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LOCAL APPROACH ON MIXED-MODE DUCTILE FRACTURE OF AN AGED STAINLESS STEEL 316L

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ABSTRACT
In the frame of the structural integrity of the fast breeder reactor vessel, the local approach of fracture is applied to the ductile crack initiation under mixed-mode I+II loading for a 316L type stainless steel thermally aged for 1000 hours at 700 °C. Experimental and numerical tests are performed on axisymmetric notched specimens, compact tension specimens and dissymmetric four-point bend specimens. From elasto-plastic finite element analyses, the damage variables are evaluated with various models : the Beremin model, the McClintock model, the Guennouni-François model and the Lemaitre model. The critical values of damage variable obtained on simple tensile specimens and axisymmetric notched specimens are used for the prediction of crack initiation under mixed-mode loading. The damage variable at crack initiation seems to be rather dependent on the fracture mode related to the stress triaxiality and the brittle fracture of banded ferrite of the aged material. The results are compared with those of the J values at crack initiation.

1. INTRODUCTION
In the frame of the structural integrity of the fast breeder reactor vessels, the defects may be often under combined loads because of the geometric or loading complexity and the structural material is ductile. Various methods are available for the fracture analysis in ductile material. Most of the analyses are based on the existence of J_{IC}, but the validity of this characteristic may be questionable in mixed-mode fracture. Another approach based on the microscopic fracture mechanics is the local approach. The damage variables are evaluated from the stress triaxiality and the equivalent plastic strain rate from finite element calculations. The aim of the present work is to evaluate the feasibility and the application of some local criteria for 4-point bend specimens under mixed-mode loading of a 316L type stainless steel and the results are compared with those of the J values at crack initiation.

2. MATERIAL PROPERTIES

The material in this study 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 thickness 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 but it keeps a high ductility. It must be noted that the fracture toughness is higher 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(T-L)	L(L-T)	TL(TL-LT)	average	initial (T)
	E (MPa)	190000	190000	190000	190000	190000
	Y.S. (MPa)	299	305	299	301	279
tension	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	Kcu(daJ/cm^2)	8.2	9.4	9.0	8.9	31.6
impact	3.2 Kcu (kJ/m^2)	262	301	286	283	1011
fracture	J_{1C} (kJ/m^2)	170	263	277	236	-
toughness J	$J_{0.2BL}$(kJ/m^2)	262	436	426	375	-

3. MIXED-MODE EXPERIMENTS

Four-point bend specimens (SENB) in T-L orientation were tested for a wide range of mode mixity : K_{II}/K_I = 1.5, 3, 6 and the pure mode II under dissymmetric 4-point loading. The hydraulic test machine of 2500 kN was used, of which the loading transmission part is blocked in rotation. 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 of the specimen surface. Some formulations concerning the experimental interpretation were already established and the validity was shown by one of the authors [3].

The experimental results are presented in table 2. The figure 1 presents the variation of the J values at crack initiation. For the SENBs the J values at crack initiation increase with the mode mixity from K_{II}/K_I=3 to the pure mode II but for the case of K_{II}/K_I=1.5 the values are rather near to that of J_{1C} in T-L orientation. These values are, in general, rather lower than that of J_{1C} in T-L orientation, but it must be noted that the definition of crack initiation of SENB is not the same as that of J_{1C} in the CTJ25 specimens.

Fractographic examinations revealed different fracture modes related to the banded brittle ferrite of the aged material for the AE2 specimens in L or TL orientations and the CTJ25 specimens. In the SENBs, brittle fracture aspects were not observed but the fracture surfaces consisted of sheared dimples of a few micrometers. For the SENBs with K_{II}/K_I=1.5, some equiaxed dimples were also observed and fracture of banded ferrite appeared after a sufficient crack propagation for the cases nearer to the mode I.

Table 2. Parameters at crack initiation for the mixed-mode tests

test	K_{II}/K_I	tri-axiality	P.c (kN)	J.c (kJ/m^2)	(R/Ro).c Beremin	(R/Ro).c McClintock	$\sqrt[3]{(f/fo)}$.c Guennouni -François	(D/Dc).c Lemaitre
N°12	1.39	0.84	831	128	1.481	1.765	1.980	0.295
N°6	1.43	0.82	679	183	1.588	1.946	2.110	0.382
N°2	1.52	0.84	843	155	1.528	1.846	2.045	0.334
N°11	2.84	0.66	892	109	1.286	1.413	1.694	0.193
N°15	2.88	0.67	909	111	1.297	1.431	1.710	0.204
N°1	3.14	0.70	875	124	1.335	1.491	1.780	0.243
N°13	5.66	0.61	998	163	1.349	1.463	1.758	0.305
N°3	6.13	0.61	991	149	1.364	1.485	1.780	0.322
N°5	infinite	0.50	971	171	1.323	1.372	1.665	0.327
N°14	infinite	0.46	1026	172	1.308	1.353	1.640	0.307

4. NUMERICAL SIMULATIONS

Elastoplastic finite element calculations were performed for the axisymmetric notched tensile specimens (AE4 and AE2), the compact tension specimen (CTJ25) and the dissymmetric 4-point bend specimens (SENB) under pure mode II, $K_{II}/K_I=3$ and $K_{II}/K_I=1.5$. The element size at the crack tip is considered as a material characteristic, particularly in the local approach. According to preceding studies [4], 8-noded isoparametric elements of 200 μm were used for the CTJ25 specimen and also for the SENBs.

