EFFECT OF LOADING RATE ON THE FRACTURE MECHANICS CHARACTERISTICS OF E420-C HIGH STRENGTH STEEL

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The effect of loading rate on the fracture mechanics properties of E420-C steel was studied using instrumented Charpy impact experiments combining with magnetic emission measurement at different temperatures. The critical stress intensity factors (K_{Id}) related to the initiation of the fracture have been determined using different methods depending on the type of the fracture. In the upper shelf region the instant of ductile crack initiation was determined on the basis of the magnetic signals applying the „field method". In the lower shelf region the impact response curve method was used for evaluating K_{Id}. Due to the strong oscillation of the force signals, the magnetic emission signals had to be used for determining the time to fracture in most of these cases. The brittle to ductile transition behaviour was then analysed and compared at the two applied loading rate.

INTRODUCTION

In the engineering practice it is of importance to know the effect of loading rate on the material behaviour. The strain rate sensitivity of the materials could be very different. So the aim of the present work was to investigate the effect of loading rate on the fracture mechanics properties and on the brittle to ductile fracture transition behaviour of the E420-C high strength microalloyed steel using instrumented impact testing.

EXPERIMENTS AND RESULTS

The chemical composition and the mechanical properties of the investigated material can be seen in Table 1. Instrumented Charpy impact experiments have been performed on pre-cracked Charpy-V specimens combining with magnetic emission measurement invented by Winkler (1) on a 300 J instrumented impact pendulum. Two different impact velocities were applied: v_0=2.75 m/s and v_0=5.5 m/s. The pre-cracking was done on an Amstler resonance machine producing $a/W \approx 0.5$ relative crack length. The impact experiments were performed at five different temperatures: 20 °C, 0 °C, -20 °C, -40 °C and -60 °C. The histories of force (F) and magnetic emission (ME) have been registered.

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TABLE 1 - Chemical composition and mechanical properties of E420-C steel

C, wt%	Si, w%	Mn, wt%	P, wt%	S, wt%	Nb, wt%	V, wt%	Cr, wt%	Ni, wt%	Cu, wt%
0.18	0.46	1.44	0.027	0.03	0.035	0.045	0.06	0.03	0.08

Yield stress, MPa	Ultimate tensile strength, MPa
444	593

The critical stress intensity factors (K_{Id}) related to the initiation of the fracture have been determined using different methods depending on the type of the fracture. The fracture characteristics were studied and checked by SEM.

In the upper shelf region the magnetic emission signals were used for determining the instant of ductile crack initiation. Stable crack initiation can usually not be determined directly from ME signals. This is demonstrated by an experimental result of a ductile behaving specimen, see Fig. 1. For these applications a method was developed by Lenkey and Winkler (2) which uses the integrated ME signal, i.e., the magnetic field history, MF(t), eq. 1:

$$MF(t) = \int_{\tau=0}^{t} ME(\tau)\, d\tau \qquad (1)$$

It was observed that ME signals originated by crack propagation can be distinguished from those originated by Barkhausen noise in the field curve by a change of the slope. This is demonstrated in Fig. 2. The rupture event is indicated by a discontinuity in the slope of the field curve. Utilising this field method the initiation point can be determined (see in Fig. 2.). The J-integral value related to the initiation can be then derived with eq. 2 (Ref. (3)):

$$J_{id} = \frac{2 \cdot U_i}{B \cdot (W - a_0)} \qquad (2)$$

where U_i is the energy absorbed by the specimen up to the initiation and was calculated by integrating the force-displacement (F-f) curve using eq. 3:

$$U_i = \int_{f=0}^{f_i} F(f)df \qquad (3)$$

Then the relevant K_{Id} value can be determined for plain stress condition using eq. 4.:

$$K_{Id} = \sqrt{E \cdot J_{id}} \qquad (4)$$

where E=210000 MPa was considered as the Young modulus of the investigated steel.

In the transition region, if brittle crack initiation occurred after significant plastic deformation, the critical J integral and K values at crack initiation was determined using eq. (2)-(4).

