Effect of Treatment on the Mechanical Properties of Additive Manufactured Ti-6Al-4V Parts

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Abstract: The paper is focused on the evaluation of the influence of surface treatment and machining parameters on the static and fatigue properties of additively manufactured parts. The internal defects and characterization of the specimens were further analyzed using scanning electron microscopy considering surface roughness, possible anomalies in surface chemistry and possible cracks. The influence of selected machining methods (heat treatment, CNC milling, electrolytic polishing, chemical polishing) and operating parameters is discussed in the paper.

Keywords: Experimental; Stress; Analysis

1 Introduction

To reduce fuel consumption and CO_2 emissions in the aerospace sector, innovative solutions are being sought to reduce aircraft weight, including additive manufacturing (AM). Therefore, a high ratio of mechanical properties to weight is required. Due to this parameter, Ti6Al4V alloys are widely used in aircraft structures [1-4]. Nowadays, conventional processes such as casting and CNC machining are commonly used, but they lead to large volume losses, which causes higher costs. Additive manufacturing (AM) offers advantages in terms of weight, lead time, design, and functionality and allows the realization of alternative geometric shapes. Material strength characteristics can be better exploited. However, there are currently technological shortcomings [5] that have led to AM not being approved for applications on parts with high safety requirements, i.e., for use in primary aircraft structures. Therefore, it is necessary to focus on improving the "damage tolerance" parameters of such parts and quality control of printed parts. From this point of view, pores and other defects are particularly important and their occurrence cannot be completely prevented at present. However, the aim is to reduce the occurrence of defects to a minimum. The mechanical properties of the parts produced by AM technology can be further improved in various ways. The test program was designed in accordance with regulation requirements [6,7]. The presented paper is focused on the evaluation of the influence of surface treatment and machining parameters on the static and fatigue properties of additively manufactured parts. The work is a part of the Clean Sky 2 Joint Undertaking (JU) under grant agreement No 101007830 [8].

2 Manufacturing

The AM parts were built from Grade 5 (Ti 6Al 4V) powder in the conditions “new powder” and “recycled powder”, the latter for assessment of the recyclability of used powder, i.e., powder which has been used in former AM processes but has not been fused. The chemical composition of the material is listed in Table 1.

Table 1. Chemical composition of the material (in wt.%).

Al	V	Ti	O	N	H	Fe	C
6.20	3.98	balance	0.09	0.01	0.002	0.03	0.01

Specimens have been built in an upright standing position on a building platform. 6 specimens of each type (round and flat) can be built in one run (totally 20 pieces per processing batch, i.e., 120 test specimens have been produced). AM part on the build plate is shown in Fig.1. The paper deals with round specimens only. Several series of specimens had been manufactured with various post-processing methods – as built, stress relief (SR) treatment at 600 °C for 90 minutes, CNC machining, electropolishing (EP), plasma-electropolishing (PEP), hot isostatic pressing (HIP) at 920 °C and 1000 bar for 2 hours, and heat treatment (HIT) at 800 °C for 90 minutes. Examples of various post-processed round specimens are shown in Fig. 2.

Fig. 1 AM-parts on the build plate.

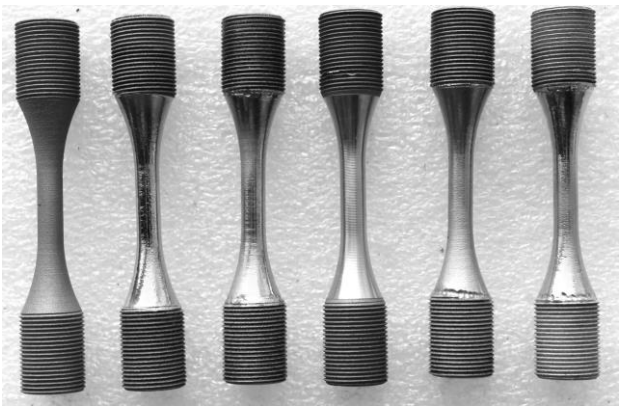

Fig. 2 Round test specimen post-processing types appearance (from left to right side: as-built, electropolished, HIP and electropolished, CNC milled, HIP and plasma-electropolished, and HIT and plasma-electropolished.

