Ductile Fracture of an Embrittled Stainless Steel under Mode I+II Loading : Experimental Evaluation of the R6 Method

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Résumé. La stabilité des fissures sous chargement de type mode mixte I+II a été étudiée pour l'acier inoxydable austénitique type 316L SPH vieilli à 700°C pendant 1000 heures. Les caractérisations métallurgiques et mécaniques ont été effectuées dans les sens de prélévement T, L et TL. Les essais en mode mixte I+II, mode II pur et mode I pur ont été réalisés sur barreaux de flexion à quatre points d'appui disymétriques et symétriques. Lors des essais, l'ouverture et le glissement de la fissure ont été mesurés à l'aide d'une extensométrie à trois capteurs. La charge limite et l'intégrale J ont été calculées et une validation de la règle R6 a été réalisée dans ses trois options. L'estimation de l'amorçage est conservative dans tous les cas : plus la sollicitation est proche du mode I pur, plus les résultats sont conservatifs. L'amorçage de la fissure peut être estimé avec le F.A.D. obtenu à partir de résultats expérimentaux pour chaque mode.

Abstract. The ductile fracture behavior under mixed mode I+II loading is studied for a 316L stainless steel thermally aged for 1000 hours at 700°C. Microstructural examinations and mechanical tests (tension, Charpy impact and fracture toughness CTJ tests) were performed in three different orientations of specimen selection (T, L and TL). Asymmetric and symmetric four-point bend specimens were tested under mixed-mode I+II and pure mode I and II loadings. Both crack opening and crack sliding displacements were measured by a triple-extensometer. The limit load and approximate J-integral analyses were carried out. The R6 method was applied in its three options, giving a conservative prediction of the crack initiation. With the F.A.D. derived from the experimental data for each mode, the crack initiation loads could be well estimated.

1. INTRODUCTION

The present work adresses the problem of ductile mixed-mode fracture behavior in fast breeder reactor components. To simulate the embrittlement of material due to thermal aging in service conditions, especially at the end of its life time, a plate of 316L stainless steel was thermally aged for 1000 hours at 700°C.

Metallurgical and mechanical properties are characterized in three different orientations of specimen selection : the anisotropy or heterogenity of the material may be important in mixed-mode fracture.

In ductile materials under mixed-mode loading, the LEFM analyses are inadequate and the plastic deformation is significant at crack tip region. The J-integral analysis is to be carried out and the R6 method using limit load analysis may be more appropriate for wide range of mixed-mode loading I+II.

2. MATERIAL PROPERTIES

The chemical composition of the 316L stainless steel is presented in table 1. Microscopic examinations in three faces T-S, L-S and L-T showed the presence of very little quantity of ferrite (<1%) and the material was rather anisotropic in microstructure with its banded ferrite along the longitudinal direction.

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

C	Si	Mn	Ni	Cr	Mo	S	P
0.024	0.34	1.82	12.4	17.0	2.49	0.002	0.020

Mechanical tests were performed in three different orientations T-L, L-T and TL-LT : uniaxial tension, Charpy-U impact and fracture toughness CTJ tests (table 2).

Table 2. Summary of the mechanical properties

tests	orient-ation	T	L	TL	aver-age	T: initial
tension	E (MPa)	190000	190000	190000	190000	190000
	Sy(MPa)	299	305	299	301	279
	Su(MPa)	658	669	652	660	596
	e.fr (%)	32,3	32	32,5	32	56
	R.A. (%)	50,7	54	56,4	54	66
Charpy impact	KCU (daJ/cm2)	8,2	9,4	9	8,9	31,6
	3.2 KCU (kJ/m2)	262	301	286	283	1011
fracture toughness J	J1C (kJ/m2)	168	263	277	236	-
	J0.2 (kJ/m2)	262	436	426	375	-

It shows that the material was significantly embrittled due to the thermal ageing for 1000 hours at 700°C and it is equivalent to that for more than 5000 hours at 650°C or 10^5 hours at 550°C in terms of Charpy-U impact energy : order of 30 daJ/cm^2 before aging and 10 daJ/cm^2 after aging. It must be also noted that the fracture toughness are more elevated in the L-T and TL-LT orientations than that in the T-L orientation, while the tensile properties are nearly equal in the three orientations concerned (figures 1, 2).

