A COMPARATIVE STUDY ON DIFFERENT METHODS TO MEASURE THE CRACK OPENING DISPLACEMENT

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ABSTRACT

The crack tip opening displacement (COD) has been measured using extrapolation methods, optical observation of the crack tip, and the infiltration technique. Steels with three different strength levels have been tested. Among the six extrapolation methods considered, three are compatible with certain basic theoretical requirements and reproduce the COD-values obtained from infiltration measurements satisfactorily. The measured normalized COD-values in small-scale yielding, $\beta = \delta\sigma_y E/K^2$, have been compared with theoretical models. The observed β-values are 0 to 100 per cent larger than the theoretical predictions, where the greater deviations are typical for high-strength, low-strain-hardening material. The variation of COD along the crack front is such that COD is larger by up to 30 per cent in the midsection of the specimen than at the specimen surface.

KEYWORDS

Fracture mechanics, crack opening displacement, infiltration technique.

INTRODUCTION

A generally successful application of the COD-criterion (COD = crack opening displacement; Wells, 1961) for crack growth initiation in elastic-plastic materials is impeded by various difficulties. Amongst them, the present paper primarily addresses the problem of defining and measuring COD. Conventional methods of calculating COD from clip gauge measurements employing empirical extrapolation formulae are compared with optical observations of the crack tip and with results of the infiltration technique (Robinson and Tetelman, 1974). Previously, considerable discrepancies between the different techniques have been found. This is illustrated by the outcome of a recent round robin test among seven German and Swiss laboratories (Zeislmair and Dahl, 1980). For instance, COD-values between 30 μm and 120 μm have been found under nominally identical conditions.

Besides an experimental comparison of the different methods, also a theoretical assessment of the extrapolation methods will be presented.

The COD-values measured by Robinson and Tetelman (1974) were by a factor of 2 to 3 greater than predicted by numerical finite element analyses (e.g. Rice and Tracey, 1973, Tracey, 1976, and McMeeking, 1977). This point will be reconsidered in the present paper. Further, the variation of COD along the crack front is studied by the infiltration technique.

EXPERIMENTAL PROCEDURE

Compact fracture mechanics specimens have been prepared according to ASTM-E 399 in the sizes CT 1 and CT 2 from the structural steel St-E 47 and from the high-strength steel 38 Ni Cr Mo V 7 3 (similar to steel AISI 4340). The tensile yield stress of the structural steel is σ_y = 465 MPa. The high-strength steel has been given two different heat-treatments which lead to strength levels of σ_y = 720 MPa (called material C hereafter), and σ_y = 1290 MPa (material B). The strain hardening curves have been fitted with a power-law relation used in the theoretical literature (e.g., Tracey, 1976), viz.,

$$\frac{\sigma}{\sigma_y} = \left(\frac{\sigma}{\sigma_y} + \frac{3G\varepsilon^{pl}}{\sigma_y}\right)^N \qquad \text{for } \sigma > \sigma_y \qquad (1)$$

to obtain the strain hardening exponent N. In eq. (1), G is shear modulus, ε^{pl} is plastic tensile strain, and σ is tensile stress. There results N = .12 for St-E 47; N = .15 for material C; and N = .05 for material B.

Fatigue cracks have been grown into the specimens using a computer-controlled servo-hydraulic testing machine. In order to minimize the complicating effects that internal stresses may have on the initial stages of the subsequent COD-test, the fatigue cracks were grown with decreasing stress intensity amplitude, ΔK, with final values as low as $\Delta K = 7\ MNm^{-3/2}$. If the COD-test was to be done at very low load levels the respective specimen was fatigued in liquid nitrogen to reduce the size of the plastic zone further. The crack fronts obtained in this way are almost straight with a maximum crack length variation of 4 per cent through the specimen thickness.

The development of the COD-value during the tensile test was recorded by (i) taking photographs of the crack tip through a microscope; in some cases the observation was aided by a fine grid applied on the specimen surface; (ii) by extrapolation methods from two clip gauges, and (iii) by the infiltration technique. The clip gauge recordings were extrapolated to the crack tip using the methods of Elliot and May (1968), Wells (1971), Venzi (1972), Schmidtmann and others (1974), Hollstein and others (1976), and Dawes (1979). Zeislmair and Dahl (1980) have assembled and described the methods. The extrapolation formulae are all based on a single clip gauge measurement. Satisfactory agreement was usually found if the COD-values calculated from the two clip gauge recordings by the same extrapolation method were compared. Wells' method was an exception and it was therefore only applied with the clip gauge directly between the load pins. The reproducibility of the measurements was within a few per cent if identical specimens were compared.

The infiltration technique consists in sucking liquid silicone rubber (viscosity ≥ 8000 centi-poise) into the crack under sustained load line displacement. Then the specimen is pulled to fracture and the hardened silicone rubber casting is sectioned along planes normal to the crack front, and the crack profiles are observed in the scanning electron microscope. Figure 1a shows such a crack profile which will be discussed in the next section in relation to theoretical aspects. The casting was taken from a CT1-specimen made of material C at a stress intensity factor of $K = 87\ MNm^{-3/2}$, i.e., slightly outside the ASTM-limit for small-scale yielding which requires $K < 72\ MNm^{-3/2}$.

