FRACTURE TOUGHNESS TESTING OF DUCTILE MATERIALS SHOWING STABLE CRACK GROWTH

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Fracture toughness tests were carried out on several HSLA steels showing different morphology of sulphide inclusions.
In order to measure the fracture toughness the following parameters were chosen: K_c, δ_c, J_c. In the case of thin specimens these parameters did not characterize the fracture toughness with sufficient accuracy. So, the specific crack propagation energy Lp was proposed as a measure of fracture toughness and a good correlation between Lp and stereological characterics of inclusions was found.

INTRODUCTION

The Griffith's model and its modifications introduced by Irwin, Orowan, Dugdale and Barenblatt [1] allowed to define some standard fracture characteristics, like K_{Ic} and δ_c. The analysis of the energy dissipation in the vicinity of the crack tip resulted in the introduction of J-integral as a measure of fracture toughness (Rice [2]). All these parameters and the characteristic T describe well the fracture toughness of the material tested while plain strain can be assumed.
As high strength low alloy steels are usually used in the form of hot rolled plates and they are materials of high ductility in many cases it is impossible to machine out of the specimens a sufficient size for fracture tests.

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In addition a large plastic deformation and stable crack growth is usually observed during fracture of those materials. It required new concepts of fracture toughness testing.

The analysis of the crack growth process in ductile steels indicates three characteristics stages [3]:

1. fracture initiation (plastic deformation of the crack tip up to
2. subcritical stable crack growth (appearing of the Neuber's zone and its development),
3. terminal instability (unstable crack growth).

The initial crack length affects the above described process as shown in Fig. 1.

The stable crack growth is accompanied by the continuous increase in stress (see Fig. 1) in the range

$$\sigma_{in} \leqslant \sigma \leqslant \sigma_c \tag{1}$$

the quantity of this range of stress determines the mechanism of fracture.

Many works [4,5,6,7,8] concerning the stable crack growth give theoretical solutions to this problem i.e. differential equations describing the relationship between load and crack length.

For example Czerepanov [5] put the following equation:

$$\frac{dR}{dl} = \frac{\partial R}{\partial l} + \frac{\partial R}{\partial P} \cdot \frac{dP}{dl} \tag{2}$$

Independently Wnuk [3] proposed:

$$\frac{dR}{dl} = \frac{R_0}{\Delta} - \frac{1}{2} \ln\left(\frac{4R}{\Delta}\right) - \frac{1}{2} \tag{3}$$

Although these equations are elegant they are very difficult in practical application.

Energetical analysis of the subcritical crack growth revealed that the cohesion energy is negligible in comparison with the energy of plastic deformation. consequently, after a theoretical approach of Orovan [7, 9] verified experimentally by Goodier and Field [9], assuming that the energy of plastic deformation is independent of the crack kdngth, the following relation can be introduced:

$$\frac{\partial W_P}{\partial A} = \frac{Y}{l} \int_l^a \frac{\partial W(r,l)}{\partial l} \, r \, dr \tag{4}$$

The quantity of the "plastic dissipation of energy" can be considered as a measure of fracture toughness of ductile materials.
Practical evaluation of this parameter requires the continuous measuring of the crack length growth.
In many cases the accuracy of such measurements is problematic.
The experience of the authors in fracture testig of HSLA steels allows to propose the specific crack propagation energy Lp as an easy to evaluate, sensitive to small changes in material structure, parameter describing the subcritical crack growth. Lp is defined as follows:

$$L_p = \frac{1}{B \cdot \Delta a} \int_{u_c}^{u_K} P du \qquad (5)$$

Lp is an integral giving the average value of energy absorbed during the stable crack growth in the range from crack initiation to terminal instability. It should be stressed that the equation [5] is valid if the constant value of Wp can be assumed.

EXPERIMENTAL PROCEDURE

The aim of the investigations carried out in this work was to establish the effect of sulphide inclusions morphology on fracture toughness and to verify the practicability of the proposed specific crack propagation energy for stable crack growth assesment, 15 different materials were used. 5 transverse (T-L) and 5 longitudinal (L-T) specimens were cut out from each steel plate. The specimens were SE(B) type with dimensions 6 x 12 x 55 mm. The specimen geometry and the procedure of preparing the fatique precrack were chosen according to the E 399 Standard [10].

