CRACK GROWTH IN A Ti6Al4V ALLOY UNDER MULTIAXIAL FATIGUE

Silva, F.S.; Pinho, A.C.M.

Department of Mechanical Engineering, University of Minho,
Campus de Azurém, 4800 Guimarães, PORTUGAL

ABSTRACT

The aim of this work is to identify the effect of steady torsion on crack growth. Crack growth was studied in a Ti6Al4V alloy at room temperature. Push-Pull tests (*R=-1*) with different levels of tension/compression were carried out with and without steady torsion. Round specimens according to ASTM E 606-80, with a pre-crack, were used and an assembly allowed to introduce the steady torsion. A Pulsed DCPD system with a very high resolution (less then 1 µm) was used to measure the crack growth.
At each level of tension, with and without steady torsion, the shape of the *da/dN-ΔK* curve was assessed. Closure effects, which are in Ti6Al4V alloys primarily associated with the roughness-induced mechanism, due to steady torsion were also assessed at different *R* (*R = -1; -0,23; 0,1 and 0,5*).
The fatigue threshold for small cracks was studied in relation to the mechanisms of propagation of short cracks with and without steady torsion.

Keywords: fatigue; crack growth; multiaxial; steady torsion.

INTRODUCTION

A combination of a steady torsion and an alternated tension is common in many practical problems such as power shafts and other rotating parts of cars, trains and airplanes.
The orientation of the principal axes associated with the alternating components remain fixed, and the steady torsion doesn't introduce a mean stress on the direction of the alternating component. Nevertheless, it's accepted that steady torsion changes the overall behavior of the components.
The role of steady torsion on the propagation behavior of specimens under alternated tension has been studied by several authors. Hourlier and Pineau [1-4] and Tschegg et al [5] used round specimens with a circunferencial crack on different alloys: Al alloys, steels, and titanium alloys. This authors detected a pronounced reduction on *mode I* fatigue crack growth rate, and imputed this effect to crack closure produced by the macrofaceted "factory roof" type fracture surface. Pinho [6] studied the influence of a steady torque on a high strength steel with a semi-elliptical crack shape and different concentration factors related to several concordance radius. The specimens didn't have a pre-crack. Pinho found the opposite behavior. Due to steady torsion, the mode I fatigue crack growth rate increases with steady mode III. Pinho also concluded that most of the cracks, in round specimens under alternated *mode I* and steady *mode III* are semi-elliptical. Only with high stresses and high stress concentrations factors the crack is circumferencial. And this happens only on a few specimens.

Tschegg et al [7] also studied the influence of steady torsion on the fatigue threshold, K_{th}. This author used a round 13 % chromium steel specimen with a circunferencial crack, and found that steady *mode III* increases the fatigue threshold.
In these studies, two mechanisms have been assumed as the causes of this behavior: work hardening at the crack tip; and closure effects. And the conclusion of most of the authors [1-5, 7] is that cyclic plastic behavior is not the dominant mechanism. Closure effect induced by roughness is assumed as the main mechanism. This effect is more relevant with an imposed steady *mode III*.
In Ti6Al4V alloys, in *mode I* crack growth, the closure mechanism is attributed mainly to roughness, Ogawa and Ravichandran [8,9].
In this work, the authors will try to explain that, under alternated tension and steady torsion, and a semi-elliptical crack, roughness may not play an important role as happens with circunferencial cracks, and cyclic plastic behavior of materials may be more relevant then roughness.

MATERIALS AND METHODS

Material and specimens

The material used in this investigation is a Ti6Al4V alloy. The chemical composition (wt.%) is Al:6,1; V: 4,21; Fe:0,20; Ni:0,01. The material was delivered on the mill annealed condition: 2h, 735±15ºC, air cool. The mechanical properties are listed in table 1. The specimens used are round specimens according to ASTM E 606-80, with a precrack. (fig.1). Stress concentration factors are respectively, for tension and torsion: 2,32 and 1,67.

