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Application of base plate preheating during selective laser melting

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- Keynote Paper -

Abstract

Base plate preheating is one of the recent enhancing tools added to the process of Selective Laser Melting (SLM). This tool aims at a reduction of thermal stresses in SLM parts, achieved by decreasing the thermal gradients during SLM processing. In the current study, base plate preheating up to a temperature of 400°C is applied during SLM of 4 different materials, including aluminum 7075 alloy, nickel alloy Hastelloy X, H13 tool steel and CoCr. General trends, as well as material specific effects are discussed regarding part density, crack formation, internal stresses, microstructure and mechanical properties. These show how base plate preheating can induce different influences according to each particular material category.

Keywords: Selective Laser Melting (SLM); Base plate preheating

1. Introduction

Selective Laser Melting (SLM) is an Additive Manufacturing (AM) technique in which thin layers of metal powder material are selectively molten by a laser, layer after layer. There is an increasing industrial demand for a larger pallet of materials that can be applied in SLM.

One of the main difficulties, which impedes the SLM material development, originates from the large thermal stresses that occur in SLM parts due to the high thermal gradients. This thermal stress issue can potentially be resolved by elevating the temperature of the base plate during the fabrication, hence reducing temperature gradients during SLM [1-3].

This addition of preheating during SLM has proven to be promising for several cases where cracks could be prohibited [1], residual stresses were decreased [3] and/or mechanical properties improved [4]. This can, however, also affect other material properties or characteristics. To better illustrate these effects, the research presented here gives an overview of the effect of preheating on a variety of SLM part characteristics such as density, internal stresses, crack formation, microstructure and mechanical properties. The corresponding drawbacks, originating from long exposure of SLM materials to elevated preheating temperatures, are also demonstrated.

Within this research, four materials are examined:

- The first material is the high strength aluminum alloy Al7075 containing 5.1-6.1wt% Zn, 2.1-2.9wt% Mg and 1.2-2wt% Cu. Because of its high specific strength, this alloy is mainly used for automotive and aerospace applications. After SLM production, Al7075 parts, however, suffer from crack formation [5].
- The nickel alloy Hastelloy X (chemical composition in Table 1) is often used in high temperature applications such as gas turbines. Depending on its exact chemical composition [6] and on the SLM parameters used, this material also suffers from cracking.

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- H13 (chemical composition in Table 1) is a hot working tool steel with a high hardness and wear resistance, a good thermal fatigue performance and high toughness and strength at elevated temperatures. This material can be processed through SLM without major difficulties. It was, however, shown that the application of preheating largely influences the microstructure and mechanical properties of SLM H13 tool steel [4].
- Lastly, CoCr (27-30wt% Cr and 5-7wt% Mo) combines good corrosion resistance (even at elevated temperatures) with mechanical properties comparable to stainless steel. It is often used in industrial as well as biomedical applications. Extensive research has been performed on SLM of CoCr [7-10].

Table 1. Chemical composition of Hastelloy X and H13 tool steel.

Wt%	Ni	Fe	Cr	Mo	Co	Si	V	W	C
HX	Bal.	17-20	20.5-23	8-10	1.5-2.5	<1	-	0.6-1	0.05-0.07
H13	-	≥91	5.13-5.25	1.33-1.4	-	1	1	-	0.32-0.4

2. Methods

For the SLM production, Materialise Magics software was used for the file preparation and an in-house developed SLM-machine of KU Leuven was used for part production. The SLM machine is equipped with a Yb:YAG fiber laser with a maximum output power of 300W and a beam diameter d_{1/e^2} of 50µm. Base plate preheating was applied using a resistive heating element underneath the base plate. The temperature is controlled within ± 0.5°C using a thermocouple attached to the heating element and a PID control loop. Since the temperature is only measured underneath the base plate, the temperature may vary depending on the part height. However, the limited height of most parts in this work, i.e. 10mm, guarantees a relatively homogeneous temperature throughout the build height.

For all materials, a parameter optimization was performed using the power (P) and scan speed (v) ranges as illustrated in Table 2. Furthermore, preheating was applied up to 400°C. Layer thickness and hatch spacing were kept constant at respectively 30µm and 105µm.

Table 2. Investigated parameter ranges to optimize the SLM process for all four materials.