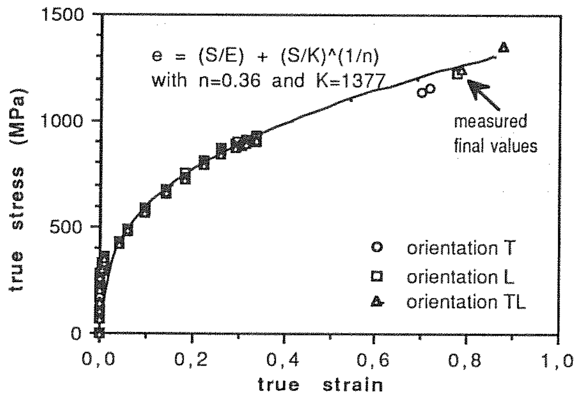

Figure 1. True stress-strain curve with the Ramberg-Osgood equation

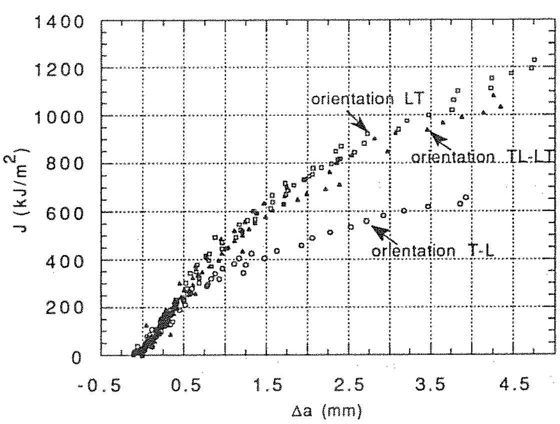

Figure 2. J-Δa curves with CTJ25 specimens

3. MIXED-MODE EXPERIMENTS

Mixed-mode experiments were performed using single edge-notched specimens : under asymmetric four-point loading for mixed mode I+II and pure mode II and under symmetric four-point bend loading for pure mode I (figure 3).

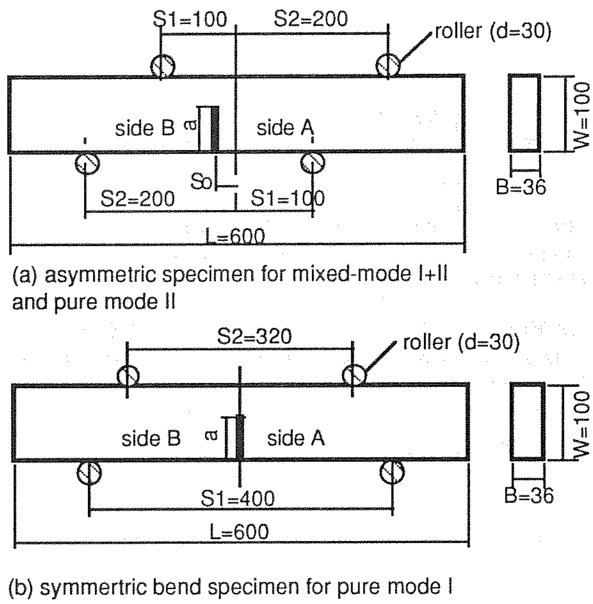

Figure 3. Asymmetric and symmetric specimens

3.1. Stress intensity factors

The stress intensity factors, K_I and K_{II}, were separately calculated by Wang et al. and the same results were deducted by Bui using the symmetrical and asymmetrical components of the J-integral in linear elasticity [1, 2, 3].

