



The second European Conference on the Structural Integrity of Additively Manufactured Materials

Fatigue crack growth of TiAl6V4 parts produced by SLM under biaxial mode I/mode II loading

L.P. Borrego^{a,b*}, J.S. Jesus^a, J.A.M. Ferreira^a, J.D. Costa^a, C. Capela^{a,c*}

^a Univ Coimbra, Centre for Mechanical Engineering, Materials and Processes (CEMMPRE), Department of Mechanical Engineering, 3004 516 Coimbra, Portugal

^b Department of Mechanical Engineering, Coimbra Polytechnic - ISEC, Rua Pedro Nunes, 3030-199 Coimbra, Portugal

^c School of Technology and Management, Polytechnic Institute of Leiria, P2411-901 Leiria, Portugal

Abstract

Mode I and mixed-mode fatigue crack growth tests were performed using compact tension shear specimens made of Ti-6Al-4V by additive manufacturing for various loading angles. The accuracy of the methodology used to determine the equivalent stress intensity factor was studied, obtaining good results in a simpler method and particularly when the crack deflection angle was included in the algorithm. The crack growth speed did not suffer significant alterations due to similar values of crack deflection angle, mode I loading predomination and similar crack closure effect. Fractured surfaces presented irregular regions consequence of intergranular separation between β phase and agglomerations of α phase.

© 2021 The Authors. Published by Elsevier B.V.

This is an open access article under the CC BY-NC-ND license (<https://creativecommons.org/licenses/by-nc-nd/4.0>)

Peer-review under responsibility of the scientific committee of the Esiam organisers

Keywords: Type your keywords here, separated by semicolons ;

* Corresponding author

E-mail address: Luis Borrego <borrego@isec.pt>

1. Introduction

Because its excellent mechanical properties combined with low specific weight Ti6Al4V alloy is widely used in aerospace components and other high-performance engineering applications, as report by Petrovic et al. (2011) and Mur et al. (2010). Consequently, the use of this alloy in transport industries, lead to weight reduction and decreasing use of energy, Guo and Leu (2013) and Frazier (2014). The LPBF process allows the production of more complex geometries with faster production times when compared with the conventional processes. This process is relatively new and the materials used are yet limited, whereby these materials have been studied in order to improve the mechanical performance and their secure application as functional and structural components. For selective laser melting (SLM) material, one topic with a strong lack of information, is the fatigue crack growth (FCGR) in Mode I+II, namely for the Ti-6Al-4V alloy, because the applications of fracture mechanics have usually been focused on crack growth problems under mode I mechanism. However, several service failures happen due to growth of cracks subjected to mixed-mode loadings, whereby it is important to study the crack growth under mixed-mode loading.

The main problem in the study of FCGR in mixed-mode is the competition between tensile and shear fracture failure mechanisms that make this analyze a complex problem. Richard and Benitz (1983) developed solutions for Stress Intensity Factor (SIF) in mode I (K_I) and the SIF in mode II (K_{II}) for Compact Tension Shear (CTS) geometry specimens, with acceptable accuracy for fracture analysis where the initial crack was obtained in mode I and does not suffer crack deflection. However, cracks submitted to mixed-mode normally present a deflection in the FCGR direction, whereby, the Richard's solutions can be inaccurate since it has been developed for straight cracks. Hussain et al. (1974) introduced the angular stress intensity factors (K_I^* and K_{II}^*) for which the crack deflection based on the strain energy release rate is considered. Antunes et al. (2019) developed a new complex approach (39 variables) to obtain the K_I and K_{II} using J integral values.

This work pretends to contribute to the understanding of these problems through the analysis of the FCGR tests under mixed-mode I+II applying different loading angles without mode I pre-crack in the CTS specimens made of Ti-6Al-4V produced by SLM process. Throughout this work, different models will be applied in order to found a simple and satisfactory solution for this case study.

