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Determination of area reduction rate by continuous ball indentation test

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ABSTRACT

Rate of area reduction is an important mechanical property to appraise the plasticity of metals, which is always obtained from the uniaxial tensile test. A methodology is proposed to determine the area reduction rate by continuous ball indentation test technique. The continuum damage accumulation theory has been adopted in this work to identify the failure point in the indentation. The corresponding indentation depth of this point can be obtained and used to estimate the area reduction rate. The local strain limit criterion proposed in the ASME VIII-2 2007 alternative rules is also adopted in this research to convert the multiaxial strain of indentation test to uniaxial strain of tensile test. The pile-up and sink-in phenomenon which can affect the result significantly is also discussed in this paper. This method can be useful in engineering practice to evaluate the material degradation under severe working condition due to the non-destructive nature of ball indentation test. In order to validate the method, continuous ball indentation test is performed on ferritic steel 16MnR and ASTM A193B16, then the results are compared with that got from the traditional uniaxial tensile test.

1. Introduction

Area reduction rate is a fundamental parameter to evaluate the plasticity of metals, which is usually got from the tensile test. This parameter indicates the plastic flow ability of ductile materials. Unfortunately, the traditional uniaxial tensile test is destructive and cannot be used to evaluate the mechanical property of in-service equipment. In order to monitor the plastic flow property of materials under working condition, other methods must be introduced. As an alternative way to evaluate the equipment mechanical property, ball indentation technique was used to get a number of material property parameters such as strain-hardening exponent [1,2], elastic modulus, yielding strength and tensile strength [3–5] and fracture toughness [6–10]. N'Jock et al. [2] proposed a simple expression between mean pressure and stress ratio. The expression is a function of strain-hardening ratio that can be determined by indentation test. Oliver and Pharr [3] suggested a method to determine elastic modulus through indentation test. Lee [7] introduced the continuum damage mechanics to indicate the damage evolution in the testing process. Thus, the fracture toughness can be calculated from the indentation test. The plasticity is an important property of metal but nobody mentioned how to get it through indentation test. A failure criterion in the indentation test is proposed and based on that the area reduction rate is calculated in this paper. It is the first time that the method of evaluating plasticity through ball indentation test is mentioned.

The technique can be applied to the in-service equipment due to its non-destructive nature. In the current study, the ball indentation test technique is used to estimate the area reduction rate of metals. Fig. 1 shows the load–displacement curve obtained through ball indentation test. The curve can be divided into two parts, loading and unloading part. In the unloading process, the deformation of material elastically recovers which shows the elastic property so it can be used to calculate the elastic parameters like elastic modulus. As showed in Fig. 1, there is residual plastic deformation h_r after unloading, which means the deformation of material contains plastic deformation that cannot recover. During the ball indentation test, there isn't any significant phenomenon like rupture to indicate the failure point where the material collapses. In order to get the area reduction rate of metals, the failure point must be identified at first.

A continuum damage mechanics is adopted in the present work to identify the failure point with the assumption that the damage is

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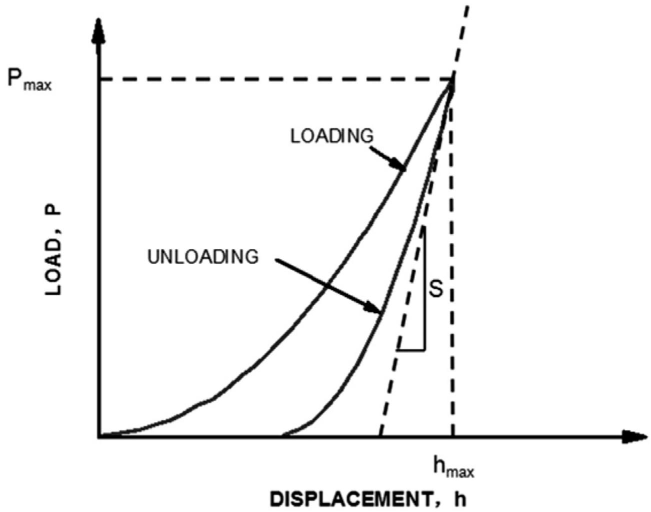

Fig. 1. Load–Displacement curve obtained from ball indentation test.

