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Correlation of the High Power SLM Process with Resulting Material Properties for IN718

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Abstract: For SLM to become suitable for series production, its productivity and, thereby, process speed have to be increased. One possibility to achieve this is by increasing laser power and adapting the process parameters (beam diameter, laser power, scanning velocity, and more) accordingly (High Power SLM). This adaption of the process parameters, however, leads to a significant change in the cooling and solidification conditions in the melt pool: The microstructure and the resulting mechanical properties are significantly changed. For this reason, it is necessary to investigate the influence of the HP-SLM process on the resulting material properties. The results show the investigation of a process window with up to 2kW laser power for the nickel-based alloy IN718, which is a material frequently used for high temperature applications in the turbomachinery branch. Here, the extent to which different process parameters influence the achievable productivity is analysed. Afterwards, the microstructure (grain size and orientation) and the mechanical properties (tensile tests) are examined for selected process windows. In the end, a correlation between process parameters, microstructure, and mechanical properties is conducted.

Keywords: Selective Laser Melting (SLM), High Power Selective Laser Melting (HP-SLM), Productivity, Process efficiency, Inconel 718 (IN718), Theoretical build-up rate, Material properties IN718

Korrelation der High Power SLM-Prozessführung mit den resultierenden Materialeigenschaften für den Werkstoff IN718

Zusammenfassung: Der Einsatz der SLM-Technologie in der Serienfertigung bedingt eine Steigerung der Produktivität und damit einhergehend eine Beschleunigung der Prozessgeschwindigkeit. Eine Möglichkeit, dieses Ziel zu erreichen, ist der Einsatz gesteigerter Laserleistungen und die Anpassung der Verfahrensparameter (Laserstrahldurchmesser, Laserleistung, Scangeschwindigkeit und mehr). Dadurch wird eine Veränderung der Erstarrungsbedingungen im Schmelzbad erreicht, was sich wiederum auf die entstehende Mikrostruktur und das Gefüge auswirkt. Aus diesem Grund ist es notwendig, den Einfluss der HP-SLM Prozessführung auf die resultierenden Materialeigenschaften grundlegend zu untersuchen. Die vorgestellten Ergebnisse beinhalten die Entwicklung einer SLM-Prozessführung mit Laserleistungen von bis zu $P_L \leq 2kW$ für den im Turbomaschinebau sehr häufig verwendeten Werkstoff IN718. Außerdem wird der Einfluss der angepassten Verfahrensparameter auf die Produktivität (Theoretische Aufbaurate) untersucht. Auf der Grundlage der Untersuchungen der Mikrostruktur und des Gefüges (Korngröße und -orientierung) wird eine Korrelation zwischen HP-SLM Prozessführung, Mikrostruktur und Gefüge und mechanischen Kennwerten erarbeitet.

Schlüsselwörter: Laserstrahlschmelzen, Selective Laser Melting (SLM), High Power Selective Laser Melting (HP-SLM), Produktivität, Prozesseffizienz, Inconel 718 (IN718), Theoretische Aufbaurate, Materialeigenschaften IN718

1. Introduction

During the last few years, the additive manufacturing technology Selective Laser Melting (SLM), developed at Fraunhofer ILT, has evolved from a manufacturing technology for prototypes and small batches into a production technology for functional parts [1]. The metal AM sector and especially the powder metal-based AM technology SLM have grown in size significantly, which can be seen in the considerable increase from approx. 202 metal AM systems sold to industry and research entities in 2012 to 808 in 2015 [2].

