BLUNTING EFFECTS ON FRACTURE TOUGHNESS
OF LOW STRENGTH STEELS

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INTRODUCTION

The fracture toughness of low strength steel decreases considerably with decreasing temperature and increasing strain rate since the fracture micromechanism changes progressively from microvoid coalescence to cleavage. It is proposed [1] that crack initiation by cleavage occurs when $\sigma_{yy}^{\text{max}}$, the cleavage strength of the material at the crack tip, is reached. It is shown [2] that $\sigma_{yy}$ changes little with temperature and thus the temperature influences $K_{IC}$ mainly due to the variation of $\sigma_{yy}$ with temperature, where the crack tip radius $\rho$ remains unchanged [1]. However, $K_{IC}$ ($K_{IC}$) is an inadequate fracture mechanics parameter when elastic-plastic or fully plastic loading situations are encountered since in low strength steel specimens fractured at high test temperatures and in such situations the parameter $J_{IC}$ ($J_{IC}$) should be used more appropriately. Accordingly, $K_{IC}$ calculated from the experimentally measured $J_{IC}$ (or $J_{IC}$ measured from specimens which do not satisfy requirements of valid $J_{IC}$ measurements) value, is termed as $K_{IC}$ ($J$) and is obtained from [3,4]:

$$K_{IC}(J) = \left[ \frac{1}{1 - \nu^2} \right]^{1/2}$$

In the above loading situations, considerable crack tip blunting occurs. It is observed that [5] calculated $K_{IC}$ values based on the achievable $\sigma_{y}\sigma_{y}^{\text{max}}/\sigma_{y}^t$ value [6,7], in the plastic zone ahead of a sharp crack are significantly lower than the experimental $K_{IC}$ ($J$) values. In addition the achievable $\sigma_{y}\sigma_{y}^{\text{max}}/\sigma_{y}$ values were higher than $\sigma_{y}/\sigma_{y}$ even at room temperature where cleavage micromechanism does not operate as confirmed by fractographic observation [5]. These observations support the contention [8] that the crack tip undergoes blunting. In fact the blunting of the crack tip is physically confirmed and supported by SEM measurement [9,10], COD measurements [11,12] and the results of crack tip profile measurements and observations [9,11,12,13].

RKR [14] used the stress distribution ahead of a crack [8] in conjunction with a two grain model [14] to calculate the $K_{IC}$ values which were compared with the experimental $K_{IC}$ values. However, the change in $\sigma_{y}/\sigma_{y}$ and $n$ values with change in temperature and strain rate were not taken into account in their calculation.

The present investigation correlates the various elastic-plastic fracture toughness such as $\delta_c$ [15], $J_{IC}$ [16,17] and $G_{IC}$, the non-linear energy parameter proposed by Liebowitz and Eftis [18] of two different class of low strength steels in the temperature range -196°C to 28°C and crosshead.

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speed range 0.5 to 200 mm/minute. In particular the effect of crack tip blunting on $K_{IC}$ ($J$) is assessed by an examination of the experimental data in the light of the well known theoretical results ($6,7,8$).

EXPERIMENTAL

The chemical analysis and the other details of the 12.5 mm thick plate materials are reported in Table 1. Three point bend toughness specimens 12.5 x 15 x 75 mm cut with the long axis along the rolling direction were prepared as per ASTM E 399-72. The tests at low temperatures were carried out with the specimens immersed in a low temperature bath. The load, load line displacement and the crack opening displacement were measured as a function of time. Companion tensile test specimens of the two steels were pulled at various temperatures and strain rates. The load-displacement ($16,21$) plots were suitably analysed to obtain $\delta_C$ ($13,19,20$), $J_{IC}$ ($16,21$) and $\delta_C$ ($18$). A measure of the crack tip strain rates was obtained, taking into account the tensile yield strength variation with temperature and strain rate ($19,20$). The tensile test data were processed to obtain the $\sigma_y/E$ values at various strain rates and temperatures.

RESULTS AND DISCUSSION

Correlation of the Fracture Mechanics Parameters

COD and $J$ relation is given by

$$\text{COD} = \frac{J}{N \cdot \sigma_y}$$

where $M$ takes into account the elevation of the local $\sigma_{yy}$ stress at which yield occurs at the crack tip. The values of $M$ have been theoretically determined to be 1.63 from deformation theory of plasticity ($31,2.32$) using an incremental plasticity theory ($24$), 2 by finite element analysis ($19,25$). Experimental values of $M$ have been reported ($26$) for three point bend specimens and lie in the range of 0.83 to 1.75 depending upon $a/W$ and $N$ values.

Figure 1 shows the correlation between $J_{IC}$, $\delta_C$ and $\sigma_y$ for the various test temperatures and crack tip strain rates for the two steels. The value of $M$ is about 1.52 and is not unreasonable. It is interesting to note that $M$ has a constant value in spite of the differing amounts of plasticity preceding fracture in the specimens tested.

