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Energy release rate for circular crack due to indentation in a brittle film on a ductile substrate

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ABSTRACT

A recent method by Steffensen et al. (2013) to estimate the fracture toughness of thin, hard films uses closed-form linear elastic fracture mechanical models for an edge crack in a semi-infinite plane to calculate the energy release rate for a circumferential crack propagating from the surface of the film. Also, in the proposed model the in-plane shear stress was neglected, and it was assumed that the crack propagates perpendicular to the surface. In this paper, the accuracy of the previously proposed method for calculating the energy release rate for axisymmetric circumferential crack during indentation is investigated. Also, neglecting the in-plane shear stress and the assumed direction of crack propagation are investigated.

The J-integral and the virtual crack closure technique are used to calculate the energy release rate on the basis of results from a large scale axisymmetric finite element model. Thereby, the proper geometry of the circumferential crack, plasticity in the substrate, material mismatch across the interface are included.

In general, it was found that the closed-form linear elastic fracture mechanics model is sufficient for the method.

1. Introduction

A method to enhance wear resistance of mechanical components is to deposit thin hard films. The films may be susceptible to failure due to brittle fracture and it is a hypothesis that the fracture toughness is linked to the wear resistance of the film. To understand and optimize the wear properties of the film, it is of paramount importance to know the mechanical properties such as the Young's modulus, hardness and fracture toughness.

Techniques and procedures for extracting mechanical properties such as hardness and modulus have been established and are widely used in the field of material testing using nano-indenters (Oliver and Pharr (1992)).

Fracture modes affecting thin films and coatings of various materials have been extensively studied using indentation, and generally three types of fracture have been observed; Radial cracks that initiate on the median planes, near-contact Hertzian cone fractures, and circumferential ring cracks that initiate well outside the contact (An et al. (1996); Chai et al. (1999); Chai and Lawn (2004); Fischer-Cripps et al. (1996); Lardner et al. (1997); Lee et al. (1998b, a); Lawn et al. (2000); Miranda et al. (2001); Pajares et al. (1996); Swain and Mencik (1994); Wuttiphan et al. (1996)).

Several experimental studies have shown that formation of radial and circumferential cracks occur during indentation and that fracture is traceable as a discontinuity in the indenter response (Hainsworth et al. (1998); Whitehead and Page (1992); Weppelmann and Swain (1996)).

Methods to calculate fracture toughness for the film during indentation, due to bending, and for micro-tensile testing have been suggested and recently, Zhang and Zhang (2012) have summarized most of these methods. The methods that can be used for circumferential cracks located at a distance away from the indenter have all been based on different estimates of the consumed energy from the discontinuity in the indenter response Li et al. (1997); Li and Bhushan (1998); Toonder et al. (2002); Michel et al. (2006); Chen and Bull (2009). Common for all of the methods are that they do not give any informations about the crack depth and, as a consequence, they all assume that the crack in the film runs all the way to the interface when it is initiated.

Wang et al. (1998) suggested a method for calculating the fracture toughness for circumferential cracks in the indentation crater based on linear fracture mechanical models. They found that the stress gradients in the film caused by bending can be neglected

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whenever the cracks propagate fully through the film and did not investigate the case where the cracks only propagate partially through the film. Also, they did not investigate circumferential cracks located outside the indenter crater as seen in experiments.

Recently, Steffensen et al. (2013) suggested a method for estimating the fracture toughness based on the first indenter-induced circumferential crack located outside the indenter crater in a thin, brittle film, without estimating the irreversible work of the indenter during fracture. The method, coupling nonlinear finite element calculations to solutions based on linear elastic fracture mechanics, is based on the stress in the uncracked film. Also, the method is independent of the length of the initial defects in the film and does not require assumptions on the depth of the crack when the crack stops propagating. Based on the stresses in the film, closed-form linear elastic fracture mechanical expressions are used to calculate the fracture toughness. Besides fracture toughness, the method gives the depth of the crack and informations on the length of the required initial defects in the film for the method to be accurate.

Steffensen et al. (2013) pointed out that the interface between the film and the substrate complicates the use of closed-form expressions to calculate the energy release rate for a plane strain crack due the elastic mismatch between the film and the substrate, E_f/E_s and plasticity in the substrate. The closed form expressions used do not take these effects into account but it was assumed in Steffensen et al. (2013) that the error introduced is negligible until the crack tip approaches the interface. Also, the closed-form expressions are derived for plane strain conditions which require that the radius of the circular crack is large compared to its depth. The purpose of this paper is to investigate the errors involved in these two approximations by use of numerical methods based on J-integral and the virtual crack closure technique to calculate the energy release rate.

