Ductile Fracture Resistance of Pipeline Steels

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ABSTRACT

The objective of this research is the development of a methodology for the characterization of the ductile tearing resistance of pipeline steels.

Tests carried out under quasistatic loading conditions have shown the effects of in-plane dimensions and the efficiency of different approaches (Sc, R-curves, local criteria). In particular, tests involving large crack propagation range are essential to the understanding of the real behaviour of the cracks in pipelines. For each crack propagation range, the parameters dJ/da, Sc, CTOA give an equivalent classification of the steels with respect to their ductile tearing resistance.

Dynamic tearing tests were conducted under different loading rates. Although these tests did not give the crack speeds representative of pipe burst tests, perceptible changes have been observed in the ductile tearing of the steels.

Mechanical results have been related to fractographic observations at each step of the research.

KEYWORDS

Steel; pipelines; ductile fracture; dynamic testing.

SITUATION OF THE PROBLEM

The risk of bursting of pipelines, even very low, is of great practical importance and must be taken into account imperatively. In such structures, a defect can become unstable accidentally and propagate by ductile fracture at hundreds of meters per second before arrest. In this eventuality, it is essential to choose the steel with the highest resistance to ductile fracture in order to restrict the consequences.

Important research programs have been devoted, since several years, to the characterization of the ductile fracture resistance of pipeline steels. Full scale burst tests have led several organizations to propose correlations for the prediction of a crack behaviour in a pressurized pipe, as a function of the CHARPY V toughness of the steel at the ductile plateau (Maxey, 1974; Poynton, 1974; Wiedenhoff, 1982). More precisely, these correlations are used for evaluating the minimum CHARPY V toughness of the steel which guarantees the arrest of the crack in the pipe, taking into account the service conditions. These correlations are convenient for predicting safely the conditions for propagation and arrest of cracks in pipes, in the case of traditional steels with API grade ≤ X70.

The increase of diameters and internal pressure of the pipes have led the steel makers to develop pipeline steels with higher strength. These characteristics are obtained for martensitic, bainitic, or acicular ferrite structures by means of appropriate chemical composition, steel-making conditions and thermomechanical processing.

Full scale burst tests performed on these steels of higher grades have shown that they need a higher CHARPY energy than predicted by the present correlations (Bonomo *et al.*, 1985). These semiempirical correlations have no general significance and must be adapted to modern high-yield strengths steels.

Following these difficulties, some researchers have developed less empirical approaches based on fracture mechanics tests (Demofonti and Maresca, 1985; Priest and Holmes, 1985). The mechanical parameters determined during these tests seem to be efficient for classifying the steels with regard to their resistance to ductile fracture but their applicability has to be proved.

OBJECTIVES AND APPROACH OF THE STUDY

The objective of the study is to develop a testing methodology for the characterization of the resistance to ductile fracture of pipeline steels of different microstructures.

The results of the ductile tearing tests are analysed by several mechanical parameters which will be presented later.

Since the crack propagates on large distances during the bursts of the pipes, it seems essential to evaluate the influence of the crack propagation range on the ductile tearing of the different steels. The propagation of cracks between 1 and 100 mm has been studied by means of ductile tearing tests on specimens with different in-plane dimensions. These tests have been carried out for the most part under static loading.

In order to take into account the dynamic aspect of crack propagation in pipes, ductile tearing tests were conducted under dynamic loading conditions. These results were compared with those obtained under static loading.

STEELS OF THE STUDY

The study has been essentially carried out on three different steels:

- steel A, with a quenched and tempered microstructure obtained by direct quenching (bainite + martensite),

- steel B, a usual API X70 grade with ferrite-pearlite microstructure,
- and steel C, an experimental API X70 grade with an ultralow carbon bainite microstructure.

In order to enlarge the validation of the approaches chosen in this study, the results obtained on these three steels have been compared with those obtained on the following structural steels:

- steel ND, a C-Mn-Nb E 36-4 offshore grade with a ferrite-pearlite microstructure, in the normalized condition,
- steel F (C-Mn-Nd) and steel X (C-Mn-Nb-V), two API X65 grades with ferrite-pearlite microstructure, in the control-rolled conditions,
- steel ULCB, an experimental high grade with and ultralow bainite microstructure in the control-rolled conditions.

The chemical composition and the mechanical properties of the steels are given respectively in the tables 1 and 2.

Table 1. Chemical composition of the steels (weight %)

PLATE MARK	C	Mn	Si	P	S	Al	Mo	Nb	Cu	Cr	N	O	Ni	V	Ti
ND	0.171	1.44	0.27	0.011	0.01	0.056	-	0.033	0.022	0.007	0.01	0.002	-	-	-
F	0.1	1.57	0.32	0.018	0.0021	0.022	0.17	0.061	-	-	-	-	-	-	-
X	0.087	1.427	0.358	0.011	0.004	0.042	-	0.028	0.012	0.02	0.01	-	0.019	0.1	-
ULCB	0.032	2.005	0.205	0.01	0.003	0.05	0.375	0.049	-	-	0.019	-	0.31	-	0.013
A	0.107	1.175	0.382	0.015	0.001	0.047	0.239	-	0.015	0.275	0.009	-	0.228	-	0.016
B	0.086	1.522	0.391	0.018	0.002	0.044	-	0.038	-	-	0.005	-	-	0.062	0.062
C	0.032	2.005	0.205	0.01	0.0025	0.050	0.375	0.049	-	-	0.009		0.111	-	-

R-curves approach

The resistance to the ductile tearing of a steel is characterized, for the given thickness of the product, by a parabolic curve called R-curve.