3 Test methods and arrangement

The static tensile tests were carried out according to the EN ISO 6892-1 standard [9] using Sinus (100 kN load cell) and Schenck (250 kN load cell) testing machines using hydraulic mechanical threaded holder fixtures. The static tests were done under displacement control at a test rate of 0.5 mm/min. The strain was measured using one axial extensometer (Instron 2620-604, gauge length of 12.5 mm) attached to the test specimen. The extensometer was always removed during the test after reaching of axial strain value of 1%. All the static properties were calculated using the analysis module of Bluehill 3 software. The tensile test set-up detailed picture is shown in Fig. 3.

The fatigue tests were carried out according to the EN 6072 standard [10] using Sinus (100 kN load cell) testing machine using mechanical threaded holder fixtures. The fatigue tests were done under load control using a harmonic loading (sinusoidal shape of the loading cycle) with a constant load amplitude. Cyclic loading of the specimens was performed at one level of stress ratio $\boldsymbol{R}$ = -1 and a nominal test frequency of 10-15 Hz. The fatigue curve was generated by performing a series of experiments at appropriate maximum stress or load levels, such that the desired range from 10^4 to 4.10^6 cycles was achieved. The run-out test specimen was tested at a higher load level in agreement with the EN 6072 standard.

The microfractographic analyses of the fracture surfaces were carried out using the TESCAN 3SBU Scanning Electron Microscope (SEM).

Fig. 3 Round static specimen test set-up – detail with an attached extensometer.

4 Results

Typical stress-strain curves of AM specimens are shown in Fig. 4. Mechanical testing of additively manufactured specimens with and without a post-treatment is summarized in Fig. 5 and Fig. 6. Quasi-static tensile tests performed at room temperature showed a negative effect of higher temperature treatment procedures on the strength properties. The lowest properties exhibited hot isostatic pressured batches (down to 80% of the as-built batch); the highest ones were found in the case of the mechanically milled (CNC) samples.

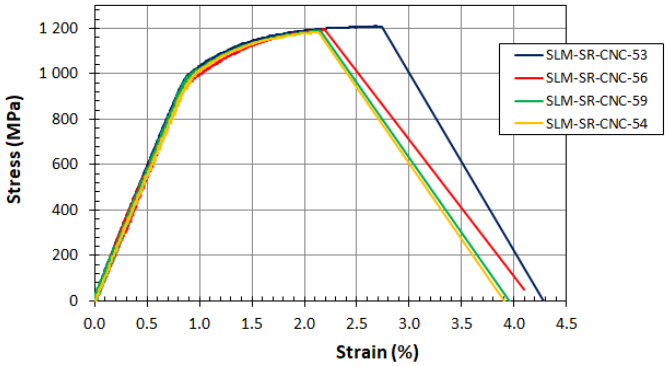

Fig. 4 Typical stress-strain tensile curves of as-built, stress-relieved, and CNC milled (SLM-SR-CNC) batch.

Fatigue test results are summarized and compared in semi-logarithmic coordinates in Fig. 7, Fig. 8, and Fig. 9. The arrows in the Fig.s indicate either samples that have failed outside the critical area in the thread (shorter lives) or completed tests without failure (run out). Tabular comparison of post-treatment effect on the fatigue life at stress level of 400 MPa is presented in Tab. 2. A slightly worse fatigue behaviour could be observed in the case of the electropolished and heat-treated samples. Contrarily, the CNC machined batch shows a significantly improved fatigue behaviour. In the case of the heat-treated batch, no substantial effect on fatigue behaviour in the linear part of the fatigue curve is present, only a lower fatigue limit caused by the heat-treatment process could be observed (a large scatter of the HIP batch results is probably affected by an electro-polishing process). A noticeable

influence of plasma-electropolishing could be observed in the case of the HIP batches when compared to standardly electropolished samples, especially in the fatigue limit region (see Fig. 9).

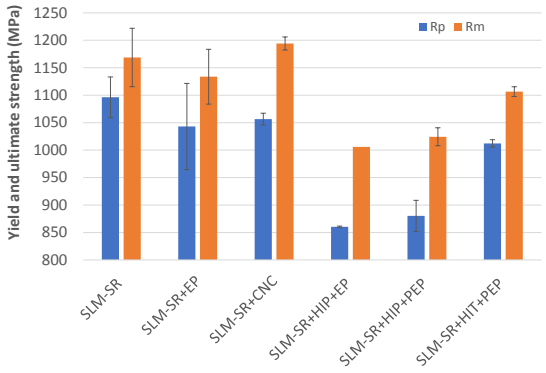

Fig. 5 Comparison of the Yield stress Rp0.2 and Ultimate tensile strength Rm for the as built condition (SLM SR) and post-treated configurations.

