Assessment of "as-printed", machined & post processed additive layer manufactured (ALM) Ti-6Al-4V for aerospace applications

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INTRODUCTION

Especially within the aerospace field there is a large interest in manufacturing increasingly complex components in the most economical way based on the relatively small volumes required by this industry. A very promising technology that may fulfil these requirements is the Additive Layer Manufacturing (ALM) process which is already used for an increasing number of metallic and non-metallic components usually under static loads only.

Within this paper the focus is on the fatigue performance and cyclic loading of ALM components made of Ti-6Al-4V material widely used in the aerospace industry. Fatigue samples were treated by different processes including machining, shot peening and superfinishing after the "printing process". In addition, the post ALM treatments have been applied in variations and combinations to determine their individual effect on the fatigue strength of the ALM components.

Based on the initial characterisation trials carried out by the Leonardo Materials Laboratory, on the static and fatigue property data for ALM produced Ti-6Al-4V, [1] Design Engineers have used this data to model and stress two ALM parts. As one of these parts was a flight critical part, Design and Stress Engineers required additional fatigue test data on both "As Printed" ALM and the effect post processing techniques, e.g. shot peening and/or superfinishing had on the fatigue properties of "As Printed" ALM. Consequently, this paper summarises the main topics results of the evaluation carried out by the Leonardo Materials Laboratory on "As Printed", machined and post processed ALM produced Ti-6Al-4V especially in terms of fatigue performance.

METHODOLOGY

Material

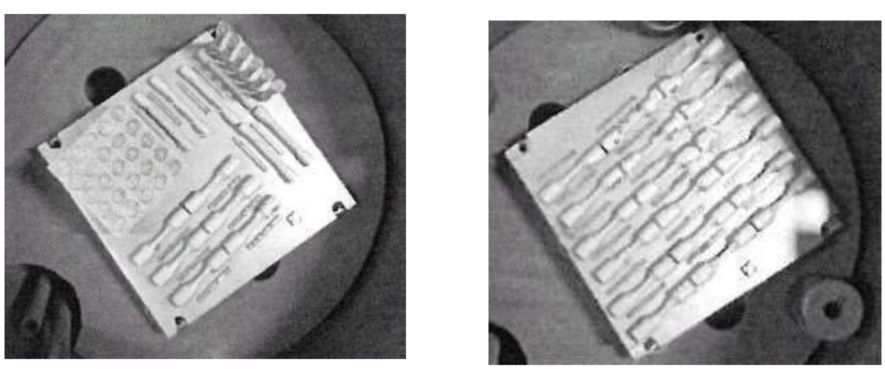
The Ti-6Al-4V powder that was used fully complied with the requirements of AMS 4998 and ASTM B348 Grade 23 Type 5. The powder size was nominally 50 µm.

ALM Processing History

ALM Manufacturing Process

The test coupons were built to the required specimen dimensions (see Plate 1). The machine used to produce these coupons was a 3TRPD M280 400W system which built up these samples in 60 µm layers, using standard Ti-6Al-4V processing parameters.

Plate 1 – Location of ALM Test Coupons on Build Platens



Hot Isostatic Pressing (HIP) and Annealing
Following ALM processing all the test coupons were HIP at 924 °C for 125 minutes at a pressure of 100 MPa using a standard cycle for Ti-6Al-4V. After HIP the samples were annealed for 2 hrs at 700 °C in an inert atmosphere.

Post Processing ALM Options (Batch Selection)
Subsequent to heat treatment the test coupons and test specimens were subdivided into the different post ALM processing batches as detailed in Table 1, together with the post ALM processing test houses.

