Creep and high temperature fatigue performance of as build selective laser melted Ti-based 6Al-4V titanium alloy

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Abstract: The present work focuses on the room and high temperature low-cycle fatigue and creep testing of Ti-6Al-4V manufactured by selective laser melting (SLM) or laser-based powder bed fusion process (LBPF). The fatigue specimens were tested in a strain control mode with the as-built and machined surfaces, evaluating the influence of the surface roughness on the fatigue performance. This helps in understanding the potential negative influence of a surface defect/roughness on the fatigue performance of the complex components produced by SLM (in as-built state), where surface machining may not be possible due to geometrical constraints. The fatigue fractures at room and high temperature were investigated with the help of a scanning electron microscope. The creep tests were performed at three different temperatures with as-built SLM samples, demonstrating an equivalent or better performance when compared to their counterparts produced by hot-forging.

Keywords: Additive manufacturing, titanium alloy, creep, high temperature fatigue, surface defect.

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1. Introduction

The extreme design flexibility offered by additive manufacturing (AM) technologies has drawn great interest both from the industry and academia. On one side, the industry aims to improve the efficiency of production by reducing the processing steps and on the amount of components to be assembled to create a complex geometry. In addition, the feasibility of producing complicated nature-inspired and topologically optimized geometries that would be expensive or impossible to be manufactured with the traditional technologies like casting, forging and material removing was explored [1]. On the other side, scientific research is focused on understanding the microstructure and performance of the components produced SLM, as compared to their cast counterparts [2,3]. The process specific conditions may create variations in the microstructure and in turn their mechanical properties [4]. The present day research is focused on the below mentioned aspects: develop rapid production and energy-effective technologies, optimize the processes to reduce the amount of defects present in the AM components and develop had-hoc criteria that may accurately predict the fatigue and fracture behavior of such materials, ideally including the effects of anisotropy, residual stresses, surface finish and internal defects generated by different combinations of the production parameters [5-8].

Ti-6Al-4V titanium alloy, one of the widely fabricated alloys by SLM, with variety of applications, ranging from the aerospace industry to biomedical applications, in virtue of its excellent mechanical properties and chemical resistance is chosen for the present study. Due to the ease of manufacturing and the importance of this alloy itself, several studies have been carried out, especially on the mechanical properties, since the early days, produced by conventional techniques like casting. The introduction of these novel production techniques and the specific properties of components produced by the means of them have attracted great interest in studying the alloy manufactured by these new AM methods. Tokaji [9] studied the fatigue behavior at elevated temperatures focusing on the propagation of small cracks at the different regimes. In terms of stress amplitude, a reduction of fatigue resistance is observed increasing with the temperature from 623 K to 723 K at low cycle regime, but not in the high cycle regime. The high temperature crack propagation is more brittle than at room temperature. Severino et. al. [10] studied the oxidation resistance of the alloy at 1073 K for different times and the influence of the oxide layer on the tensile behavior at 873 K. The ultimate strength was very slightly influenced compared to the un-oxidized, but a reduction of elongation at break was detected.

Richie et. al. [11] investigated the fatigue behavior of a Ti-6Al-4V alloy employed for the production of axial compressor blades. The study was performed on large-cracks and small-cracks at frequencies ranging from 20 Hz to 1500 Hz and load ratios R ranging from 0.1 to 0.95 in air and vacuum. No influence of the frequency was detected, while the presence of air increased of three orders of magnitude the crack propagation rate and the worst-case fatigue threshold was measured to be 1.9 MPa√m. Li et. al. [12] provided a comprehensive overview on several results obtained on traditionally and AM manufactured Ti-6Al-4V in different conditions of surface finish and thermal treatment. Molaei and Fatemi [13] studied the influence of typical defects such as entrapped gas pores or lack of fusion, correlated to the technological parameters, on the fatigue performance. Shunmugavel et. al. [14] compared the microstructure and the tensile properties of wrought and AM manufactured Ti-6Al-4V alloy, where a higher tensile strength, but decreased ductility was observed for AM processed material. Tong et. al. [15] compared the influence of different combinations of building direction and thermal treatment on hardness and static and fatigue behavior of the alloy manufactured by powder bed selective laser melting (SLM) and by electron beam melting (EBM). Wu et. al. [16] applied several failure criteria to AM processed Ti-6Al-4V and tested in proportional and non-proportional multi-axial strain controlled low-cycle fatigue, where good data correlations with the Fatemi-Socie [17] and the non-proportional strain range criteria were observed [18]. No additional hardening, but a severe reduction of the fatigue life due to the non-proportionality of the load, was detected. Zhai et al. [19] investigated the static and fatigue crack growth properties of Ti-6Al-4V manufactured with the additive techniques of Laser Engineered Net Shaping (LENS) and Electron Beam Melting (EBM), with attention to the difference in performance to wrought alloys.

