Focussed on: Fracture and Structural Integrity related Issues

The effect of steady torsion on fatigue crack growth under rotating bending loading on aluminium alloy 7075-T6

M. da Fonte
IDMEC & ICEMS, Department of Mechanical Engineering, Nautical School
fonte@enautica.pt

L. Reis, M. de Freitas
IDMEC & ICEMS, Instituto Superior Técnico, Universidade de Lisboa
luis.g.reis@ist.utl.pt, mfreitas@dem.ist.utl.pt

ABSTRACT. Axles and shafts are of prime importance concerning safety in the transportation industry and railway in particular. Design rules for axles and shafts are mainly based on endurance curves for the material used according to the established standards and procedures. Recently, the knowledge of fatigue crack growth under typical loading conditions of axles and shafts with rotating bending and steady torsion is being object of research and industrial studies in order to apply damage tolerance concepts, mainly for maintenance purposes. The effect of a steady torsion on fatigue crack growth under rotating bending is focused in this paper. While axles and shafts in the transportation industry are traditionally designed on steels, the need for weight reduction due to fuel economy and eco-design constraints, lightweight materials must be considered for these applications. In this study, fatigue crack growth on rotating bending axles and shafts with or without an applied steady torsion is presented. Fracture mechanics approaches are used to analyze the results based on Stress Intensity Factors developed for bending and torsion in shafts and show fatigue crack growth retardation when steady torsion is applied. Fractographic observations using SEM are presented and helped to explain the fatigue crack growth retardation observed when steady torsion is applied to rotating bending. Results are compared for the same loading conditions on steels and relevant differences on fatigue crack growth are commented.

KEYWORDS. Multiaxial fatigue; Mixed-mode fatigue crack growth; Axles; Shafts.

INTRODUCTION

Failure of railway axles has been a matter of concern since the development of railway industry and some dramatic failures have been reported from the early decades of the XIX century. Since the Wöhler studies on fatigue failure of railway axles in the middle of the nineteen century, endurance curves determined under rotating bending tests constitute the most important data when designing against fatigue failure and avoid crack initiation. With the development of modern high speed trains, railway axles are submitted to more severe loading conditions and it is still a challenge for the test and design engineers to accurately determine the fatigue lifetime of railway components [1]. Nowadays, due to the need of weight reduction in the transportation industry, the use of lightweight materials is being considered and aluminium alloys are one of the most used metals for the weight reduction on mechanical components, therefore their use on axles and shafts may be considered. Nevertheless, aluminium alloys are much more sensitive to fatigue crack growth than steels whereby damage tolerance studies must be performed before any industrial application.

Fatigue failure comprises three distinct phases: (i) crack initiation (including early crack nucleation and small crack growth), (ii) long crack growth and (iii) fast final failure. For long cracks, Linear Elastic Fracture Mechanics (LEFM) is a powerful tool to predict fatigue crack growth that has been proved with excellent results in aeronautic industry and has been the main tool to perform damage tolerance analysis [2]. To predict fatigue crack growth through LEFM, a Stress Intensity Factor (SIF) solution for the specific geometry is needed together with materials fatigue crack growth data. Besides, shafts are also widely used in railway, automotive, aeronautic and energy industries and in this mechanical component both a torsion and bending load are combined. Generally, fatigue failures in power shafts have origin on surface cracks that grow with semi-elliptical shape under cyclic bending, mode I (ΔK_I), combined with steady torsion, mode III (K_{III}) [3]. Large number of power plant systems run with a general steady torsion combined with cyclic bending stress either due to the self-weight bending during the rotation or possible misalignment between journal bearings [4]. In the case of power shafts such as those used in electric power plants, propeller shafts of screw ships, or any other rotary load-transmission devices, the lifetime spent between crack initiation and final fracture is of capital importance to improve the inspection intervals and maintenance procedures.

Many researchers have studied the influence of a static mode III loading on cyclic mode I for circumferential notched shafts mainly since 80's, such as Akhurst and Lindley [3], Hourlier and Pineau [5], Yates and Miller [6]. Tschegg [7, 8] has done an important contribution to clarify the influence of steady or cyclic mode III on fatigue crack propagation behaviour when combined with mode I loading. Fonte and Freitas [9] have studied the influence of steady torsion on fatigue crack growth of semi-elliptical cracks in shafts under rotating bending, and rotating bending combined with steady torsion. For the purpose a new testing machine was design and constructed.

