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Extended expanding cavity model for measurement of flow properties using instrumented spherical indentation

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ABSTRACT

We propose an extended expanding cavity model (ECM) in instrumented spherical indentation to evaluate flow properties measured in uniaxial mechanical testing. We describe the mean pressure of the projected surface from radial stress at the hemispherical core boundary with a scaling factor for strain-hardening metals. Plastic constraint factors determined by the strain-hardening exponent, yield strain and scaling factor successfully illustrate flow stress–strain points in uniaxial tension tests. We suggest a novel way to determine the strain-hardening exponent from the ratio of indentation loading slope, and a modified Meyer relation to measure yield strengths.

1. Introduction

Flow properties describing plasticity in uniaxial mechanical testing are indispensable in characterizing and predicting deformation and fracture. In conventional uniaxial tensile testing, standards or precise procedures for sample preparation and testing are required. However, tensile testing can be difficult or challenging when (1) destructive preparation of sample is infeasible and (2) testing is limited to local volumes such as a single grain in polycrystalline materials or weld regions with sharp mechanical-property gradients (Kim et al., 2006a; Shi et al., 2008; Yang et al., 2011). With these limitations on tensile testing, instrumented indentation testing (IIT) has been investigated as a tool to evaluate flow properties in tensile testing because of its simple and nondestructive sample preparation and testing (Dao et al., 2001; Herbert et al., 2001; Buclille et al., 2003; Anand and Ames, 2006; Kim et al., 2006a; Lee et al., 2005; Antunes et al., 2007; Gouldstone et al., 2007; Haj-Ali et al., 2008).

In the 1950s, Tabor (1951), on the basis of experiments on metals, suggested the following relations between flow stress and strain in uniaxial tension and parameters in spherical indentation:

$$\sigma_t = \frac{p_m}{\psi} = \frac{1}{\psi} \cdot \frac{L}{A}, \tag{1}$$

$$\varepsilon_t = 0.2\frac{a}{R}, \tag{2}$$

where σ_t and ε_t are flow stress and strain in uniaxial tension, p_m is mean indentation pressure, ψ is the plastic constraint factor (taken as 3 in Tabor's work), L is the indentation load, a and A are the contact radius and cross-sectional contact area

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of the indent and R is the radius of the spherical indenter. Since Tabor's work, extensive research has been carried out to investigate these relations. Ahn and Kwon (2001) modified the definition of flow strain to be average loading-directional shear strain beneath the indenter, and evaluated the plastic flow properties for power-law-hardening metals. Matthews (1980), Taljat et al. (1998), and Sundararajan and Tirupataiah (2006) have suggested that the plastic constraint factor in Eq. (1) is a function of the strain-hardening exponent in uniaxial tensile testing. Recently the investigation of flow stress and indentation mean pressure is extended to plastically strain graded materials (Gao, 2006; Gao et al., 2006; Shi et al., 2008; Branch et al., 2011a,b), metallic glasses (Fornell et al., 2009), and composite materials (Veprek-Heijman et al., 2009; Ma et al., 2012) and the indentation tests with wedge indenter (Kysar and Saito, 2011). These approaches are generally called representative stress–strain methods using instrumented indentations.

The representative stress–strain method is based on correlating mechanical responses in uniaxial tension and spherical indentation, and thus, understanding the stress field in spherical indentation is essential. To explain the stress field beneath spherical indenter, Johnson (1985) suggested the expanding cavity model (ECM), which applies Hill's spherical cavity model in contact mechanics to spherical indentation. Fig. 1 is a schematic diagram of the stress field in the ECM. Hydrostatic pressure is assumed to be applied to a hemispherical core corresponding to contact radius a, and the stress field in plastic region ranging from the contact radius a to plastic zone size c is explored. In the plastic zone, the ECM assumes perfect plasticity with no strain-hardening.

Although the ECM has been widely used to explain the stress field in spherical indentation, such simple assumptions as hydrostatic pressure in the hemispherical core and perfect plasticity in the plastic deformation region are likely to be unrealistic. Here we suggest an expanded ECM for describing the stress fields in spherical indentation, so that flow properties such as yield strength and strain-hardening exponent can be evaluated only by spherical IIT. In the expanded ECM, we take into account extra hardening at the core in Fig. 1, which yields good agreement between the flow stress in tension tests and representative stress–strain points in spherical IIT. We propose unique analytic models to measure flow properties, strain-hardening exponent and yield strength from the representative stress–strain points.

2. Experiments

We prepared 13 metallic alloys: aluminum alloys Al6061 and Al7075, carbon steels S45C, SK4, SKS3, SUJ2, API X100, stainless steels STS303F, STS316L, STS403, STS420J2, and titanium alloys Ti–6Al–4 V, and Ti–7Al–4Mo. Cylindrical tensile samples with gauge length 25 mm and diameter 6 mm were prepared according to ASTM E8-04 (2002). Uniaxial tensile tests were performed at crosshead speed 0.5 mm/min by Instron 5582 (Instron Inc., Grove City, PA, USA). For instrumented spherical indentation tests, cubic samples of side 5 mm were prepared and one side of the sample was polished with 1 μm alumina powder. IITs were carried out using AIS 3000 (Frontics Inc., Seoul, Korea) with a spherical indenter of radius 250 μm. Indentation depths were every 10 μm from 10 μm to 100 μm, loading and unloading rates were 1 mm/min, and we performed five repeatable tests for each point. To evaluate the mean pressure accurately, the cross-sectional contact area was measured from the residual impression. After each indentation test, the projected area as a cross-sectional contact area was measured by optical microscope (Kim et al., 2006b; Liu et al., 2008; Kang et al., 2012). An ultrasonic pulse–echo method was used to measure sample elastic moduli.

3. Theoretical models

Expanding cavity models (ECMs) have been developed to explain indentation responses of various materials (Marsh, 1964; Samuels, 1957; Mulhearn, 1959; Johnson, 1985; Shaw and DeSalvo, 1970; Yoffe, 1982) on the basis of Hill's solution

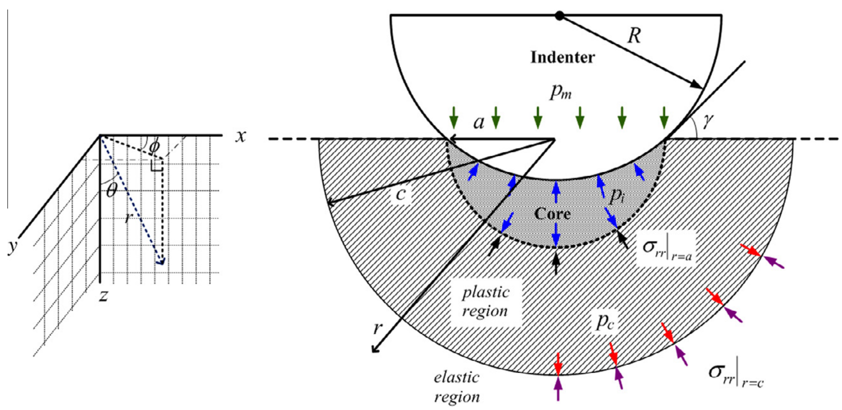

Fig. 1. Stress field in spherical indentation with the expanding cavity model (ECM) where x and y are surface plane directions and z is loading direction.