EXPERIMENTAL STUDY OF THE J-INTEGRAL IN THE PLASTIC ZONE AROUND A CRACK TIP, USING THE MOIRE METHOD

M. Gueury* and D. Francois**

**LEMTA-ISIN, Université de Nancy 1, Parc Robert Bentz, 54500 Vandoeuvre, France*
***ECP, Laboratoire des Matériaux, 92290 Chatenay-Malabry, France*

ABSTRACT

We studied the J-integral in the plastic zone surrounding the crack tip, in an austenitic stainless steel plate, under monotonic loading, before crack growth initiation in mode I. We deduced the strain fields from the in-plane moiré fringes using a new method of strain computation; we determined the stress distribution using Mendelson's plastic incremental theory which we adapted to the plane stress state and the moiré data. We showed:
(1) the path-independence of J in the plastic zone, deduced from experimental fields with improved accuracy;
(2) the agreement between the J computed values and the corresponding values of the energy rate;
(3) the concordance of the coefficient of proportionality between J and CTOD with the values found in the literature for the compact tension (CT) specimens. Finally, we found the HRR singularity field, experimentally, within the J-controlled zone, with a margin of error less than 10%.

KEYWORDS

Fracture; crack; J-integral; moiré method; path independence; plastic zone; incremental plasticity; crack tip opening displacement; mode I.

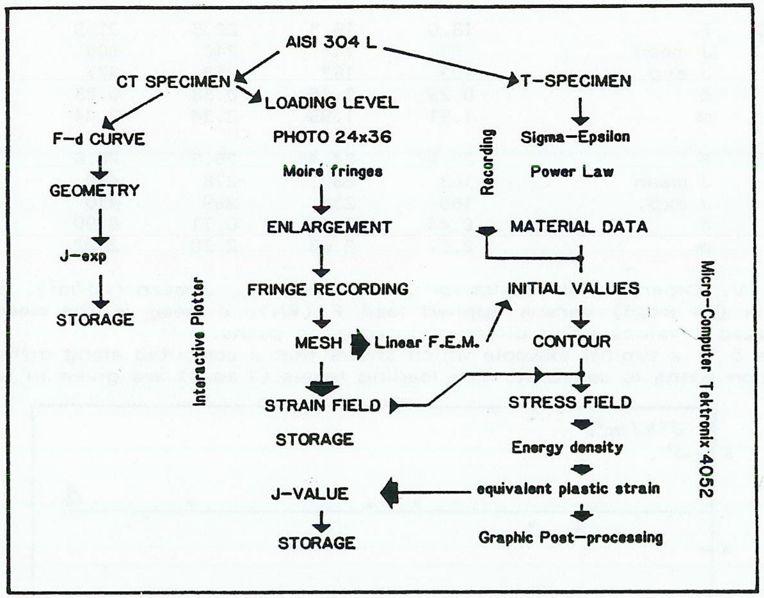
INTRODUCTION

Basically, the J-integral could be the unique parameter for the description of the strain-stress fields in front of a crack and J_{1c} could be a valid fracture criterion if J-value does not depend on the path of integration. The path independence has not been proved theoretically in the case of the incremental hardening plasticity and a fortiori when the crack grows. On the other hand, J-value is not strictly equal to the potential energy release rate in plasticity with its usual meaning of available energy rate to drive an increment of crack (Turner, 1979). Finite element method analysis (FEM) based on the incremental plasticity theory, showed that J was virtually path independent, except for the contours very close to the crack tip and was equal to the dissipative energy rate in plasticity (Turner and Sumpter, 1976). There is almost complete lack of experimental investigations of the J-path independence in the plastic zone except for Müller and Gross (1979) who measured the strain field around the crack using a photoelastic-coating technique and calculated J along

rectangular paths with different lengths. They showed that the J deviations from a constant were small for any plastic zone size.
We chose to couple a new rapid experimental process based on the moiré pattern (Gueury, François and co-workers, 1983) with an original numerical analysis (Gueury, François, 1983), in order to determine:
(1) the elasto-plastic strain fields in the plastic zone around the crack tip, for each loading step, in a strain hardening material;
(2) the J-integral properties in the crack tip vicinity under monotonic loading; in particular we examined the path-independence for any plastic zone size and the agreement between calculated values and those corresponding to the energy rate measured by the deeply notched CT specimen testing.
(3) the relation between the experimental crack tip opening displacement (CTOD) δ and the calculated J values, particularly the m coefficient of the general relationship, $J = m\sigma_0\delta$.
(4) the HRR singularity field, (Hutchinson, 1968; Rice and Rosengren, 1968).

