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Fatigue crack growth of semi-elliptical cracks under bending combined with steady torsion

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Abstract

An analysis of the influence of steady torsion loading on fatigue crack growth of semi-elliptical cracks under rotating and reversed bending is presented. The crack growth has been studied in two different fatigue machines which perform mixed mode (I+III) loading obtained by cyclic mode I (ΔK_I) with superimposed static mode III (K_{III}) loading. Tests were carried out on cylindrical specimens in Ck45k steel and the results are compared in both loading conditions: rotating and reversed bending with and without steady torsion. Results show that the static mode III loading superimposed to mode I leads to a significant reduction on the crack growth rates. The influence of these phenomena could be related with an increased "crack closure effect" associated to interlocking of rough fracture surfaces, friction and fretting debris, leading to a decrease of the ΔK effective at the crack tip. This work provides a contribution for a better understanding of the crack growth rate on shafts under mixed mode load conditions in order to predict remaining life times and to estimate the risks of precracked rotor shafts.

1 Introduction

Crack propagation under mixed mode loading on shafts under rotating and reversed bending is the reason for many failures of machines. Many service failures occur from cracks which were subjected to polymodal loadings, usually under cycle mode I (ΔK_I) with static mode III (K_{III}). Large turbo-generator shafts in electrical power plant systems or in propeller shafts run with a steady-state torque with a superimposed cyclic bending stress due to their weight or possible misalignment.

An important reduction in engineering failures has been achieved with the application of techniques for the estimation of lifetime of pre-cracked components, based on fracture mechanics theory and practice. So it is necessary to know the fatigue crack growth characteristics in order to predict remaining life times and to estimate the risks of precracked parts.

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Despite the practical importance of polymodal fatigue, the majority of the research in fatigue crack growth has been concerned with mode I crack opening. For this type of loading, many examples have shown that linear elastic fracture mechanics can be successfully applied to practical engineering problems.

Fatigue crack growth in mixed mode (I+III) has received more attention in last years. Some researchers have devoted their studies to this field of investigation, namely Yates & Miller,[1] Hourlier & Pineau,[2] Ritchie, McClintock & Tschegg,[3,6] Akhurst & Lindley[4] and Pook,[5] between others. These studies have been performed with circumferential notched cylindrical specimens, using servo-hydraulic fatigue testing machines in general.

In the field of fracture mechanics, one of the major research activities is the development of effective techniques to obtain accurate Stress Intensity Factors essential for the prediction of fatigue crack growth rates. Freitas & François[7] have studied fatigue crack growth of semi-elliptical surface cracks in cylindrical specimens subjected to rotating bending conditions. The analysis allowed to obtain the crack shape evolution and the Stress Intensity Factors (K) associated to the geometry and the loading. Results were compared with CCT specimens in the same loading conditions. K-values were obtained according to Shiratory[8] and a good correlation was achieved.

In previous work the authors[9] have presented the results of tests carried out on a testing machine which performed rotating bending with steady torsion.

Present study shows the effect of steady torsion (Mode III) on cylindrical specimens under reversed bending (Mode I) and compares these results with those obtained before.

2 Materials and experimental procedure

2.1 Testing machine

Tests were carried out on two different types of fatigue machines: one performs rotating bending with steady torsion; another one performs reversed bending with steady torsion. The first one was already presented by the authors[9]. Fig.1 shows the specimens and the principle of reversed bending machine under steady torsion.

A constant deflection is applied on the ball-bearing at the free end of the specimen. Steady torsion is loaded by an arm with a spanner clamped and welded near the ball-bearing in order to obtain the steady torsion by the application of calibrated weights.

2.2 Specimens and material

Tests were performed on cylindrical specimens with 14, 12 mm and 10 mm diameter. A Ck45k steel from a calibrated round bar of 22 mm was used. The chemical composition was (wt%): 0.45 C, 0.25 Si, 0.65 Mn. The mean value of 0.2 % proof stress was 675 MPa and the ultimate tensile stress was 850 MPa. A chordal notch was made on cylindrical surface of the specimens with 3 mm and 0.2 mm of length and depth, respectively, with a V-notch angle $30^{\circ}$and a notch root radius < 0.1 mm.

