APPLICATION OF THE J CONCEPT TO VERY SMALL TENSION SPECIMENS OF AUSTENITIC STAINLESS STEELS

J. P. Chavaillard* and D. Miannay**

**FRAMATOME, Tour Fiat, Cédex 16, 92084 Paris La Défense, France*
***Commissariat à l'Energie Atomique, Service Métallurgie, B.P. N° 511, 75752 Paris Cédex 15, France*

ABSTRACT

Research of a relevant fracture criterion in the elasto-plastic, the limited plastic and the fully plastic regime in tension is performed with subsized specimens of two austenitic stainless steels with the Double Edge Notched and the Center Cracked configurations and with a wide range of shape factors, including small cracks. From the possible alternatives, the limit load, P_{GY} or P_L, the Crack Opening Displacement, COD or CTOD and the J integral, it is shown that the J concept is the most appropriate one to describe crack growth resistance. However J is to be determined by the multiple specimen technique or by an experimental integration with averaging on the free face of the specimen and not generally by an estimation procedure. But J is doubtfully path independent and no longer describes the deformation field at the crack tip.

KEYWORDS

Ductile fracture, Austenitic stainless steels, Toughness, J contour integral.

INTRODUCTION

To evaluate the toughness of metals with specimens not satisfying size requirements of the ASTM standard E 399 for linear elastic behavior, one can use the ASTM standard E 813 - 1981 to determine J_{Ic} with specimen of bend type and of required dimensions, that contain deep initial cracks or the British standard 5762 - 1979 to measure the Crack Opening Displacement at initiation, δ_i with bend specimens that contain deep initial cracks and without required dimension. A versatile criterion is the limit load or the collapse load for the fully plastic regime without crack growth. Bending is preferred to tension because it is said that more constraint occurs at the crack tip (Mc Meeking and Parks, 1979) and deep cracks are used because there is more confidence in the estimation procedures. Moreover constraint increases with strain hardening. However, some structures under concern have not the required dimensions, have small cracks and are tension loaded.
The purpose of this paper is to present the main results of a research of relevant parameters to describe toughness of two austenitic stainless steels with specimens exhibiting the above limitations.

AUSTENITIC STEELS AND EXPERIMENTAL PROCEDURE

9.8 mm thick rolled plates of two austenitic steels in the water-quenched condition from 1050°C were tested in the transverse direction with respect to rolling. Chemical composition and tension test results are given in Table 1.

TABLE 1 Chemical Weight per cent Analysis and Mechanical Properties of the Steels.

	C	Si	Mn	S	P	Ni	Cr	Mo	Cu
Z2 CND 17-13	0.010	0.40	1.55	0.003	0.009	13.75	16.89	2.52	0.02
Z1 NCDU 25-20	0.013	0.85	1.10	0.002	0.014	25.22	20.17	4.26	1.50

	$\sigma_{Y0.2}$ MPa	σ_M MPa	A_r %	Σ %
Z2 CND 17-13	227	539	60	80
Z1 NCDU 25-20	275	631	43	79.4

Hollomon law, $\varepsilon/\varepsilon_o = \alpha(\sigma/\sigma_o)^n$ with $\sigma_o = 210$ MPa, $\varepsilon_o = 10^{-3}$

Strain and stress	rationalized								nominal	
Strain interval	.0 - .05		.05 - .15		.15 - .30		.0 - .30		.0 - .30	
	α	n	α	n	α	n	α	n	α	n
Z2 CND 17-13	6.90	4.13	15.19	2.67	24	2.13	11.5	2.81	7.06	4.48
Z1 NCDU 25-20	4.23	3.68	9.73	2.58	13.76	2.20	6.16	2.91	6.16	3.90

DEN and CC specimens of two widths, w = 40 mm and w = 80 mm with a gauge length of 2 w and with notches of root diameter .2 mm giving shape factors a/w of 0, 0.2, 0.35, 0.5, 0.65 and 0.8 and with fatigue cracks with a/w = 0.5 were tested at a tension speed of 0.6 mm.mn^{-1}. During testing, recording was done of load, elongation for an external gauge length of 1.5 w through an inductive transducer and elongation for a gauge length of 40 mm externally for DENS and of 13.5 mm axially for CCP with a double cantilever clip gage. Moreover, many photographs were taken on a face on which a grid pattern formed by adjacent 2 mm diameter circles was deposited. These photos were intended to determine crack shape evolution (blunting or crack tip opening), crack growth and the deformation of the specimen everywhere.
Finally, to determine crack growth resistance curves, the unloading method and the heat tinting technic were applied.

