PRINTING
BY THE RULES

The additive manufacturing (AM) of high-quality products requires knowledge of the 3D-printing process and the related design guidelines. Although 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.

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.
TOWARDS DESIGN GUIDELINES FOR ADDITIVE MANUFACTURING

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.

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.

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.

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).
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.

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.
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).

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:
2. Design guidelines.
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.