Fatigue Life and Surface Quality of Laser Powder Bed Fusion Manufactured 316L Parts by Laser Heat Treatment

Timo Rautio
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
0000-0002-9467-9805

Mikko Hietala
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
0000-0003-4534-4475

Marika Hirvimäki
Research Group of Laser Material Processing
LUT University
Lappeenranta, Finland
0000-0002-4769-4009

Jarmo Mäkikangas
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
jarmo.makikangas@oulu.fi

Jani Kumpula
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
jani.kumpula@oulu.fi

Antti Järvenpää
Kerttu Saalasti Institute
University of Oulu
Nivala, Finland
0000-0002-4309-4786

***Abstract*—Laser heat treatment (LHT) with two sets of energy inputs was applied to laser powder bed fusion (LPBF) manufactured 316L parts and its effects were studied in this research. LHT processed structures were compared to the as built material in terms of microstructural analysis, hardness measurements and mechanical testing, surface roughness and fatigue life. The results show that the LHT can be used to enhance the material properties of LPBF manufactured 316L parts in several ways. With the higher energy density, the surface roughness could be nearly halved while the fatigue strength was simultaneously doubled with no meaningful recorded loss in hardness or ultimate tensile strength. Microstructural evolution at the surface due to the LHT resulted in a mixture of coarse columnar dendrite and cellular grain structure. According to the findings of this work, LHT appears as an attractive tool for enhancing the properties of LBPF 316L.**

***Index Terms*—LPBF, 316L, Laser heat treatment, Bending fatigue**

I. Introduction

Additive manufacturing (AM) of metal parts is steadily gaining ground and has already been adopted by many industries, most noticeably ones including automotive [1], biomedical [2] and aerospace [3]. Laser powder bed fusion (LPBF) is the most widely used technique and can be utilized for printing many kinds of metals and alloys. In this study, we focus on one of the most popular stainless steels and materials in the LPBF industry in general, 316L. The printing process and the microstructure and mechanical properties of the LPBF 316L are well known [4]. While the material has mechanical properties beyond the wrought materials, further improvement could be achieved with a suitable post processing method. For example, Sohrabpoor et al. studied the effect of various quenching and tempering strategies and reported mechanical properties and fracture characteristics over wrought specimens [5].

Various types of laser processes have been implemented in the past with the intention of improving the material properties by surface modification. Laser heat treatment (LHT) is one of these, as shown by Zhang et al. in [6] where they focused on the LHT of alloy 800H and it's effect on microstructure and properties. The surface roughness of LPBF manufactured AlSi10Mg parts could also be improved utilizing LHT [7]. There are also several studies that have focused spesifically on the 316L material and on improving it's properties with the aid of laser processing. Mikolajczak et al. used laser borided composite layer on the top of 316L and were able to increase the hardness and wear resistance of the material [8]. On the other hand, laser surface modification can be utilized to imporove the biocompatibility and corrosion resistance of the 316L as shown by Balla et al. [9].

Fatigue properties of a material can be the key determining factor in many designs as they are directly related to weight reduction optimization and to the life time the part is targeted for. There are a few works in the open literature where the fatigue properties of the LPBF manufactured 316L have been investigated. These include a recent work by Beard et al. [10] where they compared LPBF 316L to wrought counterparts and found the latter to possess inferior fatigue performance due to higher plasticity under load. Roman et al. studied the effect of laser shock processing on 316L welds and the subsequent improvement on the fatigue life [11]. In the present work, we focus on the LHT of 316L and its effects on the material properties. The microstructural evolution of the surface together with the effect on hardness will be evaluated. Furthermore, the surface quality and the effect on mechanical properties and fatigue life on flexural bending will be analyzed.