The present work aims to integrate the number of results available focusing on the influence of surface defects and temperature on fatigue performance and creep resistance of SLM processed Ti-6Al-4V.

2. Material production and microstructure

The specimens used for the present study were manufactured by selective laser melting using a SLM Solutions (SLM 280) device. The build direction coincides with the longitudinal axis and the process details are indicated in table 1. The two geometries produced, for fatigue and creep testing, are reported in Fig. 1 (A and B) respectively. During SLM fabrication a defect was introduced in the form of a slight misalignment of the build axis in correspondence of the minimum cross section trait, as indicated in Fig. 1C. The fatigue specimens were produced to a minimum diameter of 6 mm. Four of them were being tested at room temperature with the as-built surface, while the rest of them had the surface lathe-machined down to a diameter of 5 mm as reported in Fig. 1A. The creep specimens where tested with the as-built surface. All the specimens were tested with the as-built microstructure consisting of acicular α’ martensitic phase in elongated β grains as shown in Fig. 2. A certain degree of porosity can be detected in the longitudinal cut as observed from Fig. 2.

Table 1. Table detailing the SLM process and the fabrication parameters.

Device	**SLM 280HL – SLM Solutions**
Laser power [W]	**275**
Laser scan speed [mm/s]	**1100**
Hatch style	**Strip hatch**
Hatch rotation [°]	**15**
Hatch distance [μm]	**120**
Hatch length [mm]	**10**
Atmosphere	**Argon**
Material	**Ti6Al4V**

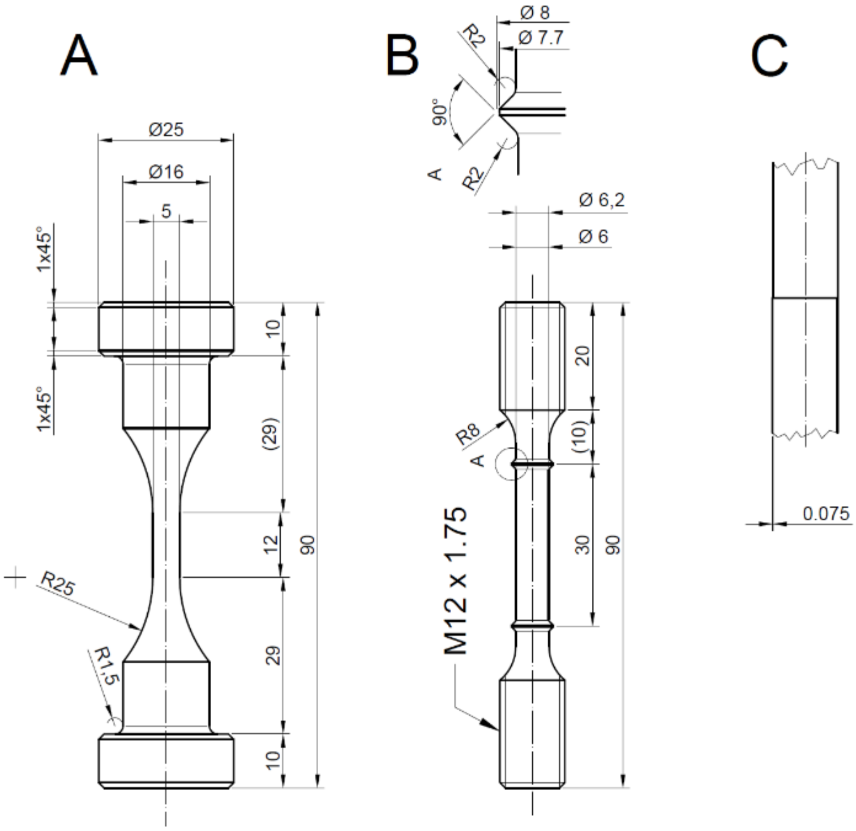

Figure 1. Room and high temperature fatigue specimen (A). Creep specimen (B). Surface defect (C).