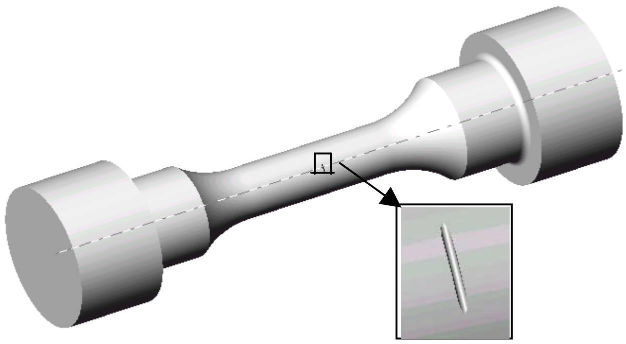


Figure 1 . Specimen geometry according to ASTM E 606-80, ∅=12 mm and L=133 mm. Pre-crack: a_0=100 μm; thickness = 300 μm; length = 2200 μm; curvature radius ρ=150 μm. K_t (tension)=2,32; K_t (torsion)=1,67

Table 1 : Mechanical Properties of Ti6Al4V

$\sigma_{ced\ (0,2\%)}$ *MPa*	σ_r *(MPa)*	*E* *(MPa)*
989	1055	$1,15*10^5$

Methods

Fatigue tests were conducted at two levels of alternated tension, *Δσ,* and one level of torsion, *τ,* as indicated in table 2, in laboratory air using a sinusoidal loading with different ratios of tension, (*R*= *-1; -0,23; 0,1*; and *0,5*) under loading control at a frequency of 8 Hz on a servo-hydraulic testing machine. The steady torsion was introduced using an assembly with dead weigth. At each level of tension and torsion the shape of the *da/dN-ΔK* curve was assessed. Tests presented in this work are representative tests of more than 50 tests. A Pulsed DCPD system with a resolution better than 1 μm [10] was used to measure the crack growth. Fracture surface examinations were made using an optical microscope.

Table 2 : Testing Conditions. Stresses don't include stress concentration factors.

Test	*R*	$\Delta\sigma$ *[MPa]*	τ *[MPa]*	$\sigma^{y}_{máx}$ *[MPa]*	σ_I *[MPa]*
1	-1	698	0	349	349
2	-1	698	349	349	573
3	-1	884	0	442	442
4	-1	884	442	442	716
5	-1	1060	0	530	530
6	-1	1060	530	530	858
7	-0,23	698	0	575	575
8	0,1	698	0	796	795
9	0,5	411,5	0	823	823
10	0,5	411,5	349	823	951

RESULTS

The relationship between fatigue crack growth and ΔK, at different *R* levels is presented in fig. 2. (tests 1,2,7,8,9,10). Tests for *R=-1* ($\Delta\sigma$ = 698 MPa) and *R=0,5*, with steady torsion are also at the same graphic.

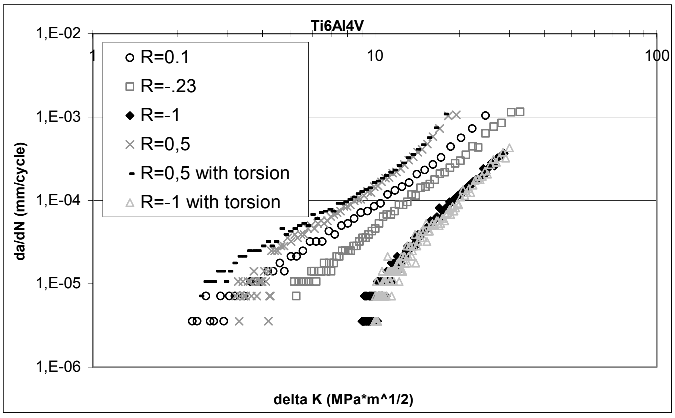


Figure 2 : Relationship between fatigue crack growth and stress intensity factor range, ΔK, at different R levels. Tests with R=-1 ($\Delta\sigma$ = 698 MPa) and R=0,5 are presented with torsion and without torsion.

