LOWERING THERMAL GRADIENTS IN SELECTIVE LASER MELTING BY PRE-HEATING THE BASEPLATE

K. Kempen*, L. Thijs†, B. Vrancken†, S. Buls*, J. Van Humbeeck†, and J.-P. Kruth*

*University of Leuven (KU Leuven) Department of Mechanical Engineering, Celestijnenlaan 300B, 3001
Leuven, Belgium
† University of Leuven (KU Leuven) Department of Metallurgy and Materials Engineering, Kasteelpark
Arenberg 44, 3001 Leuven, Belgium

Abstract

Cracks and delamination, resulting from residual stresses are a barrier in the world of Additive Manufacturing and Selective Laser Melting (SLM) that prohibits the use of many metals in this field. By pre-heating the baseplate, thermal gradients are lowered and stresses can be reduced. In this work, some initial tests were performed with M2 Tool Steel. Results show that pre-heating enables the production of dense M2 parts. The influence of pre-heating on density and mechanical and physical properties is investigated. The paper shows many promising results for the production of SLM parts in materials that are very sensitive to crack formation and delamination. When using a pre-heating of 200°C, crackles parts were produced with a relative density of 99.8%.

Introduction

Selective Laser Melting (SLM) is a Laser Additive Manufacturing technique in which a 3 dimensional product is built up in a layer-by-layer manner. Thin layers of powder are selectively irradiated by a scanning laser source. Due to the high laser energy input, the metal powder melts and consecutively consolidates upon cooling. By repeating these steps for subsequent layers, a 3 dimensional metal part is built up. The layer-wise nature of the process enables the production of complex near-net shape parts with internal cavities [1].

The SLM process can be used to produce moulds or die inserts and other tools with complex geometries. These applications require a material with a high hardness and wear resistance. M2 High Speed Steel (HSS) is a material from the group of tool steels. High speed steels maintain their high hardness, even at high temperatures (e.g. when cutting at high speeds). Due to its high hardness, high wear resistance and relatively high toughness, M2 HSS is an appropriate material for SLM of complex tools. The chemical composition of M2 HSS is displayed in Table 1.

	Fe	C	Mn	Si	Cr	Mo	W	V
wt%	Bal.	0,9	0,38	0,35	3,97	4,89	6,15	1,82

Table 1: Chemical composition of M2 HSS powder

However, the high hardness of this material goes hand in hand with a low ductility. The combination of a brittle material and a production process like SLM, that may induce high residual stresses, can easily cause problems like crack formation and delamination from the baseplate. The material has a linear thermal expansion coefficient of 13.4 µm/°C.

Preliminary tests quickly indicate that SLM of M2 HSS is nearly impossible without making changes to the process or the material. The high carbon content causes severe distortion of the tetragonal martensite crystal structure, leading to a hard martensite. By comparison, 18Ni300 maraging steel relies on the formation of intermetallics to achieve high hardness and has a low carbon content. The martensite that is formed in 18Ni300 maraging steel is relatively soft and no cracking or delamination problems occur during SLM [2].

Experimental

All SLM parts were produced on a Concept Laser M3 Linear machine in a protective Argon or Nitrogen atmosphere. The oxygen level is controlled to < 1%. The machine is equipped with a 100W Nd: YAG laser that has a wavelength of 1.064 µm and a laser beam diameter of 180 µm ($\varnothing_{99\%}$).

Test specimens were scanned in the XY plane: 20 x 20 mm² with a total height of 10 mm. The building direction is aligned with the Z-direction of the part. All test parts were produced with a layer thickness of 30 µm, a laser power of 105W (measured on the powder bed) and a hatch spacing of 128 µm. The range of scan speed is set from 250mm/s up to 550 mm/s. The island scanning strategy, patented by Concept Laser GmbH [3], consists of dividing the total scan area into smaller squares (5 x 5 mm) and scanning these squares in a random manner. Between two successive layers, the scan vectors rotate 90° in every island and the islands are shifted 1mm in both x- and y-direction.

In order to increase the density of the produced parts, re-melting can be applied [4]. This technique involves scanning every layer twice, before adding a new powder layer. In this research, re-melting of every layer was applied with a laser power of 105W, hatch spacing of 105µm and scan speed of 200mm/s.

