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# Single crystal microstructure built by Selective Laser Melting (SLM®)

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**Abstract**

Among metal additive manufacturing technologies, Selective Laser Melting (SLM®†) is a highly developed and widely used processing method. Products of arbitrary shape can be built directly from CAD data. In recent years, many groups have worked on development of processing strategies, mainly aiming at high density, decrease of defect size and smooth surfaces. Until today little has been done on design of microstructures in the products. By applying suitable processing parameters and laser sources, microstructure can be directly tailored. This work reports single crystal microstructure in INCONEL®‡ 718 specimens produced with a selective laser melting machine. The Machine was re-constructed and a laser with internal developed laser beam profile is equipped. Processing strategies and parameters were developed to obtain the single crystal microstructure in the built parts. Based on the results shown, SLM Solutions created methods to build or repair components with single crystal microstructure with SLM technology, which can be utilized for example in the aircraft engine industry.

Keywords: Selective laser melting, Single crystal, INCONEL 718, Microstructure;

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† SLM is the registered trademark of SLM Solutions Group AG
‡ INCONEL is the registered trademark of Huntington Alloys Corporation

## 1. Introduction

Selective laser melting is a powder bed based additive manufacturing technology. One or more lasers are employed as power source to melt the metal powder within selected regions. Different laser sources with varied beam profiles strongly affect final microstructure of built components. In the work of Niendorf *et al.*, both fine polycrystalline structure and large columnar grains were built with selective laser melting from stainless steel 316L [1].

In aircraft engine industry, some of the turbine blades serve under extreme conditions such as high stress at very high temperature [2]. For those parts, highly anisotropic microstructure is preferred, especially the single crystal microstructure, eliminating (high angle) grain boundaries in the part. The conventional method used to produce single crystal parts is investment casting employing special furnaces, e.g. a Bridgman furnace [2]. Recently, first studies reporting on single crystal microstructure built by additive manufacturing methods have been published. Ramsperger *et al*. reported single crystal microstructure built by Selective electron beam melting process. Samples with single crystal core featuring a diameter of about 8 mm were manufactured. Within the volume built small angle grain boundaries with maximum tolerance angles of up to 10° were present [4].

In our current work, INCONEL 718 powder was processed by selective laser melting technology. An in-house developed laser beam profile is used. Processing parameters including laser power, scanning speed *etc*. were optimized, targeting on obtaining not only dense parts, but also parts with single crystal microstructure. The samples built were thoroughly characterized by optical and scanning electron microscopy including electron backscatter diffraction.

## 2. Experiment

INCONEL 718 is a Ni-based superalloy precipitation strengthened mainly by $\gamma''$ phase (Ni3Nb), i.e. a nano-scaled secondary phase [7]. It has been widely used and studied in the additive manufacturing industry due to its good weldability and balanced mechanical properties at elevated temperature up to about 650 °C [5]. [6]. In order to process the INCONEL 718 with the SLM machine, gas atomized INCONEL 718 powder was provided as raw material. The powder particles processed are spherical, and particle diameters mainly distributed in the range of 10-45 µm. The nominal chemical composition (wt.-%) of INCONEL 718 are 19.0% Cr, 3.0% Mo, 5.1% Nb, 0.5% Al, 0.9% Ti, 18.5% Fe, 0.04% C and balance Ni [2]. In application, INCONEL 718 is not used in single crystal condition due to the limited thermal stability of the strengthening $\gamma''$ phase. However, in our current study it was chosen as a model material because of its good processability. Crack free samples can be robustly produced in a wide range of processing parameters with density higher than 99.5%. Thus, the process-microstructure relationships of the SLM built samples could be better analyzed without the detrimental influence of cracks, which have been numerously observed in Ni-based superalloys for application at temperatures above 1000 °C [8]. [9].

The machine used in this experiment is a SLM 280$^{HL}$ system produced by SLM Solutions Group AG. The machine was originally equipped with a laser with Gaussian laser profile (laser 1). Several modifications have been done so that an extra internal developed laser beam profile is available (Laser 2). The hull area of the sample was scanned by laser 1, whereas the core of the sample was scanned by laser 2. During the building process, the whole building chamber was flooded with Ar. The oxygen content in the chamber was controlled under 0.1 % in order to avoid oxidation of elements during processing.

The sample geometry was designed as a cuboid of 17 mm*17 mm*30 mm (Width*Depth*Height) edge lengths. After cutting off the samples from the substrate, they were cut in the middle alongside the building direction. The surfaces were then ground and polished. To reveal microstructure details by light microscopy, the surfaces were etched using Adler etchant for only a few seconds.

To further investigate the microstructure of the samples, a scanning electron microscope (SEM) was used. Backscatter electron (BSE) images were obtained in the core region of the sample. Electron backscatter diffraction (EBSD) maps were recorded to reveal grain structure and local texture of the vibro-polished sample. Due to the relatively large size of the sample, 12 EBSD maps were recorded and stitched to resolve microstructure of a full cross-section.

## 3. Results and discussion

By application of optimized processing parameters, samples with density higher than 99.5% were built. The samples were directly etched after cutting and polishing to reveal microstructure details inside the sample. Microstructure of the sample cross section is shown in Fig. 1(a).