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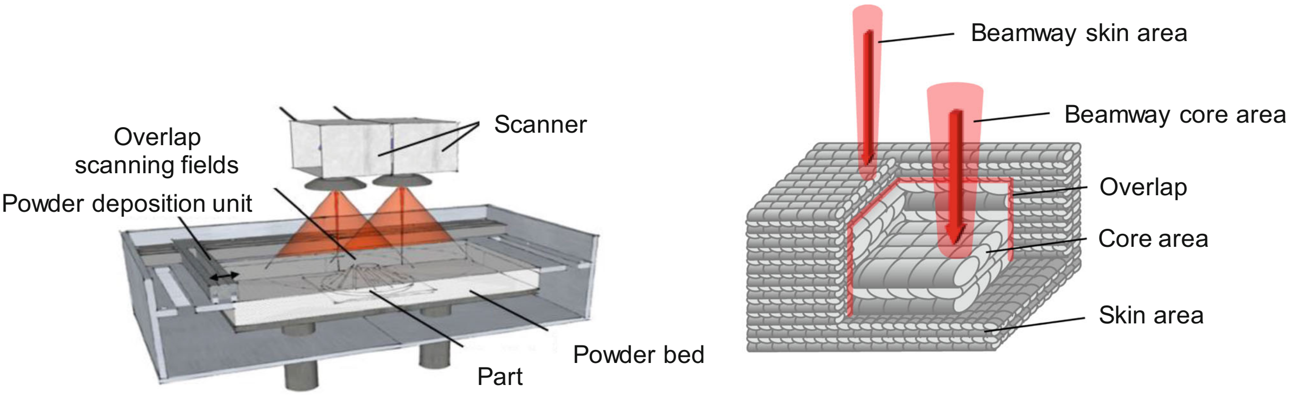

Fig. 1: Principles to increase the theoretical build-up rate of the SLM process (Right: Parallelization | Left: High Power SLM with skin-core strategy)

TABLE 1
Overview parameters and mechanical properties for SLM of IN718 [12–14]

Laser power P_L [W]	Layer thickness D_s [µm]	Th. Build-up-rate [mm^3/s]	Volume energy [J/mm^3]	Beam diameter d_s [µm]	Tensile strength R_m [N/mm^2]	Breaking elongation A [%]
200-400	20-30	3-4	75-80	approx. 100	1120-1148 (after SLM)	19-26 (after SLM)
					1280-1358 (with HT)	10-22 (with HT)

In particular, the turbomachinery branch can make good use of the geometrical freedom the SLM technology offers, which is based on layer-by-layer production to produce parts with additional integrated functions, lower weight, or monolithic design. [3–5].

Additionally, increasing productivity is one of the most important ways to enable SLM technology to reach series production with higher lot sizes. According to the current state of the art, there are two principles commonly applied in commercial SLM machines that can increase the theoretical build-up rate for the SLM process [6].

The first principle, called "Parallelisation", uses up to four fibre-laser sources in parallel within the SLM process. When this principle is applied, the theoretical build-up rate can be increased linearly by the number of laser sources used (Figure 1 left). The second principle to increase the theoretical build-up rate, called High-Power SLM, uses increased laser power ($P_L \leq 1$ kW) and adapts the following process parameters accordingly: laser beam diameter d_s, hatch distance Δy_s, layer thickness D_s, and scanning velocity v_{scan} (Figure 1 right). Increasing the laser power and keeping the beam diameter stable increases the intensity in the interaction zone between powder material and laser. Here a stable and reproducible process is not possible. In order to prevent these effects, the beam diameter must be increased to decrease the intensity in the interaction zone [7, 8].

The increased beam diameter, however, impairs both the surface roughness and detail resolution. To rectify this, the skin-core strategy can be employed, whereby two different laser beam diameters are used, one for the skin and one for the core of a component [9].

An increased beam diameter can be used to lower especially the scanning velocity, which results in a significant change of the cooling and solidification behaviour in the SLM process. This behaviour directly influences the component's microstructure and the mechanical properties.

2. State of the Art

To date, there is a limited number of research activities exploring the use of higher laser power to increase the theoretical build-up rate, which is calculated as the product of hatch distance Δy_s, layer thickness D_s, and scanning velocity v_{scan} [16].

Initial investigations dealing with the use of increased laser power for SLM were carried out by Schleifenbaum [1]. In his work, a laboratory system with an integrated 1kW laser source was designed and built. Based on this laboratory machine, Schleifenbaum developed the process for the austenitic steel 1.4404 (X2CrNiMo17-12-2) and the hot-working steel 1.2343 (X37CrMoV5-1). It could be observed that, when the beam diameter ($d_s \approx 1100$µm) was increased and the process parameters were adapted, the theoretical build-up rate could be increased by up to $V_{th}=21mm^3/s$ to manufacture test samples with an average density > 99% [9].

Further research in the field of HP-SLM was done by Buchbinder, who investigated the influence of increased laser power by up to $P_L \leq 1kW$ on the material properties of the aluminium casting alloy AlSi10Mg [10]. The results show that $P_L=1kW$ laser power can significantly increase the theoretical build-up rate ($V_{th}=20mm^3/s$) without needing to increase the beam diameter ($d_s \approx 200$µm) [11].

