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Surface roughness assessment of post-process effects on L-PBF alloy 718

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Abstract

Laser Powder Bed Fusion (L-PBF) is one of the promising Additive Manufacturing (AM) technologies to build relatively smooth surfaces belong to complex geometries with its overall technology readiness level. However, this may depend on the other parameters such as built orientation, support structures etc. Despite many advantages of AM, surface roughness of L-PBF'ed parts may still not be met in as-built condition the tight requirements of aviation industry. In this study, the surface roughness assessment of L-PBF'ed as-built Alloy 718 parts using virgin powder is evaluated by utilizing several post processes beyond the industrial preferences, in aviation standards. The surface roughness is consequently optimized based on orientation in order to define robust manufacturing tolerances in AM of aviation parts. Closed clearances or smooth surface profiles are perfectly needed in those parts to improve several aspects such as fatigue life span. In the scope of this study, Grit Blasting, Glass Bead Peening, Chemical Milling, Ultrapolish and some of their combinations on five different sloping angles were studied, surface quality was evaluated with profilometer in addition to weight loss effects based on the stock loss method. The outcomes of the study will be used as reference in the future works of TEI.

Keywords: L-PBF, Alloy 718, Surface Roughness, Stock Loss.

1. Introduction

Laser Powder Bed Fusion (L-PBF) represents an efficient manufacturing alternative compared to conventional methods in terms of low material waste, reduced lead-time per parts and ability to bring complex geometries and consolidated assemblies out at one shot. From these aspects, L-PBF becomes a popular method for aviation parts but it still needs to be improved in order to have robust outcomes in line with aviation standards. A major drawback of L-PBF systems is "surface roughness" that can arise due to the following some reasons:

- melt pool related reasons such as (in)stability and solidification [1],
- removal of support structures, if exist,
- process parameters of machine and powder characteristics,
- "stair step" effect on curved and inclined surfaces and "balling" phenomenon that avoids a uniform deposition of new powder layer [2].

Apart from the exact reasons of relatively poor surface finish on AM'ed parts compared to some conventional manufacturing methods, aviation industry may need better surface quality beyond results that are obtained by well-established manufacturing parameters in L-PBF. From the metallurgical point of view, a rough surface profile may cause additional notch effects and trigger crack initiation [3], and may result in fatigue, creep, corrosion and wear related reduced life span or failures [4, 5].

Therefore, several post processes are utilized to enhance surface finish for metals. Grit Blasting [2, 3, 6, 7], Shot Peening [5, 8, 9], Vibratory Surface Finishing [4, 10, 11] and Chemical Milling [12, 13] are some or the methods applied to AM or conventional manufacturing outcomes in order to reach necessary surface requirements.

From the studies mentioned above, Grit Blasting and Shot Peening are two methods that may look similar to each other from the point of throwing media onto a surface, but the aim of the media is pretty different: Grit Blasting is commonly used to either clean or prepare a surface for further processes while Shot Peening is used to relieve residual stresses on the surface. Götelid et al. [6] emphasized the effect of different post processes including Grit Blasting and Shot Peening regarding different heat treatments and two different AM methods. In defined circumstances, Shot Peening showed 9.3% smoother surface finish than Grit Blasting, compared to as-built Alloy 718 specimens. However, it is important to be aware of type of the media; Glass Bead Peening involves glass media while the others may utilize different types such as steel media such as in the study [6].

Ultrapolish is a special version of Vibratory Surface Finishing method developed by TEI. This method was primarily used to improve surface quality of blisk parts used in commercial engines. Kaynak et al. [4] has studied the Vibratory Surface Finishing as a part of several post-processes on Alloy 718 specimens fabricated by L-PBF. They have noted that the method is found helpful to reduce the average surface roughness about 82.49% of as-built specimens but not capable of removing the partially melted powder residuals on the surface.

Chemical Milling is a surface treatment method via etching chemicals. While the method is commonly known to be used for the removal of alpha case in Titanium alloys, it has also a usage for thickness reduction on complex geometries made of other alloys. In aerospace parts, the thickness reduction using Chemical Milling might be a preferred method but there are almost no examples for its usage on Alloy 718 in the literature. One exception is the B.S. thesis of Spear and Ingraffea [13]. In the study, researchers showed the relation of chemical concentration to surface roughness under defined bath conditions.