During the fracture toughness test the load – load point displacement curve was recorded. The initiation of slow stable crack advance from the blumled crack tip was established with the use of the potential drop (PD) method. The values of stress intensity factors were computed according to the E 399 Standard (10), assuming the load at initiation of stable crack growth was the critical one.
The values of crack opening displacement were calculated at initiation of stable crack growth according to the procedure described in the BS DD:19 Standard [11]. The values of J-integral were established with the help of single-specimen technique. The procedure was in agreement with the E 813 Standard [12].

In order to evaluable the specific crack propagation energy the range of the load-load point displacement curve record was extended up the displacement 5-10% larger than the displacement corresponding to the maximum load. In the case of more brittle materials the load displacement curve was recorded up to the unstable crack growth. The diagram obtained allowed to measure the work of extermal load:

$$W = \int_{a_c}^{a_K} P\,du \qquad (6)$$

as it is shown schematicelly in Fig. 2.
If the energy W is evaluated as:

$$W = \int_{0}^{a_K} P\,du \qquad (7)$$

the results will be overestimated (see the area marked A in Fig. 2). The error of overestimation is in this case about 5-10%.
The same specimens were used for all the K_c, δ_c, J_c and W measurements.
The crack extension Δ a was measured on the fracture surfaces of fractured specimens. In order to mark the crack extension the final fracturing of the specimens was carried out at the temperature of liquid nitrogen (-196°C). The Δa values were measured at magnification 40x using a semi-automatic measuring machine at 5 locations distributed uniformly across the specimen.
The specific crack propagation work Lp was evaluated according to the formula (5).

The scond part of measurements was the stereological analysis of the sulphide inclusions. The procedure of measurements was described by Zaczyk et al. in the reference [13]. The measurements were carried out using the Quantimet 720 image analyser. As a quantity describing the arragement of deformed non-metallic inclusions the projected length L_A was chosen [14].

MATERIAL TESTED AND RESULTS

The experiments were carried out on 15 HSLA steel plates of the same basic chemical composition, shown in Table 1.
No difference in grain size, pearlite banding and form was noticed. The steel tested was converter heat, carefully deoxidated and modified by different rare earth metals (mischmetal) additions in the range from 0 to 0,175 wt %.
The aim of the modification process was to change the deformability and, consequently, the morphology of sulphide inclusions.

Table 1. Chemical composition of the tested material (wt %).

C	Mn	Si	P	S	Al	N_2	O_2
0.15	1.30	0.35	0.20	0.18	0.05	0.0075	0.0015

The tensile properties were similar for all the steels and independently of the specimen orientation. The average values were as follows:

$\sigma_y \approx 380$ MPa, $A_5 \approx 30$ %, $Z \approx 55$ %.

The results of investigations are shown in a synthetic manner in Figs. 4-8.

DISCUSION

As K_c is a "stress-type" criterion it tends to be sensitive to similar structure features as the yield point or ultimate stress. So, it is almost stable in respect to the projected length of inclusions and shows no anisotropy (see Fig. 4). δ_c and δ_m are "strain-type" criterions and they are sensitive to the changes in morphology of sulphides (see Fig. 5 and 6). They shows also different values for L-T and T-L orientations. Nevertheless, these measures are evaluated at one, fixed point. Consequently they depend on the local volume, shape and size of inclusions. As the scatter of the inclusion distribution characteristics is very large, especially if one considers small test volumes [14], both δ_c and δ_m give a relatively large scatter of results.

J_c is an "energetic-type" measure of fracture toughness and it should be the best in this case (see Fig. 7). In fact, it gives much higher than K_c, δ_c or δ_m correlation coefficients when the effect of projected length of inclusions is discussed. Unfortunately the value of J_c is evaluated at the very beginning of stable crack growth, so it causes the same effect of large scatter of results for every material (the good correlation is observed only between mean values of J_c and L_A). It should be noticed here that because of the small size of specimens, relations as:

$$J_c = \frac{K_c^2}{E} \tag{8}$$

are not valid here.

In comparison with the above discussed fracture toughness measures, the proposed specific crack propagation energy Lp can be considered as a "integral–energetic – type" criterion. Lp covers the range of strain from δ_c to δ_m. So, the final value of Lp is affected by the inclusions distributed in the relatively large volume. It results in a very small scatter of Lp (see Fig.8) and the best correlation with the projected length of inclusions. These results suggest that Lp is the best parameter if the effect of non–metallic inclusions should be described.

