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A numerical description of short fatigue cracks interacting with grain boundaries

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Abstract

Short fatigue cracks typically propagate in stage I in which interaction with grain boundaries results in a fluctuating crack growth rate. Although there are established models, like the Bilby–Cotrell–Swinden theory and the Weertman model for crack growth and the model of Tanaka and Navarro and De Los Rios for their interaction with grain boundaries, a quantitative description of fatigue resistance is lacking. A unique technique combining focused ion beam based artificial crack initiation and three-dimensional tomography was used to separate the different influences of crack parameters and grain boundary parameters. The mechanisms which determine the strength of a grain boundary against crack propagation were thereby identified. Finally, it is shown how the models mentioned above can be easily used to calculate crack propagation through a grain boundary from single-crystal data and the orientation of the neighbouring grains only. This gives a promising perspective to improve fatigue life prediction and fatigue resistance of cyclically loaded materials.

Keywords: Short fatigue crack growth; Bilby–Cotrell–Swinden model; Grain boundaries; Microstructural crack propagation; Focused ion beam tomography

1. Introduction

Under fatigue conditions crack growth generally starts with short fatigue cracks in stage I, which indicates propagation on a single crystallographic slip plane. In most cases this is the slip plane with the highest Schmid factor. The cracks grow by the emission of dislocations on this slip plane in front of the crack tip (Fig. 1). A model describing the extent of the plastic zone formed by these dislocations was given by Bilby et al. [1], Weertman [2] and Tanaka et al. [3], based on continuously distributed dislocations. Integrating the number of dislocations emitted in the plastic zone the plastic crack tip sliding displacement $\Delta CTSD_{pl}$ is given by:

$$\Delta CTSD_{pl} = \left(\frac{4\tau^* a}{\pi^2 A}\right) \ln\left(\frac{c}{a}\right), \quad A = \frac{G}{2\pi(1-v)} \tag{1}$$

where G is the shear modulus and v is the Poisson ratio. The crack length from crack tip to crack tip is given by $2a$, while $2c$ is the crack length including the plastic zones, as shown in Fig. 1. Besides the common material parameters G and v, τ^* is the only more or less sophisticated material parameter. It is the friction shear stress necessary to move a dislocation on the active slip plane for crack propagation. In fact, the Bilby–Cotrell–Swindon (BCS) model describes the relation between c, a and $CTSD$ for a static crack, but the model can also be used for fatigue cracks under cyclic loading by considering reversed loading [4].

Since the crack growth rate depends on the plastic crack tip sliding displacement [5], the ratio of crack length to plastic zone size defines the crack growth rate in the model.

This model can be used as long as a crack propagates completely inside one grain and the emitted dislocations are not blocked by microstructural barriers, as is the case for large grains and single crystals. However, when the tip of the plastic zone comes into contact with a grain boundary generally the dislocations cannot readily cross

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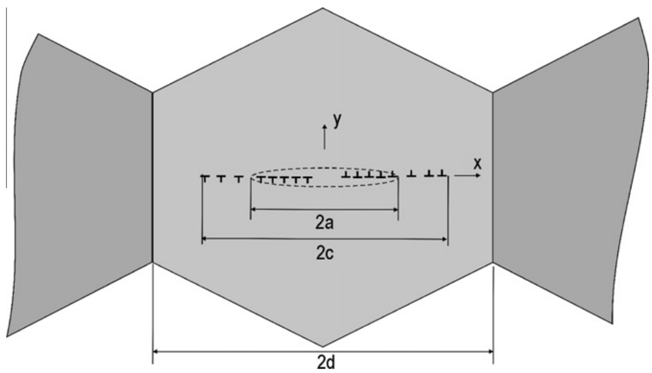

Fig. 1. BCS model for crack propagation in stage I inside a single grain.

the boundary and propagate in the neighbouring grain. This behaviour has been qualitatively described by Zhang and Edwards [6,7] and quantitatively in the model of Tanaka et al. [3] and Navarro and De Los Rios [8]. The models are based on the observation that short cracks in the neighbouring grain also propagate crystallographically as long as they are microstructurally short. Cracks which are of the order of several times the grain size show a transition to long crack behaviour, i.e. without an obvious microstructural influence. However, the strongest influence of grain boundaries on crack growth was found when cracks interact with the first grain boundary, resulting in a typically fluctuating crack propagation rate [9], which has been described qualitatively [10–13] but is hard to describe quantitatively. Thus this paper will focus on a quantitative description of the interaction.