EXPERIMENTAL PROCEDURE

The experimental process was carried out according to the following scheme:



Testing was performed, at room temperature, on AISI 304 L austenitic stainless steel in the form of a 6 mm-thick plate, without heat-treatment. Its chemical composition is given in table I and its mechanical properties in table II. The dimensions of the CT specimens used (Fig.1) are given in table III.

Table I. Chemical composition (wt%).

C	Mn	Si	Ni	Cr	Mo
< 0.03	> 2	< 1	10.5-12	18-19.5	< 0.4

Table II. Mechanical properties.

Yield stress: σ_0 = 185 MPa, ultimate stress: σ_u = 590 MPa;
Young's modulus: E = 203 GPa, Poisson's ratio: υ = 0.29 ;
Elongation at fracture: A = 57%.
Power hardening law:

$$\frac{\bar{\sigma}}{\sigma_0} = \alpha \left[\frac{\bar{\varepsilon}}{\varepsilon_0} \right]^n \qquad (1)$$

with σ_0 = 185 MPa, $\varepsilon_0 = 9.113\ 10^{-4}$, α = 1, n = 0.16.

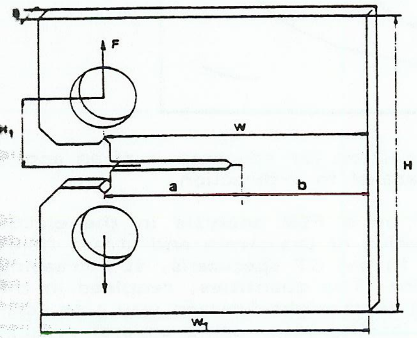


Fig.1. The CT specimen used.

(mm)	A	B	C	D
W_1	100	110	120	130
W	80	90	100	110
a	40	42	42	36.5
a/W	0.50	0.46	0.42	0.33
b	40	48	58	73.5
H	95	95	95	95
H_1	20	20	20	20
B	6	6	6	6

Table III. CT Dimensions (mm).

We employed the quickest and simplest experimental determination of J based on the single deeply notched specimen testing proposed by Rice, Paris and Merkle (1973), corrected by Merkle and Corten (1974), Sumpter and Turner (1976), and applied to CT specimen by Landes and co-workers (1976), in accordance to ASTM Committee E-24 standards (Clarke and co-workers, 1979). It is possible to determine quickly the two-dimensional plastic stress field whatever the loading process by associating a computerised in-plane moiré technique using a fine mesh and an elasto-plastic incremental method (Gueury, 1982) using Mendelson's theory (Mendelson,1968). Figures 2 and 3 are an example of a recorded moiré fringe pattern observed.

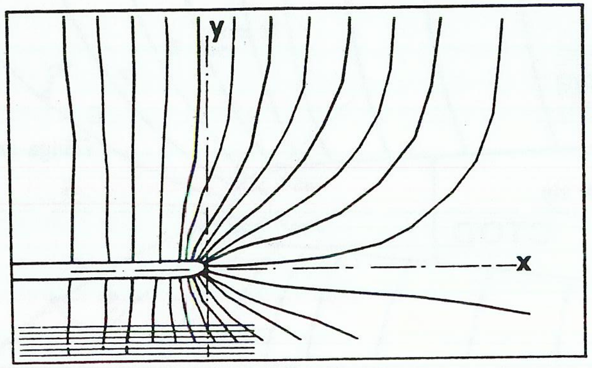


Fig.2. Example of a recorded moiré fringe pattern for specimen A at an applied load equal to 15.5 kN; grating parallel to x-direction.

