A MICROMECHANICAL MODEL FOR FATIGUE CRACK INITIATION AT INCLUSIONS OF ARBITRARY SHAPE

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INTRODUCTION

The formation of an "engineering" size (e.g., 3-10 mm) fatigue crack has been conventionally represented by two distinguishable stages: initiation and propagation. In the initiation stage, the damage accumulation occurring on the scale of the crystal lattice, dislocations, grains and etc, originates the nuclei of the microstructurally small cracks (MSCs). The subsequent propagation stage is characterized by the growth of the mechanically small cracks. The growth of MSCs is very sensitive to local grain properties. As its size becomes greater than the critical length of MSC, the fatigue crack transits to the mechanically small crack, whose propagation exhibits little or no pertinence to microstructure. During the initiation stage, the MSCs grow along slip planes as shear cracks. This regime may frequently constitute a significant portion of the total fatigue life, especially in the case of low strain amplitude.

Historically, fatigue theory presented at the early stage was described using an S-N diagram, relating stress or strain (S) and cycles-to-failure (N). In practice, a number of major achievements (1-3) deploying the S-N fatigue tests have been successfully applied to engineering design. However, due to lack of the detailed microstructural information in these semi-phenomenological models, they are incapable of predicting the MSCs stage during the early evolution of fatigue cracks, and may thus lead to inadequate estimation. Moreover, since the final conditions of the fatigue cracks nucleation and early growth become the initial conditions for the standard fatigue tests, systematical investigation of the fatigue crack initiation from a micromechanical point of view integrated to the classical fatigue theory, facilitates the adaptability of both the experimental and theoretical explorations.

APPROACH

A large number of metallographic observations have indicated that the localized cyclic deformation in persistent slip bands (PSBs) is an important mechanism responsible for fatigue crack initiation in many materials. The cyclic strain is concentrated along the PSBs and the plastic deformation ratchets up under a cyclic loading. To explain this phenomenon, Mura and his collaborators (4, 5) modeled the forward and reverse plastic flow within the PSBs as dislocation pile-ups of different signs in two adjacent layers (Figure 1). The resulting governing equation may be represented in the following dimensionless form:

$$\frac{1}{\pi}\int_{-1}^{1}\frac{\varphi(t)}{t-x}dt+\int_{-1}^{1}K(x,t)\varphi(t)dt=f(x) \qquad [1]$$

where $\varphi(t)$ is the normalized dislocation density function along the slip plane, and $f(x)$ is related to the externally applied cyclic load and the intrinsic frictional resistance to dislocation motion. The effect of the image force due to discontinuity in material properties or geometry as caused by the free surface, inclusion, and etc, is described by the kernel term $K(x,t)$.

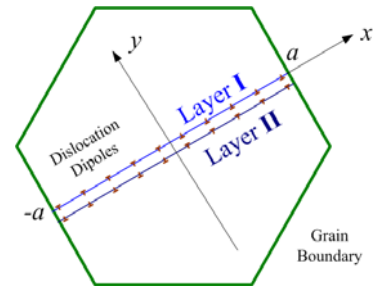

Figure 1 Mura's dislocation dipole model

For an infinite isotropic material, the kernel $K(x,t)$ vanishes, and the integral equation [1] can be solved in closed form (4). However, for the problems involving free surface or inclusion, the kernel is usually complicated in form and the equation [1] has to be solved numerically. Except for Tanaka and Mura's study (6) regarding circular inclusion subjected to anti-plane loading, there are few attempts to investigate the effect of inclusion on the nucleation of fatigue crack. In the present study, a numerical scheme based on the equivalent inclusion method (5) is employed to evaluate the kernel $K(x,t)$ for an inclusion of arbitrary shape, and the governing equation is solved numerically by a collocation method developed by Erdogan and Gupta (7).

RESULTS

The influences of the free surface and subsurface inclusions on fatigue crack initiation are examined. Comparative numerical studies are presented to illustrate the relevant mechanisms of two major fatigue crack nucleation patterns: (1) shear crack initiation at the surface, (2) subsurface crack initiation in the vicinity of cavities.

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