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Microstructural simulations of the initiation and propagation of short fretting cracks in a Ti–6Al–4V contact

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ABSTRACT

Fretting–fatigue contact has been identified as a serious actor in damaging plane engines turbine discs. It has been the subject of many studies but remains partly misunderstood especially within the initiation and growth of short cracks in the Ti–6Al–4V microstructure. Although there is microstructural effect due to the existence of grain orientations and boundaries these cracking processes are generally not modelled. In this study, a two dimensional numerical model of fretting contact based on the finite elements method is developed to simulate and reproduce the crack growth within a real Ti–6Al–4V microstructure observed by Electron Back Scattered Diffraction. This model, using constitutive relations such as crystal plasticity, is able to assess the cracking speed corresponding to the crack growth crossing the very first grains. This study brings up a new scale in the fretting life time description taking into account a real Ti–6Al–4V complex metallic microstructure.

1. Introduction

In a fretting contact, the combination of a normal force and a tangential force may enforce a partial slip regime, which in turn may induce the initiation and the growth of cracks beneath the surface [1,2]. The first stage of crack formation is generally viewed as a sequence of two phases: the initiation stage and the micro-propagation stage. This work covers both phases but focuses on the second one.

Regarding fretting crack initiation, several multi-axial criteria have been used in the literature to predict the location and the number of fretting cycles, such as the Dang Van [3], the McDiarmid [4], the Crossland [5] and the Smith–Watson–Topper [6] formulations. Nevertheless, it is still difficult to establish which criterion is the most appropriate and recent work showed increased developments of microstructure-sensitive modelling to account for the local microstructure in crack initiation criteria [7–10].

In contrast, little data can be found about the very first stages of fretting crack propagation and the effect of the polycrystalline microstructure. In the very first grains of the metallic microstructure, the cracks are qualified as short cracks [11,12], and microstructural effects due to crystallography, grain orientations and grain boundaries may affect significantly their growth. Fatigue models were first developed to predict the propagation of short cracks involving the dislocation density and Burger's vector [13–15]. It was highlighted that the use of the stress intensity factors is inappropriate in the micro-propagation regime (Stage I) which does not respect the Paris law. Thus, the crack tip opening and sliding displacements were introduced to evaluate the crack growth speed [16–19]. More than in fatigue, crack propagation mechanisms under fretting remain misunderstood due to the additional contact mechanics involved which results in a complex situation. Several models exist to describe the initiation and the micro-propagation of a fretting crack [20–22]. However, they are not able to capture the effect of particular grain orientations and the presence of grain boundaries. Therefore, a methodology taking into account these phenomena seems desirable.

The calculations of polycrystalline aggregates are increasingly used to access local variables that control the initiation and the propagation of cracks [8,23]. In addition, recent progress with numerical methods allows an easier manipulation of cracks within finite element meshes through remeshing.

In this study, those elements are combined to model the propagation of a fretting crack through a polycrystalline microstructure. After determining the crack initiation location by applying the Crossland criterion, a crack is introduced explicitly within the microstructure mesh and can propagate thanks to remeshing routines.

This methodology was first discussed for a flat/punch Ti–6Al–4V contact with a Voronoï microstructure bringing a first assessment

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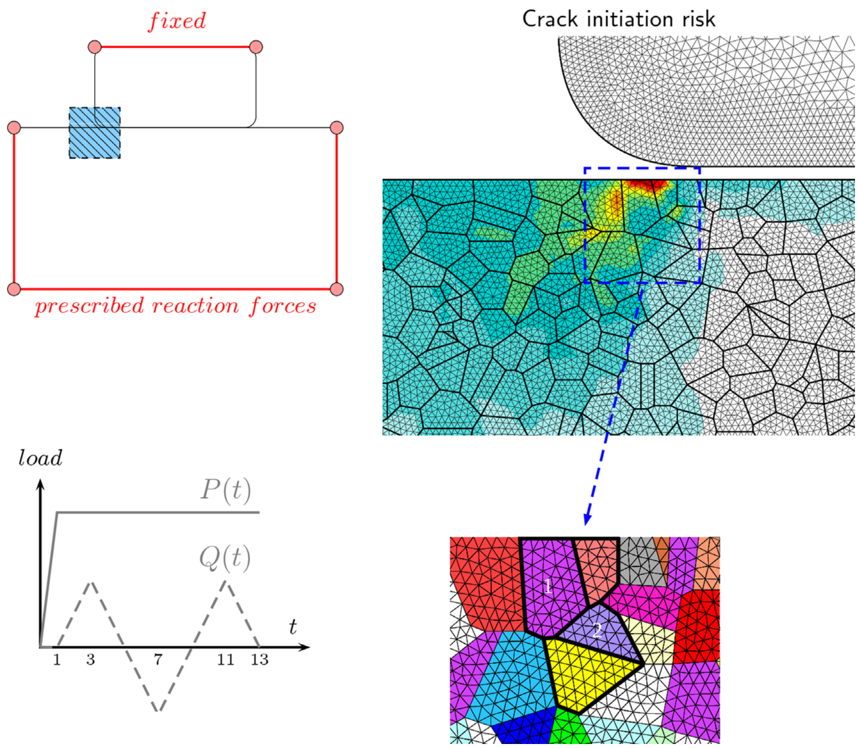

