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Evaluation of Fracture Toughness for Power Plant Materials using Continuous Indentation Technique

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Abstract. An indentation fracture toughness model is applied to estimate non-destructively the fracture toughness of power plant materials such as ASTM A53 and ASME SA335 P91. Fracture toughness evaluated using the model showed good agreement with current standard fracture toughness test results.

Introduction

Fracture toughness, which indicates the resistance to crack growth, is a very important property for assessing structural integrity. However, current standards such as ASTM [1] and BS [2], which are exact methods of evaluating fracture toughness, require specific specimen shapes and sizes for validity. In addition, complex test procedures, including fatigue precracking and crack length measurement, make evaluating fracture toughness quite difficult. Above all, current fracture-toughness-testing methods are limited in application to operational industrial structures, since they are destructive methods.

Some theories and models have been developed using indentation techniques to ameliorate these difficulties in evaluating fracture toughness [3-6]. However, current indentation models can be applied only to brittle materials and lower shelf energy level in the ductile-brittle transition temperature (DBTT) region of ductile materials. Recently, Lee et al. [7] suggested a new model for evaluating fracture toughness of ductile materials using the continuous indentation technique. In this study, this model was applied to estimate the fracture toughness of ductile power plant materials such as ASTM A53 and ASME SA335 P91. Fracture toughness from this model using only indentation data compared well with those from standard fracture toughness tests.

Theoretical Background

Critical Indentation Energy Model

For a crack of length $2a$ in a finite plate, the fracture toughness is given by [8]:

$$K_{JC} = \sigma_f \sqrt{\pi a} \tag{1}$$

where σ_f is the remote tensile stress at fracture. According to Griffith theory, σ_f is given by [8]:

$$\sigma_f = \sqrt{\frac{2Ew_f}{\pi a}} \tag{2}$$

where E is the elastic modulus and w_f is energy per unit area required to create a crack surface. Combining Eq. (1) and Eq. (2), the relationship between w_f and K_{JC} becomes

$$K_{JC} = \sqrt{2Ew_f} \tag{3}$$

To estimate K_{JC} using the indentation technique, w_f must be determined using only indentation parameters. Triaxiality ahead of the indenter tip is in the range 2~3, and the degree of constraint in the deformed indentation region is similar to that ahead of the crack tip [4-6]. Hence the indentation energy per unit contact area to the characteristic point can be related to w_f if there exists a characteristic fracture initiation point during or over the indentation process. This energy, henceforth called the critical indentation energy, is calculated from the indentation load-depth curve:

$$2w_f = \lim_{h \to h^*} \int_0^h \frac{4P}{\pi d^2} dh \tag{4}$$

where P is the applied load, h is the indentation depth, d is the chordal diameter of the impression and h^* is the critical indentation depth corresponding to the characteristic fracture initiation point. $2w_f$ indicates the formation of two crack surfaces.

Determination of h*

Since there are no distinguishing marks that can be used to identify fractures occurring during indentation, h^* in Eq. (4) cannot be measured by direct methods (optical microscope or SEM observation). Thus to determine h^*, continuum damage mechanics (CDM) was applied to the indentation process. CDM is used mainly to predict failure in structures loaded statically and dynamically. The seminal idea for this mechanics is due to Kachanov [9], who introduced a damage variable D defined in Eq. (5) and related to the surface density of microdefects in the material:

$$D = \frac{s_D}{s} \tag{5}$$

where s and s_D are respectively the cross-sectional area of the loaded region and the reduced area due to microdefects. In Eq. (5), D can be represented by an elastic modulus change using Lemaitre's strain equivalence principle [10]:

$$D = 1 - \frac{E_{eff}}{E} \quad \text{or} \quad E_{eff} = E(1-D) \tag{6}$$

where E_{eff} is the effective elastic modulus of the damaged material and E is the elastic modulus of the initial non-damaged material.

E_{eff} decreases as h increases due to the increase in damage beneath the indenter. In addition, E_{eff} is represented by a function comprised only of indentation parameters [11]:

$$E_{eff} = \frac{1-\nu^2}{\left(\dfrac{1}{E_r} - \dfrac{1-\nu_i^2}{E_i}\right)} = \frac{1-\nu^2}{\left(\dfrac{2\sqrt{A_C}}{\sqrt{\pi}S} - \dfrac{1-\nu_i^2}{E_i}\right)} \tag{7}$$

where ν and ν_i are the Poisson's ratios of the material and indenter, respectively, E_r is the reduced modulus, E_i is the elastic modulus of the indenter, A_C is the contact area between indenter and material and S is the unloading slope. After multiple loading-unloading, the values of E_{eff} for various indentation depths can be calculated from each unloading and E_{eff} vs. h may be plotted as in Fig. 1. If a critical value of the elastic modulus is known or determined, h^* can be determined from the corresponding value of h.

