Emission of an Edge Dislocation from a Thin-Film-Covered Crack

C.-F. Qian, T.-Y. Zhang and P. Tong

Department of Mechanical Engineering, Hong Kong University of Science and Technology,
Clear Water Bay, Kowloon, Hong Kong

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ABSTRACT

The emission of an edge dislocation from a thin-film-covered crack is studied in order to investigate the effects of a passive film on stress-corrosion cracking. The results show that the crack stress field in the film due to the applied loads is enhanced by a harder film or abated by a softer film. For an edge dislocation in the film, both the slip component of the image force and the shielding effect are stronger when the film is harder. Under pure mode II or III loadings a harder thin film makes the dislocation emission easier and a softer film makes the dislocation emission more difficult if the film thickness is smaller than a critical value. The opposite is also true if the film thickness is larger than the critical value. Under pure mode I loadings, however, a harder thin film makes the dislocation emission more difficult and a softer film makes the dislocation emission easier for the two film thicknesses used in this study.

1. INTRODUCTION

Stress-corrosion cracking (SCC), which occurs under the resultant action of mechanical loads and corrosive environments, can cause catastrophic failures of engineering structures and components. Although all SCC failure is macroscopically brittle, localized plastic deformation has been observed at the crack tip, which means that the dislocation activities at the crack tip must be involved during SCC. In order to understand SCC, considerable research has been addressed [1-10] and many mechanisms have been proposed, including corrosion tunnel model, adsorption-enhanced plasticity, film-induced cleavage, adsorption-induced brittle fracture and hydrogen embrittlement [2,9]. Recently, Magnin summarized experimental evidences of corrosion-deformation interactions occurring during SCC [9].

During SCC especially for a metal/environment system, a formed film, which may be a passive layer, tarnish film, or dealloyed layer, is quite different from its substrate in chemical, structural and mechanical properties. Thus, Sieradzki [3], and Sieradzki and Newman [5,6] proposed a mechanism of film-induced cleavage for SCC based on dislocation-crack interactions. The dislocation emission from a crack tip may become difficult if a thin film with a thickness of several hundred nanometers is formed around the crack tip owing to an anodic process. Also, a thin ductile film may initiate cleavage if the interface between the film and the substrate is coherent and appropriate mismatch strains exist. The model of film-induced cleavage has successfully interpreted their experimental observations [3,5,6]. Zhang and Qian [7,8] modeled SCC with a thin-film-covered crack under anti-plane deformation and studied analytically the interaction between a screw dislocation and the thin-film-covered crack. Their results show that the crack stress field, the image force, the shielding and the dislocation emission from the thin-film-covered crack tip are all affected

by the film thickness and the film stiffness. Following the previous approach [7,8], we study the interaction of an edge dislocation with a thin-film-covered crack and report briefly the results here. Detailed derivation of formulas and analysis are reported in a separate paper [11].

2. ANALYSIS AND RESULTS

Fig. 1 Schematic illustration of a thin-film-covered Mode I + Mode II crack under remote applied loads.

In order to model a crack covered by a thin film, we assume that the film has an elliptical shape of $x_1^2/a^2 + x_2^2/h^2 = 1$. Inside the film there is a crack extending from $-c$ to c along the x_1 axis with $c^2 = a^2 - h^2$. The crack and the film are embedded in an infinite medium under remote applied loads $\sigma_{11}^\infty, \sigma_{22}^\infty$ or/and σ_{12}^∞ as shown in Fig. 1. The conformal mapping function $z = \omega(\zeta) = R(\zeta + m/\zeta)$, where $z = x_1 + ix_2$, $\zeta = \eta + i\xi$, $R = (a+h)/2$ and $m = (a-h)/(a+h)$, maps the ellipse in the z plane into a unit circle in the ζ plane, and the crack $(-c, c)$ in the z plane into a circle with a radius of $\sqrt{m}$ in the ζ plane. Thus, the problem in the z plane can be solved in the ζ plane using the conformal mapping function.

