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A study of fatigue notch sensibility on titanium alloy TiAl6V4 parts manufactured by selective laser melting

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Abstract

Titanium Ti6Al4V alloy is a light alloy characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight, commonly used in biomedical applications, automotive and aerospace components. Current work analyses the fatigue behavior of titanium alloy TiAl6V4 parts, manufactured by selective laser melting (SLM), intending to characterize fatigue strength from low to high life range, under constant amplitude strain control. Fatigue tests were carried out at room temperature, using round dog bone specimens where laser powder deposition occurred in layers perpendicular to the sample axle. All specimens were subjected to stress release treatment. A second batch of specimens was tested in order to investigate the notch sensibility of the material. All tests were performed under displacement control. The material was characterized in terms of the tensile mechanical properties, cycle curve, Basquin and Coffin equations. The analysis of the results showed a strain-softening behavior that increased with applied strain, and non-linear response in and plastic regime. In addition, this alloy exhibited a low transition life, about 250 reversals, which can be attributed to the combination of high strength and relatively low ductility. The material revealed a notch sensibility factor, that was quantified for the round notch with a stress concentration factor K_t=1.7 (with respect to the effective cross section), increasing with fatigue life, from one for low cycle fatigue tending to 1.42 for high cycle fatigue (N_f of about one million cycles). SEM analysis showed that fatigue crack initiated from the surface and propagated through the cross section, occurring in many cases multi-nucleation.

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Keywords: Additive manufacturing, Fatigue, Notch sensibility, TiAl6V4 alloy.

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1. Introduction

Additive manufacturing (AM) refers to a process by which digital 3D design data is used to build up a component in layers by depositing fine powder material, which became capable of producing complex components in materials, like metals and composites. It provides a high degree of design freedom, the optimization and integration of functional features, the manufacture of small batch sizes at reasonable unit costs.

Titanium Ti6Al4V alloy is a light alloy characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight, commonly used in biomedical applications and other high-performance engineering applications, like: functional prototypes, automotive and aerospace components, as reported by Guo and Leu (2013), Petrovic et al. (2011) and Mur et al. (2010). The use of AM processes results in around 25% weight savings almost the improvement of other performance characteristics and in the reduction of the development and manufacturing time. These advantages, with regard to the automotive and aerospace industries, lead to weight reduction (raw materials) and decreasing use of the energy, as indicate by Guo and Leu (2013) and Frazier (2014).

Last years, significant research has been performed about the tensile strength values of additive manufactured TiAl6V4 alloy, as reported by Kasperovich and Hausman (2015), Leuders et al. (2013) and Rafi et al. (2013), for different heat treatments and surface conditions. In addition, the influence of surface roughness on the fatigue performance has been investigated for TiAl6V4 by Wycisk et al. (2014) and Edwards and Ramulu (2014). Edwards and Ramulu (2014) and Greitmeier et al. (2015) reported also the effect of heat treatment on the fatigue limit. Leuders et al. (2013) and Rafi et al. (2013) studied also the improvement of fatigue performance on AM TiAl6V4 alloy promoted by the reduction of defects due to optimized process parameters or by hot isostatic pressing (HIP).

Nomenclature

AM	Additive manufacturing
HIP	Hot isostatic pressing
SLM	Selective laser melting
b	Fatigue strength exponent
c	Fatigue ductility exponent
k'	Cyclic hardening coefficient
n'	Cyclic hardening exponent
E	Young´s modulus
N_f	Number of cycles to failure
$\Delta\sigma$	Stress range
σ_f'	Fatigue strength coefficient
ε_f'	Fatigue ductility coefficient
$\Delta\epsilon$	Total strain range
$\Delta\epsilon_e$	Elastic strain range
$\Delta\epsilon_p$	Plastic strain range