Gas atomized M2 HSS powder; produced by LPW [5] was used. SEM image in Figure 1 shows that the spherical powder particles with some small satellite particles on the larger fraction. The size of the powder particles ranges from 15 to 45 µm in diameter.

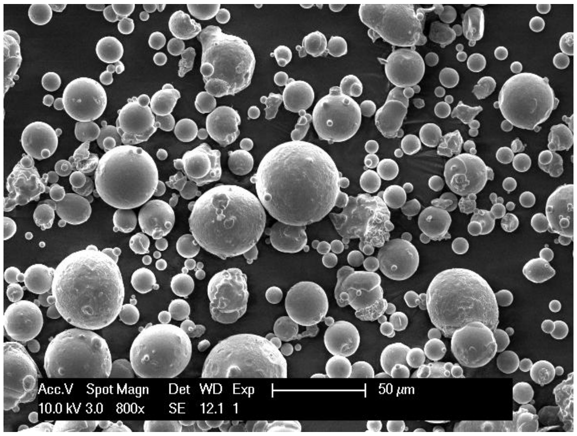

Figure 1: SEM image of M2 HSS powder by LPW

Surface roughness measurements were carried out on a Taylor Hobson Form Talysurf 120L. A probe (diameter 2 µm) scans a data length of 15 mm. Ten lines on the top surface of the part are measured according to the ISO-norm 4288. It states that for the measured surface roughness no cut-off filter can be used. The arithmetic mean surface roughness ($\boldsymbol{R_a}$) is calculated.

The Archimedes principle was used to measure the density. A bulk density of conventional M2 HSS of 8,15 kg/dm³ was used to calculate the relative density of the produced SLM parts.

Surface topology was investigated by a SEM Philips XL40.

The Rockwell hardness of the parts was measured according to the ASTM E 92-65 standard. A 150 kg load was used. Five indentations were measured. The average and a confidence interval of 95% are calculated.

Results & Discussion

1. Problem statement

When producing M2 HSS parts by Selective Laser Melting, high thermal stresses cause the parts to crack or delaminate from the baseplate, as shown in Figure 2. These thermal stresses need to be reduced in order to eliminate this cracking and to produce dense and qualitative parts in M2 HSS by SLM.

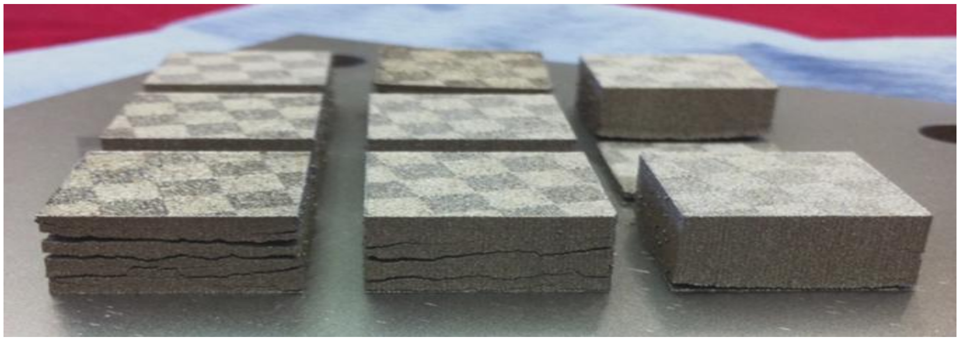

Figure 2: M2 HSS parts produced by SLM, without pre-heating the baseplate

In SLM there are two mechanisms that may induce residual thermal stresses: (i) induced stresses in the solid substrate just underneath the present layer being melted and (ii) stresses due to the cool-down phase of the melted top layers.

This first phenomenon, referred to as the Temperature Gradient Mechanism (TGM), results from large thermal gradients in the solid material just underneath the laser spot (Figure 3). Due to the high temperature in the upper layers of the solid substrate, those upper layers will expand, while the colder underlying solidified layers will restrict this expansion. This induces compressive stresses σ_{comp} in the upper layers of the substrate that may rise above the yield strength of the material and cause plastic upsetting in those upper layers. When the yield strength is reached, the compressive stresses in the material cause plastic deformation ε_{pl} of the upper layers. When those plastically upset layers cool down, their compressive state is converted into residual tensile stresses σ_{tens}. Those residual stresses may induce cracking of the part.