Batch	**Vibrophore Fatigue Sample Identity**	**Post ALM Processing**
A	AF (1 to 7 and 9 to 12)	As Machined (Compact Engineering)
B	BF (1 to 10)	As Printed
C	AF (16, 27, 29, 31, 35, 37, 39, 44)	As Printed & Shot Peened (MIC)
D	N (15, 26, 32, 33, 34, 36, 38, 41)	As Printed & Shot Peened and/or Superfinished (MIC)
E	17, 21, 22, 23, 24, 25, 26 & 42	As Printed & Superfinished (Fintek)

Table 1 – Post ALM Processing applied to the Different Batches

Fatigue Specimen Design
The axially loaded fatigue specimen used during the fatigue evaluation trials was based on a Vibrophore design (see Figure 1). The fatigue test specimens were either manufactured to the defined dimensions ("As Printed") or were machined down to the dimensions from ALM cylinders ("As Machined"). Regardless of the manufacturing method employed the specimen was designed according to dimensional requirements specified in ASTM E466. In the case of the ALM cylinders the waisted section was machined to a 0.4 μm finish.

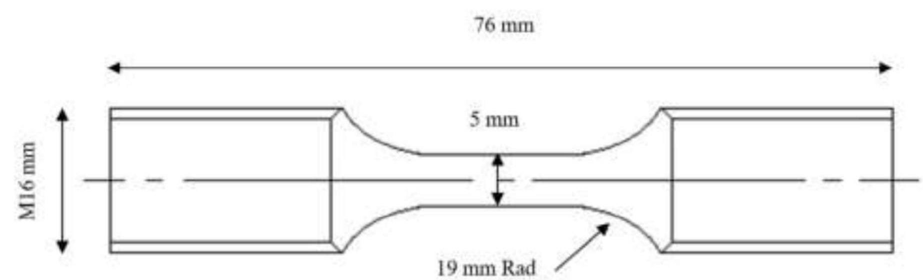


Figure 1 – Vibrophore Fatigue Test Specimen Design

Fatigue Testing
Fatigue testing was carried out at a load ratio of 0.1 under ambient conditions in order to generate stress-life (S-N) curves. In all cases, testing was carried out on a 150 kN Vibrophore fatigue test machine at a frequency of approximately 80Hz.

Residual Stress, Surface Roughness, Fractographic/Topographical Examination
Surface residual stress measurements were performed using a Stresstech XSTRESS 3000 X-Ray diffractometer. Surface roughness measurements were carried out using a MarTalk GD 25 in the longitudinal direction along the waisted section of the fatigue specimens over a traverse length of 2.5 mm.

RESULTS

Fatigue Properties

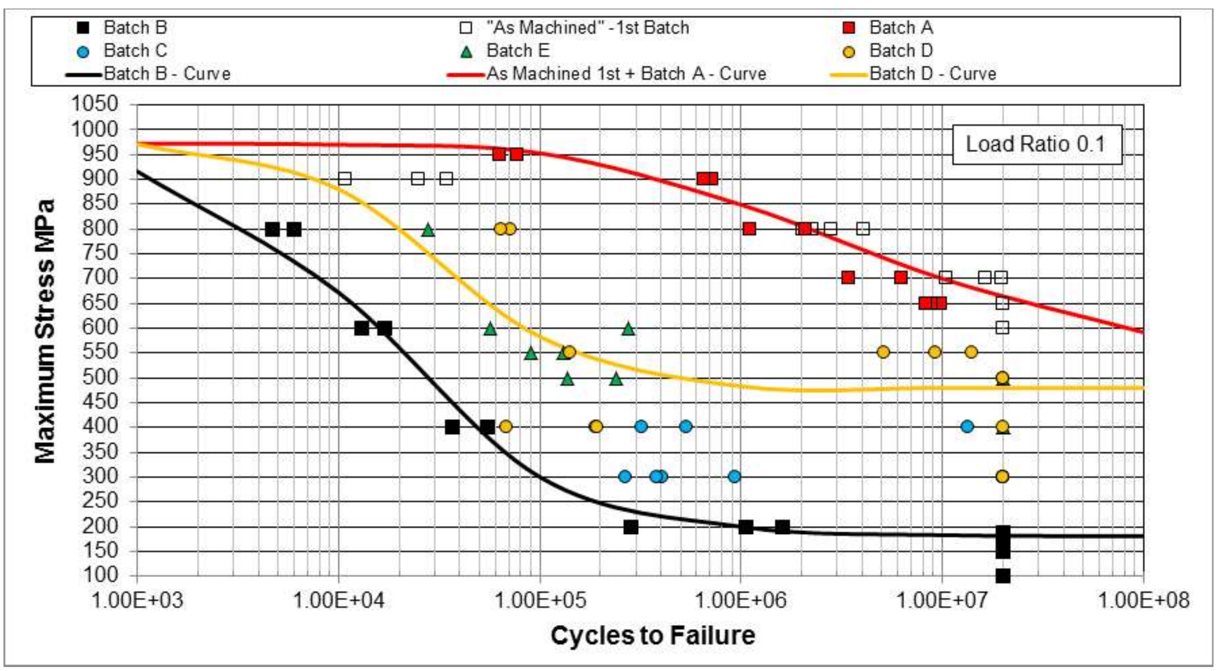
The fatigue results obtained from each group of specimens are shown in the S-N curves produced from the individual data points for each data set are shown in Figure 2.