Despite the relevant and practical importance of mixed-mode fatigue, the applications of fracture mechanics have been mainly focused on crack growth problems in mode I. Several SIF solutions have been proposed for semi-elliptical surface cracks under pure bending in round bars [10, 11]. Fonte and Freitas [12] have also presented SIF for semi-elliptical surface cracks in round bars for both pure bending and pure torsion.

Freitas et al [1] carried out an experimental work in rotary bending specimens to simulate railway axles, and it was shown that the proposed SIF are not directly applicable to the fatigue crack growth analysis because the position of fatigue crack front changes continuously during a load cycle. The maximum value of SIF is not reached at the same rotation angle for all points along the crack tip profile and it is well-known that crack initiation process in rotor shafts has generally origin on the surface and the crack grows with a semi-elliptical shape. Also in [13], both small and long fatigue crack growth data were obtained from rotating or alternate cyclic bending tests on a medium carbon steel (Ck45) are presented and results are discussed. For small crack growth, an effective strain-based intensity factor range was proposed as the parameter which correlates small fatigue crack growth data under proportional or non-proportional multiaxial loading conditions.

In this paper, the effect of a steady torsion load on fatigue crack growth due to cyclic bending in bars (axles or shafts) is studied for an aluminium alloy. Results are commented and compared with previous studies on steels under the same loading conditions, allowing designers to have tools for damage tolerance analysis.

EXPERIMENTAL PROCEDURE

Material and specimens

The material used in this study is the Al 7075 T6 in the aged condition. The chemical composition of this aluminium alloy is presented in Tab. 1 and the mechanical properties are presented in Tab. 2.

In rotating bending fatigue tests, classic cylindrical hourglass shaped specimens are used for the determination of S-N curves where the hourglass shape is adopted in order to localize the stress at the crack initiation and final failure. In this study, fatigue crack growth data for long cracks from a precrack will be studied, therefore the specimen geometry adopted was straight cylindrical specimens, Fig. 1, with two different diameters, respectively 10 mm and 12 mm. All specimens were machined from round bars of 25 mm diameter. After machining, all specimens were polished and notched on the surface (chordal notch), approximately 3 mm length and 0.1 mm depth. All specimens were pre-cracked under constant amplitude cyclic bending stress until the arc crack length reaches a minimum length of 2 to 3 mm.

Cu	Zn	Mg	Mn	Cr	Si	Fe	Ti	Al
1.267	5.66	2.72	0.05	0.197	0.156	0.228	0.21	Bal.

Table 1: Chemical composition of 7075 aluminium alloy.

Yield strength (MPa)	Ultimate tensile strength (MPa)	A (%)
513	575	10.9

Table 2: Monotonic mechanical tensile properties of 7075 T6 aluminium alloy.

Figure 1: Specimen used for fatigue crack growth data.

Testing procedure

Experiments for fatigue crack growth were performed in a rotating bending fatigue testing machine, Fig. 2, which was designed and constructed to model the real conditions of axles and shafts in service [9].

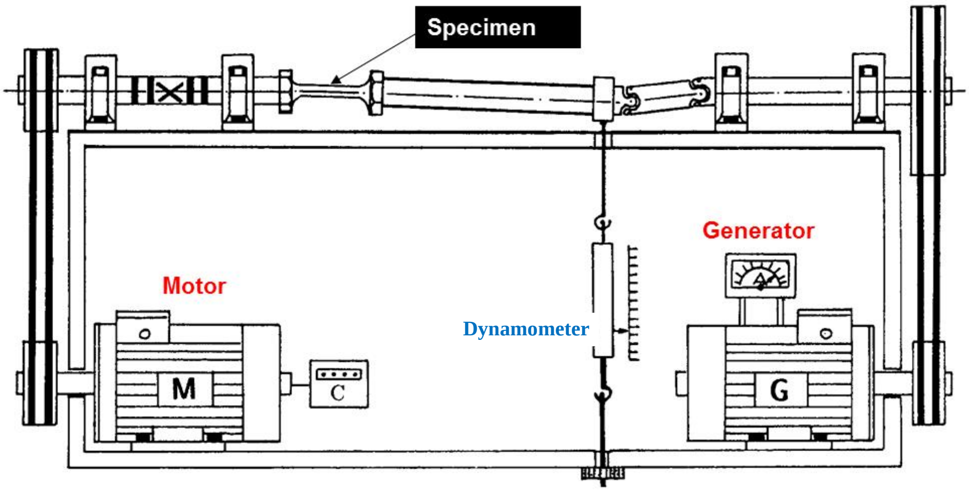


Figure 2: Schematic of testing machine for rotating bending with or without steady torsion.