In the second phenomenon, the melted top layers tend to shrink due to the thermal contraction. This deformation is again prohibited by the underlying layers, thus introducing tensile stresses in the top layer, and compressive stresses below.

From previous work on reduction of thermal stresses by Mercelis et.al [6] and Shiomi et.al [7], it is shown that so far, the best way to reduce thermal stresses is uniform pre-heating of the baseplate.

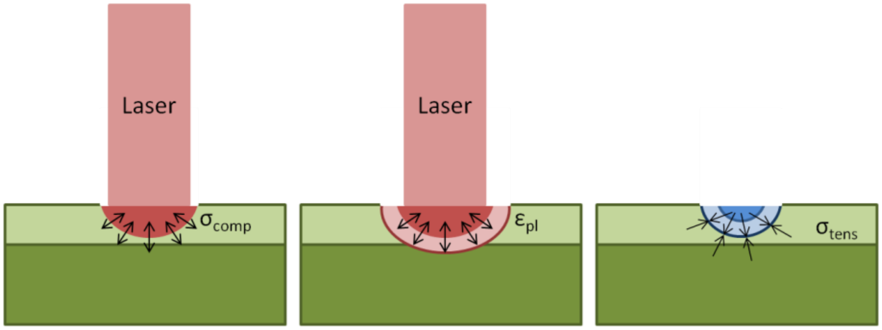

Figure 3: Temperature Gradient Mechanism in SLM

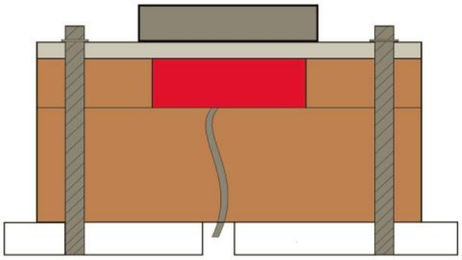

Figure 4: Schematic overview of the pre-heating module

2. Pre-heating element

Figure 4 shows the schematic overview of the heating module that was designed and installed on the Concept Laser M3 machine. The heating element itself (red) is installed underneath the building platform, on top of which the baseplate is mounted. The heating element is surrounded by insulation material so the rest of the building module doesn't heat up. The temperature of the baseplate can be controlled by the resistive heat element. A proportional and integral control loop (PI-controller) controls the power to the heat element to achieve a desired temperature on the baseplate within a range of ± 2°C.

3. Crack formation

Mercelis et al. have shown that there are more stresses built up in a part with high density [6]. Pores relax the residual stresses as they may not contain internal stresses. In order to build crack-free parts with high density, pre-heating of the baseplate was applied to lower the thermal gradient during the process. A higher pre-heating temperature results in less crack formation (Figure 5). When observing the cross-section of the crack-free part under LOM and SEM, it is shown that the part doesn't contain micro-cracks either.

Laser re-melting is a technique sometimes used to improve the properties of SLM parts [8]. It consists of laser re-melting the most recent layer before adding new layers. Laser re-melting may improve part density, microstructure and surface finish. However, when re-melting every layer of M2 parts, the formation of cracks becomes more likely due to:

- The increase of density: re-melting increases the density of the part, and thus enhances crack formation.
- The higher cooling rate: re-melting every layer involves a higher cooling rate because solid material has higher heat conductivity than powder material. Because of this higher cooling rate, more martensite phase will be formed, which is more brittle than ferrite phase. While being submitted to the same stresses, the brittle martensite phase will crack more easily than the ferrite phase. Figure 6 shows the difference of crack formation in parts that were produced with and without re-melting every layer. Figure 7 indicates the increase in martensite formation for laser re-melted parts.