Fractographic/Topographical Features

Based on the failure positions two types of fractographic features were observed, namely surface or sub-surface initiated fatigue failures. Subsurface failures associated with the "As Machined" ALM (Batch A) samples tended to fail transgranularly, from grain boundaries, as observed previously [1] or from small pores. However, these pores did not appear to have obviously influenced the fatigue life and hence would appear to be essentially benign. It is interesting to note that all the "As Printed" (Batch B) samples and all apart from one sample from Batch E ("As Printed" + Superfinished) failed from the surface. In the case of Batches C and D, where these samples had been peened with steel shot, these tended to nucleate from subsurface origins, whereas samples that were glass bead peened or simply super-finished the predominant failure site was at the surface. All the surface initiated failures tended to fail from features more normally associated with casting defects, namely oxide films/cold shuts. These casting defects were largely featureless and indicative of a lack of fusion, however at higher magnifications evidence of micro-shrinkage were observed.
Differences in the topographical features between each batch or between processing parameters within each batch were observed. From the topographical features observed it has been seen that regardless of the post processing method employed the roughness of the "As Printed" surface was reduced to a greater or lesser extent through the use of shot/glass peening, superfinishing or a combination of the two.

Residual Stress

The maximum values of tensile or compressive surface residual stresses obtained from the different conditions are shown in Figure 3.



Note: Samples tested to 20 million cycles are defined as "run outs" (i.e. un-failed samples)

Figure 2 – S/N Curve of "As Printed" [Batch B], "As Machined" [Batch A], Shot Peened [Batch C], Shot Peened/Superfinished/Shot Peened & Superfinished [Batch D] or Superfinished alone [Batch E]

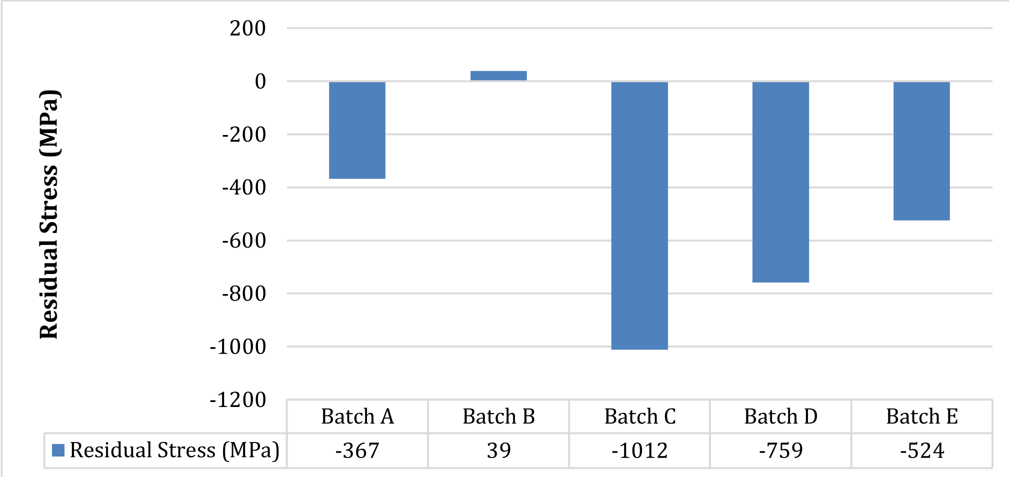


Figure 3 – Maximum Values of Measured Surface Residual Stress: "As Machined" [Batch A], As Printed" [Batch B], Double Shot Peened [Batch C], Shot Peened & Superfinished [Batch D] or Superfinished alone [Batch E]