CONCLUSIONS

1. The effect of non–metallic inclusions on the fracture toughness can be detected only by some chosen parameters.

2. In order to measure this affect properly, integral–energetic type criterions should be used. An example of such a criterion is the proposed specific crack propagation energy Lp.

SYMBOLS USED

a = crack depth (mm)

a_c = crack depth at initiation of stable crack growth (mm)

a_k = crack depth at terminal instability (mm)

A = area of the growing crack (mm^2)

A_5 = elongation (%)

B = specimen thickness (mm)

L_A = projected length of inclusions (mm^{-1})

l = crack length (mm)

Lp = specific crack propagation energy (J/mm^2)

P = load (N)

r = radius (mm)

R = plastic zone size (mm)

R_o = radius of plastic zone at initiation of plastic flow (mm)

T = tearing modulus

u = load point displacement (mm)

u_i = specimen deffection at initiation of fracture (mm)

u_k = final specimen defection during wading (mm)

W = work of external forces (J)

W_p = energy dissipated during plastic deformation (J/mm^3)

Y = yield point according to the Huber-Mises-Hencky yield criterion (MPa)

Z = reduction of area of the specimen (%)

= size of Neuber's zone (mm)

δ_c = crack opening displacement at initiation of stable crack growth (mm)

δ_m = crack opening displacement at maximum load (mm)

Δa = crack extension in the range from u_i to u_k (mm)

σ = stress (MPa)

σ_{in} = true stress at crack tip corresponding to initiation of stable crack growth (MPa)

σ_c = critical stress according to the Griffith's model (MPa)

σ_y = tensile yield strength (MPa)

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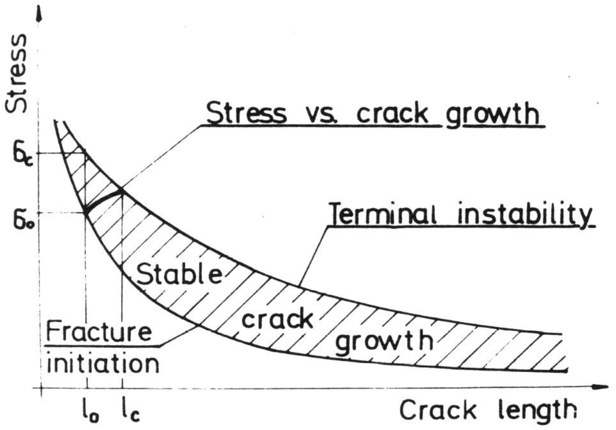

Figure 1. Diagram of the subcritical crack growth.

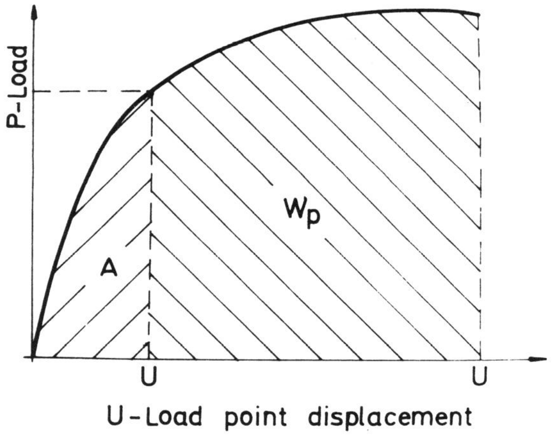

Figure 2. Ilustration of the measure of energy W.