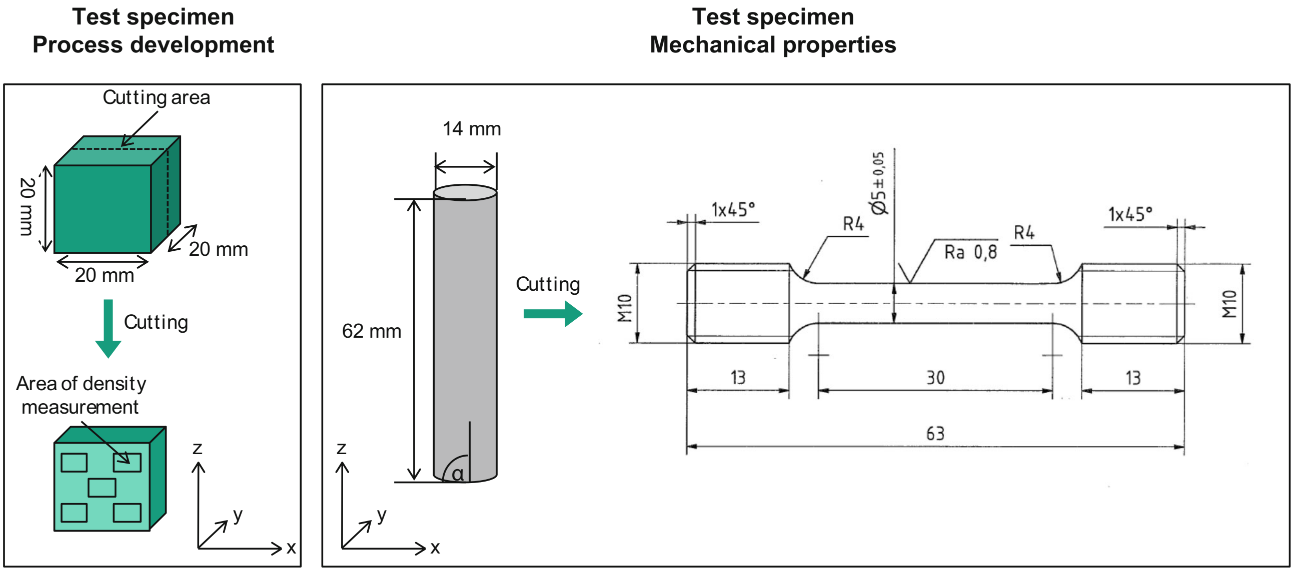

Fig. 2: Dimension and shape of test samples used for process development and testing of mechanical properties

A number of investigations deal with the process development for the nickel-based alloy IN718 and with the resulting material properties [12–14]. Amato et al. examined the influence of different heat treatment strategies on the microstructure and the mechanical properties at static load for IN718 processed with a maximum laser power of $P_L \leq 400W$. The investigations show that the test specimens have columnar grains with preferred orientation in the build-up direction. These results can also be observed from the other investigations carried out by Wang et al. and Jia et al. [13, 14]. During solidification in the SLM process, the heat flow is directed from the interaction zone between powder and laser to the substrate (parallel to the build-up direction), which can explain these results.

The mechanical properties in these investigations were determined with tensile tests according to different heat treatment strategies. The heat treatment strategies differ in the temperature and time cycles as well as in the number of annealing steps. For selected test specimens, a hot isostatic pressing (HIP) was done before solution annealing. An overview about the mechanical properties with regard to the process parameters for IN718 manufactured by SLM with laser power $P_L \leq 400$ is given in Table 1 [12–14].

The analyses show that currently there are no investigations for processing IN718 with increased laser power and adapted process parameters with respect to achievable theoretical build-up rate. In addition, no investigations exist which examine how increased laser power and adapted process parameters influence the resulting material properties.

3. Methodology

The investigations were conducted using the SLM machine SLM280HL (SLM Solutions). The machine is equipped with two laser sources, a single-mode fibre laser with a maximum laser power $P_L \leq 400W$ (beamway 1) and a multimode fibre laser with a maximum laser power $P_L \leq 2kW$. The beam diameter for beamway 1 is d_{s1} = 80µm and d_{s2}=730µm for beamway 2. The machine allows the active fibre to be changed during the process by using a beam-switching unit [15].