accumulated when the material experiences the loading-unloading-reloading process in the continuous ball indentation test. During loading process, the metal beneath the indenter experiences the localized plastic deformation, at the same time, voids nucleate and grow under the effect of localized shear stress. Then the load will be partially removed and the deformation recover to a certain extent. In the unloading process, the material will undergo a temporary tensile stress, which can show the tensile property of the material. The elastic modulus calculated from the unloading curves is dropping sharply during the continuous test process. Many factors may induce the decrease of elastic modulus, i.e. localized plastic strain, voids nucleation and growth. All of these factors eventually lead to the deterioration of the material property. In other words, the elastic modulus can be used to characterize the damage level, since the elastic modulus decreases with the damage accumulation.

Continuous ball indentation test is adopted because different damage level can be obtained from every loading-unloading process by calculating the elastic modulus. The reduction of elastic modulus indicates the level of damage accumulation in the material. When the damage accumulates to a critical level, the failure occurs. The indentation depth corresponding to the failure point can be obtained and the area reduction rate can be calculated on this basis.

In the evaluation of mechanical properties using indentation test method, the expression of representative strain is an important issue. As shown in Fig. 2, the calculation result may be influenced by the pile-up or sink-in phenomenon. Thus, many researchers tried to modify it. Mathews [11] and Hill [12] gave the empirical relationship to correct the deviation caused by pile-up and sink-in phenomenon. However, the relationship cannot be applied in the continuous ball indentation test directly. In the paper, the pile-up or sink-in phenomenon in the continuous ball indentation test is thus discussed carefully.

In order to validate the model proposed in this work, continuous ball indentation test was performed on the ferritic steel 16MnR and ASTM A193B16, and at the same time, the uniaxial tensile test was also performed. Then area reduction rate was calculated from the load-depth curve by using the method proposed in this work. The indentation area reduction rate was compared with the area reduction rate obtained from the traditional uniaxial tensile test. There is deviation between the area reduction rates obtained by two different methods. The sources of error are also discussed in this paper.

2. Methodology

In the traditional tensile test, the area reduction rate can be obtained after the rupture of the sample. However, in the ball indentation test, there isn't any significant phenomenon to indicate the failure of metals. As a result, a failure point must be found at first and then the area reduction rate can be calculated based on the indentation depth at that point. In the present study, the damage of the material can be assumed as isotropic. Kachanov [13] damage variable D to describe the level of damage in the material, which can be defined as:

$$D = \frac{C_D}{C} \tag{1}$$

Where C is the cross-sectional area of load region and C_D is the reduced area due to the appearance and growth of micro-defects. The damage variable D can be converted to the void volume fraction f:

$$f = \frac{V_D}{V} \tag{2}$$

Where V is the volume of material and V_D is the reduced volume due to the appearance and growth of micro-defects. In the Eqs. (1) and (2), s and v are the area of a circle and the volume of the sphere which has the same radius with the circle, respectively. The relationship between f and D can be expressed as:

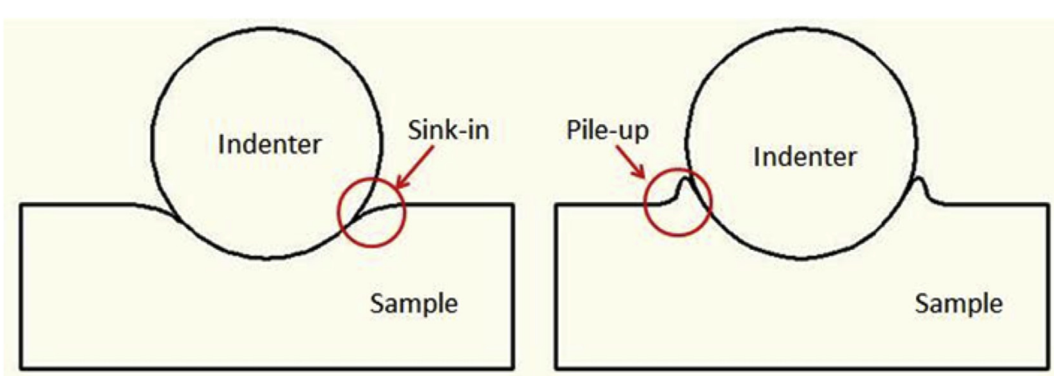

Fig. 2. The pile-up/sink-in phenomenon.

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