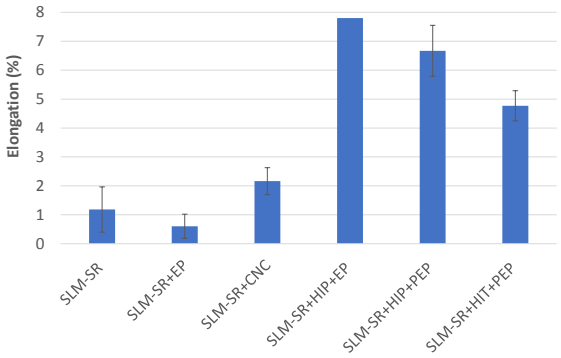

Fig. 6 Comparison of the elongation for the as-built condition (SLM SR) and post-treated configurations.

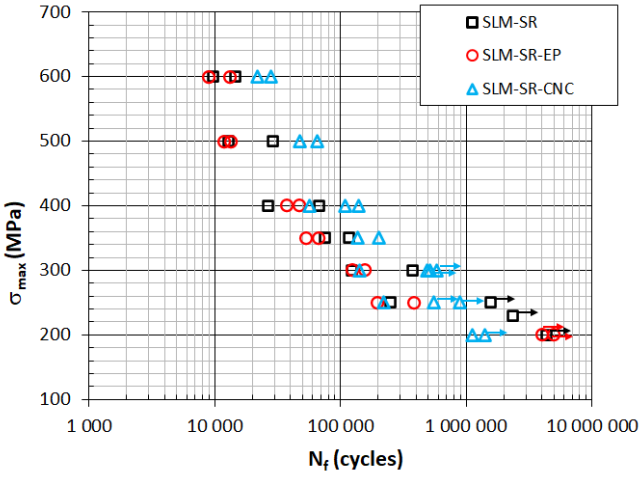

Fig. 7 Fatigue tests – Comparison of the fatigue data of electro/mechanical machining procedures with the as-built condition (SLM SR).

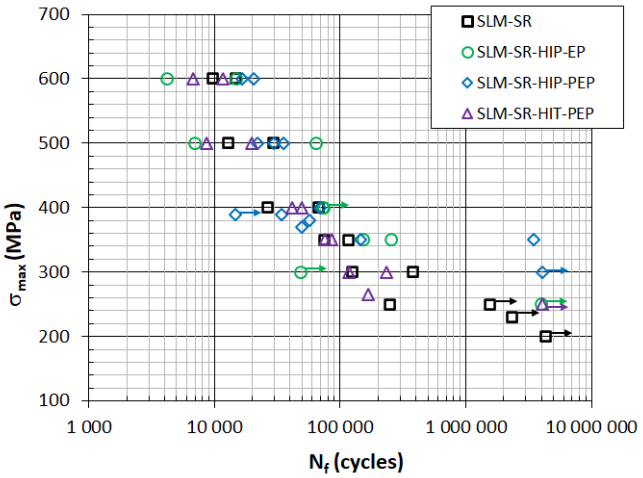

Fig. 8 Fatigue tests – Comparison of the fatigue data of a higher temperature treatment methods with the as-built condition (SLM SR).

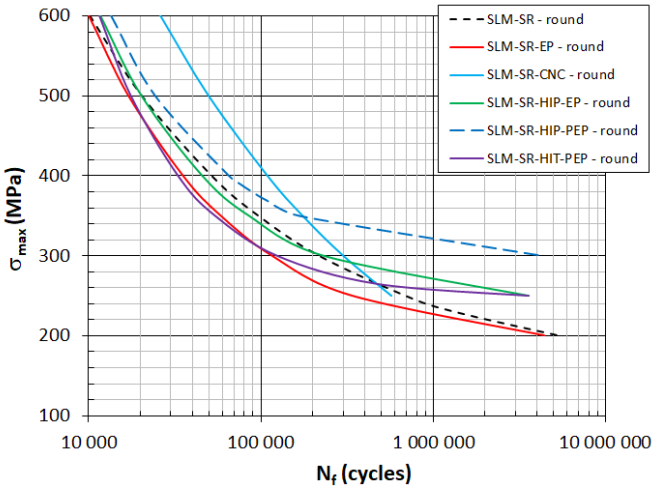

Fig. 9 Fatigue curve comparison (nonlinear 4-parametric regression) for round specimens' batches (R=-1).

