FRACTURE CHARACTERIZATION OF A PIPELINE STEEL

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ABSTRACT

A high strength low alloy steel, with considerable ductility at room temperature, used in Arctic pipelines is characterized with respect to fracture. Both static and Dynamic loading modes are examined. The fracture toughness parameters K_{Ic}, K_{Id}, J_{Ic} and J_{Id} are obtained as a function of temperature and crack orientation. A brittle-ductile transition temperature is defined which is a function of the crack orientation and the severity of the crack. The relation between the energy of initiation and propagation of the crack and temperature further substantiate this transition temperature.

INTRODUCTION

Pipeline steels, or high strength low alloy (HSLA) steels have been recently developed to withstand the low temperatures and severe environmental conditions needed for pipeline construction for oil and gas from the Arctic regions. Through controlled grain size, by controlled rolling and the addition of alloying elements such as niobium, molybdenum and other, their brittle-ductile transition temperature is considerably lowered and hence, they exhibit remarkable ductility and thus a high fracture resistance at low temperatures. The fracture behavior of these steels is generally characterized by using qualitative methods such as Charpy and Izod tests which do not yield quantitative values of fracture toughness suitable for determination of the critical crack size necessary to cause failure. The effect of alloying elements such as Nb and Mo on the fracture toughness of these steels at temperatures as low as -150°C has been studied[1,2] as well as the dynamic fracture toughness of these steels was obtained as a function of the crack orientation and temperature[3]. In that particular study, the stress intensity factor under dynamic loading K_{Id} was obtained using an instrumented Charpy test [4,5]. Also the J-integral, which represents the energy per unit of fracture surface was shown to be linearly proportional to the temperature and that it defines a transition temperature which represents more accurately the behavior of this steel from brittle to ductile fracture. This transition was also found to be a function of te crack orientation.

In this study, a complete characterization of the fracture behavior of a pipeline steel is given. Thus, dynamic as well as static fracture criteria were obtained using specimens having a sharp fatigue crack as opposed to a V-notch. The objective is to relate the effect of loading, namely strain rate and crack severity with temperature, and to demonstrate the effect of energy of propagation of a sharp crack on the ductile-brittle transition temperature.

EXPERIMENTAL PROCEDURE

The dynamic tests were obtained using an Instrumented Charpy tester described earlier.[5] For the brittle fracture, the equation for K_{Id} from ASTM Spec E399-72 was applied using the value of the maximum fracture load on the load displacement curve. For the specimens exhibiting ductile behavior the approach of the equivalent energy, developed by Witt[6] and used by Marandet and Sanz[7] was applied. In this approach an equivalent fracture load in the elastic region is obtained using an elastic energy equivalent to that needed to break the specimens. Such an approach yields conservative values for K_{Id} and thus is suitable for design. The J-integral values were obtained using the equation of Rice, Paris and Merkle[8], namely

$$J_{ID} = \frac{2U}{BL} \tag{1}$$

where U is the potential energy for fracture, given as the area under the curve load displacement B is the thickness of the specimen and L is the untorn ligament length.

Some tests were performed on V-notch Charpy specimens without any former fatigue precracking for comparison to identify the effect of introduction of the fatigue crack on the ductile-brittle transition temperature.

The static loading tests were performed on 12.7 mm thick compact tensile specimens described earlier[9], under controlled displacement. The temperature was lowered, used a Styrofoam box and pouring liquid nitrogen until the temperature was stabilized for the duration of the test (1-3 min). The J-integral was calculated from the load-displacement curves using Equation (1).

The steel used in this investigation is a pipeline steel with the composition given in Ref. 3. The alloying elements are niobium (0.058%) molybdenum (0.416%) and aluminum (0.028%).

RESULTS AND DISCUSSION

The dynamic fracture toughness parameters K_{Id} and J_{Id} as a function of temperature are given in Figs. 1 and 2. The static tests were limited to cracks oriented in the transverse direction and J_{Ic} versus temperature is shown in Fig. 3. The J-integral was calculated at the point of maximum load to be consistent with the dynamic test results. It is noticed that, for both dynamic and static tests, there is a linear relation between J_{Ic} and temperature. However, for the dynamic tests, there is a change in the slope of the two lines which define the transition between brittle and ductile behavior. For the static test, the relation is linear down to less than -120°C. The transition would occur below this temperature since, at -196°C, the value of J_{IC} is considerably lower than predicted by the straight line of Fig. 3. Thus, it may be concluded that, by decreasing the rate of application of the load, the transition temperature is shifted from -50°C to less than -120°C.

