DETERMINATION OF EXPERIMENTAL BLUNTING LINES AND COMPARISONS WITH ANALYTICAL PROCEDURES

E.Lucon *, C.Rinaldi *

Characterizing the blunting behaviour of a steel before the onset of stable tearing is a crucial point for the experimentalist. A series of EPFM tests, interrupted before the initiation of ductile crack growth, has been performed on two ferritic and two austenitic steels; experimental blunting lines were drawn after measuring the Stretch Zone Widths on the broken specimens and comparisons are presented with theoretical models proposed by ASTM and EGF. Crack-tip replicas were also obtained on one of the steels tested, thus allowing further comparisons between SZW measurements on specimens and on replicas.

INTRODUCTION

In the early stages of an Elastic-Plastic Fracture Mechanics test, before the onset of ductile stable tearing, the phenomenon of crack-tip blunting is usually observed: the crack advances because of plastic deformation at its tip, which blunts and stretches under the effect of applied load, without actually propagating. In this phase, the J-Δa curve of the specimen is represented by a straight line connecting the origin to the initiation point of ductile crack growth.

The determination of the blunting line can be either analytical or experimental. In the former case, the experimentalist can resort to one of the existing mathematical formulas relating J-integral (or CTOD) to Δa during blunting, based on certain assumptions. Alternatively, the blunting line can be derived experimentally by measuring the width of the stretch

* CISE SpA Tecnologie Innovative, Via Reggio Emilia 39, 20090 Segrate (Milano), ITALY.

zone (SZW) at the crack tip. This implies some disadvantages, namely:

- SZW measurements have to be carried out on a Scanning Electron Microscope (SEM): they are difficult, costly and hardly reproducible due to their intrinsic subjectivity;
- only the critical SZW value at the initiation of stable tearing (SZW_c) can normally be measured; information on intermediate situations can only be obtained by conducting appropriate interrupted tests;
- single-specimen techniques (Unloading Compliance or Potential Drop) cannot normally guarantee a sufficient degree of accuracy in the blunting phase.

A reliable analytical relationship, which could be applicable to a wide variety of materials, is therefore very useful in everyday testing practice.

BLUNTING MODELS

Not all existing EPFM procedures require the knowledge of the blunting line of the steel tested; the CEGB procedure, for instance, defines the critical J-value at 0.2 mm of total crack growth, thus avoiding the use of a blunting line; other examples are the BS5762 standard and the ASTM CTOD draft procedure.

The Japanese standard JSME S001-81, quoted in reference (1), requires the blunting line to be derived on the basis of at least two interrupted tests; the initiation value (J_i) is obtained by intersecting the experimental blunting line with a vertical line corresponding to the average SZW measured on at least three more specimens or with a straight line fitting experimental data.

The ASTM E813-88 standard, on the other hand, only allows a theoretical determination via the well-known equation

$$J = 2\sigma_{flow} \Delta a \tag{1}$$

Finally, the European Group on Fracture (EGF) procedure includes both possibilities; the experimental determination of the blunting line requires a minimum of three SZW measurements, while the theoretical equation that can be used for determining all critical fracture parameters (except the initiation value J_i) is the following:

$$J = \frac{E}{0.4\, d_n^*} \Delta a \tag{2}$$

derived from work done by Sih (reference (2)) and eventually developed by Schwalbe (reference (3)). Equation (2) has also been adopted by the German standard DVM 002.

MATERIALS AND EXPERIMENTAL

15 J-integral tests, interrupted during the blunting phase, were performed at room temperature on 1TCT specimens of two ferritic steels (SA533B cl.1, 5 tests, and SA333 gr.6, 5 tests) and two austenitic steels (AISI 304, 3 tests, and AISI 316L thermally aged, 2 tests). The specimens, loaded up to a value before the initiation of ductile crack growth, were eventually brought to fracture by post-fatigue; unloading the specimen and fracturing it in liquid nitrogen, as done on one of the SA533B specimens, was excluded since it caused crack-tip closure when the specimen was put off-load. A minimum fatigue load equal or greater than the final test load was also used in the post-cracking procedure.

The fracture surfaces were examined on SEM, where SZW measurements were made in accordance to the guidelines reported in Appendix 7 of the EGF P1-90 procedure. The measured SZW values were eventually coupled to J-values calculated according to ASTM E813-88, and the J-SZW points were finally fitted by a simple least squares method with a straight line coming out of the origin. The experimental blunting line was then compared to the theoretical ones obtained from equations (1) and (2).

