DYNAMIC FRACTURE TOUGHNESS OF A STRUCTURAL STEEL

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ABSTRACT

The velocity dependence of the dynamic fracture toughness, K_{ID}, associated with rapidly propagating crack in low alloy weldable structural steel has been determined and analyzed over the temperature range 0 to -140° C. Results for fractures propagating at $\dot{a}$ = = 300 m/s to $\dot{a}$ = 1200 m/s in 20 mm thick, wedge loaded, rectangular double cantilever beam (RDCB) specimens are presented. A dynamic finite element code was used to compute the K_{ID} values and check the validity of simple approximate crack propagation models in RDCB specimens based on beam theory. Both the dynamic finite element analysis and approximations agree well with the experiments. The dynamic fracture data for running cracks K_{ID} are compared with the static (K_{IC}) and dynamic (K_{Id}) fracture initiation toughness values.

KEY WORDS

Dynamic fracture toughness; crack velocity; double cantilever beam specimen; temperature; reference fracture toughness curves;

INTRODUCTION

In the broad area of dynamic fracture mechanics, the response of structural materials to fast fractures is of special importance. To stop a brittle crack in a structure requires a dynamic stress intensity factor $K_I(\dot{a})$ in the structure and the material's dynamic fracture toughness K_{ID} are in agreement with linear dynamic fracture mechanics simple concept

$$K_I(\dot{a}) < K_{ID} \qquad (1)$$

Actual quantitative treatments of criterion (1) present difficulties. Rigorour calculations for structures or specimens with finite dimensions require a fully dynamic analysis of $K_I(\dot{a})$ performed by expensive and complicated numerical methods.
Recent studies on various steels (Hoagland, 1977; Hahn, 1974; Burns,

1973; Bílek, 1978; Debel, 1977) indicate that the material property K_{ID} is a complex function of metallurgical variables, test temperature and crack velocity $\dot{a}$. Therefore, for any given steel, a three-dimensional plot of dynamic fracture toughness, temperature and velocity is needed to provide a complete characterization of resistance to fast fracture. It is the purpose of the present investigation to contribute to the scant information available concerning the temperature and crack velocity dependence of K_{ID} values for a low alloy structural steel. The experimental procedure relies on slowly wedging apart the arms of a precracked rectangular double cantilever beam (RDCB) specimen as proposed by Hoagland (1972, 1977) and theoretically treated by Kanninen (1974, 1977). The preliminary results obtained for Homalite 100 (Fig.1) and for 4340 alloy steel (Fig.2) with a series of RDCB specimens agree well with independent dynamic photoelasticity K_{ID} measurements conducted by Irwin (1979) and Dally (1979).
The agreement confirm the reliability of the experimental technique adopted in this paper and supports the K_{ID} approach to material´s evaluation.

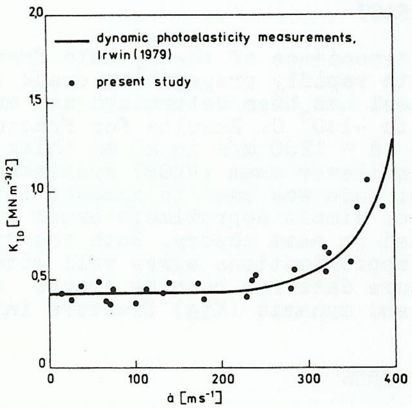

Fig. 1. Velocity dependence of K_{ID} values for Homalite 100 obtained by slow wedging of RDCB specimens at room temperature.

