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Environmental effect on the fatigue crack propagation of AM TiAl6V4 alloy specimens

L.P. Borrego[a,b]*, J. de Jesus[b], J.A.M. Ferreira[b], J.D. Costa[b], C. Capela[b,c]

[a] Department of Mechanical Engineering, Coimbra Polytechnic - ISEC, Rua Pedro Nunes, 3030-199 Coimbra, Portugal
[b] *CEMMPRE, Department of Mechanical Engineering, University of Coimbra, 3004-516 Coimbra, Portugal*
[c] *ESTG,Mechanical Engineering Department, Polytechnic Institute of Leiria, Portugal*

Abstract

Additive manufactured (AM) parts made in TiAl6V4 alloy are increasingly used in medical devices and in the aeronautical industry, because of its high strength, low weight and excellent biocompatibility. Most of these components work under environmentally assisted cyclic loading, i.e. under corrosion-fatigue. Fatigue performance of additive manufactured alloys is significantly influenced by the porosities, residual stresses, which can be reduced by optimizing the process parameters, thermal treatments or hot isostatic pressing (HIP). Those parameters can also influence significantly to the propagation of cracks under corrosion-fatigue, but the understanding of this subject still needs significant research work. This paper presents the results of a fatigue crack propagation study in titanium TiAl6V4 specimens produced by selective laser melting (SLM), under corrosive ambient. The environment solutions studied were: artificial saliva and 3.5%wt NaCl solution. Tests were performed using standard 6 mm thick compact specimens (CT) tested at R=0.05 and with frequency 10 Hz. The main objective was to study the effect of the environment solution on da/dN-ΔK curves and on the fatigue failure mechanisms. Current work shows a very important accelerating effect on the crack nucleation and fatigue crack propagation for tests under corrosion ambient, particularly for 3.5%wt NaCl solution. Fatigue path shows an irregular path. Secondary cracking was observed in air, but not detected in corrosive ambient.

Keywords: Additive manufacturing, corrosion-fatigue, crack propagation, Titanium TiAl6V4 alloy.

* Corresponding author. Tel.: +351 239790330; fax:. +351 239790331
E-mail address: borrego@isec.pt

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1. Introduction

Titanium Ti6Al4V alloy is a light alloy characterized by having excellent mechanical properties combined with low specific weight, commonly used in biomedical applications and in automotive and aerospace components, as reported by Guo and Leu (2013), Petrovic et al. (2011) and Mur et al. (2010). This alloy has also excellent corrosion resistance, making it widely used in biomedical devices like in knee and hip joints and dental implants, which are subjected to corrosion-fatigue saliva and fluorine environment, Zavanelli et al. (2000).

Leuders et al. (2013) and Rafi et al. (2013) studied also the improvement of fatigue performance on AM TiAl6V4 alloy promoted by the optimization of the process parameters or by hot isostatic pressing (HIP). Edwards and Ramulu (2014) and Greitmeier et al. (2017) reported also the effect of heat treatment on the fatigue limit.

Conventional casting Ti-6Al-4V alloy typically exhibits good corrosion and corrosion-fatigue resistance in different environments, when compared with steel and other metallic materials, due to its ability to form a thick and stable TiO2 oxide layer, Dimah et al. (2012). Dawson and Pelloux (1974) studied the crack propagation in Ti-6Al-4V alloy for several environments, concluding by a frequency independent behavior, which is typical of the alloy in vacuum, air and solutions with corrosion inhibitors. Baragetti and Arcieri (2018) obtained a reduction of about 20% in fatigue life of Ti6Al-4V in notched specimens tested in a 3.5%wt NaCl solution, at frequency of 10Hz, in comparison with inert ambient tests. In spite the good corrosion resistance of casting Ti-6Al-4V alloy, AM materials have some particularities, namely, anisotropy, presence of crack defects, stress concentrations and residual stresses, which can change corrosion-fatigue behavior. Therefore, this subject still needs further investigation.

