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Goutianos, Stergios

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Selective Laser Melting of Hot Gas Turbine Components: Materials, Design and Manufacturing Aspects

Stergios Goutianos

Department of Wind Energy, Section of Composites and Materials Mechanics, Technical University of Denmark, Risø Campus, DK-4000 Roskilde, Denmark

E-mail: `gout@dtu.dk`

Abstract. Selective Laser Melting (SLM) allows the design and manufacturing of novel parts and structures with improved performance e.g. by incorporating complex and more efficient cooling schemes in hot gas turbine parts. In contrast to conventional manufacturing of removing material, with SLM parts are built additively to nearly net shape. This allows the fabrication of arbitrary complex geometries that cannot be made by conventional manufacturing techniques. However, despite the powerful capabilities of SLM, a number of issues (e.g. part orientation, support structures, internal stresses), have to be considered in order to manufacture cost-effective and high quality parts at an industrial scale. These issues are discussed in the present work from an engineering point of view with the aim to provide simple quidelines to produce high quality SLM parts.

1. Introduction

In the field of heavy duty gas turbines there is a push toward reducing the cost of electricity, and due to legislation to lowering NOx emission levels. To lower the cost of electricity, the efficiency of gas turbines has to be increased [1]. This translates to higher turbine inlet temperature and reduced cooling consumption. To achieve higher temperatures, nickel-based superalloys can be replaced by new ceramic matrix composites with higher temperature capability [2, 3]. An alternative solution is to develop new designs incorporating complex and more efficient cooling schemes. However, such complex designs can be realised only with new manufacturing technologies such as selective laser melting (SLM) [1].

Selective laser melting is an additive manufacturing (AM) technology allowing direct production of metallic parts from powder materials. Thin layers of powder, typically between 20 and 60 μm, are deposited in a bed and locally melted by a laser beam according to a computer aided design model. The powder bed is then lowered and a new layer of powder is deposited. These steps are continuously repeated until the part is built to nearly net shape [4]. This is why AM is also called solid freeform fabrication or digital manufacturing. With SLM parts of arbitrary complexity can be manufactured, such as internal complex cavities which cannot be made by traditional manufacturing of removing material due to constraints such as tooling and physical access to surfaces for machining.

While SLM is one of the most rapidly developing manufacturing techniques [5], it is also faced with a number of issues such as cost, non-optimal processing parameters, and high internal stresses. These topics will be analysed in the following sections.

2. Cost of Selective Laser Melting

Figure 1 shows the cost of SLM relative to conventional (casting) manufacturing. SLM is competitive over conventional manufacturing when the production volume is low, as can be seen in Figure 1a. The cost per part is independent of the volume for SLM, while for casting it rapidly decreases as the volume increases. However, due to continuous technological developments (*e.g.* the cost of SLM machines decreases and the build speed increases using machines with more laser beams), the cost per part decreases over time, as indicated by the dashed line.

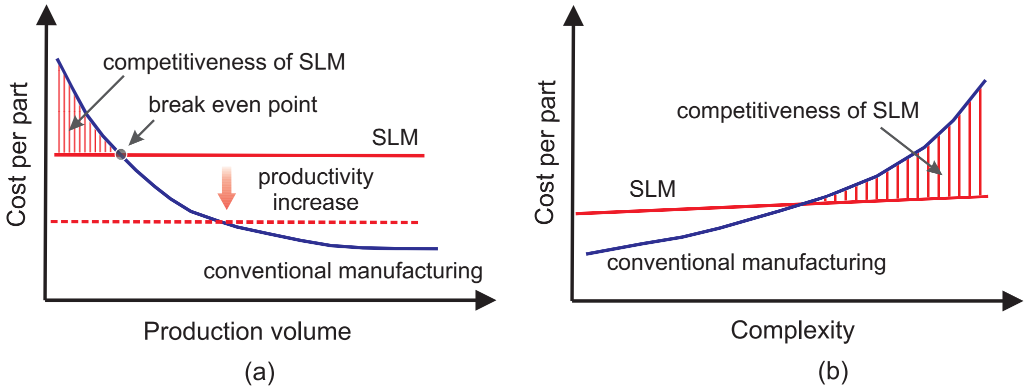

Figure 1. Cost of selective laser melting *vs* Conventional (casting) manufacturing.