The results from Conventional V-notch specimens are shown in Fig. 4. For the purpose of comparison, the transition temperature corresponding to an energy of 15 ft. lb was chosen. For this particular steel, this corresponds to about -160°C, as this is much lower than that measured for static J_{Ic} measurements using specimens with a sharp crack (Fig. 3) and, in turn, that obtained from dynamic tests with Charpy precracked specimens (Fig. 2). Table 1 gives a list of all observed transition temperatures for this particular steel.

The linearity of the J-integral as a function of temperature, both under static and dynamic loading was further investigated. In Fig. 5, the variation of the J_{Ic}, elastic obtained from using the area under the curve in the linear part of the load-displacement curve as a function of temperature is given together with the plastic energy from the non-linear part of the load-displacement curve. As expected, J_{Ic}, elastic increases with decreasing the temperature. This is due to an increase in the limit load, corresponding to the yield strength of the material as the temperature is decreased. Fig. 6 shows the variation of the dynamic yield strength, calculated from the dynamic load displacement curves as well as the fracture load as a function of temperature. On the other hand, the J_{Ic}

plastic increases with increasing temperature and thus the resultant of the two curves of Fig. 5 is the straight line relationship which is observed for the dynamic and static loading. It should be pointed out that this linearity is particular to this particular steel and is not generalized for other materials. However, it was observed[10] that other steels reach a maximum value for J_{Ic} or K_{Ic} at a given temperature which does not correspond to the highest temperature tested. The outlined explanation does account for such observations since at the given temperature, the combined effect of increasing the yield strength and increase in plasticity could result in an optimum value for J_{Ic} or K_{Ic}.

The presence of the transition temperature in dynamic tests is further demonstrated by plotting the energy of initiation and the energy of propagation of the crack as a function of temperature for both longitudinal and transverse crack orientations. This is shown in Fig. 7 and 8 respectively. As expected, the difference between the energy of propagation and the energy of initiation increases considerably above the transition temperature for both crack orientation.

Furthermore, in Fig. 9, the variation of the ratio of the energy of initiation and the total energy required to fracture the specimen (dial energy) as a function of temperature for both orientations is given. The curves are characterized by three distinctive regions which show two clear transitions. For the specimens with longitudinal cracks, Zone I, which is brittle fracture extends between -196°C and -80°C. In Zone II, between -80°C and 20°C, an elastic-plastic behavior takes place. Above -20°C, fracture is completely ductile. For the specimens with a transverse crack, Zone I extends to -50°C and Zone II lies between -50°C and -20°C. It is also evident that the difference in the ratio between the longitudinal and transverse specimens is wide in Zone I but that it decreases rapidly in Zone II and III, thus accounting for the similar behavior of longitudinal and ductile specimens fractured in a ductile mode.

CONCLUSIONS

The fracture behavior of an HSLA pipeline steel is characterized under both dynamic and static loading using the J-integral as a quantitative fracture parameter. The variation of J_{Ic} and J_{Id} as a function of temperature is linear and defines a brittle-ductile transition temperature. Such a transition is a function of the rate of application of the load (dynamic vs static) and of the presence of a sharp crack. The linearity of J_{Ic} vs temperature is explained in terms of an increase in yield strength with decreasing the temperature and a decrease in plasticity. This transition temperature is further substantiated by measuring the energy of initiation and energy of propagation as a function of crack orientation and of temperature. Three distinctive zones of brittle, brittle-ductile and totally ductile fracture are thus observed. The values of J_{Ic} and J_{ID} could be used to calculate a critical crack size which nondestructive testing methods used on this material should be able to detect.

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Table 1

Values of the transition temperatures obtained during static and dynamic tests.

