Mixed-Mode Fracture of Stainless Steel 316L : J-R curves and R6 method

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Asymmetric and symmetric four point bend specimens were tested to study the ductile fracture behavior under mixed-mode I+II, mode I and mode II for an austenitic stainless steel type 316L thermally aged for 1000 hours at 700°C.
By using the limit load and approximate J-integral analyses, the R6 approach is 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. The J-R curves are also established and compared with those of CTJ tests.

INTRODUCTION

Various methods are available for the fracture analysis in conditions of extended plasticity. The R6 method [1] extrapolating between brittle fracture and limit load is one of them. It relies on J computations, J_{IC} and dJ/da measurements. Mixed-mode loading in elastoplastic fracture has not been much studied. The aim of the present work is to evaluate the feasibility and the application of the R6 method under such conditions. The failure assessment diagram (F.A.D.) is constructed for various geometries and loading modes. From the J_{IC} values the R6 analysis in its three options is carried out for crack initiation to interpret the results obtained on various specimens loaded in bending. The crack propagation is also analysed in mixed mode.

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MATERIAL PROPERTIES

The material is an austenitic stainless steel type 316L used in fast breeder reactor components. To simulate the ageing effect in service conditions, a plate of 36 mm thick was heat treated for 1000 hours at 700°C. The material was significantly embrittled due to the heat treatment in terms of Charpy-U impact energy. 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 (table 1).

Table 1. Summary of mechanical properties

tests	orientation	T	L	TL	average	initial:T
tension	E (MPa)	190000	190000	190000	190000	190000
	Y.S. (MPa)	299	305	299	301	279
	T.S. (MPa)	658	669	652	660	596
	El. (%)	32.3	32.0	32.5	32.0	56.0
	R.A. (%)	50.7	54.0	56.4	54.0	66.0
Charpy-U impact	Kcu(daJ/cm^2)	8.2	9.4	9.0	8.9	31.6
	3.2 Kcu (kJ/m^2)	262	301	286	283	1011
fracture toughness J	J_{1C} (kJ/m^2)	168	263	277	236	-
	$J_{0.2BL}$(kJ/m^2)	262	436	426	375	-

MIXED-MODE EXPERIMENTS

SENB specimens in T-L orientation were tested for a wide range of mode mixity : K_{II}/K_I = 0.3, 0.5, 1, 2 and pure mode II under asymmetric 4-point loading, and pure mode I under symmetric 4-point loading. The crack opening and sliding displacements were measured at the crack mouth. The crack initiation was detected by a potential drop technique, a crack tip strain measurement [2] and a visual method with photos. The crack growth was also measured with photos of specimen surface and adjusted with the initial and final crack lengths.

LIMIT LOAD AND DEFORMATION J

A simple assessment of the R6 method is performed using limit load and, in the option 3, J-integral analysis is to be carried out.

The limit load can be calculated from [3] and the upper bound may be appropriate for conservative prediction.

The J expression with geometric factors is useful for laboratory conveniance [4]. In linear elasticity, J_c can be derived from elastic compliances. In perfectly plastic materials, using limit load analyses, an approximation of the plastic deformation J_p is found :

$$J_{I/IIp} = \eta_{I/IIp} \frac{U_{I/IIp}}{B\,b} \qquad (1)$$

where $\eta_{Ip} = 2$ for pure mode I, $\eta_{IIp} = 1$ for pure mode II

and $\eta_{I+IIp} = 2\,(9S_0^2+2b^2)\,/\,(9S_0^2+4b^2)$ for mixed-mode I+II

It is noted that the η_{I+IIp} tends to η_{Ip} as S_0 (distance between the resultant force and the crack) becomes sufficiently large (mode I) and equals to η_{IIp} as S_0 becomes zero (mode II).

The total J in elastic-perfect plastic materials can be given by the sum of its elastic and plastic components and the incremental procedure is used to consider the crack growth [5].

APPLICATION OF THE R6 METHOD

The three options of the R6 method [1] were applied to estimate the crack initiation without considering crack growth. In elasto-plastic fracture mechanics regime, the failure may occur when J = J_{IC}. From the limit load analysis, the crack initiation can be predicted by a linear load line as follows :

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

$$\frac{K_r}{L_r} = \left(\frac{2}{\sqrt{3}}\sigma_y\right) \frac{\sqrt{w}}{\sqrt{E\,J_{IC}}} \left(1-\frac{a}{w}\right)^2 \left(\frac{1.2606}{4}F_I\right) \quad \text{for symmetric 4-point bend specimen} \qquad (3)$$

The figure 1 presents the test results when J = J_{IC} in the option 1, 2 and 3 F.A.D.'s., where the option 3 F.A.D. was derived from the experimental data of CTJ specimens. It shows that all the predictions of the crack initiation are very conservative : the nearer to the mode I, the more conservative. It must be also noted that the F.A.D.'s of CTJ specimens seem to be nearly equal in the three orientations, while the J-Δa curves are different as mentioned above. If the F.A.D. is derived from the experimental data for each mode [6], the crack initiation loads can be well estimated using a load line K_r/L_r (figure 2 and table 2).