Material	Power [W]	Scan speed [mm/s]
Al7075	100-300	500-1500
Hastelloy X	120-270	400-1600
H13 tool steel	120-220	400-2000
CoCr	150-300	200-1400

3. Results and discussion

Each of the following paragraphs describes the effect of base plate preheating on one of the material characteristics. Density, crack formation, internal stresses, microstructure and mechanical properties are analyzed in depth. In a last section, the influence of extended exposure to elevated temperatures is described for Hastelloy X.

3.1. Density

Fig. 1 shows the Archimedes density of H13 tool steel parts produced using different laser power and scan speed, and using different preheating temperatures. First of all, it should be noted that the variation caused by preheating (within this limited range of applied preheating temperatures) is small in comparison to the influence of other process parameters such as laser power and scan speed.

Furthermore, application of preheating contributes to the total energy input required to densify the material. When the combination of scan speed and laser power results in low density, application of preheating leads to an increase of the part density (Fig. 2). Fig. 3 shows an example where full density (>99.5%) was obtained by using a higher preheating temperature.

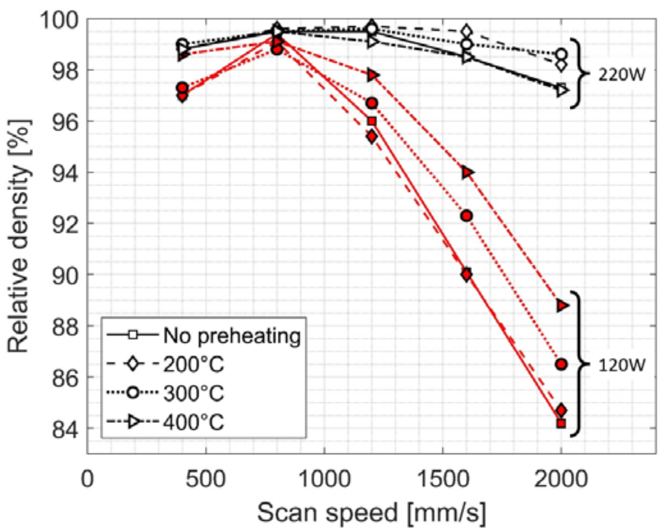

Fig. 1. Relative density graph of H13 tool steel parts produced by SLM (t = 30µm; h = 105µm).

However, when laser energy input is adequate in order to obtain a dense SLM part, addition of preheating might result in an excess of the total energy input, enlarging the melt pool size and increasing melt pool instabilities. This can decrease the part density as occurred for H13 tool steel when a power of 220W and scan speed of 1200 or 1600mm/s is applied (Fig. 1). In this case, density values decreased when the preheating temperature increased from 200°C to 400°C.

In the excessive laser energy region, when low scan speeds are applied (scan speed of 400mm/s in Fig. 1), parts suffer from keyhole porosity (Fig. 5 shows examples of keyhole porosity for Hastelloy X). In this region, there is no clear trend in the effect of preheating. The part density is, however, insufficient for all applied preheating temperatures.

Finally, a parameter window can be defined in which dense parts are obtained for all examined preheating temperatures within the considered temperature range. For H13 tool steel, a parameter set consisting of a power of 220W and scan speed of 800mm/s without and with preheating up to 400°C shows maximum part density results. It is worth mentioning that comparable trends are observed for all investigated materials since part density is rather process related.

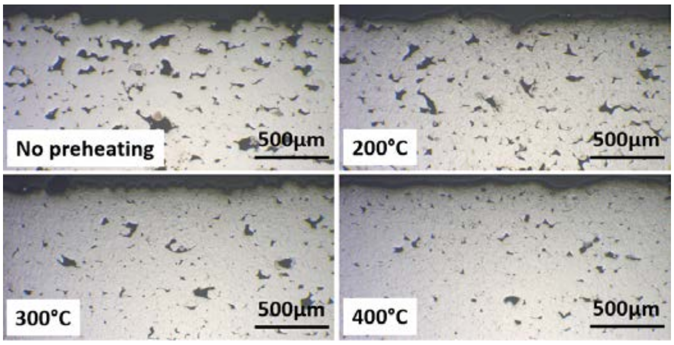

Fig. 2. Optical microscopy images of Hastelloy X specimens (side view) with increasing preheating temperature (P = 170W; v = 1600mm/s).

