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# Metallurgical aspects involved in Selective Laser Melting

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**Abstract**. Additive manufacturing using Selective Laser Melting (SLM) offers several advantages for industrial applications and has motivated many scientist and industrial R&D colleagues to add more and more innovations. Although the principles are well known, only a small number of materials have found a significant usage, others have shown serious problems during fabrication. In the paper, the influencing process parameters, the interactions of important mechanisms and the microstructural based assessment of laser weldability as well as the appearance of defect formations are considered in detail in order to understand the physical limits and to highlight the peculiarities of the SLM-process. Many problems can be solved using the lessons learned in welding technology. On one side, the high cooling rate and strong undercooling of SLM-process is quite positive to fabricate dissimilar joints and on the other side, residual stresses and distortion may be a challenge.

## 1 Introduction

Additive manufacturing has found a broad interest in the manufacturing community as a disruptive technology. Pros and Cons are now well understood in terms of economy and applicability. However, the fundamental understanding of the most influencing parameters and the microstructural phenomena involved are not so well-known. Based on an assessment of laser weldability, problems and typical failures using different alloying systems are mentioned, which provides good criteria for material selection. Residual stresses and distortion are critical issues for further development of the SLM technology. New alloys and joining of hybrids are seen as a big challenge for the future.

The advantages of the SLM-process comprise: freedom of design, enhanced complexity, direct/ tool-free manufacturing, lightweight potential via topology optimization, reduction of manufacturing steps, increase of functionality and the cons are: low production speed, high manufacturing costs, time-intensive trials for appropriate designs and processing parameters, limited part dimensions and high residual stresses and/or distortion. Further information can be found in the literature [1-7].

## 2 Influencing process parameters

The influencing process parameters can be divided into four groups [8]: a) laser related parameters (power, spot size, pulse duration and pulse frequency), b) powder related parameters (particle size distribution, shape, powder bed density, layer thickness, material properties), c) scan related parameters (scan speed, scan spacing, scan pattern) and d) temperature related parameters (powder bed temperature, powder feed temperature, temperature uniformity). All these parameters have influence on weld thermal cycle (weld pool size, cooling rate, as-welded microstructure), dendrite arm spacing, mechanical properties, residual stresses and distortion as well as on other service properties like corrosion resistance.

In principle, the laser welding process can be analyzed by the consideration of the weld thermal cycle, the microstructural changes in the weld pool area and in the heat affected zone as well as the post-weld heat treatment and their consequences on the mechanical properties.
A characteristic parameter is the heat input, which is defined as the quotient of laser power divided by scan speed multiplied by layer thickness. This parameter is typical for the weld thermal cycle with cooling rates between 10.000 to 100.000 °C/s or a cooling time $t_{8/5}$ of some microseconds. This leads to a strong undercooling (very high temperature gradient and very high solidification rate) which results in a very fine microstructure in the as-welded state. There is no time for any substantial diffusion process, i.e. there is no segregation effect and a very homogeneous structure distribution with excellent mechanical properties.
An excellent overview of the main characteristic phenomena involved and their influencing parameters, interactions and resulting effects is shown in figure 1 taken from ref [9].

