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On the application of a micromechanical small fatigue crack growth model to predict fretting fatigue life in AA7075-T6 under spherical contact

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ABSTRACT

This work presents a method for assessing the fretting fatigue life by estimating the fatigue crack growth rate from the regime of microcracks to the final failure, which is achieved using a two-threshold small fatigue crack growth model. The propagation thresholds are associated with the interaction of the "monotonic plastic zone" and the "cyclic plastic zone" with the microstructure of the material. The predicted fatigue life and the estimated non-propagating cracks agree very well with the experimental fretting fatigue tests with spherical contact in 7075-T6 aluminium alloy.

1. Introduction

The fretting fatigue failure process can basically be considered as nucleation and subsequent crack growth in a component by the action of cyclic bulk stresses combined with high local stresses due to the contact between two elements [1–4]. The high contact local stress field is usually characterised by a very high stress gradient, such that, depending on the contact geometry, the stress level may be reduced up to approximately 50% at distances on the order of the grain size, with an important scale effect associated with the initiation and small crack growth process [5,6]. The fatigue life assessment requires a suitable description of the small crack growth regime in these situations, which is highly affected by the stress gradient generated by the contact and by the variation of the asymmetry of the local stress cycles as the crack progresses in the material [7,8].

Recently, the authors have developed a micromechanical model for small fatigue crack growth analysis, which considers cracks ranging from the microstructural level (microstructurally small cracks) to the long crack regime [9,10]. This model has the novelty of considering two-threshold conditions for crack propagation based on the ability of the monotonic and cyclic plastic zones to overcome the successive microstructural barriers in the material. A fatigue crack growth rate that independently includes both the range and the maximum of the local tensions applied is finally obtained, according to the long crack description proposed by other authors [11,12]. The model can properly describe the oscillating pattern of the small cracks due to their interaction with the microstructure and the effect of the mean stress in the fatigue life. It can be applied to small fatigue crack problems under constant amplitude loading. Unlike some recent studies, such as those by McDowell and Dunne [13] and McCarthy et al. [14], which consider microstructure-sensitive fatigue models by using crystal plasticity, this microstructural model does not consider the inhomogeneity and anisotropy of the material at microscopic level in its present form.

The present work demonstrates the application of this model to the case of cracks initiated by fretting fatigue, in which a high stress gradient occurs at the initiation stage and a continuous variation of the local stress ratio, *R*, plays an important role. The predictions are compared with experimental results of spherical contact fretting fatigue tests on specimens of 7075-T6 Al alloy. According to the tests and the simulations results, the model successfully predicts the fatigue life of the specimen and the formation of non-propagating cracks.

2. Two-threshold micromechanical crack growth model

A detailed description and analysis of the two-threshold micromechanical model application can be found in [9,10]. Briefly,

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the crack propagation description relies on the assumption that fatigue cracks continuously interact with the microstructure of the material at the microscopic level and that this interaction mainly consists of successive and continuous blocking of its plastic zones at the microstructural barriers of the material.

The present model extends the original fatigue crack growth description given by Navarro and de los Rios [15–17] by assuming that both the monotonic plastic zone (MPZ) and the cyclic plastic zone (CPZ) may be blocked by the microstructural barriers. This assumption allows one to establish two independent threshold conditions for fatigue crack growth. It can be readily inferred that the MPZ-associated threshold condition will be controlled by the maximum applied load, whereas the CPZ-associated threshold condition will be determined by the applied load range or a certain effective load range.

The model applied here builds upon previous ideas and a few additional hypotheses that we summarise now for convenience:

1. Microstructural features in the material, such as grain boundaries, phase limits or inclusions, act as barriers against plastic slip and hinder the expansion of both the MPZ and the CPZ in front of the crack.
2. The expansion of the MPZ beyond a given barrier depends on its capability to produce plastic slip beyond the barrier, which in turn depends on the maximum applied load (e.g., σ_{max}, K_{max}).
3. The CPZ always expands within the MPZ, and its size depends on the applied load range (e.g., $\Delta\sigma$, ΔK, $\Delta\phi$, etc.). Microstructural barriers within the MPZ, previously overcome by the MPZ, also act as barriers for the CPZ. The ability of the CPZ to overcome such barriers depends on the applied load range (e.g., $\Delta\sigma$, ΔK, $\Delta\phi$, etc.).
4. No fatigue crack can propagate in the absence of a CPZ in its front because it is inside this zone where cyclic damage occurs.
5. Consequently, the crack growth rate, da/dN, should be a function of the range of the applied loads or their associated variables (e.g., $\Delta\sigma$, ΔK, $\Delta\phi$, etc.). Because the crack tip opening displacement range is more sensitive to the microstructure when the crack is small, it is assumed in this work that da/dN is a function of $\Delta\phi$.