2. Material and testing

Experimental tests were performed using dog bone round specimens, synthesized by Lasercusing®, with layers growing towards the direction of loading application. The samples were processed using a The ProX DMP 320 high-performance metal additive manufacturing system, incorporating a 500w fiber laser. Metal powder was the Titanium Ti6Al4V Grade 23 alloy, with a chemical composition, according with the manufacturer, indicated in Table 1. After manufactured by Selective laser melting (SLM) the specimens were machined and polished for the final dimensions. Afterwards, it was applied a heat treatment with purpose to reduce the residual stresses and consisted of slow and controlled heating to 670 °C, followed by maintenance at 670°C±15ºC for 5 hours and a finally by cooling to room temperature in air. The final geometry and dimensions of the notched specimens are shown in Fig. 1a). Side face of the specimen was prepared according to the standard metallographic practice Gammon et al. (2004); a chemical attack by Kroll`s reagent. After preparation, the samples were observed using a Leica DM4000 M LED optical microscope. Fig. 1b) reveals the microstructure showing an acicular morphology where it is identified two phases material with a martensitic phase α (or α′), due to the fast solidification. The same type of morphology was observed by Greitmeier et al. (2017) for similar material and manufacturing conditions. The observation of the figure shows also the formation of longed grains in the deposition plane and the transitions between layers.

Mechanical properties obtained by tensile testing, were a Ultimate tensile strength of 1147 MPa and a Young`s modulus of 120 GPa.

Table 1. Chemical composition of the Titanium Ti6Al4V alloy [wt.%].

Al	V	O	N	C	H	Fe	Y	Ti
5.50 - 6.50	3.50 - 4.50	< 0.15	< 0.04	< 0.08	< 0.012	< 0.25	< 0.005	Bal.

Low cycle fatigue tests were carried out, according to the recommendations of ASTM E606, under fully-reversed strain-controlled conditions ($R_\varepsilon = -1$), with sinusoidal waveforms, and a constant strain rate ($d\varepsilon/dt$) of $8 \times 10^{-3}\ s^{-1}$, using a Dartec 100 KN servo-hydraulic mechanical testing machine. Long life tests were also performed at room temperature, $R_\varepsilon = -1$, and at a frequency of 5 Hz. The stress–strain response was acquired from a 12.5 mm-long gauge extensometer (model Instron 2620-601, Instron, Norwood, MA, USA), clamped directly to the gauge section of the un-notched specimens via two separated knife-edges, and connected to a digital data acquisition system.

