APPLICATION OF LOCAL FRACTURE CRITERIA TO DYNAMIC FRACTURE TOUGHNESS

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ABSTRACT

The dynamic fracture toughness of A508CL3 steel has been studied using a variety of strain rates ($\dot{\varepsilon}$) and stress intensification rates ($\dot{K}$). Several methods has been used including the "Split Hopkinson Pressure Bars System". The relationship between the fracture toughness K_{Ic} at high and low strain rates has been investigated using an equation based on a local fracture criteria. The limitations for this model for dynamic fracture toughness are discussed.

KEYWORDS

Dynamic fracture toughness; stress distribution RKR model; A508CL3.

INTRODUCTION

Interest in the response of cracked components to dynamic load has increased considerably during recent years. A relationship between the uniaxial flow and fracture properties which could be used to predict the change in fracture toughness is required. The well-known RKR model (Ritchie, Knott and Rice, 1973) assumed that a cleavage crack propagates in an unstable manner when the stress at the crack tip exceeds a critical value (σ_c) over a critical distance (X_o). This model results in the following relationship between fracture toughness and yield strength

$$K_{Ic}(\dot{\varepsilon},T)\;.\;\sigma_y(\dot{\varepsilon},T)^{\frac{n-1}{2}} = \sigma_c^{\frac{n+1}{2}}\,.\,[\xi]^{-\frac{n+1}{2}}\,.\,X_o^{\frac{1}{2}} \qquad (1)$$

where ξ is a constant and n the strain hardening exponent. Similar models have been proposed by Pisarenko et al (1973) and Holzmann et al (1981). In all these local criteria, the cleavage strength is assumed to be independent of the strain rate. It is not clear, at the present time, if the characteristic distance can be compared with a microstructural unit and consequently be insensitive to loading rate. In order to verify the applicability of these models, static and dynamic fracture toughness experiments were conducted on specimens made from an A508CL3 steel using strain rates over the range ($10^{-3} < \dot{\varepsilon} < 10^{3}\ s^{-1}$ and stress intensification rates over the range ($1 < \dot{K} < 10^{6}$ MPa m/s. The finite element method was used to determine the stress distribution and hence the critical distance (X_o) used in this model.

MATERIAL

The material used for this study was an A508CL3 steel with the following chemical composition

TABLE 1

elements	C	S	P	Si	Mn	Ni	Cr	Mo
percentage	0,16	0,004	0,001	0,25	1,31	0,21	0,20	0,51

The tensile properties were :

Yield strength	: σ_y = 490 MPa
Reduction in cross sectionnal area at fracture	: A % = 20
Ultimate strength	: σ_{ul} = 620 MPa
Transition temperature	: T_K = - 20°C

UNIAXIAL FLOW PROPERTIES

The uniaxial flow properties have been determined for a large range of temperature (- 196°C to 20°C) and for 3 values of strain rate (Fig. 2).

- Static tests ($\dot{\varepsilon} = 10^{-3}\ s^{-1}$) have been performed in tension and compresssion by a conventional method.
- Rapid tests ($\dot{\varepsilon} = 1$ to $10\ s^{-1}$) were carried out on a close loop hydraulic testing machine. Strain and strain rate were measured with electric extensometers.
- Dynamic tests ($\dot{\varepsilon} = 10^{3}\ s^{-1}$) were conducted using cylindrical specimens inserted between the incident and the transmitted bars of a Split Hopkinson Pressure Bars system.

The yield strength increased considerably under dynamic conditions (60 %) and depended on temperature and strain rate. In the thermally activated strain rate analysis, it is always assumed that the yield stress consists of two components : an athermal component (σ_μ) and a thermally activated component (σ_θ)

$$\sigma_y = \sigma_\mu(\dot{\varepsilon}) + \sigma_\theta(\dot{\varepsilon},T) \qquad (2)$$

The athermal component is dependent on strain rate whereas the thermally activated component σ_θ is a function of strain rate and temperature.

Following Yaroshevich and Ryvkina (1970), the yield stress can be expressed as the function of overstress at 0°K

$$\sigma_y = \sigma_\mu + (\sigma_y{}^{\circ K} - \sigma_\mu)e^{-\alpha T \operatorname{Log} \dot{\varepsilon}_o/\dot{\varepsilon}} \qquad (3)$$

where $\dot{\varepsilon}_o$ is a constant.