However, no literature findings showed a comprehensive study by comparing such 5 different post processes and their combinations. Moreover, since as-built surface roughness values might differ depending on the parameters used, any of two different literature resource may not rationally be compared.

In this study, 4 different surface roughness improvement processes and some of their combinations are studied on L-PBF'ed Alloy 718 specimens. The focus of the current study is to provide the design data with the minimum and maximum percent improvement rates that can be obtained with different sloping angles by the methods specified. The stock loss method is used to determine weight losses by the applied processes.

2. Material and methods

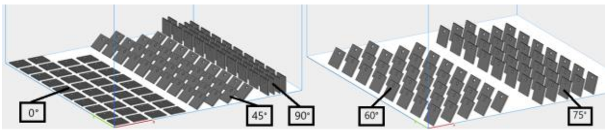
2.1. Feedstock material and L-PBF system

The feedstock material is virgin Alloy 718 (UNS N07718) gas atomized powder. The powder size distribution was in the range of 15 to 45 µm with 37 µm of D50 per ASTM B822. The samples were manufactured in L-PBF system EOS M400 equipped with single Yttrium fiber laser under Argon atmosphere. The layer thickness was 40 µm. The upskin volume energy density was 70.83 J/mm^3.

2.2. Test samples

Square prism samples with dimensions of 30 x 30 x 2 mm are manufactured all with same build parameters. The specimens were fabricated in 5 different sloping angles per each method. The distribution of samples is shown in Fig. 1.

All the 5 sloping angles subjected to evaluation are in global coordinate system.



a. b.

Fig 1. Sample sloping angles on built chamber: a) 0°, 45° and 90°; b) 60° and 75°

2.3. Post processes

For each post processes and combinations at each angle, 3 trial specimens are provided to adjust robust process parameters except for Grit Blasting process in which the number of trial specimens was 6. Depending on the trial results, 2 new specimens per each post-processes and their combination were planned to be applied.

The list of applied processes per each 5 sloping angles is given in Table 1.

Table 1. List of post processes applied.

Process	# of Trial	# of Sample
Grit Blasting	6	2
Glass Bead Peening	3	2
Chemical Milling	3	2
Ultrapolish	3	2
Grit Blasting + Glass Bead Peening	N/A	2
Grit Blasting + Chemical Milling	N/A	2
Grit Blasting + Ultrapolish	N/A	2

Grit Blasting process has been performed using several process parameters on 6 samples per each sloping angles. Resultantly, the process has been finalized using both 70 and 150 grit sizes under a range of blasting pressure of 2.50 to 4.20 bar through 4 cycles in total on two samples per each sloping angle.

In Glass Bead Peening, the trials have provided the best results under 4.40 to 5.90 bar through 6 cycles and these parameters were used to achieve the best treatment on final two samples per each sloping angles.

In Chemical Milling process, the specimens were treated through 30 minutes. The chemicals with varying concentrations in the bath were HCI, HNO_3, HF, $FeCI_3$ and a complementary amount of chips of the same metal in order to provide bath satiety.

Ultrapolish process has been performed through 6 hours with following criteria and method. The specimens were soaked in the media as upside down per 3 hours and the reverse per another 3 hours. The frequency was selected in the range of 50 Hz to 60 Hz.

The combinations were studied with parameters established on the best treatment results.

Each sample has 3 different direction of roughness measurement on upskin via profilometer, see Fig. 2. For all the measurements, average roughness (R_a) through the indicated directions were detected.

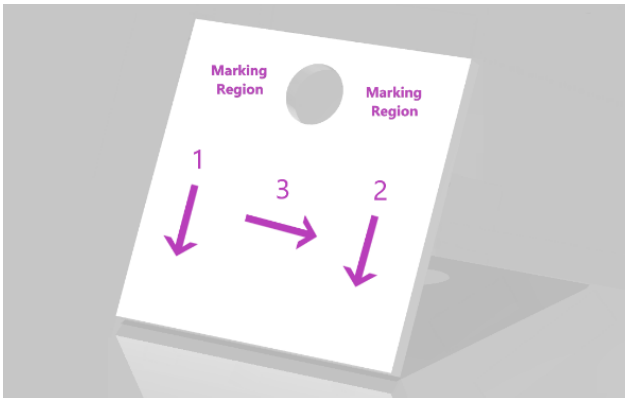


Fig 1. The direction of roughness measurements on samples.

