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Effects of Heat Treatment on Additively Manufactured 316L Stainless Steel

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The microstructure and mechanical properties of selectively laser melting (SLM)-manufactured 316L stainless steele were evaluated by scanning electron microscopy, tensile testing at ambient temperature and Charpy impact test. These samples were compared with as-built samples. Following heat treatment conditions were used: 500 °C for 2/4 hours, 650 °C for 2 hours and 900 °C for 1 hour. Cooling took place in furnace and in furnace with opened valve. Compared to as built samples the heat treatment at lower temperature negatively influenced elongation but increased the amount of energy absorbed by material during fracture.

Keywords: Additive manufacturing Heat treatment, Stainless steel, 316L

1 Introduction

Additive manufacturing has been lately evolving rapidly. It advanced from printing prototypes and non-functional parts to printing geometrically complex components and functional parts with minimal shape limitations. One of the additive manufacturing methods suitable for metals and alloys is selective laser melting (SLM) a powder bed process with laser melting layers of powder [1]. Parts are built in an inert atmosphere layer-by-layer and wide range of materials can be used – such as titanium alloys, stainless steels, nickel-base superalloys or aluminium alloys [2][5].

Components fabricated by additive manufacturing can have large residual stress, pores, defects or elemental segregation. The residual stress in SLM fabricated 316L stainless steel can reach 500 Mpa [6]. Optimalization of SLM process and heat treatment is usually used to minimize these issues. Apart from heat treatment the influence of powder speed, laser power, the size of powder etc. has been studied. Mechanical properties of additively manufactured components are heavily affected by microstructural defects [7][8]. Involving post-processing heat treatment to optimize SLM process is integral step to improve mechanical and functional properties of components before placing them in service [4][9].

316L is an austenitic stainless steel commonly used in aeronautics industry, in automotive, for medical equipment, in petrochemical and chemical industry, in food processing, for military use and in jewellery. Using additive manufacturing for complex and complicated parts instead of conventional methods is more effective and the amount of waste material is decreased [3][4]3[11].

In this paper, the mechanical performance of SLM manufactuerd 316L samples in relation to varying post-processing heat treatment conditions were investigated. Heat treated samples were commpared to samples with no post-processing (as-built samples).

2 Experimental program

2.1 Material and heat treatment

Testing samples were made on manufacturing systems on EOS M 290. The system has following parametres: Yb-fibre laser, maximum power of 400 W, F-theta lens and the building chamber has dimensions (WxDxH) 250 mm x 250 mm x 325 mm [11]. The chemical composition of 316L steel is listed in Tab. 1.

Tab. 1 *Chemical composition of 316L steel*

Wt [%]	C	Mn	Si	P	S	Cr	Mo	Ni	N	Fe
AISI316L	0.03	2.0	0.75	0.045	0.03	16.0-18.0	2.0-3.0	10.0-14.0	0.1	Bal.

As can be seen in Fig. 1 24 samples for tensile testing and 25 samples for Charpy impact testing were manufactured. Two samples from both sets remained as-built. The rest underwent various heat treatment. Summary of used heat tratment conditions is specified in Tab. 2 in a temperature – time on temperature – cooling format. Cooling took place in closed furnace or in furnace with opened valve.

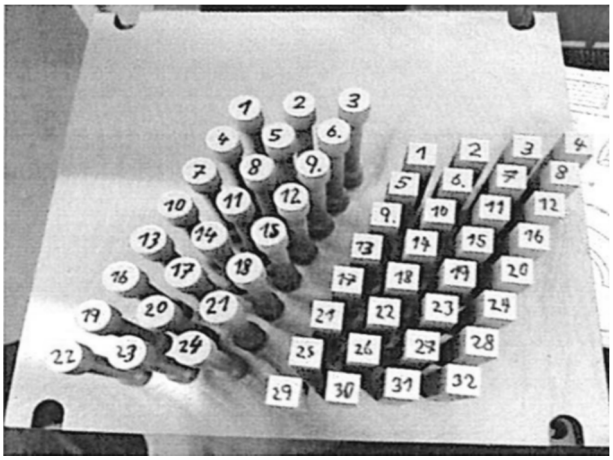


Fig. 1 *Samples for tensile testing and Charpy impact testing*

Tab. 2 *Summary of used heat threatment conditions*

No.	Heat treatment conditions
1	650 °C - 2hrs - furnace
2	650 °C - 2hrs - valve
3	500 °C - 4hrs - furnace
4	500 °C - 4hrs - valve
5	500 °C - 2hrs - furnace
6	500 °C - 2hrs - valve
7	900 °C - 1hr - furnace
8	900 °C - 1hr - valve