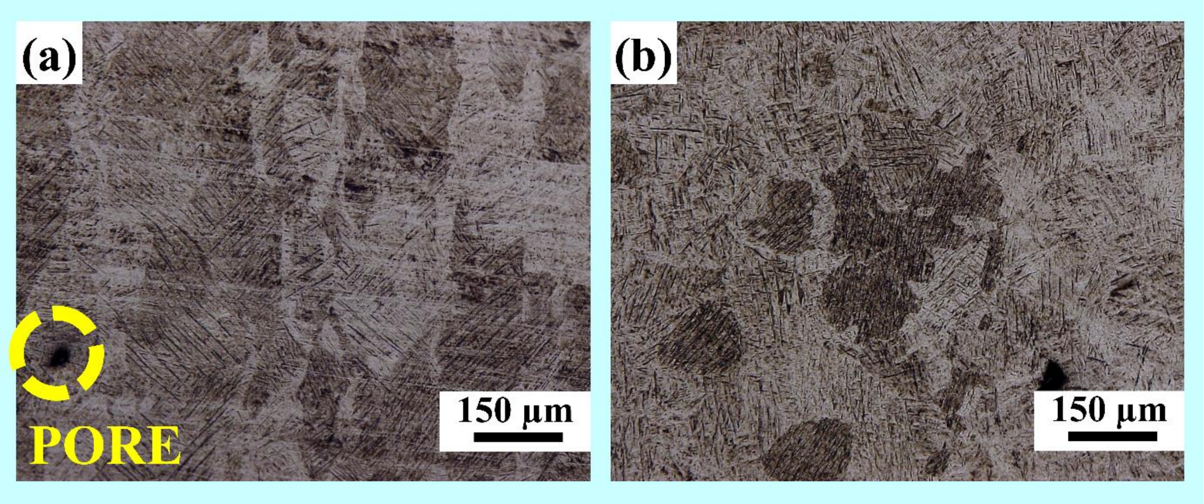

Figure 2. Optical microscopy of the as-built Ti6Al4V SLM microstructure, showing elongated β phase grains containing acicular α' martensitic phase. Along build direction (a) and horizontal direction (b).

3. Fatigue testing

The fatigue testing was performed, by a hydraulic machine, in strain control applying a fully reversed displacement at a strain rate of 0.1 %/s with the feedback provided by an induction axial extensometer. The extensometer, of the kind suited for high temperature testing, had ceramic pins clipped in small pits practiced at a distance of 10 mm in the central section of the specimen. Three series of specimens were fatigue tested: four at room temperature with the as-built surface, six at room temperature with machined surface and four at high temperature and machined surface after having been warmed up to 600 ºC for 30 min by an induction coil. The temperature was detected by a thermocouple welded to the fillet radius area, in order to not weaken the neat cross section by practicing a weld. The temperature in the center area was correctly known by having calibrated the correlation between the temperatures in the two points on a dummy specimen. The fatigue results are reported in Fig. 3.

The tests performed at room temperature on machined surface specimens show a behavior which is in perfect agreement with analogous tests in the literature [16]. Assessed so the reproducibility of the results, the other two series show the strong weakening produced by a surface defect and by an increase of temperature. The specimens tested with an as-built surface in presence of the defect have all experienced failure with cracks starting from the defect, see

Fig. 4a, and a fatigue life noticeably inferior to the machined specimens. Considered the entity of the defect, a misalignment of the build axis of 75 µm, it is evident how even a small defect can have huge repercussions on the structural integrity, which is particularly of importance for the production of complicated topology-optimized geometries, the realization of which is allowed by the great flexibility of the AM technologies, where postproduction surface machining can be non-cost effective or impossible. A similar reduction of strain-controlled fatigue life is originated by an increase of ambient temperature to 600 °C. The fatigue failure at high temperature is characterized by a diffused secondary cracking originated by weakening of the grain boundary regions, as seen in Fig. 4b.