Aerospace or gas turbine components have more than one function. A structural component such as a turbine blade also has an internal structure for passing coolant through it. As mentioned above, to improve the efficiency, advanced cooling schemes with complex internal features are required. Fabrication of such parts require expensive molds and more complex process planning if conventional casting is used. This results in a significant increase of the cost per part as shown in Figure 1b. On the other hand, the cost per part for SLM is almost independent of the part complexity (complexity for free). Furthermore, with SLM many parts can be consolidated into one integrated design [6, 7] avoiding assembly operations and increasing reliability, and thus reducing the cost per part over its lifetime.

3. Design for Selective Laser Melting

The unique capabilities of SLM offer new opportunities for the design of gas turbine components with significant improvements. However, manufacturing difficulties related to the SLM manufacturing process should be considered in the design process in order to produce high quality parts.

3.1. Overhaning structures

One of the most common issue is overhanging structures [8, 9] shown in Figure 2. When the layer build has the same dimensions as the previous layers, as shown in Figure 2a (no overhanging structures - $\alpha = 90^o$), the heat is dissipated to the previous built layers and the geometrical distortion of the part is minimal. In practice however, when building parts of complex geometries the layers have different dimensions and overhanging structures, described by the inclination angle α, cannot be avoided.

When $45^o < \alpha < 90^o$ (Figure 2b), the overhanging structure is relatively small. The previous built layers provide a conductive heat support and the distortion of the part is usually within

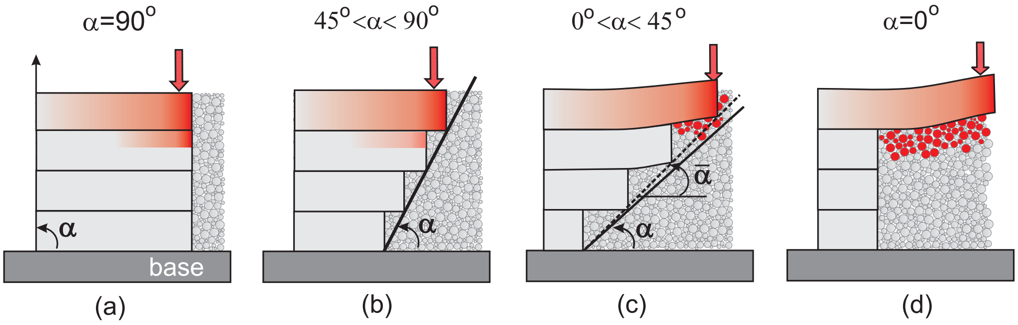

Figure 2. Overhanging structures and dross formation for large inclination angles

accepted tolerances. When α is less than 45^o, then the overhang-length of the layer build is supported by a powder zone which has significantly smaller conductivity than the bulk conductivity. As a result, such overhanging structures are distorted and the final component does not meet the design tolerances. The extreme case occurs when $\alpha = 0^o$ where a large amount of the powder below the layer is also melted. Apart from the part distortion, the surface quality of the overhanging structure is low, which is a significant drawback. The surface roughness can significantly influence for example the flow of the coolant in the internal cavities of a turbine component.

To minimise the presence of overhanging structures, the building direction has to be carefully chosen. Figure 3a, shows a simple part with a overhang structure ($\alpha = 0^o$). By rotating the part as shown in Figure 3b, the inclination angle is increased ($\alpha > 45^o$) and the quality of the built part can be significantly improved. Alternatively, a different build direction can be chosen as shown in Figure 3c with $\alpha = 90^o$ giving the optimal quality. In practice when building complex gas turbine components, it is typically not possible to find a build direction that contains no overhanging structures. In this case, the build direction has to be optimised to result in bigger inclination angles for the most critical surfaces of the component.

