SHIELDING EFFECTS AND DISLOCATION REPOSITIONING AT CLEAVAGE CRACK GROWTH

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The motion of pre-existing edge dislocations in an infinite linear elastic body is studied. Motion is due to a quasi-statically steady-state growing crack. In the model, the dislocations glide if the force on the dislocation exceeds a critical value. Obtained results are changes in dislocation density, the shielding effect on the crack tip and residual stresses. The model is applied to an isotropic material. The residual stress far behind the crack tip is tensile near the crack, decreasing to zero at a certain distance above the crack plane. The indication is that the shielding effect may be considerable.

INTRODUCTION

During pure cleavage fracture, dislocation emission from the crack tip does not occur. Thus, fracture energies usually found to be much larger than the adhesive energy as measured by, e.g., Reimanis *et al.* (1) must be due to a mechanism different from shielding by emitted dislocations. Suo *et al.* (2) suggested that energy could be consumed at cleavage during motion of dislocations already present in the material. Here, the importance of pre-existing dislocations during cleavage fracture is investigated.

The proposed model describes a mode I crack, growing at quasi-static steady-state conditions. Dislocations are present in the virgin material. The growing crack is repositioning dislocations, thereby accomplishing a variable dislocation density in the wake behind the crack tip. The focus of interest is on the work required to displace the dislocations. The obtained results are changes in dislocation density, residual stresses and the crack tip shielding.

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There is little possibility for edge dislocations to climb since that requires diffusion of atoms. Therefore, all dislocations are assumed to remain in their glide planes. It has been observed that glide of edge dislocations is controlled by the shear stress in the glide plane of the dislocation. Thus, the dominating term of the Williams expansion (3) around a mode I crack tip is used, to evaluate the stresses near the crack tip.

The forces acting on a dislocation can be separated into a) a force (Peach-Koehler (4)) due to crack tip stress field, b) a dislocation-dislocation interaction and finally c) a self-image force due to the crack. It is assumed that the dislocation density is sufficiently low to make force b) negligible in comparison with force a). Furthermore, it is assumed that the dislocations are situated at sufficiently large distances from the crack to make force c) negligible in comparison with force a). The problem is thus reduced to calculation of the Peach-Koehler interaction between a mode I crack and single edge dislocations. In the present work randomly oriented dislocations are considered.

THE MODEL

Figure 1 defines the considered geometry. An edge dislocation is situated at $x_1 = r_d \cos\theta_d$ and $x_2 = r_d \sin\theta_d$, with its orientation given by the Burgers vector, b, forming an angle ψ to the x_1-axis (see Fig. 1). The linear elastic material is given by Young's modulus E and Poisson's ratio ν. Plane strain is assumed. The stress in the neighborhood of the crack is written as follows

$$\sigma_{ij} = \frac{K_{tip}}{\sqrt{2\pi r}} f_{ij}(\theta), \quad \text{as} \quad r/r_d \to \infty \tag{1}$$

where K_{tip} is the mode I stress intensity factor and the functions $f_{ij}(\theta)$ are well known (cf. (3)). The shear stress at the dislocation in the plane containing the x_3-axis and the Burgers vector is

$$\tau_\psi = \beta_{1i}\beta_{2j}\sigma_{ij} \quad , \tag{2}$$

where β_{ij} are the direction cosines for the angle Ψ.

The dislocation is assumed to move if $|\tau_\psi| \geq \tau_C$, where τ_C is a critical shear stress (cf. Courtney (5)). The shear stress, τ_ψ, may change as the crack tip is advancing, implying that the dislocation may reverse its direction of motion. When the dislocation is sufficiently far behind the crack tip, it is either at rest in a new position above the crack plane, or has been dragged to the crack surface and vanished.

For $\left|\tau_{\psi}\right| = \tau_C$, (1) and (2) give

$$r_d = \left(\beta_{1i}\,\beta_{2j} f_{ij}\right)^2 r^*, \tag{3}$$

where

$$r^* = \frac{1}{2\pi}\left(\frac{K_{tip}}{\tau_C}\right)^2. \tag{4}$$

ANALYSIS

A Monte Carlo simulation is performed to investigate how the crack and dislocations interact during crack growth. Dislocations are generated with random angles ψ and x_2-coordinates. The dislocations are then incrementally transferred in the direction of the negative x_1-axis. In each increment τ_{ψ} is calculated. If $|\tau_{\Psi}|$ is larger than or equal to the threshold value τ_C, the dislocation is displaced along its glide plane. The work rate W is calculated as $W = b\int \tau_{\Psi}\, ds$, where s is the distance covered by the dislocation. The calculations are continued until the dislocation comes to rest.

Crack tip shielding

The crack will reposition dislocations within the layer $|x_2| \leq r_p$, where r_p is a critical distance from the crack plane above which the crack is unable to move a dislocation (see Fig. 2).