EXPERIMENTAL

We have chosen for the dynamic fracture toughness measurements a highly rate sensitive structural steel with a chemical analysis (wt %) of 0.16 C, 1.16 Mn, 0.33 Si, 0.013 P, 0.010 S, 0.04 Cu, 0.03 Ni, 0.55 Cr, 0.46 Mo, 0.025 Nb, 0.062 Al having a room temperature tensile strength σ_{TS} = 680 MPa.
The K_{IC} values were measured using three point bend tests with slow loading rate of $\dot{K}_I$ = 2.0 MPa m$^{1/2}$s^{-1}. Specimen design and the testing procedure were in general accordance with the current

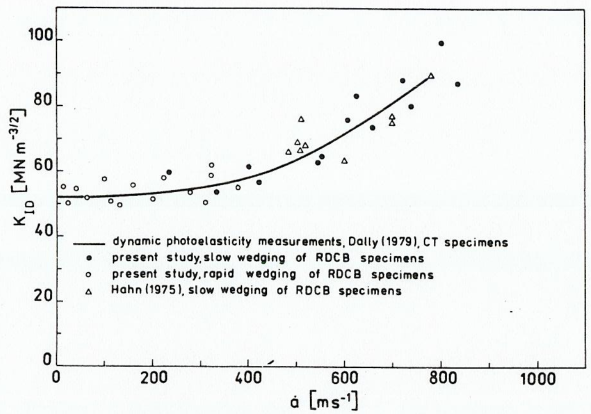

Fig. 2 Velocity dependence of K_{ID} values for 4340 alloy steel (R_c = 46) at room temperature.

ASTM recommendations. The K_{IC} data were corrected for a plastic zone size and a J_{IC} path independent integral technique was applied to determine valid values of K_{IC} at higher temperatures.
The K_{Id} values were deduced from the dynamic three point bend impact tests. The specimens having a cross section of 15 x 15 mm and span of 60 mm were loaded in the hammer machine with a striking velocity of 1.5 m/s which produces the dynamic loading rate $\dot{K}_I$ = 2.5 x x 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 both the dynamic and static tests.
The unstable crack propagation study employed RDCB specimens which were slowly wedge loaded as described by Hoagland (1972, 1977), Debel (1977) and Bílek (1978). Our experimental set up as installed on a 200 kN Zwick machine is illustrated in Fig.3.
Essentially, the identical specimen geometry used recently by Bílek (1978) to investigate 4340 steel fracture properties was used, however the specimen thickness was reduced from 25 mm to 20 mm. The crack velocity was varied by changing the root radius of the starting notch from 0.2 to 1 mm. The blunted notch permits the specimen to sustain a stress intensity K_{Iq} prior to the onset of crack propagation which is greater than the K_{IC} values. Therefore, as soon as a sharp crack emerges from starting notch, the crack immediately propagates rapidly under constant displacement conditions. The crack velocity measuring system consisted principally of a grid of silver paint strips insulated from the specimen surface by a layer of epoxy adhesive. During a typical test, a steady-state velocity was maintained from start until shortly before arrest as can be seen from Fig.4 were the crack velocity profiles are shown at various temperatures.