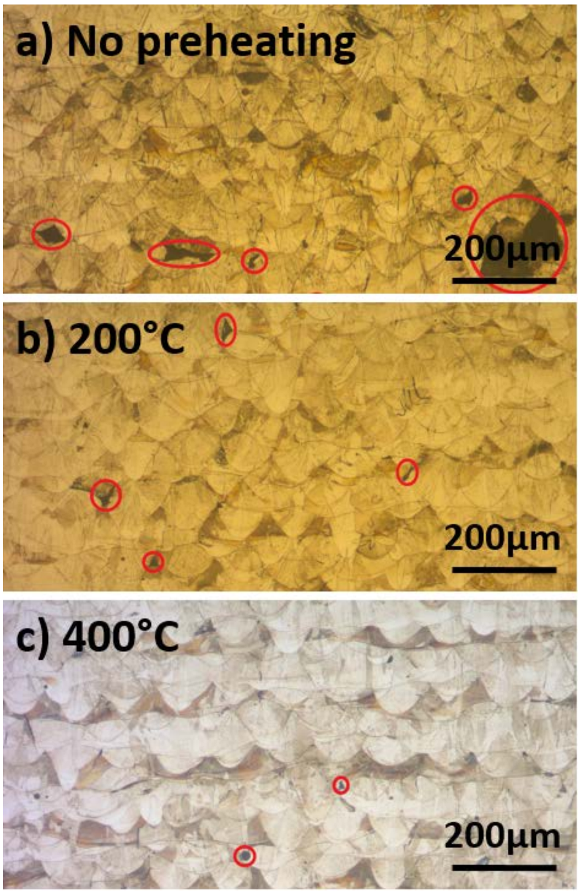

Fig. 3. Optical microscopy images of Hastelloy X produced at P = 170W and v = 1200mm/s with varying preheating temperature. The remaining porosity is indicated by red circles.

3.2. Internal stresses and crack formation

The main motivation to apply preheating during the SLM process is the possible reduction in thermal stresses. This reduction was quantified by Vrancken et. al. for the titanium alloy Ti6Al4V. A reduction of 50% in residual stresses was found when a preheating temperature of 400°C was applied [3].

Such a reduction in thermal stresses is beneficial for the overall stability of SLM parts, especially in high demanding load applications since large internal stresses might lead to geometrical deformations and premature failure. In the extreme cases, such internal stresses can even induce macrocracks developing in SLM parts. This has been well demonstrated by Kempen et. al. as the large macrocracks in SLM M2 tool steel parts without preheating have been successfully diminished by application of preheating at 300°C [1].

In addition to large macrocracks, smaller microcracks can also form in the SLM materials. For example, in the case of high strength aluminum alloys such as Al7075, microcracks can abundantly form after SLM processing without preheating (Fig. 4). Although the application of preheating largely reduces this cracking behavior, it fails to completely prevent the microcrack formation, as Fig. 4 still shows the presence of large cracks after use of preheating at 400°C. This change in crack behavior can be attributed to the precipitation phenomena of the main strengthening phase ($MgZn_2$), occurring at temperatures below 300°C [5].

Without application of preheating, the temperature of the freshly solidified material decreases below 300°C during the SLM process. This allows precipitates (such as $MgZn_2$) to form during production, which consequently may embrittle the material. This together with the high thermal stresses induced by SLM (which are intensified for this alloy due to its broad solidification interval and large thermal expansion) leads to the abundant formation of microcracks throughout the entire part.

In contrast, when the freshly solidified material is kept at an elevated temperature of 400°C, the situation changes completely. Mg and Zn will both remain in solid solution and the formation of $MgZn_2$ precipitates is postponed until after the SLM process. The embrittlement is therefore avoided, reducing the fine branched cracking. However, thermal stresses during SLM and after cooling down are still sufficiently high to cause cracks (despite the cracking significantly reduces after the application of preheating, as seen in Fig. 4).

