THE INFLUENCE OF STEEL MICROSTRUCTURE ON DYNAMIC FRACTURE TOUGHNESS

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The influence of initial microstructure of low alloy weldable (C-Mo-Cr) steel on dynamic fracture toughness \( K_{1d} \) is demonstrated. The results obtained within wide temperature range are compared with the \( K_{1d} \) values from Charpy instrumented tests for seven different microstructures. Dynamic elastic finite element analysis shows the limited applicability of static approach to the \( K_{1d} \) evaluation and demonstrates the significance of stress wave phenomena. The problems associated with application of critical stress fracture criterion in dynamic situation are briefly outlined.

INTRODUCTION

The application of a dynamic fracture mechanics approach to the safety assessment of dynamically loaded engineering structures requires the availability of relevant data. Namely it is necessary to have information on dynamic fracture toughness \( K_{1d} \) associated with rapid loading conditions that can occur during operation since \( K_{1d} \) is a decreasing function of loading rate \( K_1 \) for the most of structural steels. In this paper we apply the method developed by Klepacko (1,2) to study the temperature dependence of \( K_{1d} \) for various complex microstructures in C-Cr-Mo steel. The experimental data were evaluated using the static and dynamic finite element procedure developed by Kuna et al (3) and by Bilek et al (4).

In order to understand our experimental findings we have had to establish a detailed theoretical description of the stress field ahead of the crack by means of dynamic elastic-plastic computations for the linear hardening material. We have attempted to predict the \( K_{1d} \) values with the aid of a critical stress criterion which has already a sound theoretical basis created by Knott et al (5,6) for static fracture toughness \( K_{1c} \).

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**EXPERIMENTAL PROCEDURE**

Our steel having chemical composition 0.13% C, 0.61% Mn, 0.10% P, 0.28% Si, 0.007% S, 2.39% Cr, 0.22% Ni, 0.35% Mo, 0.05% Cu was thermally treated to seven different microstructure stages described in Table 1.

**TABLE 1 - Description of initial microstructural conditions**

<table>
<thead>
<tr>
<th>Microstructure</th>
<th>Heat treatment</th>
<th>NDT, °C</th>
<th>Static yield stress, MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>MI</td>
<td>As received</td>
<td>-15</td>
<td>444</td>
</tr>
<tr>
<td>MII</td>
<td>Q, 940°C/water</td>
<td>-25</td>
<td>1001</td>
</tr>
<tr>
<td>MIII</td>
<td>Q,T 940°C/water/550°C</td>
<td>-15</td>
<td>1034</td>
</tr>
<tr>
<td>MIV</td>
<td>Q,T 940°C/water/640°C</td>
<td>-35</td>
<td>729</td>
</tr>
<tr>
<td>MV</td>
<td>Q,T 940°C/water/720°C</td>
<td>-50</td>
<td>572</td>
</tr>
<tr>
<td>MVI</td>
<td>Normalizing 940°C/air T 720°C</td>
<td>-15</td>
<td>524</td>
</tr>
<tr>
<td>MVII</td>
<td>Normalizing 940°C/air T 780°C</td>
<td>-30</td>
<td>385</td>
</tr>
</tbody>
</table>

Experimental set up follows from Figure 1. WLC7 specimen with geometry shown in Figure 2 is placed between two steel bars. The first loading bar produces a stress pulse $\sigma_1(t)$ with duration time of $t_1 = 52\mu s$, $\sigma_2(t)$ is a stress pulse transmitted to the second bar. To evaluate the $K_{1d}$ values we used procedure given in references (1,2) completed by our finite element computations.

**FINITE ELEMENT ANALYSIS**

All calculations have been done by finite element method for the geometry given in Figure 2 and ratio $a/w = 0.5$. The problem was treated as plane one. The values of static stress intensity factor $K_1$ were determined by means of hybrid technique in reference (3).

For dynamic calculations, the program BKDYN from reference (4) was used to solve elastic and elastic-plastic problems on ICL 2950 computer. This program makes use of a four node quadrilateral elements and for time integration the explicit central difference method is implemented with automatic selection and adjustment of time step. The loading was modelled by real opening force $F(t)$ shown in Figure 3 and the values of dynamic stress intensity factor $K_1(t)$ was found from the displacements $\psi$. The boundary conditions correspond to free surface specimen during the impact loading. Typical results are summarized in Figure 4 for data corresponding to microstructure MII at $T = 20^\circ C$, mesh having 2500 elements and 2060 nodal points for one half of the specimen.
RESULTS AND DISCUSSION

