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Evaluation of indentation fracture toughness for brittle materials based on the cohesive zone finite element method

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ABSTRACT

We propose indentation fracture toughness evaluation methods based on finite element analysis adapting the cohesive zone model. Establishing an appropriate finite element model, we examine the effects of material properties on the size of the cracks formed by Vickers indentation, and then suggest a regression formula for the estimation of the fracture toughness. The formula is extended to other types of pyramidal indenters including variations of the indenter angle and the number of indenter edges. The suggested methods are examined by comparison of the experimental data, and the fracture toughness can be accurately estimated from pyramidal indentation data.

1. Introduction

In contrast to conventional fracture toughness evaluation methods, which require tedious preparation of the test specimens, the indentation test-based method does not require this kind of special specimen; instead, it can be directly applied to a part/structure with simple treatment of the surface. This huge advantage has led to numerous studies on evaluating the critical load corresponding to crack initiation or certain crack characteristics for Vickers, Berkovich, cube-corner, and other types of indenters. For brittle materials such as glass or ceramics, not only elastic–plastic deformation occurs during indentation due to stress concentrations beneath the indenter, but also various cracks can form around the impression. When using three- or four-sided pyramidal indenters, radial, median, semi-circular (half-penny) or lateral cracks can form independently and merge, depending on the material properties, the indenter geometry, and the indentation load. Based on these observations, numerous studies have been conducted to predict the fracture toughnesses of brittle materials from crack size, indentation load and/or other parameters [12,5,13,14,1,2,3,16,17,24,10,4,21,8]. The final goal of these studies is to find the fracture toughness similar to that obtained by conventional testing methods. However, indentation fracture toughnesses predicted by these formulas often exhibit quite a significant deviation from the fracture toughnesses of conventional methods, and therefore doubt remains regarding the reliability of the indentation cracking-based methods.

Before the 1950s, the cracks formed by indentation on brittle materials (to obtain hardness) were regarded as a disturbing phenomenon. Palmqvist [20] was the first performer who related the indentation crack length to the fracture toughness. He

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Nomenclature

a	impression half-diagonal
c	crack length
E	Young's modulus
H	hardness
h	indentation depth
K_c	fracture toughness
l	crack length
P	indentation load
α	correction factor
δ_c	crack-initiating separation
δ_{max}	damage-initiating separation
ε_o	yield strain
Γ	fracture energy
κ	correction factor
ν	Poisson's ratio
σ_o	yield strength
σ_{max}	damage-initiating stress
ψ	centerline-to-face angle

showed that the average length of the cracks emanating from the corners of the impression can be used to infer the fracture toughness. Later, Lawn et al. [14] and Anstis et al. [1] applied Hill [6] and established a formula for calculating the fracture toughness from the crack length, the maximum indentation load, the hardness and the Young's modulus. Lawn et al. [14] findings are based on the following two experimental observations: first, the deformation under the indenter satisfies geometrical self-similarity; second, for "well-developed" cracks, the indentation load P is proportional to $c^{3/2}$ where c is the crack length (Fig. 1). The full equation includes the Young's modulus E, the hardness H and the indenter angle ψ as follows:

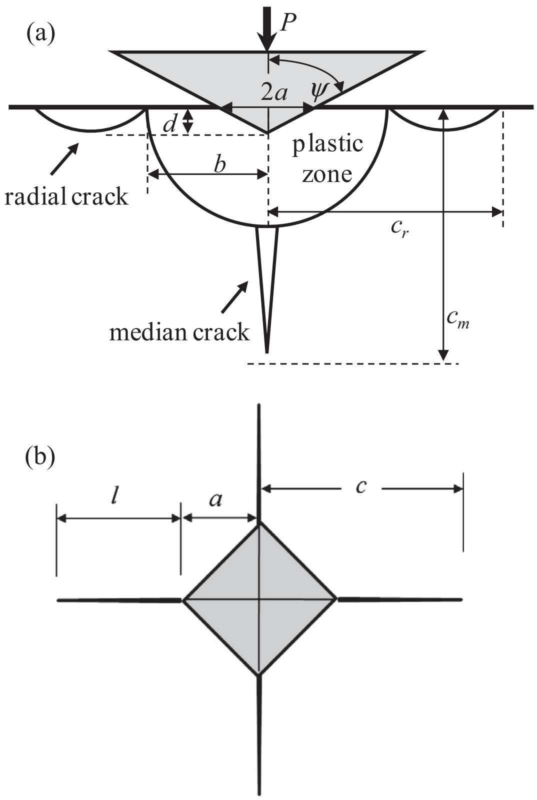

Fig. 1. Schematic of (a) the median and radial crack system and (b) the top view of Vickers indentation cracking geometry.