$$K_I = \frac{M}{B\,w^{3/2}} F_I\left(\frac{a}{w}\right) \quad \text{and} \quad K_{II} = \frac{Q}{B\,w^{1/2}} F_{II}\left(\frac{a}{w}\right) \qquad (1)$$

where $F_I(\alpha)=6\sqrt{\pi\alpha}\left\{1.122-1.4\alpha+7.33\alpha^2-13.08\alpha^3+14\alpha^4\right\}$

and $F_{II}(\alpha)=\sqrt{\pi\alpha}\left\{3.3645\alpha-1.051\alpha^2-0.526\alpha^3+1.89\alpha^4\right\}$

3.2. Test procedure and results

Six specimens in T-L orientation were tested under different mixed-mode : K_{II}/K_I = 0.3, 0.5, 1, 2 and pure mode I and II (table 3). Three relative displacements were measured instantaneously by a triple-extensometer at the crack mouth and then both crack opening and sliding displacements were calculated. The crack initiation was detected by a potential drop technique, a crack tip strain measurement [4] and a visual method with photos. The variations of load, displacement, crack mouth opening and sliding displacements at the crack initiation are presented as a function of the mode mixity $\psi = \tan^{-1}(K_{II}/K_I)$ (figure 4).

Table 3. Results of the mixed-mode experiments on asymmetric and symmetric bend specimens (at the crack initiation)

	test 1	test 2	test 3	test 4	test 5	test 6
KII/KI	1	0.5	2	0 mode I	infini mode II	0.3
ao(mm) af(mm)	63.1 73.6*	62.2 71.6	62.4 73.9	67.9 75.6	63.8 73.1	71.7 81.0
force(kN) displace-ment(mm)	890 6.17	650 3.95	955 6.17	325 2.16	970 8.05	565 3.79
CMOD(mm) CMOA(°) CMSD(mm) $\sqrt{(CMOD^2+CMSD^2)}$,mm	0.734 0.528 0.729 1.034	0.495 0.426 0.224 0.543	0.156 0.168 0.722 1.160	1.995 1.450 0.023 1.995	0.022 0.033 0.880 0.880	1.075 0.740 0.247 1.103

note *: visual crack length on the photo at fracture

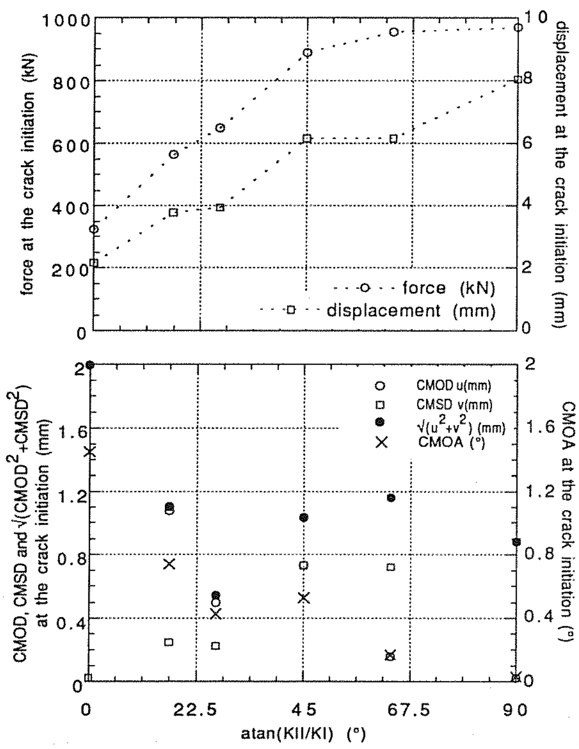

Figure 4. Variation of force, displacement, crack mouth opening and sliding displacements at the crack initiation in function of mode mixity

4. LIMIT LOAD AND DEFORMATION J

The R6 method provides an approach of interpolation between plastic collapse and linear elastic fracture. A simple assessment is performed using limit load and, in the option 3, J-integral analysis is to be carried out.