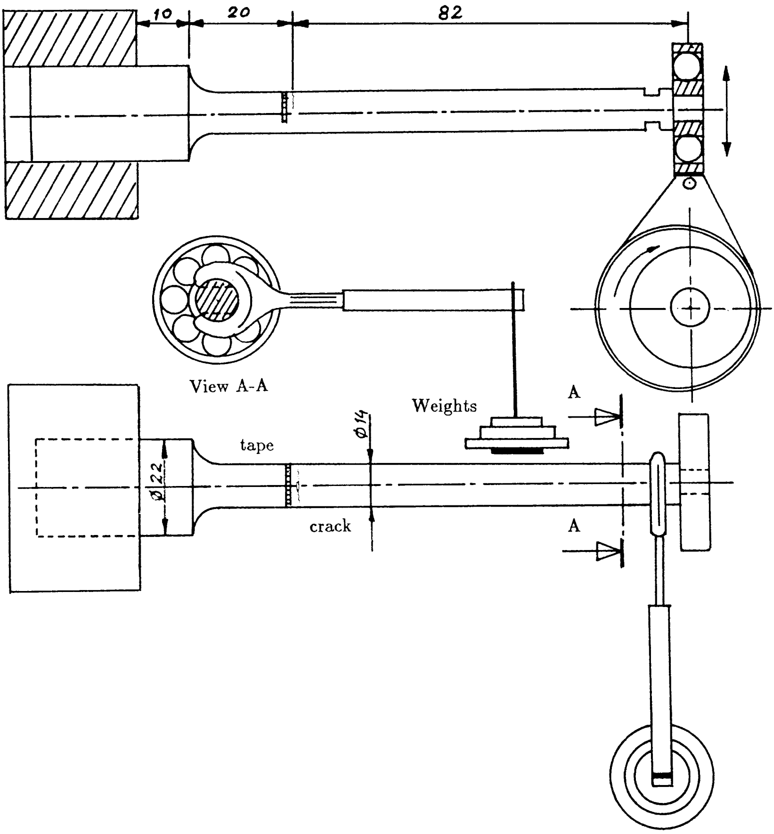

Figure 1: Reversed bending machine with steady torsion frame

2.3 Experimental procedures

Specimens were precracked under pure reversed bending using a constant stress at notch root, 200 MPa.

Bending was applied through constant deflection at the ball-bearing placed on the free end of the specimen, 82 mm from the chordal notch. A constant deflection was maintained till the end of tests.

Arc crack length measurements, 2s (length along circumferential on specimen surface), were made using a optical microscope (80x) and a tape-measure graduated in millimeters placed near the chordal notch and around the proof zone of specimen. For the continuum measurements a stroboscope was used.

Measurements were made at constant intervals till the crack depth was around 3/4 r, estimated by the authors in previous work.

In both experimental tests, rotating or reversed bending, a fixed deflection was imposed and staying hold the bending moment until the end of fatigue tests. Loading was measured by an electric strain gauge applied on opposite side to the notch specimens before starting the tests.

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After precracking, a torsion moment was applied with two different torsion stress levels: τ_1=100 MPa, τ_2=200 MPa.

Tests were performed at constant bending deflection, 25 Hz, in laboratory air, at room temperature.

After testing, all the specimens were broken by impact bending for examination on optical and scanning electron microscope.

3 Results and discussion

Crack length measurements (2s) were obtained as a function of the number of cycles N. Asymmetric growth of crack shape was obtained, and measurements were made from initial chordal notch center to each side of the arc crack in order to verify the "fastest" half crack growth and the "slowest" half crack growth, s.

The influence of the steady torsion in reversed bending is shown in Figure 2, where the arc crack growth length (2s) for pure reversed bending (200 MPa) and for two levels of steady torsion (100 and 200 MPa) are represented.

