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THE RELATION BETWEEN STATIC AND DYNAMIC FRACTURE TOUGHNESS OF STRUCTURAL STEELS

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INTRODUCTION

Fracture safety requires suitable design, careful inspection, and adequate toughness to prevent crack propagation of the most serious cracks overlooked by inspection or developed during service use. For materials with relatively small strain rate sensitivity, such as high strength aluminum and steel alloys, testing experience with methods based upon fracture mechanics permit laboratory static fracture toughness K_{IC} evaluations under sufficient control so that the test results can be connected by direct analysis to crack size and stress level in service components.

For strain rate sensitive materials, notably low and intermediate strength weldable steels, although a similar approach is applicable in principle the factors involved are more complex. If the K_{IC} test specimen is subjected to dynamic loading, the initial instability is controlled by dynamic microfracture processes and a K_{ICd} value is measured. The K_{ICd} values are lower than the K_{IC} values [1 - 8]. In addition strain rate can have a significant effect on determining the degree of plane strain. Under dynamic loading plane strain crack propagation would occur in thinner sections than would be expected on the basis of K_{IC} test results. Evaluation of fracture performance on the basis of static data could be dangerously misleading [1 - 3]. Despite a growing interest in K_{ICd} tests no generally acceptable standard measurement technique was developed up to date. Consequently several investigations have been undertaken to correlate K_{ICd} values with K_{IC} data [5 - 8]. Empirical correlation [8] is not always accurate enough - Figure 1, and simple correlation based on the strain rate temperature parameter [5 - 7] gives too conservative estimation of K_{ICd} namely for intermediate strength weldable steels.

To establish the correlation between K_{IC} and K_{ICd}, a detailed experimental study of the temperature and strain rate dependence of fracture toughness was carried out. The measurements of K_{IC} and K_{ICd} for a static crack as a function of temperature and loading rate are reported in this paper on the structural steels with various strength levels. The strain rate difference between static and dynamic test is orders of magnitude, so strain rate effect in brittle fracture is placed in better perspective. The suggested correlation K_{IC} with K_{ICd} is substantiated by the theory of thermally activated processes during the plastic deformation of metals.

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MATERIALS AND EXPERIMENTAL PROCEDURE

The extensive set of measurements of K_{IC} and K_{ICd} values for a wide range of temperatures was conducted on seven structural weldable steels having a room-temperature tensile strength σ_{TS} in the range of 455 - 765 MPa. Because of limited length of this paper only the experimental data for two steels with σ_{TS} = 455 MPa and σ_{TS} = 680 MPa are presented.

The K_{IC} values were measured using the three point bend tests with slow loading rate of $\dot{K}$ = 2.0 MPa $m^{1/2}s^{-1}$. Specimen design and the testing procedure were in general accordance with the current ASTM recommendations. The K_{IC} data were corrected for a plastic zone size and the J_{IC} path independent integral technique was applied to determine the valid values of K_{IC} at higher temperatures.

The K_{ICd} values were deduced from the dynamic three point bend impact tests. The specimens having cross section of 15 x 15 mm and span of 60 mm were loaded in the hammer impact machine [14] with striking velocity of 1,5 m s^{-1} which produces the dynamic loading rate $\dot{K}$ = $2.5.10^5$ MPa $m^{1/2}s^{-1}$. An initial sharp fatigue crack was produced by cyclic loading with the stress intensity level K_f = 20 MPa $m^{1/2}$ for specimens used in the dynamic and in the static test as well.

In order to understand the influence of loading rate on fracture toughness and to provide the data required for crack tip strain rate calculation, the mechanical behaviour of all steels was examined in detail. The tension tests were conducted over the temperature range -196°C to 20°C for strain rate of 1.10^{-3} s^{-1} corresponding well to the calculated static crack tip strain rate $\dot{\varepsilon}_s$ - Figure 4. The dynamic yield stress for various temperatures was found from well known relation derived from slip-line field theory between applied load at general yield P_{GY} and yield stress σ_y for Charpy V notch specimen

$$P_{GY} = D\,\sigma_y \,. \qquad (1)$$

The constant of proportionality D was determined from the ratios P_{GY}/σ_y corresponding to static Charpy test. Then the values of P_{GY} read off from dynamic force-deflection records could be used to estimate dynamic yield stress σ_{yd} at strain rate conformable to the crack tip strain rates $\dot{\varepsilon}_d$ - Figure 4. At low temperatures, where applied fracture force was below P_{GY}, the values of σ_{yd} were obtained by extrapolation.