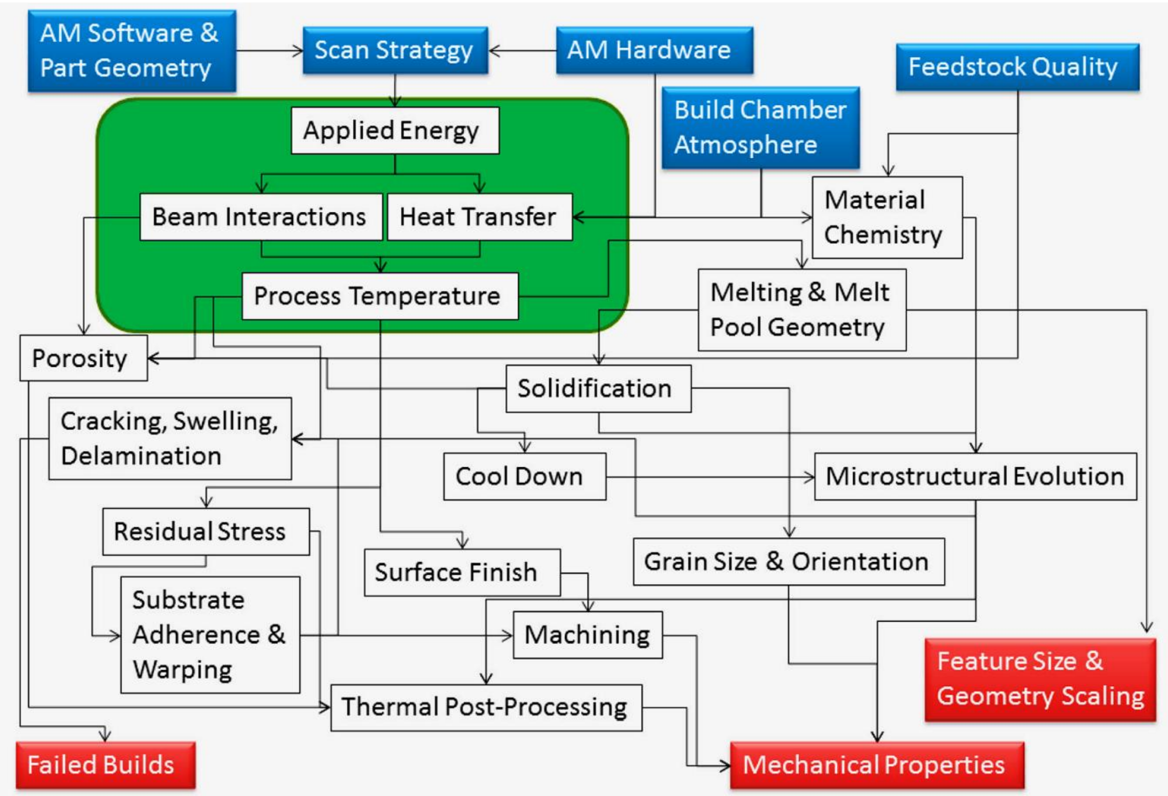



**Figure 1**. Processing map for selective laser melting [9].

Optimized SLM-parameters are found by trial and error by variation of laser power and scan speed. In cases of very high heat input, there will be large distortion. Low laser power and high speed will result in higher porosity or even insufficient fusion.

## 3 SLM printability or SLM-weldability

At the moment only a few metal powder types are commercially of interest. They cover the most important application areas. Typical examples are: Maraging steels, stainless steels incl. PH-steels, nickel-base alloys, Ti-alloys, CoCr-alloys and AlSi-alloys. The main question arises, why some alloys show a better processing performance than others?

From a metallurgical point of view the following main problems or defects can be found:

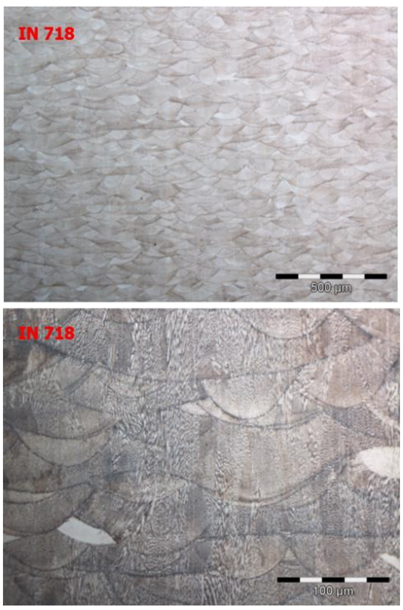
- Crack formation (i.e. cold cracking) for steels with high C-content

- Hot cracking
- Lack of fusion
- Distortion and residual stresses
- Metastable formation of brittle phases
- Evaporation effects
- and other more.

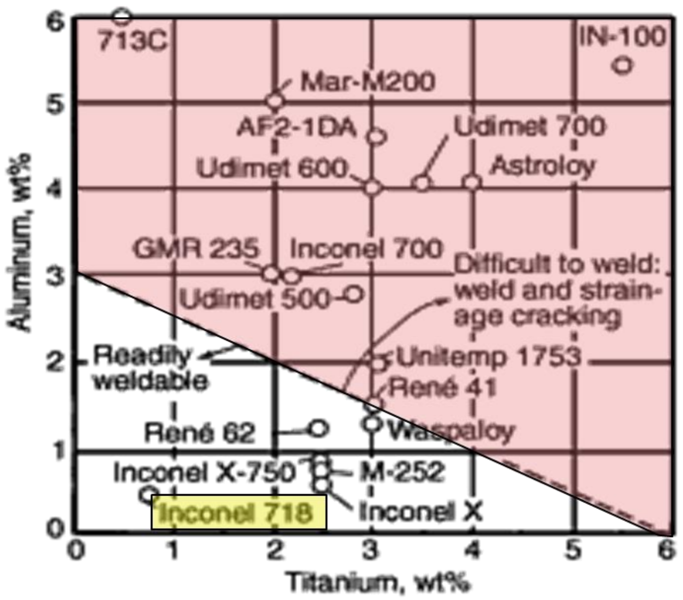
### *3.1 Main factors for weldability of low alloy steels*
The main problem for this kind of materials is based on the rapid cooling of the weld pool, which leads to 100% martensitic microstructure when the carbon content is higher than about 0,1%. The most influencing parameters in this case are the carbon equivalent, the cooling time $t_{8/5}$, the preheating temperature, component thickness and the mechanical constraints. Therefore, only steel grades with a very low C-content can be welded successfully. Maraging steels and stainless steels are good examples for this fact.