5. LOCAL APPROACH

Using the results of the finite element analyses, different models of the local approach in ductile fracture were applied : the Beremin model, the McClintock model, the Guennouni-François model and the Lemaitre model.

From the expression derived by Rice-Tracey [5] for an isolated spherical cavity, the Beremin model was proposed [6] :

$$\mathrm{Ln}\left(\frac{R}{R_0}\right)_C = \int_{\varepsilon^p_{eq1}}^{\varepsilon^p_{eq2}} 0.283 \exp\left(1.5 \frac{\sigma_m}{\sigma_{eq}}\right) d\varepsilon^p_{eq} \qquad (1)$$

where R is the cavity radius, R_0 its initial value, σ_m the hydrostatic stress, σ_{eq} the Von Mises equivalent stress and ε^p_{eq} the equivalent plastic strain.

For an isolated elliptic cavity in a work-hardening material, the McClintock model with the average diameter is written by [7] :

$$\mathrm{Ln}\left(\frac{R}{R_0}\right)_C = \int_{\varepsilon^p_{eq1}}^{\varepsilon^p_{eq2}} \frac{\sqrt{3}}{2(1-n)} \sinh\left[\sqrt{3}\,(1-n)\left(\frac{\sigma_m}{\sigma_{eq}}\right)\right] d\varepsilon^p_{eq} \qquad (2)$$

Considering the effect of secondary cavities in a viscoplastic porous material, Guennouni-François model was proposed [8] :

$$\frac{\dot{f}}{(1-f)\,f} = 3\frac{\dot{R}}{R} = \frac{1}{f}\left(\frac{B}{A}\right)^2\left(\frac{\sigma_m}{\sigma_{eq}}\right)\dot{\varepsilon}^p_{eq} \qquad (3)$$

where $A(f) = -\frac{1}{\sqrt{3}}\left(1 - 1.92\,f + 5.57\,f^2 - 6.03\,f^3\right)\mathrm{Ln}\,f$

and $B(f) = (1-1.33f^{0.6})$ for $f<0.1256$ or $\frac{2.06}{\sqrt{3}}[\exp(-4.9f) - 0.044]$ for $f\geq 0.1256$

where f is the volume fraction of cavities and f_0 its initial value. By separating the integrating variables, the criterion can be written by :

$$\left(\frac{f}{f_0}\right)_C = V^{-1}\left[\int_{\varepsilon^p_{eq1}}^{\varepsilon^p_{eq2}} \left(\frac{\sigma_m}{\sigma_{eq}}\right) d\varepsilon^p_{eq} + V(f_0)\right] \text{ with } V(f_i) = \int_{f=0}^{f=f_i} \left(\frac{A(f)}{B(f)}\right)\frac{df}{(1-f)} \qquad (4)$$

Based on a continuum damage variable in thermodynamics, the Lemaitre model, when assuming small damage, yields [9] :

$$\left(\frac{D}{D_c}\right)_C = \int_{\varepsilon^p_{eq1}}^{\varepsilon^p_{eq2}} \frac{1}{\varepsilon_R - \varepsilon_D}\left[\frac{2}{3}(1+\nu) + 3(1-2\nu)\left(\frac{\sigma_m}{\sigma_{eq}}\right)^2\right] \varepsilon^{p\,2n}_{eq}\, d\varepsilon^p_{eq} \qquad (5)$$

where ε_R is the strain at fracture in a tensile test, ε_D and D_c are material caracteristics.

ε^p_{eq1} and ε^p_{eq2} correspond respectively to the beginning of cavity growth and to the fracture. The cavity nucleation stage is neglected in the following calculations. In the Guennouni-François model, the initial volume fraction of cavities f_0 was assumed to be 10^{-2} after some numerical comparisons for values between 10^{-6} and $2*10^{-2}$. The various parameters relating to the material characteristics should be calibrated from metallographic examinations but for the sake of comparison between the mode mixities for each model, assuming some arbitrary well-chosen values could be sufficient.

