INITIATION, PROPAGATION AND ARREST OF CRACKS IN DYNAMIC OF PIPELINE STEELS AT LOW TEMPERATURES.

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Fracture toughness at arrest KIa and Dynamic fracture toughness at initiation KId was measured on two pipeline steel grades. Dynamic fracture toughness was measured at a very high loading rate with the help of Split Hopkinson pressure bars. This technique resulted in obtaining a very high loading rate ($K=10^6 MPa\sqrt{m}/s$). Crack arrest was carried out on dynamic reduced effect samples(EDR) proposed by Kalthoff and according to the ASTM standards. In order to promote crack initiation, a brittle zone was made at the tip of mechanical slot with welding metals.

INTRODUCTION

Initiation, propagation and arrest of cracks in pipelines steels are defined by three stages(Fig.1) which characterise the evolution of fissuring velocity as function of the distance travelled by the crack in its displacement. It is required to control the propagation of cracks and their arrest before they become critical and will produce catastrophic failures.

The origin of this work is to examine the possibilities of using dynamic fracture toughness at crack initiation as a lower bound of crack arrest toughness. This is of practical interest as crack arrest tests are difficult to perform, give scattered results, are costly and time consuming. Dynamic fracture toughens at crack initiation is cheap and easier to obtain. Another point was to check the validity of the ASME reference curve for our two pipeline steel types.

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MATERIALS AND EXPERIMENTAL DEVICES

A French steel type API.5L 84 and Russian steel type were studied. These two steel types are used as pipeline steels and are very similar in chemical composition and mechanical properties(Table 1).

Type	σy(MPa)	σm(MPa)	A(%)
French	500	630	24
Russ	518	596	22.5

Table 1

The dynamic fracture toughness was obtained by a stress wave produced by the shock of a projectile of the Split Hopkinson Pressure Bar device[1]. The registered transmitted pulse gives the critical applied load for rupture F_c. The small size of the sample and the relatively long time for fracturing(t_c=10μs), were compared to the travel time of the wave. This leads to the conclusion that the dynamic applied stress intensity factor is only slightly different to the static applied stress intensity factor and that the quasi-static assumption can be used to calculate the critical stress intensity factor. The dynamic stress strain curve was obtained at high strain rate($\dot{\varepsilon}$ =10^3/s) on a cylindrical sample of diameter 10mm and thickness 5mm. The specimen was compressed between the incident and the transmitted bar of the Split Hopkinson Pressure Bars device. A procedure described in[1] made it possible to obtain the stress curve at such a high loading rate and particularly the yield stress σy.

Conventional fracture toughness tests have been made on 3PB samples for Russian steel type. Static fracture toughness tests for French steels were carried out with wedge opening CT(WLCT) samples which are cubic(20mm) in order to use the same samples as for the dynamic tests. For Russian steel crack arrest, tests were made on DCB samples.

The fracture toughness value at arrest was calculated using the static stress intensity factor calculated by the following formula :

$$K_{1a} = \frac{E}{\sqrt{W}} \cdot \sqrt{\frac{B}{B_n}} \cdot V \cdot f(a/W) \qquad /1/$$

Where f(a/W) is a compliance function given by[2] and V is the crack opening displacement at a given distance behind the load line.

RESULTS AND DISCUSSIONS

From strain stress curves we pay particular attention to the evolution of the yield stress σy with loading rate ε and temperature T. Due to the fact that plasticity is a thermal activated process, experimental data are fitted (Fig. 2) according the Ryvkina and Yaroshevich[4] model. These data used later to model the evolution of fracture toughness with temperature and loading rate(Fig.3).

The fracture toughness transition curve was established by plotting the experimental data with an experimental empirical model[1] :

$$K_{1c} = K^{o}_{1c} \cdot \exp(C_2 . T) \qquad /2/$$

where K^{o}_{1c} is the absolute minimum of fracture toughness at 0°K and at very high loading rates and C_2 is a new constant(Table 3).

