Transactions of the 15th International Conference on
Structural Mechanics in Reactor Technology (SMiRT-15)
Seoul, Korea, August 15-20, 1999

Tearing Initiation and Crack Instability Assessments for an Aged Duplex Stainless Steel Pipe under Pressure Loading

B. Michel[1], C. Poette[1], M.T. Cabrillat[1] and P. Ledelliou[2]

1) DER/SERA/LDM, France
2) EDF/DER/MTC, France

ABSTRACT:

The aim of the study is to validate defect assessment method based on J criteria and to quantify the influence of residual stresses on tearing initiation and crack instability. Experimental results are coming from a failure pressure test of an aged duplex stainless steel pipe containing an axial surface crack. J Rice contour integral is derived from the Finite Element computation code CASTEM2000. Tearing initiation and instability are assessed with J_R-Δa curves, identified on aged CT specimens. Manufacturing residual stresses are taken into account with an equivalent thermal loading. Material scatter is also included using minimal and maximal J_R curves.

Tearing initiation and instability assessments are in good agreement with experimental results when taking account residual stresses. If the latter are neglected the defect assessment method give an over estimation of the failure pressure when the flaw is located in a tensile residual stress field and an under estimation of the failure pressure when the flaw is located in a compressive residual stress field. More over residual stresses have a significant influence on tearing instability, because of a low plasticity level in the uncracked ligament.

1. INTRODUCTION :

Duplex stainless steels are used in primary loop of the cooling system of pressure water reactors. These steels can be embrittled at service temperature of 320°C, because of a high ferrite level needed for the casting manufacturing process. Then the fracture toughness of an aged duplex stainless steel can be reduced significantly [1], and tearing failure mechanism has to be considered for defect assessment methods.

In order to study collapse mechanisms of a brittle structure containing a flaw, a research program was initiated in 1986 as a collaboration between CEA, EDF and FRAMATOME and experiments were carried out at C.E.A. Cadarache. Test specimens were duplex stainless steel pipes, with an external radius of 200 mm and thickness in a range of 40 to 50 mm. The initial flaw was a semi-elliptical axial surface crack, coming from an electroeroded notch and a precracked fatigue cycle. Specimens were submitted to a thermal ageing under different conditions of temperatures and ageing periods. Experiments were carried out at room temperature under pressure loading up to tearing initiation and crack instability.

The aim of the study is to validate defect assessment method based on J criteria and to quantify the influence of residual stresses on tearing initiation and crack instability. J Rice contour integral [2] is derived from the Finite Element computation code CASTEM2000. Initiation and instability are assessed with J_R-Δa curves, identified on aged CT specimens. Manufacturing residual stresses are taken into account with an equivalent thermal loading. Material scatter is also included using minimal and maximal J_R curves.

2. EXPERIMENTAL RESULTS :

Failure pressure tests were carried out for three specimens with the following geometrical characteristics :

Table 1 : Geometrical characteristics of failure pressure tests

Test	Internal radius (mm)	Thickness (mm)	Crack depth (mm)	Crack length (mm)	Crack position
1	150	50	26,8	298	external
2	160	40	28,5	300	external
3	150	50	25	300	internal

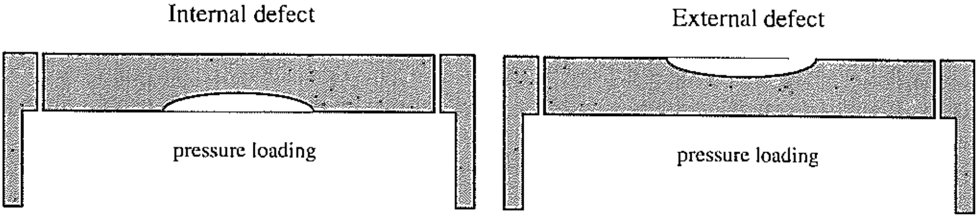

Figure 1 : Test specimen geometry

Failure mechanism for tested pipes is a tearing initiation at the deepest point of the crack and then a few millimetres stable tearing in thickness before crack instability. This failure mechanism has been deduced from a potential drop technique monitoring and destructive metalographic examinations. Experimental results for pressure failure tests are given in table 2.