Figure 2 shows the relation between $J_{IC}$ and $\delta_{IC}$ for the whole range of small scale to extensive yielding situations. The correspondence between the two is reasonable up to the limits of valid $J_{IC}$ measurements as specified in reference ($16$).

Stress Induced Fracture - Contribution of Progressive Crack Tip Blunting

An examination ($5$) of the $K_{IC}$ ($J$) values in the light of Tetenman and Malkin’s ($1$) analysis showed that sharp crack tip radius $\rho_0$ of their analysis depends on temperature and strain rate and increases with increasing $\delta_C$. It has also been shown by earlier investigators that considerable stretching occurs at the crack tip which indicates that crack tip

undergoes blunting and the stretched zone width directly relates to $\delta_C$. It is now proposed that the crack tip undergoes progressive blunting with loading and the radius reaches a critical value $\rho_C$ at the point of crack initiation and that

$$\rho_C = 0.5 \cdot \delta_C$$

Thus the effect of temperature and strain rate on $K_{IC}$ is reflected in two ways - firstly by virtue of their effect on yield strength and secondly through their effort on $\rho$.

The stress distribution ahead of a blunt crack ($8$) could not be used to examine experimental results since it is available only for a few $\sigma_y/E$ values. On the other hand $\sigma_y/E$ values change continuously in the experimental data obtained. The crack tip blunting effect is therefore assessed in an indirect manner.

The experimentally determined $K_{IC}$ ($J$) values are suitably processed to calculate hypothetical $K_{IC}$ ($J$) values as would be obtained if the crack tip were sharp. These hypothetical values are termed as $K_{IC}$ ($H$). The $K_{IC}$ ($H$) values are then compared with $K_{IC}$ ($NB$), the fracture toughness values based on sharp crack stress distribution ($6,7$) and the two grain model ($14$). At low $\sigma_y/E$ values fracture of three grains is assumed to lead to fracture.

Calculation of $K_{IC}(H)$:

In the case of a blunt crack the stress $\sigma_{yy}$ reaches a maximum value $\sigma_{yy}^{\text{max}}$ at an approximate distance $x = 1.9 \cdot \delta_C$ ($8$). It has been shown ($8$) that crack opening displacement at the tip can be represented by

$$\delta_C = 0.717 \frac{k^2}{E \sigma_y}$$

Therefore

$$(X) \sigma_{yy} = \sigma_{yy}^{\text{max}} = 1.9 \delta_C = 1.36 \frac{k^2}{E \sigma_y}$$

It is shown ($27$)

$$(X) \sigma_{yy} = \sigma_{yy}^{\text{max}} = \rho \left[ \exp \left( \frac{\sigma_{yy}^{\text{max}}}{\sigma_y} - 1 \right) - 1 \right]$$

At crack initiation $\sigma_{yy}^{\text{init}} = \sigma_{yy} + \rho \cdot \delta_C$ and correspondingly $K_I = K_{IC}(\rho)$.

Combining equations ($2$), ($4$) and ($5$)

$$K_{IC}(\rho) = \frac{E \sigma_y \delta_C}{2 \sqrt{2 \pi} \gamma_c} \left[ \exp \left( \frac{\rho \delta_C}{\sigma_y} - 1 \right) - 1 \right]$$

where $K_{IC}(\rho)$ is the calculated fracture toughness for the different values of $\rho_C$ and $\rho_C$ values change with strain rate and temperature.

$K_{IC}(\rho)$ can be calculated at various temperatures and strain rates since the experimental $\delta_C$ and $\sigma_y$ are known and $\sigma_y$ is calculated from the general
yield and fracture initiation load as per a procedure reported in reference [1]. The calculated $K_{IC}(J)$ is plotted against the experimental $K_{IC}(J)$ values at various temperatures and strain rates in Figure 3. The experimental $K_{IC}(J)$ values as reported in Figure 3 are obtained from equation (1). The experimental $K_{IC}(J)$ values at intermediate strain rates and temperatures are obtained by graphical interpolation. The higher $K_{IC}(J)$ values could not be accommodated in the figure but they clearly obey the trend shown in the graph.

Figure 3 shows that $K_{IC}(J) = K_{IC}(p)$ up to $K_{IC}(J) = 60$ MPa$m^{1/2}$ for the Ms-V steel and $50$ MPa$m^{1/2}$ for the ship building steel. Above these values, the experimental $K_{IC}(J)$ changes linearly with $K_{IC}(p)$ and obeys an equation of the form

$$K_{IC}(J) = A + B \cdot K_{IC}(p)$$

(7)

where the constants $A$ and $B$ can be evaluated from Figure 3.