The temperature of 650 °C was chosen to eliminate residual stress in material. Lower temperatures of annealing (500 °C) were used to decrease the possibility of forming M23C6 precipitates. Forming of carbides is slower at lower temperatures. Heating 316L steel to 900 °C can cause intergranular corrosion inflicted by M23C6 precipitates but was selected to evaluate its benefits with residual stress.

2.2 Microstructure and mechanical testing

Analysis of microstructure was done on BX61 Olympus light microscope, Zeiss EVO 25 (LaB6 cathode) and Tescan VEGA 3 (Tungsten cathode) scanning electron microscopes (SEM). Etched metallographic samples were inspected as well as fracture surfaces. Tensile testing was performed on Zwick Roell Z250 materials testing machine with central ball-lead screw at ambient temperature. Charpy impact testing was performer on Zwick Roell RKP450 pendulum impact tester. Hardness HV10 was measured both on top cross section and side cross section.

3 Results and discussion

When the microstructures were observed under the light microscope, it was possible to see laser tracks crossing at 67° angle on the as-built sample (Fig. 2 a). As the samples were heat treated at hight temperatures, the laser tracks were disappearing (Fig. 2 b-c). Melt pool boundaries are disappearing at temperatures around 700 °C. At 900 °C the boundaries starts to thin and as can be seen in Fig. 2 the melt pool boundaries are almost completely dissolved. The cellular structure that is common in SLM manufactured parts is also dissolving with higher temperatures. Cell walls have higher dislocation density. Melt pools and cellular structures are both chemical segregations and once they are dissolved, the grains are homogeneous[1][12].