Further experiment was performed on SA533B steel: crack-tip replicas were obtained before post-fatigue by infiltrating the notch with sylicone rubber. The replicas, coated with a thin gold layer, were examined on SEM and SZW measurements were made; the two experimental blunting lines, obtained from SZW measurements on specimens and replicas, could therefore be compared.

RESULTS AND CONCLUSIONS

The experimental blunting slopes obtained on the four steels are compared in Table 1 with the analytical values calculated according to ASTM and EGF models. A remarkable discrepancy between experimental and ASTM slopes can be remarked on all steels tested, although a similar result could be foreseen only for the two austenitic steels; EGF/DVM values are considerably closer to test results.

J-SZW data points have been plotted in Figs.1 to 4 along with experimental and theoretical blunting lines for each of the steels. Excluding the case of SA533B steel, where it falls approximately midway between the theoretical ones, the experimental blunting line is appreciably close to the EGF/DVM model. Moreover, the use of equation (1) appears to be seriously non-conservative, while the use of equation (2) is normally conservative or only slightly non-conservative: the approximation is thoroughly acceptable.

TABLE 1 - Experimental and theoretical blunting line slopes obtained on the four steels tested.

	Blunting line slopes (N/mm^2)		
Steel	Experimental	ASTM	EGF/DVM
SA333 gr.6	1787	750	1723
SA533B cl.1	1667(spec.) 1198(rep.)	1050	2267
AISI 304	2622	830	2286
AISI 316L t.a.	1882	801	2171

More observations can be made about the tests on SA533B steel. The first specimen was broken apart in liquid nitrogen, and this altered the subsequent measurements on the fracture surface, as already mentioned: the effect is evident in fig.2.

Furthermore, the experimental blunting line obtained by using crack-tip replicas is remarkably lower in slope than the one relevant to specimens (fig.2); this can be given the following explanations:

- the measurements performed on replicas reflect an "on-load" situation, where the configuration of the crack tip is due to an elastic and a plastic component; when the specimen is broken apart, the fracture surface only retains the plastic component;
- a slight expansion of the replica, pressed against the notch in order to achieve good penetration, cannot be ruled out.

A final check was made on the minimum number of interrupted tests necessary to derive a reliable experimental blunting line, by considering all the steel and calculating the corresponding blunting slope: the results demonstrate that two is indeed a sufficient number of tests, as stated by the Japanese standard.

SYMBOLS USED

σ_{flow} = flow stress, average of yield and ultimate tensile stresses at test temperature

E = Young's modulus at test temperature

d_n^* = factor depending on strain-hardening exponent n and reference stress σ_0

REFERENCES

(1) Kobayashi, G.H., Nakamura, H.H. and Nakazawa, H., ASTM STP 856, 1985, pp.3-22.

(2) Sih, C.F., "Relationship between the J-integral and Crack Opening Displacement for Stationary and Extending Cracks", G.E. Report No.79CR0075, 1979.

(3) Schwalbe, K.-H., Int.J.of Fracture, Vol.25, 1984, pp.R49-R52.

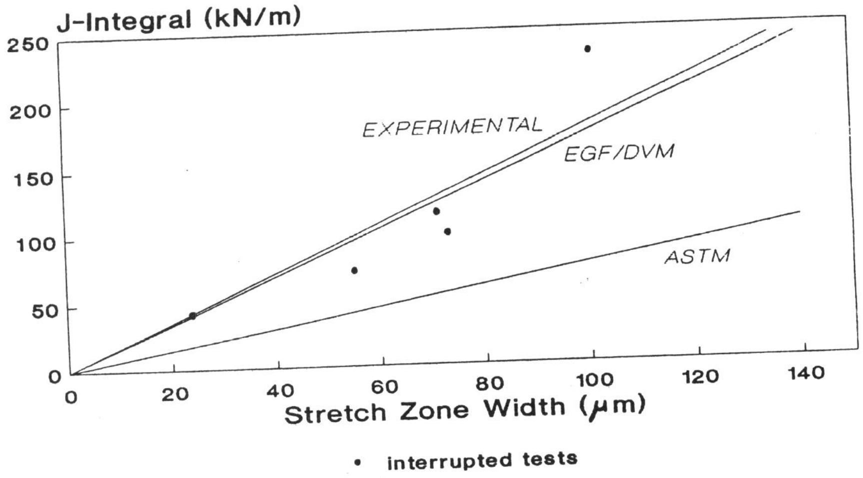

Figure 1 - Experimental and theoretical blunting lines for SA333 gr.6 steel.

