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Scanning strategy effect on the edge porosity and fatigue life of 316L PBF-LB parts

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Abstract

In addition to the surface quality and appearance, the near surface scanning strategy has an influence on the porosity beneath the surface of LBPF manufactured 316L parts. Furthermore, this porosity will influence the fatigue life of the part which will be pronounced on a flexural bending type of fatigue. In this work, the effect of scanning strategy to the edge porosity was analyzed by optical microscopy and the effect on the fatigue life was measured with flexural bending tests. The results showed that the edge porosity had a clear impact on the fatigue life and the fatigue limit was improved by 30 % to 250 MPa by a simple parameter change.

Keywords: 316L; Bending fatigue; PBF-LB; Porosity; Scanning strategy

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1. Introduction

Additive manufacturing (AM) has challenged traditional manufacturing methods in many industries and several AM techniques have been developed for part manufacturing. Laser powder bed fusion (PBF-LB) is currently the most widely used one offering high precision and good mechanical properties. Austenitic stainless steel 316L has gained wide usage in the AM sector and the microstructure of the PBF-LB manufactured 316L has been widely studied [1, 2]. In authors' previous work it was noted that the mechanical properties of the LPBF manufactured 316L can exceed the traditionally manufactured counterparts [3].

The fatigue strength of the PBF-LB manufactured 316L has recently gained increasing interest and Solberg et al. investigated the effect of porosity on the fatigue life of AM 316L using axial fatigue testing [4] and noted that the inner defects resulted to poor fatigue resistance and that different stress amplitudes resulted to changes in crack initiation locations. On the other hand, Zhang et al. [5] proposed that low pore size and distribution achieved with suitable laser power adjustment lead to minimal effect of defects on the fatigue life while the cracks initiated from slip bands. High cycle fatigue properties in axial fatigue were previously investigated by Andreau et al. for the AM 316L [6]. Jaskari et al. studied the fatigue life of PBF-LB manufactured 316L in flexural bending and noted in this case that the porosity in the surface area was the dominant factor determining the fatigue life of the material disregarding the mechanical properties and the microstructure. Bending fatigue testing concentrates the highest stresses on the surface areas.

Scanning strategies have a major impact on the properties of PLB-LB manufactured material affecting the volume energy density and the resulting porosity level as shown by Jaskari et al. [7]. The orientation of the part on the print platform can also affect the porosity as the increase in downskin increases the near surface porosity in addition to the surface roughness [8]. In this work, the edge scanning strategies for PBF-LB manufactured 316L are studied in relation to the porosity and

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the effect of near edge porosity to the fatigue life of the parts in flexural bending is investigated.

2. Material and methods

2.1. Specimen manufacturing with PBF-LB

An SLM 280 HL printer based on the PBF-LB technique was utilized for all the 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, hourglass shaped specimens in the size of 30 x 90 x 2 mm were printed in horizontal orientation.

All samples were printed on a single 280 x 280 mm platform using the same set of standard parameters provided by the printer manufacturer and 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, laser spot diameter 0.1 mm with a Gaussian laser profile and a wavelength of 1070 nm. Applying these values to Eq. 1 results to an energy density of 69.4 J/mm^3.

$$E = \frac{P}{v \cdot h \cdot t} \qquad (1)$$

Table 1. Chemical compostion of the 316L powder as stated by the powder manufacturer.

Fe	C	Si	Mn	P	S	Cr	Ni	Mo	N
Bal.	0.02	0.54	1.24	0.005	0.004	16.72	12.14	2.38	0

2.2. Edge scanning strategies

The parameters used for printing the edges of the samples were varied according to Table 2. Altogether 25 different variations of the edge printing were realized. This consisted of five strategies which are graphically detailed in Fig. 1. where arrows represent the laser scanning tracks of an example layer of a small cubic part. Borders are shown in red, fill contours in black and the inner hatching in blue. In the first, the standard procedure of printing two borders and a fill contour between the inside hatching and inner border was used and in this case the distance of fill contour to inner border varied. Second strategy had the same sweep of fill contour but only one border was printed. Three remaining strategies all had two borders with the distance between them varied. Fill contour was altered so that the third strategy had the standard setup but the fourth did not have a fill contour and the fifth had two fill contours. The platform of cubes that was printed using the above-described different edge parameters is shown in Fig. 2. Each cube was cut from the middle in z-direction and polished for near surface porosity analysis.