To determine the effect of strain rate on the fracture toughness behaviour, the crack tip strain rates were established by the procedure described in [15]. The plastic strain at the elastic plastic boundary near the crack tip for a stationary crack is differentiated with respect to time, by assuming that the applied load was proportional to the time of load application. This calculation would over approximate $\dot{\varepsilon}_s$ and $\dot{\varepsilon}_d$ but deeper in the plastic zone near the crack tip, the strain rates are higher, so we felt this is a reasonable approximation to the representative strain rates. The strain rates $\dot{\varepsilon}_s$, $\dot{\varepsilon}_d$ are shown in Figure 4 as a function of temperature for σ_{TS} = 680 MPa steel.

RESULTS AND DISCUSSION

It is generally recognized that the fracture toughness of steels with given microstructure and chemical composition can be conveniently described in terms of yield stress and other materials constants [9 - 12] (cleavage fracture stress, process zone size, crack tip radius) which are substantially independent of temperature and strain rate. The data of Figure 2 indicate that a unique relation exists between the yield stress and K_{IC}, K_{ICd} for both steels, provided the values of σ_Y, σ_{Yd} were correctly joined to the representative values of the crack tip strain rate. Therefore, the change of fracture toughness with temperature and strain rate is primarily given by temperature and strain rate dependence of yield stress. The same value of fracture toughness should be obtainable by different combinations of temperature and strain rate.

From the principles of plastic deformation theory it is possible to derive the relation between the absolute temperatures T_1 and T_2 at which $K_{IC} = K_{ICd}$ and simultaneously $\sigma_Y = \sigma_{Yd}$. Thus

$$\frac{T_1}{T_2} = \frac{\ln(C/\dot{\varepsilon}_2)}{\ln(C/\dot{\varepsilon}_1)} = \text{constant}, \qquad (2)$$

where C is a material constant. The ratios of T_1/T_2 are listed in Table 1 for the investigated steels at various fracture toughness levels. The ratio T_1/T_2 depends strongly on the type of steel and also decreases with increasing fracture toughness level for all steels. The average values of T_1/T_2 from Table 1 are compared in Figure 5 with the values of T_1/T_2 found from the condition $\sigma_Y = \sigma_{Yd}$. It is seen that the decreasing difference in the ratios of T_1/T_2 determined from toughness and yield stress analysis, respectively, leads to the better correlation between K_{IC}, K_{ICd} and σ_Y, σ_{Yd} shown in Figure 2.

Applied to the data presented here, equation (2) provides a method for converting a measured temperature dependence of K_{IC} into not easily measurable temperature dependence of K_{ICd} from the known ratio of the absolute temperatures T_1/T_2 at which $\sigma_Y = \sigma_{Yd}$. To determine T_1/T_2 it is not necessary to use the yield stress, but any temperature and strain rate sensitive metallurgical variable may be considered. For example, the notch toughness may serve well for this purpose as illustrated in Figure 5.

The correlation K_{IC} with K_{ICd} proposed in [5 - 7] is based on similar ideas. Contrary to our approach it is not necessary to determine the ratio T_1/T_2 through independent experimental procedure. The estimated crack tip strain rates and C = 10^8 s^{-1} [13] are substituted directly into the equation (2). Referring to Figure 3 it is evident that the fracture toughness is a single-valued function of the parameter $T \ln (C/\dot{\varepsilon})$ consistent only with the experimental data for σ_{TS} = 455 MPa steel. For the other steel the predicted values of K_{ICd} are lower than the measured ones. The correlation presented in [5 - 7] appears to lead to a conservative estimate of design stress to avoid fracture for σ_{TS} = 680 MPa steel. In fact, the observed discrepancy in Figure 3b can be related to the dependence of the ratio T_1/T_2 on strength and fracture toughness level previously demonstrated in Table 1, while according to [5 - 7] the ratio T_1/T_2 remains constant. Namely, substituting the strain rates of Figure 4 and C = 10^8 s^{-1} [13] into the equation (2) we arrive at T_1/T_2 = 1.72. This value is shown in Figure 5 by the dashed line.

The results of an investigation to develop a correlation between static and dynamic fracture toughness of steels having widely different strength levels may be summarized as follows.

1) The values of K_{IC} and K_{ICd} are a unique function of the crack tip yield stress.

2) The correlation of K_{IC} with K_{ICd} is derivable from the existing correlation of σ_y with σ_{Yd}.

3) The method suggested in this paper predicts K_{ICd} values which are in better agreement with the experimental measurements than K_{ICd} values predicted by methods developed up to now.