Surface Roughness

The lowest roughness values were measured in the "As Machined" condition (Batch A) with a maximum of 0,88 µm Ra. The highest values were exhibited by the "As Printed" version Batch B with up to 9,38 µm Ra.
Shot peening including glass bead peening as a single process or the combination of steel shot followed by glass beads reduced the roughness to a range between 2,9 to 5,1 µm Ra. Steel shot peening only resulted in roughness of 3,5 µm Ra.
Depending on the process time the MIC superfinishing process (CASE) produced a roughness in the range of 0,21 to 0,37 µm Ra which is similar to that of the FINTEK finishing process which resulted in 0,19 to 0,4 µm Ra.

ANALYSIS

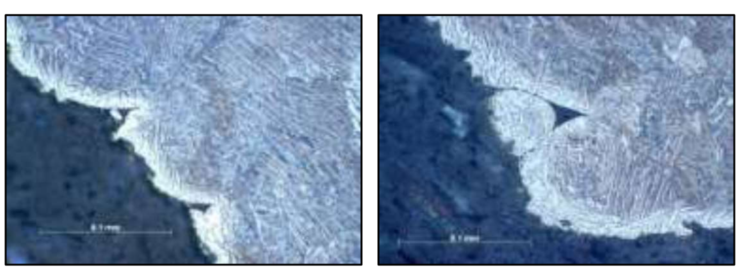
Fatigue

From the S/N curve data shown in Figure 2 it can clearly be seen that the ALM "As Printed" batch was inferior by a factor of three when compared to the ALM "As Machined" batch. The inferiority of the "As Printed" ALM is considered to be due to four main factors:-

- A far higher level of surface roughness.
- The presence of partially melted grains and unfused regions at the surfaces creating surface re-entrant angles/notches at the surface, see Plate 2.
- The surface layer was in a slightly tensile residual stressed state, see Figure 3.
- Evidence of surface oxidation(alpha case contamination), see Plate 2.

From the fractographic examination, it is interesting to note that all the "As Printed" ALM Batch B samples failed from the surface. This was in contrast to the "As Machined" Batch A samples in which sub-surface failures were the predominate failure mode.

Plate 2 – Micro-section taken through "As Printed" ALM showing Evidence of Surface Oxidation, Un-melted Powder Particles and Re-entrant Flaws/Notches



Influence of Shot Peening, Superfinishing and the combination of Shot Peening and Superfinishing on Fatigue

An overview of the influence of all three investigated post ALM treatments showing their largest improvements to the fatigue performance can be seen in Figure 4, in relation to the "As Machined" and "As Printed" conditions.

Influence of Shot Peening

Shot peening with different parameters, i.e. size, intensity and type of shot resulted in different fatigue endurances of "As Printed" ALM. Figure 4 shows the largest improvement by using a dual shot peening process consisting of steel shot followed by glass bead peening. Regardless of the type of peening employed, fatigue life of the "As Printed" batch was always enhanced. Although definite conclusions cannot be drawn due to the small sample size, i.e. in most cases single samples, the following general data trends were observed:

- The use of glass bead peening increased the endurance limit of the "As Printed" ALM batch by approximately 30%.
- Steel shot increased the fatigue endurance over the "As Printed" ALM batch by approximately 45%.
- Within the limits of the investigation, the higher the intensity, the larger the size of steel shot and the higher the coverage that was employed the higher the resultant endurance limit.

Influence of Super-Finishing on Fatigue

By investigating the changes in fatigue endurance in relation to superfinishing, the following observations were made in the relation to Figure 3.