2. Estimation of fracture toughness

The method for calculating fracture toughness by Steffensen et al. (2013) is in this paper presented in order to give an overview of the procedure. The method is for circumferential cracks located outside the indentation crater induced by a conical indenter. Fig. 1 shows a circumferential crack in a Al_2O_3 film with thickness 1.2 μm on stainless steel, taken with a scanning electron microscope (SEM). The circumferential crack and the permanent deformation from the indenter due to plastic deformation in the substrate is seen in the picture. The crack lies entirely in the film, and does not propagate all the way to the substrate.

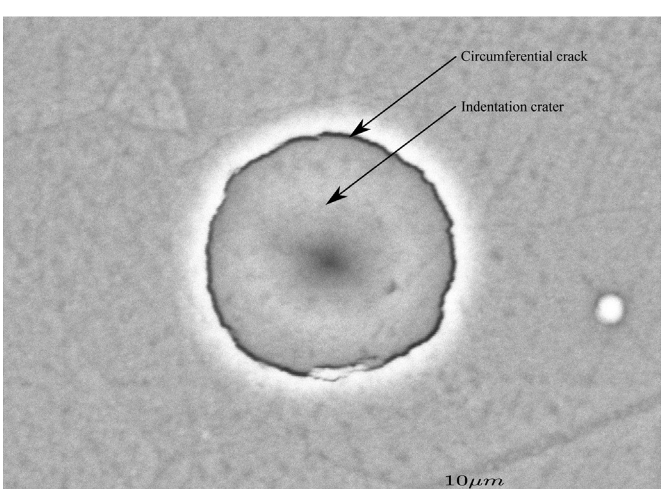

Fig. 1. Indenter-induced circumferential crack in an Al_2O_3 film.

For crack propagation to occur, the critical energy release rate of the material, the fracture toughness, Γ_f, must be reached. The energy release rate for a circumferential crack, G_{ps}, under model *I*, *II* and *III* loading is related to the stress intensity factors K_I, K_{II} and K_{III} assuming small scale yielding in the film at the crack tip. Due to axisymmetry of the indenter used, the mode *III* stress intensity factor, K_{III}, does not contribute to the energy release rate since the shear stress, $\sigma_{r\theta}$, is zero. See section (4) and in particular Fig. 7 where the coordinate system and key parameters have been defined. Thus, the relationship between the energy release rate, G_{ps}, and the stress intensity factors, K, is given by

$$G_{ps} = K_I^2\left(\frac{1-\nu^2}{E_f}\right) + K_{II}^2\left(\frac{1-\nu^2}{E_f}\right) \quad (1)$$

where E_f is Young's modulus of the film and ν is Poisson's ratio of the film.

Since the stress intensity factors depend on the stresses in the film, numerical simulations of indentation were used to calculate the stresses. The numerical model used in the work by Steffensen et al. (2013) is identical to the numerical model used in this paper except that no crack was present in the model used by Steffensen et al. (2013). Steffensen et al. (2013) showed that the only significant stress that contributes to the propagation of the circumferential crack is the radial stress, σ_{rr}, and argued that in-plane shear stress, σ_{rz}, can be neglected. Also, it was argued that the crack will propagate from the surface and it was shown that the radial stress, σ_{rr}, has a peak at a distance greater than the contact radius, R_i. Fig. 2a shows the radial stress, σ_{rr}, in the film at the surface plotted against the ratio r/R_i for various indentation depths, δ_i/t_f.

Fig. 2b shows the radial stress, σ_{rr}, in the film at the interface plotted against the ratio r/R_i for various indentation depths, δ_i/t_f. The radial stress in the film at the interface indicated that a radial stress gradient is present since the radial stress at the interface had a compressive peak at the same distance from the indenter as the tensile peak in the radial stress at the surface. Thus, the radial stress perpendicular through the film was investigated at the location where the radial stress at the surface is peaking. Fig. 3 shows the radial stress and the in-plane shear stress plotted against the ratio z/t_f, i.e. the distance through the film, for the indentation depth, δ_i/t_f=0.5.

The stresses through the film showed that the magnitude of the in-plane shear stress, σ_{rz}, compared to the radial stress, σ_{rr}, is of a size where it can be neglected without adding a significant error to the calculation of the fracture toughness, Γ_f. Thus, the circumferential crack is entirely dominated by mode *I* loading, i.e. the last term of Equation (1) was neglected.

Steffensen et al. (2013) used closed-form linear elastic fracture mechanical expressions to calculate the stress intensity factor, K, for an edge crack in a semi-infinite plane but pointed out that the interface between the film and the substrate complicates the calculation due to plasticity in the substrate and the elastic mismatch between the film and the substrate, E_f/E_s. The stress intensity factor, K, was then used to calculate the energy release rate for a plane strain crack, G_{ps} using Equation (1). The closed-form expressions used to calculate the stress intensity factor is given in section (3.1).

The energy release rate for the plane strain crack, G_{ps}, was not used to calculate the fracture toughness since the length of the initial defects were unknown. Instead, the energy release rate for a channeling crack, G_{ss}, was used. The circumferential crack will not