The results can be summarized as follows:

1. When the *R* value increase, the fatigue crack growth curve *tend to the left*;
2. For *R=-1* ($\Delta\sigma$ = 698 MPa) tests with steady torsion *tend slightly to the right*, mainly on small crack regime;
3. For *R=0,5* (almost closure free), tests with steady torsion *tend slightly to the left*;
4. On the small crack regime, steady torsion seems to be more important for *R=0,5* than for *R=-1*.
5. The fatigue crack Threshold, K_{th}, seems to decrease with steady torsion.

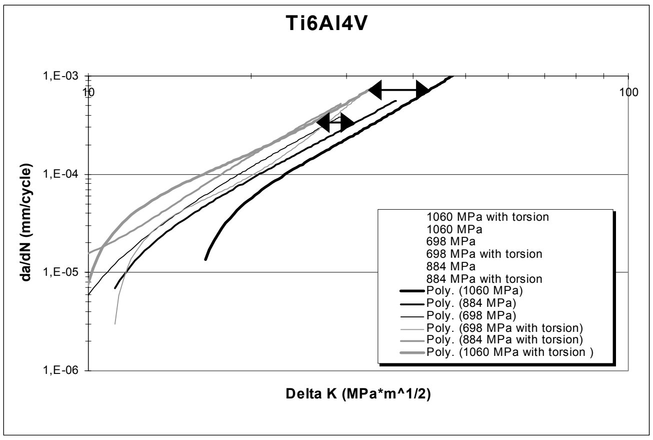
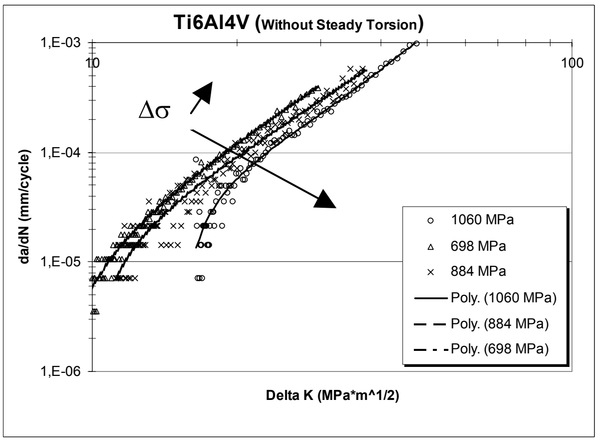


Figure 3 : Relationship between fatigue crack growth and stress intensity factor range, ΔK, at different levels of $\Delta\sigma$, and *R= -1*.

Fig 3 show the results of some other tests with different levels of alternated tension (tests 1-6) , under R= -1. Tests 2,4, and 6 have steady torsion.

a)



b)

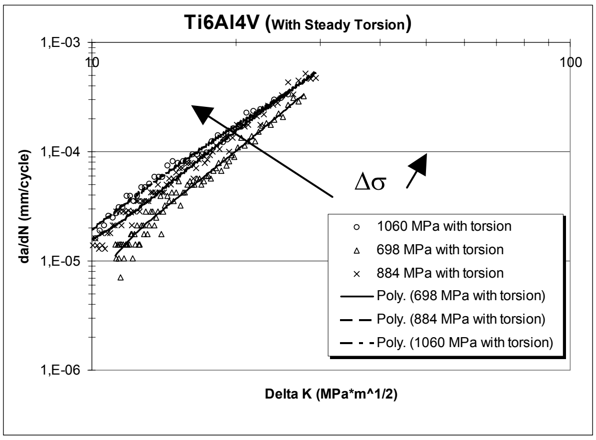


Figure 4 : Relationship between fatigue crack growth and stress intensity factor range, ΔK, at different levels of $\Delta\sigma$, and R= -1. a) Tests without steady torsion. b) Tests with steady torsion.