2.3. Flexural bending fatigue testing

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 800 MPa with a runout of 2×10^6 cycles. All conditions were calibrated separately with strain gauges before testing. Fatigue tests were conducted in room temperature using air cooling when necessary.

Table 2. Different scanning strategies for the first batch of samples printed for comparison.

Description	Matrix element	Sweep range
FC sweep with 2 borders	A1-E1	0.06 - 0.1 mm
FC sweep with 1 border	A2-E2	0.06 - 0.1 mm
Border spacing sweep	A3-E3	0.07 - 0.11 mm
Border spacing sweep without FC	A4-E4	0.07 - 0.11 mm
Border spacing sweep with 2 FC	A5-E5	0.07 - 0.11 mm

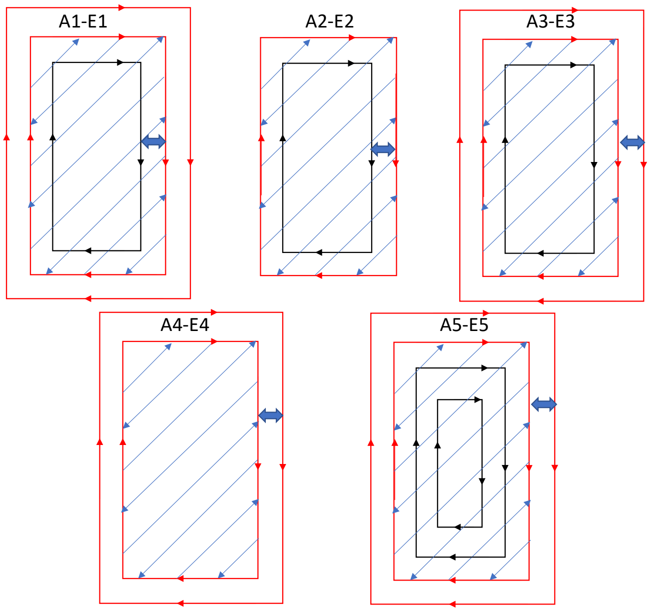

Fig. 1. Strategies used for printing the edge area. An example layer of laser scanning tracks with arrows for each case. Arrow colours: border in red, fill contour in black and hatch in blue. Double arrows representing the swept distance.

Fig. 2. The platform of cubes printed with the varied parameters for the edges.