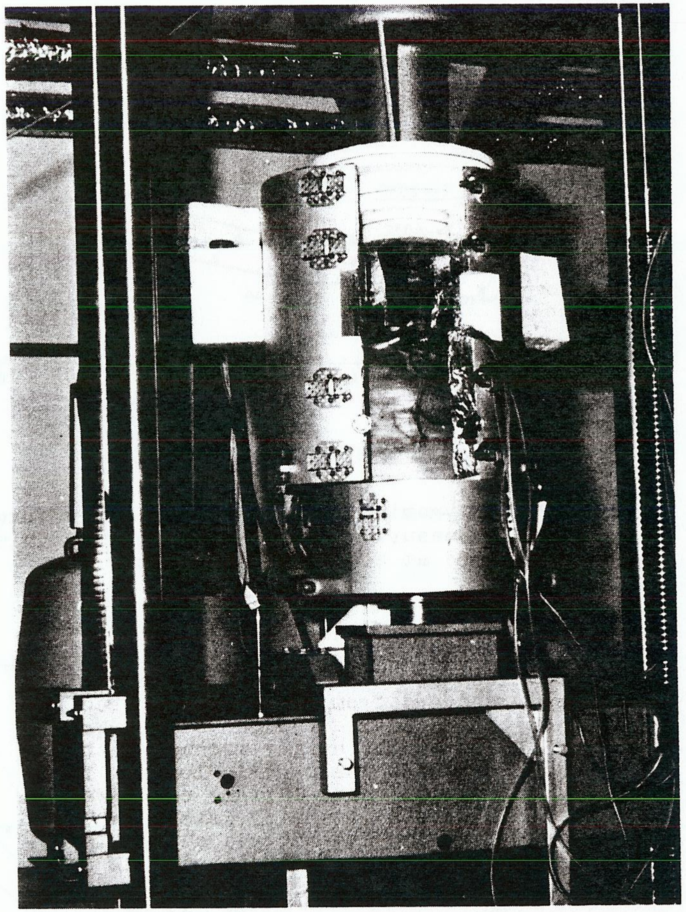

Fig. 3. Wedge loading test arrangement showing test specimen placed in cooling chamber. The specimens were loaded with a wedge having an included angle of 11°. Tie--down device is not shown.

To minimize the interaction between loading arrangement and specimen the loading pins were supported by a tie-down device similar to that used in Hoagland's (1977) experiments.

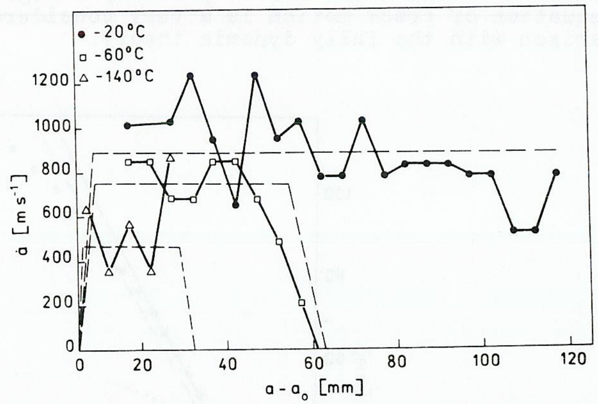

Fig. 4. Crack velocity profiles at different test temperatures. Finite element calculation are plotted by dotted lines.

RESULTS AND DISCUSSION

The values of dynamic fracture toughness K_{ID} were obtained independently from measurements of (i) K_{Iq} and crack length at arrest a_a, or (ii) K_{Iq} and $\dot{a}$. In the first case without resorting to the detailed analysis presented by Hoagland (1972) the K_{ID} values were calculated from the relation

$$K_{ID} = (K_{Iq}\ K_{Ia})^{1/2} \qquad (2)$$

where K_{Ia} denotes crack arrest fracture toughness determined by static finite element calculations due to Bílek (1980). In the second case the values of K_{ID} were determined by dynamic finite element analysis using the BKDYN program based on quadrilateral isoparametric elements and an explicit scheme of time integration. Crack propagation was simulated by the gradual release of nodal points in a similar way as proposed by Urabe (1977) and Kobayashi (1978) for dynamic RDCB specimen analysis. Applying fine finite element breakdown consisting of 600 elements for one half of RDCB specimen the K_{ID} values were calculated from the measured crack velocity profiles. The plane strain K_{ID} values determined by finite element computation were some 5 to 15 % higher than the K_{ID} values obtained from Eq. (2) in dependence on K_{Iq}/K_{ID} ratio. The crack velocity profiles calculated by the finite element technique for the values of K_{ID} predicted by Eq. (2) and taken independent of $\dot{a}$ agree well with the measured values except in the region of crack start and arrest where the actual and numerical experiment are insufficiently accurate. Also good agreement between crack growth versus time either measured or calculated by the finite element approach and by a finite difference treatment of RDCB specimen beam model on elastic foundation suggested by Kanninen (1974) can be seen from Fig.5. It can be clearly seen that the prediction of the crack arrest point by integrating of Freund's (1972) equation of crack motion is a very considerable underestimate in comparison with the fully dynamic theory.