Table 2. Effect of post-treatment on the fatigue life at stress level of 400 MPa (comparison with SLM SR).

Batch	Maximum stress (MPa)	Mean fatigue life	% ratio
SLM-SR (original)	400	51 532	–
SLM-SR-EP	400	35 289	68%
SLM-SR-CNC	400	109 147	212%
SLM-SR-HIP-EP	400	45 684	89%
SLM-SR-HIP-PEP	400	64 977	126%
SLM-SR-HIT-PEP	400	33 024	64%

Despite the improved roughness, the electro/mechanical machining procedures caused an exposition of internal subsurface defects on the surface of the samples (open pores by removing up to 0.5 mm surface layer by milling) that acted as a stress concentrator facilitating the initiation of fatigue cracks and deterioration of the fatigue behaviour. Only in the case of

the HIP samples, a limited number of open defects in the test specimen's surface have been observed that led to an improved fatigue behaviour connected with a surface initiation type. This resulted even in an order increase in fatigue life. Examples of two fatigue crack initiation modes for as-built and electropolished samples (tested at the same loading level of 400 MPa) in the form of fracture surface micrographs are shown in Fig. 10 and Fig. 11, respectively. In the case of the as-built sample, a typical sub-surface one-site initiation could be observed (Fig. 10), while the electropolished sample exhibited multiple initiations of a fatigue crack from the open pores (Fig. 11) resulting in a half fatigue life (Fig. 8).

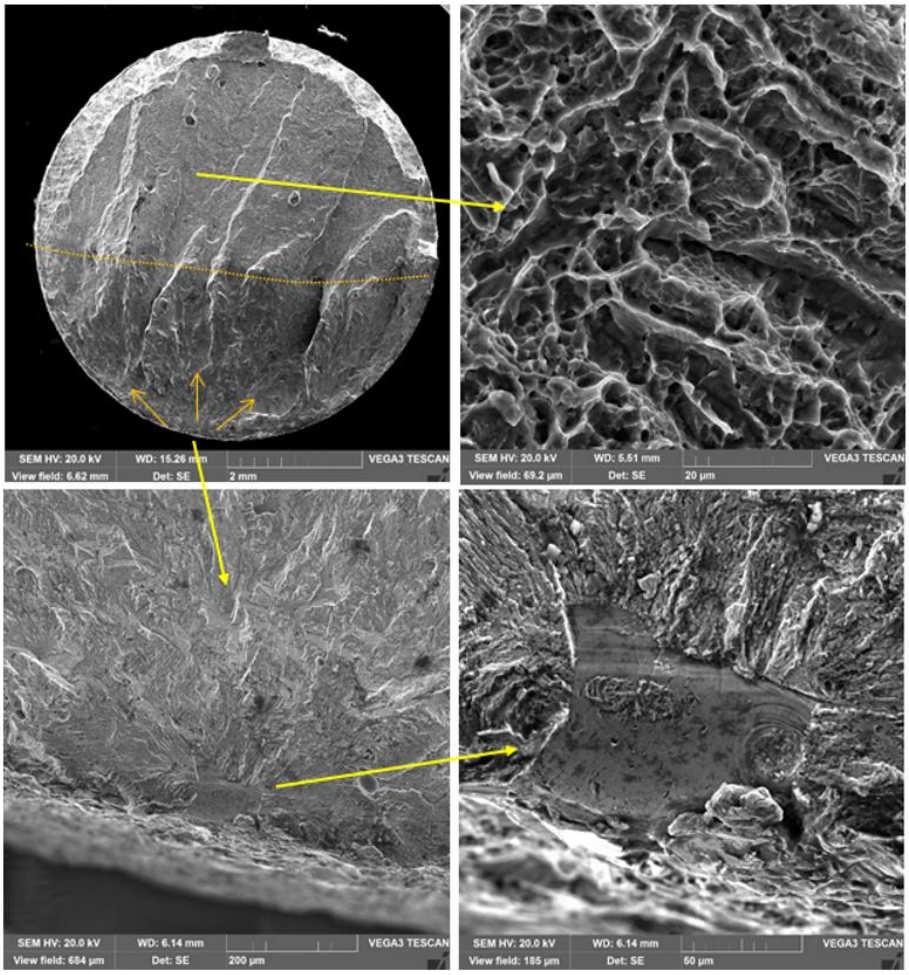

Fig. 10 Fracture surface of as built batch sample tested at the maximum loading level of 400 MPa with the resulting fatigue life of 67 483 cycles (SEM, up to 8000x magnification).