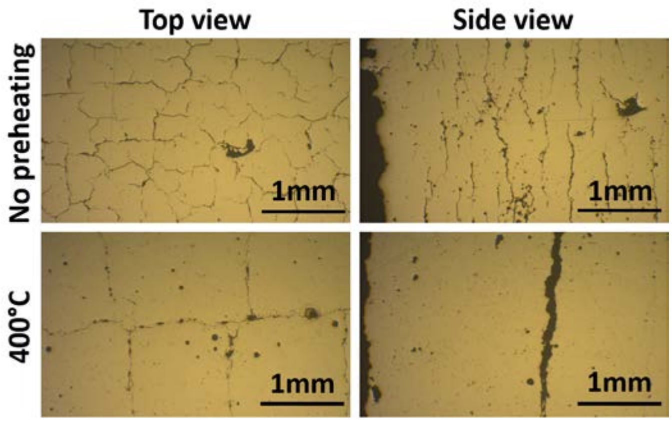

Fig. 4. Optical microscopy images of Al7075 parts produced at different preheating temperatures.

The nickel alloy Hastelloy X also suffers from crack formation after SLM processing. Hastelloy X, however, does not have a phase transformation occurring in the range of the applied preheating temperatures. Furthermore, and related to this, it was found that preheating up to 400°C does not have a significant effect on crack formation in Hastelloy X parts.

It should be noted that in addition to preheating, the applied parameter set can significantly alter the cracking. For example, high laser energy inputs can lead to the formation of excessively deep melt pools in SLM processed Hastelloy X (Fig. 5). Solidification of these deep melt pools develops from the sides towards the middle. As a result, cracks appear vertically, in the middle of the melt pool where the two solidification fronts (from left and right) should meet. In comparison, a lower laser energy parameter set leads to a shallower melt pool which can prevent cracking to a large extent even without preheating (as previously shown in Fig. 3a). Addition of the preheating to such a parameter set not only completely diminishes the cracking, but also significantly improves the density (Fig. 3c).

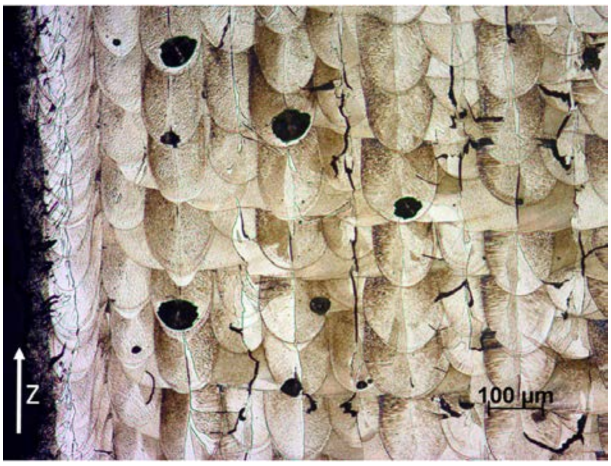

Fig. 5. Optical microscopy image (side view) of a Hastelloy X specimen produced using high laser energy without preheating (P = 270W; v = 400mm/s).

It should, however, be noted that for some materials, a reverse effect on internal stresses can occur. For H13 tool steel, for example, compressive stresses are commonly found at the outer surfaces of the parts after SLM production due to the volume increase during the martensitic transformation in the material. It was however found that higher preheating temperatures prohibit such a martensitic transformation (as will be discussed more in depth in section 3.3). Therefore, internal stresses evolved from a compressive nature without preheating to tensile after application of preheating, as shown in Fig. 6 [4].

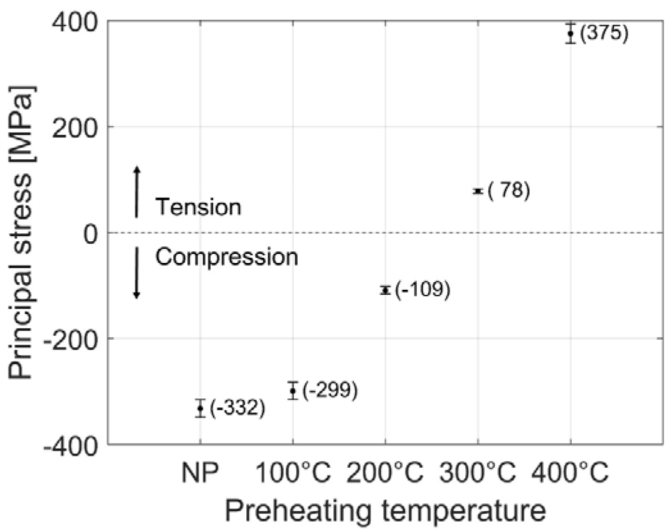

Fig. 6. Maximal principal stress measured in H13 SLM parts produced at different preheating temperatures. Residual stresses are measured in-plane on the top surface of SLM cubes using XRD.