Table 2 : Experimental results of failure pressure tests

Test	Tearing initiation pressure (MPa)	Tearing instability pressure (MPa)	Stable tearing length (mm)
1	51-54	71	2,3
2	37-39	51	4
3	22,4	32,4	4,675

3. MATERIAL DATA :

Pipe specimens were submitted to thermal ageing in order to have a reduced fracture toughness. Table 3 give characteristics of thermal ageing applied on each specimen.

Table 3 : Characteristics of the thermal ageing

Test	Temperature (°C)	Period (hour)	Cast number
1	400	1000	Y3296
2	400	700	Y4331
3	400	8000	Y3296

As shown in table 3 test specimens 1 and 3 are extracted from the same cast, and have a chemical composition slightly different from the test specimen 2.

The embrittlement due to the thermal ageing is shown for the monotonic consolidation curve on figure 2 , and for the fracture toughness on figure 3.

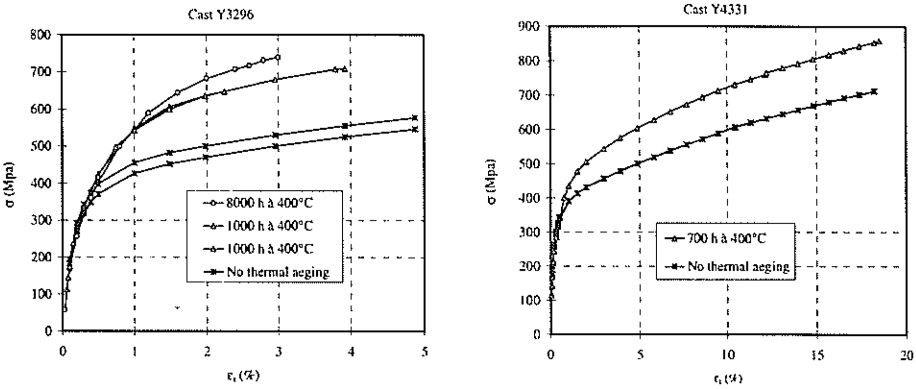

Figure 2 : Influence of the thermal ageing on the monotonic consolidation curve

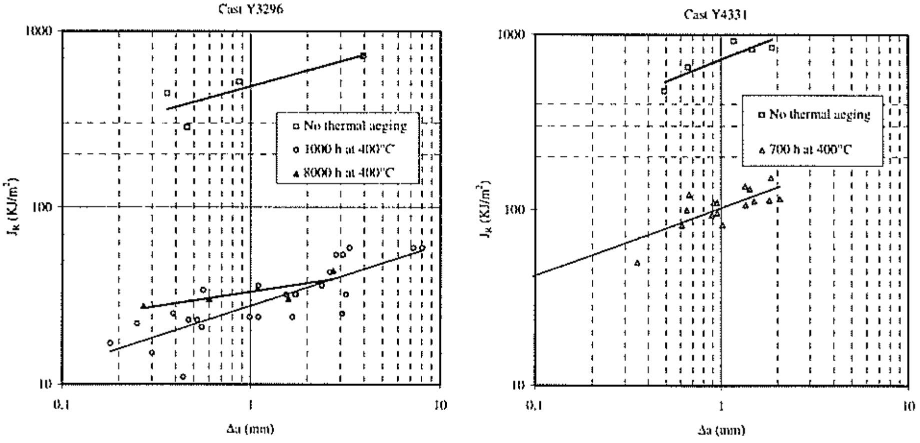

Figure 3 : Influence of the thermal ageing on the fracture toughness

On figure 2 the thermal ageing embrittlement is characterised by a higher consolidation curve and a lower maximal ductility. On figure 3 the fracture toughness is significantly affected by thermal ageing. To take into account fracture toughness scatter band, minimal and maximal J_R-Δa curves are defined in table 4, according power law given in equation (1).

$$J_R=C.\Delta a^n \qquad (1)$$

Table 4 : Minimal and maximal fracture toughness laws.

