Comparison of Polishing Methods: The Effect on The Surface Roughness and Fatigue Performance of PBF-LB manufactured 316L Stainless Steel

Timo Rautio
Future Manufacturing Technologies
University of Oulu
Nivala, Finland
0000-0002-9467-9805

Matias Jaskari
Future Manufacturing Technologies
University of Oulu
Nivala, Finland
0000-0001-8955-105X

Mikko Hietala
Future Manufacturing Technologies
University of Oulu
Nivala, Finland
0000-0003-4534-4475

Antti Järvenpää
Future Manufacturing Technologies
University of Oulu
Nivala, Finland
0000-0002-4309-4786

***Abstract*—Stainless steel 316L is currently one of the most prominent materials on the AM industry including the laser powder bed fusion (PBF-LB) manufacturing. The surface roughness of the PBF-LB manufactured material is typically over 10 µm in terms of Ra and this can have a detrimental role in the fatigue resistance of the parts. However, several techniques and machines are now available to reduce the surface roughness, but no comprehensive data is available on the limits or the effectiveness of those. In this paper, the performance of four commonly available techniques are analyzed utilizing equal PBF-LB manufactured 316L samples. The results show the effect on the surface roughness and also the surface profiles and topographies are analyzed. Up to 80% reduction in the surface roughness R_a could be reached. Moreover, the effect of each polishing method on the fatigue performance in bending fatigue testing was analyzed. The results showed that the fatigue limit of the 316L can be tripled even if mirror finish is not reached.**

***Index Terms*—PBF-LB, 316L, Laser heat treatment, Bending fatigue**

I. INTRODUCTION

Additive manufacturing (AM) has been gaining steadily more interest in the manufacturing industry for many years now. While the AM market has seen many new equipments and techniques introduced as a result, the most widely used technique of the recent years has been clearly the laser powder bed fusion (PBF-LB). One of its key benefits is the surface quality which is one of the best among the different techniques, including binder jetting [1], fused deposition modeling (FDM) [2] or powder DED [3]. Still the surface roughness is typically measured at roughly 10 µm (R_a) and some form of post processing is needed to achieve improved quality or mirror finish. Such requirements are typical in dental implants for example [4]. Many machine manufacturers have turned their focus on improving the surface quality of AM parts and some specifically designed machines and polishing medias are now available for the purpose.

Surface roughness can play also an important role in the fatigue strength of the material. The higher the surface roughness the higher the amount of critical sites for a fatigue crack to initiate from. For example, Dordlofva et al. measured a 40% drop in the fatigue limit at 10 million cycles when they compared the as built surface to a machined counterpart of PBF-LB manufactured Inconel 718 [5]. Similarly, Bezuidenhout et al. recorded a clear improvement in the fatigue life of PBF-LB manufactured Ti6Al4V when they used HF-HNO_3 chemical polishing on the material [6].

Several techniques are available for surface quality enhancement, one of the most commonly used being machining. Ali et al. used electrochemical method on PBF-LB manufactured Inconel 625 and the results showed a maximum of 93% improvement in the surface roughness and it was effective on the inner structures as well [7]. Tyag et al. used chemical and electrochemical polishing for PBF-LB manufactured 316L, and found electrochemical polishing giving the better results of the two [8]. Also shot peening can be used to improve the surface quality as shown by the authors' previous work where a 40% reduction in (R_z) of the PBF-LB manufactured AlSi10Mg could be achieved [9].

Austenitic stainless steel 316L has great mechanical properties, excellent corrosion resistance and great suitability for laser based processing such as PBF-LB, which has made it one of the most widely used materials in the PBF-LB manufacturing [10]. In this work, four different commercially available machines designed for the purpose of polishing AM parts were investigated and compared. PBF-LB manufactured 316L was used as the material for all experiments. Laser optical microscopy was used to study the effect of polishing methods on the surface roughness and it was also utilized for the surface profile and topography measurements. The results showed that all of the machines could be used to lower the surface roughness, but there were some clear distinctive features on each. Over 50% reduction in terms of R$_a$ could be reached with all methods. A clear effect on the fatigue life of the material was also observed when flexural bending fatigue testing was performed.