Test	Specimen	Crack Orientation	Transition Temperature
static	fatigue precracked	transverse	<125°C
dynamic	fatigue precracked	longitudinal	-80°C
dynamic	fatigue precracked	transverse	-50°C
dynamic	Charpy V-notch	transverse	-150°C

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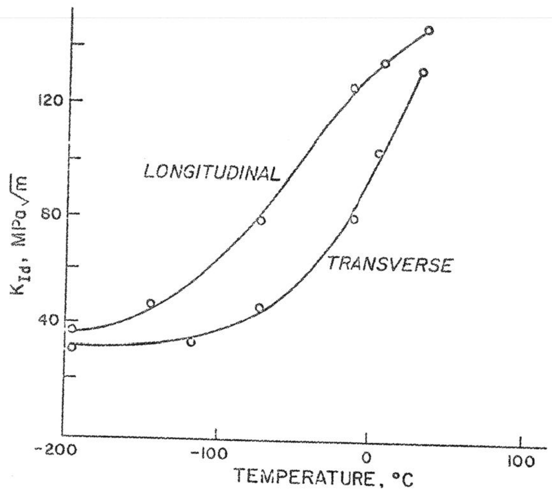

Fig. 1: Variation of the dynamic stress intensity factor, K_{Id} with temperature for longitudinal and transverse cracks.

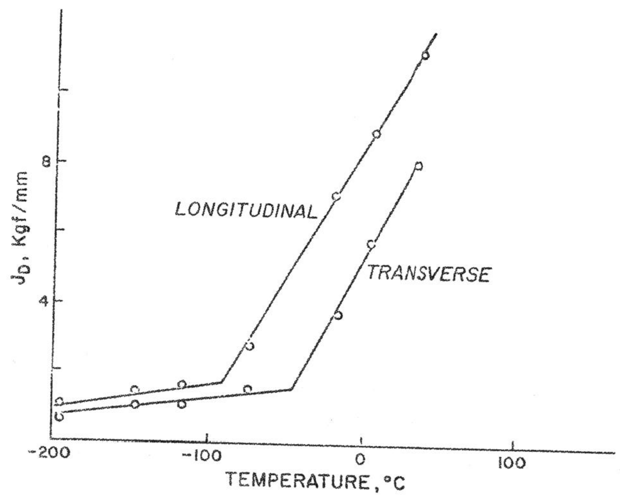

Fig. 2: Variation of the dynamic J-integral with temperature for longitudinal and transverse cracks.

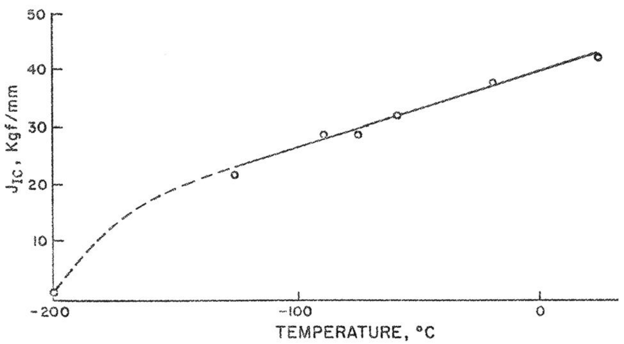

Fig. 3: The relation between J_{Ic} and temperature for specimens with a transverse crack (Ref 3).

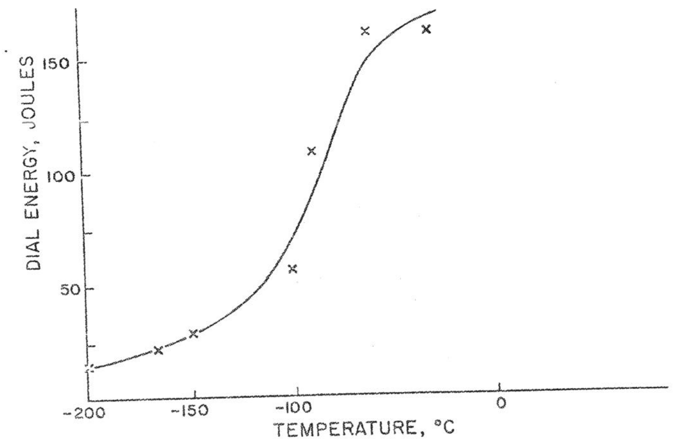

Fig. 4: Charpy V-notch energy as a function of temperature for transverse notch specimens.

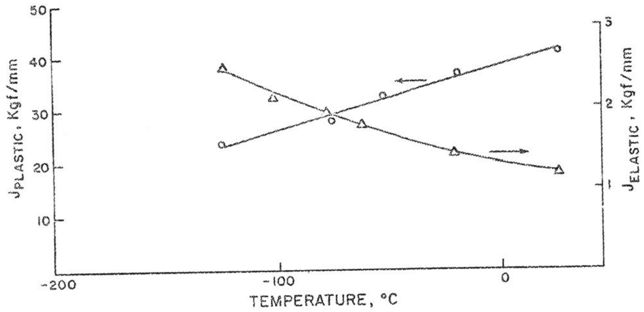

Fig. 5: The variation of J_{Ic} elastic and J_{Ic} plastic with temperature for transverse cracked specimens.

