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# Overloading effect on transient fatigue crack growth of Ti-6Al-4V parts produced by Laser Powder Bed Fusion

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## Abstract

The fatigue crack growth (FCGR) behavior of titanium alloy Ti-6Al-4V submitted to Hot Isostatic Pressing (HIP) through CT specimens manufactured by Laser Powder Bed Fusion (LPBF) is analyzed. Both the crack growth under constant amplitude loading and the transient crack growth behavior after the application of overloads were studied. Crack closure induced by plasticity for the stress ratio  $R=0$  was observed at the Paris regime. The applied overloads for  $OLR=2$  at  $R=0$  caused a FCGR retardation due to the increase of crack closure effect induced by plasticity resulting from the overloads. Rapid transient periods were registered due to small zone affected by the overloads.

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*Keywords:* Type your keywords here, separated by semicolons ;

## 1. Introduction

Laser Power Bed Fusion (LPBF) is an additive manufacturing (AM) process which constructs components through the repeated deposition and melting of metal powder layers. Because of this layer wise building, LPBF allows produce components with very complex geometries. Complex and weight minimizing geometries can be manufactured with no additional expense, and often significantly reduced processing time, than more traditional forms, i.e. those designed

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for traditional processes such as casting or milling. These features make LPBF components particularly well analyzed to the automotive, aerospace and aeronautical sectors, where the minimization of component weight is a strong and persistent requirement.

Although the tensile behavior of LPBF Ti-6Al-4V is comparable to traditional manufactured parts, this is not the case when the component is subjected to cyclic loading. Consequently, researchers and manufacturers need to take a closer look into mechanical properties of LPBF parts under cyclic loading. The fatigue behavior of LPBF Ti-6Al-4V are very dependent on geometrical irregularities formed during the manufacturing process, it was verified that parts produced by LPBF always show an inferior fatigue strength when compared to the wrought ones. In specific, a decrease of the fatigue strength, around 40–50%, was observed (Wycisk et al (2014), Fatemi et al (2017), de Jesus et al (2021) and Edwards et al (2014)). This was directly attributed to the inherent defects of the LPBF process, such as: high surface roughness, tensile residual stresses, subsurface pores, porosity and lack of fusion.

Machine components and structural parts which can be subject to the presence of fatigue cracks, such as aircraft wings, automobile axis, automotive springs, among others, are submitted to variable amplitude loads including tensile and compressive overloads during their service life, which can be result in a severe alteration of FCGR rates and thus a significant change in the service fatigue life. Chen et al (2018) studied the effect of overloads on the FCGR behavior of Ti-6Al-4V alloy, in MT specimens produced by traditional methods. The results demonstrated that both the crack propagation performance and the stress distribution at the crack tip are strongly influenced by the applied overload conditions. Neto et al (2021) detected that when applying an overload with an intensity of 100% in the LPBF Ti-6Al-4V alloy, the down peak value of  $da/dN$  was approximately 10 times lower than the baseline value, leading to a FCGR retardation due to the crack closure effect induced by plasticity. Jesus et al (2020) studied the overloads effect in the LPBF Ti-6Al-4V alloy reported that a single tensile overload promotes a short transient crack propagation rate period leading to crack growth retardation. Overloads applied with an intensity of 50% did not show any measurable effect in the fatigue crack propagation behavior. The fatigue crack closure induced by plasticity was reported as the main reason for the crack retardation after overload application in the Paris law region. Wu and Bao (2018) analyzed the fatigue crack tip strain evolution and crack growth prediction under application of a single overload in laser melting deposited Ti-6.5Al-3.5Mo-1.5Zr-0.3Si titanium alloy, observing a retardation of the FCGR after the overload application.

This work pretends to contribute to understand the overloading effect on transient fatigue crack growth of Ti-6Al-4V parts produced by LPBF through the analysis of FCGR tests. Both the propagation under constant amplitude loading and the transient crack growth behavior after the application of overloads were studied.

### Nomenclature

AM	Additive manufacturing
HIP	Hot isostatic pressing
LPBF	Laser power bed fusion
OLR	Overload ratio
$P_{max}$	Maximum load
$P_{op}$	Opening load
$P_{min}$	Minimum load
U	Crack closure parameter

## 2. Experimental Procedures and Methodologies

FCGR tests were performed in mode I loading using compact tension (CT) specimens with a width  $W=36$  mm and a thickness of 6 mm, following ASTM E647 (2016) recommendations. The specimens, made of Ti-6Al-4V alloy, were obtained by LPBF. The machine used a high-power laser type Nd: YAG with a maximum power of 500 W in continuous wave mode, a wavelength of 1064 nm and 0.04 mm of laser beam diameter and energy density used to

produce the specimens was  $57 \text{ J/mm}^3$ . The Ti-6Al-4V alloy powder used to produce the samples showed an average particle size of  $40 \text{ }\mu\text{m}$ , giving layers of  $30 \text{ }\mu\text{m}$  thickness. These sample layers were deposited in planes perpendicular to the loading direction. All specimens were submitted to the HIP process. The HIP technique was performed submitting the specimens to  $920 \text{ }^\circ\text{C}$  for a period of 2 h in a pressured chamber at 100 MPa and finally followed by cooling in air to room temperature.