It should be noticed that in fatigue microcrack growth, the MPZ threshold will be controlled not only by the maximum applied loads but also by the microstructure: barrier strength, slip planes orientation, microscopic stresses, number of grains crossed by the crack front, etc. This model is a simplification of the real case that assumes average values for the parameters affecting the crack growth at any time, neglecting their scatter. Regarding the CPZ, the same can be said, except that in this case the only driving forces are the stress ranges produced by cyclic loads, independently of the monotonic loads.

Briefly, let us assume a crack with length of $2a$ crossing a certain number of grains of a polycrystal when the maximum stress of a cycle, σ_{max}, is applied (Fig. 1a). Its MPZ is assumed to be blocked by a generic barrier, i. For simplicity, a constant grain size in the crack growth direction is assumed to be D, and only the grain boundaries act as barriers. The crack itself, its plastic zone and the zone of the grain boundaries are modelled using a continuous distribution of dislocations. In general, σ_1^i represents the opposition to the relative displacement of the crack faces, which is generally assumed to be negligible;σ_2^i, the so-called "friction stress", represents the opposition to plastic slip within the MPZ, i.e., the local yield stress at the MPZ, which extends from the crack tip to the barrier where it is blocked. Finally,σ_3^i represents the pressure supported by the microstructural barrier, where the dimension r_0^ican be neglected. The variablesn_1^i and n_2^i

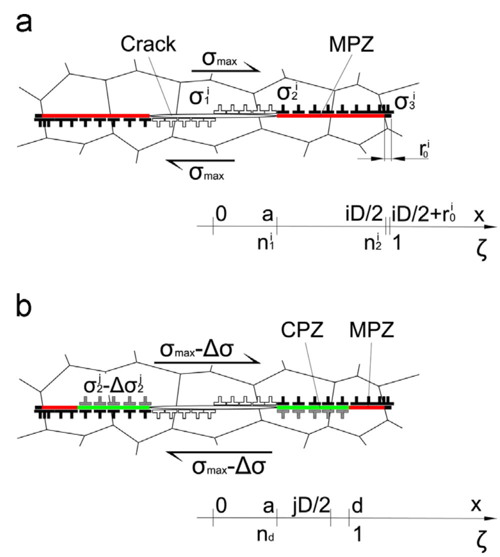

Fig. 1. Scheme of the crack, the plastic zones and the barrier at the maximum load for the MPZ blocked at a microstructural barrier (a) and, at the minimum load, where the CPZ is in equilibrium within a grain (b).(Schematic representation in Mode II).

represent the non-dimensional position of the crack tip and the barrier where the MPZ is blocked, $iD/2$, which is obtained by dividing these values by $(iD/2+r_0^i)$. A detailed description of the evolution of the MPZ and the crack tip opening displacement at the maximum of the loading cycle can be found in [9,10].

During unloading, a CPZ is generated at the front of the crack, within the MPZ. The size of the CPZ will depend on the decrement of the load, i.e.,$\Delta\sigma$ (Fig. 1b), which increases with the value of the decrement.

As in the previous case, the microstructural barriers will block the advance of the CPZ. Basically, two cases can be distinguished: (a) the CPZ is not blocked by a barrier (Fig. 1b), or (b) the CPZ has reached a generic barrier j ($j \le i$) and is blocked by that barrier. The non-dimensional length of the crack is defined as $n_d = a/d$ (Fig. 1b), where d is the position of the CPZ tip.

In the first case, the position of the tip of the CPZ,d, is obtained by imposing the equilibrium of the distribution of dislocations shown in Fig. 1b, yielding the following equation (see [10,18] for details):

$$\frac{\pi}{2}\Delta\sigma - \Delta\sigma_2^i \cos^{-1} n_d = 0 \quad \rightarrow \quad n_d = \frac{a}{d} = \cos\left(\frac{\pi}{2}\frac{\Delta\sigma}{\Delta\sigma_2^i}\right) \tag{1}$$

where$\Delta\sigma_2^i$ is the reversal local yield stress. Assuming a perfectly plastic material behaviour, the reversal local yield stress can be taken as twice the monotonic yield stress at the same barrier:$\Delta\sigma_2^i \approx 2\sigma_2^i$. In the second situation, the position of the CPZ coincides with a microstructural barrier, and it is represented by $d = j\ D/2$, and the non-dimensional crack length is given by

$$n_d = \frac{a}{j\,D/2} \tag{2}$$

Fig. 2 shows the evolution of the CPZ during the growth of the crack. Because the MPZ grows by jumps between barriers, the CPZ can be in different situations during its evolution within the MPZ. The CPZ can be growing within any one of the grains included in the MPZ. In addition, it can be blocked in a grain boundary within the MPZ or just in the same barrier where the MPZ is blocked. In this last case, the CPZ will not be able to continue growing until the MPZ does. All growth will depend on the stress state and the length of the crack, which will determine the magnitude of the