In the lower shelf region and in some cases in the transition region brittle crack initiation occurred preceding by no any macroscopic plastic deformation. One example is shown in Fig. 3. In these cases the „3τ" criteria - proposed by Ireland (4) - was usually not fulfilled therefore the quasistatic equations cannot be used any more for determining K_{Id}. For these cases the impact response curve method -proposed by Kalthoff (5) - was applied. For this method the time to fracture (t_F) is necessary to be determined. Unstable crack propagation is indicated by a force drop and usually is accompanied by a sharp peak of the magnetic signal according to a rapid crack jump. But due to the strong oscillation of the force signals sometimes it was difficult to determine the instant of the brittle fracture from the force-time curves. In these cases the magnetic emission signals or sometimes the magnetic field signals had to be used for determining the time to fracture (see in Fig. 4.).

With the measured time-to-fracture the dynamic fracture toughness can be determined with eq. 5:

$$K_{Id} = R \cdot v_0 \cdot t'' \qquad (5)$$

where t''= f(t') is given in tables of reference (5)

and $$t' = g(t) = t_F \cdot \left\{ 1 - 0.62\left(\frac{a_0}{W} - 0.5\right) + 4.8\left(\frac{a_0}{W} - 0.5\right)^2 \right\} \qquad (6)$$

where R=301 GN/m$^{5/2}$ for a machine with c_M=8.1x10^{-9} m/N machine compliance. If the machine complience differs from this value, a first-order correction factor should be used in calculating R that is: 1.276/(1+0.276 c_M/8.1x10^{-9} m/N). The machine compliance was c_M=2.335x10-^{8} m/N in our case.

The experimental results are summarised in Fig. 5. and Fig. 6. For characterising the brittle to ductile transition behaviour of the material the following mathematical function was used to fit the experimental data:

$$K_{Id} = A_0 + A_1 \cdot \tanh[\frac{1}{A_2} \cdot (T - A_3)] \qquad (7)$$

where A_0, A_1, A_2, A_3 are empirical constants. The results of fitting procedure can be seen in Fig. 5. and Fig. 6. The temperature at a fracture toughness level of 100 MPa√m is often used for characterising the brittle-ductile transition region of ferritic steels (Ref. (6)). The transition temperatures (TT) based on this interpretation evaluated with eq. (7) are: $TT_{2.5}$=-54.2 °C for the lower impact velocity, and $TT_{5.5}$=-34.1 °C for the higher one.

It can be seen from Fig. 5. and Fig. 6. that the K_{Id} values in the upper shelf and in the lower shelf region do not differ significantly for the two different loading rate. But the brittle crack initiation appeared at higher temperature (-20 °C) in case of the higher impact velocity at the very beginning of the loading process following by crack arrest and stable crack propagation (lowest point in Fig. 6.). While in case of the lower impact velocity brittle initiation was observed at T=-40 °C preceding by significant plastic deformation and the linear elastic behaviour has been reached only at T=-60 °C.

CONCLUSIONS

From the results the following can be concluded:

1. The loading rate in the order of 1 m/s has significant effect on the brittle to ductile fracture transition behaviour of the investigated high strength microalloyed steel.

2. The magnetic emission measurement applying the „field method" could be used for determining the instant of stable crack propagation in case of this material.

3. The position of the $K_{Id}(T)$ curve has been shifted by ΔT=20.1 °C to higher temperatures due to increasing the impact velocity from 2.5 m/s to 5.5 m/s.

ACKNOLEDGEMENTS

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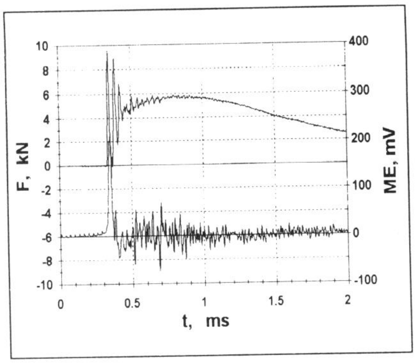

Figure 1. Force and ME signals of pre-cracked sample (v_0=5.5 m/s, T=20 °C)