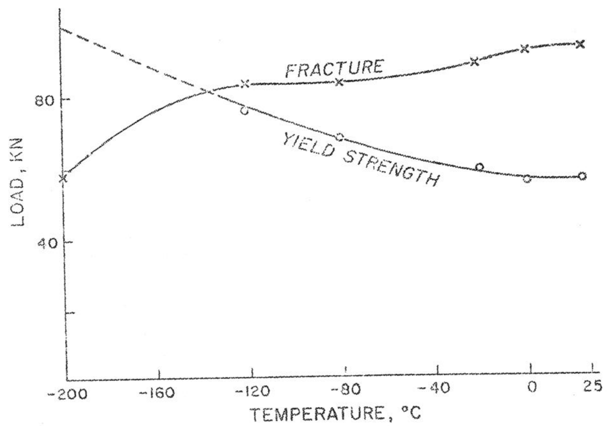

Fig. 6: The dynamic yield stress and fracture load as a function of temperature for transverse cracked specimens.

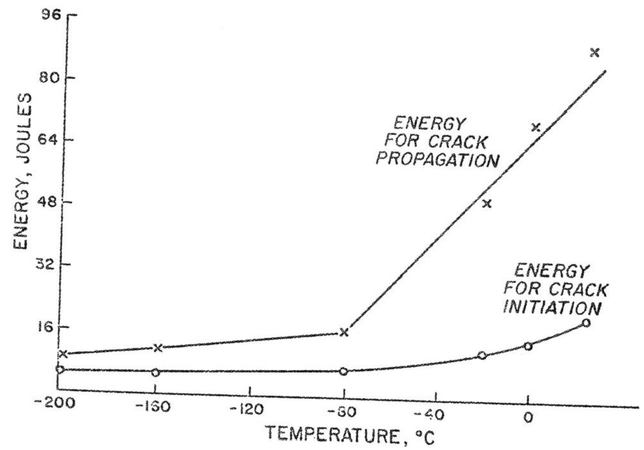

Fig. 7: The relation between the energy of initiation of a crack and the energy of propagation of a crack and temperature for longitudinal cracked specimens under dynamic loading.

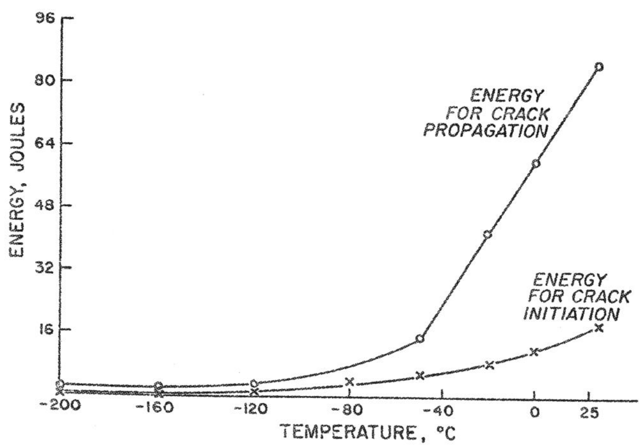

Fig. 8: As in Fig. 7 but for transverse cracked specimens.

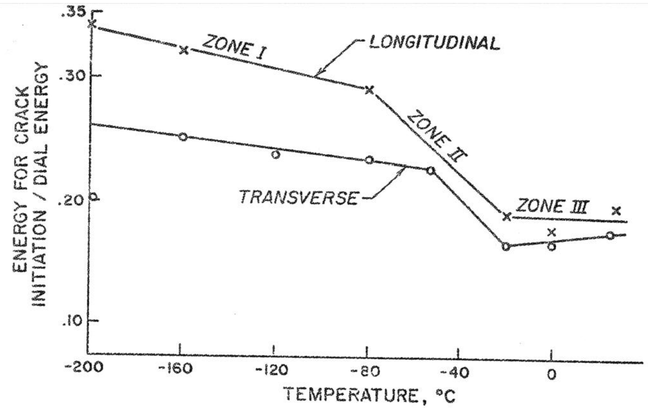

Fig. 9: The ratio of the energy of initiation over the total (dial) energy for longitudinal and transverse cracks as a function of temperature.