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Analysis of fatigue crack growth under cyclic mode II + static biaxial compression

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Abstract — Cracks initiated in gears by rolling contact fatigue are subjected to triaxial compression with cyclic shear. In order to determine the crack growth kinetics for such loading, cyclic shear tests with static biaxial compression were performed on bearing steel, and resulted in long cracks propagation in mode II, with many secondary branches which influences the crack growth rate. Simulations highlight the crack growth competition and the role of biaxial compression on the extensive coplanar growth observed experimentally.

Mots clefs — Mode II; compression; fatigue crack growth; DIC; friction; plasticity.

Introduction

Cracks initiated in rolling contact fatigue are mostly loaded in mode II and III, with static normal and parallel compression. Theoretical or numerical works on the influence of biaxial compression on the bifurcation of a closed crack loaded in mode II can be found in the literature [4-6]. However, these works, which consider static rather than cyclic mode II do not agree regarding the impact of compression on the crack path. They focus on crack kinking from the tip, while -as shown in this study- branches also develop from the crack flanks, and compete with the main crack, especially when compression is present. Besides, crack face friction is often taken into account using Coulomb's law, with a constant friction coefficient, which, as observed in the present work, captures neither its evolution during crack growth, nor the effects of normal compression on its value, through its effect on the degree of crack face oxidation. The purpose of this study is first, to provide an experimental methodology for shear mode fatigue crack growth tests under a static biaxial compression and second, to improve the understanding of mode II crack growth in conditions representative of RCF.

Test Method/Overview

16NCD13 or 58NCD13 bearing steel cruciform specimens with a central notch inclined by 45° with respect to the two loading axes were used to apply cyclic mode II with superimposed static biaxial-compression. The shear stress range, as well as the static compression were varied. The positions of the crack tips was determined by direct optical observation on one side of the specimen (figure 1), and digital image correlation (DIC) on the other side. For that purpose, an approach based on the evolution of the standard deviation of the displacement gradient along a potential crack path [3] was used.

To determine the effective mode II stress intensity factor, the classical method based on a comparison of measured displacement fields with those predicted by Williams' series expansion could not be used, because the assumption of stress-free crack faces is not valid in these tests. An inverse numerical method, based on the measured crack face sliding displacement profiles, and taking into account crack-tip plasticity, as well as the contact and friction stresses along the crack [1] was thus used. This method also allows the determination of an apparent friction coefficient.

Results/Discussion

Depending on the amplitude of the cyclic shear and the magnitude of the static compression, coplanar crack growth or bifurcation was observed (figure 1). The fracture surfaces exhibit wear marks, mated, and more or less oxidized areas, indicating an important friction between the crack lips. A significant increase of the apparent friction coefficient was observed during mode II crack growth under constant shear stress range (from 0.08 to 0.56 within a few millimeter), and attributed to an evolution of the degree of crack face oxidation. Normal compression was observed to hinder oxygen access into the closed crack, and thus to modify crack face oxidation and friction (figure 3). Finally, the crack growth rates measured under different loading conditions were successfully correlated with the effective stress intensity factor, and a Paris law for mode II crack growth kinetics was identified, and compared to the mode I kinetics (figure 2).

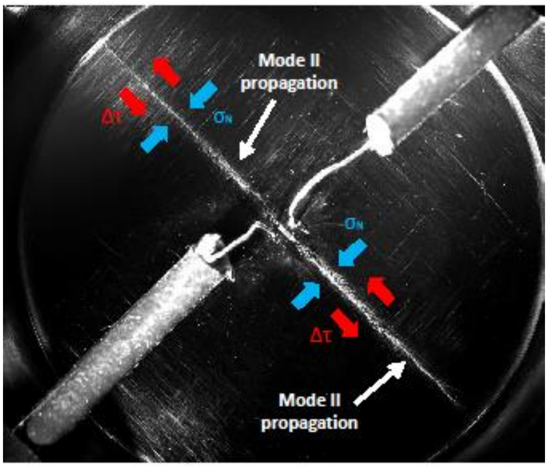

Figure 1 - Crack growth propagation in mode II

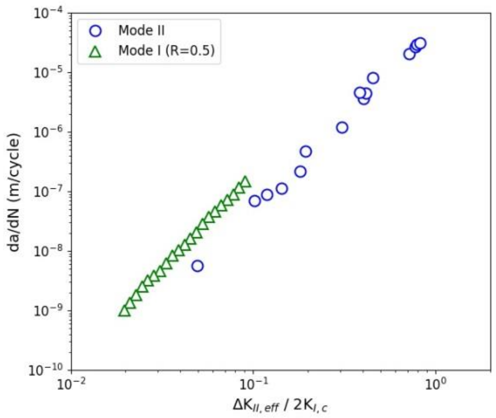

Figure 2 - Mode I and mode II kinetics (16NCD13 steel)

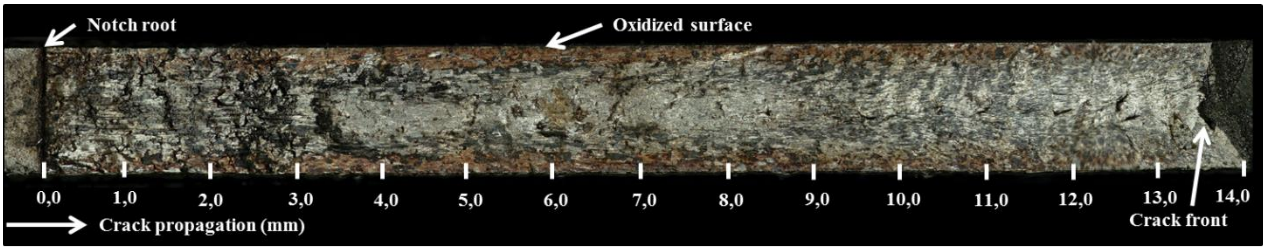

Figure 3- Fracture surface after shear mode crack propagation on 58NCD13 steel

Along the flanks of cracks propagated in mode II many arrested branches (figure 4), 20 to 500 mm long, inclined from 90° to 110° with respect to the main crack plane can be observed. Elastic finite element computations show that these branches are mostly loaded in mode I, and that their presence reduces $\Delta K_{II,eff}$ at the main crack tip, due to the shielding effects [2].