On the contrary, for CoCr, a material without phase transformations below 400°C (as will be discussed in section 3.3), no significant difference in residual stresses at the outer surface of SLM parts was measured, as illustrated in Fig. 7.

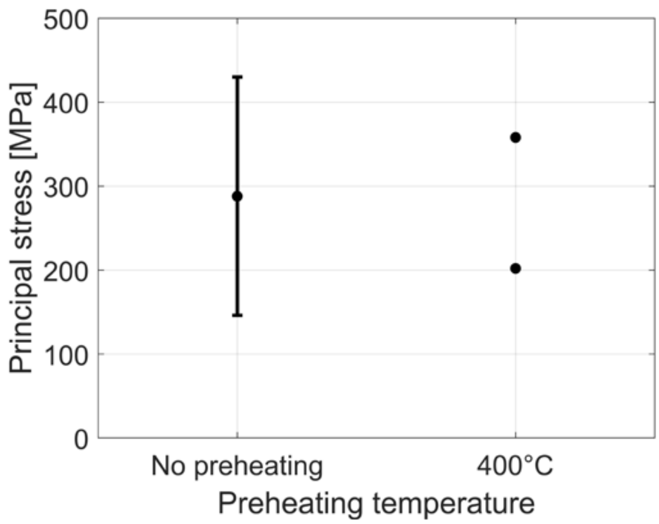

Fig. 7. Maximal principal stress measured in CoCr SLM parts produced at different preheating temperatures. 6 measurements were performed without preheating (95% confidence interval shown), 2 with preheating at 400°C (single measurements shown).

3.3. Microstructure and mechanical properties

Applying preheating influences the thermal history of the material and might therefore influence the microstructure of the parts. This influence is not equal for all materials, as it depends on the transformation temperatures of the phases and the melting points of the materials. When a phase transformation or precipitation is possible below the preheating temperature, significant changes are obtainable depending on the preheating temperature. However, when such transformations only occur above the preheating temperature, microstructural variations due to preheating are smaller or non-existing.

Fig. 8 shows a first example, as Al7075 is largely affected by preheating. As seen from Fig. 8, in parts produced without preheating, melt pool boundaries are clearly visible in the microstructure. These melt pools are visible due to the cell size differences at the melt pool borders and interiors [5]. This can be enhanced due to the precipitation in the heat affected zone of each melt pool. The precipitates are mainly $MgZn_2$ particles forming below 300°C for this alloy [5]. However, at a preheating temperature of 400°C, Zn and Mg fully dissolve in the aluminum matrix, prohibiting the formation of $MgZn_2$ precipitates in the melt pool. As a result, the melt pool borders fade and a more uniform microstructure appears (Fig. 8).

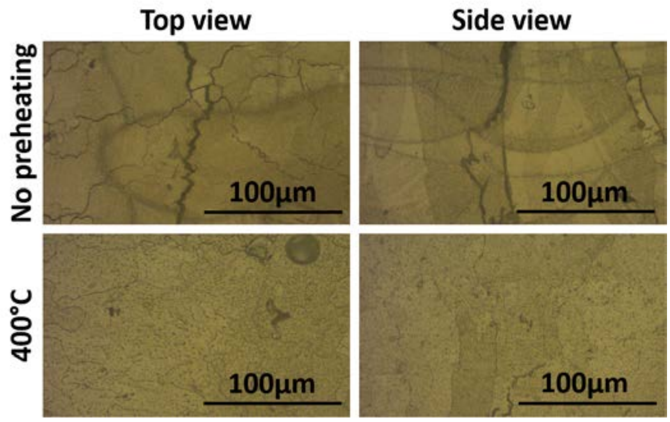

Fig. 8. Optical microscopy images of etched Al7075 parts produced using different base plate preheating temperatures (P = 270W; v = 1100mm/s).