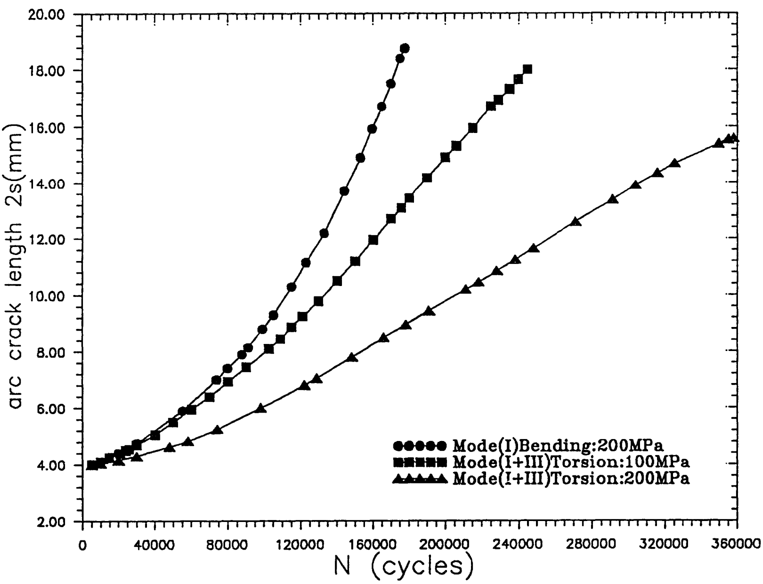

Figure 2: Arc crack growth for Mode I and Mode (I+III)

Fig.4 plots the crack growth rates for pure reversed bending and for two levels of steady torsion where a significant retardation in crack growth rates is observed similar to the retardation obtained in rotating bending for the same loading conditions. The analysis is carried out considering the determination of crack growth rate, ds/dN, calculated by secant method, versus the arc crack length, 2s, since no Stress Intensity Factor for this configuration in mode III loading is available.

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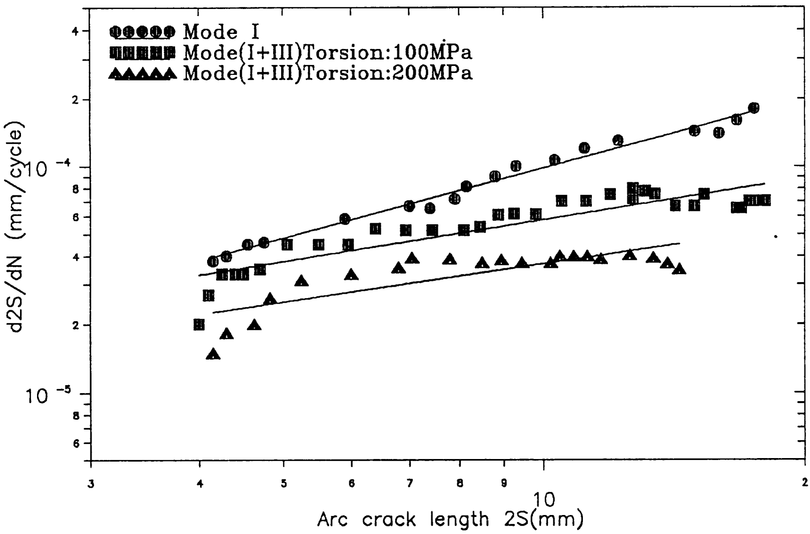

Figure 3: Crack growth rates for mode I and mixed mode (I+III)

In order to compare their results, Table 1 presents the testing conditions (specimen diameter, bending and torsion stress) and the equations of crack growth rates for rotating bending obtained before, and Table 2 the same parameters for the present case, reversed bending.

Diameter [mm]	Bending Stress [MPa]	Torsion Stress [MPa]	Crack Growth Equation $d(2s)/dN = C(2s)^n$ C	n
14	200	0	1.20E-06	2.00
14	200	50	1.50E-06	1.53
10	200	0	1.20E-06	2.00
10	200	100	1.36E-06	1.36
10	200	140	3.82E-06	0.98

Table 1: Testing conditions and crack growth equations for rotating bending with steady torsion.

