Fatigue Properties of Laser Welded Laser Powder Bed Fusion Manufactured 316L Parts

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Abstract. Laser welding (LW) is a promising method for joining the additive manufactured (AM) laser powder bed fusion manufactured (LPBF) 316L parts and increases the use cases for the technique by overcoming some of its limitations. The fatigue properties of LW LPBF 316L parts have not been previously studied, but it is an important factor in wide range of products where the weight and life time should be optimized. The LW joints are analyzed by optical microscopy, tensile testing and bending fatigue testing and the results show that this type of joints can be succesfully used to manufacture products from LPBF parts. Strength and fatigue properties comparable to the base material were achieved in the as built condition of the material.

Introduction

Additive manufacturing (AM) has already gained footing in many industries including automotive, aerospace, dental and biomedical [1, 2, 3]. Laser powder bed fusion (LPBF) is the predidominant method on the current market owing to the great mechanical properties and good surface quality compared to other printing methods. In many cases the manufacturing costs are still high compared to traditional methods, but many special features of the technique outweight this disadvantage. Costs are very competitive when the need is for complex parts and the technique also enables designing features that would not be possible in others. Higher strength of the AM parts can also be utilized to reduce weight which is beneficial for the energy efficiency of the products.

Currently, LPBF has still some limitations and usually the orientation is limited in which a part can be printed due to the limitation on which angle the part can grow relative to the build direction. This property can also limit the usage of some design features if their use requires a spesific printing orientation. One possible tool to go around this problem is to manufacture the product from several parts and join them after the printing. This can be achieved for example with laser welding.

This work continues the authors' work on the research of laser welded AM parts manufactured by LPBF. In terms of mechanical properties, LW is a suitable tool for joining AM parts with many materials including 316L [4], Ti6Al4V [5] and Inconel 718 [6]. Laser welded 316L sheet material joints in terms of fatigue strength have been studied in several researches. Puchi-Cabrera et al. studied the fatigue properties of gas-metal arc welding process welded 316L under a pulsed arc mode and short circuit and also investigated the effect of shielding gas [7]. Xiong et al. investigated the very high cycle fatigue performance of the laser butt-welded sheet metal 316L [8] and found that the fatigue cracks initiated from internal pores of the weld, but still reached a fatigue strength comparable to the base material due to the convenient size of the pores. Laser shock processing can be used to increase the fatigue life of laser welded sheet metal 316L as shown by Roman et al. [9]. However, there are no reports on open literature about the fatigue properties of laser welded AM manufactured 316L and this work addresses this viewpoint. The microstructure of the material and the laser welds are investigated using optical microscopy and tensile test are used to verify the mechanical properties. In addition, the effect of LW on the fatigue life of the material is studied using flexural bending fatigue machine.

Table 1: 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

Material and methods

Manufacturing of the samples for laser welding experiments. An SLM 280 HL printer based on the LPBF technique was utilized for all samples manufactured for this work. Spherically shaped 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 mean size of 31.7 µm. The composition of the powder batch used in this work is detailed in Table 1. For the bending fatigue experiments, rectangularly shaped specimens were printed in the size of 30 x 90 x 2 mm. Simultaneously, tensiles were printed in the size of 120 x 20 x 2 mm. To reduce printing time and cost, the tensiles were printed on 0°orientation, but the bending fatigue samples were 90°.

All samples were printed on a single 280 x 280 mm platform using the same set of 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

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

Heat treatment for the stress relief purposes was carried out in a muffle furnace (Sarlin 1000HS-436) under argon atmosphere after the printing. This process consisted of the following steps: heating at a rate of 10 °C/min to 600°C and annealing for two hours followd by slow cooling to room temperature inside the furnace.