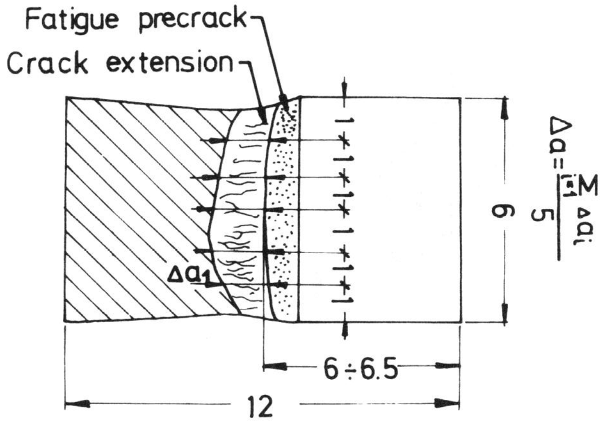

Figure 3. Procedure of evaluation of crack extension

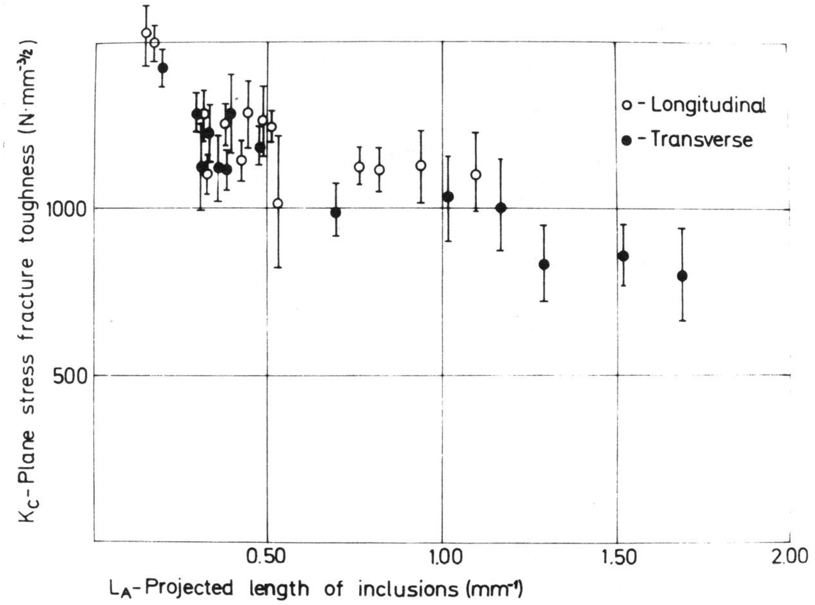

Figure 4. Effect of projected length of inclusions L_A on plane stress fracture toughness K_c.

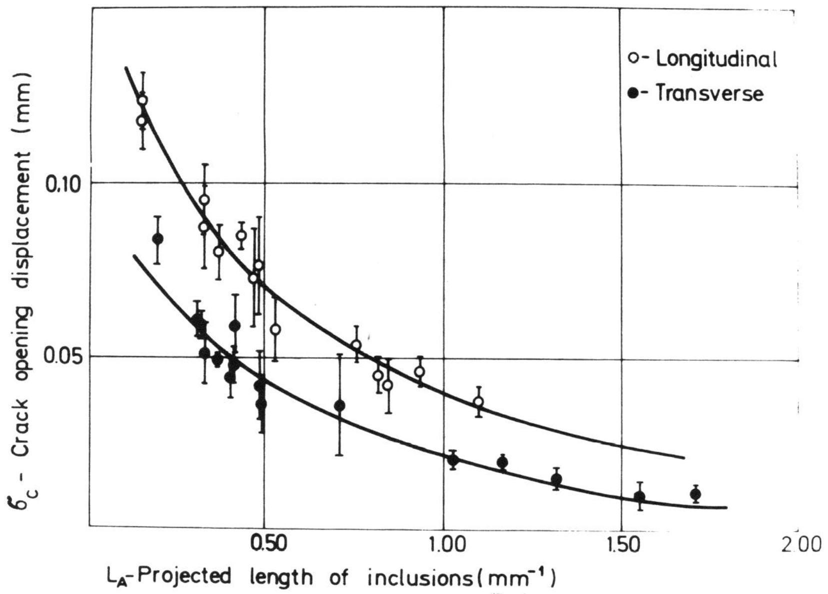

Figure 5. Effect of projected length of inclusions L_A on crack opening displacement δ_c.