Values of these parameters for A508CL3 steel are listed in table 2.

TABLE 2

A508CL3	σ_μ= 445 MPa	$\sigma_y{}^{\circ K}$ = 1850 MPa	$\dot{\varepsilon}_o = 10^{8}$
$\dot{\varepsilon}$	$10^{-3}s^{-1}$	$10\ s^{-1}$	$10^{3}s^{-1}$
α	4,6 10^{-4}	3,77	2,34 10^{-4}

FRACTURE TOUGHNESS

Fracture toughness was measured in quasi-static conditions ($\dot{K}$ = 1 MPa√m/s) according to ASTM E399 standards with 25,20 thick CT and WLCT specimens(mm).

Rapid rupture tests ($\dot{K} = 3 \times 10^{2}$ and 2×10^{4} MPa√m/s) were performed on a servo-hydraulic machine using an hydraulic system with a delivery sufficient to produce a ram speed of about 500 mm/s.

High loading rates ($\dot{K} \simeq 2 \times 10^{6}$ MPa√m/s) were obtained by placing a WLCT specimen between two instrumented Hopkinson bars.

In this method, the effect of friction between the wedge and the specimen was taken into account in measuring the loading tensile force and determining the calibration function.

The small specimen size caused the characteristic oscillations of the dynamic stress intensity factor to drop very early and resulted in only a slight perturbation of the ratio dynamic to static stress intensity factor and in this case suggested that the effective dynamic stress intensity factor was equivalent to the static value.

The experimental results shown in Fig. 1 and Table 3 indicate that the transition temperature defined at the conventional level of 70 MPa√m was raised with increasing loading rate $\dot{K}$ and strain rate $\dot{\varepsilon}$ according to

$$\operatorname{Log} \dot{\varepsilon} = \operatorname{Log} (\sigma_y / EK_{Ic}) + \operatorname{Log} \dot{K} \qquad (4)$$

In this relationship (4), σ_y is the yield strength measured at the given strain rate $\dot{\varepsilon}$.

TABLE 3

$\dot{K}$.MPa√m/s	$\dot{\varepsilon}\ s^{-1}$	σ_y(TK)MPa	TK
2	2 10^{-4}	720	- 128°C
5 10^{2}	4 10^{-3}	750	- 105°C
10^{4}	11	780	- 68°C
2 10^{6}	10^{3}	950	+ 26°C

All the data obtained over a wide range of temperature and strain rate fall on to a single curve with a small scatter band and may be represented by the following relationship

$$K_{Ic} = 30 + 10^{-7} (T \, Log_{10} (10^8/\varepsilon)^{2,69}$$

EXPERIMENTAL DETERMINATION OF CRITICAL CLEAVAGE STRESS

The critical cleavage stress has been measured on axysymetric specimens with a total working length of 100 mm and 3 types of notch acuity ; 2,4 and 10 mm. In each case, the initial diameter of test section (ϕ_o) was constant.

Althought it was possible to calculate the stress distribution with the help of an analytical formula (Bridgmann, 1952; Mudry, 1982) ; a finite element method was used.

The maximum stress distribution was identified to determine the critical cleavage stress. The average values for different notch acuities are listed in Table 4.

TABLE 4

acuity	ρ = 2 mm	ρ = 4 mm	ρ = 10 mm
average critical cleavage stress (σ_c)	1692 MPa	1585 MPa	1464 MPa

The average critical cleavage stress was measured in the temperature range 196°C < T < + 20°C. It can be seen to be only slightly dependant on the notch acuity and hence on the volume of material in the plastic zone as found by Kaechele and Tetelman (1969).

For the critical stress, an average value of (σ_c) = 1585 MPa was taken and was used later in local fracture criteria calculations.