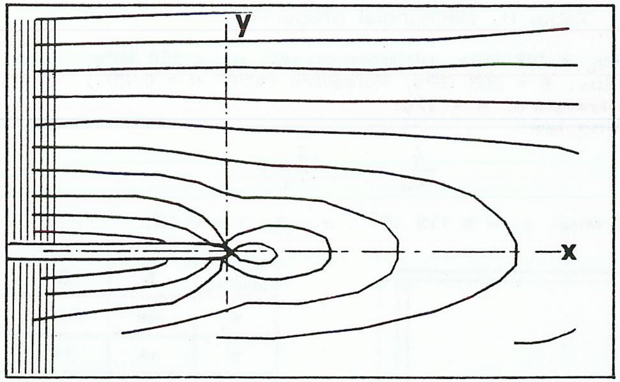


Fig.3. Example of a recorded moiré fringe pattern for specimen A at an applied load equal to 15.5 kN; grating parallel to y-direction.

Starting from a known initial state given by a FEM analysis in the elastic range, this procedure led to the determination of the strain and stress fields within the plastic zone near the crack tip in the CT specimens, at increasing loading levels, before crack growth initiation. The quantities, required in the Rice's line integral definition, are deduced in straight-forward way ; to compute the J-integral is then easy, for each loading step, using several symmetrical rectangular contours with respect to the crack direction. Still, J can be computed on any kind of path, with the method described above. The most practical way of precisely defining the CTOD (δ) is to draw two lines inclined at ± 45°to the crack plane backward from the crack tip and to measure δ where those lines intersect the crack profile (Knauf and Riedel, 1981). CTOD measurement is simple enough, using moiré fringes obtained with the 1/12 mm-pitch grating lines parallel to the crack direction: (Fig.4)

$$\delta = p(N-1) \qquad (2)$$

where p is the pitch of the grating and N the number of the fringes.

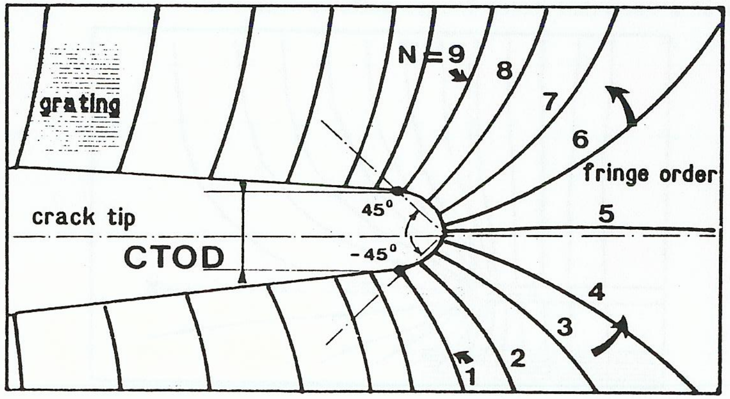


Fig.4. CTOD measurement, using moiré fringes. Grating parallel to x-axis.

EXPERIMENTAL RESULTS

The load-versus load point deflection (F-d) curves allowed us to determine the experimental J value for each loading level before crack propagation which occured at about 600 kJ/m². The main results are given in table IV.

	Loading step	1	2	3	4
A	F	12.3	13.4	14.4	15.5
	J mean	115	155	258	421
	J exp.	94	150	242	390
	δ	0.33	0.5	0.75	1.09
	m	1.52	1.62	1.74	1.95
B	F	13.4	16.5	17.3	19.0
	J mean	55	160	210	380
	J exp.	46	134	190	364
	δ	0.17	0.46	0.59	1.0
	m	1.49	1.59	1.84	1.97
C	F	18.0	19.3	20.5	21.5
	J mean	81	148	240	304
	J exp.	103	163	253	377
	δ	0.29	0.46	0.58	0.83
	m	1.91	1.93	2.34	2.44
D	F	23.2	24.4	25.2	26.6
	J mean	163	230	278	440
	J exp.	169	238	289	410
	δ	0.44	0.63	0.71	0.99
	m	2.07	2.06	2.20	2.22

Table IV. Experimental results for J exp. (kJ/m²), J mean (kJ/m²), δ (CTOD) (mm), m ($J = m\sigma_0\delta$) versus applied load F (kN). J mean is the mean of the calculated J-values along different integration paths.