II. MATERIAL AND METHODS

A. Manufacturing of the samples for the polishing experiments.

All samples for the polishing experiments were manufactured with a PBF-LB machine SLM 280 HL by SLM Solutions, Germany and printed on the standard 280 x 280 mm platform. The powder had a particle size distribution of 15-45 µm with a mean size of 31.7 µm and it was supplied by Carpenter Additive of Carpenter Technology Corporation (UK). The composition of this 316L powder is presented in Table I. Same printing parameters were used for all of the samples and the most relevant were: 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. Using Eq. 1 for these parameters results to an energy density of 69.4 J/mm^3

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

All samples for flexural bending fatigue testing were printed in 90 degree orientation in the size of 30 x 90 x 2 mm. Altogether 11 samples was printed for each case, 10 for bending fatigue and one for other experiments. Before removing the specimens from the printing platform, the platform was heat treated in a furnace. Argon shielding gas was used during the process consisting of heating to 600 °C with a heating rate of 10 °C/min followed by annealing for two hours. Finally, slow cooling to room temperature was allowed with the furnace off and door closed.

B. Polishing methods

Four different polishing methods and machines were selected for the comparison. These were Hirtisation by Rena, PostProcess by Rador, CF18 by Otec and HF100+ by Dlyte. HF100+ is a dry electropolishing machine utilizing a solid polymer media and is equipped with a 16 L container. The polishing media is selected depending on the material and is supplied by the machine manufacturer. The time media has been used is measured and limited to 100 hours by the machine to control the quality and repeatability of the polishing process.

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

The Hirtisation process is both chemical and electrochemical and also fully automated. It can be used to remove the support structures of the printed parts in addition to the polising of the surfaces and it uses material-spesific treatment medias.

In contrast to the two previously presented techniques, Rador and CF18 are completely mechanical solutions for surface enhancement and equipped with drums. Rador is based on a Suspended Rotational Force (SRF) technique which is a mechanical and abrasive process. It can be used with medias designed for printed parts and the selection includes different grades with more abrasive and others that are more polishing in nature. CF18 is a disc finishing machine and the operation is based on centrifugal forces affecting the workpieces and the medium. Both wet and dry treatments are possible and parts can be finished upto mirror finish.

C. Characterization.

The fatigue properties of the material in as built and polished with different machines was measured using a reversed flexural bending machine by Carl Schenck. The used stress ratio was R=-1 and used frequency at 10 Hz. Stress range from 50 MPa to 600 MPa was used and a runout of 2 x 10^6 cycles. Fatigue testing was conducted in room temperature which was ensured with air cooling. Surface roughness and the profiles and topographies of the 316L alloy in different conditions were measured with a Keyence VK-X200 series laser microscope.

III. RESULTS AND DISCUSSION

A. Surface roughness of the PBF-LB manufactured 316L before and after polishing.

Surface roughness of the PBF-LB manufactured 316L material in heat treated condition and after the various polishing methods were analyzed utilizing laser microscopy. The average surface rougness R$_a$ and peak to valley values R$_z$ were measured for all cases and the results are collected in Table II. The results show the typical quite rough surface roughness directly after printing associated with this manufacturing method. R$_a$ was measured at 9.33 µm and the corresponding R$_z$ was 55.57 µm. All of the studied polishing methods could be used to at least halve the roughness in terms R$_a$. The lowest improvement was measured with the Rador equipment, which still could reduce the average roughness for about 50% and R$_z$ by 30%. Next best results were achieved with the Dlyte, which resulted to a 57% and 43% reduction of R$_a$ and R$_z$, respectively.

TABLE II
MEASURED SURFACE ROUGHNESSES BEFORE AND AFTER POLISHING FOR THE PBF-LB MANUFACTURED 316L.

Surface condition	**R$_a$ [µm]**	**R$_z$ [µm]**
no polish	9.33	55.57
Rador	4.6	38.6
CF18	1.9	26.9
Hirtisation	3.0	25.3
Dlyte	4.0	31.5

The highest imporovement in terms of R_a was measured with the CF18 machine reaching the lowest value of 1.9 µm. Hirtisation treatment gave also good results reaching a R_a of 3.0 µm and simultaneously the lowest measured R_z of all at 25.3 µm. It can be seen from these results that albeit considerable improvements can be reached, mirror finish is not possible with any of the methods. Achieving that would require some form of preprocessing such as pregrinding for example.