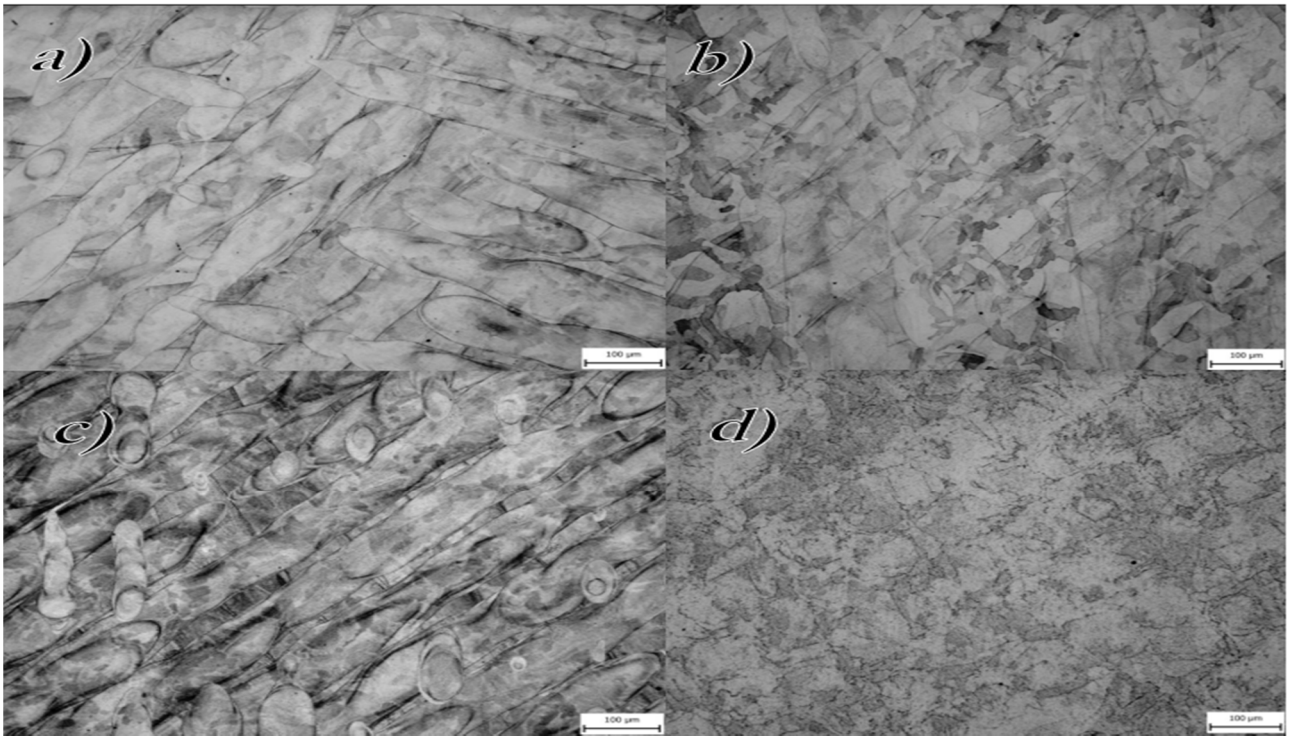


Fig. 2 *Light micrographs of top cross sections of various heat treatments – a) as built sample; b) 500 °C – 2hrs – valve; c) 650 °C – 2hrs – furnace; d) 900 °C – 1hr - furnace*

On the Fig. 3 can be seen SEM micrograph of sample 500 °C – 2hrs – valve with a energy dispersive spectroscopic (EDS) map. Cellular structure can be seen, but elements are evenly distributed. On the other hand in the Fig. 4 of sample 900 °C – 1hr – furnace it is clearly wisible, that cellular structure is almoct completely dissolved and new particles (σ precipitates) are forming. The particles are situated on the boundaries of austenite grains and have higher density of Cr and Mo[3].