If $\sigma_y$ for a sharp crack is known, $K_{IC}(J)$ values for a sharp crack can be calculated from equation (6). In these calculations $\sigma_y$ is assumed to be $2.7 \mu$m since the fatigue crack width and the is known the corresponding $K_{IC}(J)$ values for a sharp crack can be calculated from equation (7) and these $K_{IC}(J)$ values are termed as $K_{IC}(H)$, the hypothetical $K_{IC}(J)$ value for a sharp crack. The $K_{IC}(H)$ values are calculated in this manner in Figure 4. These $K_{IC}(H)$ values can be compared with $K_{IC}(NB)$ values calculated at the different temperatures and strain rates since both these parameters refer to a sharp crack.

It should be noted that equation (6) and Figure 3 are not based on any microstructural features such as grain size. The change in slope of the lines becomes too blunt (of the order of the grain size) at higher $K_{IC}(J)$ values, induced to a strain induced one; 3) the higher $K_{IC}(J)$ values (+66 MPa$m^{1/2}$ from valid $J_{IC}$ values and +45 MPa$m^{1/2}$ for ship building steel) are not derived from higher temperatures (i.e., higher $K_{IC}(J)$ values) and lower strain rates. The relation between $K_{IC}(J)$ and $K_{IC}(p)$ obeys a linear relationship as given by equation (7).

Calculation of $K_{IC}(NB)$:

The stress distribution ahead of the crack is influenced by $n$ as [8]. The result of the previous investigators [28,29] that $n$ depends only on $\sigma_y$. The results were confirmed and the relation was also confirmed from the examination [5] of the unnotched and notched tensile test data reported in reference [30,31] that $n$ values are not significantly influenced by triaxiality. Thus $n$ values of the material at the crack tip can be calculated from the $\sigma_y$ value at a given temperature and crack tip strain rate.

Figure 4 in reference [8] plots $\sigma_{cr}/\sigma_y$ versus $X/(K_{IC}(p))^2$ in case of a sharp crack for $n = 0.1$ and $0.2$. An approximate plot for $n = 0.15$ was generated by graphical interpolation. According to the two grain model [14], $X = 2$ grain diameter. With $\sigma_{cr}/\sigma_y$ and $n$ values known for a given temperature and crack tip strain rate, the value of $X/(K_{IC}(p))^2$ is known from the above figure. Since $X$ is known the corresponding $K_{IC}$ can be calculated. This $K_{IC}$ is $K_{IC}(NB)$. The $K_{IC}(NB)$ values are also plotted in Figure 4.

It may be noted that at higher temperatures when $\sigma_y$ values are low, $\sigma_{cr}$ is not reached in the very first grain near the crack tip. In these cases based on $\sigma_{cr}$ quantity, a value of $X=5$ grain diameter is assumed and $K_{IC}(NB)$ values are computed.

Comparison of $K_{IC}(H)$ and $K_{IC}(NB)$:

The $K_{IC}(NB)$ values exhibit a somewhat irregular trend since the intermediate $n$ values are approximately approximated to either 0, 0.1, 0.15 or 0.2 in the calculations. If one were to ignore this irregularity, $K_{IC}(NB)$ values fall reasonably close to $K_{IC}(H)$ values up to a temperature where agreement between $K_{IC}(NB)$ and $K_{IC}(H)$ has an interesting consequence. The experimental $K_{IC}(J)$ values contain a contribution due to the crack tip blunting in addition to the contribution due to yield strength. It may be written as

$$K_{IC}(Blunting) = K_{IC}(J) - K_{IC}(H)$$

where $K_{IC}(H) = K_{IC}(NB)$.

CONCLUSIONS

1. In the specimen geometry investigated, the critical COD is observed to relate to $J_{cr}$ by the relation

$$COD = J_{cr} \cdot 1.53 \cdot \sigma_y$$

2. Experimental $J_{IC}$ values show a reasonably good agreement with $\sigma_y$ as long as $J_{cr}$ measurements are valid.

3. Significant amount of crack tip blunting occurs during elastic-plastic loading situation and this contributes considerably to the toughness. The contribution can be evaluated from a relation of the type

$$K_{IC}(Blunting) = K_{IC}(J) - A \cdot B \cdot \sqrt{\frac{\sigma_{cr}}{\sigma_y}} - \frac{\exp\left(\frac{\sigma_{cr}}{\sigma_y} - 1\right)}{1}$$

where the value of $\sigma_{cr}$ corresponds to the critical crack tip radius at the initiation of a sharp crack and $A$ and $B$ are numerical constants.

REFERENCES

Table 1 Chemical Analyses, Tensile Properties and Grain Size of Steels Investigated

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<th>S</th>
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<th>YS</th>
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Figure 1 Relation Between Critical COD and $J_{CT}/Y$
Figure 2 Comparison Between Experimental $J_{cr}$ Values and $\bar{G}_f$ Values of Liebowitz and Eftis

Figure 3 $J_{IC}^{(c)}$ as a Function of Cleavage Parameter Toughness
Figure 4 Temperature Variation of $K_{IC(H)}$ and $K_{IC(NB)}$