4.1. Limit load

For asymmetric four-point (bend) specimen in plane strain condition with the Von Mises criteria, the lower and upper bounds of limit load can be calculated from the formulas derived by Ewing et al. [5, 6] :

$$P_L = \frac{S_2+S_1}{S_2-S_1}\,\frac{b^2 B}{\left[16b^2+4b^2\right]^{1/2}}\left(\frac{2}{\sqrt{3}}\sigma_f\right) \quad \text{nominal lower bound} \quad (2)$$

$$P_L = \frac{S_2+S_1}{S_2-S_1}\,\frac{b^2 B}{\left[9b^2+4b^2\right]^{1/2}}\left(\frac{2}{\sqrt{3}}\sigma_f\right) \quad \text{approximate upper bound} \quad (3)$$

And for symmetric four-point bend specimen,

$$P_L = \frac{B\,b^2}{S_2 - S_1}\left(\frac{2}{\sqrt{3}}\,\sigma_f\right) \quad \text{lower bound} \quad (4)$$

$$P_L = 1.2606\,\frac{B\,b^2}{S_2 - S_1}\left(\frac{2}{\sqrt{3}}\,\sigma_f\right) \quad \text{upper bound} \quad (5)$$

For conservative prediction in the R6 method, an upper bound may be appropriate.

4.2. Deformation J

The usual form of J-integral is given by :

$$J = -\frac{1}{B}\frac{\partial U}{\partial a} \quad \text{or} \quad J = -\frac{1}{B}\int_0^{\delta}\left|\frac{\partial P}{\partial a}\right|_{\delta} d\delta = \frac{1}{B}\int_0^{P}\left|\frac{\partial \delta}{\partial a}\right|_{P} dP \quad (6)$$

where U = total absorbed energy at load point (or area under the load-displacement curve), P = applied load and δ = displacement at load point

For laboratory estimation of J-integral, more general form of equation (6) with geometric correction factor η is useful [7, 8] :

$$J = J_e + J_p = \eta_e \frac{U_e}{B\,b} + \eta_p \frac{U_p}{B\,b} \quad (7)$$

Here the total energy is divided into elastic and plastic components U_e and U_p respectively.

In linear elasticity for mixed-mode loading, the geometric factors $\eta_{I\,e}$ and $\eta_{II\,e}$ can be calculated from the elastic compliances and the stress intensity factors :

$$J_e = J_{Ie} + J_{IIe} = \eta_{Ie}\frac{U_{Ie}}{B\,b} + \eta_{IIe}\frac{U_{IIe}}{B\,b} \quad (8)$$

$$\text{where } \eta_{Ie} = \frac{K_I^2}{E'}\,\frac{B\,b}{U_{Ie}} \quad \text{and} \quad \eta_{IIe} = \frac{K_{II}^2}{E'}\,\frac{B\,b}{U_{IIe}}$$

In perfectly plastic materials, if we have a functional relation of load and displacement, P = A(a) ϕ and δ = C(a) ξ, where A(a) and C(a) are functions of a only and ϕ is a function of ξ, the J-integral can be represented for a non-growing crack [9] :

$$J = \frac{1}{B}\left\{-\frac{dA/da}{A}\int_0^{\delta} P\,d\delta + \frac{dC/da}{C}\int_0^{P}\delta\,dP\right\} \quad (9)$$

Using limit load analyses, the $\eta_{I\,p}$ and $\eta_{II\,p}$ can be determined and an approximation of the plastic deformation J_p is found :

$$J_{Ip} = \eta_{Ip}\frac{U_{Ip}}{B\,b} \quad \text{with } \eta_{Ip}=2 \text{ for pure mode I} \qquad (10)$$

$$J_{IIp} = \eta_{IIp}\frac{U_{IIp}}{B\,b} \quad \text{with } \eta_{IIp}=1 \text{ for pure mode II} \qquad (11)$$

$$J_{I+IIp}=\eta_{I+IIp}\frac{U_{I+IIp}}{B\,b} \text{ with } \eta_{I+IIp}=\frac{2(9S_0^2+2b^2)}{(9S_0^2+4b^2)} \text{ for mixed-mode} \qquad (12)$$