RESULTS AND DISCUSSION

Elastic behaviour

The elastic compliance of the CCP is in a very good agreement with the value given by Eftis and Liebowitz (1972). On the other hand, for the DENS compliance shows an unexplained erratic scatter about the value given by Bowie (1964). In the latter case, parasite bending may be advocated. So the unloading method to determine crack growth has been disregarded, though nice re-

Plastic behaviour, crack growth and toughness.

Fig.1 shows the relationship between load and current crack length. It is apparent that the plastic collapse load related to the initial crack length is not the relevant parameter. Moreover, for the geometries under concern the behaviour is of plane stress nature and not of plane strain nature and with the Tresca yield criterion being more appropriate for the CCP and with the Von Mises yield criterion for the DENS, i.e., more constraint occurs in the DENS than in the CCP. As to the steel for the same thickness w = 40 mm, the above behaviour is more pronounced for the Z2 CND 17-13 steel than for the Z1 NCDU 25-20 steel. This descrepancy is obviously related to the strain hardening exponent value which is bigger for the Z2 CND 17-13 steel, so giving more spreading of plasticity, and not to the crack growth resistances which are equal as it will be seen later. Moreover, it is apparent that the net section stress criterion is invalid by more and more when width increases and when crack length decreases.
The next criterion considered is the J integral as introduced by Rice and Johnson (1970). The values used are :

- The J, or V as stated by Miannay and Pélissier-Tanon (1977), calculated from the pseudo-potential as proposed by Begley and Landes (1972)

$$V = -\frac{1}{B}\left(\frac{\partial U}{\partial a}\right)_V$$

U being the area under the load displacement record.
This value is the reference value of this study. This was obtained by parabolic fitting with U = 0 for a/w = 1 and experimentally it is observed that $\partial U / \partial a = 0$ for a = 0.

- The J calculated by the estimation procedures
  - estimation of Sumpter and Turner (1976) for a rigid-perfectly-plastic material

$$J_{ST} = \frac{U}{B\,b}$$

  - estimation of Rice, Paris and Merkle (1973) for materials for which $v_P / b = f(P/b)$, i.e. for deep notched specimens under tension

$$J_{RPM} = J_E + J_P = J_E + \frac{\int_o^{v_P} P dv_P - \int_o^{P} v_P dP}{B\,b}$$

Just form normalized load-displacement curves, it is shown that the Rice estimation is effectively possible just for deep notched specimen.

  - estimation of Kumar, German and Shih (1981) deduced from finite element calculus for Hollomon materials :

$$J_{KGS} = \alpha\,\sigma_o\,\varepsilon_o\,a\,(1-\frac{a}{b})\,h_1(\frac{a}{b}, n)\,(\frac{P}{P_o})^{n+1}$$

$$\text{with } \Delta_{crack} = \alpha\,\varepsilon_o\,a\,h_3(\frac{a}{b}, n)\,(\frac{P}{P_o})^n$$

$$\text{and } \Delta_{n.c.} = \alpha\,\varepsilon_o\,(\frac{P}{P_o})^n\,2\,L\,(\beta\,\frac{b-a}{b})^n$$

with $\beta = 1$ for CCP and $\beta = \frac{2}{\sqrt{3}}$ for DENS

and so, though it is not a recommended procedure :

$$J = \sigma_o\,(\alpha\,\varepsilon_o)^{-1/n}\,K(\frac{a}{b}, n)\,(\Delta)^{\frac{n+1}{n}}$$

with h_1 and h_3 depending on geometry ans stress state.