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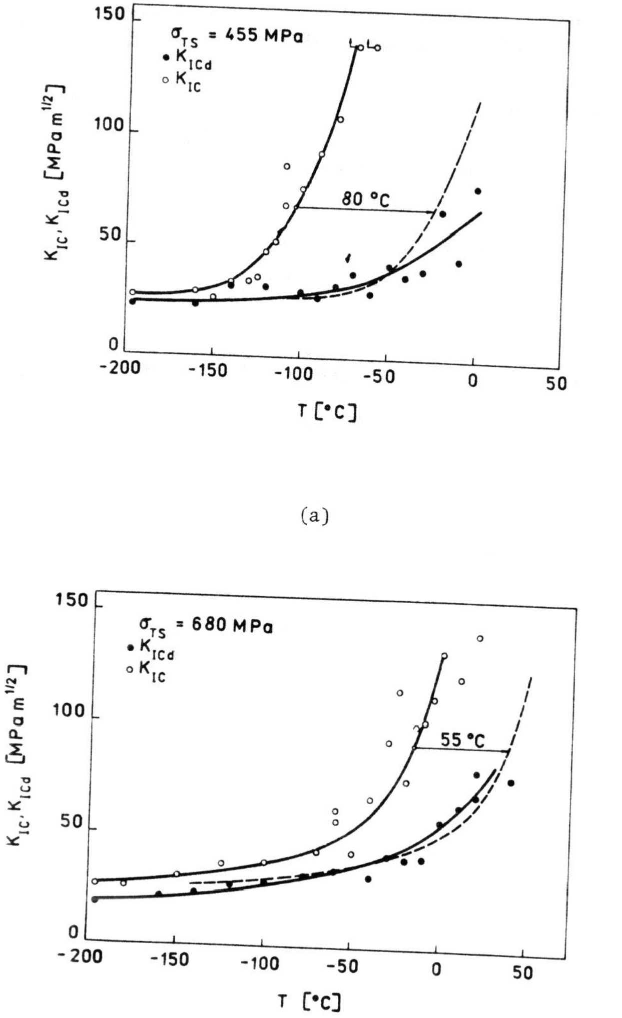
Table 1 The Ratio T_1/T_2 Determined from the Condition $K_{IC} = K_{ICd}$ for the Investigated Steels and Several Fracture Toughness Levels

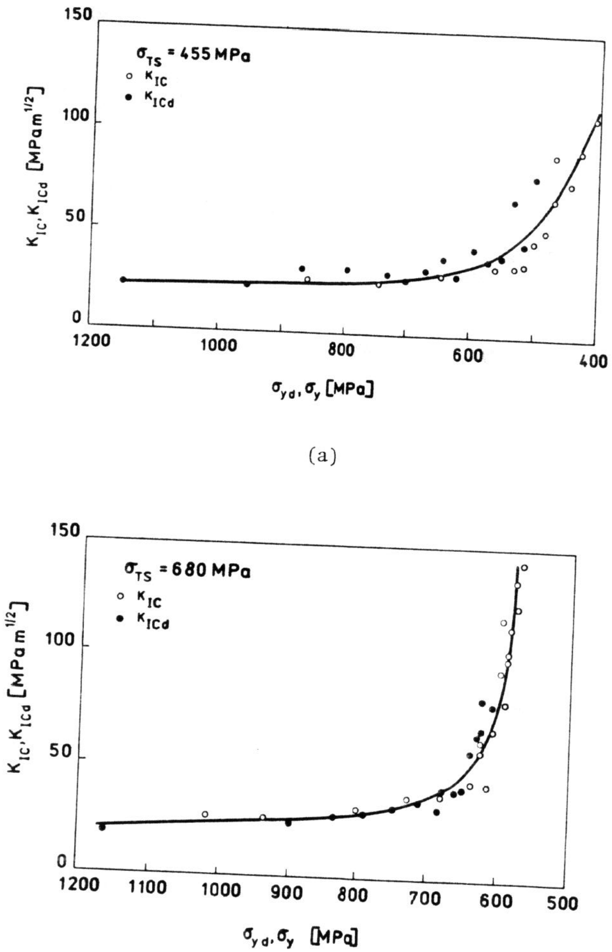
σ_{TS} [MPa] / K_{IC}, K_{ICd} [MPa m$^{1/2}$]	T_1/T_2						
	455	542	549	582	678	629	760
78.5	-	1.36	1.68	-	1.22	-	1.18
71.0	-	-	-	1.32	-	1.30	-
63.0	1.61	1.45	1.57	1.35	1.21	1.35	1.19
47.0	1.59	1.49	1.70	1.45	1.24	1.37	1.20
39.2	1.57	1.45	1.81	1.52	1.30	1.37	1.20
31.6	1.60	1.49	1.96	1.67	1.48	1.48	1.22
28.2	1.68	1.50	-	-	1.50	1.45	1.26
23.6	-	-	-	1.60	-	-	-
T_1/T_2 Average	1.61	1.45	1.74	1.48	1.34	1.38	1.20