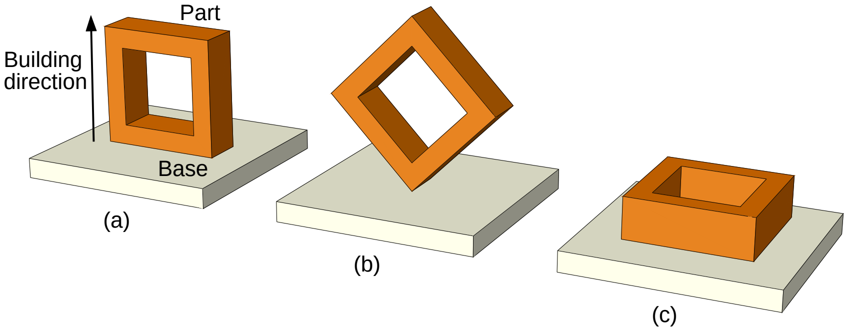

Figure 3. Dependence of the overhanging structures with the building direction [9].

3.2. Support structures

Alternatively, instead of producing one integrated component, several parts can be printed separately and then joined together. In this case it may be easier to define an optimal building direction and thus obtain better quality components. In this solution there are issues with the joint strength, which is critical for structural gas turbine components. A different approach is to use support structures as shown in Figure 4. To avoid the critical ($\alpha = 0^o$) overhang structure for the building direction (Figure 4a), the empty volume can be filled with the same material (Figure 4b - block support) during the SLM process, preventing the collapse of melted metal to the powder bed below. Such a support structure is inefficient since it slows significantly the build time due to its large volume and results in an increased cost per part. It is used rarely, for example, to support massive overhanging structures. This is one of the reasons that support structures are typically lattice structures, as shown in Figure 4c. Additionally, the support structures are removed after the build through post-machining operations. It is easier and less costly to remove lattice support structures than block support structures. To ease the removal of support structures, the support structure is decomposed in two parts: teeth that connect the main support with the part, and the main support [9].

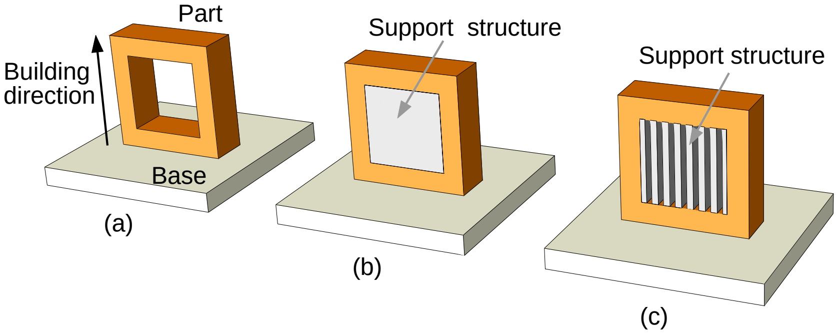

Figure 4. a) Unsupported overhang structure, b) solid support structure and c) lattice structure as support structure

There are many factors that have to be considered in designing support structures, such as the additional build time, post-machining operations and the mechanical strength of the supports to constrain the deformation of the part. In practice, the build direction is optimised in such a way as to minimise any overhanging structures and to minimise the use of support structures [10, 11].

3.3. Self-supporting structures

From the above, it is clear that overhanging structures are in general present when building complex parts, and that the use of support structures should be minimised in order not to increase the cost of the part.

After the build direction is defined, there are several options in the design process to minimise the use of support structures by using SLM-friendly design features. In Figure 5, a circular hole (*e.g.* a cooling hole in a turbine component) with a critical overhanging structure is replaced with an elliptical hole that is a self-supporting structure. Sharp edges (see Figure 6) should be avoided by using fillets or chamfers that have a self-supporting shape.

