BULETIN ŞTIINŢIFIC, Seria C, Fascicola: Mecanică, Tribologie, Tehnologia Construcţiilor de Maşini
SCIENTIFIC BULLETIN, Serie C, Fascicle: Mechanics, Tribology, Machine Manufacturing Technology, ISSN 1224-3264, Vol. 2022 No.XXXVI

Investigating the Importance of Base Plate Preheating in the Selective Laser Melting Process

***Jiri Hajnys*[1,*]*, Marek Paga*[2]*, Jiri Kratochvil*[3]

Abstract: *The article deals with the impact of preheating the base plate on the generated residual stress in additive metal 3D printing technology, namely the Selective Laser Melting (SLM) method. Fifty pieces of bridge-shaped samples were experimentally printed (aluminum and stainless steel). Twenty samples were made of aluminum alloy AlSi10Mg, ten without preheating the base plate and the other ten with preheating the base plate to 170 °C. In each set, the bridges were further divided into groups. The given groups differ in the direction of the scanning vector, it also affects the residual stress. The residual stress is evaluated by measuring the deflection of the bridges. Each measurement was repeated four times and the resulting values were compared. Using the same methodology, 316L stainless steel samples were also printed and verified.*

Keywords: *SLM, Heat Treatment, Base Plate, 3D Print*

1 INTRODUCTION

3D printing is a process where a three-dimensional model is converted from a digital file into its physical form. The model is first cut into individual layers in a program called "slicer". According to these layers, the slicer determines the print vectors, and these vectors are subsequently converted into G code, which is transferred to the machine. The machine then begins to apply the material layer by layer according to the G code until the entire part is made. The most widespread 3D printing technologies now are FDM/FFF, SLA, SLS/SLM. These technologies differ from each other in the material used, the size of the applied layer, the method of melting the layer and, of course, the stand on which the part is produced.

One of the main problems with SLM metal printing is the generation of internal stresses that can cause a variety of defects in the final product. These are, for example, defects such as deformation, warping, delamination, detachment from the base plate, thermal cracks, etc. One of the methods to effectively reduce internal stress is to use preheating of the base plate on which prints are printed. This fact was confirmed by a study by Mertens et al. [1] however, it depends on the printed material and also the magnitude of the temperature. For example, the use of 400℃ preheating of the base plate for Al7075 material results in a change in crack morphology, and not a significant reduction. The purpose of preheating the base plate is not only to reduce internal stress, but also to help the material maintain its strength. This can be observed mainly with the H13 material, this material is also further heat-treated after printing, however, preheating the base plate effectively helps to maintain strength, see the research [2].

1.1 Effect of preheating on the microstructure

From a microstructural point of view, the preheating of the base plate is also important, in a study by Boes et al. [3] and also a study by Vrancken et al. [4] it was found that there is a change in the microstructure during the SLM process by reducing the temperature gradients of the preheating will not only allow the decomposition of martensite, but also reduce the residual stress. However, there will be associated problems such as increased oxygen uptake. Increasing the preheat temperature to 400℃ changed the microstructure and the residual stress in the top layer was reduced by 50% due to the overall reduction of temperature gradients. Although the transformed microstructure should lead to a tougher material, the increased oxygen and nitrogen uptake of the hot melt bath caused embrittlement, increasing hardness but decreasing ductility.

1.2 Energy efficiency of preheating

The study [5] deals with the energy efficiency of preheating in the SLM process. The energy consumed during preheating is approximated using transient finite element analysis. In the case study, energy efficiency was measured during the production of a cantilever beam with preheating of the base plate, preheating of the chamber and laser pre-scanning heating. The conclusion of this study was that chamber and base plate preheating methods are more suitable for tall or large volume components in terms of energy consumption. For small parts or parts with a small height, it is more appropriate to use pre-scanning preheating, this will cause less energy loss of the surrounding unused powder, because only the powder that will be subsequently transformed into the part is selectively preheated.