Using the experimental results of tensile specimens and axisymmetric notched specimens AE4 and AE2, the critical values of the damage variables were determined. The values corresponding to the crack initiation of the SENBs were calculated (table 2). The figure 2 represents the damage variables at the crack initiation of the SENBs as a function of the mode mixity. For the cases from $K_{II}/K_I=3$ to the pure mode II, these values are slightly less than the critical value determined on tensile specimens and axisymmetric notched specimens but they are nearly constant, particularly in the Beremin model and the Guennouni-François model. Similarly to the J values, the damage variables for the SENB of $K_{II}/K_I=1.5$ are much higher than this critical value.

6. CONCLUSIONS

For the SENBs, the J values at crack initiation increase with the mode mixity from $K_{II}/K_I=3$ to the pure mode II but for the case of $K_{II}/K_I=1.5$ the values are rather near to that of J_{IC} in T-L orientation.

From the application of some local criteria, for the mixed-mode loading from $K_{II}/K_I=3$ to the pure mode II, the values of the damage variables at crack initiation are slightly less than the critical value determined on tensile specimens and axisymmetric notched specimens but they are nearly constant, particularly in the Beremin model and the Guennouni-François model. Similarly to the J values, the damage variables the SENBs for $K_{II}/K_I=1.5$ are higher than the critical value. It seems that the fracture mode is significantly influenced by banded brittle ferrite, especially in the case of the high stress triaxiality.

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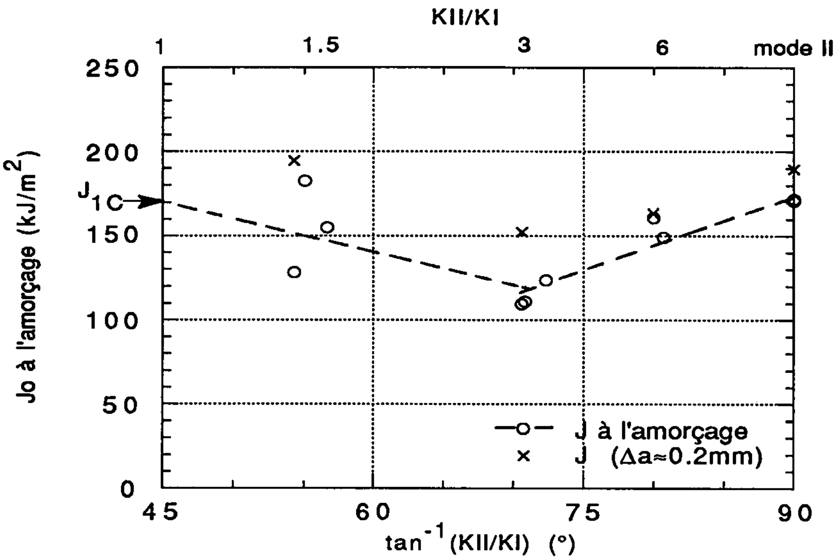

Fig. 1. Variation of the crack extension force J at the crack initiation as a function of the mode mixity $\tan^{-1}(K_{II}/K_I)$

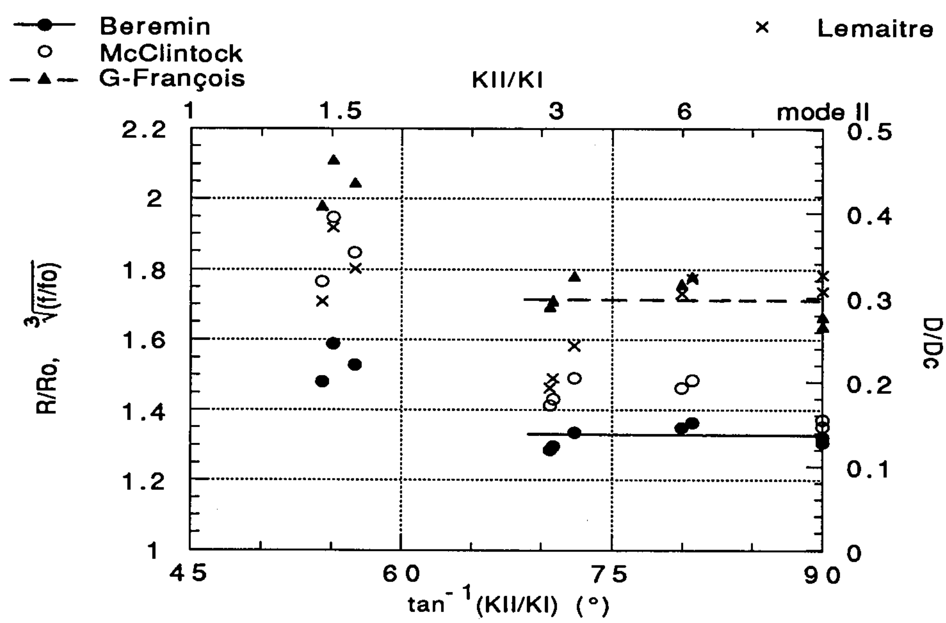

Fig. 2. Variation of the damage variables at the crack initiation as a function of the mode mixity $\tan^{-1}(K_{II}/K_I)$