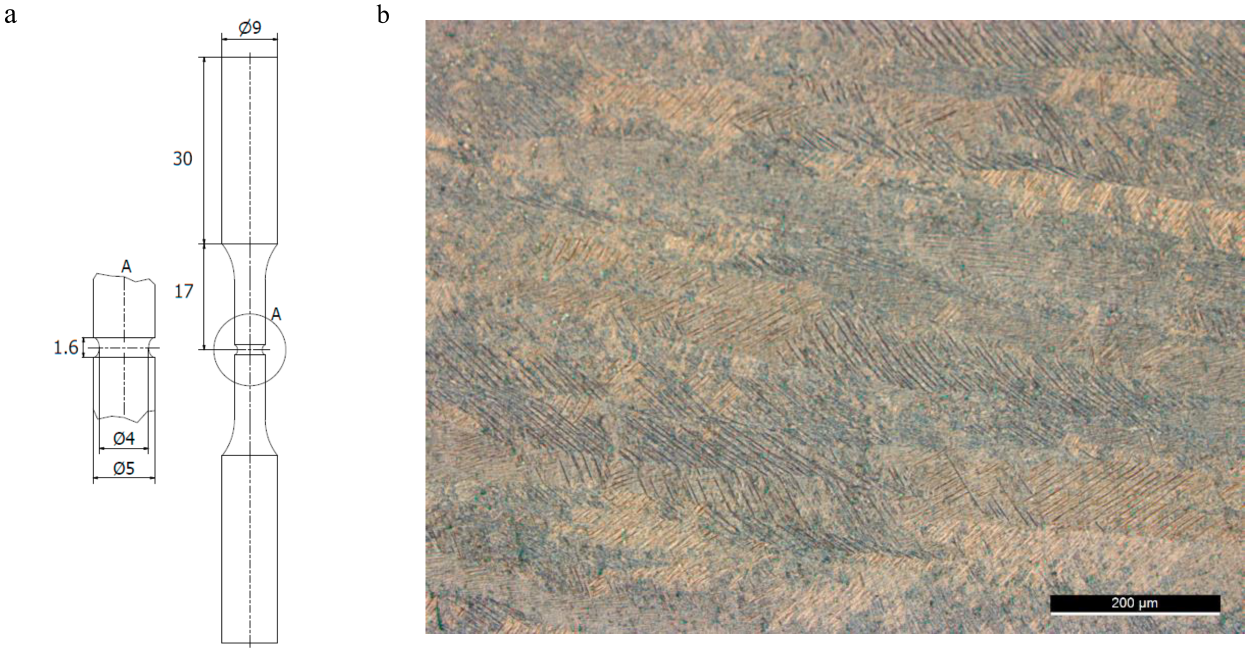

Fig. 1. (a) Geometry and dimensions of the notched specimens; (b) Material microstructure.

3. Results and discussion

Fig. 2 presents the variations of the peak stresses with the life ratio (N/N_f, where N is the current number of cycles and N_f is the number of cycles to failure), at various strain amplitude levels, during the low-cycle fatigue tests. For high strain amplitude levels, it was observed that the peak stresses decreases in an initial stage (about 10-15% of the total life), and afterwards there is a continuous and very slow reduction until a final drop very closed to final failure, while a well-defined stable response occurs at lower strain amplitudes.

The cyclic stress-strain response, relying on the fact that the saturated regime is achieved in the early stage of the tests, was studied via the data collected from the hysteresis loops at half-life. Fig, 3a) displays the monotonic stress-strain curve and superimposes the cycle curve. In the plastic region, it was observed that the cyclic curve is significantly lower the than monotonic one, indicating cyclic softening of the material for that strain levels. The cyclic stress-strain curve, was fitted by the Ramberg-Osgood equation, where: $\Delta\sigma$ is the stress range, $\Delta\epsilon$ the total strain range, k' and n' are the cyclic hardening coefficient and exponent, respectively. The values obtained for these parameters are indicated in Table 2.

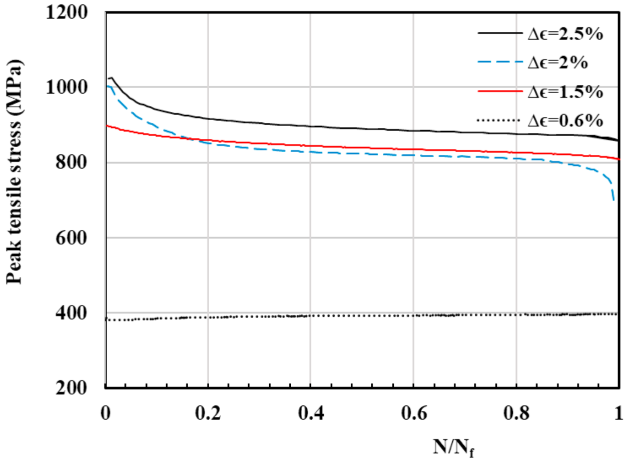

Fig. 2. Variation of peak stress with the normalized fatigue life during the low-cycle fatigue tests at various strain amplitudes.

Fatigue results, analyzed in terms of elastic, plastic, and total strain amplitudes against the number of reversals to failure, are shown in Fig. 3b). Experimental results were fitted by the well-known Basquin and Coffin-Manson formulations, where: σ_f' is the fatigue strength coefficient, *b* is the fatigue strength exponent, ε_f' is the fatigue ductility coefficient, *c* is the fatigue ductility coefficient and N_f is the number of cycles to failure. The values obtained for these parameters are indicated in Table 2. The transition life obtained for this alloy was quite low, 164 reversals, which can be attributed to the combination of high strength and relatively low ductility.