Laser welding. Bending fatigue properties of the laser welded parts were determined for two series of LBPF manufactured 316L, the as built and HT conditions and compared to similar series without LW. A diode pumped continuous power Ytterbium-doped: yttrium aluminium garnet (Yb:YAG) laser with a maximum power of 4 kW, wavelength of 1030 nm and optical fibre diameter of 200 µm was utilized for the LW experiments. All welding was carried out using argon, which was directed right after the weld using a special shielding gas nozzle and at a flow rate of 30 l/min. 6-axis robot was utilized for the task and the lase beam was directed perpendicular to the work piece. The following LW parameters were chosen for the welds: power of 2.2 kW, speed of 70 mm/s and focus at 1 mm below the work piece. After the LW, the bending fatigue samples and the tensiles were machined to the appropriate shapes.

Characterization. Instron universal material testing machine (Instron 8802) was used to conduct the tensile tests according to the standard SFS-EN ISO 68921:2016 with a constant loading rate of 0.5 mm/min. For each case, the tests were repeated four times. Standard hourglass shaped specimens with outer dimensions of 30x90x2 mm were manufactured

On fatigue experiments, a reversed flexural bending fatigue machine by Carl Schenck was used with a stress ratio of R=-1 and frequency of 10 Hz. Stress amplitudes were used in the range from 200 MPa to 700 MPa with runout of 2e6 cycles. Both as built and HT conditions were calibrated separately with strain gauges before testing. Fatigue tests were conducted in room temperature using air cooling when necessary.

Separate samples from all four conditions were prepared for metallographical analysis and analyzed with an optical microscope (Keyence VHX 2000 E) after polishing and etching.

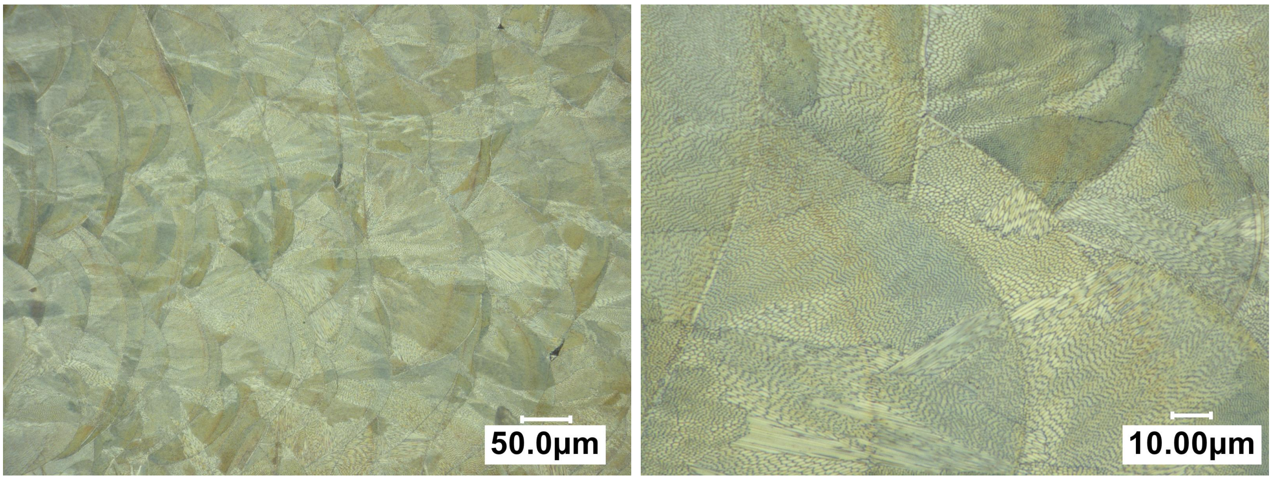

Fig. 1: a) Microstructure of the laser powder bed fusion manufactured 316L and b) high manification of a).

Results and discussion

Microstructure of The Printed 316L. Microstructure of the printed material in as built condition is presented in Fig. 1a). The fish scale pattern formed by the meltpools introduced by the laser scanning tracks during printing are clearly visible. The build direction from right to left can also be identified from the figure. The microstructure mainly consists of columnar grains and cellular grains in very fine size. The cross-section did not reveal significant porosity, but area of the image was chosen from an area where one lack of fusion fault is visible as black area. The high magnification in Fig. 1b) reveals that the smallest grains are only one micrometer in diameter. Some of the columnar dendrites can be seen to grow across the meltpool boundaries by epitaxial growth in the general direction of the heat flow during the printing. Microstructure after the heat treatment for residual stress relief does not present any visible changes in the microstructure by optical microsopy analysis so they are not presented separately.

