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Experimental quantification of the plastic blunting process for stage II fatigue crack growth in one-phase metallic materials

P. Peralta [a,*], S.-H. Choi [a], J. Gee [b]

[a] *Department of Mechanical and Aerospace Engineering, Arizona State University, P.O. Box 876106, AZ 85287, USA*

[b] *Department of Radiology, University of Pennsylvania Medical Center, 3400 Spruce Street, Philadelphia, PA 19104, USA*

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Abstract

The plastic blunting process during stage II fatigue crack growth was studied in pure polycrystalline Ni to investigate effects of strain localization and inelastic behavior on the kinematics of crack advance. Correlations were obtained between strain fields ahead of a fatigue crack, crack advance per cycle and crack growth kinetics. Strain fields were quantified using a combination of *in situ* loading experiments, scanning electron microscopy and digital image correlation for $8 < \Delta K < 20$ MPa m$^{1/2}$ and a fixed load ratio of 0.1. Results indicate that strain localized along a dominant deformation band, which was usually crystallographic and carried mostly pure shear for large loads and was of mixed character for lower loads. Instances of double deformation bands were observed, with bands acting either in a simultaneous or alternating fashion. It was found that the area integral of the opening strain for values larger than a given threshold, an "integrated" strain, had a power-law relationship with ΔK, with the exponent approximately equal to the Paris exponent (m). Therefore, the crack growth rate was proportional to the integrated strain. An analysis based on this correlation and the presence of dominant shear bands indicated that the integrated strain is related to the accumulated displacement in the band. This, in turn, is proportional to the product of the cyclic plastic zone radius and the average shear strain ahead of the tip, which represents a basic length scale for plastic blunting. Assumptions on the load dependence of these quantities, based on their observed spatial variation, allowed estimating $m = 2\left(1 + \frac{1}{1+n'}\right)$, where n' is the cyclic hardening

* Corresponding author. Tel.: +1 480 965 2849; fax: +1 480 965 1384.
E-mail address: pperalta@asu.edu (P. Peralta).

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exponent ($0 < n' < 1$). This gives $3 < m < 4$, which accounts for about 50% of the observed values of m between 1.5 and 6 for a wide variety of metallic materials.

Keywords: Crack tip plasticity; Fatigue; Metallic material; Electron microscopy; Fracture mechanisms

1. Introduction

A complete understanding of fatigue crack propagation is important in the design and verification of metallic structures. Therefore, studies on the mechanisms of fatigue crack growth have been extensive and covered many materials (Suresh, 1998). These studies have shown that, under mode I loads, fatigue cracks propagate in two well-defined steps: stage I, where the crack grows along a crystallographic slip band and stage II, where the crack grows on a plane normal to the applied stress. A significant fraction of the life of structures can be spent propagating stage II cracks, so they have been studied closely. The research has shown, conclusively, that there is a close relationship between stage II crack advance and the plastic strain around the tip, e.g., (Neumann, 1974; Peralta and Laird, 1998; Suresh, 1998). Therefore, fatigue crack tips have been observed *in situ* in one-phase metallic materials including polycrystalline aluminum and nickel (Laird and Smith, 1962; Tomkins and Biggs, 1969), polycrystalline copper (Tanaka et al., 1984), monocrystalline copper (Neumann, 1974a; Vehoff and Neumann, 1979) and Fe–Si single crystals (Vehoff and Neumann, 1979; Gerberich et al., 1990), among others. This led to models of fatigue crack growth based on either ductility exhaustion or plastic blunting. In ductility exhaustion, fatigue cracks grow by damage accumulation ahead of a stationary tip until the material breaks. This is likely to play an important role in materials with planar slip character, where saturation is not achieved and plastic strain increases continuously with cycling (Hong and Laird, 1990; Li and Laird, 1994; Wang et al., 1999). In plastic blunting, fatigue crack growth takes place via the deformation process at the tip. This should dominate in materials with wavy slip behavior, since they present saturation of cyclic strains, which implies that crack tip deformation can be sustained in a mechanically reversible fashion (Laird, 1996).

Cyclic saturation combined with direct observations on geometrical changes at a crack tip during fatigue at high strain in ductile metals, caused (Laird, 1967) to offer a model whereby the creation of new fracture surface occurs by plastic lengthening of the material at a crack tip, due to two deformation bands pointing "forward". This is followed by re-sharpening of the tip in compression, hardly a fracture process in a strict sense. In single crystals with high symmetry orientations this is dominated by slip bands at the crack tip, acting either in a simultaneous (Laird, 1967) or alternating fashion (Neumann, 1974b), but the corresponding mechanisms in polycrystals, where the crack tip may be contained in a grain with arbitrary orientation, are not clear. Plastic blunting is accepted as one of the main mechanisms of fatigue crack growth in one-phase metallic materials (Suresh, 1998). Furthermore, recent finite element simulations (Tvergaard, 2004; Levkovitch et al., 2005) have shown that cracks can indeed grow via this mechanism and have been able to reproduce the geometry changes in the crack tip observed by Laird (1967). Therefore, one would expect that a relationship exists between crack advance, plastic blunting