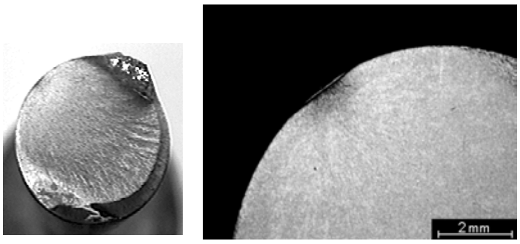
This results, for R= -1 can be summarized as follows:

1. Without steady torsion, as $\Delta\sigma$ increases, the fatigue crack growth curve *tends to the right* (fig.4 a). On the small crack regime the influence is more relevant and K_{th} increases with $\Delta\sigma$.
2. With steady torsion, as $\Delta\sigma$ increases, the fatigue crack growth curve *tends to the left* (fig.4 b). On the small crack regime the influence is more relevant and K_{th} decreases with $\Delta\sigma$.
3. As $\Delta\sigma$ increases, the difference on crack propagation rate between curves with steady torsion and without steady torsion, increases also (fig. 3);

Macroscopic observations of fracture surfaces

Figs. 5 - 6 show macroscopic photographs of fracture surfaces of tests with R=-1, with and without steady torsion. Fig. 6 have an alternated tension of 698 MPa, and fig. 7 have an alternated tension of 1060 MPa.

a)



b)

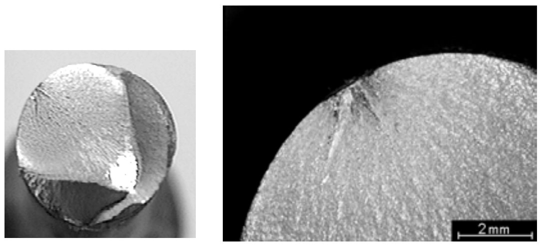
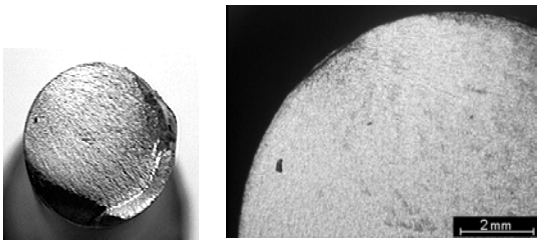


Figure 5 : Macroscopic appearance of fracture surfaces. $\Delta\sigma$= 698MPa. a) without torsion; b) with torsion

a)



b)

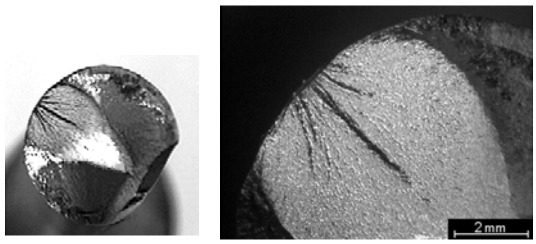
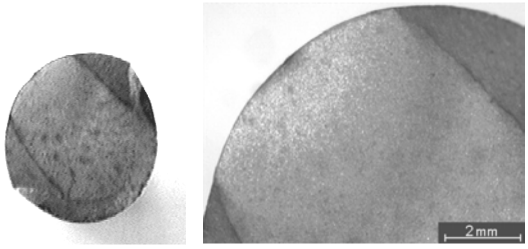


Figure 6 : Macroscopic appearance of fracture surfaces. $\Delta\sigma$= 1060 MPa. a) without torsion; b) with torsion.

In fig. 7 we can observe macroscopic photographs of the fracture surfaces of tests with R=$0,5$, with and without steady torsion.

a)



b)

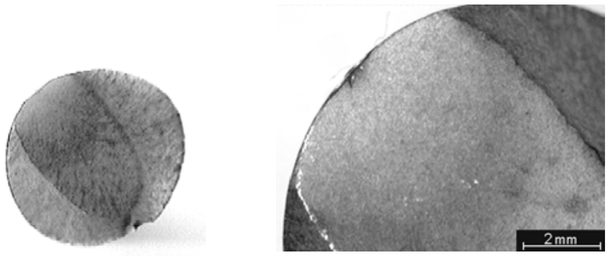


Figure 7 : Macroscopic appearance of fracture surfaces. *R=0,5.* a) without torsion; b) with torsion.