Diameter [mm]	Bending Stress [MPa]	Torsion Stress [MPa]	Crack Growth Equation $d(2s)/dN = C(2s)^n$ C	n
14	200	0	9.13E-06	1.03
14	200	100	1.40E-05	0.61
12	200	200	1.01E-05	0.56

Table 2: Testing conditions and crack growth equations for reversed bending with steady torsion.

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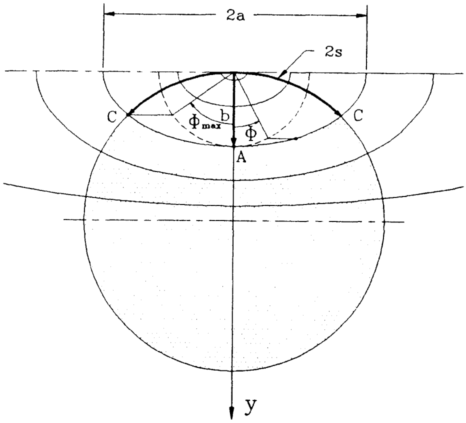
Results show that the superimposed static mode III loading to a crack growing in cyclic mode I, leads to a significant fatigue crack growth retardation. So the crack growth rates decrease with increasing mode III load for cyclic mode I (ΔK_I)+ static Mode III (K_{III}) loading.

The shape of the final crack was obtained after final fracture of specimens by measuring the crack length and depth. It was found that the crack depth b of semi-elliptical cracks related with the arc crack length 2s does agree with the equation already found in experimental tests by Freitas & François[8] for pure rotating bending, Fig.4:



$$b = \frac{2s}{\pi} \qquad (1)$$

b→ radial crack depth

2s→ total arc crack length

Figure 4: Semi-elliptical crack shape

In reversed bending the crack tip shape of semi-elliptical crack leads a rotation due different crack growth rates in opposite directions with increasing steady torsion similar to the rotating bending situation. So the same behavior of crack shape is observed with the same direction of the torsion moment.

Scanning electron microscopy revealed several distinct morphologies similar to rotating bending tests. In pure Mode I the surfaces were microscopically flat. With superimposed Mode III, striations on cracks surfaces can be observed and a evidence of severe rubbing, abrasion and fretting were found. Wear like debris emerged from the crack opening.

Fatigue crack growth properties of metallic materials are significantly influenced by crack closure effects. This mechanism reduces the effective cyclic stress intensity ranges at the crack tip. It has been suggested that crack closure due to contact between such ridges on the opposing fracture surfaces may be the reason for the reduction in crack growth rates resulting from the application of a steady mode III load, e.g. Tshegg[3]. The magnitude of this reduction can depend on the crack length and the load level.

For both experimental tests a superimposed mode III, leads to a surface crack changes from flat crack surface to helical surface crack with an angle of inclination proportional to the steady torsion and $K_{III}/\Delta K_I$ ratio. In order to obtain the magnitude of this crack growth retardation, an analysis can be performed considering the ratios between crack growth rates:

$$f = \frac{d2s/dN(\Delta K_I + K_{III})}{d2s/dN(\Delta K_I)} \qquad (2)$$

Stress Intensity Factor equations, K, for semi-elliptical surface crack shape are known for tension and bending loadings. The same geometry in mode III loading is a problem of difficult resolution due to the complexity that involves a three dimension calculation, were analytical solutions are rare due to the need of approached solutions always based on numerical solutions.

The existence of striations and ridges led to difficulties in the ΔK_{eff} determination since crack closure depends on many variables as a result of the effect of steady torsion. More investigations are needed to obtain the accurate Stress Intensity Factors in mixed mode (I+III).

4 Fractography

Fig.5 shows the crack surfaces on two specimens: one tested in rotating bending and another one in reversed bending, both with torsion. Fatigue crack growth surfaces show the semi-elliptical crack growth in the beginning and the rotation of crack tip during fatigue test. The change of the brightness shows the helical crack surface due to the torsion effect.

