STATIC AND DYNAMIC FRACTURE TOUGHNESS OF TWO PIPELINE STEELS AT LOW TEMPERATURE

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Dynamic fracture toughness at initiation K_{1d}, and fracture toughness at arrest 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. The values of K_{1d} and K_{1a} are compared to see if the dynamic fracture toughness can be compared as a lower bound of crack-arrest toughness.

INTRODUCTION

Structural failures are often caused by cracks or defects. Such failures can be avoided if these defects are detected and accepted as sufficiently small not to initiate or start to grow in an unstable manner. Extra safety can be obtained if a rapidly growing crack can be stopped before a catastrophic failure has developed. Since there is always some degree of uncertainty in inspection, this extra safety is of importance for such structures as pipelines.
To assess the arrest capability, information on dynamic fracture properties are needed.

It is customary to introduce the following relation for the dynamic strain energy release rate :

$$G = F_{stat}(a) \cdot g(\dot{a}) \qquad /1/$$

where G_{stat} (a) is the crack extension force for the same body under static conditions and g(a) is a function of geometry and crack velocity.

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The resistance to fracture is also a function of the crack speed :

$$R = \Gamma(\dot{a}) \qquad /2/$$

Combining /1/ with /2/ we obtain an approximate equation to describe the crack motion. Experiments show that Γ (a) increases rapidly with velocity. The minimum value of Γ (a) is approximately equal to Γ (0).

The aim of this project is to investigate the crack arrest fracture toughness K_{1a} of two very similar steel grades used for pipelines.

One of these steel types is Soviet, the second is French. The choice is a consequence of a cooperative programme between the Institute for Strength of Materials in Kiev (USSR) and the University of Metz (France).

The dynamic fracture toughness at initiation for these two steel grades was measured on Split Hopkinson Pressure Bars over the same time period. This technique resulted in obtaining a very high loading rate. ($K = 10^6$ MPa$\sqrt{m}$/s)

In the light of some theories which consider crack propagation as a succesive series of reinitiations, the dynamic fracture toughness during crack propagation can be related to the dynamic fracture toughness at initiation and can be considered as a lower bound of K_{1a}. This piece of work is a contribution to this approach.

Materials and experimental devices

A French steel type API . 5L 84 and a Soviet steel type were studied. The chemical composition and the mechanical properties of the materials are listed in Table 1 and 2 :

%	C	Mn	Si	S.	P.	Nb.	Ni	V
Soviet steel	0,1	1,6	0,33	0,004	0,02	0,031	0,05	-
French steel	0,075	1,65	0,43	0,003	0,013	0,037	-	0,05

Table 1

	Re (MPa)	Rm (Mpa)	A%
Soviet steel	500	630	24 %
French steel	518	596	22,5 %

Table 2

These two steel types are used as pipeline steels and are very similar in chemical composition and mechanical properties.
Three kinds of mechanical tests were performed :

- Determination of the static and dynamic stress-strain curve ;
- Static and dynamic fracture toughness ;
- Fracture toughness at arrest.

Conventional fracture toughness tests have been made on 3 PB samples for Soviet steel type. The samples have the following size: length = 165mm, height = 36mm, thickness = 18mm.

Static fracture toughness tests for French steels were carried out with wedge opening CT (WLCT) samples which are cubic (20 mm) in order to use the same samples as for the dynamic tests.

The dynamic stress strain curve was obtained at high strain rate ($\varepsilon = 10^3 \ s^{-1}$) on a cylindrical sample of diameter 10mm and thickness 5mm. The specimen was compressed beetween 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 particulary the yield stress Re.

The dynamic fracture toughness was obtained by a stress wave produced by the shock of a projectile of the same Split Hoplinson Pressure Bar device. This method is shown schematically in Figure 1 and described in reference [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 ($t_c = 10 \ \mu$ s) 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.

Crack arrest for the French steel was carried out on dynamic reduced effect samples (EDR) proposed by Kalthoff [2] and according to the ASTM standards [3]
In order to promote crack initiation, a brittle zone was made at the tip of the mechanical slot with welding metals of hardness 750 Hv.

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

$$K_1 = \frac{E}{\sqrt{W}} \cdot \sqrt{\frac{B}{B_n}} \cdot V_1 f_1 \left({}^{a}\!/\!_{w} \right) \qquad /3/$$

where f_1 is a compliance function given by [3] and v_1 is the crack opening displacement at a given distance behind the load line.

For Soviet steel crack arrest, tests were made on DCB samples.