The density of the test samples (20x20x20mm^3) was measured by light microscopy. The average density of the test cubes has to be ≥99.5%, a limiting condition for parts manufactured with SLM. For each test sample, five density measurements were made and the values averaged (see Figure 2). Additionally, the standard deviation has been calculated.

In order for the process windows to be be evaluated, the theoretical build-up rate and the volume energy are calculated. The theoretical build-up rate is an estimation of the manufactured volume per time by the use of the values independent of a machine: scanning velocity, hatch distance, and layer thickness, as seen in Equation 1. The theoretical build-up rate V_{th} can be used as a reference value of the productivity of the SLM process.

$$V_{th} = v_{csan} \cdot \Delta y_s \cdot D_s \left[mm^3/s\right] \quad (1)$$

$$E_V = P_L / \left(v_{csan} \cdot \Delta y_s \cdot D_s\right) \left[J/mm^3\right] \quad (2)$$

In order to quantify the efficiency of the SLM process, one uses the volume energy, calculated by the product of employed laser power and theoretical build-up rate (Equation 2). This value describes how efficient the laser power used is transferred into an increased theoretical build-up rate.

4. Results

4.1 Process Development

For the development of a HP-SLM process window, beamway 2 with a beam diameter $d_s \approx 730µm$ and increased laser

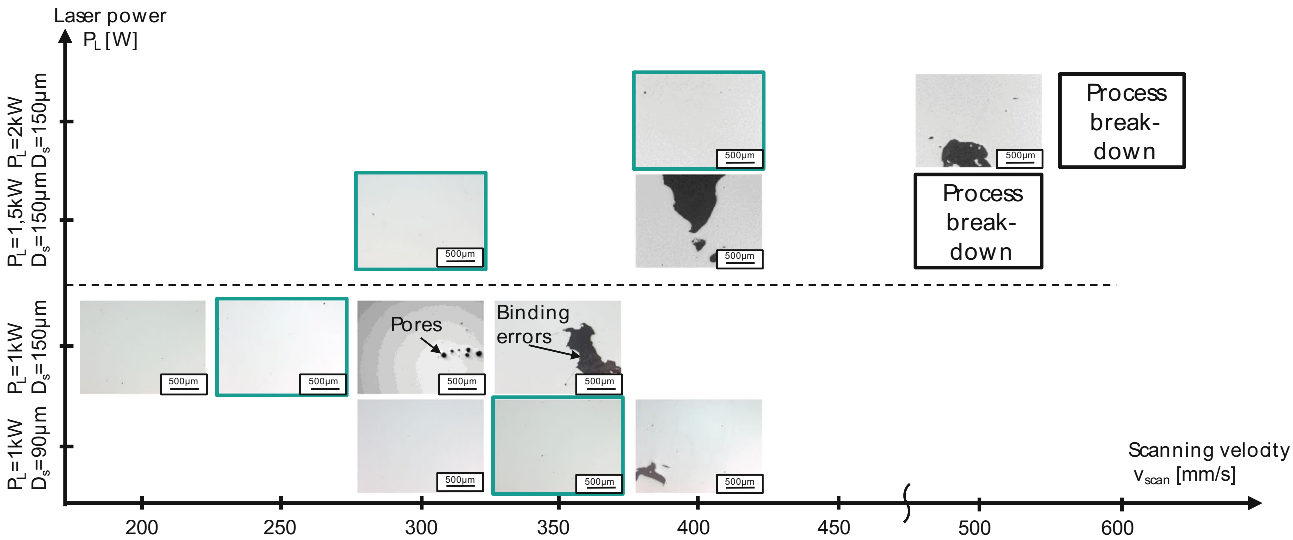

Fig. 3: Cross-sections of test cubes manufactured by HP-SLM according to scanning velocity (beamway 2 | Ds=90+150µm | PL=1-2kW)