1.1. Parameters of interaction

There are several parameters which determine the strength of the interaction between a crack and a grain boundary. They can be divided into crack parameters and grain boundary parameters. While the first describe the driving force of dislocation emission, the second should give a measure of the resistance of a grain boundary to crack propagation.

Let us begin with the crack parameters. They have a strong influence on the stress field at the crack tip and thereby on the driving force for dislocation emission and movement. The factors which are most important are the crack length and the distance to the grain boundary. It is obvious from the elastic and the elastic plastic fracture mechanics that longer cracks have a higher (cyclic) stress intensity factor at the crack tip, which is a common damage parameter. Although the stress intensity factor is no longer valid for short cracks the number of dislocations emitted from the crack tip and, so the length of the plastic zone, scale with crack length in the BCS model. Therefore, the driving force to cross a grain boundary should be higher for longer cracks. The second parameter, which is not independent of crack length, is the distance between the crack tip and the grain boundary. The influence of a boundary on crack growth rate can only be seen from the point when the stress field produced by the crack or its plastic zone come into contact with the grain boundary. Additional incompatibility stresses near the grain boundary due to possible elastic anisotropy are not taken into account here.

Now let us look at the grain boundary parameters. One grain boundary parameter is the orientation difference of adjacent grains and, due to this, the orientation differences in the potential slip systems. The second parameter which is often neglected in descriptions and models is the inclination angle between surface and grain boundary. So far most have models described grain boundaries perpendicular to the surface, which is generally not the case.

There are two different models which describe the resistance of a grain boundary to crack propagation. However, they include the grain boundary parameters in different ways. The first model is the BCS model, as used by Tanaka and further developed by Navarro and De Los Rios. In their description of crack propagation the resistance of a boundary is given by the orientation of the neighbouring grain and the potential slip planes in this grain, i.e. by the stress which is necessary to initiate yielding in the neighbouring grain. In the BCS model the friction stress τ^* to move dislocations on the preferred slip system is the factor which determines crack growth. Additionally, we assume that there is only one class of slip system ($\{1\,1\,1\}\langle 1\,1\,0\rangle$) active, as often observed for fcc crystals. This results in a constant friction stress τ^* for all slip systems of all the grains. The applied shear stress on the preferred slip plane in the neighbouring grain changes due to the orientation difference between the initial grain and neighbouring grain. This is introduced into the model and therefore Eq. (1) is modified as shown in Eq. (2):

$$\Delta CTSD_{\mathrm{pl}} = \left(\frac{4\tau^* a}{\pi^2 A}\right)\ln\left(\frac{c}{a}\right) + \left(\frac{2\tau_2^* - 2\tau^*}{\pi^2 A}\right) g(a;c,d)$$
$$g(a;c,d) = d\cdot\ln\left|\frac{\sqrt{c^2-d^2}+\sqrt{c^2-a^2}}{\sqrt{c^2-d^2}-\sqrt{c^2-a^2}}\right| - a\cdot\ln\left|\frac{a\sqrt{c^2-d^2}+d\sqrt{c^2-a^2}}{a\sqrt{c^2-d^2}-d\sqrt{c^2-a^2}}\right| \quad (2)$$

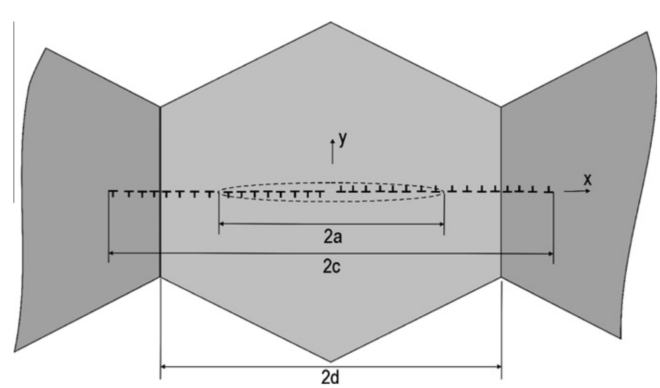

Fig. 2. BCS model for crack propagation in stage I when crossing grain boundaries.