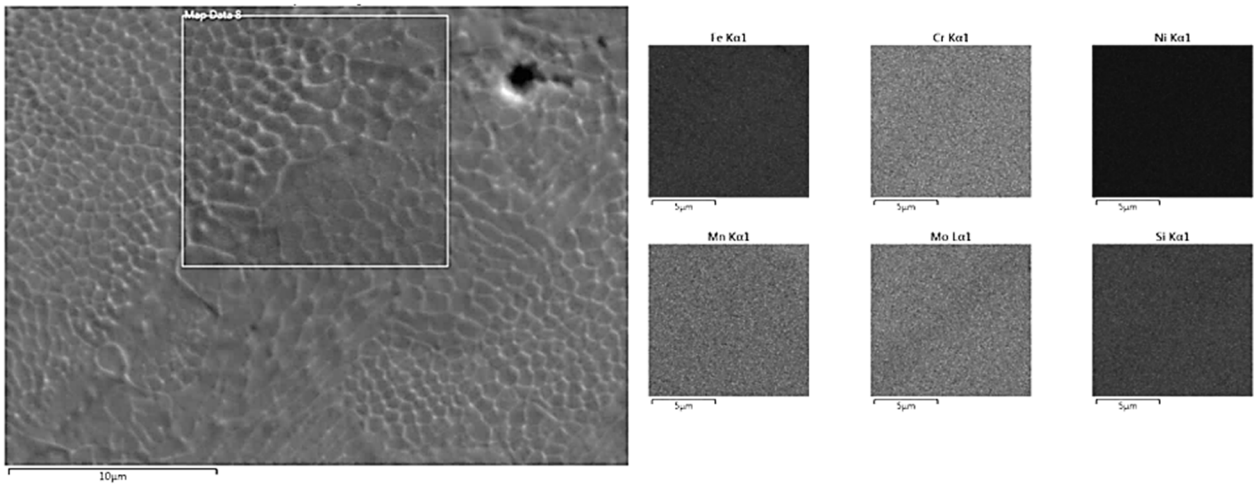


Fig. 3 *EDS of sample with heat treatment of 500 °C – 2hrs - valve*

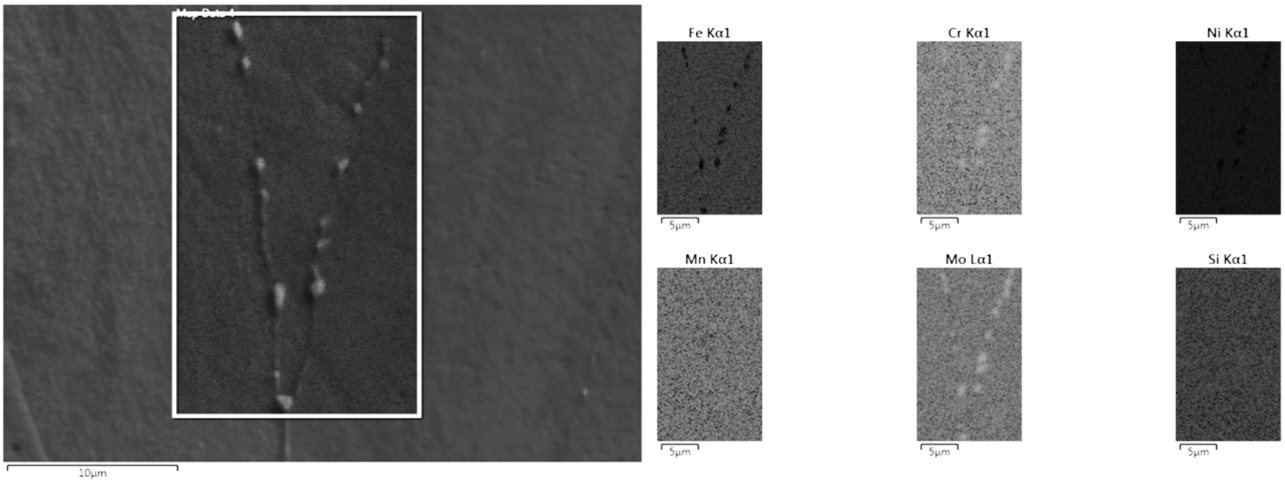
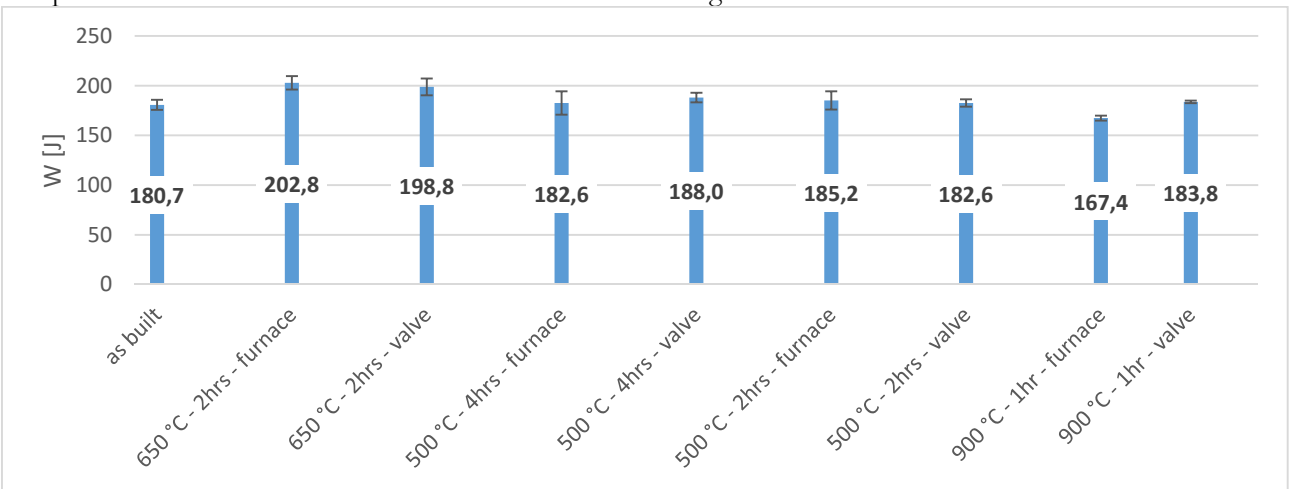