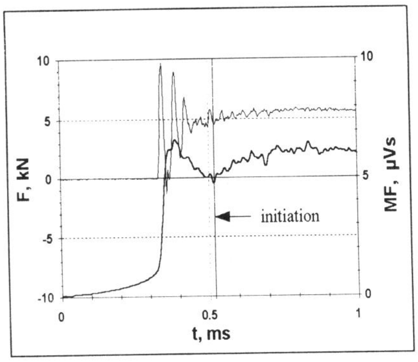

Figure 2. Force and MF signals of pre-cracked sample (v_0=5.5 m/s, T=20 °C)

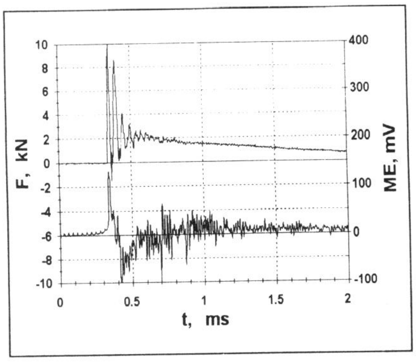

Figure 3. Force and ME signals of pre-cracked sample (v_0=5.5 m/s, T=-40 °C)

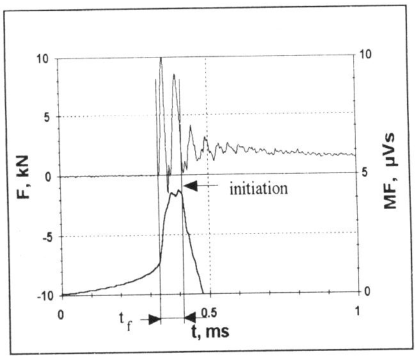

Figure 4. Force and MF signals of pre-cracked sample (v_0=5.5 m/s, T=-40 °C)

$$K_{Id} = 126.5 + 61.8 \cdot \tanh[\frac{1}{8.87} \cdot (T + 50)]$$

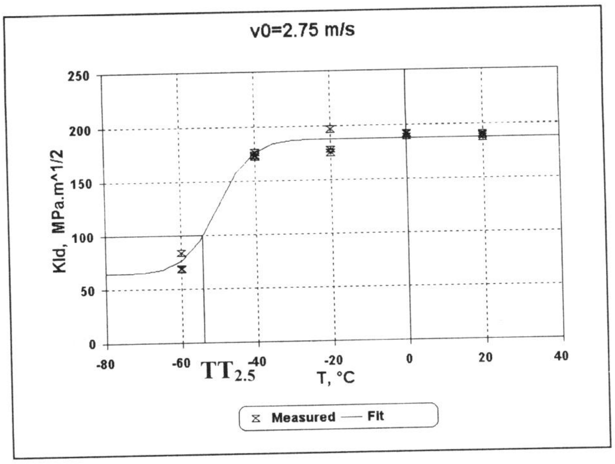

Figure 5. Dynamic fracture toughness vs. temperature for v_0=2.75 m/s impact velocity

$$K_{Id} = 126.5 + 64 \cdot \tanh[\frac{1}{13.7} \cdot (T + 27.95)]$$

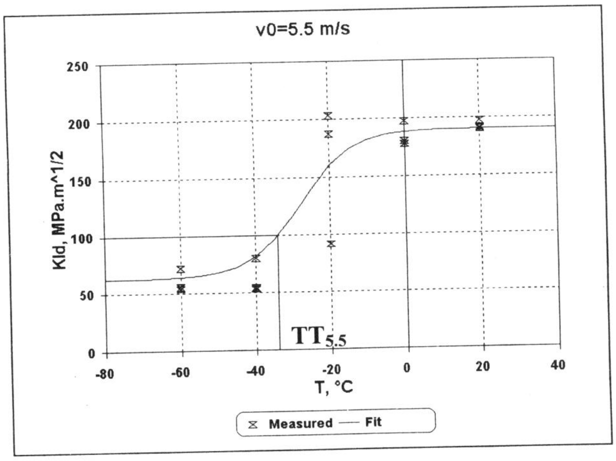

Figure 6. Dynamic fracture toughness vs. temperature for v_0=5.5 m/s impact velocity