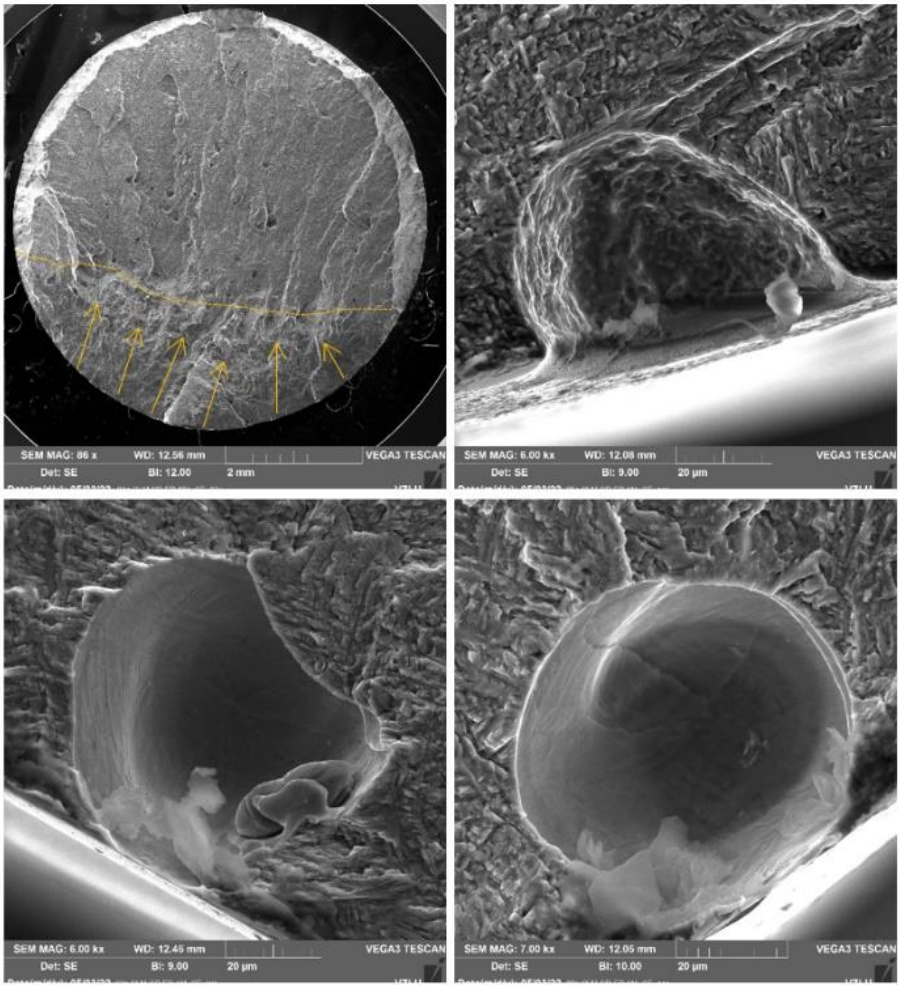

Fig. 11 Fracture surface of electropolished batch sample tested at the maximum loading level of 400 MPa with the resulting fatigue life of 37 372 cycles (SEM, up to 7000x magnification).

Conclusion/Summary

The following conclusion are stated: a negative effect of higher temperature treatment procedures on the strength properties; the lowest properties exhibited hot isostatic pressured batches (down to 80% of the as-built batch); the highest ones were found in the case of the mechanically milled (CNC) samples; a slightly worse fatigue behaviour in case of the electropolished samples (as compared with the as-built batch); improved fatigue behaviour in case of the CNC machined and HIP batches. Fractographic analyses supported the discussion of the results.

Acknowledgements

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[8] Annex: 11th Call for Proposals (CFP11) - List and Full Description of Topics, JTI-CS2-2020-CFP11-AIR-01-46: Evaluation of NDT Techniques for Assessment of Critical Process and Manufacturing Related Flaws and Defects for a Ti-alloy 2019. *Available from* https://3tanium.eu/.

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