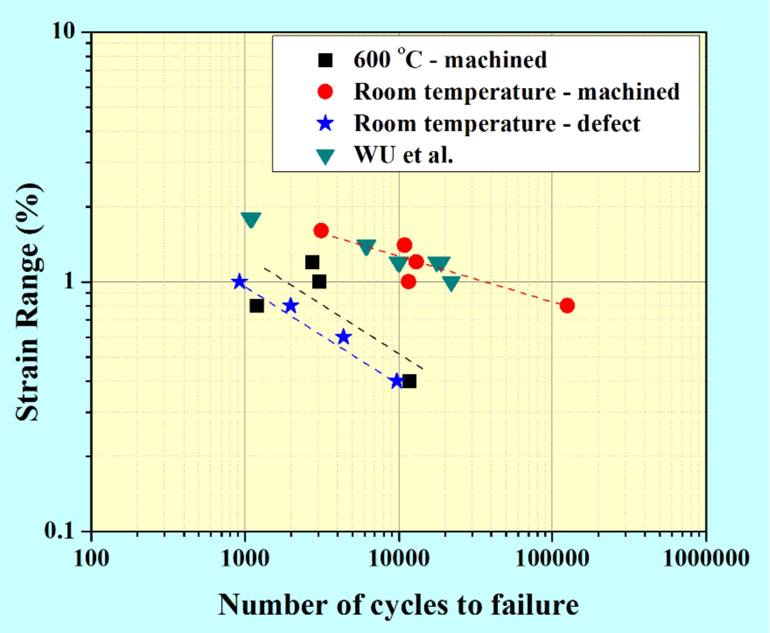

Figure 3. Fatigue results summary [16].

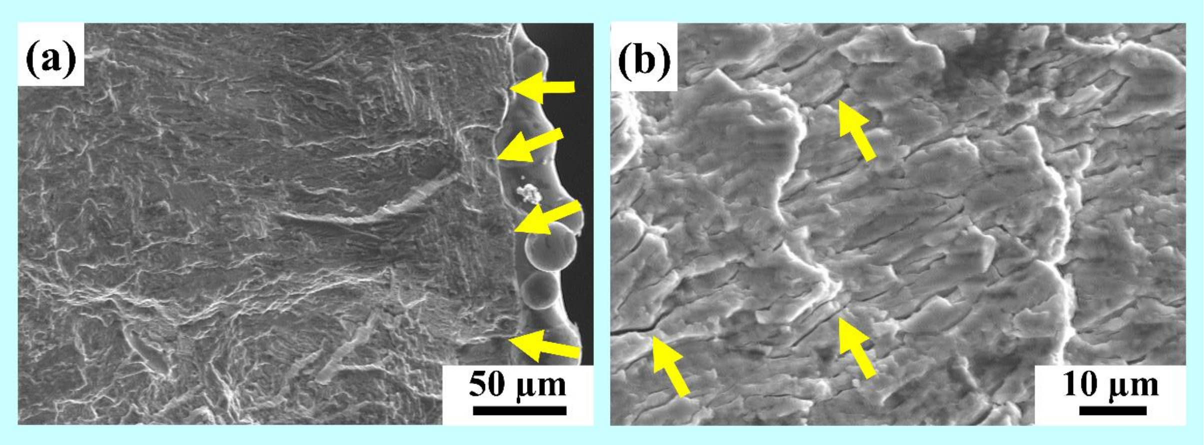

Figure 4. Fatigue crack initiation at a surface defect and partially melted particles (a). Secondary cracking in high temperature fatigue fracture (b).

4. Creep testing

The creep testing was performed on a series of 8 specimens of the geometry specified in Fig. 1b. The samples where tested applying a constant nominal stress with a drop weight machine with induction heating at temperatures of 450, 550 and 650 ºC, respectively. The results are reported in Fig. 5 in terms of nominal stress vs time to failure, showing a consistent behavior for the whole range of time to failure, from 120 s to 655 h. The consistency of the behavior is evident in the summary of the results in terms of nominal stress versus Larson Miller parameter, in Fig. 6, in which all the results can be approximately described by a single power function. Observing the steady state creep behavior reported in Fig. 7 as applied stress versus strain rate, the stress exponent shows a reduction with increased temperature and lower applied stress, thus indicating an increased importance of the diffusive creep deformation versus the dislocation dominated creep, which is predominant for lower temperatures and higher stress levels. Comparing the results obtained to creep testing results available in the literature in hot forged and forged and annealed Ti6Al4V alloy, the as built SLM material has an analogous performance in terms of Larson Miller parameter vs applied stress [20,21].