As a second example, the effect of preheating up to 400°C on the microstructural and mechanical properties of SLM made H13 tool steel is presented [4]. For this steel, the austenite-martensite transformation temperature is about 300°C. Application of a preheating temperature below this critical temperature results in a largely tempered martensitic microstructure after SLM. When higher preheating temperatures are applied, on the other hand, the material remains in its austenitic state during the SLM process. Afterwards, during cooling down to room temperature, a bainitic microstructure forms and a low fraction of austenite retains. This bainitic microstructure is only slightly tempered after cooling down to room temperature at the end of the process (in contrast to the highly tempered martensite formed during SLM without preheating). Therefore, parts with this bainitic microstructure, obtained via SLM at 400°C, possess a higher hardness and a higher ultimate tensile strength compared to parts produced without preheating, as illustrated in Fig. 9. To further analyze and predict such phenomena, one may study the Continuous Cooling Transformation (CCT) curves of a particular steel before selecting the preheating temperature for SLM processing.

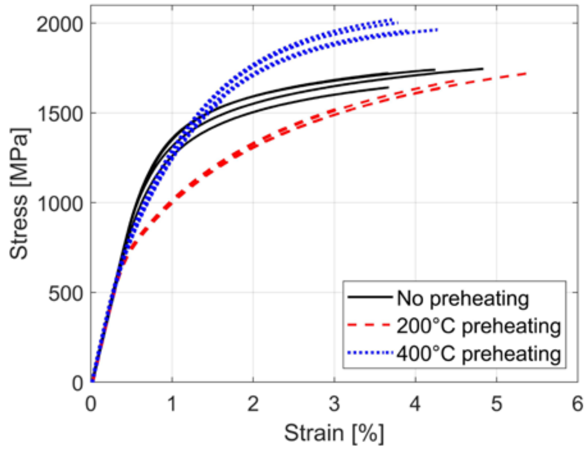

Fig. 9. Tensile stress-strain curves for SLM-produced H13 using different preheating temperatures [4].

The two previous examples showed materials that are to a large extend affected by preheating up to 400°C. In a contrary case, CoCr is investigated. For CoCr, no precipitation or transformation normally occurs below 400°C that influence the properties. In fact, CoCr only undergoes an FCC to HCP transformation around 1000°C, leading to a stable hexagonal structure below this temperature. However, due to the fast cooling during SLM, the metastable FCC phase largely remains at room temperature. Interestingly, the amount/type of this metastable FCC structure is not significantly influenced by preheating up to 400°C. This can be seen in Fig. 10 where the XRD diffraction pattern shows similar peaks in the two different cases. As a result, no significant effect on tensile properties was obtained (Fig. 11).

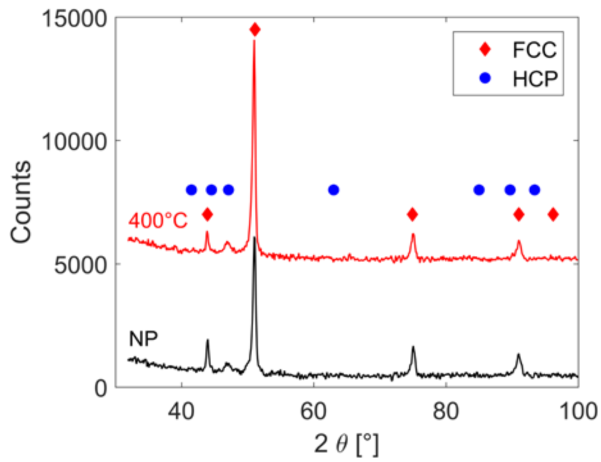

Fig. 10. X-ray diffraction patterns for CoCr parts produced without preheating (NP) and with a preheating temperature of 400°C.

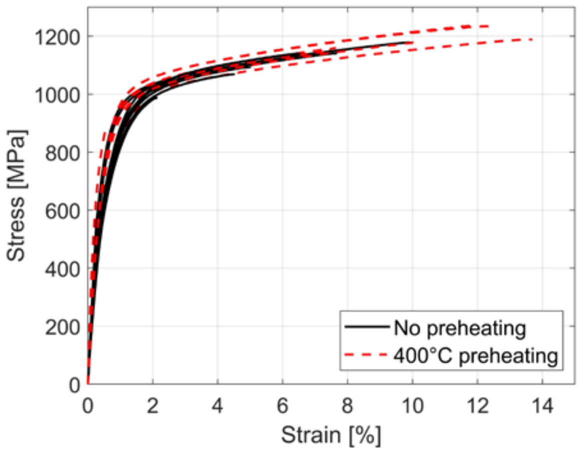

Fig. 11. Tensile stress-strain curves for SLM-produced CoCr using different preheating temperatures.