Nomenclature

a	Crack length
AM	Additive manufacturing
HIP	Hot isostatic pressing
N	Number of cycles
SLM	Selective laser melting
ΔK	Range of the stress intensity factor

2. Results and discussion

Experimental tests were performed using 6 mm thickness compact tension (CT) specimens, with the final geometry and dimensions shown in Fig. 1, manufactured by Lasercusing®, with layers growing towards the direction of loading application. The samples were processed using a 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.

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

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

After manufacturing by selective laser melting (SLM), the specimens were machined for the dimensions indicated in Fig. 1, and afterwards subjected to a stress relieve heat treatment to reduce the residual stresses. The stress relieve treatment consisted of a slow and controlled heating up to 670 °C, followed by maintenance at 670 °C±15 ºC for 5 hours in argon medium at atmosphere pressure and finally by cooling to room temperature in air.

The faces of the specimens were polished and subjected to a chemical attack by Kroll`s reagent. Afterwards, they were observed using a Leica DM4000 M LED optical microscope. Fig. 2 shows an example of the observed microstructure revealing a fine acicular morphology mainly the primary α' phase heterogeneously dispersed and a β phase distributed in the contours of the grains, quite similar to that observed by Greitmeier et al. (2017) for similar material and manufacturing conditions.

Fatigue tests were carried out in agreement with ASTM E647 standard, at room temperature using a 10 kN capacity Instron EletroPuls E10000 machine, under loading control and stress ratio of R = 0.05, with the frequency of 10 Hz. The tests were conducted under constant load, i.e. under growing ΔK. Corrosion-fatigue was conducted under two environmentally solutions, namely artificial saliva and 3.5%wt NaCl solution, with the chemical composition indicated in Table 2.

During the tests, the crack length was measured using a travelling microscope (45x) with an accuracy of 10 µm. Fig. 3 depicts the experimental apparatus, detailing the specimen, the box with corrosive fluid and the system for the crack length measurement.

Table 2. Chemical composition of the corrosive solutions [g/l].

Corrosive solution	NaCl	KCl	$CaCl_2.2H_2O$	KH_2PO_4	$Na_2HPO_4.12H_2O$	KSCN	$NaHCO_3$	Citric Acid
Artificial saliva (pH=6.5)	0.6	0.72	0.22	0.68	0.856	0.06	1.50	0.03
3.5%wt NaCl solution	35	-	-	-	-	-	-	-

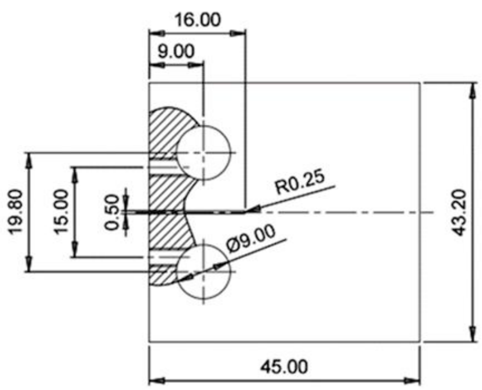

Fig. 1. Specimen geometry (dimensions in mm).

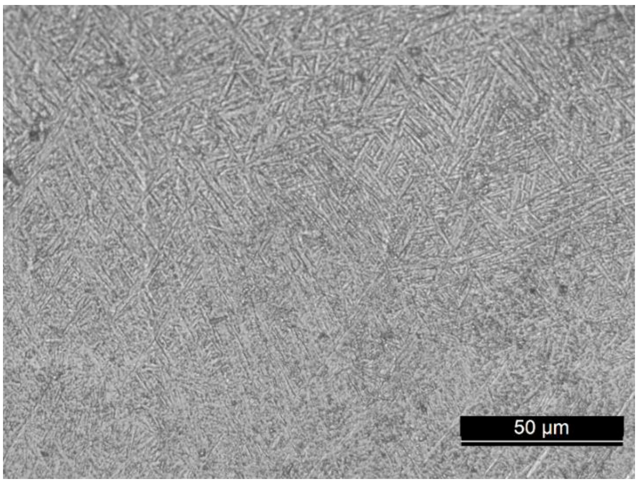

Fig. 2. Microstructure of the SLM Titanium Ti6Al4V alloy.