Microstructure of The Laser Welded 316L. Both as built and HT conditions of LPBF manufactured 316L were laser welded and the overall weld geometry is presented in Fig. 2. The weld is very narrow in general having a width of around 700 µm for the most part, but the top of the weld is wider at 1.2 mm. The weld center line is straight with no solidification cracking and the weld is higly symmetrical with full penetration. Fusion zone of the weld is presented in Fig. 2b) showing the microstructural characteristics of the weld. The weld consist mainly of columnar dendrites and cellular grains. The size of both is largest near the weld center and reduced when approaching the base material. At the heat affected zone 2c), no clear changes could be observed in the microstructure.

The Effect of LW and HT on The Mechanical Properties of 316L. To measure the mechanical properties of the LBPF manufactured 316L, tensile testing was carried out for both as built and heat treated conditions. Both conditions were also laser welded and the tensile tests repeated for comparison. Figure 3 presents these tensile test results in stress-strain curves for all four series and the extracted values for yield strength (YS), ultimate tensile strength (UTS) and elongation at break are collected in Table 2. The results showed that the HT for stress relief reduced the YS by 6% from 495 MPa of the as built condition to 465 MPa. On the other hand, a gain of 3.9% was recorded for UTS in exchange resulting to 653.3 MPa for the HT condition. The elongation at break was nearly identical for the two around 42%. Applying LW reduced the YS by 1.8% and 4.0% for as built and HT conditions, respectively. LW of the as built condition did not results in any measureable difference in UTS but in HT condition 3.2% drop was recorded. The results show that LW can be used without a siginificant effect on the strenght of the LPBF 316L parts. However, in extreme conditions the ductility is not at the same level as before the welding which should be considred.