The fatigue testing machine can perform rotary bending with or without steady torsion under load control either in bending or torsion. Due to the load capacity of the machine presented in Fig. 1, when higher torsion levels were required, the specimen diameter must be reduced, therefore two specimen diameters, were used, respectively 10 mm and 12 mm. Rotating bending fatigue tests were carried out for nominal bending stresses from 140 MPa up to 190 MPa and nominal steady torsion from 60 MPa up to 127 MPa. Tab. 3 presents the specimen diameters and loading conditions used on fatigue crack growth tests, representing a wide range of bending stresses and steady torsion. These testing conditions refers to multiaxial loading, with a cyclic normal stress, σ, and a static shear stress, τ, therefore it is helpful to full characterize the stress state during a cycle loading. Tab. 3 also presents the ratio between the maximum normal and the maximum shear stress achieved in each loading cycle as well as the maximum and minimum principal stresses, $S_{I,max}$ and $S_{III,min}$, the maximum shear stress τ_{max} and the maximum equivalent (von Mises equation) stress $\sigma_{equiv,max}$.

The detection of fatigue crack initiation from the notch and surface crack length measurements were carried out with an optical microscope at a magnification of 80X. Measurements of crack length were obtained at constant intervals, interrupting the tests, till the crack depth reaches approximately 3/4 r. In some selected specimens the crack front shape was marked through beach marks, using a lower bending stress level in order to obtain experimentally the crack shape geometry i. e. crack length vs. crack depth.

Diameter d (mm)	Bending σ (MPa)	Torsion τ (MPa)	τ/σ	$S_{I,max}$ (MPa)	$S_{III,min}$ (MPa)	τ_{max} (MPa)	$\sigma_{eqiv,max}$ (MPa)
10	162	0	0	162	0	81	162
10	162	112	0.691	219	-57	138	252
10	140	127	0.907	215	-75	145	260
12	146	0	0	146	0	73	146
12	152	0	0	152	0	76	152
12	182	0	0	182	0	91	182
12	190	0	0	190	0	95	190
12	152	71	0.467	180	-28	104	195
12	158	60	0.379	178	-20	99	189
12	190	71	0.373	214	24	118	226

Table 3: Specimen dimensions and loading conditions.

RESULTS

Several torsion stress levels and two specimen diameters were used in order to determine the effect of torsion on fatigue crack growth rates obtained by rotating bending. Fig. 3 a) and 3 b) shows two examples of the fracture surface of two different specimens with two different loading cycles, respectively rotating bending, and rotating bending with steady torsion. It is clearly seen that crack initiation starts from the notch, growing in the radial direction under an elliptical shape and when a steady torsion is applied a different crack growth rate is observed for both sides of the semi-elliptical crack shape, as already mentioned in [9] for steels under similar loading conditions.

The geometric parameters of cylindrical specimens and semi-elliptical crack dimension are characterized according to Shiratori nomenclature [11] as shown in Fig. 4 and also adopted in [12], i.e. the semi-arc crack length is denoted by *s* and the minor semi-ellipse axis corresponding to the maximum crack depth is denoted by *b*.

a) b)

Figure 3: Fracture surfaces for: a) pure rotating bending (symmetrical crack growth); b) rotating bending with steady torsion (nonsymmetrical crack growth).

The semi-elliptical crack depth b was related with the total arc crack length $2s$ and agrees with the equation $b=2s/\pi$ already found before in previous experimental tests for pure rotary bending and mixed-mode [1, 9] as shown in Fig. 3. Some deviation for the largest applied torques was found, however for the crack depth b up to $r/2$ the equation is still valid.