B. Surface profiles of the PBF-LB manufactured 316L and the effect of polishing.

In addition to the surface rougness values, laser microscopy was used to measure the surface profiles of the samples polished with different methods and compared to the as built surface profile. These profiles are collect in Fig. 1 and correspond to the side of the part in building direction (y-z plane). The profile for the as built material clearly shows the wavy appearance of the surface directy after the print job. The highest deviations from the mean value can be seen to occur as peaks in the positive direction from the surface and have quite sharp appeareance. Similarly, many of the valleys penetrate deep into the material and have abrupt change back upwards. It must be noted though that the y-axis in the figure is magnified compared to the x-axis emphasizing the variations. The as built material has highest peaks of around 30 µm up from the zero mean and a little over 20 µm in the negative direction.

Polishing with the Dlyte has clearly cut down the peaks from the surface and narrowed them in the x-direction. However, there are still clearly visibile spikes and some sharp valleys are also present. Peak deviations from the zero mean have reduced roughly by 50% from the as built state in both directions. Rador polishing has been able to cut nearly all of the sharp spikes and changed the visual appearance of the surface profile greatly. The upper portion of the curve shows clearly smoother transition along the surface. This method is also not able to influence the deepest valleys in the material and those can be still indentified. Similarly, the other drum based machine CF18 has also been able to considerably smoothen the surface. As shown by the rougheness measurements in Table II, the peak to valley variation is even lower than of the Rador. Hirtisation treatment shows visually as the most smooth curvature of the profiles which also reflects the measured R_z which was the lowest among the machines compared. In contrast to other techniques, there are no sharp peaks either up from the surface nor in the valleys.

C. Surface topographies of the PBF-LB manufactured 316L and the effect of polishing.

Laser scanning was used to measure the surface topographies of the as built and polished materials. For comparison, the measured topographies are collected in Fig. 2. The as built surface in Fig. 2. a) shows the rough appearance of the printed material without polishing. There are several round shapes distinctive in the topography belonging to the partially melted powder particles that have adhered to the side of the part during printing. The build direction from left to right can also be identified from the figure as top-down stripes in alternating green and blue shades.

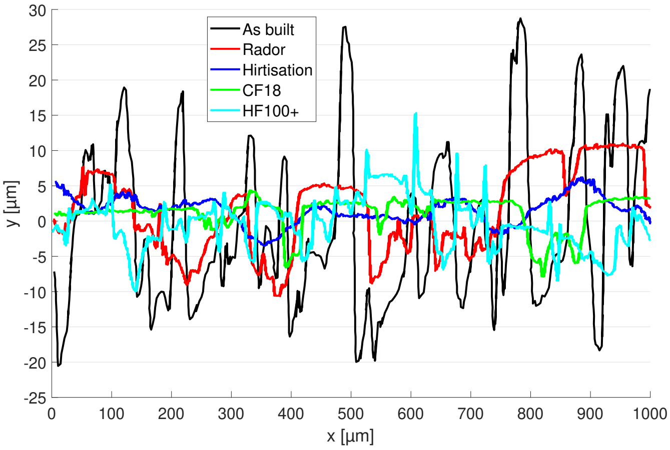

Fig. 1. Surface profiles for the PBF-LB manufactured 316L in as built and polished conditions.