The FCGR tests were carried out at room temperature using a 10 kN capacity Instron EletroPuls E10000 machine, at constant and variable amplitude loading in stress ratio equal to 0. In order to evaluate the transient crack growth behaviour, overloads with OLR=2 and 1.5 at stress intensity factor of 9, 14 and  $20 \text{ MPa}\sqrt{\text{m}}$  in the Paris regime were applied. The crack length was measured every 0.1 mm of crack propagation using a travelling microscope (45x) with an accuracy of  $10 \text{ }\mu\text{m}$ . Crack growth rates under constant amplitude loading were determined by the incremental polynomial method using five consecutive points of a-N curves and for variable amplitude loading were calculated through the incremental linear method using two consecutive points. Crack closure was measured using the load-displacement data acquired at 0.1 mm of crack length increments using an extensometer MTS (displacement of  $\pm 2.5\text{-mm}$ ) placed remotely from the crack tip. The opening load was estimated using the maximization of correlation coefficient method. The portion of the load cycle when the crack remains open can be represented by the load ratio parameter, U, estimated by the equation:

$$U = \frac{P_{\max} - P_{\text{op}}}{P_{\max} - P_{\min}} \quad (1)$$

### 3. Results and discussion

Figure 1 shows the  $da/dN$ - $\Delta K$  curve obtained for the specimens studied. In concern to the zone where exist a linear relation between  $da/dN$  and  $\Delta K$  (Paris regime) the presence of crack closure mechanism induced by plasticity was observed. The value of U estimated for the HIPed samples was 0.881. Table 1 presents the fatigue threshold ( $\Delta K_{\text{th}}$ ) determined at  $10^{-7} \text{ mm/cycle}$  and the Paris law parameters.

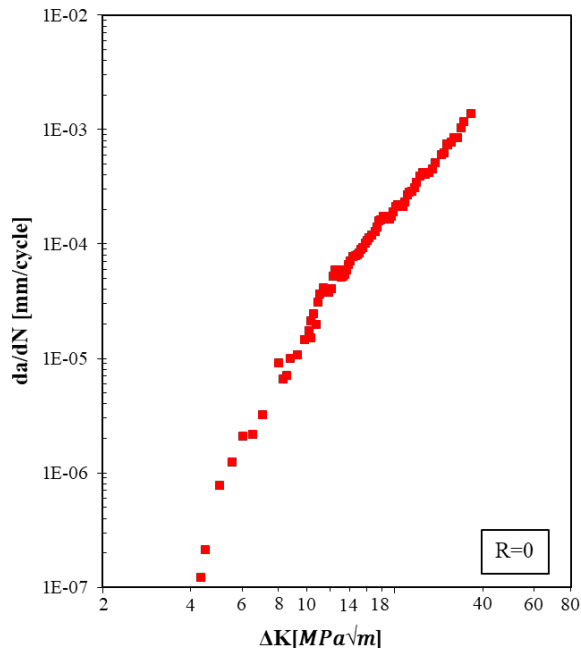


Fig. 1.  $da/dN$ - $\Delta K$  curve for HIPed specimens,  $R=0$ .

Table 1.  $da/dN-\Delta K$  curve parameters

$\Delta K_{Ic}$ (MPa $m^{1/2}$ )	C (mm/cycle)	m	R
4.35	$1.007 \times 10^{-8}$	3.293	0.983

The comparison between the effect in the FCGR behaviour of overloads (OLR) application with intensities of 100 % (OLR=2), 50% (OLR=1.5) and constant amplitude loading for R=0 are presented in Figure 2. The FCGR did not suffer any alteration when an overload with an OLR=1.5 was applied, maintaining the FCGR rate similar to the  $da/dN-\Delta K$  curve at constant amplitude loading. In this case, the U parameter referent to the crack closure remained unchanged. On the other hand, the OLR =2 overload application caused a FCGR speed reduction about 3.42 times when compared with the constant amplitude loading curve in all overloads applied. This reduction leads to crack growth retardation in the fatigue life in comparison to the  $da/dN-\Delta K$  constant amplitude loading curve.

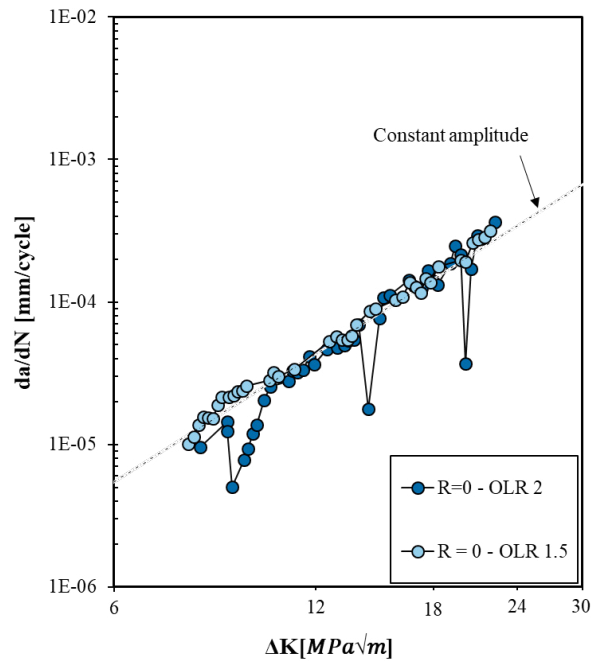
Fig. 2.  $da/dN-\Delta K$  curves for HIPed specimens for R=0 with overloads application of OLR=2 and OLR=1.5.