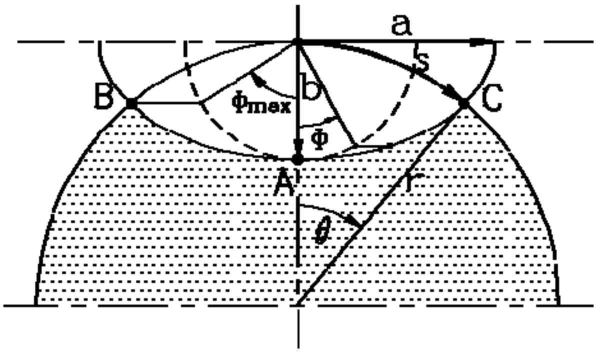
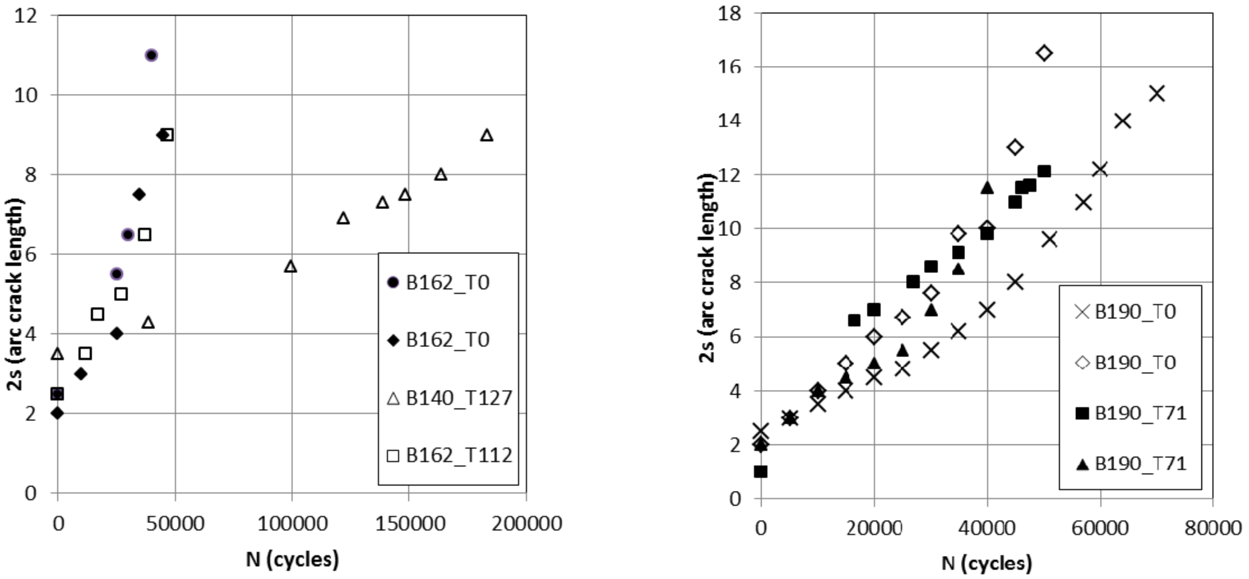


Figure 4: Geometry parameters of semi-elliptical surface crack.

Fatigue crack growth tests were performed under two different loading conditions respectively: (i) cyclic bending; (ii) cyclic bending with a steady torsion, and results were first analyzed in crack length versus number of cycles. Crack growth results determined for two specimens diameters, with and without steady torsion, are presented in Fig. 5 a) for the arc crack length, $2s$ as a function of number of cycles, N after precrack initiation, for 4 specimens of 10 mm diameter, where *Bxxx* denotes the bending stress and *Txxx* the torsion stress levels corresponding to two bending/torsion stress ratios, respectively 0.7 and 0.9. Fig. 5 b) presents similar results for 12 mm specimen diamenter ad only one bending/torsion stress ratio. Results presented in Fig. 5 clearly show that there is an influence of a steady torsion in crack growth under rotating bending, where it can be seen that for lower levels of steady torsion similar trends of crack growth are obtained for both loading conditions, with and without steady torsion; in opposite, for the highest steady torsion applied to rotating bending, a crack growth retardation is observed, which is consistent with previous results from the authors for similar fatigue tests in steels [9]. Therefore a significant effect of steady torsion on fatigue crack growth can be observed for the levels of torsion presented. Results show that fatigue crack growth rate in rotating bending can decrease in the presence of a steady torsion and this retardation effect increases with the level of steady torsion, even though the Von Mises equivalent stress increases.



a) b)

Figure 5: Arc crack length evolution with number of cycles: a) 10 mm specimen diameter; b) 12 mm specimen diameter.