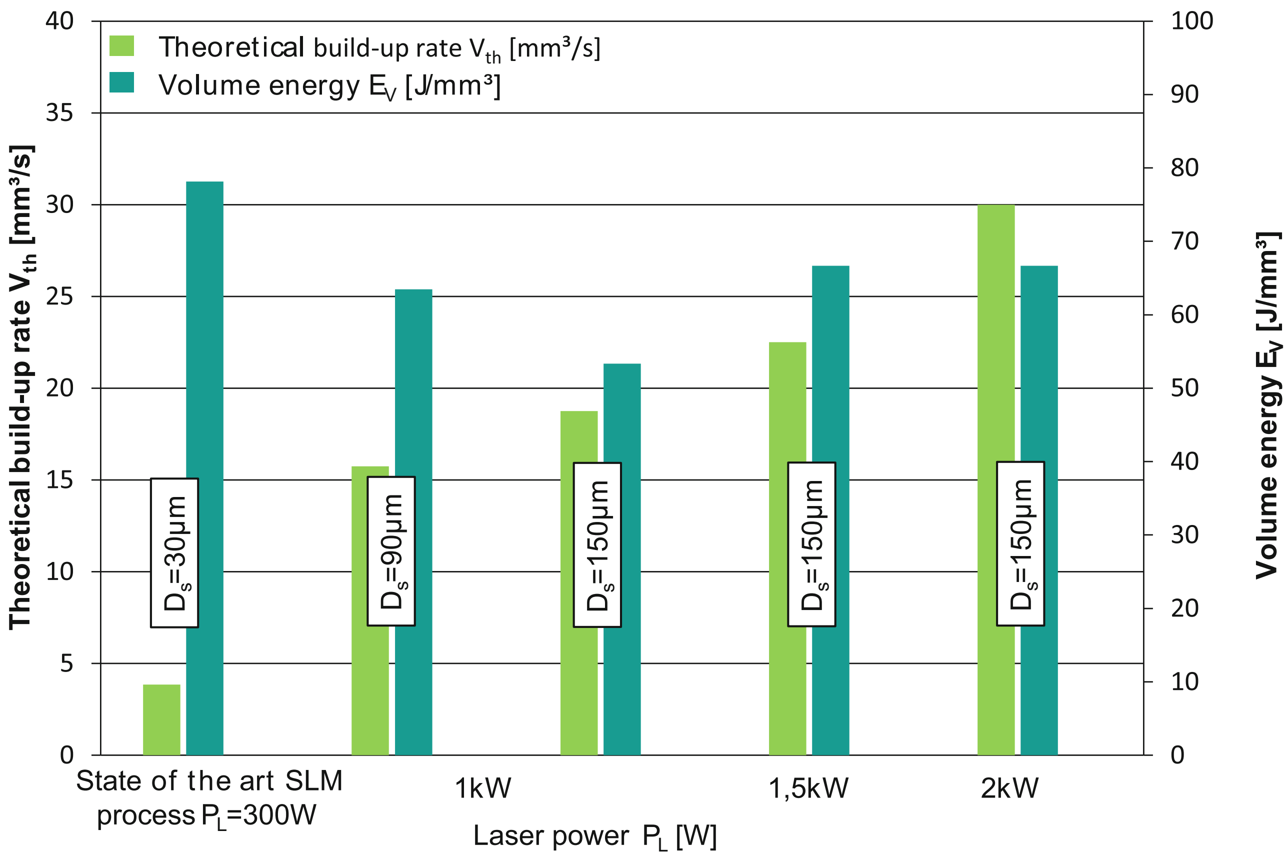

Fig. 4: Theoretical build-up rate and volume energy for state of the art and HP-SLM process

power ($P_L \leq 2$kW) was employed to manufacture test samples as seen in Figure 2. For a laser power of P_L=1 kW, cubic test cubes with a density ≥99.5% can be produced with a layer thickness of D_s=90µm (v_{scan}=350mm/s) and D_s=150µm (v_{scan}=250mm/s) (see Figure 3). The theoretical build-up rate can be calculated to V_{th}=15.75mm^3/s (D_s=90µm) and V_{th}=18.75mm^3/s, which is a significant increase compared to the theoretical build-up rate achieved for the conventional SLM process V_{Th}=3-4mm^3/s (see Table 1).