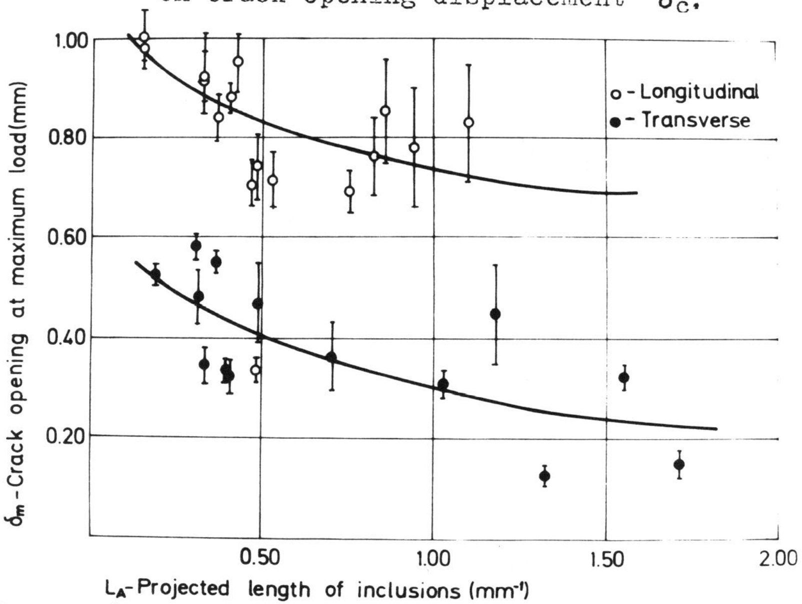

Figure 6. Effect of projected length of inclusions L_A on crack opening at maximum load δ_m.

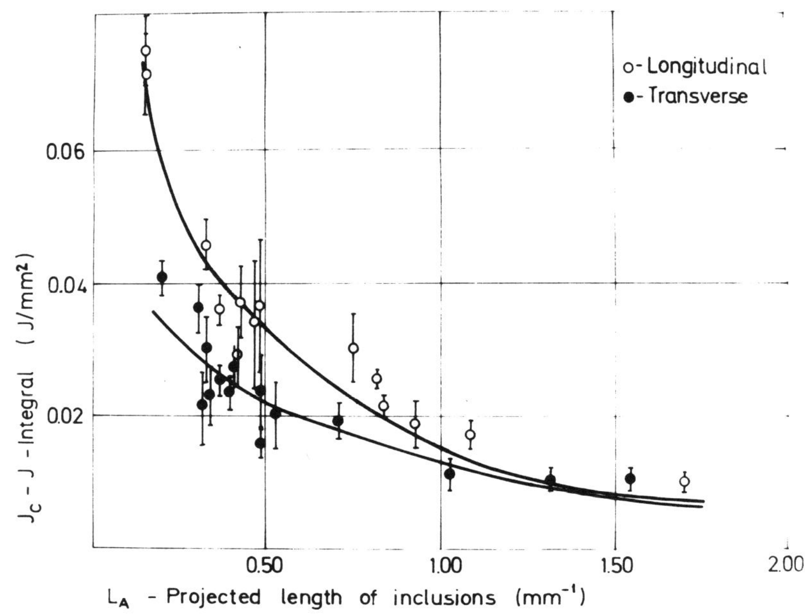

Figure 7. Effect of projected length of inclusions L_A on J-integral.

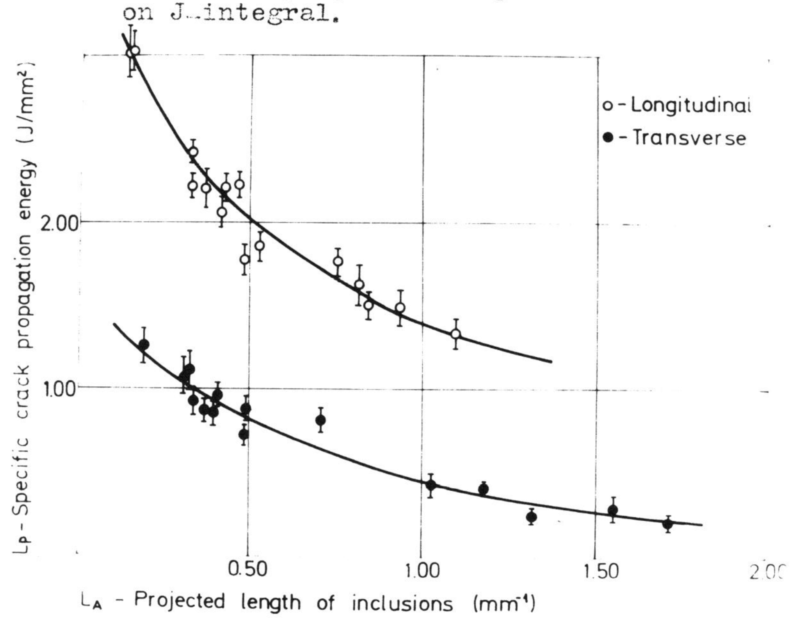

Figure 8. Effect of projected length of inclusions L_A on specific crack propagation energy Lp.