Figure 5 is a typical example which shows that J computed along different integration paths is constant. The loading levels (1 to 4) are given in table IV.

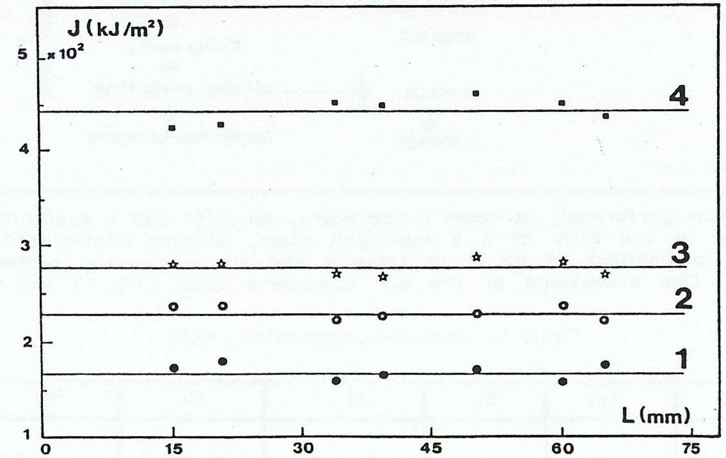


Fig.5. Computed J-values versus path lengths, four levels in D-specimen.

Figure 6 shows the variations of J as a function of the applied load and the computed J values for the various specimens.

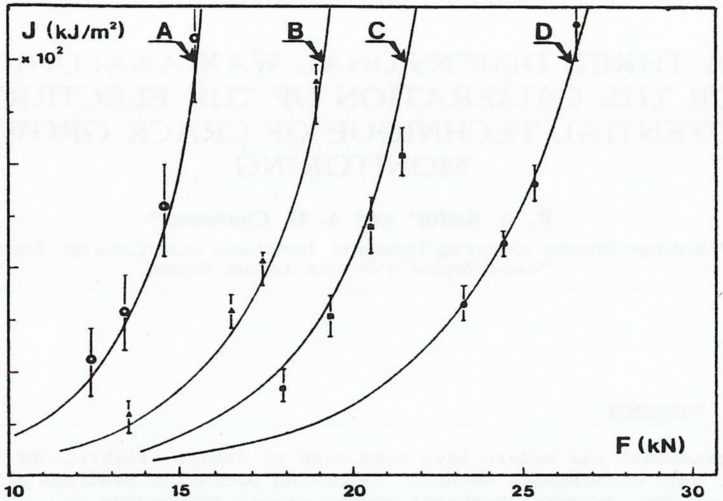


Fig.6. CT-specimens, J versus applied load F curves and the calculated J values for the loading levels given in table IV.

DISCUSSION

Arc element length (2.5 mm) has a small effect upon the computation accuracy (less than 1%). On the other hand, the Von Misès' yield criterion we used is approximate to within 5%. The strains are deduced from the moiré data also with a precision of 5%, because of the processing used. The mean of the relative deviations from a constant, for any specimen, is less than 10%. The maximum root-mean-square (RMS) of the differences between J-mean and J-experimental values is also less than 10% (Table V), except for the A-specimen for which initially a manual moiré analysis only was used. The D-specimen gives more homogeneous results; this specimen is the closest to the well known J-dominance conditions (Hutchinson, 1981) for the CT-specimens used.

Specimen	A	B	C	D
RMS (%)	10.5	8.2	9.2	4.5

Table V. Root-mean-square (RMS) of the differences J mean and J exp.

The definition of the CTOD adopted here and the HRR strain field yield the usual proportionality relation between J and the CTOD:

$$J = m\sigma_0\delta \qquad (3)$$

The coefficient m is essentially a function of configuration, degree of plasticity and work-hardening. Figures 7 and 8 show that the values of m are in accordance with the previously reported ones (Turner,1979; Mioyoshi and Shiratori, 1979; Shiratori and Mioyoshi, 1979). However figure 8 shows that m is not really constant and that it tends to increase with the CTOD. This may be due to larger and larger deviations from the HRR small transformation theory.