Test	law	$J_{0,2}$ (KJ/m^2)	C	n
1	min	7	14	0,43
	moy	13,2	26,4	0,43
	max	20	40	0,43
2	min	40,2	75	0,3872
	moy	55	102,5	0,3872
	max	77,2	144	0,3872
3	min	21,6	28,2	0,1655
	max	26	33,2	0,1655
	moy	28,4	37,1	0,1655

4. RESIDUAL STRESSES :

Residual stresses in pipe specimens 1,2 and 3 are due to a thermal hardening treatment included in the casting manufacturing process. The circumferential stress measured through the thickness for pipe specimen 1 and 3 (see figure 4) shows a compressive residual stress field on the outer surface and a tensile residual stress field on the inner surface.

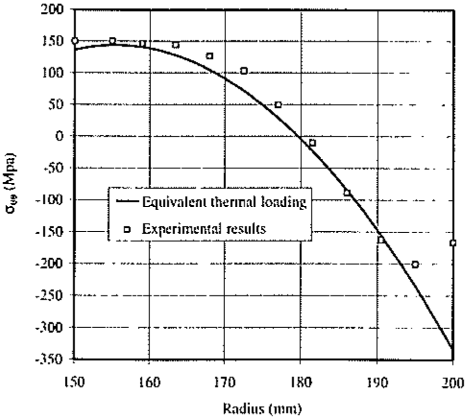

Figure 4 : Residual stress field through the thickness.

This residual stress field is approximate with an equivalent thermal loading given by equation (2).

$$T(r) = T_0 - \frac{83{,}157.(1-\nu)}{E.\alpha}.r + \frac{0{,}2645.(1-\upsilon)}{E.\alpha\cdot}.r^2 \qquad (2)$$

Where r is radius (mm), T(r) temperature (°C), E Young's modulus (MPa), α thermal expansion ratio (°C^{-1}) and ν Poisson ratio.

Residual stress field shown on figure 4 has been also used for the pipe specimen 2, stress relaxation due to thickness reduction (50 mm to 40 mm) has been computed with elastic theory. The equivalent thermal loading for pipe specimen 2 is also given by equation (2).

5. FINITE ELEMENT COMPUTATION

In order to validate defect assessment method based on J criteria the J Rice contour integral has been computed with Finite Element computation code CASTEM2000. Meshes used for pipe specimens 1,2 and 3 are shown on figure 5. Mesh refinement use at the crack tip is shown on figure 6.

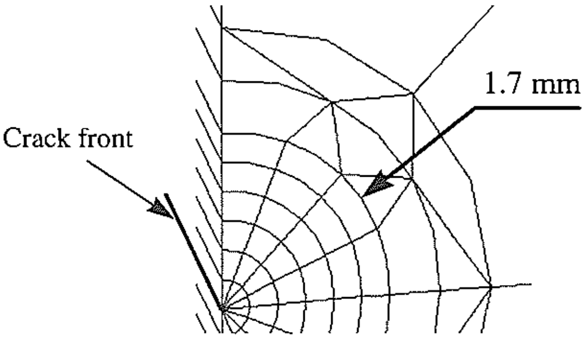

Figure 6 : Mesh refinement at the crack tip

Monotonic consolidation curves needed for incremental elasto-plastic Finite Element computation are given on figure 2. Thermal loading is applied before pressure to simulate residual stress field. For internal defect pressure is also applied on the free surface of the defect. The J Rice contour integral is computed with G_THETA method [3], and sensitivity to the number of layer, used in the virtual displacement field, doesn't exceed 5%. For external defect, located in a compressive residual stress field, the crack tip opening displacement is not monotonic at the beginning of the pressure loading. However the integral J is not contour dependant, according Finite Element results, because inelastic strain is negligible compare to elastic strain.

Finite Element results computed for different crack depths under pressure loading are plotted in a plane J-Δa, with experimental tearing initiation and instability pressures to derive the J_R-Δa curve of the pipe specimen (figures 7 and 8). On these figures Δa represents the tearing length from the initial crack depth.

