STATISTICAL MODELLING OF THE DUCTILE - BRITTLE TRANSITION OF FERRITIC STEELS

S. Renevey[1], S. Carassou[1], B. Marini[1], C. Eripret[2] and A. Pineau[3]

Mechanical tests on axisymmetrically notched specimens and on CT type specimens were carried out at various temperatures (from -150°C to 0°C), in order to investigate the ductile-brittle transition of a low alloy ferritic steel. The results on notched specimens were used to determine the parameters of the local approach based on Weibull statistics. These parameters in conjunction with finite element calculations were used to interpret the variations of fracture toughness with temperature both in the regime where fracture takes place without ductile crack extension and in the regime corresponding to significant ductile crack growth before cleavage fracture.

INTRODUCTION

It is well known that cleavage fracture is preceded by a certain amount of ductile crack growth, Δa, when low alloy ferritic steels are tested in the ductile-brittle transition close to the upper shelf. As a rule, for a given specimen geometry, the fracture toughness and ductile crack growth are increasing functions of test temperature. Moreover another characteristic of the transition is the wide scatter observed in the test results which makes difficult the modelling of the transitional behaviour.

Two explanations are usually given for this behaviour. In the first one, it is assumed qualitatively that cleavage is triggered by an increase of the strain rate due to ductile crack extension. In the second one, two features are taken account : (i) Crack extension produces an increase of the "loading" applied to the crack tip. In the following, the broad term "loading" will be referred as the "Weibull stress" ; (ii) The increment of sampling volume due to ductile crack growth produces an increase of the probability of finding a weak link in the vicinity of the crack tip (Wallin (1), Amar and Pineau(2)).

1 CEREM/SRMA CEA / Saclay, Saclay 91191 Gif sur Yvette Cedex, France
2 EDF, DER Centre de Recherche Les Renardières, 77250 Moret sur Loing, France
3 Centre des Matériaux, Ecole des Mines, BP 87 91003 Evry Cedex, France, URA CNRS N° 866

In the present paper, an attempt is made to show that the results, obtained on a low alloy steel tested in the transition regime where the interpretation of fracture toughness measurements is problematic because of large scale yielding conditions and ductile tearing prior to cleavage initiation, can be interpreted in terms of the second explanation which can be made quantitative through the use of the local approach to brittle fracture.

MATERIAL AND EXPERIMENTAL PROCEDURES

The material was taken from a PWR nozzle cut-out. The composition was, in weight percent : C=0.16, Mn=1.38, Ni=0.70, Mo=0.50, Si=0.24, Cr=0.17, S=0.008, P=0.005. The material had mainly a tempered bainite microstructure with isolated ferritic islands. The tensile and CharpyV impact properties determined at various temperatures are given in Table 1.

Temp. (°C)	$Rp_{0,2}$ (MPa)	UTS (MPa)	A (%)	R.O.A. (%)	K_{cv} (daJ/cm²)
-150	762	882	28	56	0.5
-120	654	808	28	61	0.6
-90	604	768	29	64	-
-60	565	725	26	64	3.1
-30	547	701	26	67	-
0	528	671	28	68	14.7

Table 1 : Tensile and CharpyV impact properties

Tests on axisymmetric notched specimens were performed at -150°C. The dimensions of the specimens were : minimum diameter = 6mm ; notch radius = 1.2mm ; outer diameter = 10.8mm. SEM observations showed that the fracture mode was essentially pure cleavage. The results of these tests were used to determine the characteristic parameters describing brittle fracture. In the local approach, the probability to failure is written by : (Beremin (3))

$$P_R = 1 - \exp\left[-\left(\frac{\sigma_w}{\sigma_u}\right)^m\right] \quad (1)$$

where $\sigma_W = \left[\int_{PZ} \sigma_1{}^m dV / V_0\right]^{\frac{1}{m}}$ is the Weibull stress. In this expression σ_u, V_0 and m are the characteristic parameters, σ_1 is the maximum principal stress acting in the volume element V_0 while PZ is the volume plastically deformed. These tests carried out in the transverse orientation, led to m=16 and σ_u=3575 MPa, assuming that $V_0=(50\mu m)^3$.