3.4. Topology optimisation

As mentioned above the build time has a significant impact on the cost per part. Topology optimisation [12, 13] can be applied to reduce the weight/volume of the part and thus reduce the cost (the build time is proportional to the weight of the part). First a finite element mode of the part is created and then a material density value equal to 1 (1 → fully dense) is assigned to each element. The optimisation algorithm determines the optimal material density distribution to achieve the optimisation objective (*e.g.* strain energy) and constraints (*e.g.* final volume).

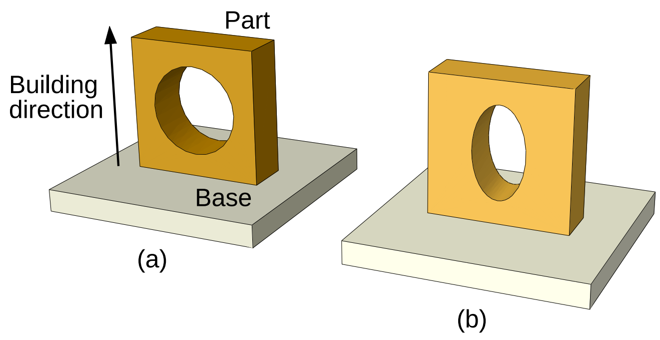

Figure 5. Design features with self-supporting structures.

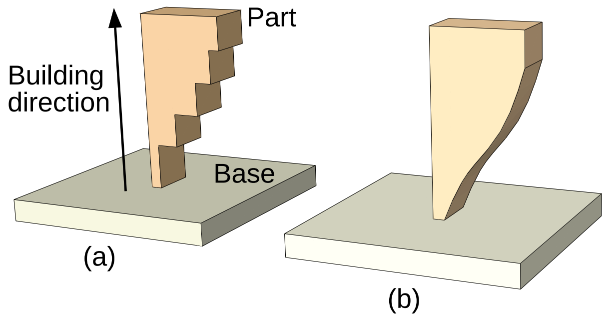

Figure 6. Design features with self supporting shapes.

A simple example is given in Figures 7 and 8. A cantilever plate is loaded with a force on its right side. Figure 8 shows the stresses in the optimised (reduced weight) part. The dark colours indicate regions of high stresses.

Figure 7. Simple topology optimisation example.

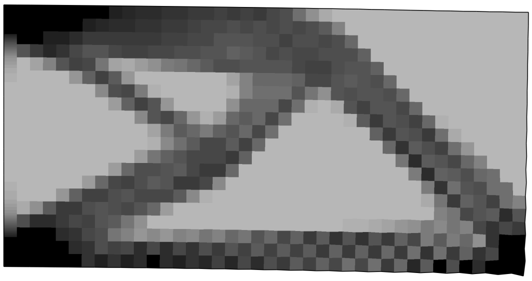

Figure 8. Contour of Von Mises Stresses after optimisation with dark colours indicating highly stressed regions.

The corresponding material density contour is given in Figure 9. In this optimisation problem, the material density is allowed to vary between 1 (initial density) and 0 (no material is present / material is removed). As can be seen, there are regions with intermediate densities between 0 and 1. These regions cannot be manufactured in practice as they indicate that a material with lower density should be used, which is unphysical. Therefore, a density of 1 is assigned to these regions before manufacturing the part. If the volume of the intermediate density regions is large then the manufactured part is not fully optimised in terms of weight reduction. It should be mentioned that modern optimisation algorithms minimise these regions by penalising the occurrence of regions with intermediate densities. A different approach is shown in Figure 10 where the minimum material density is set to 0.2. As a result almost the entire part has an intermediate density. With SLM it is feasible to replace these artificial volumes with lattice structures having the same density. Care should be taken that the mechanical response of the lattice structures is very close to the mechanical response of the material that they replace.