Results

From strain stress curves we pay particular attention to the evolution of the yield stress Re with loading rate ε and temperature T. Due to the fact that plasticity is a thermal activated process, experimental data are fitted according the Ryvkina and Yaroshevich model /4/.

$$R_e = R_e^{\mu} + (R_e^{0} - R_e^{\mu}) \exp\left(-C_1 . T \log \frac{A_F}{\dot{\varepsilon}}\right) \qquad /4/$$

where R_e is the yield stress, R_e^{μ} the athermal component of the yield stress, R_e^0 the yield stress at 0°K, A_F the frequency factor with a value of 10^8 according to the dislocation theory and C_1 a constant. For the two steels and the two rolling directions (longitudinal and transverse), the two parameters R_e^{μ}, R_e^0 are similar : $R_e^{\mu} = 260$ MPa and $R_e^0 = 940$MPa.

These data are used later to model the evolution of fracture toughness with temperature and loading rate.

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

$$K_{1C} = K_{1C}^{\circ} \exp(C_2 . T) \qquad /5/$$

where K^0_{1C} is the absolute minimum of fracture toughness at 0°K and at very high loading rates and C_2 is a new constant.

	Soviet Steel		French Steel	
	static L	dynamic L	Static L	dynamic L
K1° (MPa √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 70MPa √m.

The fracture toughness at arrest K_{1a} versus the temperature has been reported in figure 4. Brittle crack propagation is allowed at temperatures of less than -100°C. The graph confirms that the fracture toughness at arrest increases when the temperature increases. It was seen that there is a dependance of K_{1a} with initial value K_Q (i.e with the strain energy stored at the notched tip during loading).

Discussion

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 > 1 000 MPa) and it is necessary to notice here that the two steel types have a static yield stress close to 550 MPa.

The value of yield stress at 0°K is often taken as the critical cleavage stress σ_c^*.

$$\sigma_c^* = R_e^0 \qquad /6/$$

and can be used to calculate the minimum fracture toughness K_{1c}^0 according to the following relationship :

$$K_{1c}^0 = \sigma_c^* \sqrt{\pi} X_c \qquad /7/$$

where X_C is the critical distance. The use of this equation indicates that this critical distance is the same for the two materials of the order of 30 microns.

Due to the fact that the two materials have different grain sizes, it is difficult to give a physical meaning to the quantity X_C.

The experimental values of $K_{1C}{}^0$ are practically the same as the value given by the reference curve of the ASME code (26,7 MPa √m). These satisfactory results do not obliterate the fact that values of $K_1{}^0$ were found to be below the minimum value of the reference curve /1/.

The shift of the transition temperature was found to be 31°C for the Soviet steel and 42°C for the french steel.

This shift is moderate due to the fact that the steels are medium strength steels. The shift of the transition temperature depends on the static yield stress according to the empirical formula.

$$\Delta T = (0{,}17 \text{ Re} - 125) \qquad /8/$$

This empirical formula was used rather than the Barsom and Rolfe formula which has been found to be inadequate.

Data from the evolution of the yield stress with temperature and loading rate can be used to model the evolution of the fracture toughness with the same two parameters.

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

$$K_{1c} K_{1c}{}^0 \{R_e{}^\mu + (R_e{}^0 - R_\mu) \exp(-C + \log \frac{A_F}{\varepsilon}\}^{\frac{1-N}{2}} \qquad /9/$$

This model includes several assumptions, particulary that the strain hardening exponent and the critical cleavage stress are independant 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.

The origin of this work was 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 toughness 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. By looking at figure (4) we can see that K_{1a} values are sometimes below the K1d values but not below the ASME reference curve.

CONCLUSIONS

The equations representing the evolutions 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 K1a are below K1d values and it seems difficult to use the dynamic fracture toughness as a lower bound of crack arrest toughness .

These results do not coincide with other results published in the litterature. But further investigations are needed to increase the degree of confidence of this conclusion.

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 a local fracture criteria like RKR criteria we can obtain a good estimation of the absolute minimum of fracture toughness.