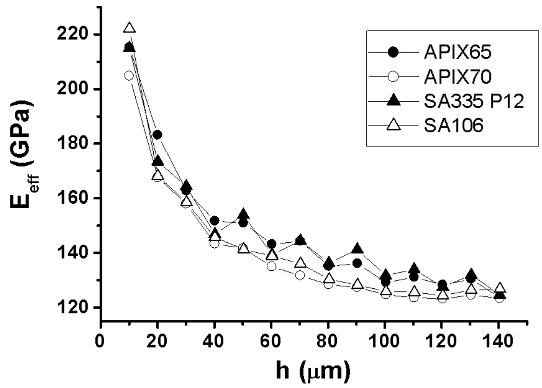

Fig. 1 Change in damaged elastic modulus of structural steels with indentation depth [7].

Since the indentation load is compressive in terms of the loading axis, the deformed region beneath the indenter experiences compressive stress. Hence, voids will be nucleated by localized shear due to compressive stress, and the void volume fraction f will increase as h increases [7,12-14]. f can be represented by [9]:

$$f = \frac{\frac{4}{3}\pi}{\pi^{\frac{3}{2}}} D^{\frac{3}{2}} \quad \text{or} \quad D = \frac{\pi}{\left(\frac{4}{3}\pi\right)^{\frac{2}{3}}} f^{\frac{2}{3}} \tag{8}$$

To determine the critical value of the elastic modulus, the concept of critical void volume fraction was introduced. The numerical analyses by Andersson [15] show f ≅ 0.25 at the initiation of stable crack growth for ductile materials, and Tvergaard and Needleman [16] have applied these criteria to the analysis of cup-cone fracture. From these results, $f^* = 0.25$ (void volume fraction at initiation of stable crack growth) are employed here to determine the critical values of elastic modulus. f^* can be converted into corresponding damage variables D^* through Eq. (8); then corresponding value of E^* are calculated by Eq. (6). Therefore, h^* is determined as the corresponding h by using critical value of elastic modulus, E^*.

Experiments

To verify this critical indentation energy model, fracture toughness tests and indentation tests were performed for two ductile materials (ASTM A53 and ASME SA335 P91), which have been widely used as power plant pipeline steels. In fracture toughness tests, CTOD tests were performed according to ASTM E1290 [1]. At least ten toughness values were obtained from CTOD tests for each material, and the average value was used as the representative fracture toughness. Indentation tests were performed under displacement-controlled conditions: the maximum indentation depth was 150 μm and multiple loading-unloading cycles were applied at 10 μm intervals using a 500 μm diameter ball indenter with $\nu_i = 0.07$ and $E_i = 600$ GPa. The loading and unloading rates were both 0.1 mm/min. At least five sets of indentation data were obtained from indentation tests for each material, and the average value was used in analyzing the fracture toughness.

Results and Discussion

Figure 2 shows E_{eff} vs. h for ASTM A53 and ASME SA335 P91 from indentation data: as h increases, E_{eff} decreases with similar manner to Fig. 1. These phenomena result from increase in damage accumulation due to localized shear stress beneath indenter tip with increase in indentaiton deformation [7]. If the E^* can be determined for each material in Fig. 2, h^* can be also determined. Figure 3 shows how to determine h^* for ASTM A53.

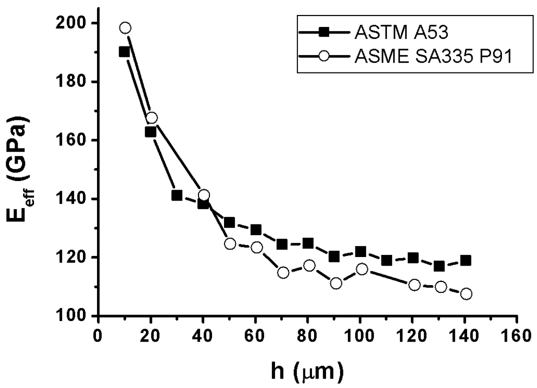

Fig. 2 Change in damaged elastic modulus of power plant materials with indentation depth.

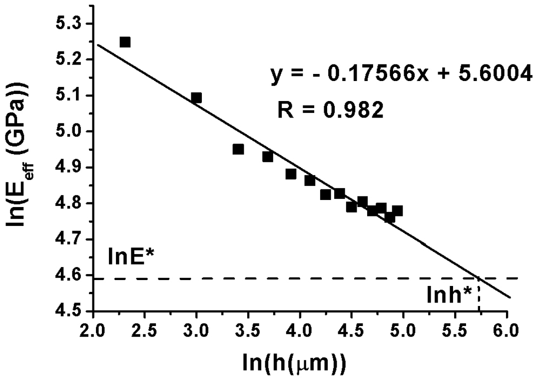

Fig. 3 Method of determining h^* for ASTM A53.