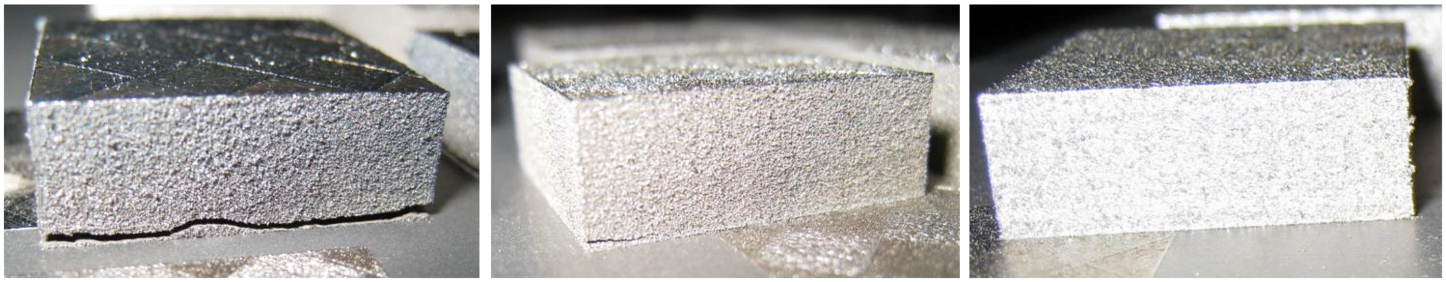

Figure 5: M2 HSS parts produced with a pre-heating temperature of 90°C (left), 150 °C (middle), 200 °C (right)

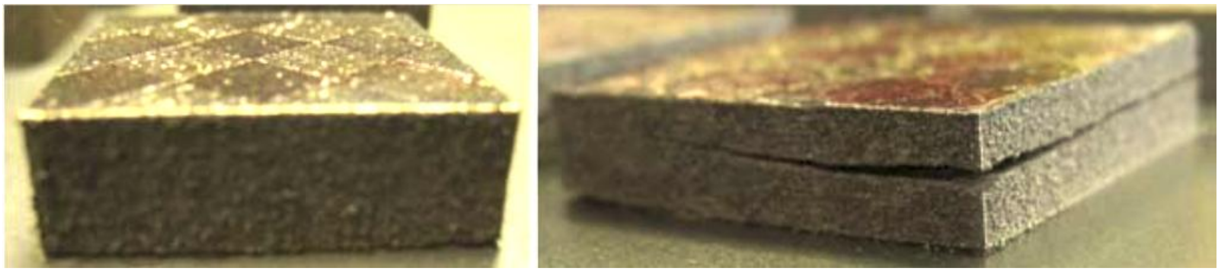

Figure 6: M2 HSS parts produced with P = 105W, v = 250 mm/s and h = 128µm.
Left: SLM -- Right: SLM + re-melting at 200mm/s

