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Understanding indentation-induced elastic modulus degradation of ductile metallic materials

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ABSTRACT

Noticeable degradation of the measured elastic moduli of ductile metals has been found in meso-/macro-indentation tests. Although this phenomenon has been exploited to estimate the fracture properties of ductile metallic materials, the mechanism of the indentation-induced damage is rarely studied. Finite element simulations show that the finite stiffness of an indentation system can cause a false degradation of the effective indentation modulus. However, the decay pattern is different from that due to the indentation damage. Through theoretical analysis and experimental measurements, it is shown that the elasticity degradation can be mainly attributed to the anisotropic damage caused by the shear deformation in the indentation test.

1. Introduction

As a well-established technique, the instrumented indentation has found wide applications in characterizing the mechanical properties and investigating the mechanism of deformations of materials. Valuable information can be deduced from the indentation measurements performed on a relatively small surface in a non-destructive way, which constitutes an important advantage when dealing with highly radioactive specimens under in situ conditions [1–7]. When the indentation test is performed at the nano-scale, due to the possible effects of surface adhesion, surface friction or strain-gradient plasticity [8–10], the measured mechanical parameters such as the elastic modulus or the hardness, may change with the indentation depth. However, this indentation size effect becomes negligible when the indentation is beyond a certain depth (e.g., 1 μm) [8–10]. When the indentation test is performed at the meso- or the macro- scale, the indentation size effect is usually assumed to be negligible and the measured mechanical parameters should be insensitive to the large indentation depth. However, the micro-indentations of steels [11] (Fig. 1(a)), titanium alloys [12] and aluminum alloys [13–15] (Fig. 1(b)) show that the measured elastic moduli decrease exponentially with the indentation depth up to hundreds of micrometers and the magnitude of the degradation even reaches 40%. Considering the degradation of elastic moduli is a direct index to the damage of materials, investigations have been conducted to estimate the damage or even the fracture properties of ductile alloys from the measured elasticity degradation [11–15]. Since fracture toughness is one of the important life limiting parameters of structural components, the technique provides a very attractive measure to monitor the safety of in-service structures considering the indentation tests are nearly non-destructive and can be performed on non-standard samples such as pipes, tubes or vessels [2,3,11].

Unlike the micro-indentation of brittle materials by which well-defined cracks can be induced and the fracture toughness can be estimated from the size of the cracks [16], no apparent cracks are observed in either spherical or sharp indentations of ductile metallic materials. One critical question is that the observed elasticity degradation is just a false conclusion due to, for example, the improperly calibrated structural compliance of the indentation testing facility, or really caused by some kind of damage. According to the classical damaged plasticity models such as the Gurson-Tvergaard-Needleman (GTN) model [17–19] and the Rousselier model [20], no or only insignificant damage would be induced by the shear-compression-combined indentation deformation. Although experiments have shown that shear deformations do induce damage to ductile metals due to the rotation and distortion of grains, the breakage of particles and micro-cracks occurred in the shear bands [21,22], the resulted degradation of the shear moduli is no more than 1%. So another question is that if the elasticity degradation is really due to the indentation-induced damage, can the damage lead to such a big elasticity degradation?

The major purpose of the work is to investigate the mechanism of the degradation of the indentation moduli of ductile metals. The influence of the structural compliance of the indentation system on the measured indentation moduli is firstly studied through finite element simulations. Then the characteristics of the shear damage of ductile metals is investigated through experimental measurements and theoretical analysis. And then an extended GTN model including the

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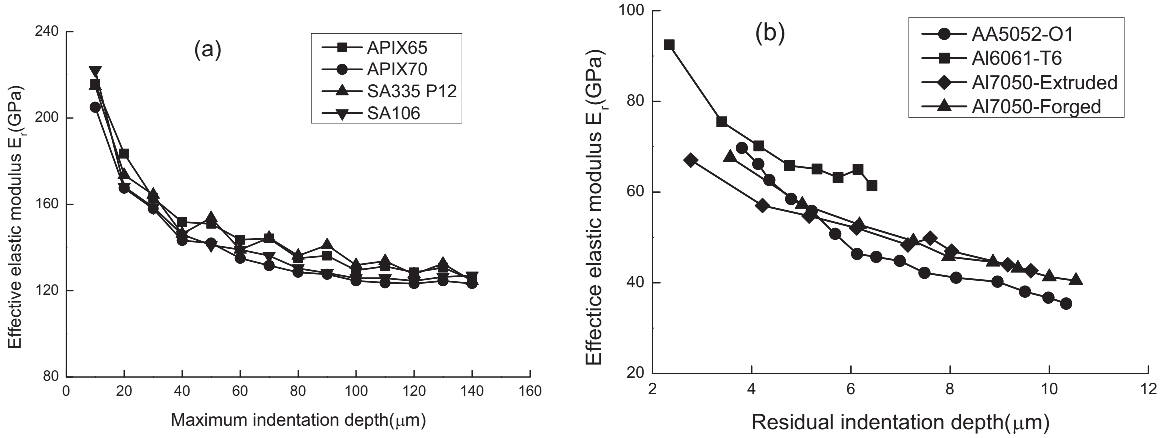