DISCUSSION

Stress Intensity Factors

Assuming that cracks have always a semi-elliptical shape as shown in Fig. 4, the points on crack front at deepest crack depth (A) and where the crack intersects the external surface (points B and C) are the most important ones. The semi-ellipse axes are obtained according to the equation $b=2s/\pi$ experimentally obtained [1, 9], and Eq. (1) was deducted.

$$a = \frac{r \cdot sen\,\theta}{\sqrt{1 - \frac{r^2}{b^2}(1 - cos\,\theta)^2}} \tag{1}$$

The major research field of fracture mechanics is the determination of the Stress Intensity Factors. In this study, SIF for mode I and mode III along the crack front of semi-elliptical surface cracks normal to the axis in shafts subjected to bending, torsion and bending-torsion simultaneously, determined by a three-dimensional finite-element analysis [12] will be used.

The total arc crack length $2s$ was chosen as the experimentally obtained crack parameter in fatigue crack growth tests and according to Shiratori et al [11] and Freitas et al [12]. Therefore the mode I Stress Intensity Factor K_I for any point along the surface crack was obtained by the equation:

$$K_I = F_I\left(\tfrac{b}{r},\tfrac{b}{a},\phi\right)B_s\sqrt{\pi s} \tag{2}$$

where B_S is the remote applied bending stress, s is the half arc crack length and F_I is the boundary correction factor or the dimensionless SIF for mode I which is a function of the semi-elliptical crack shape *(b/a),* relative crack depth *(b/r)* and of the position points along the crack front defined by the parametric angle Φ, Fig. 3, which was determined taking into account the FEM calculations presented in [12].

As indicated before, limited results for the SIF of semi-elliptical surface cracks in round bars subjected to torsion stress levels are available, and the results presented in [12] are used in this paper. Therefore, SIF K_{III} will be obtained using the same geometric parameters that were used for mode I (bending):

$$K_{III} = F_{III}\left(\tfrac{b}{r},\tfrac{b}{a},\phi\right)T_s\sqrt{\pi s} \tag{3}$$

where T_S is the remote applied torsion stress on the outer surface of the shaft, s is the half arc crack length and F_{III} is the boundary correction factor for mode III which is a function of the semi-elliptical crack shape *(b/a),* relative crack depth *(b/r)* and of the position along the crack front determined by the referred parametric angle Φ in Fig. 3 that was determined taking into account the FEM calculations described in [12].

Mixed-mode crack growth under multiaxial loading

Most of fatigue crack growth studies have been done on single-mode loading and usually are performed under mode I loading condition. However, single-mode loading seldom occurs in practice, and in many cases cracks are not normal to the maximum principal stress direction. The multiaxial mixed-mode fatigue crack growth is a common problem in many engineering structures and components.

For long cracks, the propagation mechanisms are often analyzed using linear elastic fracture mechanics approach. Under combined axial and torsion loading, the surface corner of the semi-elliptical crack has mixed mode I+mode II, but at maximum depth of the semi-elliptical cracks has only mixed mode I+mode III [12].

For mixed-mode loading, one can assume that the fatigue crack growth rate may be expressed by the Paris law where the stress intensity factor range is replaced by an equivalent SIF range, ΔK_{eq}:

$$\frac{da}{dN} = C\left(\Delta K_{eq}\right)^m \tag{4}$$

There are many approaches proposed to define the equivalent SIF range ΔK_{eq} for mixed-mode loadings. One of them is based on the addition of the Irwin's elastic energy release rate, G parameters for the three loading modes:

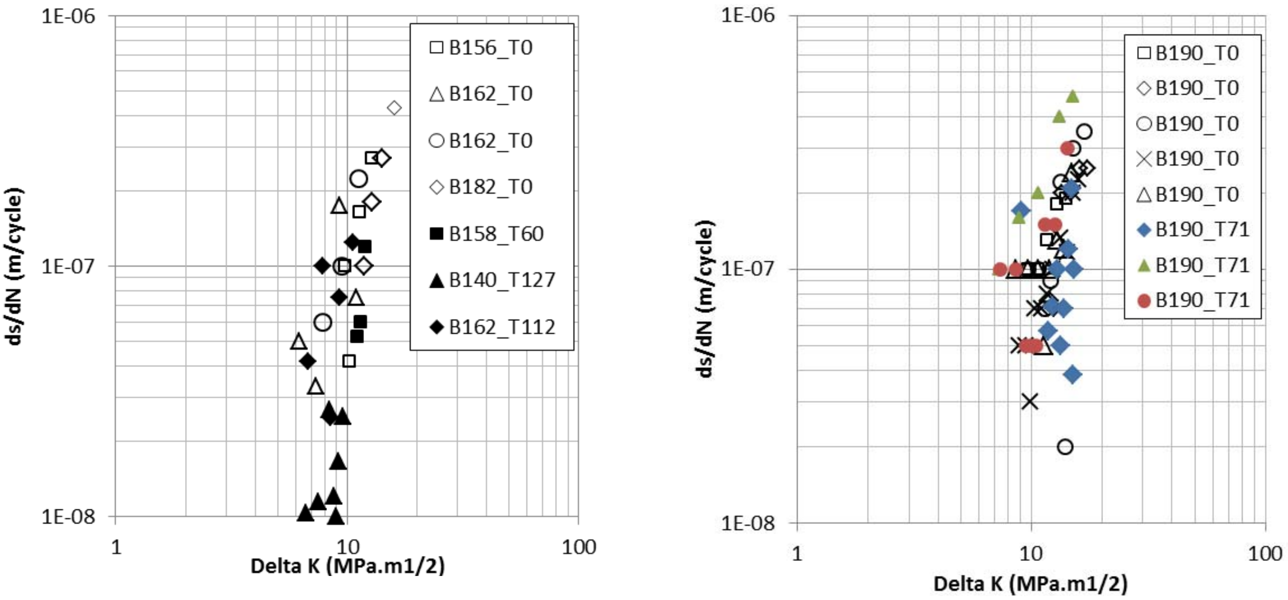
$$\Delta K_{eq} = \left(G_{total}\,E\right)^{1/2} = \left[\Delta K_I^2 + \Delta K_{II}^2 + (1+\nu)\Delta K_{III}^2\right]^{1/2} \tag{5}$$

where ΔK_I, ΔK_{II} *and* ΔK_{III} are the stress intensity factors for mode I, II and III respectively and E and ν are the elasticity modulus and the Poisson's ratio. Therefore, Eq. (4) can be used to correlate the fatigue long crack growth data in a mixed-mode loading condition.

Fatigue crack growth

Under rotating or alternate (reversed) bending a stress ratio $R=-1$ exists, therefore $\Delta K_{Imax}=-\Delta K_{Imin}$ and according to the recommendations specified on ASTM E647, in this study $\Delta K_I=K_Imax$ will be used. For static torsion $\Delta K_{III}=0$, therefore Eq. (5) is reduced to ΔK_I, since only mode I is activated in cyclic loading.

Fig. 6 shows the fatigue crack growth rate as a function of the mixed-mode equivalent energy release range which in this case reduces to the mode I stress intensity factor range, determined as mentioned before, for several loading conditions and 10 mm and 12 mm diameter specimens: rotary bending, and bending conditions combined with steady torsion. As observed in Fig. 6, an effect of steady torsion on fatigue crack growth (FCG) rate is observed. Results show that fatigue crack growth in rotating bending decreases with higher levels of steady torsion while for lower levels of steady torsion a small retardation effect is observed. These results represent a similar trend to the one obtained in steels under the same loading conditions that were presented before [9, 13].