2.1. Stress fields due to applied loads

Using superposition the stress field due to applied loads, in either the film or the substrate, is divided into three parts. The first part is given by the solution for a crack-free elliptical inclusion embedded in an infinite medium under the remote applied loads. The second part is also analytic, obtained from Cauchy integration, satisfying partially the traction-free condition along the crack faces and the continuity of displacement and traction along the interface between the film and the substrate. The third part consists of series which are used as a supplement for the analytical parts to satisfy totally the boundary conditions. The effects of the ratio Γ of the film's shear modulus over the substrate's (i.e. $\Gamma = \mu^*/\mu$) and the film thickness, which is defined as the distance from the crack tip to the interface along the x_1 axis (i.e. $a-c$), on the stress field are investigated. For simplicity, Poisson ratios for both the film and the substrate are assumed to be 0.3 in this study.

Fig. 2 shows the normalized stresses in the crack line at $50b$ away from the crack tip as a function of the shear modulus ratio, Γ , where $b = \sqrt{b_1^2 + b_2^2}$ is the magnitude of the Burgers vector $\mathbf{b} = b_1 + ib_2$ of an edge dislocation, and b_1 and b_2 are, respectively, the components of the Burgers vector along the x_1 and x_2 axes. As shown in Fig. 2, increasing the shear modulus ratio enhances the stresses in the film. Under the condition of traction continuity, there is a jump in stresses, when crossing the interface. Fig. 3 shows σ_{22} distribution along the x_1 axis for two different ratios of shear moduli. It is clear that σ_{22} is discontinuous across the interface and the magnitude of the jump is a function of the ratio of shear moduli.

Fig. 2 The variation of the normalized stresses in the film at a point of 50 b away from the crack tip along the x_1 axis, with the shear modulus ratio Γ .

Fig. 3 Distribution of the normalized stress $\sigma_{22}/\sigma_{22}^0$ in front of the crack tip along the x_1 axis for $\Gamma=0.5$ and $\Gamma=2$.

Fig. 4 The normalized stress intensity factors as a function of film thickness for $\Gamma=0.5$ and $\Gamma=2$.

Fig. 5 The normalized stress intensity factors as a function of the shear modulus ratio Γ .

Fig. 4 shows the normalized stress intensity factors as a function of the film thickness $a-c$ for $\Gamma=0.5$ and $\Gamma=2$, where $K_I^0 = \sqrt{\pi c} \sigma_{22}^0$ and $K_{II}^0 = \sqrt{\pi c} \sigma_{12}^0$ are the nominal stress intensity factors without any film. As in the case for a thin-film-covered mode III crack [7], the normalized stress intensity factors decrease with increasing film thickness as long as the film is harder than the substrate, as shown in Fig. 4 for $\Gamma=2$. However, if the film is softer than the substrate, the normalized stress intensity factors increase with increasing film thickness, as shown also in Fig. 4 for $\Gamma=0.5$. It is also seen that the influence of the film thickness on the normalized stress intensity factors is stronger for mode II loading than that for mode I loading. Fig. 5 shows the normalized

stress intensity factors as a function of the ratio of shear moduli. Increasing Γ increases the normalized stress intensity factors and this influence on mode II is also stronger than that on mode I.

2.2. Image force and shielding effects of an edge dislocation in the film

The stress field induced by a dislocation near a finite crack is related to the dislocation source [12, 13]. For simplicity, this study considers only dislocations emitted from the crack tip. For the stress fields induced by an edge dislocation in the film, we divide the stress field in the film into three parts and the stress field in the substrate into two parts. The first part for the film is the solution of an edge dislocation around a finite crack embedded in an infinite medium [13]. The second part for the film is specially constructed to facilitate the following numerical calculation by canceling the singular (in the substrate) logarithm terms. The first part for the substrate is obtained by applying Cauchy integration to the interface conditions and collecting all analytical terms. The third part for the film and the second part for the substrate consist of series which are used as a supplement to satisfy the boundary conditions.

Fig. 6 The slip force on an edge dislocation in the slip plane at 70° as a function of the shear modulus ratio Γ .