Fig. 1. Measured elastic moduli of steels (a) and aluminum alloys (b) decrease with the indentation depth.

shear effect is applied to simulate the initiation and the evolution of the indentation-induced damage. Finally, the implication of the findings to the damage-based indentation technique for estimating the fracture properties of ductile metals is discussed.

2. Methods and models

2.1. Finite element modeling of the indentation with a finite system stiffness

Finite element models of both the spherical indentation and the sharp indentation are built by using the general-purpose finite element code, i.e., ABAQUS. The sample material is assumed to be a typical aluminum alloy of which the Young's modulus and the yield strength are respectively 73.4 GPa and 340 MPa. For the finite element model of the spherical indentation, the radius of the rigid spherical indenter is set to be 500 μm. For the finite element model of the sharp indentation, the Berkovich indenter is modeled as a rigid cone with a half-included angle of 70.3°. The indentation system is simplified as a Hookean spring in series with the indenter (Fig. 2). The indentation load is applied on the top end of the spring and then transferred to the rigid indenter. The displacement of the top end of the spring is recorded as the nominal indentation depth which includes both the deformation of the spring and the true indentation depth. The stiffness of the spring is chosen with reference to a typical indentation contact stiffness (the slope of the unloading curve). For the spherical indentation, the stiffness of the spring is set to be 100 N/μm which is close to the contact stiffness at the indentation depth of 60 μm. For the sharp indentation, the stiffness of the spring is set to be 4.0 N/μm which is close to the contact stiffness at the indentation depth of 60 μm. The maximum indentation depth is chosen according to literature values, i.e., 120 μm for the spherical indentation [11] and 10 μm for the sharp indentation [15]. Quadratic quadrilateral elements (CAX4) with reduced integration are used to discretize the samples. Mesh sensitivity analysis has been conducted and the results are convergent on the mesh size. The nominal indentation modulus is determined from the unloading curve by using the Oliver-Pharr method [23].

2.2. Measurement of shear damage

The 2024-T351 aluminum alloy is studied in the present study. It is an aluminum-copper type of alloy and of high strength. Its chemical composition is shown in Table 1. The Young's modulus, the yield strength and the tensile strength are respectively 73.4 GPa, 340 MPa and 480 MPa.

The shear damage is measured through conducting the single shear test of which the specimen is designed based on the ASTM B831-93 standard (Fig. 3). Loading-and-unloading tests are performed by using an universal material test machine. The damage is defined as the degradation of the measured shear stiffness during the unloading process.

To study the damage along the transverse direction, tensile tests are further performed along the transverse direction after the shear tests (Fig. 4).

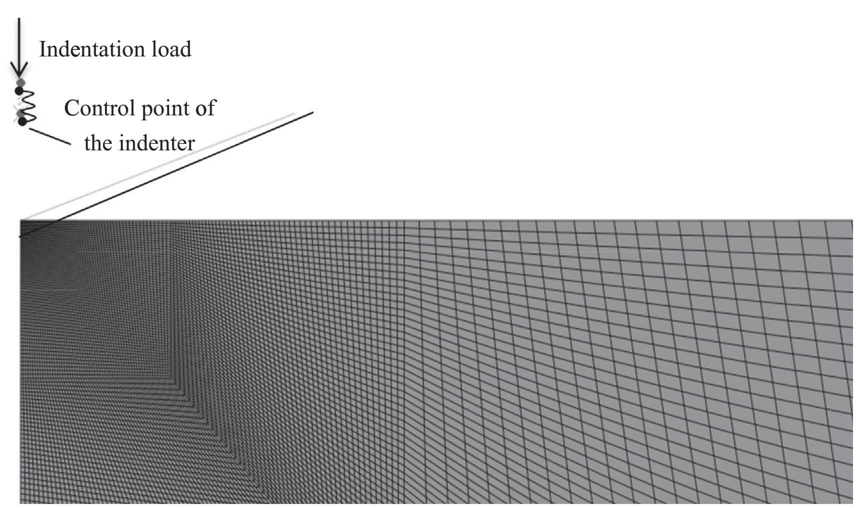

Fig. 2. Finite element model of the sharp indentation with the system compliance included.