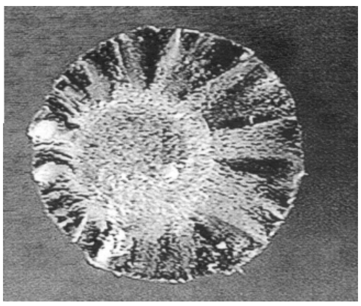
The results can be summarized as follows:

1. As the *R* value increase, the macroscopic fracture surface is smoother;
2. For *R=-1*, steady torsion produces the so called “factory roof” effect. This effect is more relevant as the level of $\Delta\sigma$ increases.
3. For *R=0,5* steady torsion doesn’t introduce the “factory roof” effect;
4. “Factory roof” effect, at *R=-1*, seems to be present since the very beginning of the tests. For crack lengths less than 0,1 mm.

DISCUSSIONS

In terms of propagation life it’s clear that decreasing *R* (fig.2) the fatigue crack growth curve tends to the left and it’s observed that the fracture surface becomes smoother. This result is in accordance with theories [8-9,11-12]. When imposing steady torsion, the surface roughness increases because of the so called “factory roof” effect. This is true only for *R=-1*, and not for *R=0,5*. For *R=0,5* it’s observed that the propagation rate with steady torsion is slightly higher than without steady torsion. If there is no effect of surface roughness one may conclude that another mechanism than surface roughness is responsible for this behavior. Let’s assume that this mechanism is related with cyclic plastic behavior of this alloy (or plastic zone size).
For *R=-1* (fig.2) there is no significant difference on propagation rate in tests with and without steady torsion at an alternated tension of $\Delta\sigma =$ 698 MPa. When the amplitude of tension increases, curves of tests without steady torsion tend to the right (fig.4 a) while curves of tests with steady torsion tend to the left (fig.4 b). This could mean that cyclic plastic parameters push the curve to the left, but another mechanism, which may be surface roughness (without steady torsion) and “factory roof” effect, with steady torsion, pushes it to the right. As a result it’s observed that those two mechanisms, surface roughness or “factory roof” effect, and cyclic plastic behavior compete with each other. It’s interesting to observe that, without steady torsion, when stresses increase, roughness effect prevails, and curves tend to the right. This is because plastic effect is not relevant. When steady torsion is imposed, cyclic plastic effects become more important then roughness or “factory roof” effect. And this is more relevant when stresses are high. The difference between curves with and without steady torsion increase with increasing alternated tension (fig. 3).
On the small crack regime it’s observed that the tendency of the threshold, K_{th}, is the same as for long crack regime, but it’s even more relevant. This behavior is opposite to the behavior in the work of Tschegg, Pineau and Hourlier [1-5]. This authors worked with round specimens with a circumferential crack. Fig. 7 show the fracture surfaces of tests with a circumferencial crack and with a semi-elliptical crack. Both with steady torsion. As it’s observed, it seems that with a circumferential crack, the effect of the faceted structure is greater, because the surface of the crack is much bigger. With a semi-elliptical crack the effect of the faceted structure may not be so relevant because the surface of the crack is smaller.

34CrNiMo6 with a cincumferencial crack [6]



Ti6Al4V with a semi-elliptical crack

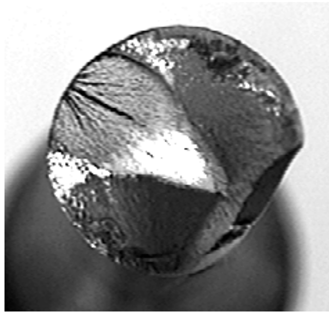


Figure 8 : Macroscopic appearance of fracture surfaces under a test with *R=-1* with steady torsion.