Despite the comparable phases in the SLM CoCr parts made with or without preheating (Fig. 10), there is however a difference in their texture as the intensity of the peaks is different. In fact, the (200) FCC peak at 2θ = 51° is more pronounced when a preheating temperature of 400°C is applied. This means that preheating intensifies the texture in the (200) direction, which is regularly observed in SLM parts due to the layered build [8, 11, 12]. This can be attributed to deeper melt pools when preheating is applied.

3.4. Long exposure to preheating temperature

One of the concerns regarding the application of preheating is the effect of prolonged exposure to a certain preheating temperature. Within this research, a significant effect was observed after long exposure to a temperature of 400°C for nickel alloy Hastelloy X, as the microstructure was different at the bottom and the top of a 90mm high part that was SLMed for 32 hours. In fact, 32 hours of preheating at 400°C significantly coarsened the grain structure, as shown in Fig. 12. The coarser microstructure at the bottom of the part is visible in as built parts, but becomes more clear in heat treated parts (solution treatment at 1200°C, followed by air quenching).

This is very remarkable since the alloy does not have low temperature phase transformations (as discussed earlier), and especially since this alloy is also used for elevated temperature applications. Analyzing the effect of long exposure to preheating temperatures is in particular important for industrial applications, as large parts will require long production times.

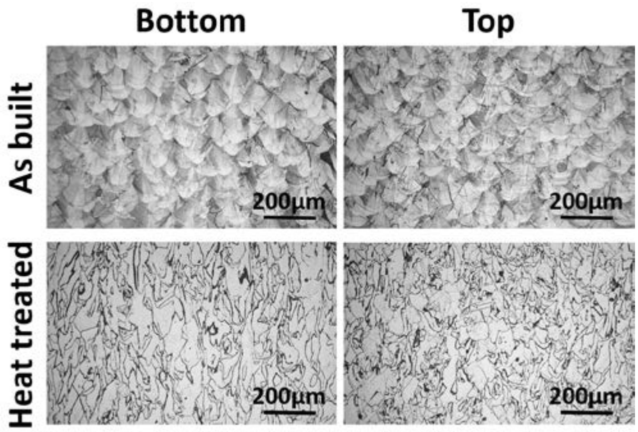

Fig. 12. Optical microscopy images of 90mm tall SLM Hastelloy X bars made in the vertical direction using a preheating at 400°C (side view). The pictures are taken before and after a solution heat treatment at 1200°C.

4. Conclusion

This research investigated the effect of base plate preheating during SLM on part density, crack formation, internal stresses, microstructure and mechanical properties for 4 different materials (Al7075, Hastelloy X, H13 tool steel and CoCr).

It was found that an elevated base plate temperature provides an extra source of energy and densifies the SLM material when laser energy is insufficient to obtain a dense part. However, this densifying effect of preheating is less strong compared to the effect of main laser parameters such as laser power and scan speed, as was shown for the case of H13.

In some cases, such as for Al7075, application of preheating can also reduce the crack formation in the parts, though it may fail to completely prevent cracking. In the case of Al7075, a change in crack morphology was obtained due to preheating at a temperature of 400°C.

Residual stresses can partly be controlled by application of preheating. Other factors such as phase transformations (e.g. the martensitic phase transformation in H13 steel), however, also largely affect stress formation in SLM parts.

Microstructural changes due to application of preheating strongly depend on the processed material and its phase transformations. It was found that the precipitation in Al7075 and the austenite-martensite transformation in H13 tool steel, both occurring at temperatures lower than 400°C, induce large differences depending on the preheating temperatures applied during SLM. In contrast, when the investigated material has no transformation below the maximal preheating temperature, the effect of preheating is non-existing or less pronounced.

Lastly, it should be noted that the texture can still vary due to preheating below the material transformation temperatures, even when no clear change in tensile properties is observable (as shown for CoCr). Also, the prolonged exposure to a preheating temperature of 400°C can have a grain coarsening effect such as in the case of Hastelloy X.

Acknowledgements

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