Table 2. Results of the mixed-mode experiments

KII/KI	infini mode II	2	1	0.5	0.3	0 mode I
Ao (mm)	63.8	62.4	63.1	62.2	71.7	67.9
Af (mm)	73.1	73.9	73.6*	71.6	81.0	75.6
Pmax (kN)	1310	1435	1260	1280	900	800
apparent crack propagation angle(°)	16	15	13	6	11	0
at the crack initiation						
force Pc (kN)	970	955	890	650	565	325
displacement (mm)	8.05	6.17	6.17	3.95	3.79	2.16
CMOD (mm)	0.022	0.156	0.734	0.495	1.075	1.995
CMOA (°)	0.033	0.168	0.528	0.426	0.740	1.450
CMSD (mm)	0.880	0.722	0.729	0.224	0.247	0.023
CMOD eq (mm)	0.880	1.160	1.034	0.543	1.103	1.995
S.F. op.1	1.21	1.23	1.40	1.38	2.79	1.47
S.F. op.2	1.18	1.19	1.32	1.33	2.70	1.42
S.F. op.3(with CTJ)	1.10	1.13	1.28	1.32	2.67	1.40
S.F. op.3	1.01	0.98	1.05	0.91	1.25	1.05
J at Pc (kJ/m²)	162	157	220	-	264	178
$J_{0.2BL}$ (kJ/m²)	100	210	405	-	490	235

note *: visual crack length on the photo at fracture

DETERMINATION OF J-ΔA CURVES

The J-Δa curves were established according to the French Group Fracture Recommendations. The curves are between those of the CTJ tests in T-L and L-T orientations and have no significant difference according to the mode mixity (figure 3 and 4). For the cases of K_{II}/K_I=0.3 and 0.5, nearer to the mode I, the J values increase rapidly as the applied load increases but the crack growth seems to be restricted by the compression resulting from the specimen constraints.

For each test, the values of J at crack initiation and $J_{0.2BL}$ were determined. It must be noted that for the case of K_{II}/K_I=0.5 it was not possible to determine the J values because of a technical incident. The J values at crack initiation are comparable to J_{IC} of CTJ in T-L orientation, but the conventional $J_{0.2BL}$ show a wide scatter (table 2). The high values of J found for the case of $K_{II}/K_I=0.3$ are due to the very long initial crack.

CONCLUSIONS

The R6 method appears to be very conservative for all the test results in its three options : the nearer to the mode I, the more conservative. With the F.A.D. derived from the experimental data, the crack initiation load could be well estimated using a load line K_r/L_r.

The J-Δa curves are between those of the CTJ tests in TL and LT orientations and have no significant difference according to the mode mixity.

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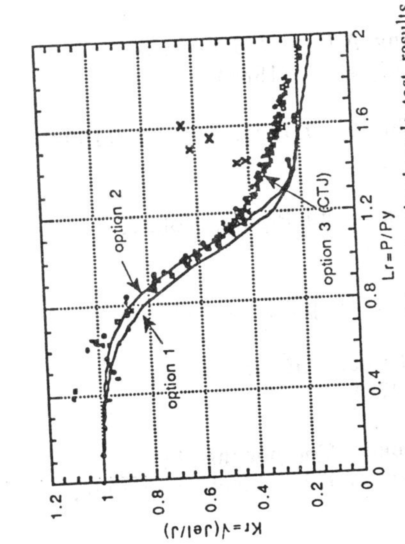

Figure 1. The F.A.D.'s and mixed-mode test results

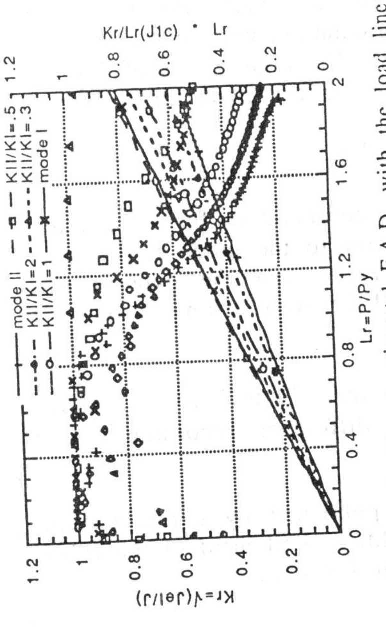

Figure 2. The experimental F.A.D. with the load line

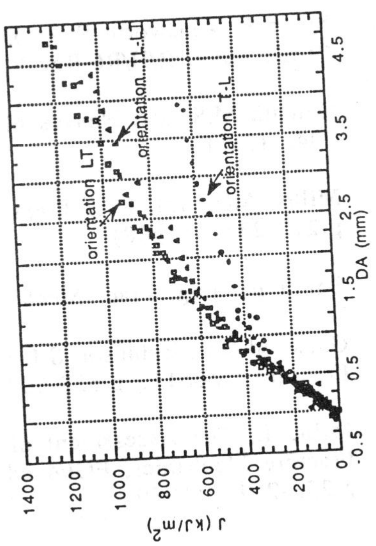

Figure 3. J-Δa curves of CTJ25 tests

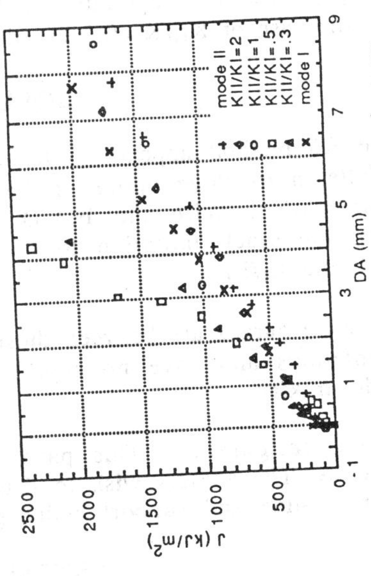

Figure 4. J-Δa curves of mixed-mode tests