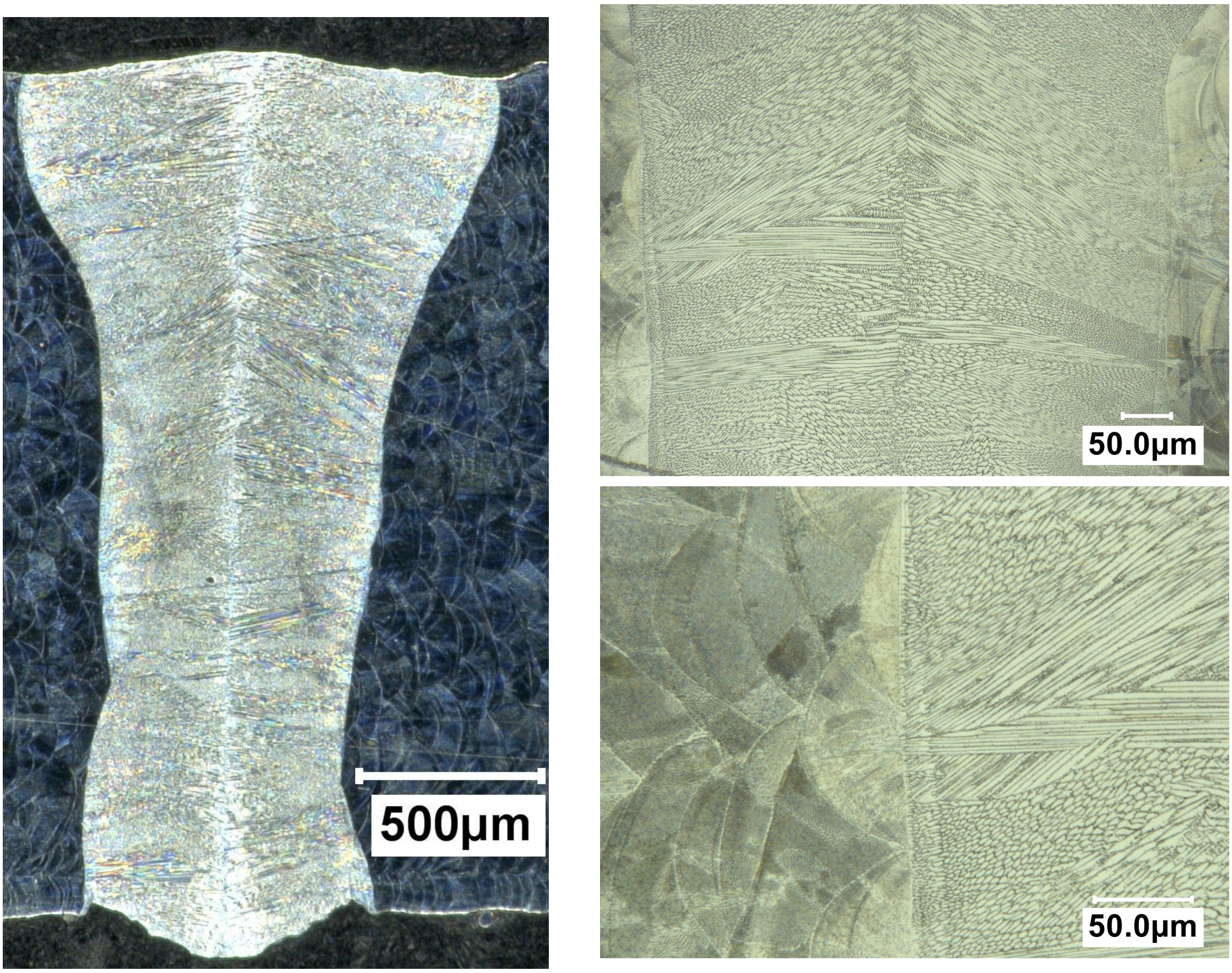

Fig. 2: a) Full weld profile of the laser welded 316L, b) the fusion zone and c) heat affected zone.

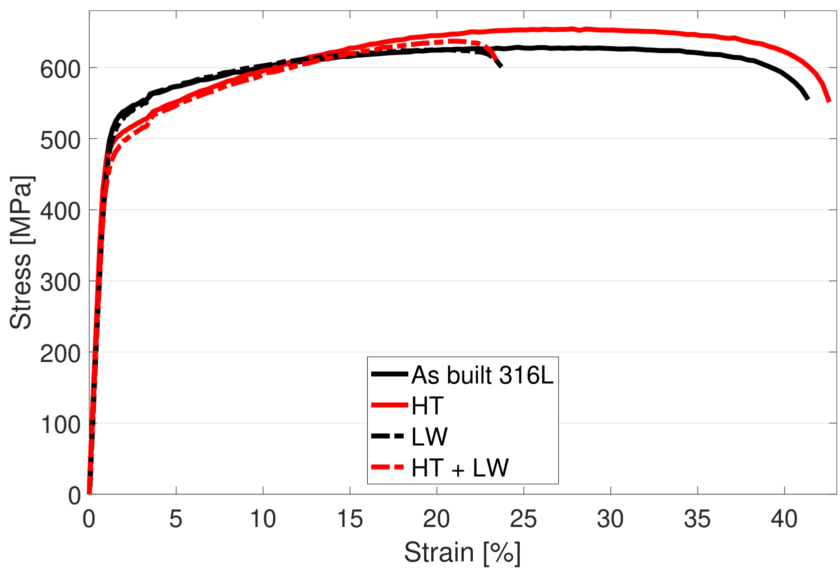

Fig. 3: Tensile test results for the LPBF manufactured 316L in as built and heat treated conditions together with laser welded versions of both.