Plane stress state is considered here and, in this case,

$$P_o = 2\beta \quad (b - a) \quad \sigma_o$$

By identifying, we get :

- For Z2 CND 17-13 : $J = 623\ K\ (\frac{a}{b}, 5)\ \Delta^{1.21}$ with $J, N.mm^{-1}$; Δ, mm ; n=4.76
- For Z1 NCDU 25-20 : $J = 748\ K\ (\frac{a}{b}, 5)\ \Delta^{1.19}$ with n = 5.23

The results are shown on figure 2 for the CCP specimen w = 40 mm of the Z2 CND 17-13. The Sumpter and Turner approximation always overestimates the true value. For deep cracks the other estimations give the same value. For the other lengths, estimations are overestimations with the Shih estimation being higher for mean cracks and lower for short cracks than the Rice estimation. For other geometries and steel, the same trend is observed. However, the discrepancy from the reference value is bigger for the Z2 NCDU 25-20 steel, for the DENS specimen and for the width 40 mm. For the Shih estimation, more accuracy could be obtained with a Ramberg-Osgood relation.

Another estimation of the J integral is obtained from the grid patterns observed at different loads or displacements. From the displacements, total or incremental strains ε_{xx} , ε_{yy} and ε_{xy} are obtained, with the hypothesis $\varepsilon_{xz} = \varepsilon_{yz} = 0$ and $\varepsilon_{zz} = -1/2\ (\varepsilon_{xx} + \varepsilon_{yy})$, i.e., neglecting contraction. From the strain components, the equivalent strain is deduced. To deduce the stress components with the hypothesis $\sigma_{zz} = \sigma_{yz} = \sigma_{xz} = 0$, the incremental and the deformation theories have been considered. However, the first one has been disregarded because giving oscillating results due to the precision on strain increments. So the results presented here are an estimation.

For all crack lengths, it is seen that J shows a scatter band of ± 20 % around the mean value when the integration path length varies. For short cracks, the mean value is equal to the reference value. For mean crack lengths (a/w = 0.5), the mean value overestimates for CCP and underestimates for DENS, as shown on figure 3, and the discrepancy increases with crack length. None explanation has been found.

This method also allows to test if the HRR strain field occurs at the crack tip, i.e., if $\varepsilon \alpha r^{-n/1+n}$ (J , θ , n). In fact, h = n/1+n varies with θ, w and J and not clearly with the steel. So for w = 40 mm, h varies between 0.6 and 1 (0.7 for θ = 0 ; .6 for θ = 45° ; .9 for θ = 90°). For w = 80 mm, h varies between 0.4 and 0.8. These values are to be compared to the theoretical ones, 0.69 to 0.82. An example is given on figure 4. It is shown that the considered distance is quite large. So it is not excluded that the HRR field occurs. Such a conclusion has already been drawn by Hodkinson (1980) for a CT specimen of 316 L steel.

The last criterion considered is the COD. This parameter has been obtained experimentally by the conventional 90° angle intercept method from the crack tip. A linear or a bilinear relation with J is obtained and in the relation

$$V = J = m\ \sigma_{Y0.2}\ \text{CTOD}$$

m increases with the crack length for the two geometries. m shows more scatter for the DENS, 0.8 < m < 2.05, than for the CCP, 1.22 < m < 1.85. These values are comparable to the values 1.15 - 2.2 for CCP and SENT, as compiled by Paranjpe and Banerjee (1979) from experimental and calculated values of the literature.

Finally, crack growth resistance curves have been determined with w = 40 mm specimens with a/w = 0.5. The results given on figure 5 show that the two steels have the same resistance. And this resistance determined with CCP is the same as the resistance determined with TPB and CT specimens of 316 L

steels by other authors (Tanaka and Harrison (1978), Bamford and Bush (1979), Hodkinson (1980)). One 316 L steel investigated by Balladon, Héritier and Rabbe (1983) is very clean and its resistance is very high. So, this result tends to confort the idea that J can be the relevant fracture toughness parameter for very small specimens. However, it is noticed on figure 5 that crack growth is higher with DENS, which is very striking because more triaxiality is built-up in this specimen.