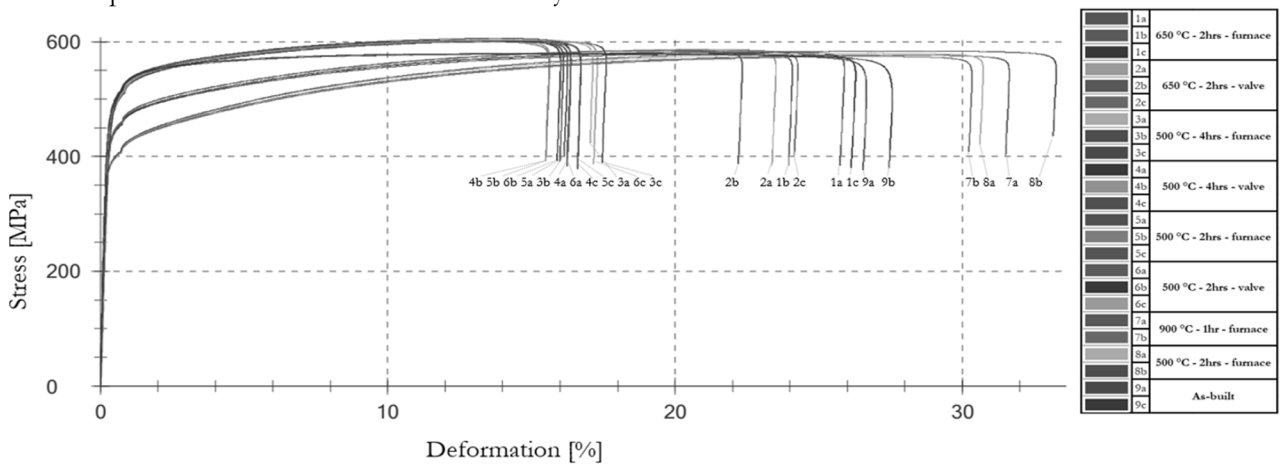
Fig. 4 *EDP of sample with heat treatment of 900 °C – 1hr – furnace*

In the Graph 1 is a summary of results from Charpy impact testing. Every executed heat treatment except 900 °C – 1hr – furnace are the levels of absorbed energy higher than in as built samples. This can be caused by forming M23C6 precipitates or intergranular corrosion.