,where U_{Ip} is the plastic portion of the absorbed energy in mode I, U_{IIp} in mode II and U_{I+IIp} in mode I+II respectively

Here U_{I+IIp} may be obtained directly from the area under load - plastic displacement curve or from the sum of areas under moment - plastic rotation curve and shearing - plastic sliding curve. It is noted that the η_{I+IIp} tends to η_{Ip} as S_0 becomes sufficiently large respect to b (i.e. pure mode I) and equals to η_{IIp} as S_0 becomes zero (i.e. pure mode II).

Finally, the J-integral in elastic-perfect plastic materials can be determined by sum of its elastic and plastic components and the incremental procedure may be used to consider the crack growth [10].

5. APPLICATION OF THE R6 METHOD

The R6 method (Rev.3) [11] was applied to the mixed-mode experiments to estimate the crack initiation.

The option 1 F.A.D. is

$$K_r=\left(1-0.14\,L_r^2\right)\left[0.3+0.7\exp\left(-0.65\,L_r^6\right)\right] \qquad (13)$$

, which is particularly useful for austenitic materials.

For the option 2 F.A.D., the true stress-strain curve of the material is used :

$$K_r=\left(\frac{E\,\varepsilon_{ref}}{L_r\sigma_y}+\frac{L_r^3{}_{ref}\sigma_y}{2\,E\,\varepsilon_{ref}}\right)^{-1/2} \quad \text{and} \quad L_r=\frac{\sigma_{ref}}{\sigma_y} \qquad (14)$$

, where (ε_{ref}, σ_{ref}) are coordinate points on the true stress-strain curve.

The option 3 F.A.D. requires a J-integral analysis of the cracked structure. The coordinate of the assessment curve is

$$K_r=\left(\frac{J}{J_{el}}\right)^{-1/2} \quad \text{and} \quad L_r=\frac{P}{P_y} \qquad (15)$$

, where J may be evaluated either by numerical or analytical methods, or from experimental data [12].

In elasto-plastic fracture mechanics regime, the failure occurs when $J = J_{IC}$. From the limit load analysis, the crack initiation can be predicted by a linear load line as follows :

For asymmetric four point (bend) specimen,

$$\frac{K_r}{L_r}=\left(\frac{2\sigma_y}{\sqrt{3}}\right)\frac{\sqrt{w}\,(1-\frac{a}{w})^2\,F_I F_{II}}{\sqrt{E\,J_{IC}}}\left[\frac{1+(K_I/K_{II})^2}{9F_{II}^2(K_I/K_{II})^2+4(1-\frac{a}{w})^2F_I^2}\right]^{1/2} \qquad (16)$$

For symmetric four point bend specimen,

$$\frac{K_r}{L_r}=\left(\frac{2}{\sqrt{3}}\sigma_y\right)\frac{\sqrt{w}}{\sqrt{E\,J_{IC}}}\left(1-\frac{a}{w}\right)^2\left(\frac{1.2606}{4}F_I\right) \qquad (17)$$

The figure 5 presents the test results when $J = J_{IC}$ in the the option 1, 2 and 3 F.A.D., where the option 3 F.A.D. was constructed from the experimental data of CTJ specimens. It shows that all the predictions of the crack initiation are very conservative and the nearer to the mode I, the more conservative. It must be also noted that the F.A.D.'s of CTJ specimen seem to be nearly equal in the three orientations concerned, while the J-R curves are different as