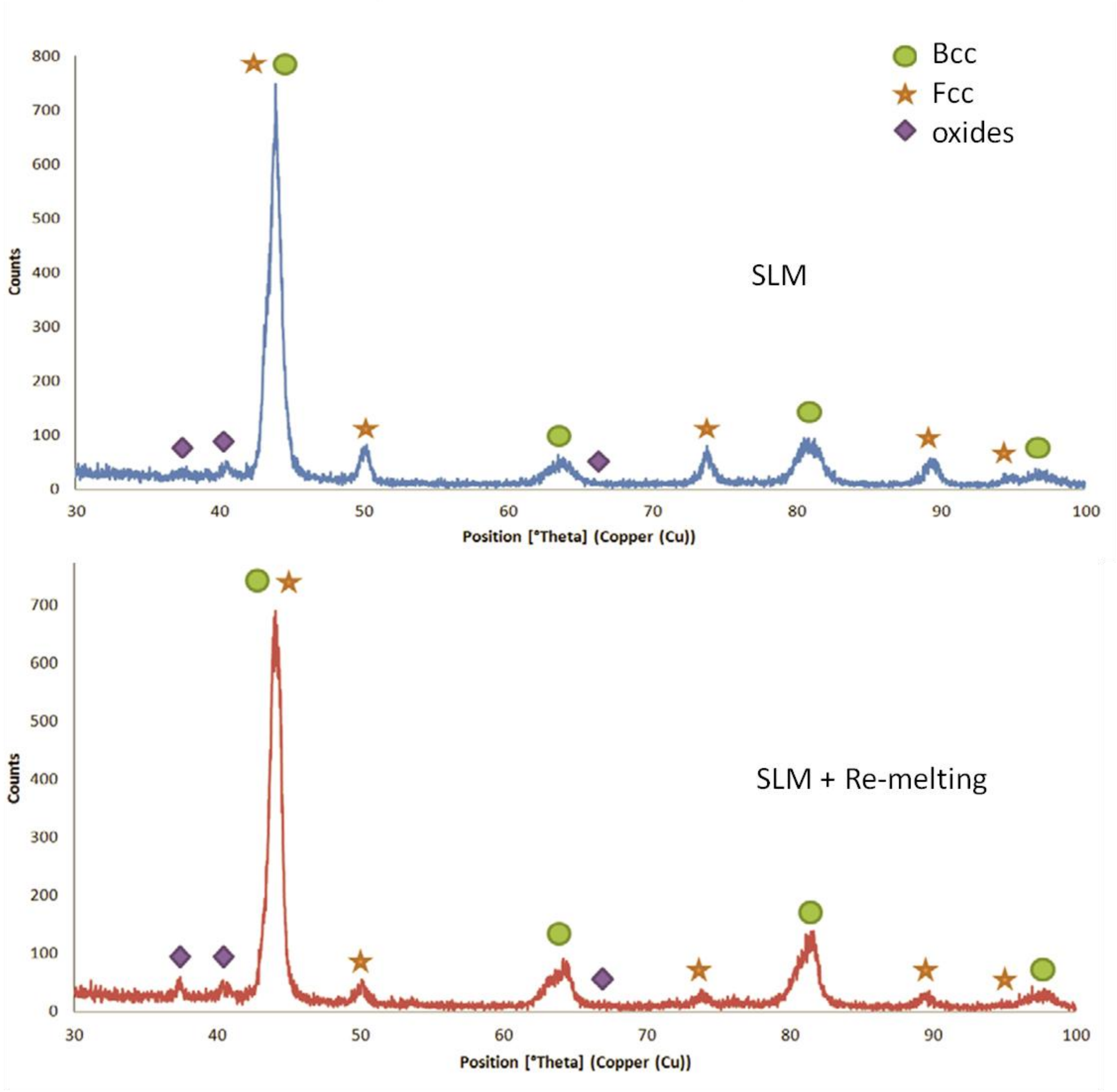

Figure 7: XRD measurements of M2 HSS parts produced with and without re-melting of every layer

4. Density optimization

Part density is one of the most important physical parameters to optimize, because it has a direct influence on the part's mechanical and physical properties. The part density depends on many process parameters, while this research focuses on the effect of scan speed v_s, re-melting and the pre-heating temperature T. The influence of these parameters on other properties like hardness and surface roughness has also been studied.

Numerous cubic test parts were produced with a laser power of 105W, scan speeds varying from 150mm/s to 550 mm/s and pre-heating temperatures of 90°C and 200°C. For some parts, every layer was re-melted with a laser power of 105W and scan speed of 200mm/s before adding a new layer. Relative densities of these parts are depicted in Figure 8.