Maybe this is the reason why when imposing steady torsion, curves of crack propagation rate tend to the right, in work of Pineau, Hourlier and Tschegg, and tend to the left in this work.
Work of Tschegg [7] conclude that steady torsion increases threshold, K_{th}.This work concludes the opposite. The reason may be the same as for long crack regime.
Another possible explanation may be on cyclic plastic behavior of different materials with and without steady torsion. Steady torsion may have a softening or hardening influence on the cyclic plastic behavior of the materials. And this may be another possible reason for the behavior of this alloy in this work.
In high cycle fatigue, and with high frequencies, because plastic effects are small, roughness effect may prevail over cyclic plastic effects.

CONCLUSIONS

The main conclusions of this work can be summarized as follows:

1. With semi-elliptical cracks, between the two mechanisms which are present at the tip of the crack, cyclic plastic behavior seems to prevail over roughness or “factory roof” effect;
2. This effect causes crack propagation curves to move to the left with imposed steady torsion;
3. This tendency is more relevant for high stresses and in the small crack regime;
4. Fatigue threshold for small crack regime follows the same tendency.

References

1. Hourlier, F., Pineau, A., “Propagation of Fatigue Cracks Under Polymodal Loading”, Fatigue Fract. Engng. Mat. Struct., 5, 1982, pp. 287-302
2. Hourlier, F., Pineau, A., “Fissuration par Fatigue Sous Solicitations Polymodales (Mode I ondulé + Mode III Permanent) d’un Acier Pour Rotors 26 NCDV 14”, Mémoires Scientifiques Révue Metallurgie, 1979, pp. 175-185
3. Hourlier, F., Mclean, D., Pineau, A., “Fatigue Crack Growth Behavior of Ti5Al2.5Sn Alloy Under Complex Stress (Mode I + Steady Mode III), Metals Technology, 1976, pp.154-158
4. Hourlier, F., Hondt, H., Truchon, M., Pineau, A., “Fatigue Crack Path Behavior Under Polymodal Fatigue”, ASTM STP 853, 1985, pp. 228-247
5. Tschegg, E.K., Stanzl, S.E., Mayer, H., Czegley, M.,”Crack Face Interactions and Near Threshold Crack Growth Fatigue”, Fatigue Fract. Engng. Mat. Struct., 16, 1992, pp. 71-83
6. PINHO, A.C.M., “Fatigue Design of Power Shafts Using Fracture Mechanics”, PhD Thesys, 1996
7. Tschegg, E.K., Mayer, H.R., Czegley, M., Stanzl, S.E., “Influence of a Constant Mode III Load on Mode I Fatigue Crack Growth Thresholds”, ESIS 10, 1991, pp. 213-222
8. Ogawa, T; Tokaji, K., “The Effect of microstructure and fracture surface roughness on fatigue crack propagation in a Ti6Al4V alloy”, Fatigue Fract. Engng. Mater. Struct., Vol. 16, nº9 (1993), pp. 973-982.
9. Ravichandran, K.S., “Near Fatigue Crack Growth Behavior of a Titanium Alloy: Ti6Al4V"” Acta Metall. Mater., 1991, 39 (3), pp. 401-410
10. Silva, F.S.; Pinho, A.C.M.; Peixinho, N.; Meireles, J., “ Validation of a calibration procedure for fatigue crack growth measurement in circular section specimens” Damage and Fracture Mechanics VI (2000), Wit Press, pp. 353-364.
11. Finney, J.M., Deirmendjian, G.,”Delta K Effective: Which Formula?”, Fat. Fract. Engng. Mater. Struct., 15, 1992, pp. 151-158
12. Katcher, M., Kaplan, M., “Effects of R-Factor and Crack Closure on Fatigue Crack Growth for Aluminum and Titanium Alloys”, ASTM STP 559, 1974, pp. 264-282