1.3 Analysis of other available publications

The analysis consists of a short summary of ten different papers by ten different authors. The first eleven papers deal with the use of base plate preheating on certain materials and its impact. The results are varied, and the parameters for one material cannot be implemented on other materials with the same result. Tool steels, titanium alloys and aluminum alloys appeared most often in the works. The work shows that preheating can have a positive effect on the density of the manufactured part, the formation of cracks, the microstructure, and the mechanical properties, especially the hardness. However, in all works it is mentioned that the positive results are not only due to the application of preheating, but the correct combination of all input parameters, which are scanning speed, laser power, environment and preheating, see Table 1.

Table 1. Analysis of available publications dealing with pre-heat base plate

Source	**Material**	**Temperature of pre-heat [°C]**	**The effect of preheating**
[1, 2]	Al7075	400	changes the morphology of cracks and does not prevent their formation a more unified structure of the material is created
	Hatelloy X	400	does not affect the formation of cracks longer exposure may cause uneven texture
	H13	200	reaches the highest density (> 99.5%)
	CoCr	< 400	does not affect the residual stress in the material
[5]	M2 HSS	200	99.88% density was achieved and the remelting of each layer reaches a hardness of 64HRC
[3]	X65MoCrWV3-2	300	reaches density > 99.5%
[6]	H13	100-300	with increasing temperature, the formation of cracks decreases
[7]	Ti6Al4V	570	changes the martensitic structure
[4]	Ti6Al4V	400	surface residual stress reduced by 50%
[8]	316L	180	reduces the measured angle on the sample by 10%
[9]	316L	150	reaches density >99.4% ,Young's modulus in elasticity 194.8 Gpa, tensile strength 594.9 Mpa
[10]	tungsten	< 400	does not affect the formation of cracks

2 MATERIALS AND METHODS

During the production of SLM technology, the product is exposed to a huge temperature load, this results in residual stress remaining in the material after the product cools down, which can manifest itself in the deformation of the product. To evaluate this phenomenon, an experiment was conducted in which fifty bridge-shaped products were produced. Twenty bridges were made of aluminum alloy AlSi10Mg, half of which were made without preheating and the other half with preheating of the base plate to 170 °C. Each half was further divided into groups. The given groups differed in the direction of the scanning vector, which could also affect the resulting residual stress. A similar principle was used for the remaining thirty bridges, but a different material. This material was 316L stainless steel. After the bridges were cut off from the base plate, the amount of deflection in the center of the bridge was measured against the value at its edge.

2.1 Aluminum alloy AlSi10Mg

AlSi10Mg alloy contains aluminum alloyed with silicon with a mass fraction of up to 10%, small amounts of magnesium and iron along with other minor elements. The presence of silicon makes the alloy harder and stronger than pure aluminum due to the formation of a Mg2Si precipitate. Due to the natural formation of an oxide layer on the surface of the aluminum alloy, the material has a high resistance to corrosion, which can be further improved by chemical anodization. The chemical composition can be seen in Table 2.

Table 2. Chemical composition of AlSi10Mg [wt.%]

Si	**Fe**	**Cu**	**Mn**	**Mg**	**Ni**	**Zn**
9-11	<0.55	<0.05	<0.45	0.2	<0.55	<0.1

2.2 Stainless steel 316L

Alloy 316L is an austenitic stainless steel that contains up to 18% chromium alloyed iron, up to 14% nickel and up to 3% molybdenum, along with other minor elements. The alloy is an extra low carbon variation of the standard 316L alloy. Due to its low carbon content, 316L-0407 is resistant to sensitization (carbide precipitation at grain boundaries) and displays good welding properties. It also has low breaking stress and high temperature tensile strength. The chemical composition can be seen in Table 3.