- Improvements in the "As Printed" fatigue endurance were observed as a result of superfinishing modifying both residual stress and surface roughness. The most likely explanation for the change in residual stress were due to the abrasive removal of the alpha case. It is interesting to note that the level of compressive residual stress was less with the MIC CASE superfinishing process which was probably due in part to the chemically assisted abrasion process used which is known to be less abrasive than the more straightforward abrasive process used by Fintek.
- While improvements in the "As Printed" fatigue endurance were observed through the use of superfinishing, large variations in fatigue endurance between the two superfinishing processes (i.e. MIC & Fintek) were observed. The most likely explanation for this difference is likely to be due to the amount of material removed during superfinishing. With regards to the Fintek process approximately 0.16 mm was removed per surface, whilst the MIC CASE process removed far less material, i.e. 0.07 mm. However, while the Fintek superfinishing process removed more material, cold shuts/re-entrant flaws/defects from the ALM process were still present, see Plate 3a. Moreover the presence of these ALM processing defects were further confirmed by the fractographic evidence in which the majority of the fatigue failures were still initiated from the surface. The detrimental influence that these cold shuts/re-entrant flaws/defects have on fatigue can be seen in Plate 3b in which a secondary fatigue crack has initiated from one of these features.
- The most likely reason why the "As Machined" ALM batch was superior to both super-finishing processes is due to the fact that all the ALM surface features were removed even though residual compressive stress and surface finish was inferior.

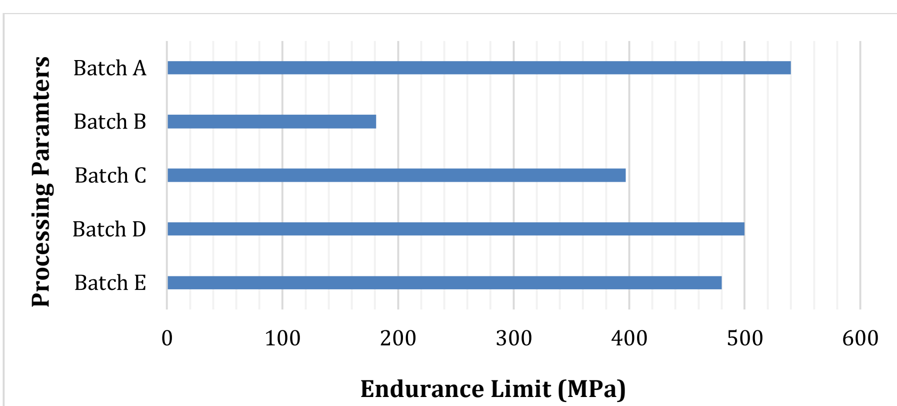
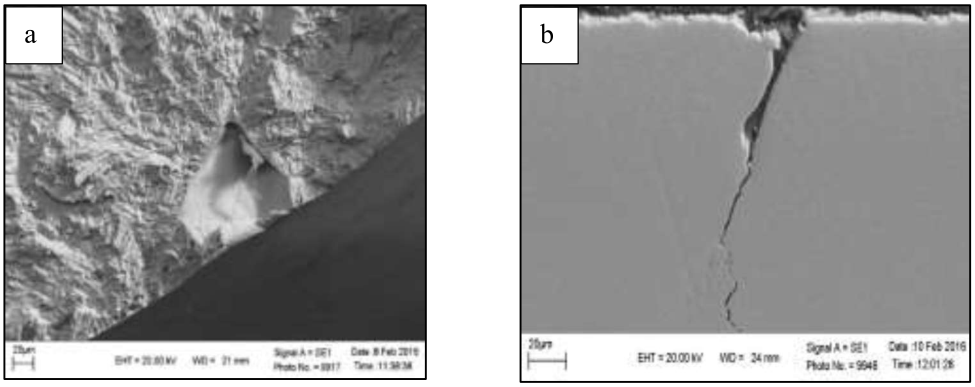