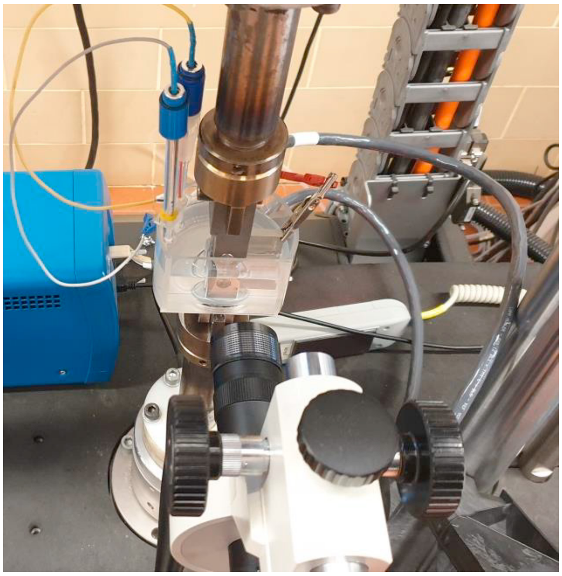

Fig. 3. Testing apparatus, box with corrosive solution and system for the crack length measurement.

3. Results and discussion

Figs. 4 and 5 compare the fatigue crack propagation in air and under the two corrosion solutions analyzed, in terms of the crack length versus the number of cycles and the da/dN-ΔK curves in the Paris regime, respectively. Contrary to the expected, taking in account the studies of Dawson and Pelloux (1974) and Baragetti and Arcieri (2018) on traditional manufactured TiAl6V4 alloys, the current study shows a more significant acceleration effect on the propagation of fatigue cracks in the SLM specimens under the effect of both corrosion solutions.

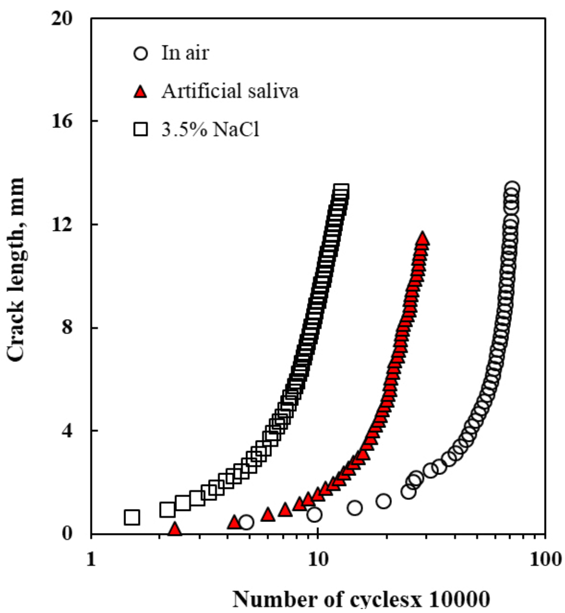

Fig. 4. Effect of the corrosive solution on the crack length versus number of cycles curves.

Fig. 4 reveals a significant decrease in crack nucleation for the tests under corrosion ambient in comparison with tested in air, particularly with the 3.5%wt NaCl solution. Fig. 5 shows an important effect of the corrosion ambient on the fatigue crack growth rate, which increases with decreasing ΔK. In this figure is clearly observed that the crack growth resistance is lower in artificial saliva and even lower in the 3.5%wt NaCl solution.

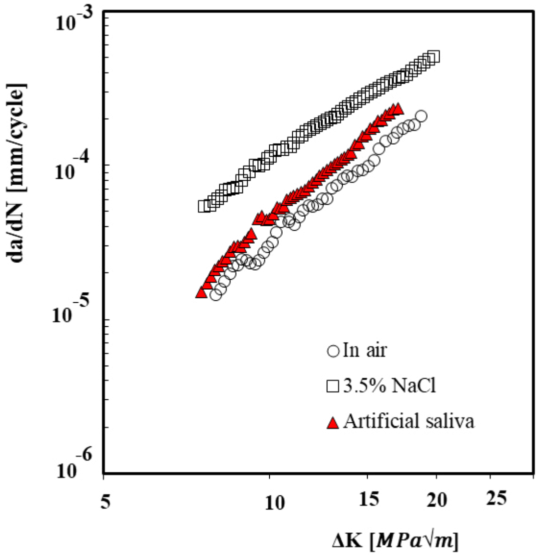

Fig. 5. Effect of corrosive solution on the da/dN-ΔK curves.