Fracture toughness experiments were carried out at various temperatures (from -150°C to 0°C) on CT 25 specimens tested in the TS orientation. These specimens were instrumented to measure both the load-line displacement, δ, and stable crack growth, Δa, when it occurred prior to unstable cleavage fracture. Stable crack growth was measured using a potential drop technique and checked afterwards. These tests were performed using a servohydraulic machine operating under displacement control with a ramp rate of 0.25 mm/mn. Most of these tests were interpreted in terms of J. ASTM E 813-87 standards were used to calculate J and the effect of eventual ductile crack growth on J.

RESULTS AND DISCUSSION

The results of fracture toughness tests are shown in Fig.1 where the values of ductile crack growth preceeding brittle fracture are given. In this figure a large scatter in the results is observed especially around 0°C. It is also observed that ductile crack growth Δa tends to increase with test temperature. In Fig.1 the line corresponding to the limit load in plane stress ($KL_{P\sigma}$) is also drawn. It can be noticed that test performed above -120°C were beyond this limit load.

In the following an attempt is made to interpret these results. For this purpose we distinguish the tests in which there was no stable crack growth before brittle fracture from those in which crack growth took place. The reason for this lies in the fact that an analytical expression for the prediction of the fracture toughness can only be derived for the first set of results when they are obtained under small scale yielding conditions (3). The probability to failure can then be written as :

$$P_R = 1 - \exp\left[-\frac{K_{IC}^4 \sigma_0^{m-4} B C_m(n)}{\sigma_u^m V_0}\right] \qquad (2)$$

where B is the specimen thickness, σ_0, the yield strength at a given temperature and C_m, a numerical constant depending on the work hardening exponent, n ($\sigma = k\varepsilon^n$)

In Fig.1, we have drawn the results derived from Eq.2 (with $C_m = 5\ 10^3$), using the values of σ_u, V_0 and m which were determined on notched specimens, as indicated previously. A good agreement between the theory and the experiments is observed, even above the limit load but only when cleavage is initiated after small ductile crack growth. In particular at 0°C where large crack increments prior to brittle fracture were observed, as shown in Table 2, Eq.2 largely underestimates the observed fracture toughness for cleavage initiation. An illustration showing ductile crack growth over a distance of the order of 1mm in a specimen tested at this temperature is shown in Fig.2.

Specimen	321	314	320	323	316	322	326	325	318	324
KJ (MPa√m)	158	219	301	320	335	367	374	466	547	555
Δa (mm)	0.00	0.00	0.57	1.46	1.04	1.90	1.61	2.95	5.22	5.96

Table 2 : fracture toughness and ductile crack growth before cleavage at 0°C

In the presence of significant crack growth before cleavage fracture and largely above the limit load, it is necessary to use numerical calculations to determine the Weibull stress ahead of the crack tip and to predict, from Eq.1, the probability to failure for a given value of J parameter. The results of the F.E. calculations are shown in Fig.3. Fine meshes (1.5μm) were used to simulate crack blunting effect. Full details are given elsewhere (4). The main difficulty is related to the three dimensional aspect of the problem. The CT specimens used in our study had no side-grooves. They should necessitate therefore full 3D calculations. In this work, only 2D (plane stress, Pσ, and plane strain, Pε) numerical computations were performed. The value of J was supposed to be a linear combination of $J_{P\sigma}$ and $J_{P\varepsilon}$, i.e. :

$$J = \frac{B_{P\sigma}}{B} J_{P\sigma} + \frac{B_{P\varepsilon}}{B} J_{P\varepsilon} \qquad (3)$$

where $B_{P\sigma}$ and $B_{P\varepsilon}$ are the part of the thickness under plane stress and plane strain, respectively. The comparison of J calculated from Eq.3 and J determined experimentally showed that $B_{P\sigma}$ = 22mm and $B_{P\varepsilon}$ = 3mm. These values of $B_{P\sigma}$ and $B_{P\varepsilon}$ were then used to calculate the Weibull stress as :

$$\sigma_W = \left[B_{P\sigma}\left(\sigma'_{w,P\sigma}\right)^m + B_{P\varepsilon}\left(\sigma'_{w,P\varepsilon}\right)^m \right]^{\frac{1}{m}} \qquad (4)$$

where σ' denotes the Weibull stress calculated for a specimen of unit thickness.