When the volume energy for the two process windows is taken into account, an increase of the layer thickness and a reduction of the scanning velocity leads to an increased

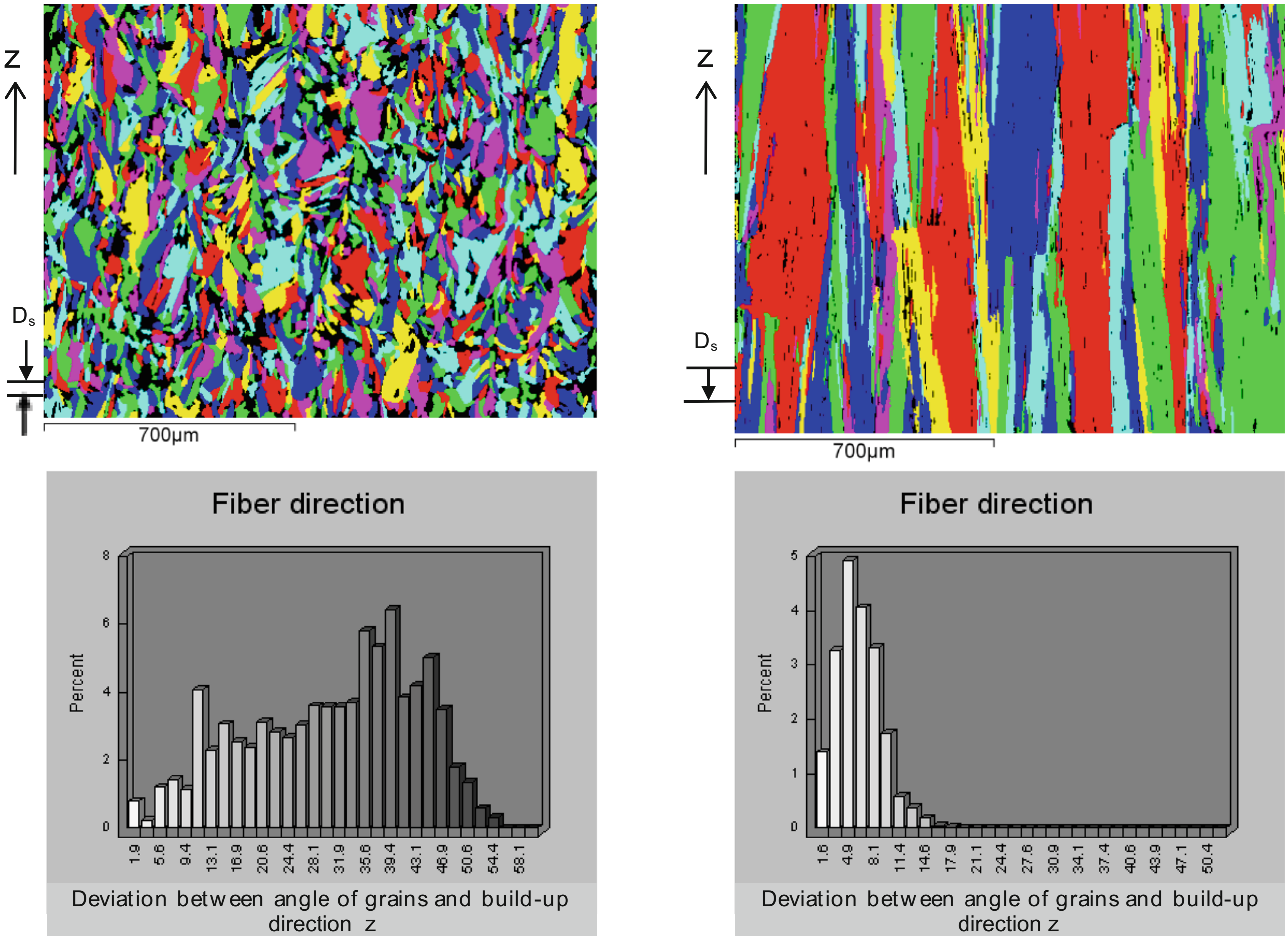

Fig. 5: Results of the EBSD analysis for state-of-the art SLM process (P_L=300W) and HP-SLM process (P_L=1kW| D_s=90µm|v_{scan}=350mm/s)

theoretical build-up rate, and a lower volume energy is needed ($E_{V,Ds=90\mu m}$=63,5J/mm^3 | $E_{V,Ds=150\mu m}$=53.3J/mm^3).