Table 3. Chemical composition of 316L [wt.%]

Fe	**Ch**	**Ni**	**Mo**	**Mn**	**Si**	**N**
Balance	16-18	10-14	2-3	<2	<1	<0.1

2.3 Renishaw RenAM 500E

The RenAM 500E is one of the latest 3D printer models from Renishaw. The predecessor of this printer is the AM 400 which has been improved with technology based on the RenAM500Q. Its build volume is 250mm x 250mm x 350mm, and one of the biggest advantages of this printer is the efficient gas flow through the powder bed, which is vital to maintaining consistent power transfer. On this machine was performed the samples.

2.4 Manufacturing samples

A sketch of the sample can be seen in Figure 1. The bridge as such will consist of three parts. Part A is the base of the bridge and serves to lay down the first layers during printing. Part B is the section where the bridge is then separated from the base plate. Part C is then a separate body on which the measurements will take place.

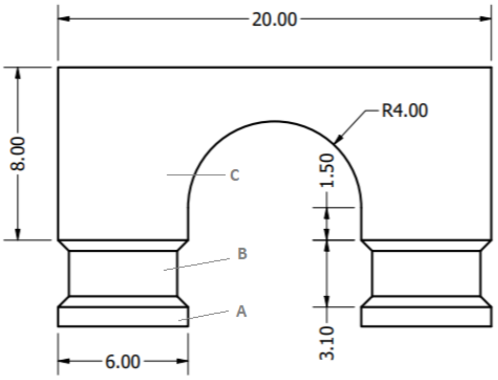

Fig. 1.Sketch of sample

After creating a model with STL format, we can upload it to Slicer, which cuts this model into individual layers of 50 µm (316L) and 30 µm (AlSi10Mg). Slicer will also allow us to change the dimensions of the product, the number of pieces we want to print in one batch and their distribution. See figure 16. Another very important tool that the slicer has is the management of supports, which serve to prevent the material, which is still malleable, from sagging due to the force of gravity during printing. The bridges are small enough that the use of supports is not necessary.

3 EVALUATION

The evaluation of the experiment took place by measuring the difference between the edge of the bridge and its center. The bridge was aimed from both sides and only the larger difference was recorded, see Figure 2. Each measurement was repeated four times. These differences are listed in Tables 4 and 5.

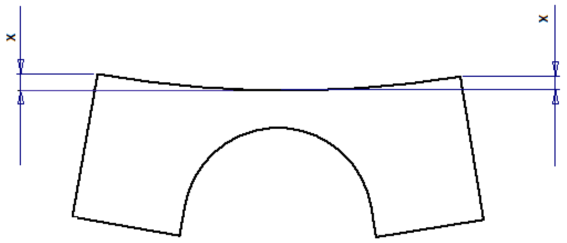

Fig. 2.Measuring of the sag

Twenty aluminum alloy bridges were produced, samples one and eleven were produced with exactly the same technological parameters. The only difference between the two samples was the preheat temperature used. In this way, pairs were formed from all the samples produced. By comparing these pairs, it was found that in half of the pairs preheating significantly affected the deformation of the bridge, with values over half a tenth of a millimeter. For pairs number six and ten, there was a slight positive influence, the differences in deflection were over two tenths of a millimeter. The first pair did not show significant improvement or deterioration. The ninth pair shows a slight deterioration, with the sag worsening by 4 hundredths of a millimeter. The least favorable result was measured for the eighth pair, where the difference is almost a tenth of a millimeter. Furthermore, it is necessary to note that sample eighteen has an unusually high deviation value. This deviation may be caused by manufacturing error or human factor during handling. The average deflection for bridges made without preheating is 0.118 mm, while the average deflection for products with preheating is 0.061. By comparing these values, we can say that preheating for aluminum alloy reduces the deformation by 0.056 mm.