2.4. Stock Loss

The initial and post processed weight measurements are recorded to define average mass offset to be added to the surface of further study cases such as fatigue specimens.

Two measurements under same conditions were recorded before and after post processes. The stock loss calculation was performed with equation (1) in accordance with SAE ARP1755.

$$Stock\ Loss = \frac{W_i - W_f}{D * A} \quad (1)$$

where

W_i - Initial weight of specimen,
W_f - Final weight of specimen,
D - Density of specimen,
A - Area of specimen.

3. Results and discussion

Surface roughness determination via profilometer on upskin of the samples were recorded and the data were processed to have simple demonstration for comparison between processes and sloping angles.

Average R_a values per different sloping angles for as-built L-PBF Alloy 718 trial samples and samples to be post-processed are given in Table 2.

Table 2. As-built R_a values in average.

Sloping Angle	**Ra [µm]**
0°	1.8468
45°	6.8407
60°	6.0592
75°	6.2845
90°	5.4850

In each post-process, average of two samples with evaluation from 3 different directions per 5 different sloping angles was involved to calculate R_a.

R_a % improvement results are given in Fig. 3. and Fig. 4 for percentage changes after being processed.

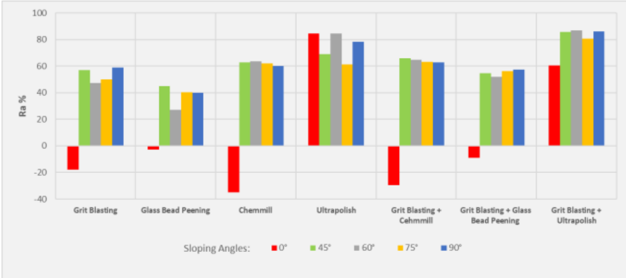


Fig 2. R_a % improvement after being processed per each process.

The results in Fig. 3 showed that the Glass Bead Peening provides less improvement in surface finish. The process provided best improvement on 45° samples by 44.79% while had a negative effect on horizontal samples. The 0° samples became slightly coarser by 2.09% change. In a broad sense, the process is used to produce a compressive residual stress on the applied surface. From this aspect, the results confirm that the shooting effect of the process does not aim such a surface finish improvement.

The variance between as-built and processed samples were highest in “Ultrapolish” and “Grit Blasting + Ultrapolish”. The best improvement has been provided by “Grit Blasting + Ultrapolish” combination on 60° samples by 87.06%. Following the best, same combination has been provided the improvement of 86.08% on 90° samples and 85.55% on 45° samples. The process “Ultrapolish” has provided high improvement rates on 0° and 60° samples by 84.65% and 84.68%, respectively.

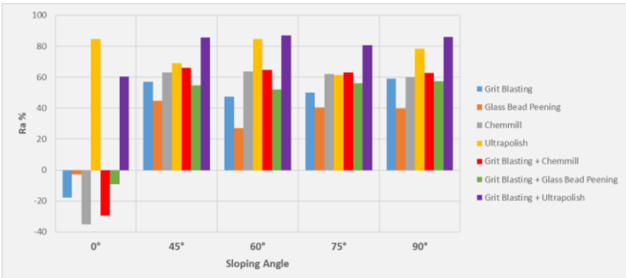


Fig 3. R_a % improvement after being processed per each sloping angles

Considering the sloping angles in Fig. 4, general trend shows that post-processing on horizontal samples have shown a negative impact except Ultrapolish affected samples compared to other sloping angles. Roughly noting that the results did not show an interpretable trend based on changing sloping angles.

Grit Blasting samples treated with the best process parameters obtained from trials, provided more than 40% improvement on surface finish except on horizontal samples. Comparing the results of the combinations with Grit Blasting to the Grit Blasting itself, the general trend was an increasing improvement in R_a. The exception was seen in some sloping angles of samples exposed to the combination Grit Blasting + Glass Bead Peening. Nevertheless, this exception might be interpretable to the fact that essential function of Glass Bead Peening does not primarily aim to enhance surface finishing as mentioned.

From both Fig. 3 and Fig. 4, it is evident that solely Ultrapolish effected samples, meaning that both Ultrapolish and secondarily Ultrapolish applied, have shown a significant improvement on the surface finish of the horizontal samples.