Subsequently, the laser power was increased up to P_L=1.5kW and P_L=2kW, and the layer thickness was constant at D_s=150µm. The results show that, when the laser power is increased, the scanning velocity can be increased by up to v_{scan}=300mm/s (P_L=1.5kW) and v_{scan}=400mm/s (P_L=2kW), which, in turn, leads to theoretical build-up rates of V_{th}=22.5mm^3/s and V_{th}=30mm^3/s (see Figure 4). The volume energy is calculated to E_v= 66.7J/mm^3 for a laser power of P_L=1.5kW and P_L=2kW. In comparison to P_L=1kW at D_s=150µm, the theoretical build-up rate can be increased, but the volume energy decreases, which means that the increased laser power cannot be transferred proportionally into an increased theoretical build-up rate.

These results could be explained by the appearance of spatters from the increased laser power. Due to the increased beam diameter and the reduced scanning velocity, the interaction time between laser and powder material is significantly increased, although the intensity for beamway 2 at P_L=1kW ($I_{1kW,\,BW2}$= 2,46 10^3 W/mm^2) is an order of magnitude smaller in comparison to the beamway used according to the state of the art ($I_{300W}\approx$5,4 10^4 W/mm^2). Nevertheless, the number of spatters and the size of spatters increase. These spatters are deposited on the molten layer and have a size between 50 - 200µm. Therefore, these spatters are not completely melted in the following scanning step, thus resulting in bonding errors. Nevertheless, increased laser power and adaption of the process parameters scanning velocity v_{scan} as well as layer thickness D_s can be used to significantly increase the theoretical build-up rate for IN718.

4.2 Microstructure

After process windows for HP-SLM were developed, the microstructure was investigated. Therefore, the grain size, shape, and orientation for the process windows were investigated by EBSD. The results are illustrated in Figure 5. It can be observed that small grains exist with a diameter of d_K= 25µm for the SLM process according to the state of the art. These grains grow over two to ten layers and are elongated in the build-up direction. Most of the grains have an angle of 35 - 40° according to build-up direction. In comparison, for test cubes generated with HP-SLM at P_L=1kW at D_s=90µm, the EBSD shows grains with a diameter of d_K=97µm. The grains grow over the whole height of the test cube and are strictly directed in the build-up direction.