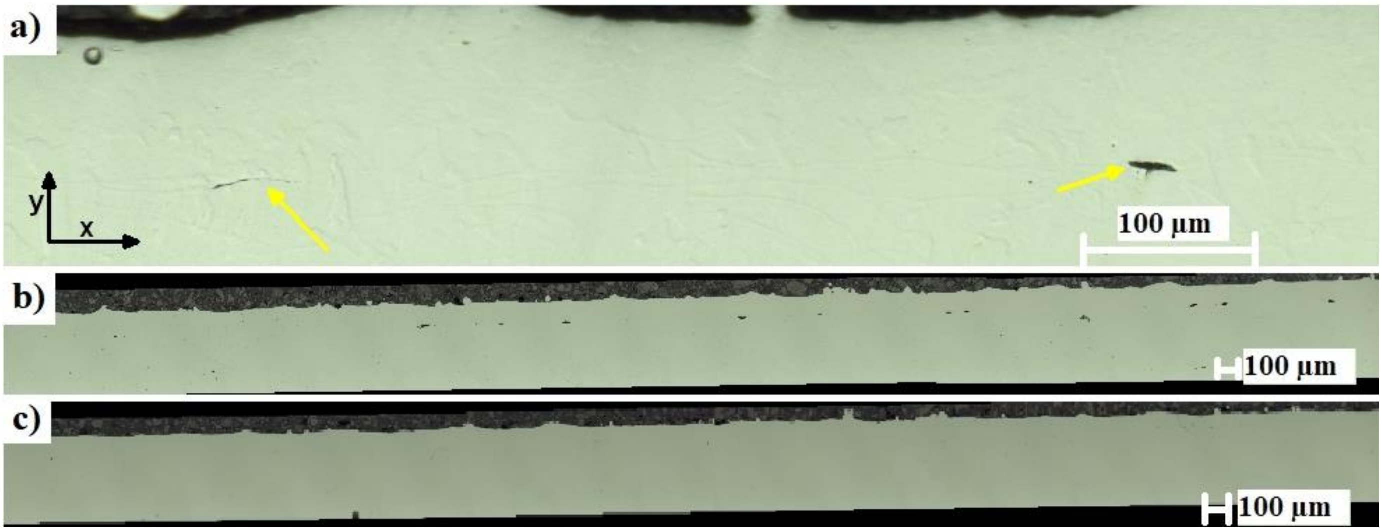

Fig. 3. Porosity near the edge for a) the standard parameters C3 (high magnification), b) added porosity E3 (low magnification) and c) reduced porosity A2 (low magnification).

2.4. Characterization

Microstructure and the porosity of the printed specimens with different edge parameters were analyzed with a Keyence VHX 2000 E optical microscope after polishing and etching in a 60% HNO3 liquid using a voltage of 1.5V for 10 s. Surface roughness of the specimens was measured with a profilometer (Mitutoyo Surftest 211) and repeated five times for each to get the averages and standard deviations. Only the sides of the cube were measured as the top and bottom are not affected by the strategies. The cubes were placed close to each to minimize the effect of shielding gas flow variation in the chamber to the surface roughness.

3. Results and discussion

3.1. The effect of edge printing parameters on the porosity of the 316L

Optical microscopy was used to investigate the effect of edge printing parameters on the porosity on the edge areas of the parts. The image in Fig. 3. a) shows some typical defects observed near the edge when the standard parameters (corresponding to C3 of Table 2) are used. The defects marked with yellow arrows represent typical lack-of-fusion defects which have a very long and narrow characteristics in this case. The length varies roughly from 50 µm to 100 µm and they are located approximately 100 µm from the edge of the part. The sharp edges associated with this kind of defects can be assumed to be very detrimental for the fatigue life of the parts as they will work as crack initiation sites when the part is under fatigue.

For instance, when the distance between the two borders is increased (parameters E3), it has a drastic effect on the porosity as shown in Fig. 3. b). The amount of pores is greatly higher, and several can be observed in a length of one millimeter along the border. On the other hand, when only one border scan was used with FC distance of 0.06 (parameters A2), the porosity could be nearly eliminated as evidenced by the Fig. 3. c). The edge has very similar properties to the bulk of the material and the number of sharp lack-of-fusion defects has been reduced near zero. Some round pores accompanied with lack-of-fusion defects with rounder appearance could still be observed comparable to the bulk of the material.

3.2. Surface roughness

The effect of the edge printing parameters on the surface roughness was analyzed with profilometer measurements. The average Ra values and standard deviations for each parameter type (one cube per parameter, 25 samples in total) are presented in Fig. 4. The roughness values ranged between 5-10 µm and due to the large deviation on the results the presented values are calculated averages for the whole swept range, for example A1-E1. A distinguishable rise in the surface roughness was noted on the samples printed with only one border scan (A2-E2). While the other series had Ra values between 6.7-7.0 µm on average, it was measured at 7.6 µm on average on A2 through E2. This result is obvious when looking at the scanning tracks labeled A2-E2 in Fig. 1 which shows the inside hatching reaching the outer edge of the part due to the one border used instead of two as in the other parameter sets. In the standard procedure the borders are printed first and the inside hatching afterwards. Printing the inside hatch partially on top of the