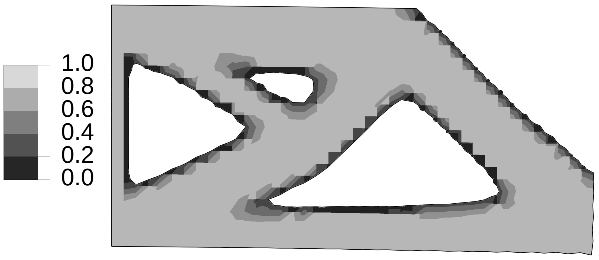

Figure 9. Contour of material density, ρ_m, when ρ_m is allowed to vary between 1 and 0.

Figure 10. Contour of material density, ρ_m, when ρ_m is allowed to vary between 1 and 0.2.

Topology optimisation has few drawbacks when applied in practice. It is computationally demanding, especially when multiple load cases have to be analysed. Also, additional surfaces are created (see Figure 9 and 10), leading to an increased number of overhanging structures. Optimised geometries of complex parts are not manufacturable directly as they contain many irregular surfaces that need to be smoothed, as well as regions of high local stresses (stress concentrations). These high stresses can be reduced by shape optimisation but usually topology optimisation results are used as a guide to create a novel design.

A secondary but important benefit of topology optimisation is that it leads to designs with thin walls and less residual stresses. This reduces the occurrence of cracks in parts after the SLM process or after subsequent heat treatments.

4. Materials

High temperature alloys such as Ni-based alloys are used for the hot gas path components of gas turbines or jet engines. Many Ni-based alloys, such as MarM247 [14] and CM247LC [15, 16], crack under high solidification rates and thus there is a continuous effort to develop improved powders for these alloys. It was shown for example that the powder chemical composition has a strong influence on the hot cracking of IN738LC [17]. So far, several nickel-based alloys such as Hastelloy X [18] or IN718 [19] have been successfully processed by SLM. It should be added that the chemical composition and the powder manufacturing process affects the porosity of the SLM manufactured parts.

The grain structures of the SLM processed alloys are different from those processed by other manufacturing processes (*e.g.* casting) due to the high solidification rate. The high thermal gradients cause crystals to grow preferentially in well defined directions. As a result, the mechanical properties are different between the build direction and the direction perpendicular to the build direction (mechanical anisotropy). In many cases when a cast material is replaced by the corresponding SLM material, this anisotropy is not desired and it is usually reduced by high temperature heat treatments [20]. Optimising the laser scanning strategy during the SLM process can also reduce the anisotropy [21].

Removal or reduction of the anisotropy stems mainly from the replacement by SLM of existing components manufactured by investment casting, whose lifetime calculations are based on isotropic material properties. In the future, and as the SLM process matures, it may be feasible to apply complex scanning strategies to tailor the texture [22] and thereby the anisotropic mechanical properties spatially during the SLM process. The local optimisation of material properties could result in an increase of the lifetime of SLM-manufactured components.

5. Concluding remarks and Outlook

Selective laser melting has the potential to change the design of the hot gas path components of gas turbines. Novel designs and concepts can be realised, leading to more efficient gas turbines. The differences in the design process and in the production of hot gas path components by SLM compared to conventional manufacturing processes have been highlighted. It was shown that:

- Several parameters, such as building direction, overhanging structures, support structures, self-supporting structures and topology optimisation, have to be considered or used to manufacture high quality components with lower cost. This high degree of flexibility enables the designer to explore the trade-offs in order to find the parameters that best meet the final goal/design.
- The material properties used of SLM-manufactured parts differ from the material properties of the cast counterparts. The main difference is the anisotropic nature of the SLM processed materials. Methods to remove or reduce the anisotropy are available and may also lead to new design optimisation.

Further progress and standardization in materials, process developments and design practices will establish selective laser melting as a manufacturing process for serial production of structural components in gas turbines. Non-destructive methods to efficiently assess the quality and dimensional accuracy of the produced parts are needed to increase the confidence in serial production with SLM.

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