II. MATERIAL AND METHODS

A. Manufacturing of the samples for laser heat treatment experiments.

Sample manufacturing was performed with the LPBF technique utilizing an SLM 280 HL machine with a 280 x 280 mm platform. The 316L powder was supplied by Carpenter Additive of Carpenter Technology Corporation (UK) and had a particle size distribution in the range of 15-45 µm and a mean size of 31.7 µm. The powder composition is detailed in Table I. All samples were produced with the same parameters which were as follows: laser power (P) of 200 W, speed (v) of 800 mm/s, hatch spacing (h) of 120 µm, layer thickness (t) of 30 µm and laser spot diameter 0.1 mm with a Gaussian laser profile. Applying these values to Eq. 1 results to an energy density of 69.4 J/mm^3

$$E = \frac{P}{v \cdot h \cdot t} \tag{1}$$

Samples for the bending fatigue experiments were printed in 90° orientation in the size of 30 x 90 x 2 mm. These specimens were printed in a rectangular shape, then laser heat treated and finally machined to the specific hourglass shape. Tensiles were similarly prepared using printed plates in the size of 20 x 120 x 2 mm. In addition, smaller samples were prepared for microstructural analysis. Samples did not go through any kind of heat treatment besides the laser HT.

B. Laser heat treatments.

The mechanical properties and the bending fatigue performance of the LPBF fusion manufactured 316L parts were evaluated in as built condition and using LHT with two laser processing parameters. LHT experiments were carried out with a diode pumped continuous power Ytterbium-doped: yttrium aluminium garnet (Yb:YAG) laser (Trumpf HLD 4002) with a maximum power of 4 kW, wavelength of 1030 nm and optical fibre diameter of 200 µm. The laser head was controlled by a 6-axis robot and the laser beam was directed perpendicular to the work piece. Argon shield gas was fed to the area under heat treatment during the process at 30 L/min. The parameter sets used for the LHT are summarized in Table II (focus in relation to the plate top). All bending fatigue samples and tensiles were LHT processed from both sides, but the samples for microstructural analysis were treated from one side only.

TABLE I
CHEMICAL COMPOSITION OF THE 316L POWDER.

Fe	C	Si	Mn	P	S	Cr	Ni	Mo	N
Balance	0.02	0.54	1.24	$<$0.005	0.004	16.72	12.14	2.38	0

TABLE II
USED PARAMETERS FOR THE LASER HEAT TREATMENTS.

	Power [W]	Speed [mm/s]	Focus	Hatch spacing [mm]
Set 1	500	16	+40	1.5
Set 2	900	16	+40	1.5

C. Characterization.

Universal material testings machine (Instron 8802) was utilized for the tensile tests and were conducted according to the standard SFS-EN ISO 68921:2016 with a constant loading rate of 0.5 mm/min. Surface hardness measurements were conducted with an Innovatest Falcon 511 using Vickers indenter with 0.2 kg load and repeated 10 times for each case. Tests were performed perpendicular to the LHT. Samples for metallographic analysis were polished and etched before analysis with optical microscope (Keyence VHX 2000 E). Reversed flexural bending machine by Carl Schenck was used to analyze the fatigue properties of the material in differenct states. Stress ratio of R=-1 and frequency of 10 Hz were used with a stress range from 200 MPa to 900 MPa with a runout of 2 million cycles. Bending fatigue testing was conducted in room temperature which was ensured with air cooling.

III. RESULTS AND DISCUSSION

A. Microstructure of the printed 316L and the effect of laser heat treatment.

The microstructure of the LPBF manufactured 316L after the printing is presented in Fig. 1, which clearly shows the building direction from left to right identifiable from the melt pool boundaries formed by the laser scanning tracks overlapping each other. These melt pool boundaries form a fish scale pattern typical for the LPBF technique. In a closer inspection, the printed material can be seen to mainly consist of columnar grains with a very fine sized (1-2 microns) substructure of cellular grains. These features are shown in the high magnification at the inset of Fig. 1 which also shows that some of the columnar grains have grown across the melt pool boundaries by epitaxial growth. There was no notable porosity visible for optical microscopy in any of the investigated cross-sections.