Fig. 1. Simulation of crack propagation in a flat/punch contact a Voronoï microstructure of the Ti–6Al–4V metal [24]: in the left the geometry is presented; in the right, the initiation position is located through the application of a multi-axial fatigue criterion.

about the method capabilities [24]. The present paper aims to detail the results obtained for a cylinder/flat fretting contact featuring a more realistic Ti–6Al–4V microstructure (real geometry, distribution and grain orientations) used in the simulations. For this, Electron Back Scattered Diffraction (EBSD) mappings are used as input to produce a mesh in order to account for the microstructure of the Ti–6Al–4V material in the simulations (Fig. 1).

2. Propagation model

The purpose of this model is to capture the effects of the microstructure on the propagation of short cracks. Starting from a flat/cylinder structure in a 2D plane strain conventional finite element configuration [25], a numerical process is carried out with the following aspects: the crystal plasticity constitutive behaviour, the determination of the cracking propagation direction in a grain, the orientation of slip planes and the calculation of the local speed of propagation.

The material studied is the Ti–6Al–4V titanium alloy for the disc/fan jet engine application. A classical crystal plasticity constitutive behaviour (not discussed in this paper) is used to describe the crystal plasticity with Meric–Cailletaud's viscoplastic model [26]. The identified material parameters are the same as those published previously [8].

2.1. Determination of the crack initiation location

Before studying the crack propagation in a fretting contact, it is important to determine the crack initiation location. In the literature, various multi-axial fatigue criteria exist to highlight the crack initiation position. As stated in the introduction, the choice of the initiation criterion is still under debate. In the presented methodology, it can be changed easily to another criterion. For example, a crystallographic criterion such as the direction of the slip plane showing the most plastic activity can be used. Such a criterion could be discussed in further work as it needs more experimental evidences. Here, for simplicity, we propose to use the Crossland criterion as described in [5,27] which is expressed by the following non-cracking condition:

$$\xi_a(t)+\alpha_C P_{h\ max} < \tau_d \tag{1}$$

where

$$\alpha_C=\frac{\tau_d-\sigma_d/\sqrt{3}}{\sigma_d/3} \tag{2}$$

with σ_d the alternating bending fatigue limit (MPa), τ_d the alternating shear fatigue limit (MPa) and $P_{h\ max}$ is the maximum hydrostatic pressure over the period T (one fretting cycle) defined by the relation

$$P_{h\ max}=\max_{t\in T}\frac{1}{3}\,\mathrm{tr}[\Sigma(t)] \tag{3}$$

with $\Sigma(t)$ the fretting stress path tensor and $\xi_a(t)$ the maximum amplitude of $\sqrt{J_2(t)}$, the square root of the stress deviator second invariant, over the fretting cycle.

A scalar variable d_C can be used to quantify the cracking risk. If $d_C \geq 1$ a crack is likely to appear. Otherwise, there is no risk of cracking. The Crossland scalar variable is expressed as follows:

$$d_C=\frac{\xi_a}{\tau_d-\alpha_C P_{h\ max}} \tag{4}$$

2.2. Determination of the propagation direction

2.2.1. Description of Ti–6Al–4V microstructure

In this study, the propagation model is applied to a realistic Ti–6Al–4V microstructure obtained by EBSD technology which is able to measure precisely the local crystalline orientation ($<0.5°$). A 500 μm^2 map using a 1.2 μm step was obtained on a carefully polished specimen using sand grid paper and electrolytic polishing. The complete Ti–6Al–4V microstructure as measured by EBSD