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Evaluation of the fracture toughness of brittle hardening materials by Vickers indentation

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ABSTRACT

We propose a Vickers indentation cracking-based method for evaluating the fracture toughness of brittle materials exhibiting strain hardening. The approach is an extension of the recent method by Hyun et al. (2015) for non-hardening materials to hardening materials. The hardening material is simplified by an equivalent non-hardening material with an elevated modified yield strain so that the fracture toughness of a hardening material can be evaluated with the formula proposed by Hyun et al. The proposed extension is verified by comparison with experimental results from nanoindentation tests on Ge(100) and Si(100).

1. Introduction

The fracture toughness K_c, which describes the resistance to crack growth, is an important parameter in the reliability assessment of structures. Traditional test methods for fracture toughness evaluation are well standardized, but specimen fabrication and testing are tedious and expensive. A fast, simple and inexpensive method with minimum specimen preparation, the sharp indentation test represents yet another potential way to evaluate the fracture toughness of brittle materials. Here, it is made use of the final length c of the cracks that have initiated at the surface (radial crack) or inside the material (median crack) and have grown to full size (radial-median crack or half-penny crack) during unloading, where it is driven by the increasing mismatch between the contracting outer elastic matrix and the inner, nearly rigid, plastic zone (Fig. 1). However the indentation-based method lacks in terms of accuracy due to an insufficient understanding of the complex relation between the crack and the simultaneously evolving stress field under the indenter, which depends on material properties, indentation load (or depth) and indenter shape.

To establish and improve the sharp indentation method, numerous studies were conducted in the late 1970s [1–3], culminating in the often-applied equation suggested by Lawn et al. [4], who provided a link between the stress field and the fracture mechanics side of the problem. Accordingly, the fracture toughness K_c was calculated from Young's modulus E, hardness H, the maximum indentation load $P_{\max}$, and crack length c (Fig. 1) as follows

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Nomenclature

a	impression half-diagonal
c	crack length measured on surface
E	Young's modulus
E_R	Young's modulus ratio (E/1000 GPa)
h	indentation depth
H	hardness
K_c	fracture toughness (mode I)
n	strain hardening coefficient
$P_{\max}$	maximum indentation load
α	correction factor
Γ	fracture energy
δ_c	crack-initiating separation
$\delta_{\max}$	damage-initiating separation
ε_o	(initial) yield strain
ε_{om}	modified (initial) yield strain
κ_h	correction factor (hardening material)
κ_{nh}	correction factor (non-hardening material)
ν	Poisson's ratio
$\sigma_{\max}$	damage-inducing stress threshold
σ_o	(initial) yield stress

$$K_c = \alpha\left(\frac{E}{H}\right)^{1/2}\left(\frac{P_{\max}}{c^{3/2}}\right) \tag{1}$$

The coefficient α was initially introduced to account for the indenter shape represented by the number of edges and indenter angle ψ. Fitting experimental data for diverse brittle materials, Anstis et al. [5] found $\alpha = 0.016 \pm 0.004$. Eq. (1) has been the basis of most subsequent studies on indentation cracking [6–9], and a number of modified formulations have emerged (e.g. [10–12]; see [13] for a detailed discussion). However, studies also revealed that Eq. (1) lacks accuracy due to an oversimplified stress field (for instance, the comparison of the sub-indenter stress field to a pressurized cavity means a neglect of the free specimen surface and associated pile-up/sink-in) and, as a consequence, application of Eq. (1) may lead to inaccurate K_c values.

Many attempts have been made since then to account for the influence of material properties and the indenter shape. Jang and Pharr [14] carried out indentation tests on single-crystalline Ge(100) and Si(100) using 3-sided pyramidal indenters of diverse angles ψ; based on the derivation of Eq. (1) outlined in [4] an attempt was made to include the influence of Poisson's ratio ν in the formulation. Lee et al. [15] simulated Vickers indentation cracking by using the cohesive zone model (CZM). Finite element (FE) results were in a good agreement with the experimental observations made by Lawn et al. [4]. Making use of the proportionality $P_{\max} \propto c^{3/2}$, Hyun et al. [16,17] recently extended the study and suggested a fracture toughness equation, which takes into account E, ν, yield strain ε_o, which replaces H, as well as ψ and the number of indenter edges. The material was assumed to be elastic-perfectly plastic and $\varepsilon_o = \sigma_o/E$ was estimated by varying σ_o until the hardness from FE

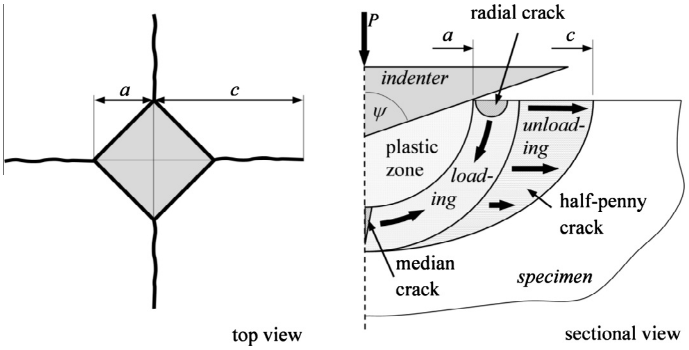

Fig. 1. Schematic figure of radial-median cracking under a quadrangular pyramidal indenter.