Overview of the sample microstructure after the LHT with 900 W is shown in Fig 2. Only the surface shown at the bottom of the sample was treated and a clear microstructural change is visible, reaching 200-300 µm beneath the surface. Compared to the top of the sample which was not treated, a clear distinction in terms of surface roughness is also visible. The surface in as built condition at the top side has a rough appearance on the contrary to the smooth look of the bottom surface which received the LHT. In addition to the clearly visible microstructural changes right beneath the surface, the color change in the etching can be used to estimate the heat affected zone (HAZ) continues over 500 µm deep.

The cross-sections of the LHT samples with 500 W parameters are presented in Fig. 3 and with 900 W in Fig. 4. The cross-sectional area presented in these figures is from the middle of the sample surface where the effect of the LHT was most prominent in both cases. It is evident from the figures that using a higher energy density results in an effect that penetrates much deeper in the material. On the left side of the Fig. 3 there is an area where the as built material is still present after the 500 W LHT processing. It can be seen that there is

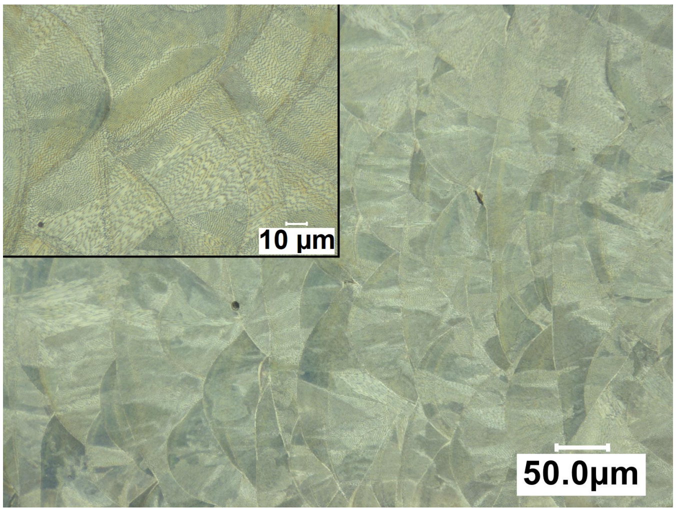

Fig. 1. Microstructure of the laser powder bed fusion manufactured 316L.

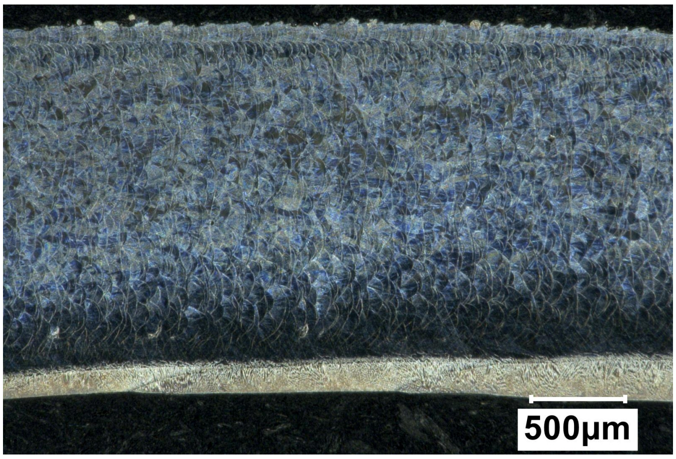

Fig. 2. Overview of the laser heat treated 316L by 900 W.

a clear microstructural change about 500 µm wide along the surface area in the middle of the sample and recrystallization has occurred. Heat dissipation is higher at the edges resulting to more pronounced effect in the middle of the sample. HAZ in the Fig. 3 can be seen to reach nearly 300 µm deep.

Higher energy input with 900 W LHT results in a markedly wider microstructural change and recrystallization below the surface as shown in Fig. 4. Approximately 250-300 µm wide area has changed to a structure consisting of cellular grains and columnar dendrites. The average grain size is much larger than of the printed substructure and is very similar to the structure of a laser weld in a LPBF manufactured 316L [12]. Furthermore, the near surface area has a very fine structure and grain coarsening can be evidenced when moving deeper into the material. The HAZ can be seen to extend over 600 µm deep. The surface appearance difference is also clear when comparing the different LHT parameters used in Figures 3 and 4. Over 10 µm tall reminders of the non-melted powder particles are visible on the surface which 500 W LHT has not