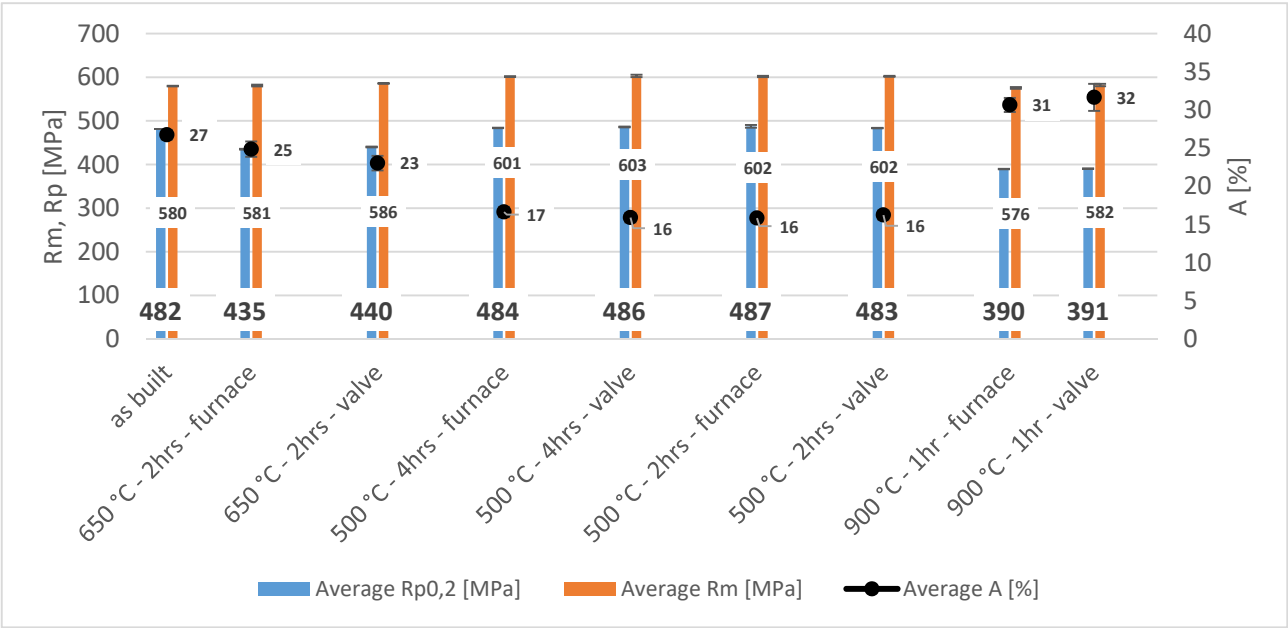


Graph 1 *Results of Charpy impact testing – amount of energy absorbed by material during fracture*

As seen in Graph 2 and Graph 3 heat treatment at lower temperatures resulted in decrease of elongation during tensile testing. In heat treatment at the temperature of 900 °C is elongation slightly higher than in as built samples. Similar trend can be seen in yield strength. In comparison ti as built samples heated to 900 °C have lower yield strength. In ultimate tensile strenght are not any radical diferences between as built samples and heat treated samples.



Graph 2 *Stress – deformation graph*



Graph 3 *Results of tensile testing*

In Tab. 3 is a summary of measured hardness HV10. Average values do not differ too much from as built sample. The lowest average hardness values were measured on sample 900 °C – 1hr – furnace on both top cross section and side cross section.

Tab. 3 *Hardness HV10*

	HV10 - top cross section				HV10 - side cross section			
	1	2	3	Average	1	2	3	Average
as built	208	210	213	210	211	215	219	215
650 °C - 2hrs - furnace	200	198	197	198	199	198	194	197
650 °C - 2hrs - valve	197	198	199	198	199	203	205	202
500 °C - 4hrs - furnace	208	214	212	211	223	226	225	225
500 °C - 4hrs - valve	210	207	208	208	219	221	219	220
500 °C - 2hrs - furnace	209	215	213	212	210	213	219	214
500 °C - 2hrs - valve	216	215	215	215	215	218	217	217
900 °C - 1hr - furnace	193	187	185	188	184	182	194	187
900 °C - 1hr - valve	183	188	190	187	203	188	194	195

4 Conclusions

This study investigated the effects of heat treatment on mechanical properties and microstructure of additively manufactured stainless steel 316L. Three different heat treatment temperatures were used: 500 °C, 650 °C and 900 °C with cooling in closed furnace or in furnace with opened valve. Heat treated samples were compared with as built samples.

The mictrostructue and mechanical properties of stainless steel 316L are affected by heat hreatment conditions. Lower temperatures (recovery process) causes decrease of elongation but increse in the amount of absobed energy during fracture. Cellular structure and melt pools are not dissolving.

Higher temperatures (homogenisation process) causes increase of elongation. Samples treated at 900 °C reached elongation values 30 % - in comparison samples treated at 500 °C had elongation valus as low as 16 %.

At the temperature of 900 °C was clearly seen how melt pools and cellular structure were dissolving. In the microstructure were forming new particles identified as σ precipitates. Since these particles were foming on the boundaries they could have contributed to the change of mechanical properties. The results of HV10 hardness measurements does not show any grand differences.