Table 4. Measured values for bridges made of aluminum alloy AlSi10Mg

AlSi10Mg	**No. sample**	**1 [mm]**	**2 [mm]**	**3 [mm]**	**4 [mm]**
Without pre-heat	1	0.07	0.068	0.066	0.068
	2	0.194	0.195	0.199	0.2
	3	0.227	0.226	0.228	0.227
	4	0.219	0.22	0.216	0.217
	5	0.146	0.146	0.149	0.143
	6	0.057	0.056	0.059	0.06
	7	0.085	0.085	0.086	0.084
	8	0.047	0.047	0.045	0.045
	9	0.052	0.05	0.054	0.052
	10	0.084	0.083	0.085	0.084
With pre-heat	11	0.078	0.077	0.073	0.072
	12	0.041	0.04	0.043	0.044
	13	0.077	0.078	0.077	0.076
	14	0.026	0.028	0.028	0.03
	15	0.067	0.067	0.069	0.065
	16	0.017	0.02	0.014	0.017
	17	0.015	0.014	0.017	0.018
	18	0.14	0.143	0.144	0.141
	19	0.092	0.092	0.092	0.092
	20	0.061	0.06	0.061	0.062

Stainless steel bridges were evaluated similarly to aluminum bridges. Fifteen pairs were formed. For six bridges, preheating had a big impact, the deflection decreased by more than half a tenth of a millimeter. In the case of three other pairs, the preheating was milder, the deflection values were around four hundredths of a millimeter. Another four pairs showed that the preheating had a very small effect, the deflection did not change by more than two hundredths of a millimeter. The other two pairs show the negative impact of preheating, the values of these deflections are around three hundredths of a millimeter. The average deflection of bridges made without preheating is 0.137 mm. Bridges made with preheat have an average deviation of 0.092 mm. By comparing these values, we can say that preheating for aluminum alloy reduces the deformation by 0.045 mm.

Table 5. Measured values for bridges made of 316L

316L	**No. sample**	**1 [mm]**	**2 [mm]**	**3 [mm]**	**4 [mm]**
Without pre-heat	1	0.12	0.123	0.124	0.121
	2	0.134	0.134	0.135	0.133
	3	0.212	0.216	0.213	0.215
	4	0.146	0.15	0.15	0.146
	5	0.12	0.116	0.12	0.116
	6	0.135	0.137	0.135	0.133
	7	0.113	0.114	0.115	0.114
	8	0.09	0.092	0.091	0.091
	9	0.113	0.109	0.115	0.111
	10	0.186	0.187	0.186	0.185
With pre-heat	11	0.198	0.194	0.196	0.196
	12	0.032	0.03	0.03	0.032
	13	0.093	0.093	0.094	0.092
	14	0.137	0.136	0.136	0.135
	15	0.225	0.227	0.226	0.222
	16	0.08	0.078	0.081	0.077
	17	0.069	0.07	0.068	0.069
	18	0.177	0.177	0.175	0.179
	19	0.094	0.098	0.1	0.1
	20	0.15	0.151	0.152	0.151

The measurement showed that preheating has a positive effect on the residual stress in both materials. The measurement also showed that aluminum alloy is less susceptible to residual stress compared to stainless steel. Aluminum alloy has less than two hundredths less value of average deflection for bridges produced without preheating. In the case of bridges made with preheating, this difference is up to three hundredths.

4 CONCLUSION

It is clear from previous research that each material behaves differently during this production and the input parameters for the perfect production of one material cannot be applied to another material with the same results. In all research where improvements were achieved using preheating, attention is drawn to the fact that all input parameters must be in balance and the mere application of preheating without sufficient balance of other parameters can have a negative effect on production.

Fifty bridges were made in this experiment. Twenty bridges were made of aluminum alloy AlSi10Mg. Bridges from this alloy were made on a Renishaw RenAM 500E machine. These bridges were divided into two halves. The first half was made without preheating and the second with base plate preheating. The remaining thirty bridges were made using the same principle, but from stainless steel 316L. To evaluate the experiment, the deflection in the center of the bridge was measured. The measured values show that preheating has a positive impact on both of these materials. The aluminum alloy was more affected by the preheating, the measured deflection value decreased by 0.056mm on average. For stainless steel, a smaller impact of preheating is observed, the measured deflection value decreased by 0.045 mm on average.