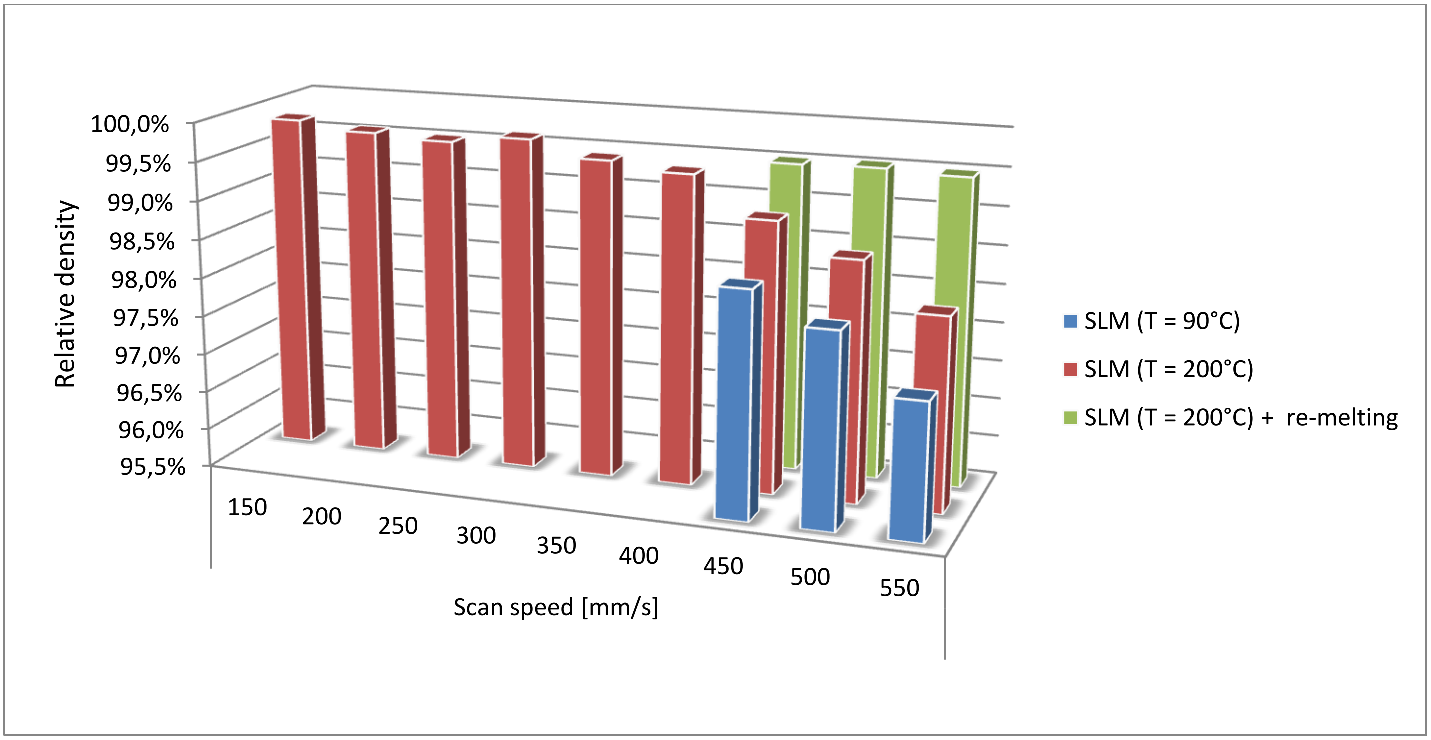

Figure 8: Influence of scan speed, pre-heating temperature and re-melting on part density

Relative density increases with decreasing scan speed (within this parameter range). For scan speeds over 450 mm/s, the melt pool becomes too narrow. This results in higher porosity. Figure 10 (left) shows the pores (indicated in red) that are formed in between tracks due to insufficient overlap between adjacent scan tracks. The powder that wasn't melted in the first scan-step may melt when re-melting the layer, or prematurely trapped gas bubbles can escape during re-melting. This results in higher densities for re-melted parts, as indicated in Figure 8.

The pre-heating temperature T also influences the part density. When applying more pre-heating, less heat input is needed from the laser source to melt the powder. That is why, for higher pre-heating temperatures, higher scan speeds can be used to produce equally dense parts. Figure 8 shows that parts produced with a pre-heating of 90°C need a scan speed of 500 mm/s to result in 98.3% density. While parts produced with a pre-heating temperature of 200°C can be scanned with a scan speed of 550 mm/s to get the same density.

5. Surface roughness

The influence of scan speed on surface roughness is negligible, within this applied range. The best way to improve top surface quality is re-melting (Figure 9). By re-melting the top layer, the surface roughness can be improved by 47% (from 18.3 R_a to 8.6 R_a). Both high pre-heating temperatures and re-melting improve the top surface quality, because they both cause the formation of a stable melt pool. This is also shown in the SEM images of Figure 10.