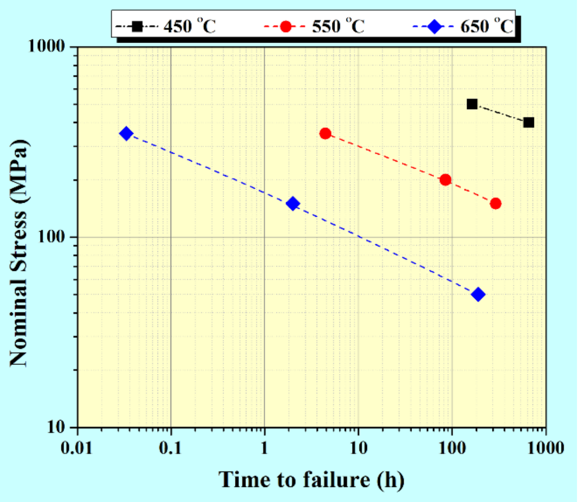

Figure 5. Creep testing results: nominal stress vs time to failure.

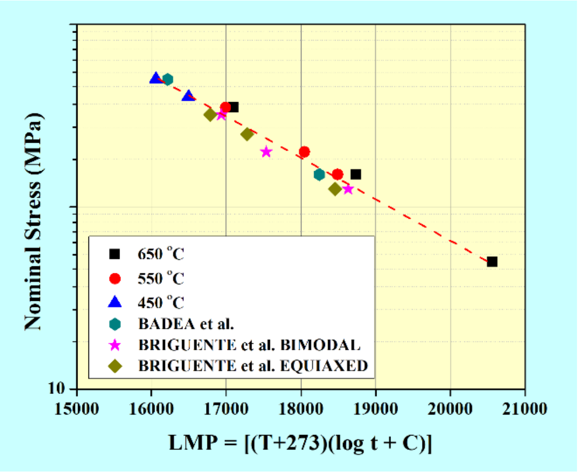

Figure 6. Creep testing results: nominal stress vs Larson Miller parameter [19,20].

Fig. 8 reports the correlation between the applied stress and the ductility for the three test temperatures. The nominal strain was measured during the creep tests by the means of an extensometer attached to the two rings, which delimitate the uniform diameter section of the creep specimens. Despite the important scatter of the results, it is evident that the applied stress has a determinant influence on the elongation to failure, with values ranging from 75 % at a nominal stress of 50 MPa at 650 ºC down to 20 % for 500 MPa applied at a temperature of 450 ºC. Fig. 9 presents the SEM magnification of the fracture surfaces of two creep specimens, tested at 650 ºC, 50 MPa and 450 ºC, 500 MPa. The failures are characterized by pore nucleation and growth, but they present a different aspect according to the test duration, with a much rougher surface in case of higher T and lower stress. This is possibly due to material oxidation.

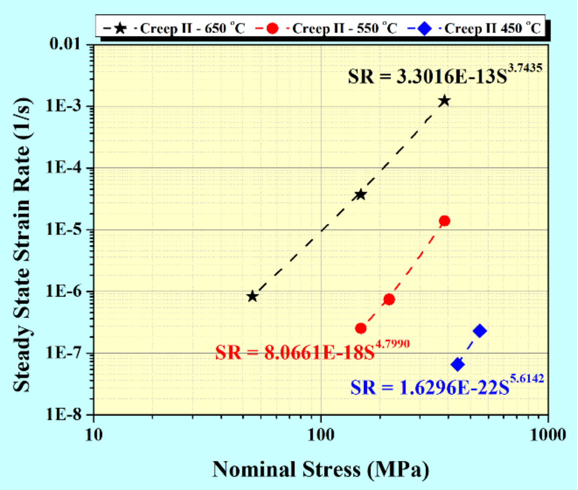

Figure 7. Creep testing results: secondary creep (steady state) strain rate vs nominal stress.