The results shown in Figure 3 indicate a great difference between $K_I^s$ and $K_I(t)$ so one should be very carefully evaluating $K_{Id}$ values and the procedures based on static analysis as recommended in references (1,2). The extensive plastic zone development studies in the particular form of Figure 4 suggest that despite the very small specimens the plane strain conditions prevail and our $K_{Id}$ data are valid from this point of view. Figures 3, 4 and 5 demonstrate the complicated way of crack tip loading during the test. Figures 7 to 9 show temperature dependence of $K_{Id}$ for all microstructures investigated. Considering the scatter of experimental data the inexpressive decrease of $K_{Id}$ in comparison with Charpy test data can not be interpreted clearly in terms of $K_I$ increase from $10^5$ to $10^6$ MPa m$^{1/2}$ s$^{-1}$ to e.g. see Figure 8. The Charpy $K_{Id}$ values determined in accordance with ASTM recommendations represent the minimum on $K_{Id}(K)$ curves. This conclusion is also valid for microstructures W (tempered martensite) and WI (bainite) below NDT. But for $T > NDT$ Hopkinson split bar technique data lie substantially below Charpy $K_{Id}$ values. For martensite microstructures (MI, MII) the $K_{Id}$ values at $K_I = 10^6$ MPa m$^{1/2}$ s$^{-1}$ are above the K,$_{Id}$ data at $K_I = 10^5$ MPa m$^{1/2}$ s$^{-1}$ for $T > -50^\circ C$. In general, it appears that Charpy impact data represent good approximations for the minimum of dynamic crack initiation toughness important in engineering design.

Knot et al. (5,6) have presented an analysis which related $C_{FF}$ to $K_{Id}$. Essentially this approach was adopted in this paper for $K_{Id}$ interpretation. The cleavage stress $C_{FF}$ and process zone size $R_c$ over which this stress is reached were found following paper by Holzmann et al (7). For example, for microstructure MIX, $C_{FF}$ = 1600 MPa and $R_c = 0.065$mm. Assuming that both quantities $C_{FF}$ and $R_c$ are independent of strain rate and temperature we find with the help of Figure 6 that fracture criterion $\delta_{YY} = C_{FF}$ is met for $x = R_c$ at time $t = 15\mu s$. On the other hand at this time the dynamic stress intensity (Figure 3) reaches the value of $K_{Id}(t) = 40$ MPa m$^{1/2}$ which is below $K_{Id} = 203$ MPa m$^{1/2}$. This value of $K_{Id}$ is reached later at $t = 25.5 \mu s$, which supports the existence of incubation time (10.5 $\mu s$) proposed by Kalkhoff and Sontag (8) to initiate a fracture by stress pulse loading. It appears that $K_{Id}$ is not controlled only by $C_{FF}$ and $R_c$ but also by incubation time necessary to start a crack. Stress analysis to this check hypothesis at other temperature (different loading) is in progress.

SYMBOLS USED

- $a = $ crack length (mm)
- $A = $ bar cross section (m$^2$)
- $E = $ Young modulus (MPa)
- $F(t) = $ applied force (kN)
- $2H = $ height of the specimen (mm)
- $K_{Id}^s = $ static and dynamic stress intensity factor (MPa.m$^{1/2}$)
- $r' = $ loading rate (MPa.m$^{-1/2}$)
- $t' = $ loading rate (MPa.m$^{1/2}$)

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K_{10}, K_{1d} = static and dynamic fracture toughness (MPam\(^{1/2}\))
NDT = nil ductility transition temperature (°C)
R_{p} = process zone size (mm)
t = time (µs)
T = temperature (°C)
w_{y} = displacement component in y direction (mm)
w = length of specimen (mm)
x = distance from a crack tip
α = wedge angle
\lambda_{t} = loading pulse duration
\varepsilon_{I}(t), \varepsilon_{T}(t), \varepsilon_{R}(t) = loading, transmitted and reflected stress pulse (MPa)
\varepsilon_{yy} = normal stress component in y direction (MPa)
\sigma_{CF} = critical cleavage stress (MPa)

REFERENCES

Figure 1 Schematic experimental set up for $K_{Id}$ measurements.

Figure 2 Wedge loaded compact tension WLCT specimen geometry.
Figure 3 Static $K^S$, dynamic $K_d(t)$ stress intensity factor and loading pulse per 1 mm thickness $F(t)$ vs. time.

Figure 4 Plastic zone development for 20, 25 and 30 $\mu$s for linear hardening with secant modulus $E/165$.
Figure 5 Crack profiles

Figure 6 Normal stress behaviour at the crack tip

Figure 7 Temperature dependence of $K_{1d}$ for various microstructures
Figure 8 Instrumented Charpy $K_{ld}$ data

Figure 9 Comparison of experimental $K_{ld}$ data for two microstructures at two loading rates