STRESS DISTRIBUTION AT THE CRACK TIP

The stress and strain fields were calculated using a finite element method providing a stress distribution near the crack tip which is a function r^{-1}

$$\lambda = n/1 + n \qquad 0 < \lambda < ½$$

and r is the distance head of the crack tip. An initial blunting of 10% of the critical crack opening displacement was a characteristic feature of this method. For a high strain rate, negative plastic modulus just after yielding was used in the finite element model to take into account the instability which plays an important role in the stress distribution. The critical stress distribution at the crack tip for a high loading rate and static conditions at low temperature (75°K) is shown in Fig. 3.

RESULTS

Assuming that the critical cleavage stress is strain rate independent, the following values of the critical distance were obtained (Table 5) and compared with the plastic zone size (r_p) in the θ = 0° direction which was determined from the finite element model using Von Mises' criteria.

TABLE 5

T	75°K		193°K		215°K		295°K	
	$X_o(\mu)$	$R_p(\mu)$	$X_o(\mu)$	$R_p(\mu)$	$X_o(\mu)$	$R_p(\mu)$	$X_o(\mu)$	$R_p(\mu)$
$10^{-3}s^{-1}$	26	9	47	70				
$10^{3}s^{-1}$	12	4			12	8	41	30

It is therefore apparent that the critical distance is not constant and cannot be compared with any microstructurals units. If it is assumed that the critical distance cannot be less than the unit size to have a physical meaning, a threshold value of the critical stress intensity factor can be found from

$$K_{Ic} = \sigma_c \sqrt{\pi} X_o$$

which results in a value close to the experimental value of 30 MPa√m.

DISCUSSION

Applying the well known RKR local fracture criteria at high strain rate requires 3 assumptions : the critical distance, the strain hardening and the cleavage stress are strain rate independant.

We have seen that until $\dot{\varepsilon} = 10\ s^{-1}$, the cleavage stress measured on axysymetric specimens is constant. Figure 4 shows that the strain hardening is not constant.

In the range of strain rate and temperature studied, 3 different types of behaviour can be seen :

- a constant strain hardening exponent area
- constant strain hardening exponent lines
- tensile instability area

This tensile instability range appears at low temperature and high strain rate and can modify the stress rate at the crack tip, in particular the hydrostatic pressure

The difficulties of using local fracture criteria depends on the physical significance of the characteristic distance. This characteristic distance can be considered as the minimum volume of material in which the fracture process can operate and can be introduced as a parameter in a probabilistic theory of fracture. this volume can be associated with the stress gradient and may be strain rate dependant.

The second point is to consider the statistical competition between different size crack nuclei. this competition can be modified at high strain rate. According to Kipp (1980), several crack sizes can be activated. This physical phenomena modifies the second parameter of a probabilistic model of fracture. the Weibull exponent increases by reducing the scatter of fracture toughness data.

CONCLUSION

This work indicates the difficulties of using local fracture criteria at high strain rates. Somes assumptions on the RKR model cannot be met as the critical distance and the strain hardening exponent which are both sensitive to strain rate. Further research from a probabilistic point of view is needed. A simple model using RKR and introducing the yield stress as a function of temperature and strain rate is inadequate.

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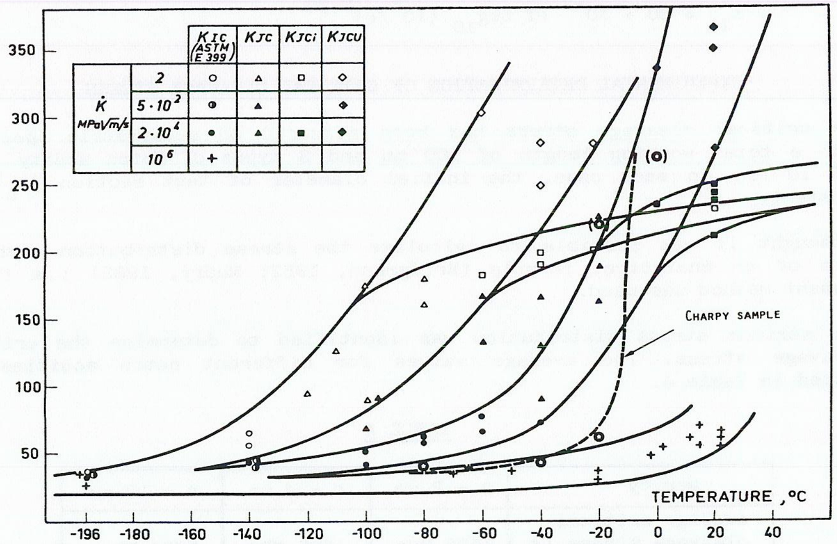