In Fig.3, it is observed, as expected, that the Weibull stress is independent of the initial crack length provided that the limit load is not reached. The slope of the line $\ln\sigma_w$ - lnJ is equal to 0.143 which is very close to the theoretical value (Eq.2). On the other hand , beyond the limit load, the calculated Weibull stress is dependent on crack length. It was assumed that this dependence of the Weibull stress with crack length can be used to model simply the effect of crack growth prior to cleavage initiation.

This assumption, already made in a previous study (2), was used to interpret the results obtained at 0°C (Table 2), as shown in Fig.4. In this figure we have drawn the measured J-Δa and calculated lines corresponding to different probabilities to fracture. These lines were obtained from the calculations reported on Fig.3. Fig.4 shows that the experimental results are included between the two calculated lines corresponding to P_R=0.10 and P_R=0.90. It is also observed that the probability to failure is an increasing function of crack growth. However a close examination to the results shows that our model tends to underestimate the values of J. This might be related to the beneficial effect of large plastic strains ahead of the crack tip, as discussed in previous studies (2, 3). However this beneficial effect will be counterbalanced by the sampling effect associated with ductile crack extension, as indicated in the introduction.

CONCLUSION

It is confirmed that the analytical expression derived from the theory of brittle fracture valid for small scale yielding (Eq.2) describes correctly the variation K_{IC} with temperature in the absence of significant ductile crack growth. This expression applies also to some extent above the limit load. Encouraging results have been obtained using the same theory for cleavage fracture, in the presence of significant ductile crack extensions prior to cleavage. This tends to demonstrate that the ductile-brittle transition behaviour is essentially related to the increase of the loading parameter (here, the Weibull stress) applied to the test-pieces and not to a strain rate effect.

REFERENCES

(1) Wallin, K., Eng. Fract. Mech., Vol. 32, 1989, pp. 523-531.

(2) Amar, E., and. Pineau, A., Nucl. Eng. & Des., Vol. 105, 1987, pp. 89-96.

(3) Beremin, F.M, Met. Trans. A, Vol. 14A, 1983, pp. 2277-2287.

(4) Di Fant, M. et al., MECAMAT'96, to be published.

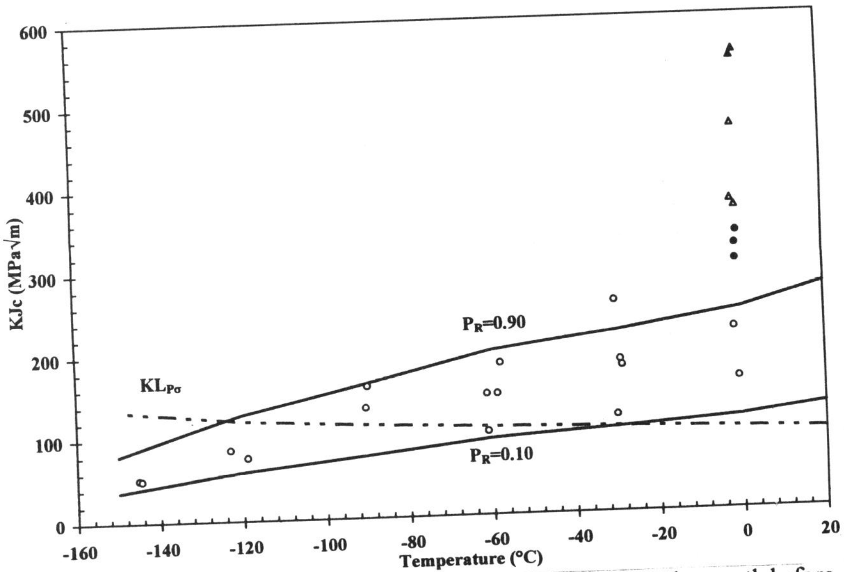

Figure 1 : Results of fracture toughness measurements with crack growth before cleavage (o$\Delta a<0.5$mm, ● $0.5mm<\Delta a<1.5mm$, △ $1.5mm<\Delta a<3mm$, ▲ $3mm<\Delta a<6mm$).