CONCLUSION

In small tension specimens of austenitic stainless steels with high strain hardening, the net section stress criterion cannot be retained for rupture. As to the J integral, it is seen that the Rice and Shih estimates are in agreement with the reference V value for deep cracks ; otherwise, V is the one parameter. The J measured on the specimen surface is another estimation which is correct for short cracks and less correct otherwise. The discrepancy is attributed to experimental precision. Moreover, J describes the strain field and gives for CCP correct crack growth resistance. This is strangely not true with DENS. So J is considered to fulfil partially requirements of the relevant fracture toughness. Finally the J - COD relation has been established.

ACKNOWLEDGMENTS

The work described in this paper formed part a submission by one of the authors (J.P. Chavaillard) for the degree of Ph.D. The provision of facilities by the Commissariat à l'Energie Atomique is gratefully acknowledged.

REFERENCES

Balladon, P., J. Héritier and P. Rabbe (1983). To be published in ASTM-STP - 14th National Symposium.

Bamford, W.H., and A.J. Busch (1979). Fracture behavior of stainless steel - ASTM-STP 668, 553-577.

Begley, J.A. and J.D. Landes (1972). The J integral as a fracture criterion - ASTM-STP 514, 1-20.

Bowie, O.L. (1964) - Rectangular tensile sheets with symetric edge cracks. Trans.ASME Serie E, J. Appl. Mec., 31, 208.

Eftis, J., and H. Liebowitz (1972). On the modified Westergaard equation for certainplane crack problems. Inter. J. Fract. Mec., 4.

Hodkinson, P.H. (1980). An elastic-plastic fracture mechanics study of crack initiation in 316 L steels. Technical note MAT 27, Royal Military College of Science. Shrivenhain - England.

Kumar, V., M.D. German and C.F. Shih (1981). An engineering approach for elastic-plastic fracture analysis, EPRI - NP - 1931. Research project 1237-1.

Mc. Meeking, R.M., and D.M. Parks (1979). On criteria for J-dominance of crack tip fields in large scale yielding. ASTM STP 668, 175-194.

Miannay, D., and A. Pélissier-Tanon (1979). Principe des mesures de ténacité basées sur l'intégrale J et le concept de l'énergie équivalente. Mécanique, Matériaux, Electricité, 328-329, 29-40.

Paranjpe, S.A., and S. Banerjee (1979). Interrelation of crack opening displacement and J integral. Eng. Fract. Mec., 11, 43-53.

Rice, J.R., and M.A. Johnson (1970). Inelastic behavior of solids,Mc Graw Hill

Rice, J.R., P.C. Paris and J.G. Merkle (1973). Some further results of J integral analysis and estimates. ASTM STP 536, 231-245.

Sumpter, J.D.G. and C.E. Turner (1976) Method for laboratory determination of Jc, ASTM STP 601, 3-18.

Tanaka, K., and J.D. Harrison (1978). An R curve approach to COD and J for an austenitic steel. Int. J. Press. Vess. and Piping, 6, 177-200.