Fig. 6 compares the crack path of two specimens tested in air (Fig. 6a)) and in 3.5%wt NaCl solution (Fig. 6b)). For the tests in air, it is noticed that crack growth occurs predominantly in mode I, following the weaker way in the boundary of the acicular morphology or crossing the grains. It can also be observed frequent crack bifurcation. However, crack growth follows always the path of a predominant crack. For the specimens tested in corrosive ambient, namely in 3.5%wt NaCl solution shown in Fig. 6b, the crack path is quite similar, but the secondary cracks were not observed.

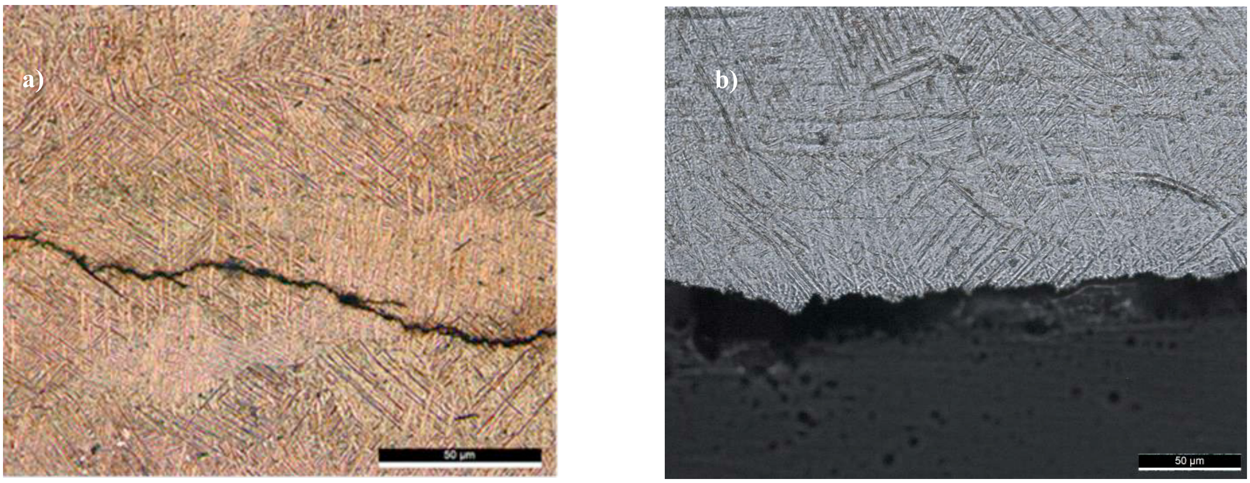

Fig. 6. Fatigue crack path (a) In air; (b) In 3.5%wt NaCl solution.

4. Conclusions

This study analyses the effect of corrosive solutions, namely artificial saliva and 3.5%wt NaCl solution, on the corrosion-fatigue of TiAl6V4 specimens produced by SLM. The following conclusions can be drawn:

- AM Titanium Ti6Al4V alloy exhibits a significant effect of the corrosive ambient, both on fatigue crack nucleation and on fatigue crack propagation;
- The effect of the corrosion ambient on the fatigue crack rate, increases with decreasing ΔK;
- The faster corrosive effect, in comparison with test in air, was obtained for the testes with 3.5%wt NaCl solution, for which fatigue crack growth is 3 times higher;
- In air, fatigue failure showed an irregular surface with secondary cracking, mixed crack path in boundary or crossing the acicular grains. For the specimens tested in corrosive ambient crack path is quite similar, without observance of secondary cracking.

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