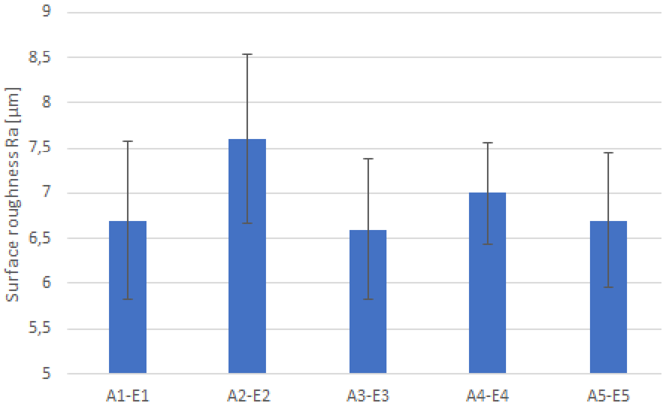

Fig. 4. Surface roughness of the series.

border scan track will interfere with the surface layer and leads to an increase in the surface roughness as seen on the measurements.

3.3. Bending fatigue results

Flexural bending fatigue tests were used to determine the effect of edge porosity on fatigue life of the PBF-LB manufactured 316L. The resulting SN-curves for standard parameters and for added and reduced porosity series are collected in Fig. 5. The results show that using the standard parameters for the 316L results in a fatigue limit of roughly 200 MPa. An intentional addition of porosity on the edge had only a minor effect on the fatigue life of the material. The same fatigue limit was still reached and only on the low cycle fatigue regime a slight deviation to the worse could be noticed. However, reducing the number of lack-of-fusion defects with improved parameter selection in the edge area resulted in a clear improvement in the fatigue life from low cycle to high cycle regime. In agreement, the lack-of-fusion defects were found to be the predominant factor in the fatigue performance of the PBF-LB manufactured 316L in [9]. In this case, the estimated fatigue limit was measured roughly 30% higher compared to the standard parameters as a result.

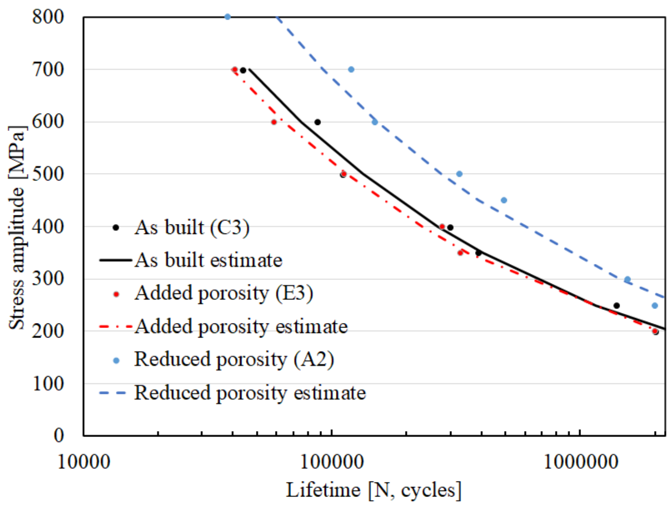

Fig 5. Bending fatigue results for the different edge porosity series.

4. Conclusions

The effect of edge scanning strategy on the porosity, surface roughness and fatigue life of the laser powder bed fusion manufactured 316L was investigated. The following conclusions could be drawn from the results:

- Simple parameter changes of border distance or border count has a clear impact on the porosity (lack-of-fusion defects) near the surface of the part (100 µm from the surface). By printing only one border the porosity could be reduced evidenced by optical microscopy.
- A minor surface roughness increase results from the one border scanning strategy.
- The fatigue life of the material is clearly dependent on the near edge porosity. The standard parameter set results to high enough porosity so that no considerable change could be observed with increased porosity in the fatigue limit.
- Lowering the edge porosity resulted in a 30% increase in the fatigue limit showing the near surface porosity is a limiting factor, not the surface quality.

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