2. Experimental Procedures and Methodologies

2.1. Material, process parameters and specimens geometry

Experimental fatigue tests were performed using 3 mm thickness CTS specimens with the geometry and dimensions shown in Fig. 1. The powder material used to manufacture the specimens was produced from a Ti-6Al-4V titanium alloy (with the chemical composition in Table 1). SLM process was carry out in a 3D Systems equipment model ProX DMP 320 applying a energy density of 57 J/mm³ and the thickness of each layer was about 30 μm. The build direction of specimens production was longitudinal to the initial crack

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

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

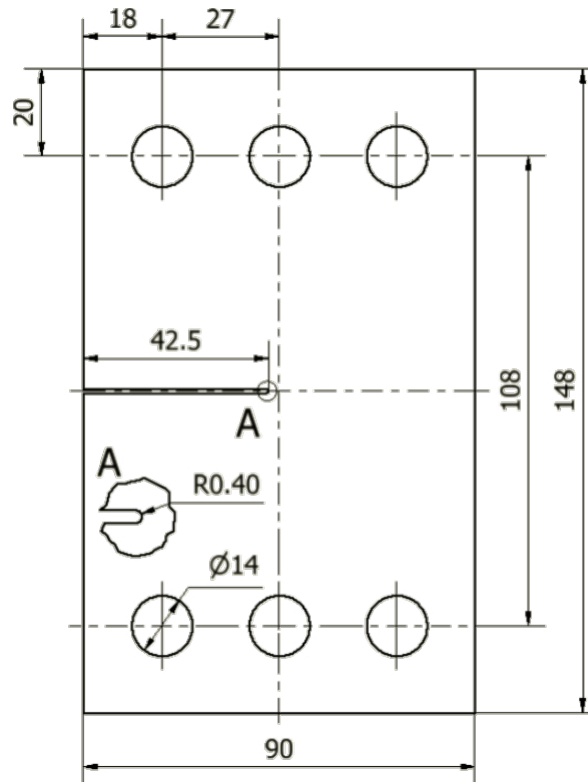


Fig. 1. Specimens geometries (mm).

The specimens were submitted to the Hot Isostatic Pressing (HIP) procedure, performed submitting the specimens to a controlled heating up to 920 °C, followed by maintenance period at 920 °C±15°C for 2 hours in pressured chamber at 100 MPa and cooling in air to room temperature.

One face of the all specimens was submitted to a polishing process in order to reduce the surface roughness ($R_z=0.517 \mu\text{m}$) and consequently allows a better observation of crack growth in FCGR tests, while the other face was painted to apply the Digital Image Correlation (DIC) technique.

2.2. Fatigue crack growth tests

The FCGR tests were carried out in a Dartec servo hydraulic machine, applying a sinusoidal wave at 10 Hz of frequency under a loading ratio of $R=0.05$. The loading angles (α) applied were 0°, 15°, 30° and 45°. Fig. 2 presents the apparatus used in the FCGR tests. This apparatus was composed by different systems. The measurement system applied in order to record the crack length using a travelling microscope (45×) with an accuracy of 10 μm . The crack length was measured every 0.5 mm of propagation registering the x and y coordinate and the resultant, both from the notch to the crack tip. Crack growth rates under constant amplitude loading were calculated by the incremental polynomial method using five consecutive points. The results were plotted as $\frac{da}{dN}$ versus ΔK_{eq} curves. The DIC system was composed by Allied Vision Stingray camera (20+75 mm) to take images and the image acquisition system. The DIC processes was used to analyze the crack closure and was measured using the load-displacement data acquired at 0.5 mm of crack length increments through the captured images in one loading cycle at 1 Hz. These images were subsequently processed by digital image correlation (DIC) with the GOM correlate software. The crack opening load was estimated using the maximization of correlation coefficient. The photographs taken also served to estimate each crack deflection angle (θ) for the different FCGR tests using Inventor® CAD software. Finally, the fracture surfaces were observed and analysed by SEM using a scanning electron microscope Philips XL 30.