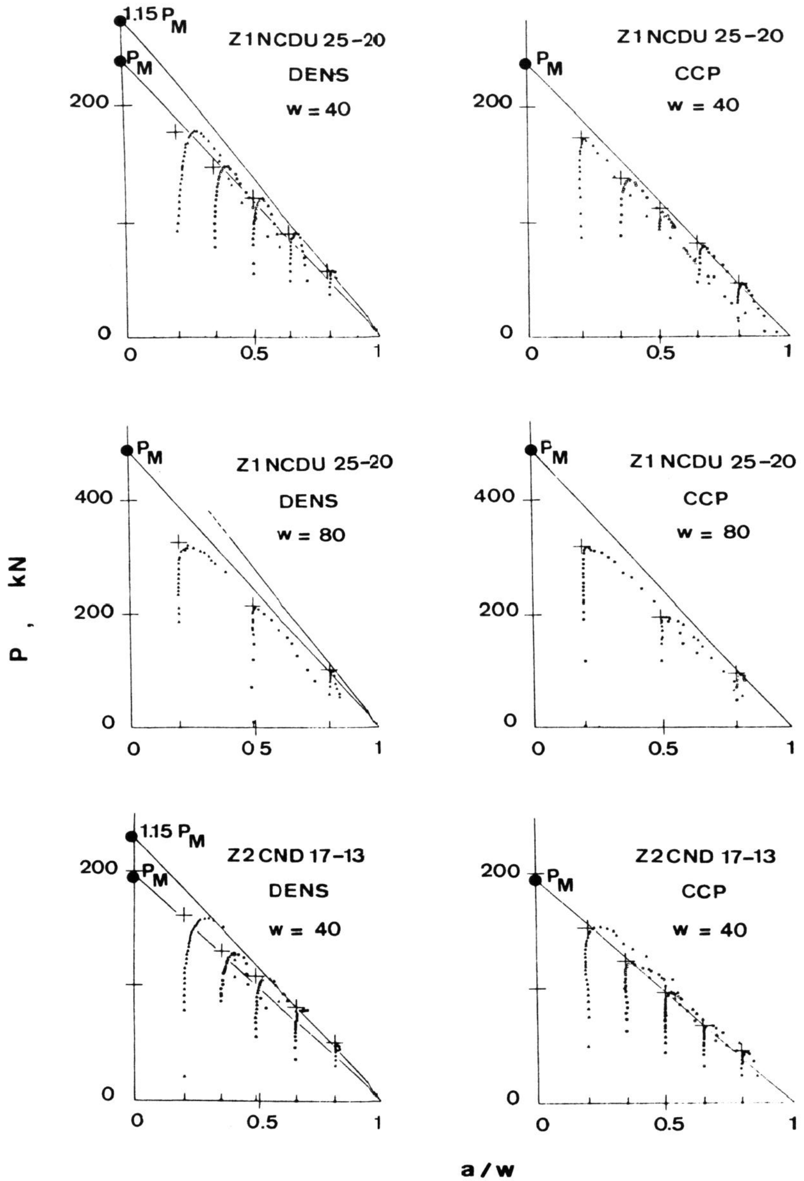

Fig. 1. Relationship between load and crack length (ultimate load for a/w = 0 ; current load for a/w ≠ 0 ; + , ultimate load for initial crack length for a/w ≠ 0).