Figure 4 - Nearly-transverse secondary branches in mode II for 16NCD13 steel

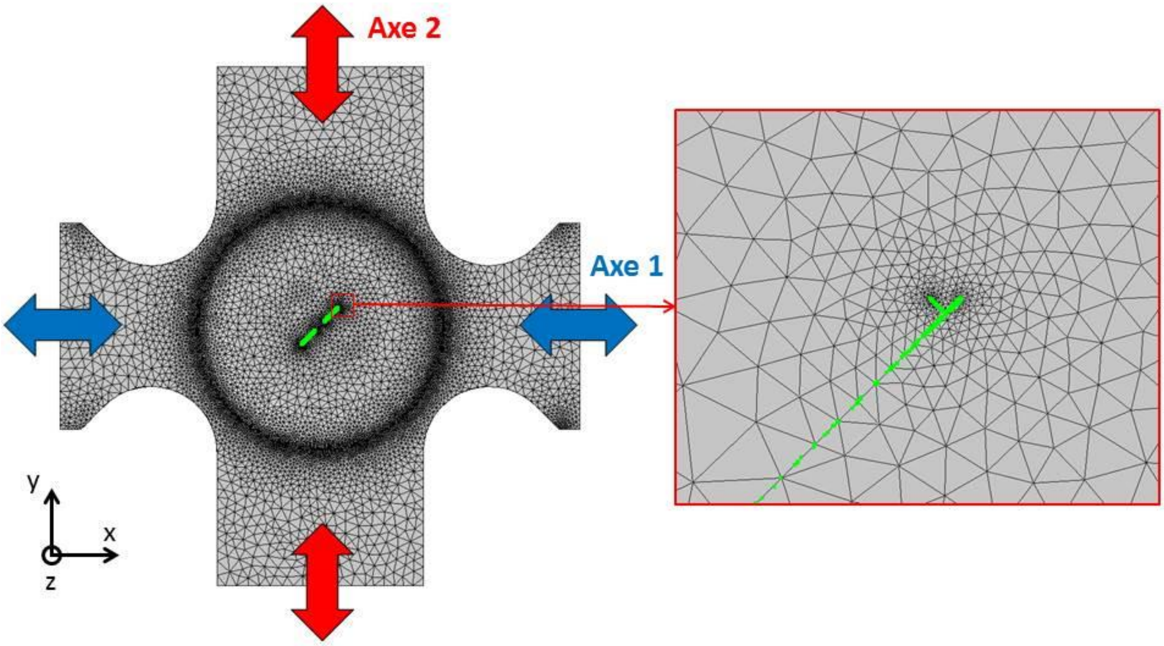

Figure 5 - Mesh of the cruciform specimen with the main crack and the secondary branch

In order to explain the coplanar propagation of the main crack, an iterative finite element model (figure 5) based on the integration of the mode I and mode II kinetics, was developed to simulate this crack growth competition. For the simulated loading conditions, after some propagation, the effective ΔK_{II} of the main crack increased, due to the decreasing shielding effect of the secondary branch left behind, while the mode I driving-force of the secondary branch decreased as the singular stress field of the main crack moved away. The reduction by the compressive T stress, parallel to the main crack of the opening displacement of the secondary branches is found to play a central role in the competition between continued mode II crack growth and crack branching.

Conclusion

Extensive mode II fatigue crack growth was obtained in bearing steels when biaxial static compression was superimposed to fully reversed cyclic shear. A friction-corrected kinetic law for such propagation was obtained. Crack face friction appeared to vary during mode II propagation, in close connection with the varying degree of crack face oxidation. Normal compression restricts the access of oxygen to contacting surfaces, thus favoring adhesive rather than abrasive wear, and probably increasing the friction coefficient. Mode II propagation is associated with the formation, along the crack flanks, of many nearly-transverse branches, mostly loaded in mode I, which have a shielding effect on the main crack, as long as they are close enough to its tip. For some of the applied loading conditions (large shear stress range plus large biaxial compression), the compression parallel to the main crack reduced ΔK_I on the branches, and did not allow them to propagate at the expense of the main crack. Even though the normal compression reduced $\Delta K_{II,eff}$, the main crack grew fast in mode II, thanks to the important shear stress range.

Références

[1] T. Bonniot, V. Doquet, S.H. Mai. Determination of effective stress intensity factors under mixed-mode from digital image correlation fields in presence of contact stresses and plasticity, Strain, 56, 2020.

[2] V. Doquet, J. Frelat. Branch crack development from the flank of a fatigue crack propagating in mode II. Fatigue Fract. Engng Mater. Struct. 24, page207-page214, 2000.

[3] S. Feld-Payet, G. Le Besnerais, V. Bonnand, D. Pacou, L. Thiercelin. Crack path tracking from full field measurements: A novel empirical methodology, Strain 56, 2020.

[4] Leblond JB, Frelat J. Crack kinking from an initially closed crack. Int J Solids Struct 37, page1595–page1614, 2000.

[5] Li XF, Liu GL, Lee KY. Effects of T-stresses on fracture initiation for a closed crack in compression with frictional crack faces, Int J Fract 160, page19–page30, 2009.

[6] Melin S. When does a crack grow under mode II conditions? Int J Fract 30, page103-page114, 1986.