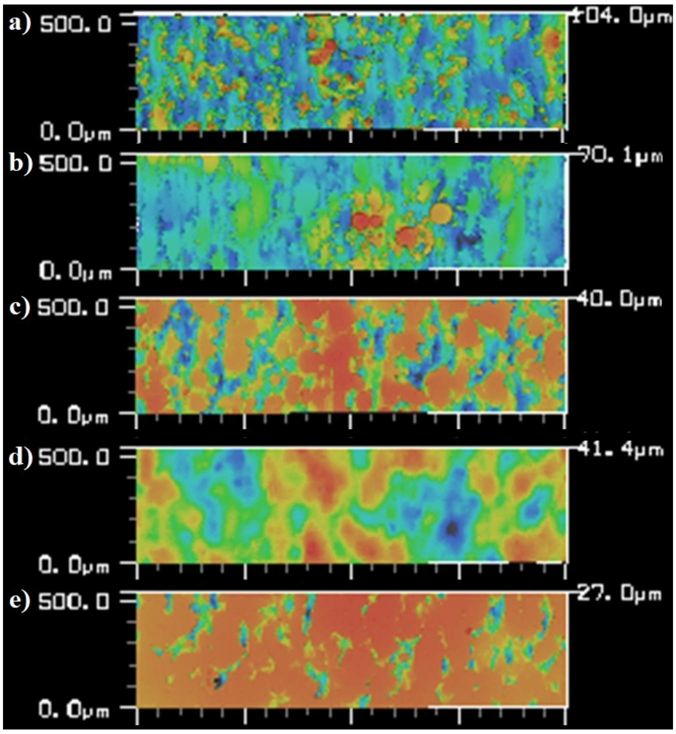

Fig. 2. Surface topographies for the PBF-LB manufactured 316L in as built and polished conditions. a) as built, b) HF100+ c) Rador, d) Hirtisation, e) CF18

The build direction characteristics are also still somewhat visible in the topography after the polishing with the HF100+ machine as shown in Fig. 2. b). Most of the round partially melted powder particles have been removed, but some of the larger ones are still present. However, those cannot be identified from the other topographies associated with the three other machines. The topography after the treatment with Rador in Fig. 2. c) shows clearly smoother surface. It can be seen that the highest peaks have been cut down, but there are some valleys that show quite abrupt transition from the surroundings. A lot smoother appeareance all around was achieved with the Hirtisation treatment shown in Fig. 2. d). The transitions from peaks to valleys are clearly smoother compared to the other methods as already evidenced by the profile measurements also. CF18 polishing has also clearly removed all of the high peaks in the material as seen in Fig. 2. e). The topmost surface is now in an even level and only small local valleys are present. It appears as material was removed from the surface, but not enough to even out the deeper imperfections.

D. The effect of surface polishing on the fatigue life of 316L.

Flexural bending machine was used the determine the effect of polishing methods to the fatigue life of the PBF-LB manufactured 316L material. The results are presented as SN-curves in the Fig. 3. The results show that the base material without polishing has a fatigue limit of only a little over 50 MPa when a runout of 2 x 10^6 is used. Polishing the material with HF100+ machine does not result in any kind of measurable difference in the fatigue performance, but a large amount of scattering can be evidenced in the low cycle regime not experienced with other test series. This could be due to uneven polishing results. A clear improvement in the fatigue limit of the material was achieved with all the other polishing methods. Using Rador or Hirtisation machine to polishg the material results to nearly identical fatigue performance with a fatigue limit of roughly 120 MPa, which corresponds to a 140% improvement from the as built state. The fatigue strength is also higher throughout the used cycle range from low cycle to high cycle.

The best fatigue performance was recorded with the CF18 machine which resulted to the highest fatigue limit of 150 MPa, which is three times the fatigue limit of as built material. However, moving from high cycle to low cycle regime the difference to Rador and Hirtisation narrows and the fatigue strength in the low cycle regime is the same. These results show, that while none of the machines was able to produce mirror finish the effect to the fatigue strength can be considerable. The differences between the machines could be due to differences in residual stresses near and at the surface. This effect will be studied in authors' future work.

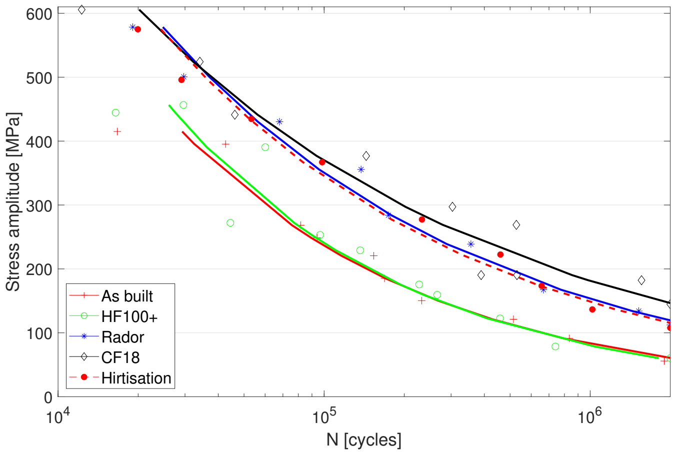

Fig. 3. Fatigue life of the laser powder bed fusion manufactured 316L in as built condition compared to polished material.