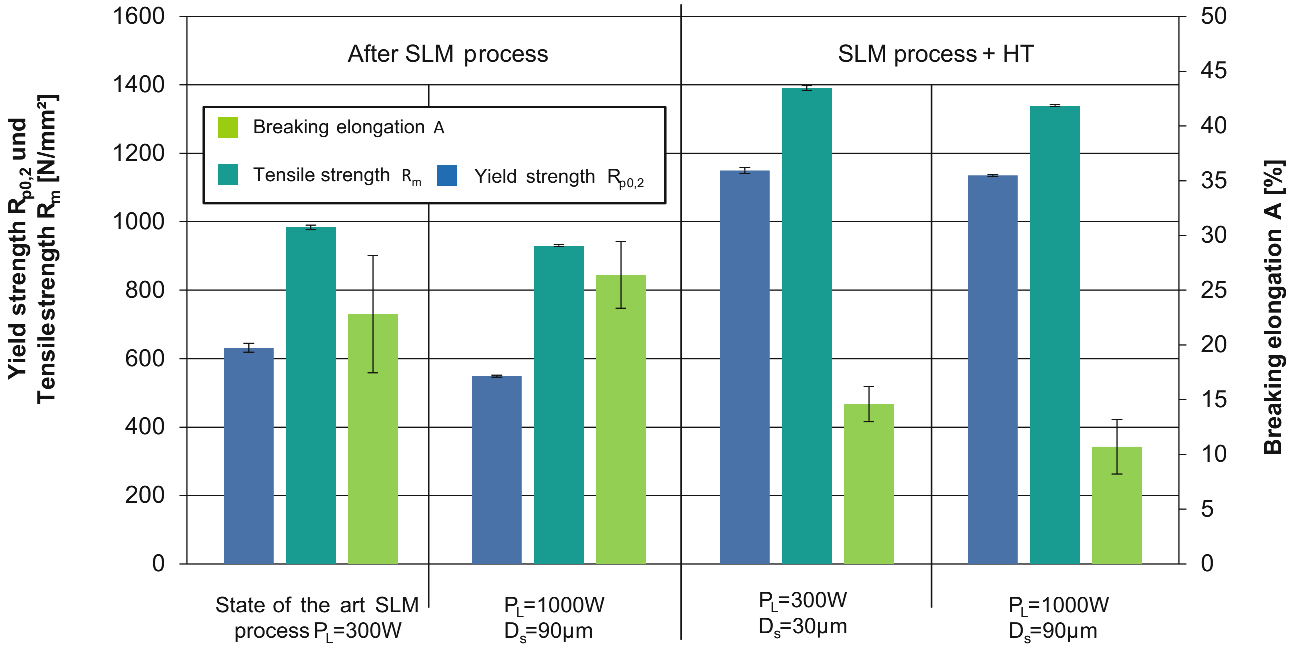

Fig. 6: Mechanical properties for SLM-manufactured test specimens according to employed process parameters and heat treatment

These results can be explained by the cooling and solidification conditions. For SLM according to the state of the art (P_L=300W), the scanning velocity is much higher (v_{scan}=1600mm/s) than with HP-SLM (v_{scan}=300-600mm/s). In addition, the melt pool shape differs significantly between conventional SLM and HP-SLM. Both facts are directly influenced by the cooling and solidification rates, both of which in turn directly influence the refinement and the morphology of the microstructure [11]. In order to prove these assumptions, temperature field calculations for these process windows were necessary.

4.3 Mechanical Properties

After the microstructure was examined, the mechanical properties at static load were investigated for the two process windows (P_L=300W | P_L=1kW, D_s=90µm). Therefore, ten bars per process window with cylindrical shape, as seen in Figure 2, were manufactured with an inclination angle of 90° to the substrate and then cut to final dimensions. Afterwards, one half of the test specimens were heat treated according to AMS 5662 with an additional hipping process before the solution annealing (T=965°C, t=1h, p=2000bar). The results for the tensile tests are shown in Figure 6.

The mechanical properties for process window 1 after SLM process (P_L=300W) show a tensile strength of R_m= 983N/mm² and a yield strength $R_{p0.2}$=632N/mm² with a breaking elongation of A=22.8%. In contrast, the mechanical properties for HP-SLM (P_L=1kW, D_s=90µm) show slightly reduced tensile strength of R_m= 930N/mm² and yield strength $R_{p0.2}$=549N/mm². But the breaking elongation (A=26.4%) is higher in comparison to conventional SLM (A=22.8%).

After heat treatment, the tensile strength and yield strength had increased and the breaking elongation was lower. For conventional SLM a tensile strength of R_m= 1391N/mm², a yield strength of $R_{p0.2}$=1150N/mm² at A=14.9% can be observed. For HP-SLM manufactured tensile specimens (P_L=1kW, D_s=90µm), the tensile strength is in the same range (R_m=1340N/mm²) as well as the yield strength ($R_{p0.2}$=1136N/mm²). Thus, both process windows show values that exceed the requirements for heat-treated and forged IN718 [17]. The requirements demand a tensile strength of R_m=241 - 1275N/mm², a yield strength of $R_{p0.2}$=862N/mm², and a breaking elongation of A=6 - 12%. Only the breaking elongation for the HP-SLM manufactured test specimen does not exceed the requirements but is within the given range between A=6 - 12%.

These results show that the nickel-based alloy IN718 can be manufactured by HP-SLM with increased laser power $P_L \leq$2kW and that the resulting mechanical properties are comparable to conventionally manufactured IN718. Furthermore, for the SLM state of the art process (P_L=300W) the mechanical properties are higher than for conventionally manufactured IN718.

5. Summary and Conclusion

The initial investigations for HP-SLM with laser power $P_L \leq$2kW presented above contain the process development, analysis of the microstructure, and the mechanical properties for the nickel-based alloy IN718. The results prove that the theoretical build-up rate can be significantly increased from V_{th}=3.84mm³/s to V_{th}=30mm³/s by using increased laser power and adapted process parameters, such as scanning velocity and layer thickness.

Furthermore, the volume energy is used to quantify the process efficiency of the SLM process. The results for HP-SLM show that an increase of the layer thickness and a reduction of the scanning velocity decrease process efficiency.

In addition, the grain size, shape, and orientation show significant differences between conventional SLM and HP-SLM.

The mechanical properties according to heat treatment were investigated for conventional SLM and HP-SLM. When HP-SLM is used along with heat treatment, tensile strengths, yield strengths, and breaking elongations can be achieved that fulfill the requirements for conventionally manufactured IN718.

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