REFERENCES

[1] MERTENS, Raya,at al., 2018. Application of base plate preheating during selective laser melting. Procedia CIRP [online]. 74, 5-11 [cit. 2022-03-18]. ISSN 22128271. from: doi:10.1016/j.procir.2018.08.002

[2] MERTENS, Raya Selective. Laser melting of aluminum, Hastelloy X, tool steel and cobalt-chrome. Arenberg, 2018.Disertation thesis . ARENBERG DOCTORAL SCHOOL- Faculty of Engineering Science

[3] BOES, Joe. et al. , 2018. Microstructure and mechanical properties of X65MoCrWV3-2 cold-work tool steel produced by selective laser melting. Additive Manufacturing [online]. 23, 170-180 [cit. 2022-03-18]. ISSN 22148604. from: doi:10.1016/j.addma.2018.08.005

[4] VRANCKEN, Bey, BULS, Sam. KRUTH, Jean-Pierre. a HUMBEECK, Jan Van. 2016. Preheating of Selective Laser Melted Ti6Al4V: Microstructure and Mechanical Properties. VENKATESH, Vasisht, Adam L. PILCHAK, John E. ALLISON, et al., ed. Proceedings of the 13th World Conference on Titanium [online]. Hoboken, NJ, USA: John Wiley, 2016-05-06, s. 1269-1277 [cit. 2022-03-18]. ISBN 9781119296126. from: doi:10.1002/9781119296126.ch215

[5] Kempen, Karolien, LOWERING THERMAL GRADIENTS IN SELECTIVE LASER MELTING BY PRE-HEATING THE BASEPLATE. KU LEUVEN [online]. 2013. From:https://limo.libis.be/primo-explore/fulldisplay?docid=LIRIAS1748401&context=L&vid=Lirias&search_scope=Lirias&tab=default_tab&fromSitemap=1

[6] KRELL, Julian. RÖTTGER, Arne. GEENEN, Karina. a THEISEN, Werner, 2018. General investigations on processing tool steel X40CrMoV5-1 with selective laser melting. Journal of Materials Processing Technology [online]. 255, 679-688 [cit. 2022-03-18]. ISSN

09240136.from: doi:10.1016/j.jmatprotec.2018.01.012

[7] ALI, Haider. MA, Le. GHADBEIGI, Hassan. a MUMTAZ, Kamran. 2017. In-situ residual stress reduction, martensitic decomposition and mechanical properties enhancement through high temperature powder bed pre-heating of Selective Laser Melted Ti6Al4V. Materials Science and Engineering: A [online]. 695, 211-220 [cit. 2022-03-18]. ISSN 09215093. from: doi:10.1016/j.msea.2017.04.033

[8] KRUTH, Jean-Pierre. Assessing Influencing Factors of Residual Stresses in SLM using a Novel Analysis Method. KU LEUVEN [online]. 2010. From: https://limo.libis.be/primo-34 explore/fulldisplay?docid=LIRIAS66154&context=L&vid=Lirias&search_scope=Lirias&tab=default_tab&fromSitemap=1

[9] ZHANG, Baicheng. DEMBINSKI, Lucas. a CODDET, Christian. 2013. The study of the laser parameters and environment variables effect on mechanical properties of high compact parts elaborated by selective laser melting 316L powder. Materials Science and Engineering: A [online]. 584, 21-31 [cit. 2022-03-18]. ISSN 09215093 from:: doi:10.1016/j.msea.2013.06.055

Authors addresses

[1] *Jiri Hajnys, VSB-TU Ostrava, 17.listopadu 15, +420 596 999 064, jiri.hajnys@vsb.cz*
[2]*Marek Pagac, VSB-TU Ostrava, 17.listopadu 15, +420 597 321 285, marek.pagac@vsb.cz*
[3]*Jiri Kratochvil, VSB-TU Ostrava, 17.listopadu 15, +420 596 994 476, jiri.kratochvil@vsb.cz*

Contact person

* *Jiri Hajnys, VSB-TU Ostrava, 17.listopadu 15, +420 596 999 064, jiri.hajnys@vsb.cz*