In order to analyze the notch effect, a batch of notched specimens was prepared machining an outer semi-circular notch in all contour with 1.5mm diameter and 0.5mm depth (see Fig. 1a)), corresponding to the stress concentration factor K_t=1.7, with respect to the effective cross section. Fatigue results of un-notched and round notched specimens are depicted in Fig. 4a), which presents the stress amplitude against the number of cycles to failure. Nominal stress amplitude was obtained from load range (P_{max}-P_{min})/2, divided by the effective cross area, where P_{max} and P_{min} are the maximum and minimum values of the load at mid-life hysteresis circuits, respectively. The analysis of Fig. 4a) shows an important notch effect reducing fatigue strength, which like the majority of bulk metals increases with fatigue life. The ratio of stress amplitude for notched specimens and un-notched specimens is the dynamic stress concentration factor K_f, which can be obtained for a given life. Current results show that K_f increases with fatigue life, from one for low cycle fatigue tending to 1.42 for high cycle fatigue (N_f of about one million cycles), meaning a notch sensibility of approximately 0.7.

Fracture surface analysis was performed with a scanning electron microscope (Philips XL30). Fig. 4b) shows an exemplary SEM image of the crack initiation and propagation near surface. The fracture surface analysis showed that the crack initiated around the surface, and propagated through the cross section. In many cases, it was observed a multi-nucleation.

Table 2. Mechanical cyclic properties.