As a part of the research, stock losses per each process have been studied. In Fig.4, due to abrasive effect of chemicals on surface, Chemical Milling effected samples have higher stock losses compared to samples which were processed using other methods. The average of stock losses obtained by 5 different sloping angles are 320.42 µm and 298.91 µm for “Chemical Milling” and “Grit Blasting + Chemical Milling”, respectively. On the other hand, Glass Bead Peening has almost no material removal effect due to its nature. The stock loss obtained by the process “Glass Bead Peening” is 4.58 µm in average. A similar trend is also valid for Ultrapolish effected processes.

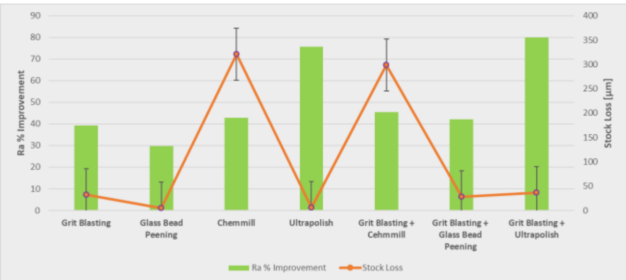


Fig 4. Stock loss vs. R_a % improvement obtained by average of 5 different sloping angles.

Simplifying the sloping angle effects by having their average, the best two processes in R_a % improvement are found to be Ultrapolish and Chemical Milling effected processes, respectively. However, stock loss indicators in Fig. 5 shows a visible difference between them: the abrasive effect of Chemical Milling causes a massive amount of material removal from surface in comparison with other methods. As a matter of fact, considering higher improvement rates in R_a and the stock losses, a trade-off analysis might be required if the final geometry is complex and thin. Additionally, if a final geometry has internal structures such as lattice structures, those internal surfaces may not be treated with the media used in Ultrapolish. In such a situation, the advantage of chemical fluids of Chemical Milling may preferably be chosen.

4. Conclusions

In the current study, the surface roughness assessment of 4 different post-processes and 3 combinations of them has been performed on L-PBF’ed as-built Alloy 718. R_a % improvements obtained on 5 different sloping angles by post-processes comparing to as-built specimens were investigated. A comprehensive comparison between methods were provided. Average stock loss values were provided to have a clear understanding of material removal rates from surface regarding relevant post-process methods. The following conclusions can be put forward from the study:

- Surface finish can be increased by the mentioned 4 methods or with their combinations. An absolute improvement in R_a was obtained in 45°, 60°, 75° and 90° with respect to global coordinate system. However, researchers of the study have experienced a deterioration on surface quality on 0° samples except Ultrapolish effected processes.
- A significant interpretable trend from sloping angle 0° to 90° cannot be obtained on the post-process basis.
- Post-processes that have main target for generating compressive residual stresses on surface such as Glass Bead Peening and Ultrapolish do not provide a significant stock loss. Similarly, Glass Bead Peening has provided less improvement on surface finish compared to the other methods.
- Excluding some fact such as cost, timing and accessibility to relevant process and considering equal circumstances, user may consider to apply Ultrapolish or Chemical Milling effected post-processes in order to obtain best surface finishes by having a look to the results in Fig. 2, Fig. 3 and/or Fig. 4. However, the stock loss between these two solution-oriented processes shall be considered for design especially for thin structures or the specimens will be used as test specimens.
- The geometry details may be an important criterion to choose the post-process. Even though the result says Ultrapolish effected methods provide best R_a % improvements with very low stock losses, the method is pretty useful for simple surfaces but not suitable for internal channels. For the cases with inner channels, user may consider Chemical Milling effected methods as the most efficient option in R_a % improvement.
- Last but not least, it shall be emphasized that a geometry may be AM’ed in a different orientation than design due to some other performance requirements or manufacturing plans in L-PBF. This means that the accepted orientation for a surface of that geometry may be changed in final. For this reason, user should pay attention to possible orientation changes in manufacturing plan when it comes to the selection of the

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mentioned post-processes that target better surface finish.

The future work is planned to investigate more post-processes and their effects on more sloping angles. Moreover, additional R_a % improvement studies in-line with the specific requirements of aerospace industry. Further, determination of stock loss based on a specific geometry such as test specimens will be studied.

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Author's statement

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study. Ethical approval: The research related to human use complies with all the relevant national regulations, institutional policies and was performed in accordance with the tenets of the Helsinki Declaration, and has been approved by the authors' institutional review board or equivalent committee.

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