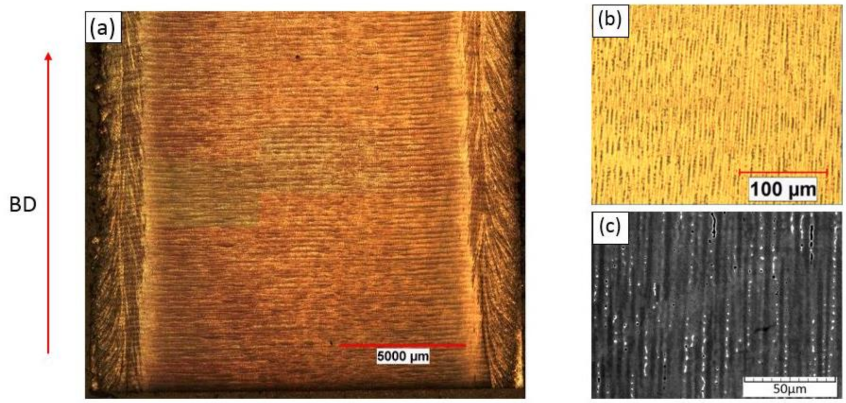


Fig. 1. (a) Overview image depicting the cross section of a SLM as-built sample obtained by optical microscopy, building direction (BD) is shown on the left; (b) dendrite structure in the core region, (c) BSE image of the core region.

The hull and core structure is clearly revealed in Fig. 1(a). In the hull region of the sample, fine columnar grain structure was obtained, whereas in the core region, no grain boundaries can be identified. Fig. 1(b) shows the dendritic microstructure in the core region. All the dendrites are parallel to the building direction. Fig. 1(c) is a BSE image taken within the core region of the sample. It is in agreement with the fine dendritic microstructure shown in Fig. 1(b). In this image, the interdendritic region shows brighter color. From this, it can be deduced that elements with larger atomic number segregate in between the dendrites. In the case of INCONEL 718, the interdendritic region is enriched in Nb and Mo [9].

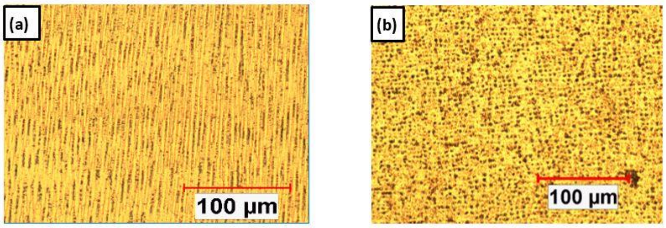


Fig. 2 Dendritic microstructure of SLM as-built sample observed in directions of (a) alongside and (b) perpendicular to the building direction

Fig. 2 shows the dendritic microstructure of the SLM sample. Due to the high cooling rate, the dendrites in the SLM sample are much finer compare to the conventional single crystal cast in a Bridgman furnace. According to Fig. 2(a), the primary dendrite arm spacing (PDAS) can be calculated. The SLM sample (within the core processed by the laser 2) is characterized by a PDAS of 6.3±0.5 µm whereas the PDAS of casted single crystal is in the range of 100µm to 400µm. For any kind of post-processing treatment, the finer dendrites will lead to shorter diffusion distances for elements and, thus, will enable significant reduction of time and cost for the solution heat treatment for parts processed by SLM.

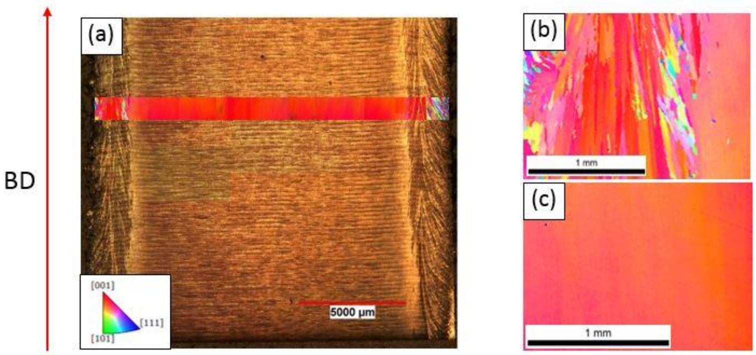


Fig. 3 (a) Merged IPF map superimposed to the optical micrograph (cf. Fig. 3 (a)) highlighting grain orientation with respect to building direction; (b) magnified IPF map for the hull region; (c) magnified IPF map for the middle of the core region. In order to clearly reveal that the core region of the SLM sample is free of high-angle grain boundaries 12 EBSD maps have been recorded and stitched (Fig. 3). Furthermore, from EBSD analyses local texture and orientation deviations within hull and core sections are obtained,Fig. 3(b) and (c). A cross section about 12mm above the single crystal substrate has been analyzed (cf. optical micrograph in Fig. 3 (a)).

It can be clearly seen in Fig. 3(b) that relatively fine columnar grain structure evolved within the hull region. The same kind of structure can be seen in the entire hull regions of the optical micrograph. In the core region, no grain boundaries with misorientation angles higher than 5° could be found. Thus, this region can be defined as single crystal region.

As mentioned above, the hull region was built with laser 1 with Gaussian laser profile. The fine columnar grain structure built by such kind of laser has been reported by many researchers[8]. [9]. [11]. But the single crystal microstructure shown in the core region has never been reported. This clearly reveals that laser source and scanning parameters are by far dominating aspects for building the single crystal microstructure.

## 4. Conclusions

In this work, the INCONEL 718 superalloy was processed by SLM 280$^{HL}$ machine. Hull and core scanning strategy was applied to build the sample. With the help of EBSD analyses, fine columnar grains were observed in the hull region. In the core, which was built by the laser with modified beam profile, the single crystal microstructure was shown. No grain boundary with a misorientations of larger than 5° was observed. This work highlights the possibility of repairing or even building single crystal parts with the selective laser melting process.

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