### *3.2 Weldability of Al-alloys*
A main factor for the weldability of Al-alloys is the high hydrogen solubility in the melt with a big change of solubility during solidification in the solid state, which leads to very high porosity. A second aspect is the likelihood for hot-cracking mainly caused by a large solidification range. Near eutectic systems like AlSi10Mg are favored because of the low melting temperature and the very fine and homogeneous microstructure with excellent mechanical properties. In addition, using PWHT by tempering at about 180°C can also increase the strength value.

### 3.*3 Weldability of nickel-base alloys*
The main factor for a good weldability of Ni-base alloys is the sum of Al- and Ti-content, which form the precipitation hardening phase gamma prime. Standard alloy for many cases is Inconel 718, which shows excellent laser weldability. Figure 2 shows a typical microstructure of an IN718 as welded SLM-microstructure and on the left side a processing limit diagram (alloys in the shadowed area are difficult to weld).



a)



b)

**Figure 2.** a) As-welded microstructure of IN718 and b) limits of weldability of Ni-base alloys defined by their Al and Ti-content.

### *3.4 Post weld treatments*

There are many types of PWTs applied after welding. Quite common are heat treatments for stress relieving or to reorganize the microstructure by a full heat treatment. Al-alloys may be tempered directly after the SLM-process to get additional strengthening effects by fine precipitates.

HIP (hot isostatic pressing) treatment is done for high performance components to close the remaining pores and to improve impact and fatigue properties. Surface treatment (mainly by peening or also by electro-chemical processing) is performed to reduce the surface roughness.

### *3.5 Quality control of SLM-processing*

Applications in the areas of medicine or aerospace dictate very tough QC requirements. A direct process control is quite difficult to execute because of the closed working platform with vacuum or shield gas and the thousands of layers and the immense volume of process data. Nevertheless, laser signals and optical sensor data or acoustic emission data are recorded and analyzed by fast numerical methods.

After SLM-fabrication, the components can also be tested by conventional NDT-methods or by computer tomography. Further information on this important issue are given in [10-12].

### *3.6 Residual stresses and distortion*

A very severe problem for SLM-use is given by the formation of high residual stresses in case of rigid construction or high distortion in case of flexible or thin designs. Heat transfer and the development of high thermal strains are responsible for high stresses during the building process, which can also lead to cracking during the welding process. These delamination cracks are visible to the naked eye and may also lead to interruptions of the process, because of a collision with the doctor blade.

The main influencing factors for the stress development are the temperature gradient, the volumetric change, the heat input per unit length, the Fourier number, the rigidity of the component and the deposition time. An analytical expression for the thermal strain was defined by Mukherjee et.al. [13].

The complexity of this issue requires very sophisticated numerical FE-models. The authors use two software systems, i.e. Amphyon (Additive Works, Bremen) and simufact additive (simufact, Hamburg). An example of the stress development during the SLM-process and removal from the building platform is shown in figure 3.

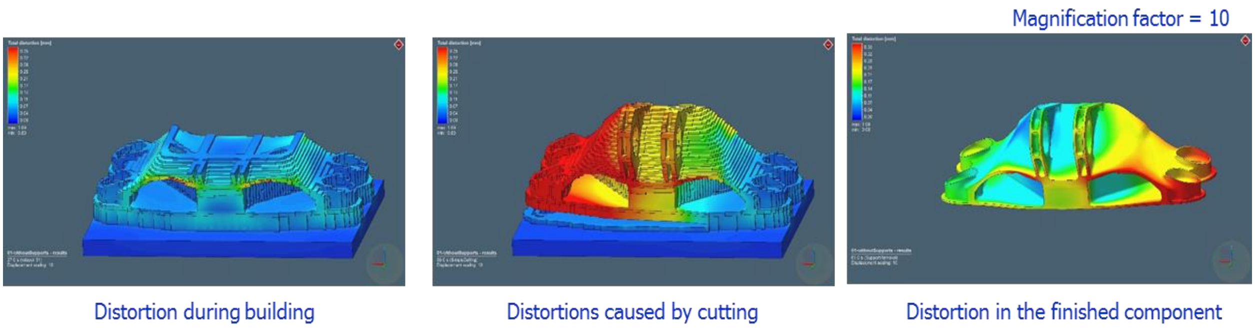



**Figure 3.** FEM prediction of residual stresses and distortion during building of a bracket (software used: simufact additive).