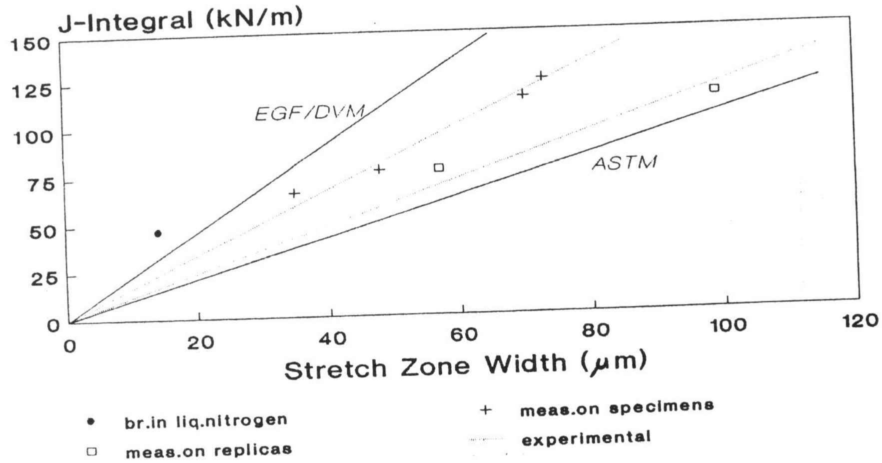

Figure 2 - Experimental and theoretical blunting lines for SA533B cl.1 steel.

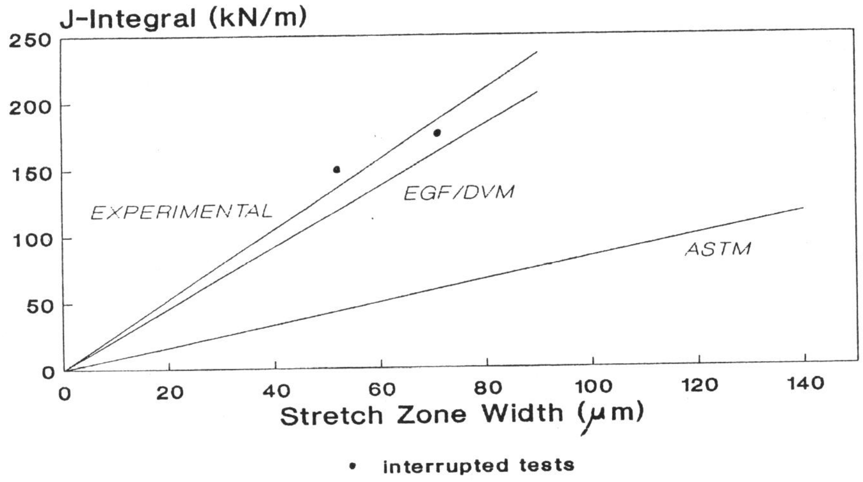

Figure 3 - Experimental and theoretical blunting lines for AISI 304 steel.

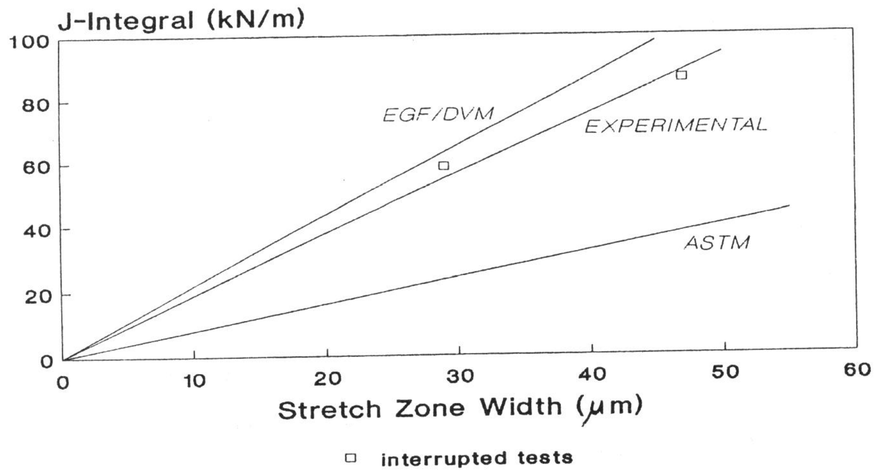

Figure 4 - Experimental and theoretical blunting lines for AISI 316L thermally aged steel.