	Russian steel		French steel	
	Static L	Dynamic L	Static L	Dynamic L
K_{1c}^{o} (MPa $\sqrt{m}$	28	26	27	24
C_2	6.10^{-3}	5.10^{-3}	6.10^{-3}	$5,1.10^{-3}$
T_t	152	183	167	209

Table 3

The value of the constants and the minimum for fracture toughness are given in Table 3 for the two materials. In the same table, fracture toughness transition temperature T_t is also given. This temperature is defined conventionally at 70 MPa $\sqrt{m}$. The shift of the transition temperature was found to be 31°C for the Russian steel and 36°C for the French steel.

The fracture toughness at arrest K1a versus the temperature has been reported in figure 3. Brittle crack propagation is allowed at temperatures of less than -100°C.It was seen that is a dependence of K_{1a} with initial value K_0 (i.e with the strain energy stored at notched tip during loading).By looking at figure 3 we can see that K_{1a} values are sometimes below the K_{1d} values but not below the ASME reference curve. The experimental values of $K_{1c}°$ are practically the same as the value given by the reference curve of the ASME code (26.7MPa $\sqrt{m}$.). These satisfactory results do not obliterate the fact that values of $K_{1c}°$ were found to be below the minimum value of the reference curve[3].

Using the well-known Ritchie, Knott and Rice(RKR) local fracture criteria model which assumes that the product $K_{1c} . (\sigma)^{[(1-N)/2]}$ is constant(N is the strain hardening exponent of the Ramberg-Osgood law), we can write :

$$K_{Ic} = K_{Ic}^{o} . \left(\frac{\sigma^{\mu} + (\sigma^{o} - \sigma^{\mu}) . \mathrm{Exp}(- C_1 + T . \log(A_F / \dot{\varepsilon}))}{\sigma^{o}} \right)^{(1-N)/2} \qquad /3/$$

This model includes several assumptions, particularly that the strain hardening exponent and the critical cleavage stress are independent of the loading rate. For this reason the model does not work very well in our case but can be used to obtain the value of the minimum of fracture toughness which is of practical importance. Results for these two values of dynamic fracture toughness confirm numerous results previously obtained.

We can now assume that by using a description of thermal activated plasticity and local fracture criteria like RKR criteria[1] we can obtain a good estimation of the absolute minimum of fracture toughness.

Near the crack arrest zone, the facies reveal a mixed failure produced by cleavage and ductile failure(Fig.4). At this stage, a particular effort will be made for understanding the mechanisms which are the origin of the crack arrest.

CONCLUSION

The observation of macrographic of facies show a fragile failure. So we conclude that in the range of the explored temperature, the brutal propagation of the crack is made on a state of dominant plane deformation. The occurring of small lips of shear show a confined plasticity and in the mean time a state of plane stress very limited.

The equations representing the evolution of the applied stress intensity factor and the resistance to fracture with loading rate suggest that there is a continuity of approach between dynamic crack initiation and crack propagation which can be considered as a successive series of reinitiations.

Experimental results on two line pipe steel types show that some values of K_{1a} are below K_{1d} values and it seems difficult to use the dynamic fracture toughness as lower bound of crack arrest toughness. These results do not coincide with other results published in literature. But further investigations are needed to increase the degree of confidence of this conclusion.

Our data confirm that the Ryvkina and Yaroshevich model used to describe the evolution of the yield stress with temperature and loading is adequate. It has been seen[1] that this model does not work very well for high strength steel ($Re > 1000$ MPa) and it is necessary to notice here that the two steel types have a static yield stress close to 550 MPa.