Fig. 7 The mode I and Mode II stress intensity factors induced by an edge dislocation in the slip plane at 70° as a function of the shear modulus ratio Γ .

The force exerting on a dislocation is given by the Peach-Koehler formula and the image force of the dislocation can be calculated from the stress fields due to its images by letting $z = z_d$ ($\zeta = \zeta_d$). The image force has, in general, slip and climb components and only the slip component of the image force is discussed here. Fig. 6 shows the slip image force of an edge dislocation in the slip plane inclined at 70° to the crack plane and the distance between the right crack tip and the dislocation is $9b$. It is seen that the slip force is proportional to the ratio of shear moduli Γ .

The shielding (or anti-shielding) effect is gauged by the stress intensity factor induced by the dislocation. Fig. 7 shows the stress intensity factors induced by the same dislocation as the one discussed for the image force. As can be seen in Fig. 7, the stress intensity factors are also proportional to the ratio of shear moduli Γ , which means a harder (or softer) film leads to a stronger (or weaker) shielding effect.

2.3. Dislocation emission from the crack tip

Following the Rice-Thomson treatment [14, 15], the critical stress intensity factor for a two-dimensional dislocation emission is given by

$$K_{crit} = -\frac{\sqrt{2\pi r_0}}{b} f(r_0), \quad (1)$$

Fig. 8 The normalized critical stress intensity factor for an edge dislocation emission from the crack tip as a function of the shear modulus ratio Γ for some given slip planes and film thickness.

where r_0 is the radius of the dislocation core.

In this study we consider two cases for dislocation emission, dislocation emitted to the crack plane ($\theta = 0^\circ$) under a pure mode II loading and dislocation emitted into the slip plane inclined at 70° to the crack plane under a pure mode I loading. The critical stress intensity factors for dislocation emission are expressed in terms of the nominal stress intensity factors $K_{I,e}^0$ and $K_{II,e}^0$ and then normalized by the corresponding stress intensity factors at $\Gamma=1$. It is seen in Fig. 8 that under the mode I loading the normalized critical stress intensity factor increases with increases in the ratio of shear moduli for the given two film thicknesses and a crack length. Under the mode II loading, however, the normalized critical stress intensity factor increases and decreases with increases in the ratio of shear moduli for the film thickness $a-c=10$ (b) and 5 (b), respectively. The results for mode II loadings are similar to those for mode III

loadings [7]. Therefore, there must exist a critical thickness of the thin film at which the thin film has no influence on the dislocation emission under pure mode II or III loadings. Under pure mode II or III loadings a harder thin film makes the dislocation emission easier and a softer film makes the dislocation emission more difficult if the film thickness is smaller than the critical value. If the film thickness is larger than the critical value, a harder thin film makes the dislocation emission more difficult and a softer film makes the dislocation emission easier under pure mode II or III loadings. Under pure mode I loadings, however, a harder thin film makes the dislocation emission more difficult and a softer film makes the dislocation emission easier for the two thicknesses of the thin film used in this study.

3. CONCLUSIONS

This work studies the interaction of an edge dislocation with a thin-film-covered crack. The stress fields induced by the remote applied loads and by an edge dislocation in the film have been evaluated using a new hybrid method. The shielding effects, the image force and dislocation emission from the film-covered crack tip have been investigated. The following conclusions are drawn from the results:

1. The stress field in front of the crack tip due to the applied load is enhanced by a harder film or abated by a softer film.
2. The slip component of the image force on an edge dislocation in the film emitted from the crack tip is proportional to the ratio of the film's shear modulus over that of the substrate.
3. The shielding effect of an edge dislocation in the film on the local stress intensity factor is stronger when the film is harder, and the opposite is also true.
4. Under pure mode II or III loadings a harder thin film makes the dislocation emission easier and a softer film makes the dislocation emission more difficult if the film thickness is smaller than a critical value. The opposite is also true if the film thickness is larger than the critical value. Under pure mode I loadings, however, a harder thin film makes the dislocation emission more difficult and a softer film makes the dislocation emission easier for the two film thicknesses used in this study.

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