Figure 4 – Endurance Limit of "As Machined" [Batch A], As Printed" [Batch B], Double Shot Peened [Batch C], Shot Peened & Superfinished [Batch D] or Superfinished alone [Batch E]

Plate 3 – Surface Failure from a) Cold Shut/Oxide Film and b) Micro-section showing a Fatigue Crack Initiating from a Cold Shut



Influence of Shot Peening and Super-Finishing on Fatigue

The effect shot peening combined with super-finishing had on the fatigue endurance of “As Printed” ALM can also be seen in Figure 4, Batch D. From this figure it is interesting to note that the fatigue endurance limit was approaching the value obtained with the “As Machined” batch. Although the difference in endurance limits between the “As Machined” Batch A and the Shot Peened and Superfinished samples from Batch D would appear to be less than 8%, care must be taken with this assumption due to the curve shape of Batch A. Hence based on Figure 4, a more realistic difference of 15% should be assumed.

The reason for the resultant enhancement was due to a large reduction in surface roughness, a substantial increase in compressive stress and the removal of alpha case contamination evident on the “As Printed” batch. The reason why the endurance limit of these samples is not comparable to that obtained from the “As Machined” batch cannot be explained by the presence of cold shuts/re-entrant flaws/defects as fractographically these samples did not fail from this type of defect.

Influence of Shot Peening on Residual Stress & Surface Roughness

Based on the measured data following shot peening data trends were observed:-

- A reduction in the level of surface roughness and a substantial increase in compressive residual stress of the “As Printed” ALM was achieved through the use of either steel shot or glass beads.
- Regardless of the type of shot or glass beads used, by increasing the level of coverage from 100% to 200% a reduction in surface roughness was obtained, although the improvement was only slight.
- The use of C Glass tended to produce a lower level of surface roughness and a higher level of residual compressive stress when compared to AF Glass.
- By increasing the level of shot peening intensity a reduction in surface roughness and an increase in compressive residual stress was obtained.
- Higher levels of residual compressive stress were observed through the use of hard steel shot when compared to glass.

While improvements in the endurance limit of the “As Printed” batch was achieved by selecting the best combination of peening parameters (i.e. large high intensity steel shot) the resultant improvements was still below that obtained from the “As Machined” batch. The reason for the improvement is due to a reduction in surface roughness and a substantial improvement in compressive residual stress. However the reason why the resultant endurance limit was not comparable with that obtained from the “As Machined” batch was due to the detrimental influence of cold shuts/re-entrant flaws/defects from the ALM process.

CONCLUSIONS

When compared to the “As Machined” ALM produced fatigue samples the “As Printed” ALM fatigue samples exhibited a substantial loss in fatigue life. The reason for this substantial loss in fatigue was due to four main factors, i.e. a rough surface, presence of surface contamination, evidence of tensile residual stresses in the surface and the creation of surface flaws/notches caused by partially remelted powder particles resulting in cold shuts/oxide films.

The fatigue life of the "As Printed" ALM can be increased by using shot peening, super-finishing or a combination of both post processing techniques, in which the greatest improvement in fatigue was achieved by the use of shot peening combined with super-finishing. However, although substantial improvements in fatigue endurance are possible, fatigue endurance cannot be restored to the "As Machined" condition largely due to the fact that surface flaws/notches caused by partially remelted powder particles resulting in cold shuts/oxide films are still present.

REFERENCES

[1] D P Davies, S L Jenkins & B Geary, "Assessment of Additive Layer Manufactured (ALM) Ti-6Al-4V for Aerospace Applications", SAP DMS Reference NA00K0057W, LR14,043 and Materials Technology Laboratory Report AWTL00MM005, 2014

[2] 3T Titanium Alloy Test Data

[3] B Rosa, P Mognol & J Hascoet, "Laser Polishing of Additive Laser Manufacturing Surfaces", Jounal of Laser Applications, Volume 27, Number S2, 2015

[4] D W Sokol, A H Clauer & R Ravindranath, "Applications of Laser Peening to Titanium Alloys", ASME Conference Proceedings, San Diego CA, July 25-29, p1, 2004