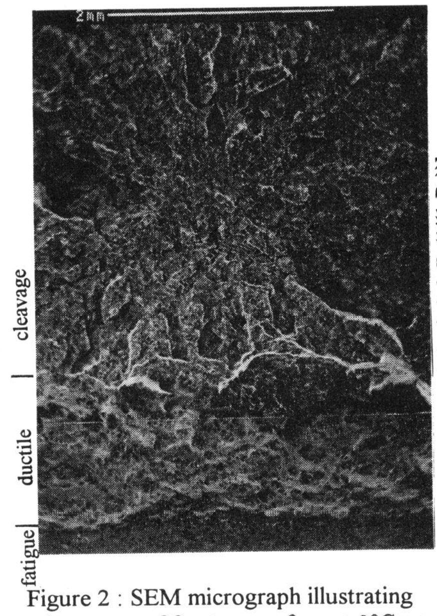

Figure 2 : SEM micrograph illustrating the aspect of fracture surface at 0°C.

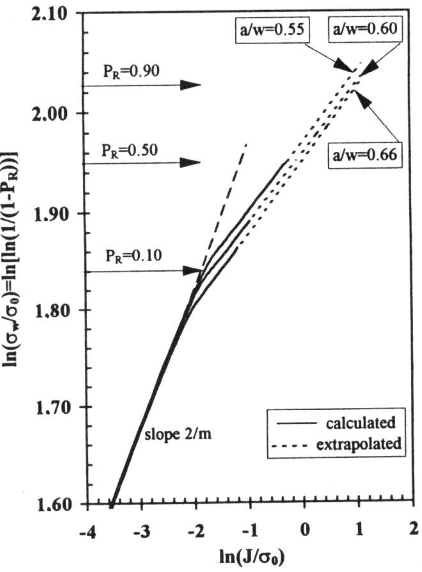

Figure 3 : Variation of the Weibull stress with J for increasing crack lengths, a/w.

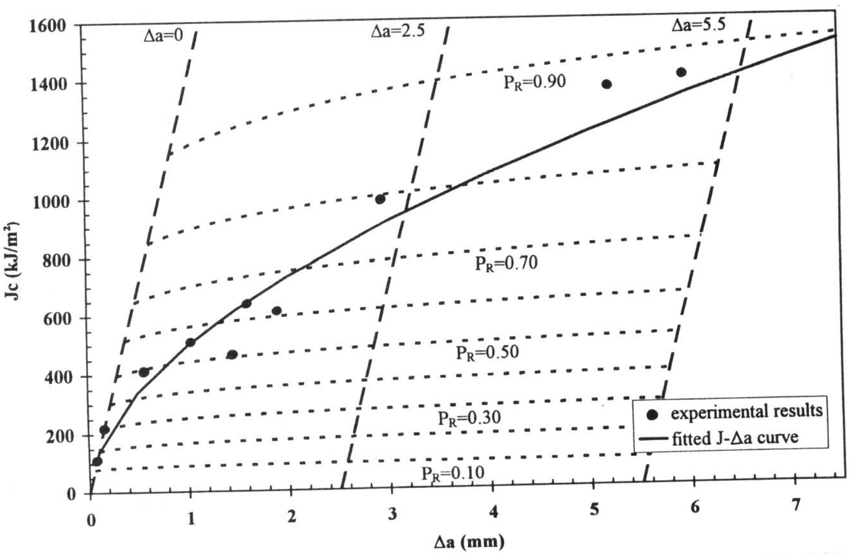

Figure 4 : Comparison between experimental and calculated values of J_c and Δa_C at 0°C for different cumulative probabilities, P_R.