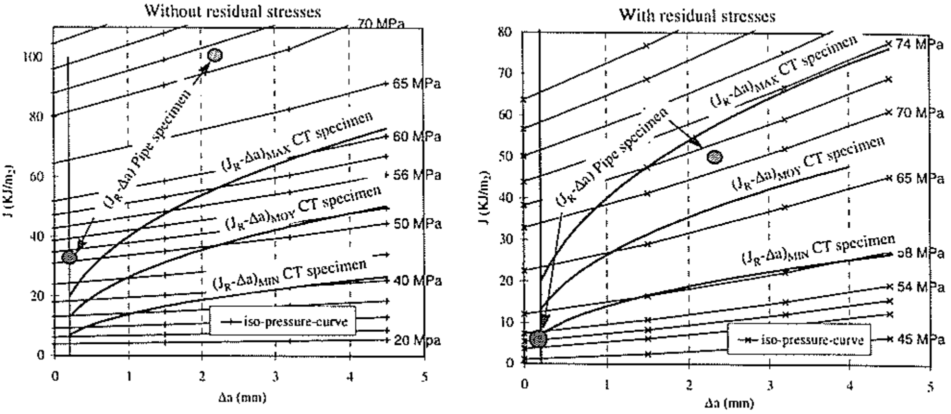

Figure 7: Tearing initiation and instability in Pipe specimen 1.

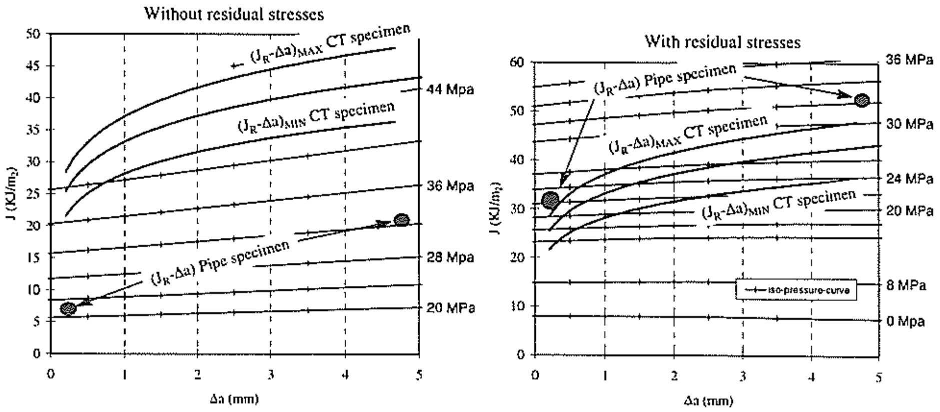

Figure 8: Tearing initiation and instability in Pipe specimen 3.

6. DISCUSSION :

As we can see on figure 7 and 8 (J_R-Δa) pipe specimen curve is different from (J_R-Δa) CT specimen curve when J is computed without taking account residual stresses. However on same figures pipe and CT specimens lead to closer (J_R-Δa) curves when residual stresses are added as a prior loading before pressure. According Finite Element results the influence of residual stresses on tearing initiation and instability is significant and explains an over estimation of the (J_R-Δa) curve for external defect (pipe specimen 1) and an under estimation of the (J_R-Δa) curve for internal defect (pipe specimen 3).

Tearing length assessment, using criterion $dJ/da > dJ_R/da$, is in good agreement with experimental data for pipe specimen 1, but doesn't seem to be well adapted for pipe specimen 3. In this last tearing length has to be limited to approximately 5 mm for instability pressure assessment.

The influence of residual stresses on tearing instability pressure can be explained by a low plasticity level in the uncracked ligament according a detailed examination of Finite Element results.

7. CONCLUSIONS

Failure pressure tests carried out for aged duplex stainless steel pipe specimens containing axial surface flaws show that collapse mechanism is a tearing initiation at the deepest point of the crack and then a few millimetres stable tearing in the thickness before crack instability. The embrittlement effect due to thermal ageing has been characterised on fracture tests for CT specimens.

The integral J has been computed with Finite Element for tearing initiation and instability pressure assessments. Finite Element results show that discrepancy between (J_R-Δa) curves for CT specimen and pipe specimen can be mainly explained by residual stresses. Then, when residual stresses are taken into account, tearing initiation and instability pressure assessments are almost included in experimental scatter band of (J_R-Δa) CT specimen curves.

REFERENCES :

1. "Modelling of the effect of thermal ageing of duplex stainless steels on their fracture toughness", P. JOLY, A. PINEAU, Scandinavian Jour. of Metallurgy, 1995, Vol 24,p 226-236.

2. "A Path Independent Integral and the Approximate Analysis of Strain Concentration by Notches and Cracks." J.R. RICE, Journ. of Applied Mech., Vol 35, 1968, pp 379-386.