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References

[1] RONNEBERG, T., DAVIES, C.M., HOOPER, P.A. (2020). Revealing relationship between porosity, microstructure and machanical properties of laser powder bed fusion 316L stainless steel through heat treatment. In: *Materials and Design,* Vol. 189, pp.1-14. Elsevier BV, Amsterdam. ISSN: 0264-1275

[2] YADOLLAHI, A., SHAMSAEI, N., THOMPSON, S.M., SEELY, D.V. (2015). Effects of process time interval and heat treatment on the mechanical and microsctructural properties of direct laser depostited 316L stainless steel. In: *Materials Science & Engineering A*, Vol. 644, pp. 171-183. David Publishing Company, Wilmington. ISSN: 0921-5093

[3] CHAO, Q., THOMAS, S., BIRBILIS, N., CIZEK, P., HOGSON, D.F. (2021). The effect of post-processing heat treatment on the microstructure, residual stress and mechanical properties of selective laser melted 316L stainless steel, In: *Materials Science & Engineering A*, Vol. 821, pp. 1-13. David Publishing Company, Wilmington. ISSN: 0921-5093

[4] SHIN, W.S., SON, B., SONG, W., SOHN, H., JANG, H., KIM, Y.J., PARK, C. (2021). Heat treatment effect on the microstructure, mechanical properties, and wear behaviors of stainless steel 316L prepared via selective laser melting, In: *Materials Science & Engineering A*, Vol. 806, pp. 1-14. David Publishing Company, Wilmington. ISSN: 0921-5093

[5] KUČEROVÁ, L., ZETKOVÁ, I., JENÍČEK, Š., BURDOVÁ, K. (2020). Hybrid parts produced by deposition of 18Ni300 maraging steel via selective laser melting on forged and heat treated advanced high strength steel, In: *Additive Manufacturing*, Vol. 32, pp. 1-11. Univerzita J. E. Purkyně, Ústí nad Labem. ISSN: 2214-8604

[6] WU, A.S., BROWN, D.W., KUMAR, M. (2014). An Experimental Investigation into Additive Manufacturing-Induced Residual Stresses in 316L Stainless Steel, In: *Metallurgical and Materials Transactions A*, Vol. 45, pp. 6260-6270. Springer Science+Business Media. Berlin/Heidelberg. ISSN: 1073-5623

[7] LIVERANI, E., TOSCHI, S., CESCHINI, L., FORTUNATO, A. (2017). Effect of selective laser melting (SLM) process parameters on microstructure and mechanical properties of 316L austenitic stainless steel, In: *Journal of Materials Processing Technology,* Vol. 249, pp. 255-263. Elsevier BV, Amsterdam. ISSN: 0924-0136

[8] YUAN, W., CHEN, H., CHENG, T., WEI, Q. (2020). Effects of laser scanning speeds on different states of the molten pool during selective laser melting: Simulation and experiment, In. *Materials and Design,* Vol. 189, pp.1-14. Elsevier BV, Amsterdam. ISSN: 0264-1275

[9] WILLIAMS, R.J., VECCHIATO, F., KELLEHER, J., WENMAN, M.R., HOOPER, P.A., DAVIES, C.M. (2020) Effects of heat treatment on residual stresses in the laser powder bed fusion of 316L stainless steel: Finite element predictions and neutron diffraction measurement, In. *Journal of Manufacturing processes,* Vol. 57, pp. 641-653. Elsevier BV, Amsterdam. ISSN:1526-6125

[10] HANZL, P., ZETKOVÁ, I., KUČEROVÁ, L. (2019). Structural Changes and Microstructure of Maraging Steel Lattice Structures using Additive Manufacturing, In: *Additive Manufacturing*, Vol. 19, No. 1, pp. 37-41. Univerzita J. E. Purkyně, Ústí nad Labem. ISSN: 2214-8604

[11] MORAVEC, J., DIKOVITS, M., BEAL, C., NOVAKOVA, I., CHANDEZON, R. & SOBOTKA, J. (2017). Selection of the Proper Diffusion Welding Parameters for the Heterogeneous Joint Ti Grade 2/AISI 316L, In: *Manufacturing Technology*, Vol. 17, No. 2, pp. 231-237. Univerzita J. E. Purkyně, Ústí nad Labem. ISSN: 2214-8604

[12] KUČEROVÁ, L., BYSTRIANSKÝ, M., JENÍČEK, Š. (2019). Thermo-mechanical Treatment of 0.4C-0.6Mn-2Si Steel with Various Soaking and Annealing Hold Temperatures, In: *Manufacturing Technology*, Vol. 19, No. 1, pp. 95-100. Univerzita J. E. Purkyně, Ústí nad Labem. ISSN: 2214-8604