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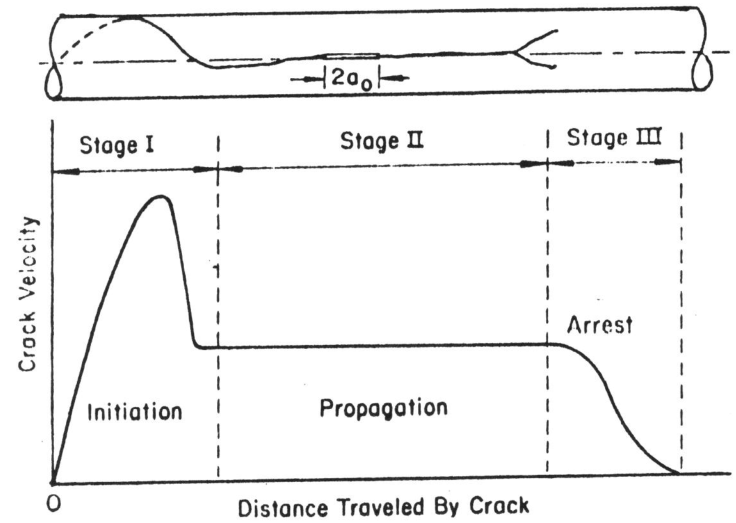

Fig. 1. - Stages of crack propagation.

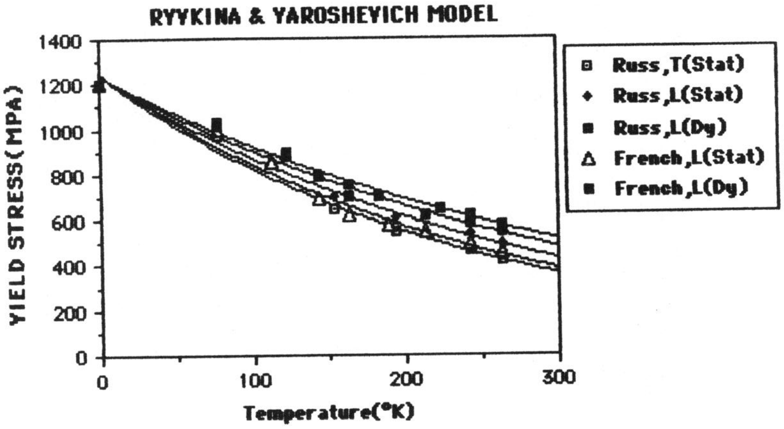

Fig. 2. - Yield stress versus temperature.

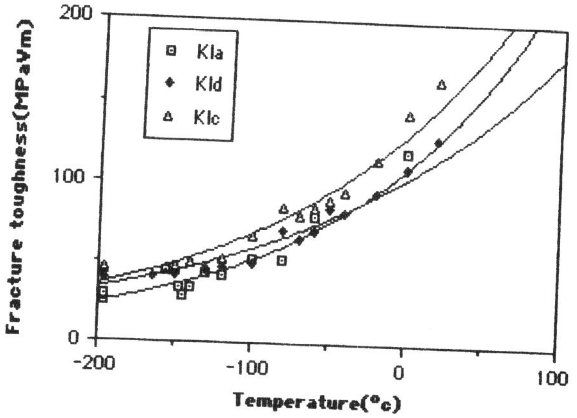

Fig. 3. - Comparison between KId and KIa.

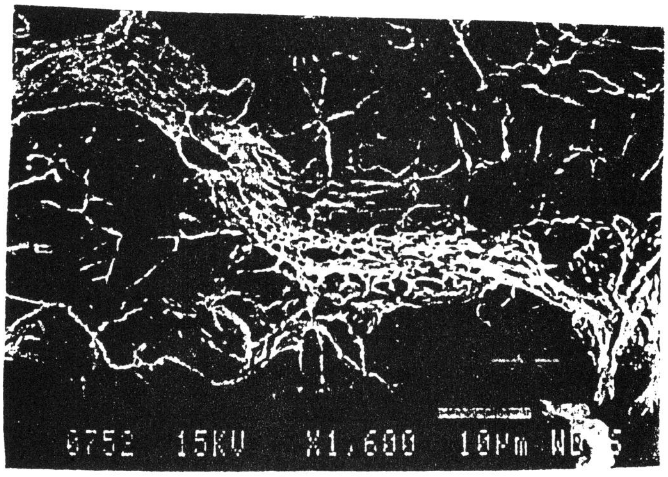

Fig. 4. - Fractographic of the crack arrest zone at -100°C.