Table 2: Yield strength (YS), ultimate tensile strength (UTS) and elongation at break for the laser welded 316L

	As built 316L	HT	LW	HT + LW
YS [MPa]	495.3 ± 0.7	465.3 ± 2.9	486.2 ± 8.3	446.5 ± 9.3
UTS [MPa]	628.7 ± 1,0	653.3 ± 1.2	627.7 ± 2	632.2 ± 9.0
Elongation at break [%]	41.6 ± 0.2	42.4± 0.2	24.2 ± 0.5	24.3 ± 1.1

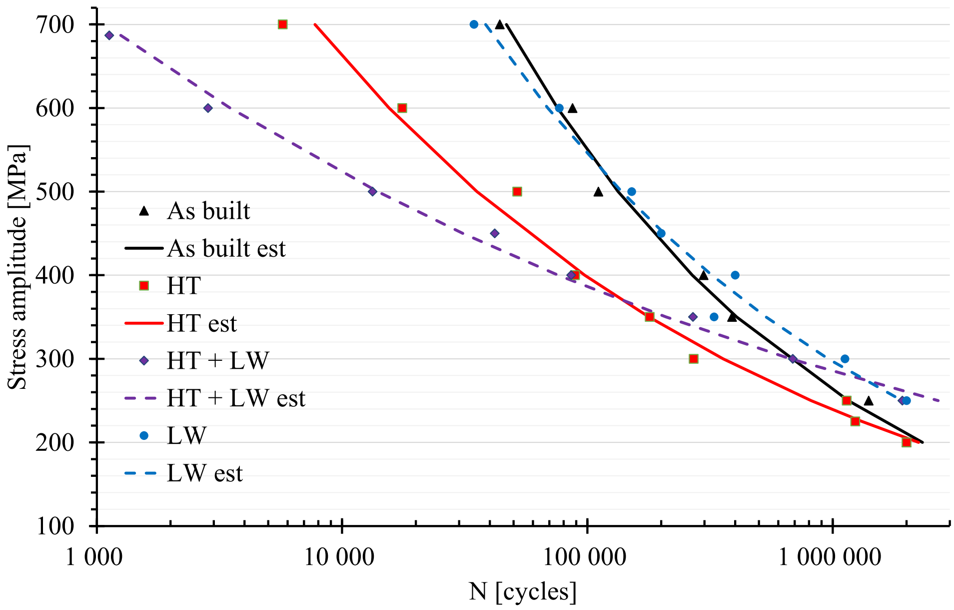

Fig. 4: Stress amplitudes and the corresponding fatigue lives for the as built, heat treated, laser welded and laser welded after heat treatment conditions.

The Effect of LW and HT on The Fatigue Life of 316L. Fatige properties of the LPBF manufactured 316L in as built and HT conditions were studied with the effect of LW on both conditions using flexural bending machine. Based on the results on fatigue life on a stress amplitude range from 200 MPa to 700 Mpa the acquired S-N curves are presented in Fig. 4. The results show that the fatigue limit of the material is not affected by the HT, but stays at the level of 200 MPa. However, at low cycle regime the as built condition is superior compared to the HT condition withstanding 44 000 cycles at 700 MPa compared to only 5 700 of HT specimen at the same stress amplitude.

LW of the HT condition leads to further reduction in fatigue life at low cycle regime as at the 700 MPa level the specimen endured only little over 1 000 cycles. At lower stress levels the fatigue strength becomes more and more similar with the non welded material and surprisingly the fatigue limit was measured 25 % higher at 250 MPa. Similar fatigue limit was reached with the laser welded as built material, but in this case the results with higher stress amplitudes were nearly identical independent of the LW. These results suggest that the selected set of LW parameters work best for the as built condition. It would be interesting to see if the results would improve if the HT was carried out only after the LW, but this was out of the scope of this study. Nevertheless, the results show that LW can be utilized without degrading the fatigue strength of the 316L material.

Conclusions

Laser welding (LW) of additively manufactured 316L was studied in this work focusing on the microstructure, mechanical properties and the fatigue life of the joints compared to the base material in as built and heat treated (HT) conditions. The following conclusions can be drawn from this study:

- LW structure is characterized by columnar grains and the weld is nearly free of any porosity. Symmetrical welds with very narrow heat affected zones were achieved in all cases.
- Joint strength comparable to the base material in terms of yields strength and ultimate tensile strength were achieved in as built condition of the material. In addition, minor reduction was observed in HT condition.
- The fatigue life of the base material is not affected by the LW joint in as built condition, but nearly identical results were achieved by flexural bending fatigue testing. On the other hand, low cycle strength of the HT condition was reduced with the studied LW parameters.

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