This curve expresses the direct relationship between the stable crack advance, Δa, and a mechanical parameter which will be for this study either the J integral or δ, the crack tip opening displacement.

The higher the resistance to ductile tearing of a steel, the higher is the slope of the J-Δa or δ-Δa curve. The resistance to ductile tearing can be thus characterized by the values of the slopes $\frac{dJ}{da}$ or $\frac{d\delta}{da}$.

Table 2. Mechanical properties in the transverse direction

MARK	R_e (MPa)	R_m (MPa)	A (%)	Z (%)	KCV* (J)	TK 28 (°C)
ND	398	550	29.5	63	65	- 40
F	461	631	25.5	63	155	- 77
X	437	532	17.5	79	200	- 95
ULCB	432	625	-	-	> 358	- 130
A	503	620	26	80	250	- 90
B	467	567	27	67	215	- 120
C	483	671	22	75	270	- 125
E	421	486	52	66.5	240	- 73

CHARACTERIZATION OF THE RESISTANCE TO DUCTILE TEARING - THEORETICAL BACKGROUNDS

It is also possible to characterize the ductile tearing resistance by means of the opening angle of the crack at its actual tip, called CTOA** (Venzi *et al.*, 1980), during its propagation. We have already shown that, as a first approximation, the slope of the curve δ-Δa is analogous to the tangent of the CTOA (Maas and Marandet, 1986).

Rc-Sc approach (Priest and Holmes, 1981)

In this approach, tests are carried out on bend precraked specimens with different initial crack lengths. During each test, the fracture energy per unit ligament surface is recorded and then plotted in a diagram as a function of the ligament size, as indicated in the Fig. 1. The relationship of proportionality between these experimental values is characterized by the Y-axis intercept Rc and the slope Sc.

The authors of this approach give the following meaning to these parameters:

- Rc corresponds to the fracture energy associated with the initiation and propagation of the crack,
- Sc corresponds to the plastic deformation of the specimen "away" from the cracked plane.

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* CHARPY V energy at the upper shelf.

** Crack Tip Opening Angle.

Although these parameters do not derive from a theoretical fracture mechanics approach and that their physical meaning is not clearly established, we have looked for a relationship between the parameter Sc and the slope of the R-curves.

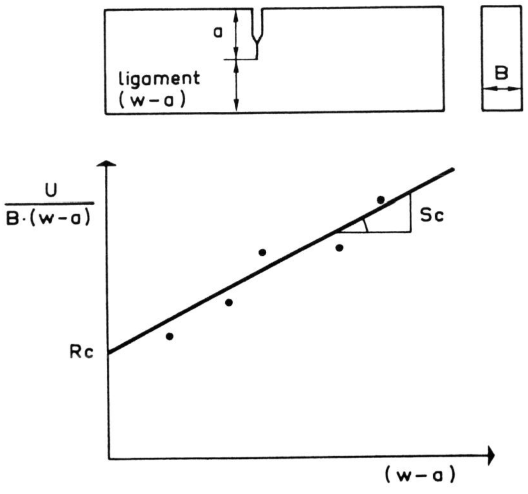

Fig. 1. Definition of Sc and Rc parameters

RESULTS

Behaviour of cracks under static loading

Ductile tearing tests have been carried out, for each steel of the study, on CT type specimens of different widths (50 mm ≤ W ≤ 750 mm). This procedure allows to study the influence of size effects and crack length range on the evolution of parameters $\frac{dJ}{da}$ or $\frac{d\delta}{da}$.

The experimental details of the tests are given elsewhere (Maas, 1988). The following results have been deduced:

- generally, the parameters $\frac{dJ}{da}$ or $\frac{d\delta}{da}$ give the same classification of the steels with respect to ductile tearing resistance for all the crack propagation range. More precisely, it is shown that the theoretical relationship (Demofonti and Maresca, 1985) between the two parameters $\frac{dJ}{da}$ and $\frac{d\delta}{da}$ is verified experimentally with a good approximation (Fig. 2). This relationship is the following:

$$\left[\frac{d\delta}{da}\right]_{\text{calculated}} = \frac{1.25}{\overline{V}_o}\left[\frac{dJ}{da} + \frac{J}{w-a}\right] \quad (1)$$

where $\overline{V}_o$ is the yield stress.

