plastic products can also be printed, see Figure 8.



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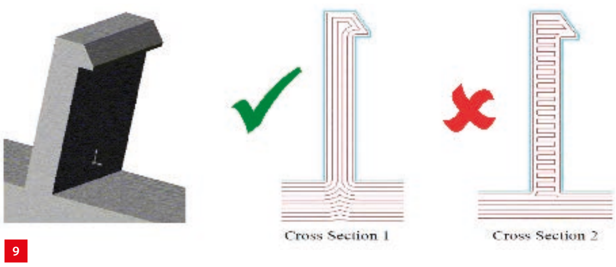
5 *'Bridges' can connect vulnerable parts to increase stiffness.*

6 *Modification of the design in case of an overhanging structure, in order to prevent the need of a support structure.*

7 *With a droplet-like hole the (steeper) surfaces at the top do not need a support. (Source: 3D Design For 3D Printing by tinygeek in 3D-Printing, www.instructables.com)*

8 *A monolithic linear guiding mechanism utilising elastic cross-hinges has been printed by Fontys students. They proved that a low-cost FDM printer can produce a complex product like this and showed that it functions properly, without claiming that it meets industrial specifications.*

For the FDM process, similar considerations as with the SLM process apply, regarding aspects such as the staircase affect and the need for support structures. The quality, density and mechanical properties of FDM-printed products are determined by the binding process between the filaments. Products exhibit anisotropy, with the highest tensile strength in the printing direction, which therefore has to match the orientation of external loads (Figure 9).



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9 *Matching the the printing direction with the orientation of external loads.*

Here, the printing resolution is primarily determined by the diameter of the filament after exiting the printer nozzle. This diameter also determines the required thickness of thin-walled structures. As a minimum, twice the filament diameter is taken, but three or four times this diameter is recommended for better quality (Figure 10).

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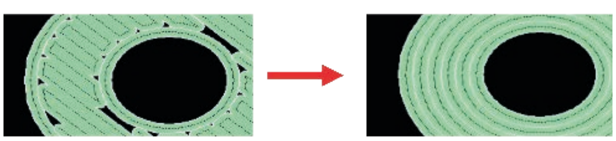
10 *Recommended thickness of thin-walled structures.*

Research has been conducted at ObjeXlab on the printing of sloping surfaces. It was found that for angles as low as 25° (with the horizontal plane), printing without adding support structures is feasible, depending on the printing strategy. For example, with an Ultimaker printer it is possible to first print the 'bulk' of a structure and then the contour/edges. This improves the internal cohesion and hence the strength. Some other printer suppliers provide 'closed' software, which does not allow for selecting the optimum printing strategy.

When printing infill filaments, 'filling effects' occur: when the printer nozzle scanning movement reverses its printing direction, voids may occur. This can be prevented by using thinner filaments, decreasing the raster distance or devising clever strategies, such as for a circular structure (Figure 11).



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11 *Recommended printing strategy for a circular structure, in order to prevent the occurrence of voids.*

To conclude

Not much more than a tip of the veil has been lifted. Many design rules may seem logical, but explicit formulation may help prevent design errors. Sets of design guidelines for additive manufacturing are 'under construction'. Sharing knowledge on this topic may advance the adoption of 3D-printing.

ObjeXlab research programme

Fontys University of Applied Sciences in Eindhoven in 2012 took the initiative to set up a laboratory for AM, called 'ObjeXlab'. As part of the Centre of Expertise High Tech Systems & Materials at Fontys (CoE HTSM), ObjeXlab aims for a public-private cooperation to explore AM opportunities in applied research projects with both industrial (engineers, researchers) and educational participants (students, teachers).

The ObjexLab research programme comprises five AM areas:

1. Processes: determining optimal parameters for FDM and SLM printing processes.
2. Design guidelines.
3. Killer applications: investigating competitive advantages via product attributes that would be impossible using conventional manufacturing technology.
4. Material properties: analysing the properties of printed products.
5. Hybrid technologies: combining AM with conventional manufacturing technologies such as machining, and integrating different printed/machined materials (plastics, metals) in one product.

AM design rules online

Searching on the internet for 'additive manufacturing design guidelines' yields a lot (scientific publication) hits. Practical information is also available online. For example, the Belgian 3D-printing service providers Materialise and Shapeways present design guidelines for a variety of materials.

I.MATERIALISE.COM/3D-PRINTING-MATERIALS
WWW.SHAPEWAYS.COM/MATERIALS