IV. CONCLUSIONS

The effect of different polishing machines on the surface quality and properties of the laser powder bed fusion manufactured 316L was studied in this work. The machines included Hirtisation by Rena, PostProcess by Rador, CF18 by Otec and HF100+ by Dlyte. In addition to the surface condition, the effect on the fatigue life of the material was also analyzed with flexural bending fatigue tests. The results of the work can be concluded as follows:

- The as built material has a surface roughness of 9.33 µm and 55.57 µm in terms of R_a and R_z, respectively. Over 50% imporovement could be achieved with all of the machines but only CF18 nad Hirtisation were able to reduce R_z as much.
- Greatest roughness reduction measured in R_a was achieved with the CF18 (1.9 µm), but lowest R_z was recorded with the Hirtisation.
- The surface profiles and topographies showed that the smoothest transitions in the surface can be achieved with the Hirtisation while the Dlyte was not able to remove all of the partially melted particles from the surface.
- A clear impact on the fatigue life of the material was recorded in the flexural bending fatigue tests depending on the polishing method used. Using CF18, the fatigue limit could be tripled from 50 MPa to 150 MPa while no measurable difference was recorded using Dlyte.

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REFERENCES

[1] A. Mostafaei, A. M. Elliott, J. E. Barnes, F. Li, W. Tan, C. L. Cramer, P. Nandwana, and M. Chmielus, "Binder jet 3d printing—process parameters, materials, properties, modeling, and challenges," *Progress in Materials Science*, vol. 119, p. 100707, jun 2021.

[2] S. Rahmati and E. Vahabli, "Evaluation of analytical modeling for improvement of surface roughness of FDM test part using measurement results," *The International Journal of Advanced Manufacturing Technology*, vol. 79, no. 5-8, pp. 823–829, feb 2015.

[3] K. S. Ribeiro, F. E. Mariani, and R. T. Coelho, "A study of different deposition strategies in direct energy deposition (DED) processes," *Procedia Manufacturing*, vol. 48, pp. 663–670, 2020.

[4] L. Lebea, H. M. Ngwangwa, D. Desai, and F. Nemavhola, "Experimental investigation into the effect of surface roughness and mechanical properties of 3d-printed titanium ti-64 ELI after heat treatment," *International Journal of Mechanical and Materials Engineering*, vol. 16, no. 1, nov 2021.

[5] C. Dordlofva, S. Brodin, and C. Andersson, “Using demonstrator hardware to develop a future qualification logic for additive manufacturing parts,” *Proceedings of the International AstronauticalCongress, IAC*, vol. 7, p. 25, 2019.

[6] M. Bezuidenhout, G. T. Haar, T. Becker, S. Rudolph, O. Damm, and N. Sacks, “The effect of HF-HNO3 chemical polishing on the surface roughness and fatigue life of laser powder bed fusion produced ti6al4v,” *Materials Today Communications*, vol. 25, p. 101396, dec 2020.

[7] U. Ali, H. Fayazfar, F. Ahmed, and E. Toyserkani, “Internal surface roughness enhancement of parts made by laser powder-bed fusion additive manufacturing,” *Vacuum*, vol. 177, p. 109314, jul 2020.

[8] P. Tyagi, T. Goulet, C. Riso, R. Stephenson, N. Chuenprateep, J. Schlitzer, C. Benton, and F. Garcia-Moreno, “Reducing the roughness of internal surface of an additive manufacturing produced 316 steel component by chempolishing and electropolishing,” *Additive Manufacturing*, vol. 25, pp. 32–38, jan 2019.

[9] 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, dec 2020.

[10] Qu, Li, F. Zhang, and JiamingBai, “Anisotropic cellular structure and texture microstructure of 316l stainless steel fabricated by selective laser melting via rotation scanning strategy,” *Materials & Design*, p. 110454, feb 2022.