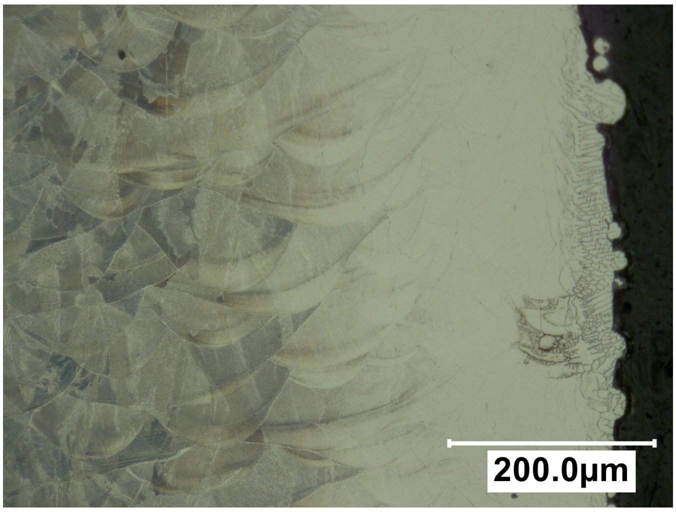

Fig. 3. Microstructure of the surface after laser heat treatment with 500 W.

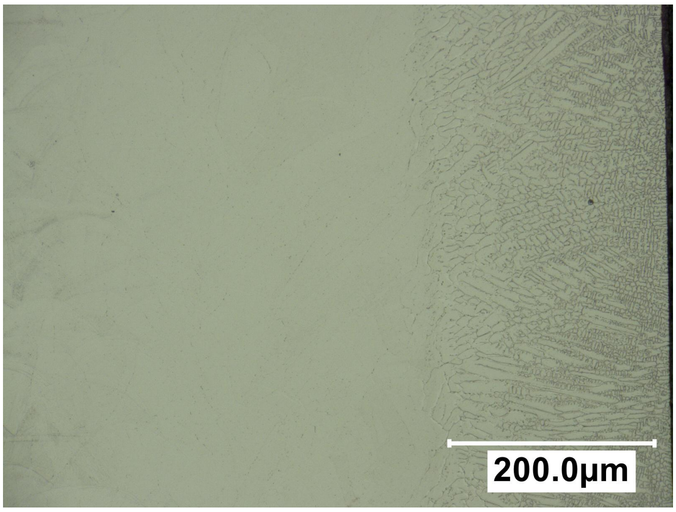

Fig. 4. Microstructure of the surface after laser heat treatment with 900 W.

been able to suppress. On the other hand, 900 W LHT shown in Fig. 4 has clearly smoothened the surface.

B. The Effect of Laser Heat Treatments on The Mechanical Properties and Hardness of 316L.

The effect of LHT on the mechanical properties of the material using laser power of 500 W and 900 W was investigated by using tensile testing. The engineering stress-strain results are plotted and shown in Fig. 5 and the corresponding values for yield strength (YS) and ultimate tensile strength (UTS) in MPa and elongation at break in % are collected in Table III. The resuls show that the LHT has a measureable effect on the strength of the material which is most prominent in the YS. Compared to the as built condition, using LHT with 500 W and 900 W reduces the YS by 10.1 % and 21.1 %, respectively. LHT changes the microstructure of the material to more coarse grained reducing the YS compared to the as built structure. It was shown that the higher power led to more

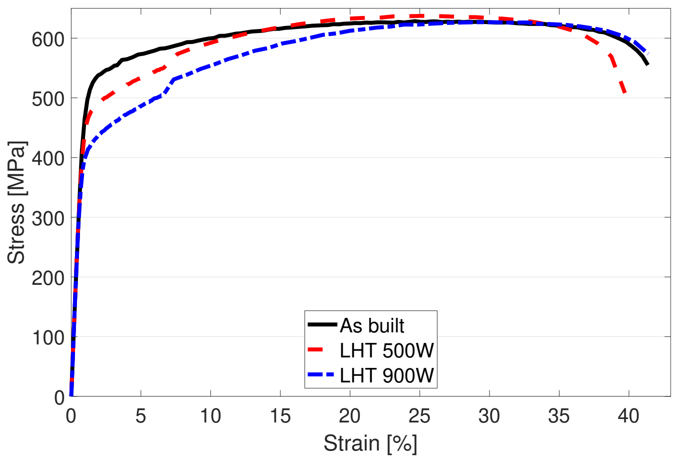

Fig. 5. Tensile test results for the LPBF manufactured 316L in as built and laser heat treated conditions.