k' (MPa)	n'	σ_f' (MPa)	b	ε_f'	c
957.3	0.0167	1734.4	-0.109	10.38	-1.399

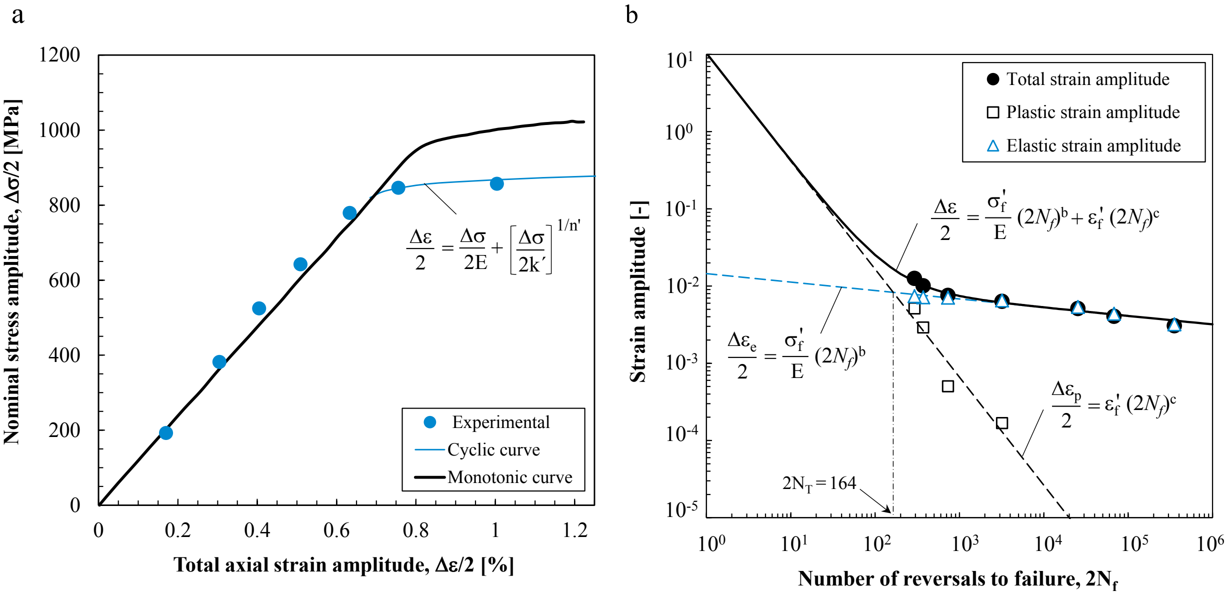

Fig. 3. (a) Cyclic and monotonic stress-strain curves for Titanium Ti6Al4V alloy; (b) Total, plastic, and elastic strain amplitudes versus number of reversals to failure.

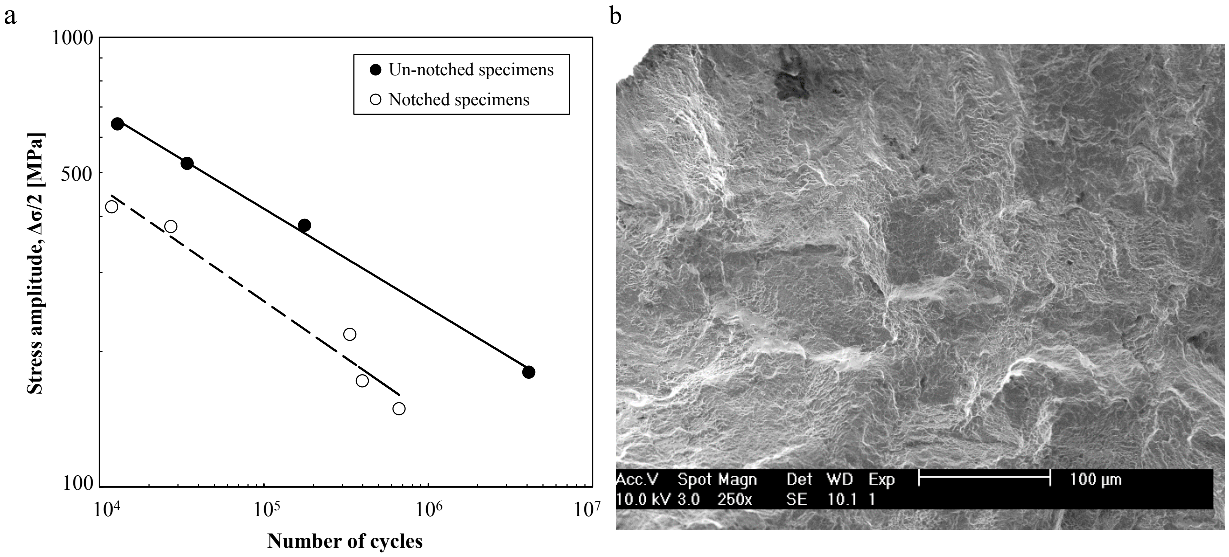

Fig. 4. Fatigue strength of notched specimens. (a) Notch effect on the S – N curve; (b) SEM observation of failure surface.

4. Conclusions

This work studied the fatigue behavior of titanium alloy TiAl6V4 parts, manufactured by selective laser melting (SLM), characterizing low cycle fatigue parameters and investigating the notch sensibility of the material. The following main conclusions can be drawn:

- Microstructure shows an acicular morphology where were identified two phases, with good transition and low micro porosity;

- In plastic region, the cyclic curve is significantly lower than monotonic one, indicating cyclic softening of the material for high strain levels;
- Fatigue results under constant strain control were well fitted by well-known Basquin and Coffin-Manson equations. The transition life obtained was 164 reversals;
- Dynamic stress concentration factor was quantified for specimens with k_t=1.7, revealing that K_f increases with fatigue life, from one for low cycle fatigue tending to 1.42 for high cycle fatigue (N_f of about one million cycles);
- SEM analysis showed, for both samples geometry, fatigue crack initiation from the surface, observing in many cases multi-nucleation.

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