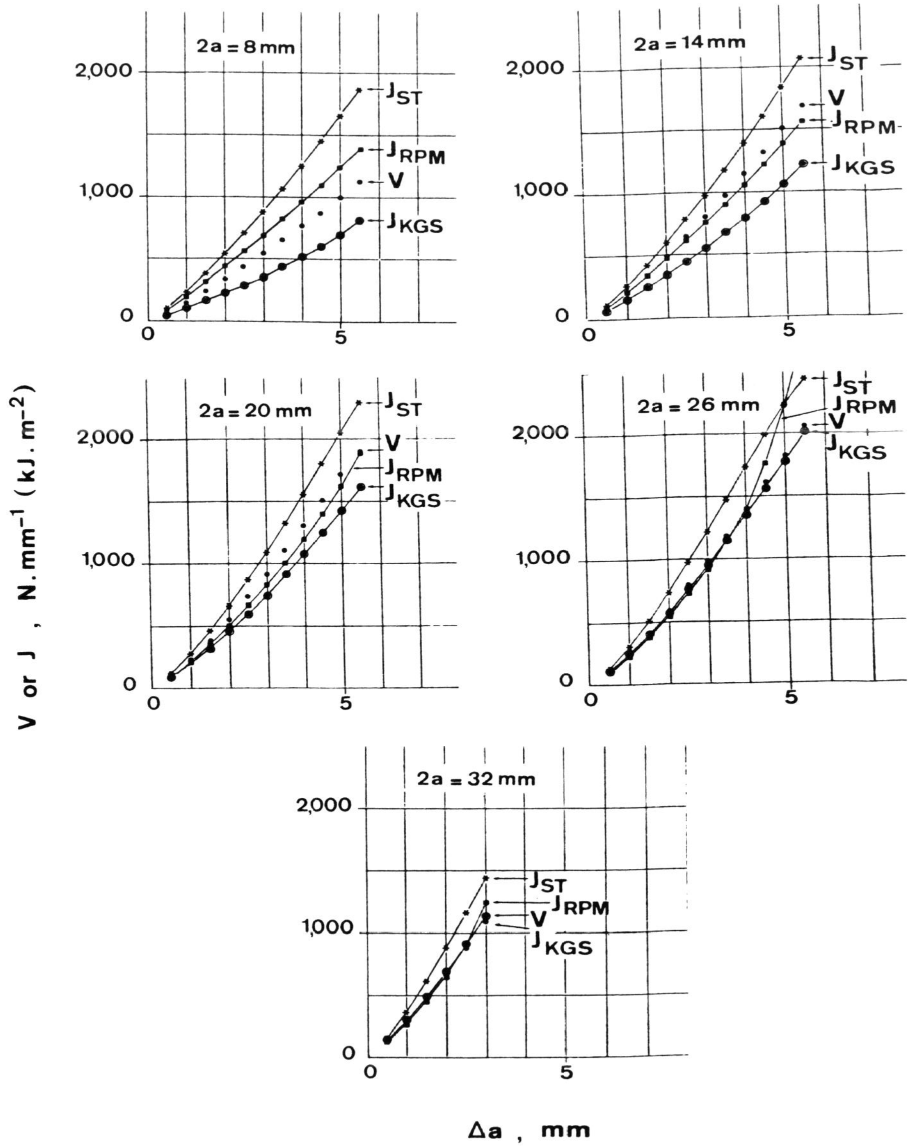

Fig. 2. V or J estimates versus load point displacement for the CCP with w = 40 mm. Z2 CND 17-13 steel.

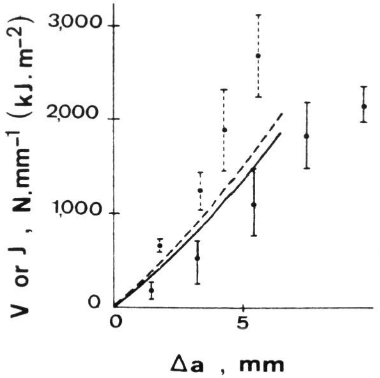

Fig. 3. V derived from the pseudo-potential and J calculated by contour integration for CCP and DENS specimens of w = 80 mm and a/w = 0.5 (- ● : DENS ; -- ● : CCP; I gives scatterband for several integration paths)

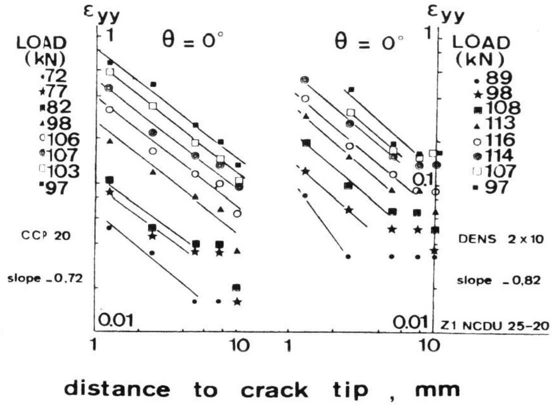

Fig. 4. Strain ε_{YY} for θ = 0° versus distance to crack tip for CCP and DENS of Z1 NCDU 25-20 with a/w = 0.5.

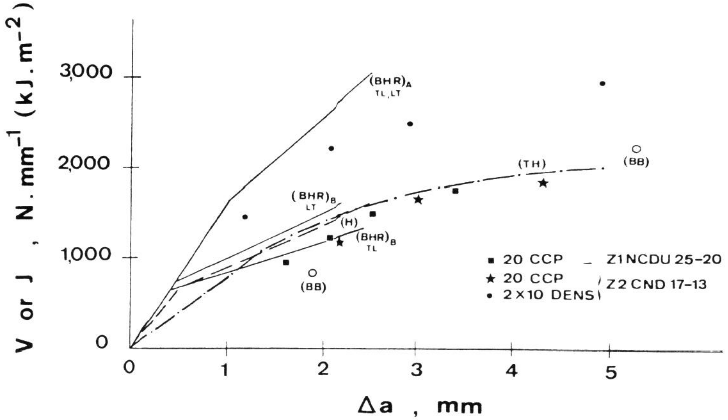

Fig. 5. Crack growth resistance curves for austenitic stainless steels (■, ★, ● : present study ; (BHR) : Balladon, Héritier and Rabbe ; (BB) : Bamford and Bush ; (H) : Hodkinson ; (TH) : Tanaka and Harrison).