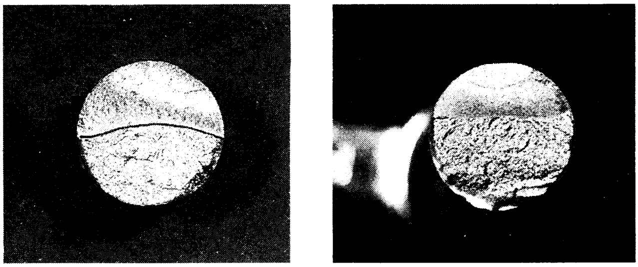


Figure 5: Fracture surface of two specimens: rotating and reversed bending with steady torsion.

5 Conclusions

Crack growth measurements under reversed bending conditions seem to be important for an experimental verification of life time calculations and risk assessments.

It was found that a superimposition of a constant torque (steady mode III) on the reversed bending (mode I) always gave rise to a very significant decreasing in crack propagation rate. Mode III loading induces a retardation on the crack growth behavior similar to rotating bending with steady torsion.

With the superimposed static mode III to cycle mode I the flat crack surfaces change to helical cracks surface depending on the stress torque.

Fatigue crack growth properties of metallic materials are significantly influenced by crack closure effects. This mechanism reduces the effective cyclic stress intensity ranges at the crack tip.

It has been suggested that crack closure due to contact between such ridges on the opposing fracture surfaces may be the reason for the reduction in crack growth rates and can be explained by the "crack closure effect", depending on the diameter, b and arc crack length 2s.

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The semi-elliptical crack shape in reversed bending is similar to the rotating bending.

References

1. Yates, J. R. & Miller, K.J., "Mixed Mode (I+III) Fatigue Thresholds in a Forging Steel", *Fatigue Fract. Engng. Materials and Structures,* Vol. 12 No. 3, pp. 259-270, 1989.

2. Hourlier, F., d'Hondt, H., Truchon, M. & Pineau, *A.*, "Fatigue Crack Path Behavior Under Polymodal Fatigue", *Multiaxial Fatigue, ASTM STP 853,* K. J. Miller and M. W. Brown, Eds., pp. 228-248, 1985.

3. Ritchie, R. O., McClintock, F. A., Tschegg, E. K., & Nayeb-Hashemi, H., "Mode III Fatigue Crack Growth Under Combined Torsional and Axial Loading", *Multiaxial Fatigue, ASTM STP 853,* K. J. Miller and M. W. Brown, Eds., pp. 203-227, 1985.

4. Akhurst, K. N., Lindley, T. C. & Nix, K. J., "The effect of mode III loading on fatigue crack growth in a rotating shaft", *Fatigue of Eng. Materials and Structures*, Vol. 6, No.4, pp. 345-348, 1983.

5. Pook, L. P., "Comments on Fatigue Crack Growth Under Mixed Modes I and III and Pure Mode III Loading", *Multiaxial Fatigue, ASTM STP 853*, K. J. Miller and M.W. Brown, Eds., pp. 259-263, 1985.

6. Tschegg, E. K., Stanzl, S. E., Mayer, H. R. & Czegley, M., "Crack Face Iterations Near-Threshold Fatigue Crack Growth", *Fatigue Fract. Engng.. Mater. Struct.* Vol. 16, No. 1, pp. 71-83, 1992.

7. Freitas, M. M. and François, D., "Analysis of Fatigue Carck Growth in Rotary Bend Specimens and Railway Axles", *Fatigue Fract. Engng. Mater. Struct.*, K. J. Miller, Ed., Vol. 18, No. 2, pp. 171-178, 1995.

8. Shiratory, M. M., Miyoshi, T., Sakay, Y. & Zhang, G. R., *Analysis and Application of Influence Coefficients for Round Bar with a Semi-Elliptical Surface Crack*, in: Handbook of Stress Intensity Factors, Ed. Y. Murakami, Pergamon Press, Vol. II, pp. 659-665.

9. Fonte, M. A. & Freitas, M. M., Fatigue Crack Growth Under Rotating Bending and Steady Torsion/94 (ed. Societe Francese de Metallurgie et de Materiaux-SF2M), Vol. I, pp. 159-170, *Proceedings of 4th International Conference on Biaxial/Multiaxial Fatigue,* St Germain en Laye, France, 1994.