(a)

(b)

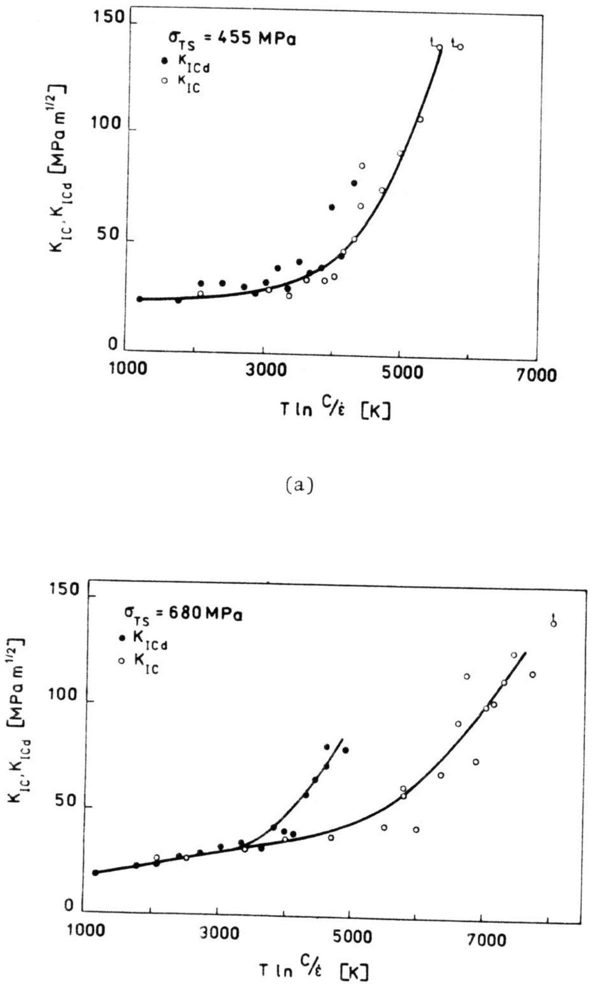
Figure 1 Experimental Values of K_{IC}, K_{ICd} versus Temperature for (a) σ_{TS} = 455 MPa Steel and (b) σ_{TS} = 680 MPa Steel. Dashed Line Indicates the K_{ICd} Temperature Dependence Determined According to [8]



(a)

(b)

Figure 2 Fracture Toughness Data Plotted versus Yield Stress



(a)

(b)

Figure 3 Relation Between Fracture Toughness and the Strain Rate Temperature Parameter T ln $(C/\dot{\varepsilon})$

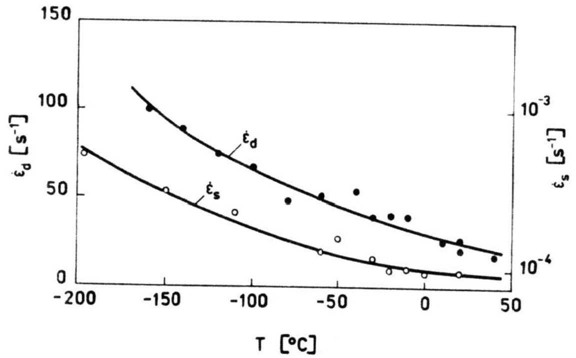


Figure 4 Temperature Dependence of the Strain Rate at the Plastic Elastic Boundary for Static ($\dot{\varepsilon}_s$) and Dynamic ($\dot{\varepsilon}_d$) Three Point Bend Tests [15]

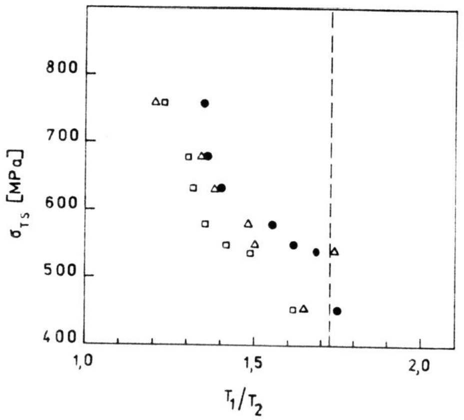


Figure 5 The Ratios T_1/T_2 Found From Temperature Behaviour of Fracture Toughness (Δ), Yield Stress (•) and Notch Toughness (□)