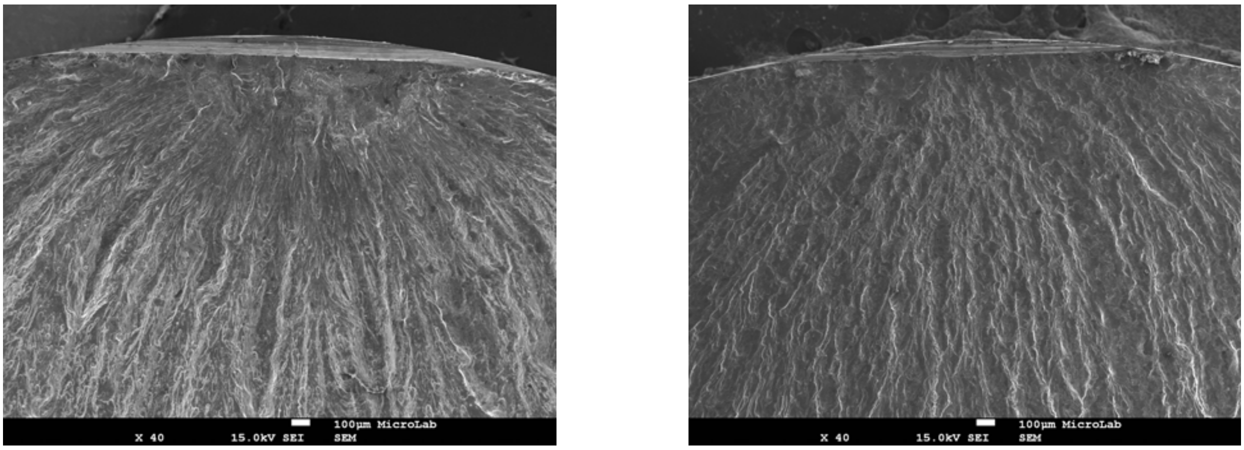
a) b)

Figure 6: Fatigue crack growth a) 10 mm specimen diameter; b) 12 mm specimen diameter

Fractography

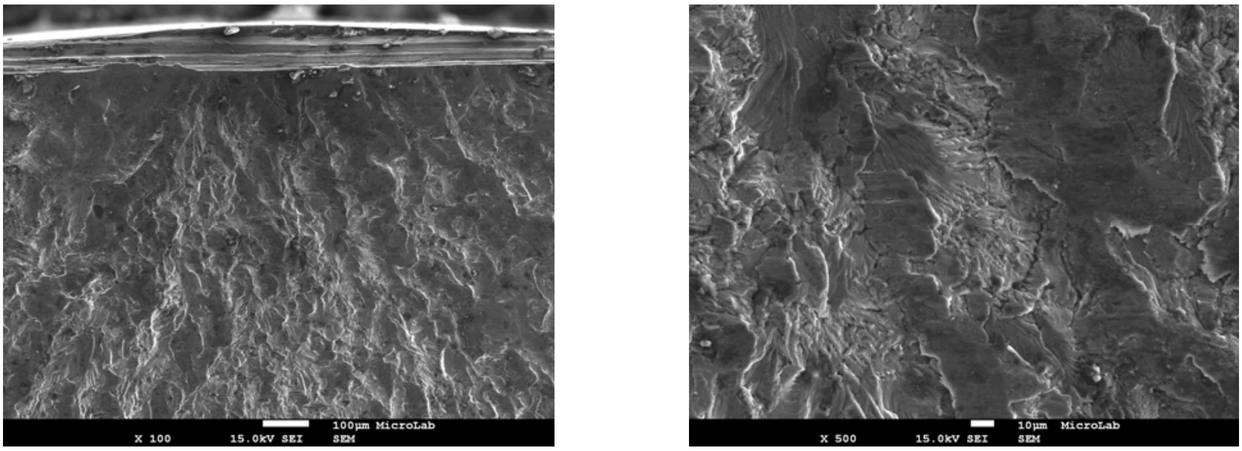
Scanning electron microscopic (SEM) observations were carried out for both types of fracture surfaces, pure mode I, due to rotating bending only, and mode (I+III) due to rotating bending and steady torsion, and the crack growth profiles created by two different types of loading are shown in Fig. 7 a) and b) respectively. They correspond to the formation of regular sets of inclined micro facets corresponding to mode I crack growth inclined due to mode III loading, and are similar to the "factory roof" markings observed in previous similar studies. This "factory roof" crack growth is completely "rubbed" by the strong torque imposed during rotating bending. While some "rubbing" is also visible on crack growth due to rotating bending, this is due to the tension/compression loading cycle observed in rotating bending.