TABLE III
YIELD STRENGTH (YS), ULTIMATE TENSILE STRENGTH (UTS) AND ELONGATION AT BREAK FOR THE LASER HEAT TREATED 316L

	As built 316L	LHT set 1	LHT set 2
YS [MPa]	495.3 ± 0.7	445.1 ± 2.5	390.9 ± 4.1
UTS [MPa]	628.7 ± 1,0	638.6 ± 1.1	623.7 ± 2.9
Elongation at break [%]	41.6 ± 0.2	38.9± 0.6	42.5 ± 1.0

area with coarse grain structure which shows also in the higher reduction of YS with the 900 W. However, the UTS of all three cases were very close to each other. With the 500 W LHT, a small increase was recorded and less than a percent drop after the 900 W LHT. Very subtle changes were recorded also in the elongation at break. The trend on the changes in tensile test results is similar to the effect of heat treatment at 600 °C for two hours where the YS drops but the UTS increases. It is also worth noting that the used sample dimensions with a 2 mm thickness gives a higher reduction in YS that would be seen in thicker samples. Increasing the sample thickness would reduce the volume of LHT processed area in proportion.

The surface hardness measurements in HV are presented in Fig. 6. Considering the measurement accuracy the structures have a very similar hardness properties in all measured cases. The as built hardness is the lowest at 224.8 HV and the increase by LHT with 500 W and 900 W results in approximately 4 and 2.5 HV higher results, respectively.

C. Surface Quality Properties of The Structures

Comparison of the surface quality in Ra to the as built structure after the LHT with 500 W and 900 W was conducted and these results are collected in Table IV. The as built structure has quite a coarse surface quality with an average Ra of around 8.7 µm. This surface is the one along the build direction which is usually rougher compared to the top surface. LHT with 500 W does not improve the surface quality as could be predicted from the cross-sectional images. The energy input is not high enough to considerably melt the surface features to smoothen the surface. However, applying 900 W

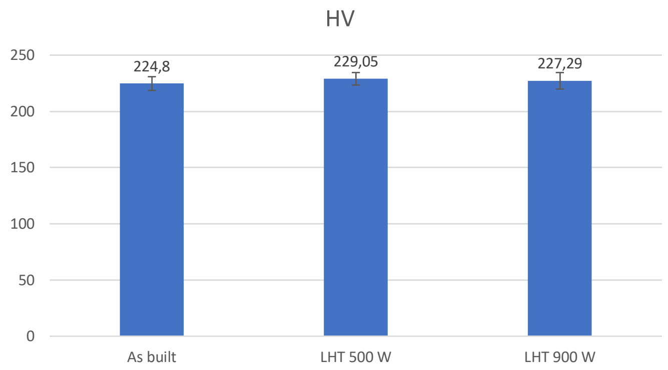

Fig. 6. Hardness of the laser powder bed fusion manufactured 316L in as built condition compared to the laser heat treated material.

LHT has clearly reduced the surface roughness resulting to a reduction of 44 %. Laser scanning back and forth results in an identifiable pattern in the surface that shows also in the surface roughness measurements. In the direction of the scanning tracks (LD) the roughness was measured lowest at 2.16 µm and perpendicularly (LP) at 4.86 µm.