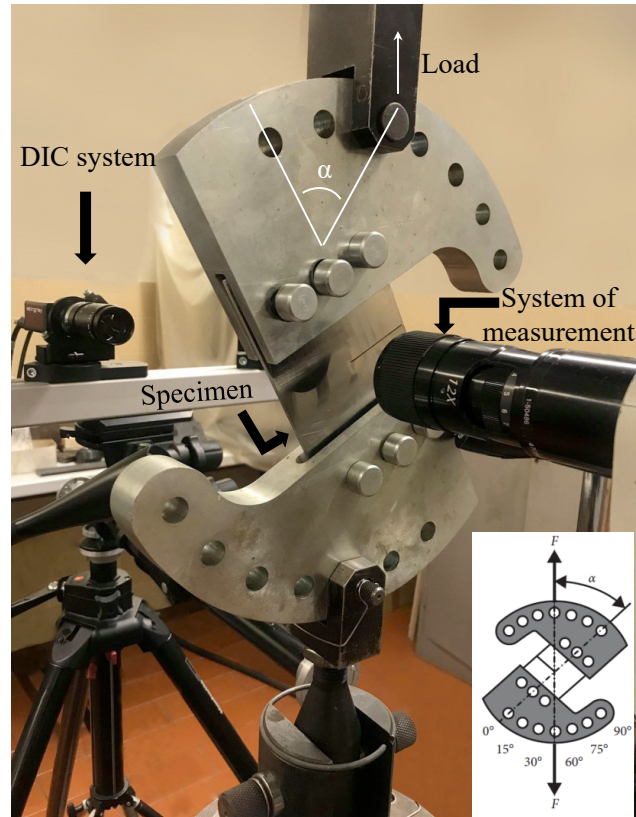


Fig. 2. Mixed-mode loading device, system of measurement and DIC system.

3. Results and discussion

Fig. 3 shows two exemplary crack path obtained for the specimens tested at a loading angle of $\alpha=15^\circ$ (Fig. 3a) and $\alpha=30^\circ$ (Fig. 3b). In both figures, it is possible to observe that the initial crack path started longitudinal to the initial crack deflecting rapidly for $\theta=19.27^\circ$ and $\theta=21.14^\circ$, respectively. This means that the crack initiation and the initial crack path is highly influenced by mode I and mode II loading despite the component of mode I being higher than mode II.

However, the crack path rapidly deflects from the initial path for a stable crack growth where the mode I loading is predominant given that the crack path becomes closer to the perpendicularity with the applied load, in other words, the component of the mode II loading decreases with crack deflection.

The methodology to obtain ΔK_{eq} consists in determine ΔK_I and ΔK_{II} followed by the calculation of ΔK_{eq} for the mixed loading.

The method used in current study uses the equation (1) (Yan et al. 1992), which proposes the introduction of the crack deflection angle (θ). Fig. 4 shows the da/dN - ΔK_{eq} curves where ΔK_{eq} was determined by this equation for $\alpha=0^\circ$, 15° , 30° and 45° .

$$\Delta K_{eq} = \frac{1}{2} \cos \frac{\theta}{2} [\Delta K_I (1 + \cos \theta) - 3\Delta K_{II} \sin \theta] \quad (1)$$

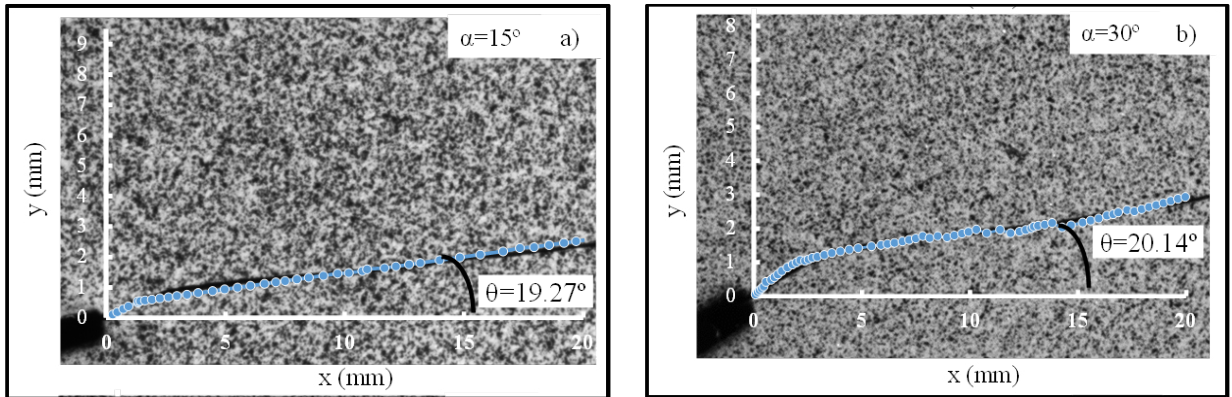


Fig. 3. Crack path. a) $\alpha=15^\circ$, b) $\alpha=30^\circ$ and.

The analysis of this figure shows that this methodology led to a reasonable correlation between results for the different loading angles.