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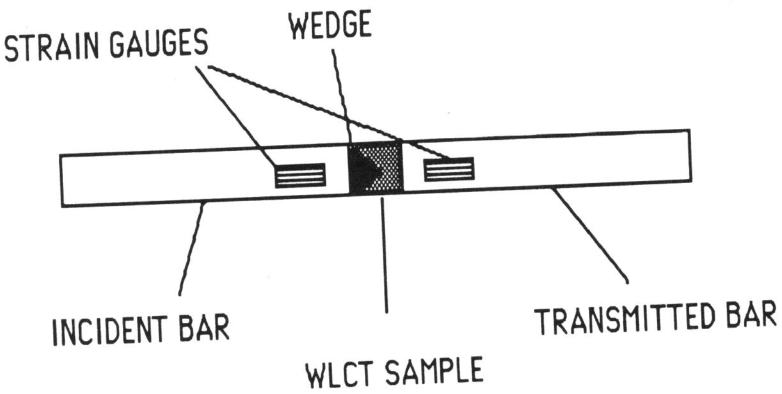

FIGURE N°1:SPLIT HOPKINSON EXPERIMENTAL DEVICES

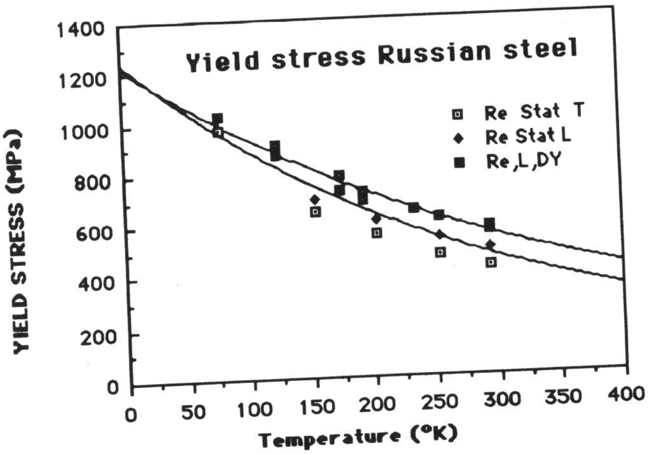

FIGURE N°2: YIELD STRESS VERSUS TEMPERATURE FOR RUSSIAN STEEL

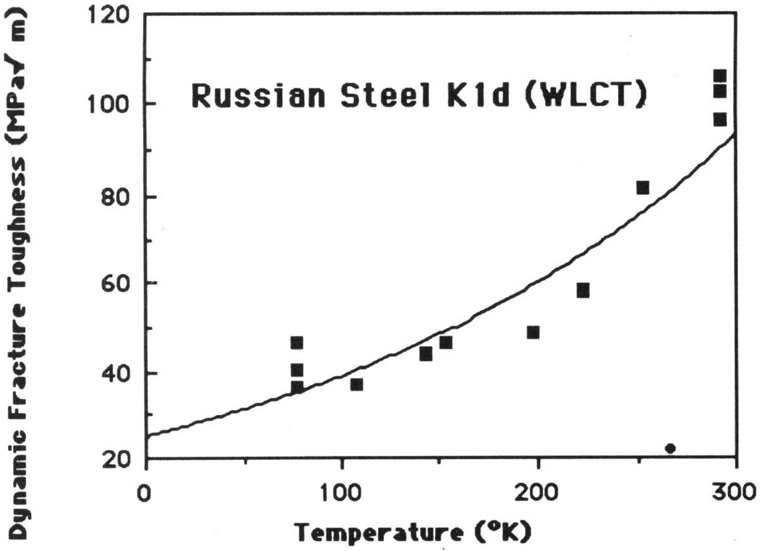

FIGURE 3 :DYNAMIC FRACTURE TOUGHNESS VERSUS TMPERATURE FOR RUSSIAN STEEL

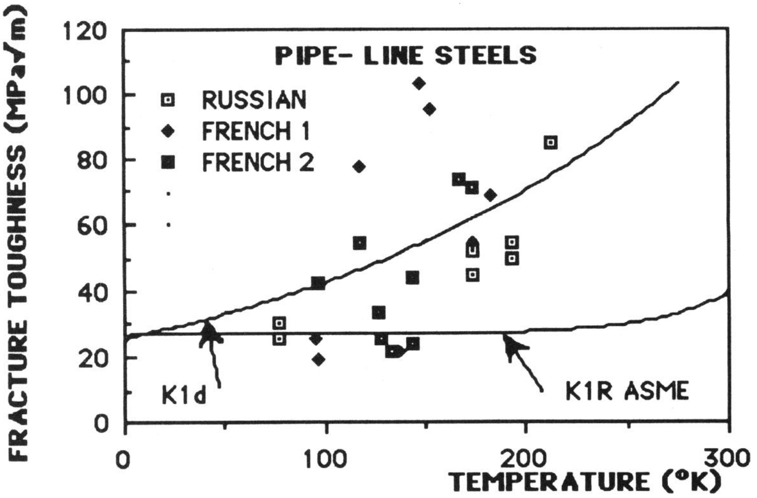

FIGURE 4: COMPARISON BEETWEEN DYNAMIC AND ARREST FRACTURE TOUGHNESS.