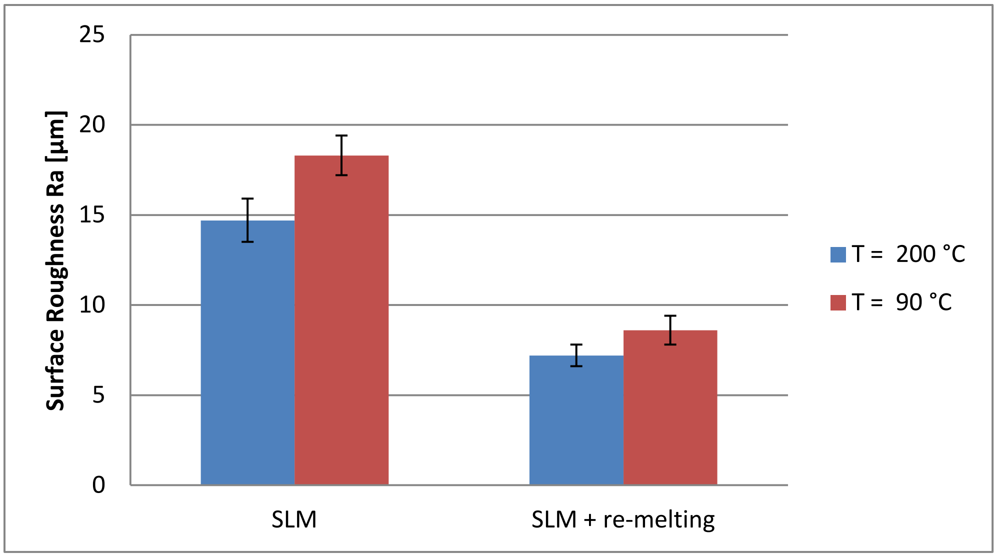

Figure 9: Influence of pre-heating temperature and re-melting on top surface roughness

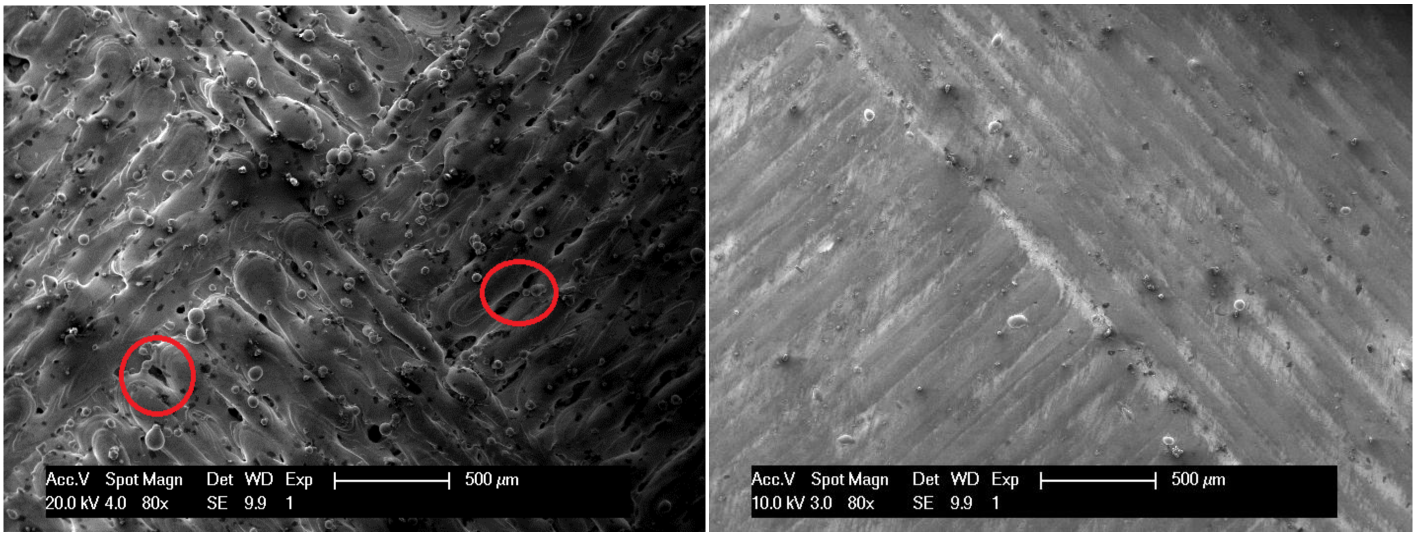

Figure 10: Top surface of parts produced with P = 105W, v = 500mm/s and no re-melting (left), re-melting at 200 mm/s (right)