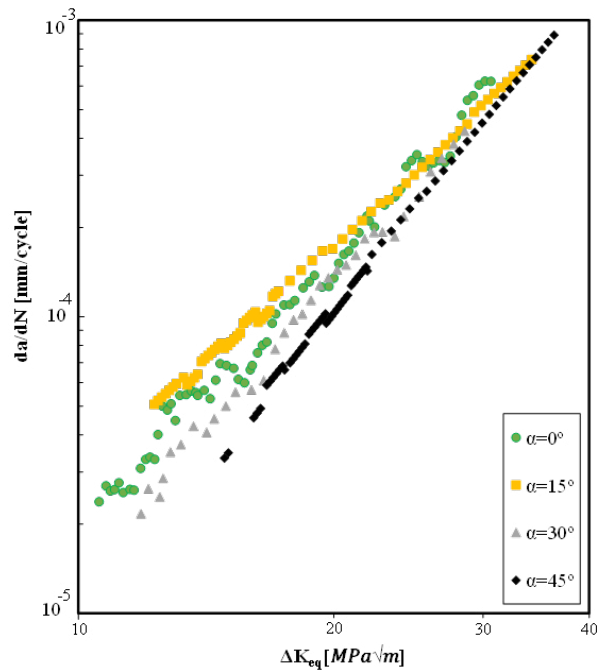


Fig. 4. $\frac{da}{dN} - \Delta K_{eq}$ curves, ΔK_{eq} determined by the methodology used.

4. Conclusions

An experimental study was developed to study the effect of mix-mode (I+II) in the fatigue crack growth of Ti6Al4V specimens produced by additive manufacturing, using different loading angles (0° , 15° , 30° and 45°). The methodology used to calculate the equivalent stress intensity factor revealed good results because was achieved a good correlation between the $\frac{da}{dN} - \Delta K_{eq}$ curves in pure mode I and mode I+II loading. The fatigue crack growth speed for the same

ΔK_{eq} did not suffer significant alterations for $\alpha=0^\circ$, $\alpha=15^\circ$, 30° and 45° , due to similar values of crack deflection angle (θ) for all the loading angles analysed, the predomination of mode I loading (ΔK_I) and a similar crack closure effect.

Acknowledgements

The authors would like to acknowledge the sponsoring under project no. 028789, financed by the European Regional Development Fund (FEDER), through the Portugal 2020 program (PT2020), under the Regional Operational Program of the Center (CENTRO-01-0145-FEDER-028789). This research is also sponsored by FEDER funds through the program COMPETE, Programa Operacional Factores de Competitividade, and by national funds through FCT, Fundação para a Ciência e a Tecnologia, under project UIDB/00285/2020. Finally, the authors acknowledge the project POCI-01-0247-FEDER-042536, financed by European Funds, through program COMPETE2020, under the Eureka smart label S0129-AddDies.

References

- Petrovic, V., Gonzalez, J.V.H., Ferrando, O.J., Gordillo, J.D., Puchades, J.R.B., Grinan, L.P.: Additive layered manufacturing: sectors of industrial application shown through case studies. *International Journal of Production Research* 49, 1061–1079 (2011).
- Murr, L.E., Gaytan, S.M., Ceylan, A., Martinez, E., Martinez, J.L., Hernandez, D.H., Machado, B.I., Ramirez, D.A., Medina, F., Collins, S., Wicker, R.B: Characterization of titanium aluminide alloy components fabricated by additive manufacturing using electron beam melting. *Acta Materialia* 58, 1887–1894 (2010).
- Guo, N., Leu, M.C.: Additive manufacturing: technology, applications and research needs. *Frontiers of Mechanical Engineering* 8, 215–243 (2013).
- Frazier, W.E.: Metal additive manufacturing: a review, *Journal of Materials Engineering and Performance* 23, 1917–1928 (2014).
- Richard, H.A. and Benitz, K. (1983). A loading device for the creation of mixed mode in fracture mechanics, *International Journal of Fracture*, 22, pp. R55-R58.
- M.A. Hussain, S.L. Pu, J.H. Underwood, Strain energy release rate for a crack under combined mode I and mode II, *Fract. Anal. ASTM STP 560* (1974) 2–28.
- Antunes F.V., Branco R., Ferreira J.A.M., Borrego L.P. Stress intensity factor solutions for CTS mixed mode specimen, *Frattura ed Integrità Strutturale*, 48 (2019) 676-692.
- Yan, X., Du, S., Zhang, Z. Mixed-mode fatigue crack growth prediction in biaxially stretched sheets. *Eng. Fract. Mech.* (1992) 43, 471–475.