3. "Energy Release Rate Calculation by the Finite Element Method", H.G. DELORENZI, Engineering Fracture Mech., Vol 21, 1985, pp 129-143.

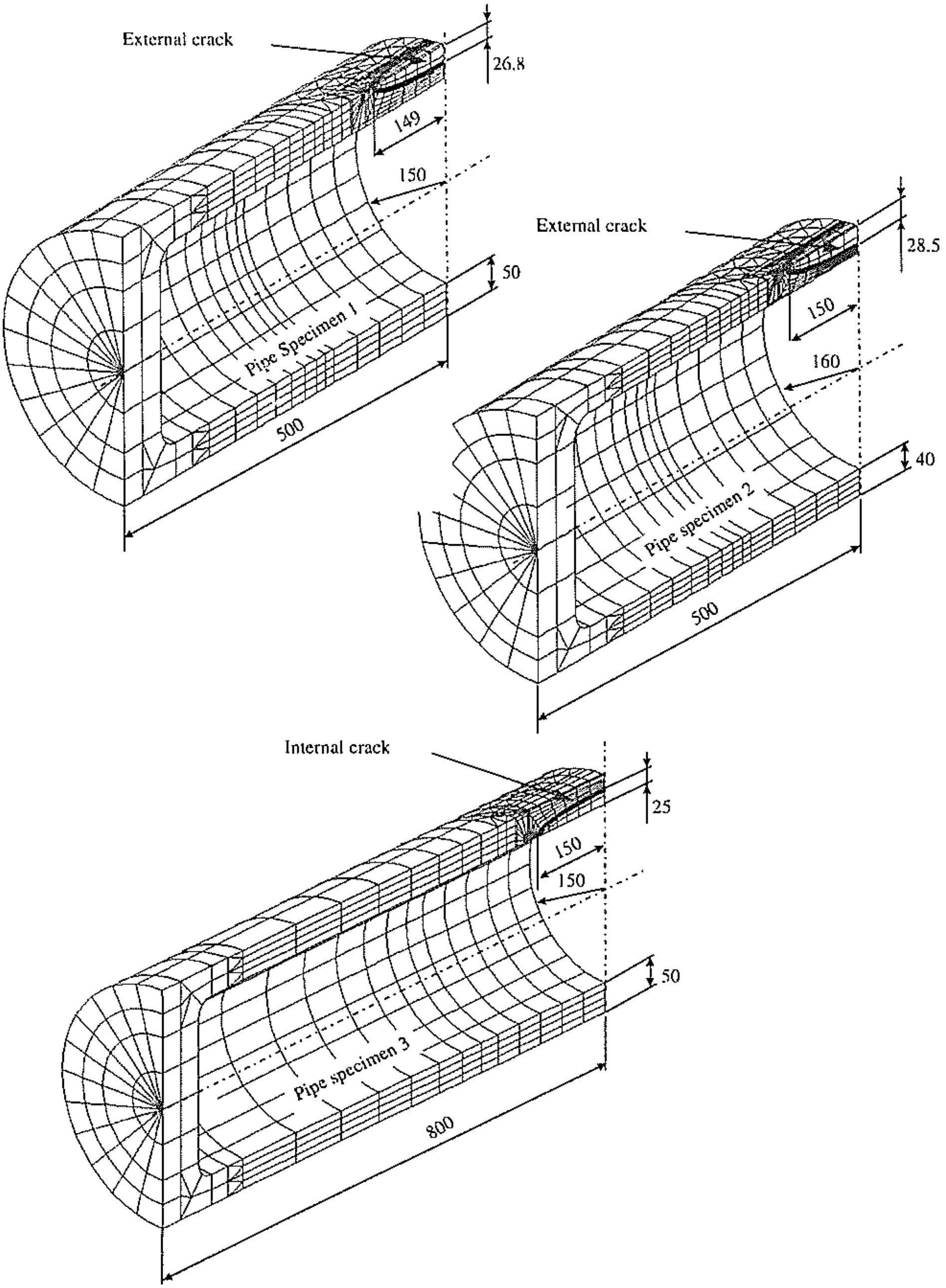

Figure 5 : Finite Element meshes for pipe specimen 1,2 and 3.