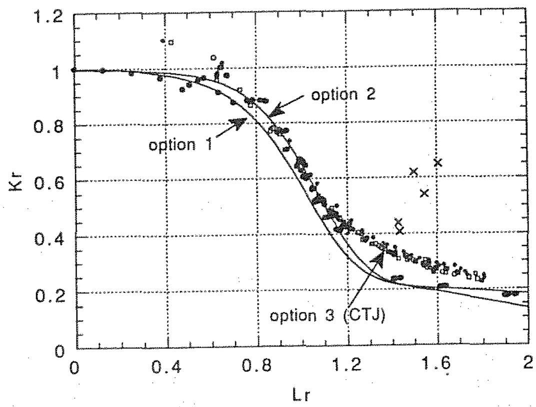

Figure 5. The test results and F.A.D. of option 1, 2 and 3 constructed from the experimental data of CTJ specimens

mentioned above. If the F.A.D. is derived from the experimental data for each mode (figure 6), the crack initiation loads may be well estimated using a linear load line K_r/L_r. The safety factors, defined as the inverse of the reserve factor, are presented in function of the mode mixity $\psi = \tan^{-1}(K_{II}/K_I)$ (figure 7).

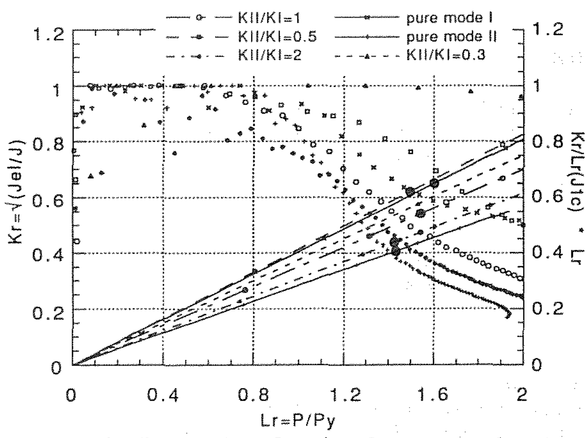

Figure 6. The F.A.D. of option 3 constructed from the experimental data and the load line for each mixed-mode test

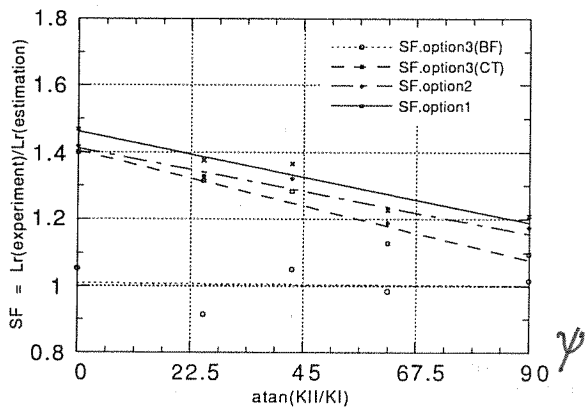

Figure 7. Variation of the safety factors (inverse of the reserve factors) in function of the mode mixity $\psi = \tan^{-1}(K_{II}/K_I)$

6. CONCLUSIONS

The 316L type stainless steel is significantly embrittled due to the thermal ageing for 1000 hours at 700°C: order of 30 daJ/cm^2 before aging and 10 daJ/cm^2 after ageing. It was also observed to be rather anisotropic in microstructure with its banded ferrite along the longitudinal direction. The fracture toughness was more elevated in the L-T and TL-LT orientations than that in the T-L orientation, while the tensile properties were nearly equal in the three orientations concerned.

The mixed-mode experimental results show that, at the crack initiation, the loads and the displacements increase, the opening displacements decrease and the sliding displacements increase along the mode mixity, while the equivalent opening displacements are nearly constant.

Using the limit load and an approximate J-integral analyses in mixed-mode loading, the R6 method appears to be very conservative for all the test results in its three options and the nearer to the mode I, the more conservative. If the F.A.D. is derived from the experimental data for each mode, the crack initiation loads may be well estimated using a linear load line K_r/L_r.

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