The rubbing of the fracture facets is very well observed in Fig. 8 a) and b) which shows the fracture surface near the initial phase of fatigue crack growth and much more clearly on Fig. 8 b), where the higher amplification clearly shows two types of fracture facies, one strongly "rubbed" at the tip of "factory roof" fracture followed by more "normal" facies characteristic of fatigue crack growth under mode I.



a) b)

Figure 7: SEM micrographs a) Bs=190 MPa; Ts=0; b) Bs=152 MPa_Ts=71 MPa



a) b)

Figure 8: SEM micrographs Bs=152 MPa_Ts=71; a) initial crack growth b) crack growth path

CONCLUSIONS

The effects of steady torsion on fatigue crack growth under cyclic bending were studied for long crack growth on aluminium alloy 7075-T6 specimens under multiaxial fatigue loading conditions.

For long cracks a superimposed steady mode III loading to a crack growing in cyclic mode I can lead to significant fatigue crack growth retardation, depending of the ratio between maximum bending stress and maximum steady torsion. Crack growth rates decrease with increasing mode III for cyclic mode I (ΔK_I) + static mode III (K_{III}) loading.

These results are consistent with similar ones obtained for Ck45 steels for the same loading conditions, therefore the retardation effect on crack growth can be considered as an effect of the steady torsion on rotating bending. Due to steady torsion effect superimposed to rotating bending, the crack path is in zig-zag which creates a helical surface crack morphology.

Fractographic observations lead to the conclusion that this retardation effect is due to a significant higher irregularity on fatigue crack path which is observed when steady torsion is applied to rotating bending.

REFERENCES

[1] de Freitas, M., François, D., Analysis of fatigue crack growth in rotary bend specimens and railway axles. Fat Fract Engng Mater Struct, 18 (1995) 171-78.

[2] Newman, J. C., Philips, E. P., Swain, M. H., Everett, R. A., Fatigue mechanics: an assessment of a unified approach to life prediction. ASTP STP 1122 (1992), pp 5-27.
[3] Akhurst, K. N., Lindley, T. C., Nix, K. J., The effect of mode III loading on fatigue crack growth in a rotating shaft. Fatigue Engn Struct, 6 (1983) 345-348.
[4] Fonte, M., de Freitas, M., Marine main engine crankshaft failure analysis: a case study, Engineering Failure Analysis 16 (2009) 1940–1947.
[5] Hourlier, F, McLean, D, Pineau, A., Fatigue crack growth behaviour of Ti-5Al-2.5Sn alloy under complex stress (modeI+steady mode III). Metals Tech, 1978:154-158.
[6] Yates, J.R., Miller, K.J., Mixed Mode (I+III) fatigue thresholds in forging steel. Fatigue Engng Mat Struct, 12 (1989) 259-270.
[7] Tschegg, E.K., Stanzl, S., Mayer, H., Czegley, M., Crack face interactions near threshold fatigue crack growth, Fatigue Fract Engng Mater Struct, 16 (1983) 71-83.
[8] Tschegg, E.K., Mode III and mode I fatigue crack propagation behaviour under torsional loading, J Mat Science, 18 (1983) 1604-1614.
[9] Fonte, M., Freitas, M., Semi-elliptical crack growth under rotating or reversed bending combined with steady torsion. Fat Fract Engng Mater Struct, 20 (1997) 895-906.
[10] Raju, I.S., Newman, J.C., Stress intensity factors for circumferential surface cracks in pipes and rods under tension and bending loads, Fracture Mechanics, ASTM STP 905 (1986) 789-805
[11] Shiratori, M., Miyoshi, T., Sakay, Y., Zhang, G.R., Factors Analysis and application of influence coefficients for round bar with a semi-elliptical surface crack. Murakami Y. editor. Handbook of Stress Intensity Factors, II; Pergamon Press, Oxford, 1987:659-65.
[12] Fonte, M., Freitas, M., Stress Intensity Factors for semi-elliptical surface cracks in round bars under bending and torsion. Int J of Fatigue, 21 (1999) 457-463.
[13] de Freitas, M., Reis, L., da Fonte, M., Li, B., Effect of steady torsion on fatigue crack initiation a nd propagation under rotating bending: Multiaxial fatigue and mixed-mode cracking. Engineering Fracture Mechanics, 78 (2011), 826-835.