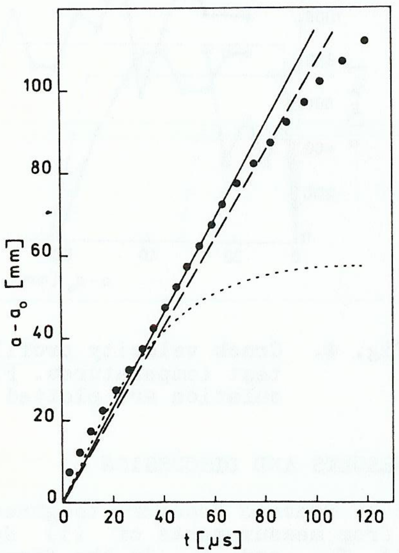

Fig. 5. Theoretical calculation and experimental measurement of crack propagation at -100^{o} C. $a_o = 3 \times 10^{-2}$ m K_{Iq}/K_{ID} = = 3.2. (● experimental points, —— RDCB model due to Kanninen (1974), --- finite element calculations, ····Freunds (1972) equation of crack motion).

Figure 6 demonstrates the effect of crack velocity on K_{ID} values at selected temperatures; a trend toward higher K_{ID} values with increasing fracture velocity is apparent. However, the exact form of the dependence is not clear because of limboo range for crack velocities lower than 300 m/s. Further experimental work using the rapid wedging of RDCB specimens due to Burns (1973) is required to complete the K_{ID} - $\dot{a}$ curves.

Figure 7 compares the K_{ID} values with our K_{IC} and K_{Id} measurements made for the same heat of steel. The most striking feature of the results is the large difference between the K_{ID} values for a propagating crack, and the dynamic initiation values K_{Id} for a rapidly loaded, but stationary crack. It has generally been thought that K_{Id} values approximate the toughness of propagating cracks. On the other hand this might be true for slower cracks in our steel. It should be pointed out that Hahn (1974) observed

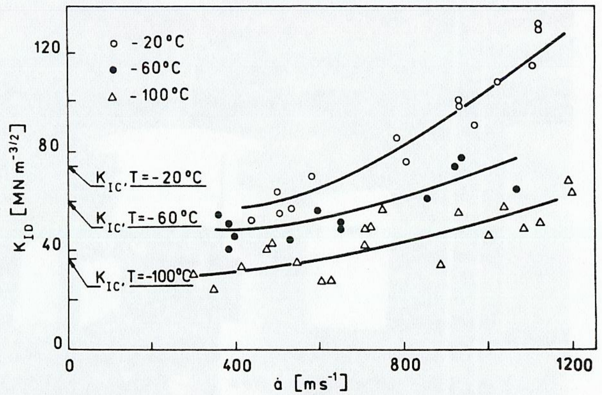

Fig. 6. Dynamic toughness K_{ID} versus the measured mean crack extension velocity $\dot{a}$ at three temperatures.

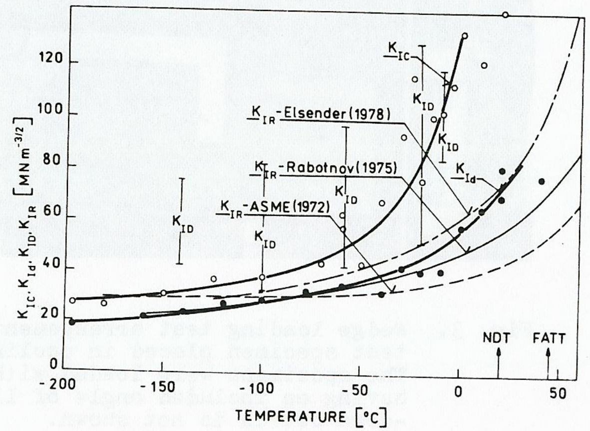

Fig. 7. Estimated fast fracture toughness (K_{ID}) compared with static (K_{IC}) and dynamic (K_{Id}) fracture initiation toughness at various temperatures. The reference fracture toughness K_{IR} curves constructed according existing procedures are also shown.

similar behaviour in A517F steel. Our K_{ID} values are well above the reference fracture toughness curves K_{IR} also drawn in Fig.7.

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