D^* can be determined as 0.48 by putting $f^* = 0.25$ into Eq. (8). The almost undamaged elastic modulus (which can be obtained from the first point in Fig. 2) of this material is about 190 GPa. By Eq. (6), therefore, the elastic modulus corresponding to D^*, i.e., E^*, becomes 99 GPa (= 199×(1–0.48)). Note that, for a ductile material such as ASTM A53, the critical indentation depth h^* corresponding to this E^* cannot be obtained directly from indentation tests (such as in Fig. 3), and hence must be determined by extrapolation of the proper fit of E_{eff}-h relations. Figure 3 shows the relation of lnh and $\ln E_{eff}$ for ASTM A53 steel, whose fitting line shows good linearity; the correlation factor of this fitting line (R) is more than 0.98. From extrapolation of the lnh-$\ln E_{eff}$ fitting curve, the value of $\ln h^*$ corresponding to $\ln E^*$ (ln 99 (= 4.59)) was determined as shown in Fig. 3. In addition, Figure 4 shows how to determine h^* for ASME SA335 P91. h^* for ASME SA335 P91 can be determined in the same manner as those for ASTM A53. Fianlly, we can estimate K_{JC} values of these power plant materials through Eqs. (3) and (4) by using h^* values determined in Fig. 3 and Fig. 4.

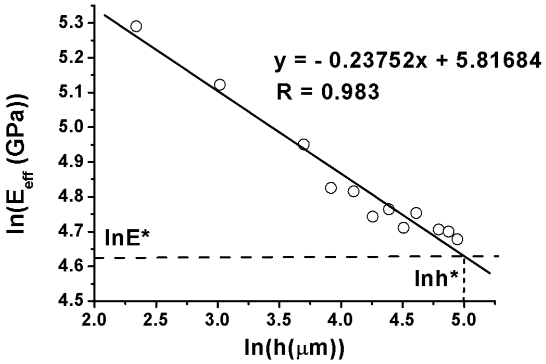

Fig. 4 Method of determining h* for ASME SA335 P91.

Figure 5 compares the fracture toughness K_{JC} obtained from the indentation technique and from conventional CTOD tests. To convert from CTOD values to K_{JC}, the following general equation was applied:

$$K_{JC} = \sqrt{2\sigma_Y E \delta_{IC}} \tag{15}$$

where σ_Y is the yield strength and δ_{IC} is the critical CTOD value. In the figure, the mean value and standard deviation of K_{JC} from the model and CTOD tests are indicated. The K_{JC} from indentation tests have about 10% self-standard deviation, and there is approximately 10% difference in the values between the indentation tests and CTOD tests. However, if we take into account that K_{JC} values from CTOD tests include standard deviation more than 10% (this deviation may arise because CTOD test is very sensitive to the location of precrack tip), Fig. 5 shows good agreement in K_{JC} values between the indentation tests and CTOD tests.

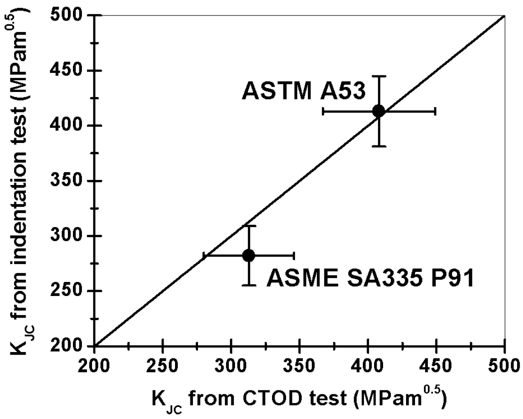

Fig. 5 Comparison of fracture toughness in CTOD tests and indentation tests.

The above results for power plant materials support the validity of the new indentation technique suggested by Lee et al. [7], and it is expected that this technique can be applied to *in-situ* estimation of the fracture toughness of power plant steels in a nondestructive way.

Summary

The methodology for evaluating the fracture toughness of ductile materials by using continuous indentaiton technique was applied to power plant steel such as ASTM A53 and ASME SA335 P912. To diagnosis the applicablity of indentation method for estimating fracture toughness of power plant materials, indentation test and conventional fracture toughness test were carried out, and then, fracture toughness from indentation test was compared with those from conventional fracture toughness test and showed good agreement with those. From these results, it is expected that the applicablity of indentation method for estimating non-destructively fracture toughness of power plant materials is considerable.

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