D. The effect of laser heat treatment on the fatigue life of 316L.

The fatigue properties of the as built structure was compared to the LHT structures utilizing a flexural bending fatigue machine. Compared to axial fatigue testing, bending fatigue tests give more pronounced effect on the surface properties. The results are collected in SN curves presented in Fig. 7. The as built structure had a fatigue limit around 200 MPa and a moderate improvement could be achieved using the LHT at 500 W, but the low cycle fatigue properties had a more pronounced improvement. However, a clear improvement in both the low cycle and high cycle regimes was achieved with the 900 W LHT which is most likely enabled by the improved surface quality. There are various types of pores and cracks on the surface of LPBF material [13] which are closed by LHT processing resulting in a substantial reduction in fatigue crack nucleation sites. While not verified in this work, LHT most probably lowers the residual stresses on the surface which also increases the fatigue life of the parts. Such a reduction in residual stresses after laser heat treatment was recorded by Deenadaylan et al. in [14]. This phenomenon would partially explain why the 500 W treatment also resulted in improved fatigue life without the surface roughness improvement. On the other hand, the subtle change in hardness after the LHT

TABLE IV
THE EFFECT OF LASER HEAT TREATMENT ON THE SURFACE QUALITY (RA) OF 316L IN THE DIRECTION OF LASER TRACKS (LD) AND PERPENDICULARLY (LP).

	Average LD	σ	Average LP	σ
Printed	8.71	1.35	8.67	1.08
LHT 500 W	9.41	0.78	9.04	0.8
LHT 900 W	4.86	0.72	2.16	0.93

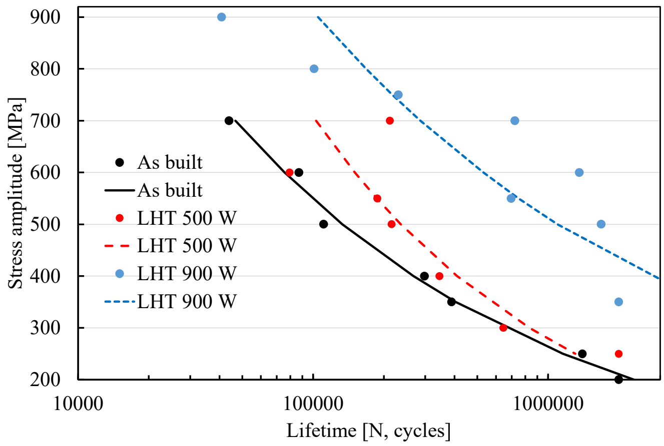

Fig. 7. Fatigue life of laser powder bed fusion manufactured 316L in as built condition compared to the laser heat treated material.

suggest that the microstructural changes had greater influence on the fatigue life as the residual stresses and hardness are usually related.

The fatigue limit of the 900 W series was almost double compared to the other series and the cyclic strength at all levels was also higher compared to the as built structure. The measurement points showed quite a large variation due to the area LHT processing had covered in the samples. While the whole narrowed sections of the samples were treated, it was afterwards noticed that more safe margin should have been left as some of the samples broke outside of the hourglass shape at the untreated base material. Nevertheless, this only further proves that the treatment increases the fatigue strength of the material considerably.

IV. Conclusions

The effect of laser heat treatments (LHT) at 500 W and 900 W was studied on the laser powder bed fusion manufactured 316L parts. Results were analyzed in terms of microstructural analysis, mechanical testing including hardness, surface quality and fatigue testing. From the results, the following conclusions can be drawn:

- Clear microstructural changes with both LHT parameters were achieved. Higher power resulted in coarse columnar dendrite and cellular grain structure compared to the fine structure of as built material.
- Coarser grain structure after the LHT resulted in reduced yield strength compared to the as built, but had very little effect on the ultimate tensile strength or the ductility. The hardness of the material was hardly affected by the treatment.
- Surface quality improvement was clearly achieved with the higher 900 W power, reducing it more than 44 %. 500 W was not high enough power to have a measureable improvement.
- The fatigue properties of the material were clearly improved with the LHT owing to the improved surface properties. The fatigue life was nearly doubled with the 900 W treatment and similar improvement in stress levels was recorded in all regimes.