Figure 3 shows a noteworthy similar decreased in the U parameter values after the overloads application which means a similar increment in the crack closure levels and subsequently retardation on the fatigue crack propagation life. From this figure, also can be reported a short transient period during the overload effect returning to the averages U value obtained under constant amplitude loading that will be deepened in the fractography section.

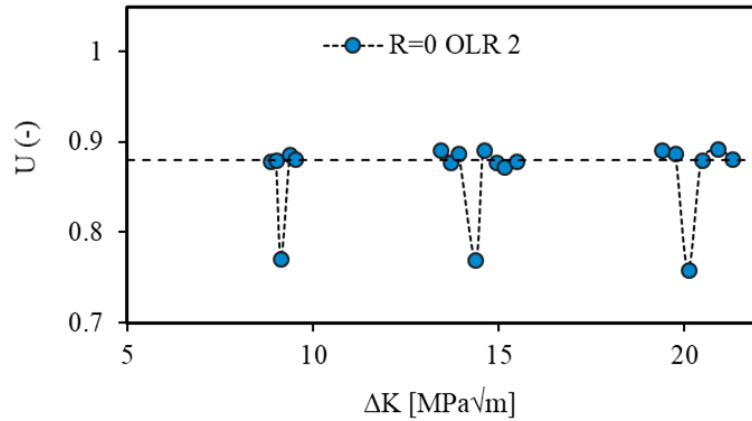


Fig. 3. Crack closure levels due to overloads application, R=0 OLR 2.

A representative example, can be observed in Figure 4 showing the FCGR fracture surface for R=0 with OLR=2 applied at  $\Delta K=14 \text{ MPa}\sqrt{\text{m}}^{1/2}$ . The red arrows point to the overload mark, in this case a very short transient period during the overload effect can be observed (2.89  $\mu\text{m}$  approximately) which is coincident with the FCGR behaviour observed and described previously for the applied overloads at R=0

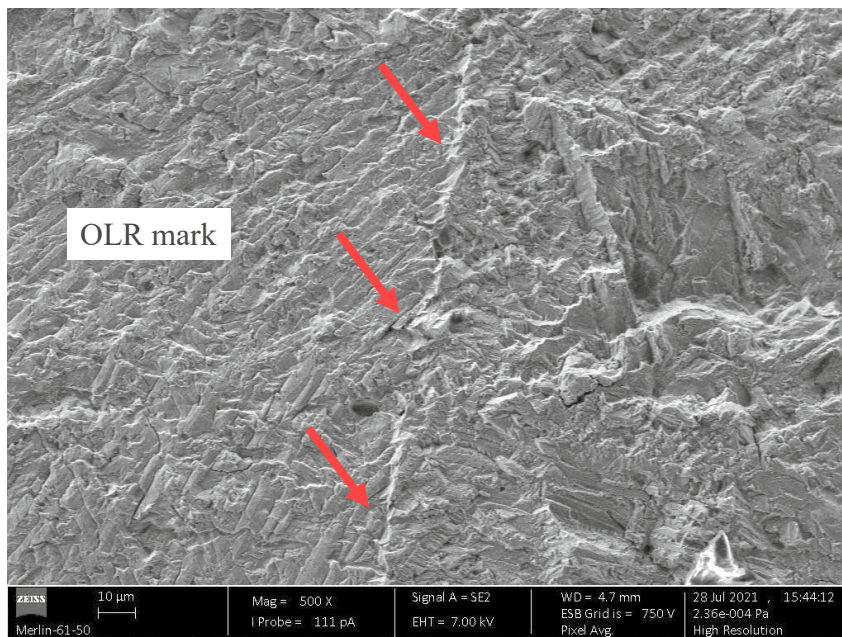


Fig. 4. Fracture surface for R=0 with OLR=2 at  $\Delta K=14 \text{ MPa}\sqrt{\text{m}}^{1/2}$ .

#### 4. Conclusions

In the current investigation, an experimental FCGR study using CT specimen made of Ti-6Al-4V produced by LPBF process submitted to HIP process, was performed for constant and variable loading. The main conclusions are listed as follows: Crack closure induced by plasticity for the stress ratio R=0 was observed for the Paris regime; The applied overloads for OLR=2 caused a FCGR rate retardation due to the increase of crack closure mechanism induced

by plasticity resulting from the overloads; Surfaces failure analysis revealed that overload with  $R=0$ , OLR 2 showed a small affected zone which leads a short transient period during the overload effect.

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