Engineering Fracture Mechanics 78 (2011) 2082–2087

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Technical Note

A model to predict the fracture distance of cleavage fracture as a function of temperature

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ARTICLE INFO

Article history:
Received 15 April 2010
Received in revised form 24 December 2010
Accepted 18 March 2011
Available online 24 March 2011

Keywords:
Fracture distance
Modeling
Cleavage fracture
Low temperature
Ferrite steels

ABSTRACT

We propose a model which computes the fracture distance of materials (reactor pressure vessel steel, C–Mn steel, and four heat-treated HSLA steels) as a function of temperature. The fracture distance, an important length scale for predicting cleavage fracture, is determined using the parameters such as mean grain size, fracture toughness and yield stress of the material in the range of −250 to 0 °C. The fracture distances computed from the proposed model agreed with measurements for the materials. Some differences between the predictions and the measurements were observed for HSLA steel with fine grain size (30 μm) and coarse grain size (55 μm).

1. Introduction

Wilshaw et al. [1] proposed that the unstable fracture of material occurs when a critical tensile stress attains over a small volume in front of the notch. It denotes that a material with the notch begins cracking when the stress at the crack tip generated by an external load reaches the failure stress inherent in the material over a distance from the crack tip. Ritchie et al. [2] estimated the distance about twice the grain size in the mild steel in case that the pre-cracked specimen was subjected to mode-I loading condition. The fracture distance was proved to be dependent on the temperature of material [3,4], but was independent of strain rate of material [5]. This distance measured in experiments has been defined in various ways by different researchers as a minimum distance and/or maximum distance. The average distance measured in experiments was defined by some researchers as the characteristic distance. In this study, the distance from the crack tip to a point where cleavage fracture initiates is defined as 'fracture distance'.

Many research groups measured the fracture distance as a function of temperature. Yang et al. [6] conducted a four-point bending test over a temperature range from −200 to 0 °C to measure the fracture distance as a function of temperature. The materials used in their study were two kinds of reactor vessel steels, SA 533-B1 and SA 508-3. They reported that the fracture distance increased rapidly with increasing temperature in the transition temperature region. Wang et al. [7] performed a COD (Crack Opening Displacement) test with heat-treated C–Mn steel over a temperature range of −200 to 0 °C to investigate the fracture distance and fracture toughness for cleavage fracture. Chen [8] measured the fracture distance by examining COD test results with HSLA steel at various temperatures (−196 to −30 °C) to analyze the mechanism of cleavage fracture.

These experimentally measured fracture distance and fracture toughness are valuable data but cannot be used directly in simulating the cleavage fracture where temperature gradient prevails along the crack growth direction because the fracture

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doi:10.1016/j.engfracmech.2011.03.008

distance varies with the temperature of material changed. To simulate the cleavage fracture, we need a model which predicts the fracture distance as a function of temperature. Once the fracture distance is calculated from the model for a specific temperature, we can then simulate the cleavage fracture using, for example, the element removing technique [9], which eliminates any element ahead the crack tip that reaches a prescribed failure stress inherent in the material over the fracture distance. A complete loss of load carrying capacity which stems from progressive degradation of the stiffness of the element denotes the cleavage fracture in FE simulation.

In this study, we propose a semi-empirical model capable of predicting the fracture distance as a function of temperature. The proposed model was not made by fitting experimental data, neither was it derived from perfect theoretical considerations. This model has a form with an exponential function and three parameters, fracture toughness, yield strength, and mean grain sizes. We have compared the fracture distance computed by the proposed model with the experimental data reported in previous studies [6–8]. The applicability of the proposed model is limited to steels (C–Mn steel, HSLA steel and reactor pressure vessel steels) usually used in low temperature environments.

2. Modeling

Two assumptions were made in modeling. First the fracture distance increases as an exponential function of temperature since that the fracture distance increases very rapidly with increasing temperature is observed from the experimental data [6–8]. The second one is that the fracture distance is one-twentieth of the mean grain size at absolute temperature (−273.15 °C). Chen [8] reported that a crack initiates at the carbide particle at extremely low temperature (−196 °C). The carbide particle size is in the range of about one-sixth to one-fourteenth of the grain size [10,11]. The carbide size decreases linearly with decreasing temperature below −100 °C [12]. Thus, we assumed that the fracture distance at −273.15 °C was one-twentieth of the mean grain size.

From the first assumption, the fracture distance (X_c) may have a following form

$$X_C = \alpha e^{nT}, \tag{1}$$

where T denotes the temperature of the specimen (or material). The second assumption gives

$$\alpha = S_g/20, \tag{2}$$

where S_g represents the mean grain size of the specimen. The exponent, n in Eq. (1) is expressed in terms of the plastic zone size at the ahead of the crack tip in plane strain condition, r_y [13] and mean grain size as follows

$$n = \left(\frac{\ln(r_y/\alpha)}{273 + T_{ref}}\right)/\beta, \tag{3}$$

where

$$r_y = \frac{1}{6\pi}\left(\frac{K_{Ic}}{\sigma_y}\right)^2. \tag{4}$$

K_{Ic} and σ_y stand for plane strain fracture toughness and yield strength at a reference temperature, respectively. β is a material-dependent constant and was assumed to be 1.8. T_{ref} indicates the reference temperature. It was set to −100 °C since the beginning temperature of the transition region of the materials employed in this study was in the range of −110 to −70 °C. [14–16] The constant n in the proposed model has nothing to do with the work hardening exponent.

The computed values for α and n used in the proposed model are summarized in Table 3. Note that the yield strength and fracture toughness for specimen CG (HSLA steel with coarse grain) and specimen FG (HSLA steel with fine grain) were unavailable at the reference temperature, −100 °C (see Table 1). Hence, we used the data available at −110 °C to compute the exponent, n.

3. Experimental data reported by previous studies

Table 1 summarizes the fracture toughness, yield strengths, mean grain sizes and fracture distances for different temperatures and materials. Yang et al. [6] used two types of reactor pressure vessel steels as specimen, depending upon spheroidization annealing temperature. One was an SA 533-B1 plate (JRQ), and the other was an SA 508-3 steel forging (JFL). These steels were not heat-treated. The mean grain size of specimen JRQ and JFL were 30 μm and 25 μm, respectively. The fracture toughness and fracture of specimen JRQ and JFL were obtained from a curve which fits best to a series of data. Wang et al. [7] used C–Mn steel as specimen, which were heat-treated. The mean grain size of specimen C–Mn was 9.3 μm. Chen [8] heat-treated HSLA steel and fabricated four types of specimens depending upon mean grain size and carbide particle size, i.e., specimen with (i) coarse grain(CG), (ii) fine grain(FG), (iii) small carbide(SC) particles and (iv) large carbide(LC) particles. The specimens with large carbide particles or large carbide were obtained by controlling spheroidizing temperature and time. The mean grain size of specimen SC and LC were 9.7 μm and 9.4 μm, respectively. The chemical compositions of the steels are summarized in Table 2.