Fig. 1. Fracture toughness

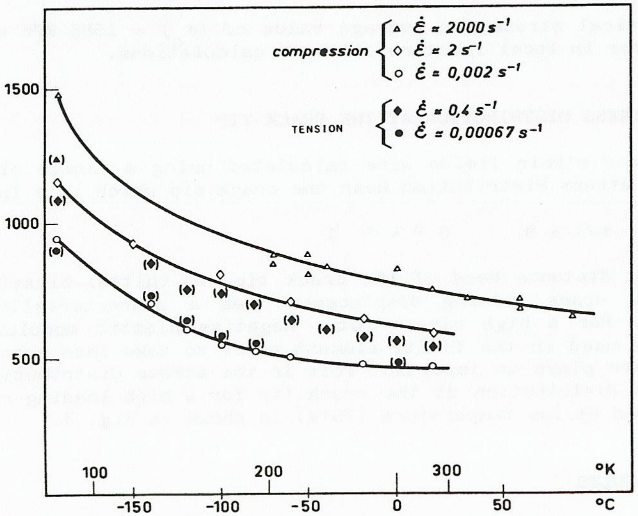

Fig. 2. Variation of the yield strength with the temperature for A508CL3 steel

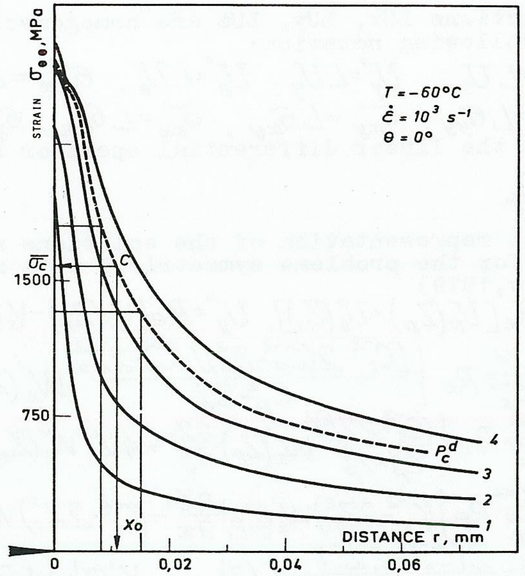

Fig. 3. Stress distribution obtained by finite element analysis

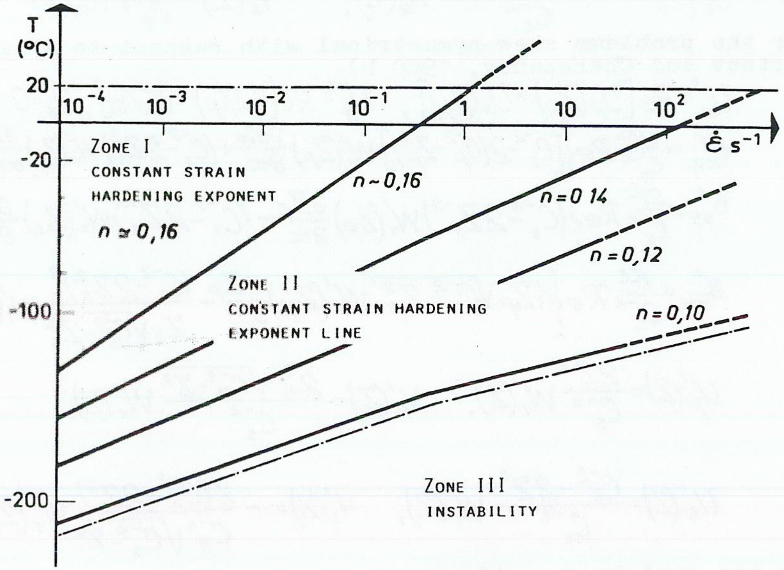

Fig. 4. Influence of the temperature on the strain hardening exponent for A508CL3 steel