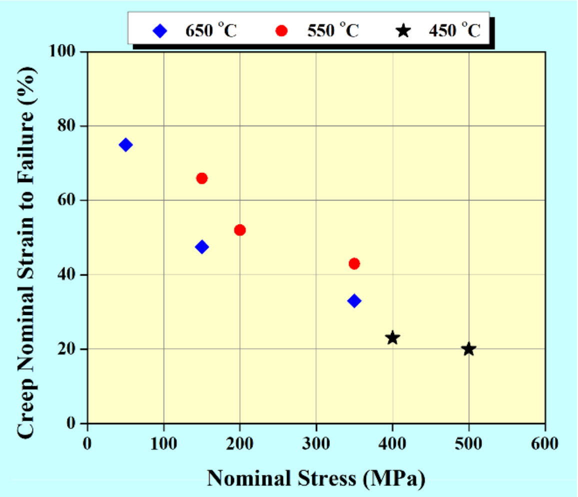

Figure 8. Creep testing results: Influence of stress on ductility for different temperatures.

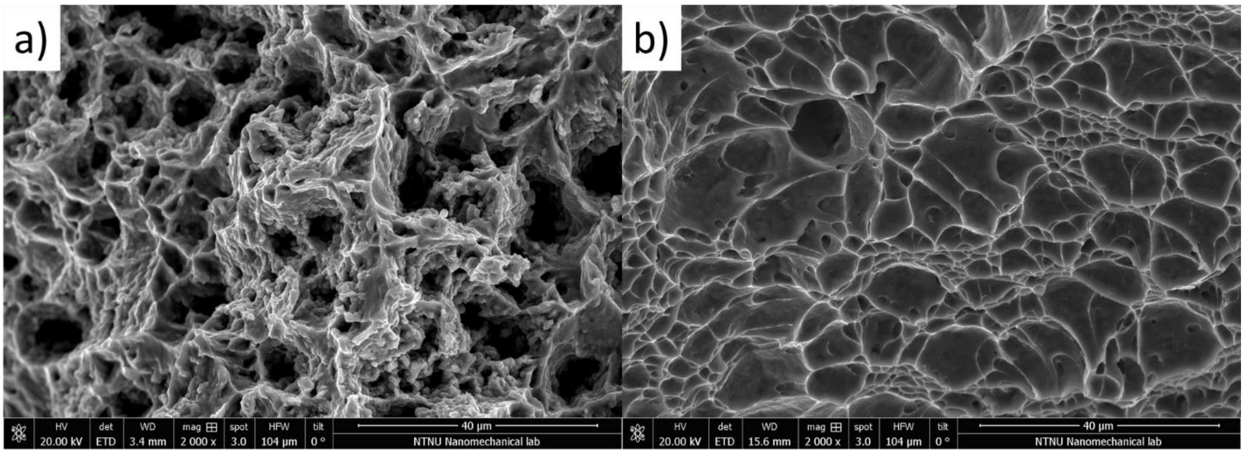

Figure 9. Fracture surface of specimen creep tested at: 650 ºC, 50 MPa (a) and 450 ºC, 500 MPa.

5. Conclusions

A series of fatigue and creep tests has been performed on Ti-6Al-4V alloy processed by SLM without post-processing thermal treatment. The fatigue tests were executed in strain control mode with the as-built surface at room temperature and with machined surface at room temperature and 600 ºC. The creep tests were carried out on as-built specimens using a drop weight machine with the following temperatures: 450, 550 and 650 ºC. The high temperature fatigue tests show a strong influence of ambient temperature at 600 ºC. Most importantly, it is evidenced the high decrement of fatigue resistance caused by a poor as-built surface. This is particularly relevant for the case of intricated geometries, the surface of which might result unfeasible to machine after the additive production process. The creep tests show a performance analogous to the same alloy produced in the form of forged billets and bars in terms of Larson Miller parameter vs nominal stress. The steady state creep rate exponents, ranging from 3.7 to 5.6 and with inverse proportionality to temperature, indicate the dominant presence of dislocation driven creep with an increased influence of diffusion at higher temperatures. The creep ductility at failure presents a reversed proportionality to the applied load. The surface defect had no influence on the creep failure.

Acknowledgements

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