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Fatigue crack shielding and deflection in plain bearings under large-scale yielding

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ABSTRACT

Multi-layered bearing systems used in the automotive industry show shielding and anti-shielding effects that reduce or amplify the crack driving force under large-scale yielding conditions. Using finite element analysis, it is shown that shielding in such systems results in path deflection and bifurcation despite the absence of mixed-mode loading. As the crack approaches a stiff layer, the tangential strains measured around a blunted crack tip model show a maximum corresponding to the direction of crack propagation. The distribution of such strains indicates the effect of shielding and the likelihood of the tip to deflect or bifurcate. The suitability of bi-layer and tri-layer bearing architectures is assessed through crack path and respective crack driving force predictions.

1. Introduction

Fracture and fatigue failure has been extensively studied within both academic and industrial environments due the cost involved in rectifying service failures, production of spare parts, service intervals and lead times. New materials and design processes have supported the introduction of more demanding service conditions. This trend is evident in the automotive industry where power efficiency and component packaging drive the requirement for smaller, more lightweight and durable components. The design of plain bearings is one case in point, due to their importance in the powertrain system and their strategic position within the engine. In machine design, more emphasis is usually given to heavier components such as connecting rods, pistons or shafts [1]. However, the bearing design process is complex and involves assessment of manufacture, assembly and service conditions. The analysis of bearings under such conditions is especially interesting and challenging since it relies on predictions of the hydrodynamic oil film pressure and the associated housing deformation. As shown in Fig. 1, the film pressure has steep gradients causing mixed-mode loading and, consequently, may lead to complex crack growth patterns in the lining.

Bearing performance has been enhanced through the use of multi-layered architectures and the development of lining materials with favorable mechanical properties. These multi-layered systems provide the required compromise between stiffness and tribological performance through a stiff backing layer and a conformable and low-friction lining. An additional attribute of multi-layered structures is the shielding effect that reduces the growth rate as cracks approach stiffer layers [2–5], thus increasing service life. The opposite effect is observed as a crack approaches a more compliant layer. Bifurcation events have also been observed in bi-layered architectures in compact specimens of plastically-mismatched materials [4], especially at high levels of loading.

Most of previous work concerns small scale yielding conditions (SSY) in elastically or plastically-mismatched materials, but not both. Crack growth in multi-layered architectures subjected to cyclic loading has been studied through an analytical

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model [3], which identified a further shielding effect arising from CTOD dropping as a result of crack closure since the reversed plasticity should not be affected by the layered architecture. Related numerical work based on predefined paths has been carried out using various techniques, such as cohesive elements [6], re-meshing [7] and configurational forces [8], to account for crack extension. Such techniques have been widely applied to cracked specimens of homogeneous and inhomogeneous materials subjected to monotonic loading. The study of crack growth under cyclic loading is often restricted to few or representative load cycles and involves greater theoretical challenges for inhomogeneous materials as explained by Groh et al. [9].

Flat strip specimens with a multi-layered composition identical to that of formed bearings have been tested under cyclic three-point bending conditions. This architecture consists of elastically and plastically-mismatched materials. Crack shielding has been shown to cause deflection and bifurcation in such specimens despite the absence of far-field mixed-mode loading [10,11], as shown in Fig. 2a. *J*-integral estimations based on finite element modeling of the three-point bending tests [10] reported a strong tendency for highly deflected bifurcated crack paths, corresponding to a sharply increasing *J*-integral, representing the crack driving force as the crack tip approaches a stiffer layer. This was in accordance with experimental results and explained in terms of the crack following the path that offers the least resistance or maximizes the CDF.

Crack path deflection has been extensively studied in brittle and ductile materials [12–14]; the prediction of crack deflection and bifurcation has been pursued due to the importance of such events in shaping the crack path and affecting the value of CDF. Detailed observation of tested components has identified coalesced cracks, as schematically shown in Fig. 1, that release lining fragments under bearing service conditions; similar behavior has been observed in flat strip specimens of the same architecture under simpler three-point bending tests [15]. It is assumed here that deflected or bifurcated crack paths may be responsible for such failure mechanisms [16,17].

Deflected crack growth under mode I-dominant, monotonic loading can be consistently simulated using various deflection criteria. Such applications to engineering problems have often used the criterion based on closed-form solutions for the maximum tangential stress around the crack tip [18]; this is obtained in the context of LEFM. However, no single approach to crack deflection prediction has been tested for optimum performance over a full range of mixed-mode loading.

The objective of this work is to explain further the shielding and bifurcation phenomena leading to fatigue failure in tri-layer material systems. The methodology is based on the evaluation of the crack tip opening displacement (CTOD), an alternative CDF parameter suitable to large-scale yielding (LSY) conditions. The crack path and respective CDF evolution is investigated for growing cracks in multi-layer flat strips with mismatched mechanical properties that are subjected to three-point bending causing extensive plasticity. The state of stress around the crack tip is studied to assess the conditions that promote crack deflection and bifurcation despite the absence of far-field mixed-mode loading. Thus, it becomes possible to assess the impact of multi-layered architectures on crack growth under LSY, which also occurs in plain bearings under service conditions. The focus of the numerical investigation is tri-layer architectures in order to assess the influence of a compliant interlayer, which is found in some plain bearing designs as it provides a protective deposition layer for the steel and improves the bonding between layers. An equivalent bi-layer system is also analyzed for comparison purposes.

2. Methodology

The first part of this numerical investigation is concerned with straight cracks of variable length in a tri-layer system in order to assess the combined effect of anti-shielding and shielding. Bi-layer architecture is also analyzed for comparison with a pure shielding case at this stage. For each assumed crack length, crack tip strains and CTOD are recorded for further assessment of possible deflection and shielding.

In the second part, crack growth along deflected and bifurcated paths is simulated to investigate the experimentally observed tendency of the cracks to grow parallel to the layers' orientation and the effect of crack deflection on CDF estimates. These simulations are based on an automatic crack extension routine based on the estimates of crack tip tangential strains (CTTS) so that the maximum tangential strain (MTSN) deflection criterion could be implemented using ANSYS Parametric Design Language (APDL) [19]. This routine extended the crack by small straight segments with gradually changing orienta-

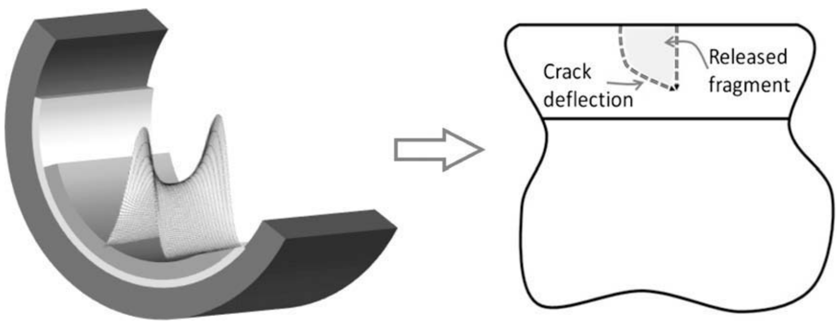

Fig. 1. Multi-layered plain bearing under hydrodynamic oil film pressure and possible fragment release caused by fatigue cracks.