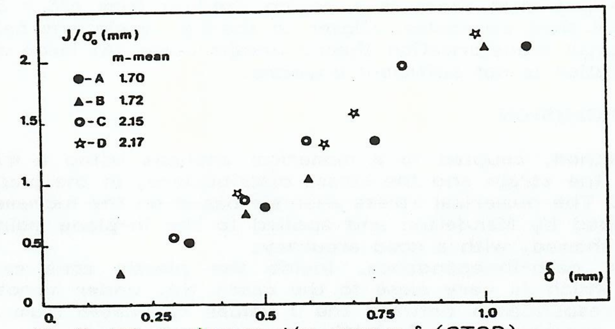


Fig.7. CT-specimens: J/σ_0 versus δ (CTOD).

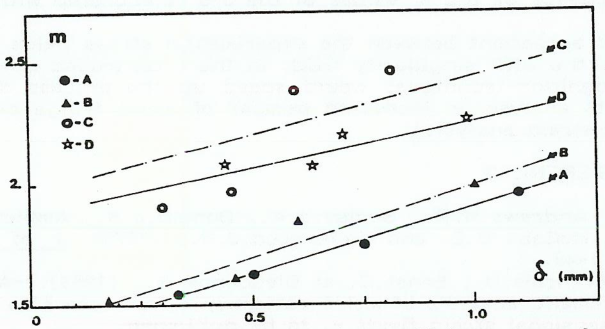


Fig.8. CT-specimens: variations of m coefficient versus δ (CTOD).

The comparison of the stress field deduced from experiments and HRR singularity field is illustrated by figure 9. The HRR Von Mises equivalent stress was determined according to the formula:

$$\sigma_e = \sigma_0 (J/I_n \varepsilon_0 \sigma_0 r)^{n/(n+1)} \tilde{\sigma}_e(\theta,n) \qquad (4)$$

where the values of σ_0, ε_0, n are given in table II; the dimensionless values of I_n (3.27) and $\tilde{\sigma}_e(\theta,n)$ are given by Hutchinson (1968).

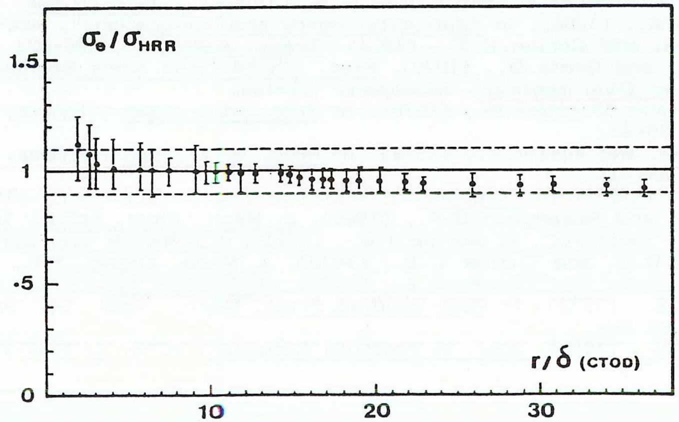


Fig.9. Von Misès' equivalent stress/ HRR equivalent stress versus r/δ (CTOD)

This figure shows that there is a region ranging from $r/\delta = 3$ to $r/\delta = 15$ where the HRR field dominates. Closer to the tip, deviations begin to appear as the HRR small transformation theory breaks down. At large distances, the asymptotic solution is not sufficient anymore.

CONCLUSION

The moiré method, coupled to a numerical analysis using a micro-computer gives rapidly the strain and the stress distributions, in the plastic zone near the crack tip. The numerical stress analysis based on the incremental plasticity theory developed by Mendelson and applied to the in-plane moiré fringe data by ourselves showed, with a good accuracy:
(1) J-integral path-independence, inside the plastic zone except for the necked zone which is very close to the crack tip, under monotonic loading;
(2) close correspondence between the J values calculated from contour integrals and the corresponding dissipative energy rate values;
(3) the accordance of the m values of the J-δ relationship with those already known;
(4) The good agreement between the experimental stress fields in front of the crack tip and the HRR singularity field, in the J controlled zone.
(Pattern recognition-techniques would speed up the process described here, enabling us to analyse an increased number of moiré fringe data and to realize real-time strain analysis).

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