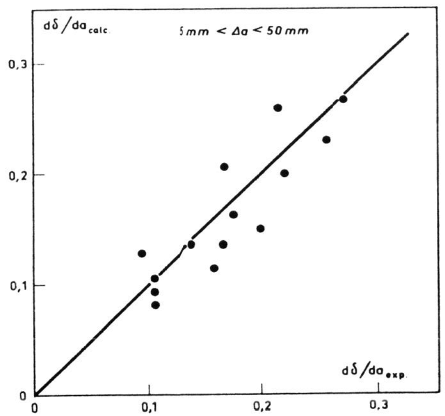

Fig. 2. Comparison of the experimental $\frac{d\delta}{da}$ values with the ones calculated by equation (1)

- the behaviour under ductile tearing of small crack range ($\Delta a \leq 10$ mm) may be different from the one of larger crack range (Fig. 3). It can be seen that steel A (tempered martensite + bainite) exhibits a better crack growth resistance in the small crack range than steels C (bainite) and B (ferrite + pearlite). This classification is not influenced by the specimen size. Above this crack range, steel C has the best crack growth resistance. In the case of steel A, the decrease of the ductile tearing resistance for large crack range can be explained by the occurrence of unstable fractures (pop-ins) encountered systematically for the largest specimens.

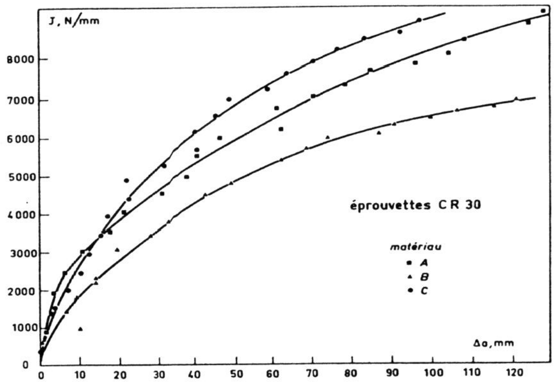

Fig. 3. J-Δa resistance curves

Fractographic studies show numerous separations perpendicular to the crack plane. These separations are particularly important for the large crack range. S.E.M. observations show cleavage occurrence in the separation planes and mixed cleavage and ductile areas in the crack plane for the steels A and C. These "mixed" fractures may explain the pop-ins behaviour of the steels. A previous study (Maas, 1988) has shown that delaminations do not modify significantly the slope of the R-curves.

The values of the parameter Sc have been determined for each steel by means of slow bend tests (width of specimens w = 76 mm). These results are compared with the values of $\frac{dJ}{da}$ measured in the same crack propagation range ($30 \text{ mm} < \Delta a < 60 \text{ mm}$) on Fig. 4. It is shown that both approaches are equivalent and that the best ductile tearing resistance is obtained for bainitic, or quenched and tempered microstructures.

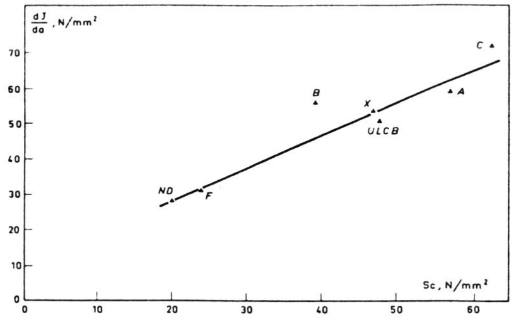

Fig. 4. Relationship between the parameters Sc and $\frac{dJ}{da}$

Behaviour under dynamic loading

R-curve tests were carried out on CT specimens loaded at $\dot{K} \approx 2.10^4$ MPa $\sqrt{m}$ s^{-1}. The calculated crack speeds are about 0.2 m/s, significantly lower than the speeds measured in the full scale burst test (between 100 and 150 m/s). This type of test is not appropriate for the simulation of in-service behaviour of cracks in the pipes.

Dynamic bending tests have been realized with a 15 000 J impact pendulum. The measured crack speeds are between 5 and 10 m/s, which is closer to in-service ones. The Sc values obtained during these tests are reported in table 3 for steels A, B and C, comparatively with the Sc values obtained under static conditions. For all the steels the increase of the loading rate is responsible for the decrease in the Sc value. This decrease is more significant in the case of steels A and B. These results are qualitatively explained by the fractographic examinations. Thus, in the case of steel B (ferrite + pearlite) the dynamic effect is responsible for a decrease of the plastic deformation and for an increase in the delaminations during the crack propagation. The increase of stress triaxiality under dynamic loading may explain the decrease of ductile tearing resistance. In the case of steel A (tempered martensite), the shear fracture changes with the loading rate, but this observation does not account for the decrease in ductile tearing resistance.

Table 3. Comparison of Sc values under static and dynamic loading

	S_c (kN/mm^2)	
	Static	Dynamic
A	0.057	0.030
B	0.040	0.025
C	0.062	0.056

CONCLUDING REMARKS

The quasistatic tests show that the classification of the steels with regard to their ductile tearing resistance may be influenced by the crack length range. From a practical point of view, it is necessary to compare the steels in the case of crack length range larger than 10 mm.

The different mechanical parameters give the same classification of the steels.

The crack speeds measured during the dynamic tests are not representative of those encountered during full scale burst tests. Nevertheless, significant changes in the tearing behaviour of the steels have been observed by means of impact bending tests. It has been generally possible to explain the change in the mechanical parameters by the fractographic observations. On the other hand, the interpretation of the shear fracture behaviour remains difficult.

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