6. Hardness

For conventionally produced M2 HSS parts, the high hardness (of about 65 HRC) is reached by a post-process hardening heat treatment as defined by ASM [9]. Rapid cooling rates and high temperatures are typical for the SLM process. The rapid cooling results in rapid solidification of the melt pool and thus a very fine microstructure. Therefore, a relatively high hardness (57 HRC) is achieved for SLM produced M2 HSS parts, without need for a post-process thermal treatment. When every layer is re-melted, the hardness of the final part even increases up to 64 HRC. The higher hardness of the re-melted parts is due to the increase of martensite phase. More martensite is formed because the cooling rates are much higher for re-melting (on solid material) than for first time melting (powder material), as shown in XRD measurements (Figure 7). All hardness results are depicted in Figure 11.

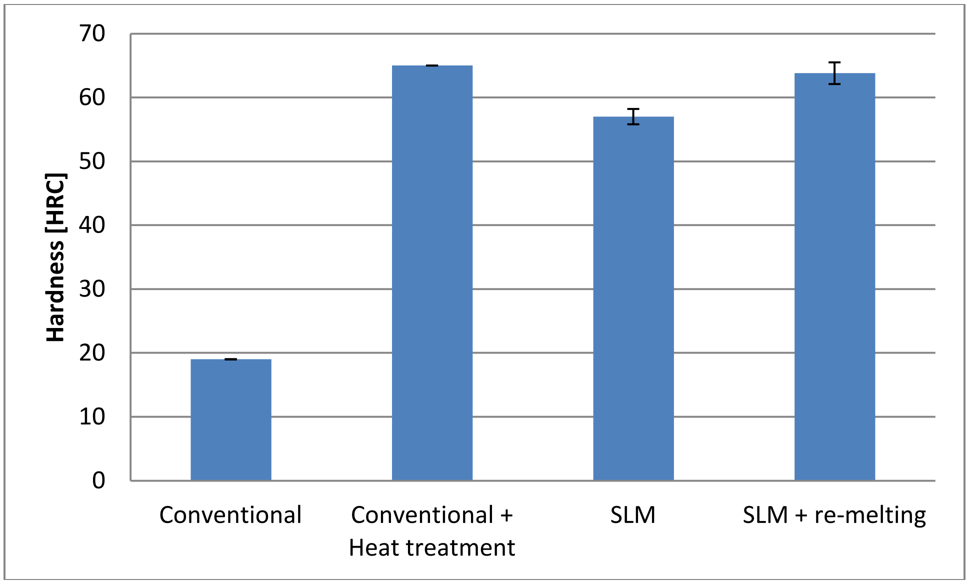

Figure 11: Hardness of M2 HSS SLM parts compared to conventionally produced parts

Conclusions

1. The objective of this study, to produce crack-free M2 HSS parts with a high density by Selective Laser Melting, is achieved. The part with the maximum density of 99.88% is produced at a pre-heating of 200°C,a laser power of 105W, a scan speed of 150 mm/s and a hatch spacing of 126 µm. Lower scan speed, re-melting and higher pre-heating temperature all lead to higher densities. The influence of these parameters on the density is strongly dependant on each other and it is not linear.

2. The best way to improve surface quality on the top surface is to apply re-melting. A top surface roughness of 8.6 µm R_a has been reached by re-melting.

3. When scanning without re-melting, parameters which lead to a higher density, also lead to a better surface quality.

4. The applications of M2 HSS in mind, a high hardness is very important. The high hardness in conventional HSS M2 is obtained by an aging heat treatment. However, there is already an intrinsic heat treatment in the SLM process due to the typical characteristics of the process, which makes post heat treatment obsolete with SLM. In this study, hardness up to 57 HRC has been reached, without applying a post-treatment. Applying re-melting in every layer, improves the hardness even up to 64 HRC, which is comparable to conventional heat treated M2 HSS.

5. Lowering the thermal gradient reduces the thermal stresses and hereby the amount of cracking. Pre-heating of the base plate lowers the thermal gradient. It also lowers the cooling rate, leading to less martensite formation. Re-melting leads to more cracks because the higher cooling rates lead to more formation of a brittle martensite phase. While re-melting every layer induces the same residual stresses, cracking will occur sooner because of the brittle phase.

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