The energy consumed by the dislocations per unit length of crack growth is W. Thus, the total energy rate G during crack growth can be expressed as

$$G = G_{tip} + W, \tag{5}$$

where G_{tip} and G are the crack tip and remote energy release rates, respectively (see Fig. 3). Here, W can be written

$$W = \alpha G_{tip}^2, \tag{6}$$

where α is given by

$$\alpha = \frac{\omega \rho_o \, b \, E^2}{(1-\nu^2)^2 \tau_C^3} . \tag{7}$$

Here, ρ_o is the dislocation density in the uncracked material and ω is a non-dimensional number that remains to be determined. The shielding, Ω, is defined by

$$\Omega = \frac{G}{G_{tip}} = \frac{2 \alpha G}{\sqrt{1+4 \alpha G} - 1} . \tag{8}$$

Residual stresses

Assume that the initial distance from a dislocation to the crack plane is x_2' and the final distance, far behind the crack tip, is x_2. Let the relation between these distances be given by

$$x_2 = g(x_2', \psi) . \tag{9}$$

Thus, the relation between the initial density, ρ_o, and the final density, ρ, is obtained as

$$\rho = \rho_o \left[\partial g / \partial x_2' \right]^{-1} . \tag{10}$$

The components, b_i, of the density of the Burgers vector is given by

$$b_i(x_2) = b \left\{ \int_0^{2\pi} \rho \, \beta_{1i} \, \mathrm{d}\psi \right\} \bigg/ \left\{ \int_0^{2\pi} \rho \, \mathrm{d}\psi \right\} . \tag{11}$$

The stresses in the wake far behind the crack tip are obtained as follows

$$\sigma_{11}(x_2) = \frac{E}{(1-\nu^2)} \int_{x_2}^{r_p} b_1 \rho \, \mathrm{d}s \tag{12}$$

and $\sigma_{22} = \sigma_{12} = 0$ throughout the wake layer (cf. Andersson and Ståhle (6)). Furthermore, $\sigma_{11} = \sigma_{22} = \sigma_{12} = 0$ for $|x_2| > r_p$.

RESULTS AND DISCUSSION

The relative density for dislocations is unchanged for $|x_2| > 0.25\, r^*$ (see Fig. 3). Thus, $r_p = 0.25r^*$. The crack has decreased the dislocation density in the region $|x_2| \le 0.2\, r^*$; the density is reduced to about 32% at $|x_2| = 0.08\, r^*$. In $0.2\, r^* < |x_2| \le r_p$. The dislocation density has acquired an increase varying from zero to almost 150%. The dislocation density close to the crack represents the dislocations that have been pushed to the crack and vanished. The peak is truncated in the Fig. 3, but was calculated to around 12, i.e. about 29%, of the total number of dislocations in the region $|x_2| \le r_p$ have been pushed to the crack.

The non-dimensional energy dissipation due to dislocation motion was found to be $\omega = 3.8 \times 10^{-3}$.

If 20 MPa $m^{1/2}$ is chosen for K_I, αG becomes equal to 0.4 if 10^8 m^{-2} (cf. Leslie (7)) is chosen for ρ. This gives an estimated shielding $\Omega = 1.31$, which corresponds to a K_{tip} that is about 90% of the remote K_I.

The residual stress σ_{11}, calculated according to (12), is displayed in Fig. 4. The maximum of σ_{11} occurs in the vicinity of the crack plane. With $\tau_C = 27.5$ MPa, $E = 276$ GPa, $b = 0.248$ nm, $\rho = 10^8$ m^{-2} and $K_I = 20$ MPa $m^{1/2}$, as for polycrystalline α-Fe, a residual stress $\sigma_{11} \approx 25$ MPa is obtained in the vicinity of the crack surface, far behind the crack tip.

CONCLUSIONS

A model for discrete dislocations is used to estimate changes in dislocation density, shielding effects on the crack tip and residual stresses due to pre-existing dislocations in the material.

The shielding effect of the crack tip due to pre-existing dislocations is found to be substantial. The results of the calculations, further show that the residual stresses are tensile near the crack, decreasing to zero further away from the crack plane. These stresses may be considerable for relevant material data.

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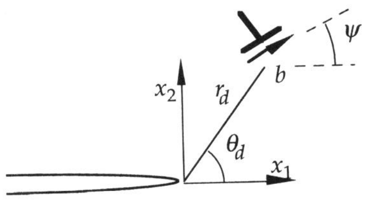

Figure 1 Edge dislocation with Burgers vector (b, Ψ) at (r_d, θ_d)

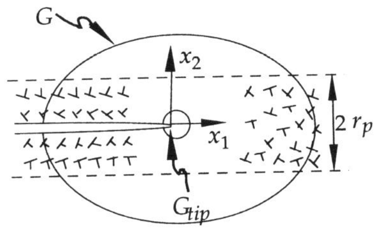

Figure 2 The growing crack affecting dislocations in $|x_2| \leq r_p$.

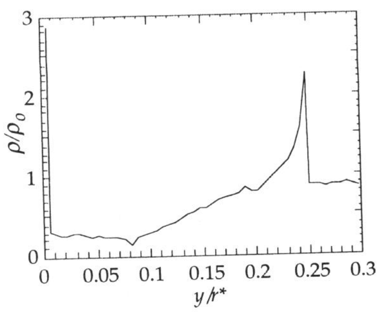

Figure 3 Dislocation density in the wake behind the crack tip

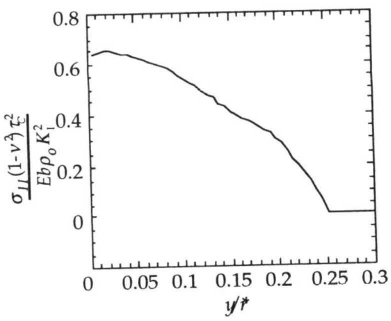

Figure 4 The only non-vanishing stress component σ_{11} in the wake