## 4 About the role of metal powders on the quality of SLM-products

Metal powders for the SLM-process are usually gas-atomized to achieve spherical particles with a good flow-performance. Beside the aforementioned process- and materials-related aspects, the powder quality and proper size distribution are quite essential for the properties of the final product. Based on a recent study, the authors have found quite significant differences in the powder characteristics and the consequent component behavior. Some of the important parameters have been considered in the standard VDI 3405, which provides hints for the characterization and testing of metallic powders for additive manufacturing.

Beside chemical composition, particle size distribution, flowability testing, density, humidity and absorption rate are considered in detail. Using laser diffraction analysis, a complete size distribution curve as shown in figure 4 can be measured in a short time.

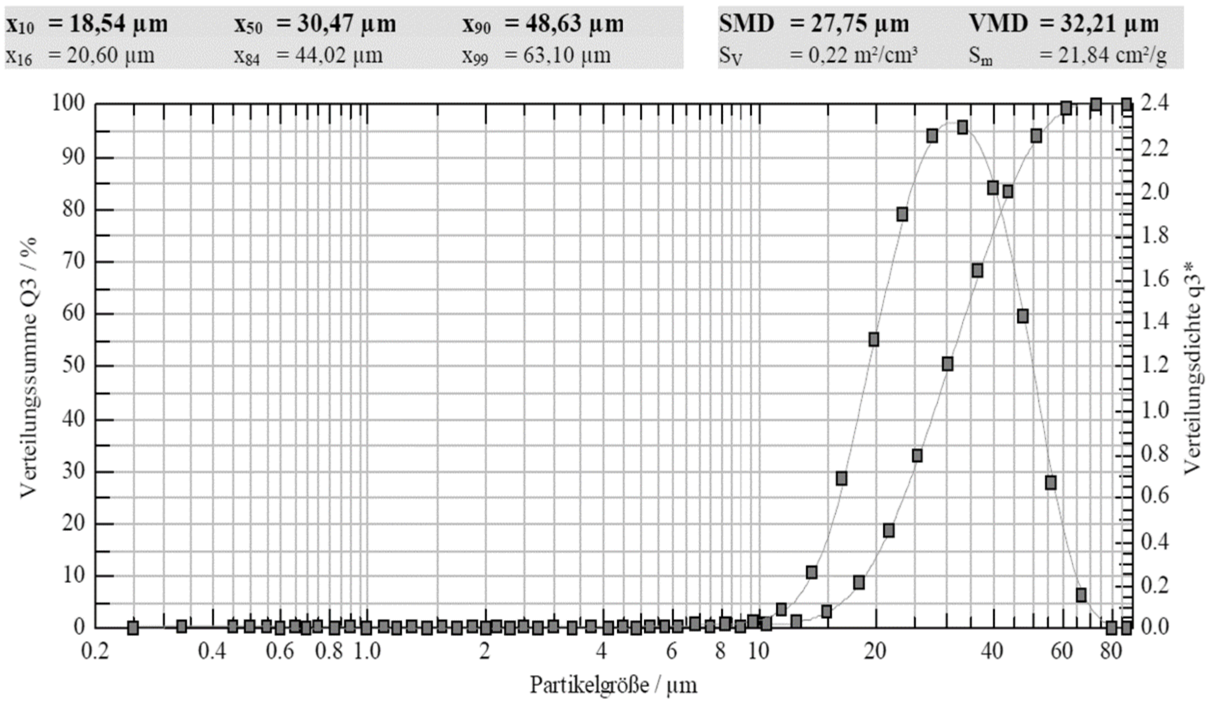



**Figure 4.** Measured particle size distribution of HX-alloy using a HELOS-system.

In general, small size distributions show a better flowability, a higher accuracy of geometrical reproduction and a less surface roughness. However, the productivity is less and the oxygen absorption is higher compared with powders showing a broader distribution. Coarse particles lead to higher porosity and as a consequence to lower strength values [14].

## 5 Conclusions

The final properties of products made by selective laser melting depend very strongly on the processing conditions/parameters, on the weldability of the considered alloys and on the properties/ characteristics of the metallic powders. Many fundamental aspects can be taken from former findings of weldability of various alloys, which need only be modified according to the special conditions of the SLM-process. The guideline VDI 3405 Bl.2.3 provides a first step for a better and unified characterization of metallic powders. Same alloys produced on different machines or same alloys with powders from different suppliers may result in significant processing performance and final product properties.

## Acknowledgements

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