V. Acknowledgements

The authors would like to acknowledge the financial support received from the Council of Oulu Region and the European Union (European Regional Development Fund) for the “Hybridi” and M3D projects.

References

[1] R. Agrawal and S. Vinodh, “Life cycle assessment of an additive manufactured automotive component,” in *Advances in Additive Manufacturing and Joining*, M. S. Shunmugam and M. Kanthababu, Eds. Singapore: Springer Singapore, 2020, pp. 219–228.

[2] H. Attar, S. Ehtemam-Haghighi, N. Soro, D. Kent, and M. S. Dargusch, “Additive manufacturing of low-cost porous titanium-based composites for biomedical applications: Advantages, challenges and opinion for future development,” *Journal of Alloys and Compounds*, vol. 827, p. 154263, 2020.

[3] F. Froes, *Additive manufacturing for the aerospace industry*. Amsterdam, Netherlands: Elsevier, 2019.

[4] X. Wang, J. A. Muñiz-Lerma, O. Sánchez-Mata, M. A. Shandiz, and M. Brochu, “Microstructure and mechanical properties of stainless steel 316l vertical struts manufactured by laser powder bed fusion process,” *Materials Science and Engineering: A*, vol. 736, pp. 27–40, 2018.

[5] H. Sohrabpoor, V. Salarvand, R. Lupoi, Q. Chu, W. Li, B. Aldwell, W. Stanley, S. O'Halloran, R. Raghavendra, C.-H. Choi, and D. Brabazon, “Microstructural and mechanical evaluation of post-processed SS 316l manufactured by laser-based powder bed fusion,” *Journal of Materials Research and Technology*, vol. 12, pp. 210–220, 2021.

[6] W. Zhang, T. Jiang, J. Li, and L. Liu, “Effect of laser heat treatment on the microstructure and properties of alloy 800h,” *Metals*, vol. 9, no. 3, p. 379, 2019.

[7] T. Rautio, J. Mäkikangas, A. Mustakangas, and K. Mäntyjärvi, “Disk laser assisted surface heat treatments of alsi10mg parts produced by selective laser melting (slm),” *Procedia Manufacturing*, vol. 36, pp. 95–100, 2019.

[8] D. Mikołajczak, M. Kulka, and N. Makuch, “Laser borided composite layer produced on austenitic 316l steel,” *Archives of Mechanical Technology and Materials*, vol. 36, no. 1, pp. 35–39, 2016.

[9] V. K. Balla, S. Dey, A. A. Muthuchamy, G. D. J. Ram, M. Das, and A. Bandyopadhyay, “Laser surface modification of 316l stainless steel,” *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 106, no. 2, pp. 569–577, 2017.

[10] W. Beard, R. Lancaster, J. Adams, and D. Buller, “Fatigue performance of additively manufactured stainless steel 316l for nuclear applications,” in *Solid Freeform Fabrication 2019: Proceedings of the 30th Annual InternationalSolid Freeform Fabrication Symposium*, 2020.

[11] R. I.B., M. Tierean, and J. L. Ocaña, “Effects of laser shock processing on 316l stainless steel welds,” *Journal of Optoelectronics and Advanced Materials*, vol. 15, p. 121–124, 2013.

[12] T. Rautio, J. Mäkikangas, M. Jaskari, M. Keskitalo, and A. Järvenpää, “Microstructure and mechanical properties of laser welded 316l SLM parts,” *Key Engineering Materials*, vol. 841, pp. 306–311, 2020.

[13] T. Rautio, A. Hamada, J. Kumpula, A. Järvenpää, and T. Allam, “Enhancement of electrical conductivity and corrosion resistance by silver shell-copper core coating of additively manufactured AlSi10mg alloy,” *Surface and Coatings Technology*, vol. 403, p. 126426, 2020.

[14] K. Deenadayalan, V. Murali, A. Elayaperumal, and S. Arulvel, “Effective role of short time furnace heat treatment and laser treatment on the residual stress and mechanical properties of NiCrBSi–WC weldments produced using plasma transferred arc welding process,” *Journal of Materials Research and Technology*, vol. 15, pp. 3492–3513, 2021.