The onset of stable crack growth was monitored using the electric potential drop technique. Silicone rubber castings that showed stable crack growth were evaluated

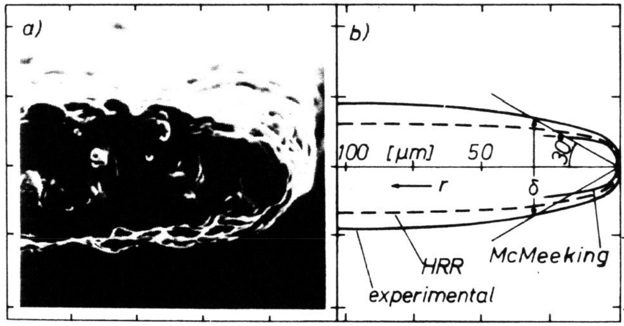

Fig. 1. Crack profile $\Delta u(r)$. (a) Silicone rubber casting. (b) Calculated profiles compared with observed profile.

for COD at growth initiation by measuring the height of the step at the initial crack tip position. Figure 2 shows two examples. The step is pronounced in Fig. 2a (steel C), whereas the step in the high-strength material (B) is small.

THEORETICAL ASPECTS

The experimentally observed crack profile shown in Fig. 1a is compared now with the theory of Hutchinson (1968), and Rice and Rosengren (1968) (henceforth jointly referred to as HRR) and with the finite element calculations of McMeeking (1977). The theory of HRR is based on small-strain, small-deformation continuum mechanics, and the crack-tip deformation fields in a power-law hardening material are calculated. For the crack profile, $\Delta u(r)$, there results in small-scale yielding

$$\Delta u = \frac{4}{3}(1+\nu)\alpha\frac{\sigma_y}{E}\left[\frac{3K^2(1-\nu)}{2I_{1/N}\,\sigma_y^2}\right]^{1/(1+N)} r^{N/(1+N)}\,\tilde{u}(\pi,N). \qquad (2)$$

Here, E is Young's modulus, ν is Poisson's ratio, K is the tensile stress intensity factor, r is the distance from the crack tip, $\tilde{u}(\pi, N)$ and $I_{1/N}$ are dimensionless numerical quantities given in the papers of HRR and subsequent workers. The dimensionless numerical factor α is unknown. From the form of eq. (1) and dimensional

a) b)

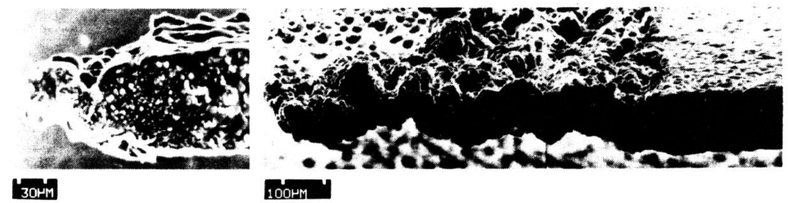

Fig. 2. Silicone rubber castings of cracks with little (a), and pronounced (b) stable crack growth.

considerations it follows that α may depend on N and ν, but not on K, σ_y, and E. If the J-integral is assumed to be path-independent (which is in fact only an approximation in elastic-incrementally plastic materials), α assumes the value α = 1 for plane strain. According to the (small-strain) finite element calculations of Rice and Tracey (1973), and Tracey (1976) the values α = .69, .88, and .90 are more accurate for N = o, .1, .2, and .3, respectively, taking ν = .3. The dashed line in Fig. 1b shows the crack profile according to eq. (2) with α = 1 and with the material parameters and K as in Fig. 1a. For comparison, the experimental profile and the result of the large-strain, large-displacement finite element analysis of McMeeking (1977) are also shown. Figure 1b shows that, in this particular example, the supposedly more accurate method of McMeeking yields results that deviate from the experimental curve more than does the presumably less accurate HRR-profile. This point will be explored more exhaustively in the next section.

Since the crack tips are always rounded it is necessary to define at which distance behind the apex of the crack COD is to be measured. It turned out during the tests that the definition of COD shown in Fig. 1b is the most convenient one: two lines are drawn through the apex of the crack at an angle of $\phi = \pm 30^0$ to the crack plane; COD ($\equiv\delta$) is defined where the lines intersect with the crack profile. This is a slight modification of the definition due to Rice and Schwalbe (1973) who suggested an angle of 45^0 instead of 30^0. The larger angle, although equally justified in principle, turned out to be impractical in some cases. (COD can be used as a fracture-characterizing parameter no matter where it is defined as long as it is defined within the distance from the crack tip where the HRR-field dominates the deformation field. The size of this zone is of the order of the plastic zone size in small-scale yielding and has been studied by McMeeking and Parks (1979)). For arbitrary angle ϕ, COD follows from the HRR-field, eq. (2), to be

$$\delta = \beta \frac{K^2}{\sigma_y E} \qquad (3)$$

for small-scale yielding. Unlike the non-hardening case, the dimensionless factor β depends here on the ratio σ_y/E and on N as

$$\beta = \frac{3(1-\nu)}{I_{1/N}} \left[\frac{2(1+\nu)\alpha}{3} \tilde{u}(\pi, N)\right]^{1+N} \left(\frac{\sigma_y}{E \tan\phi}\right)^N . \qquad (4)$$

Since N is usually a number much smaller than unity the dependence on σ_y/E as well as on ϕ is weak. For the materials B, C, and St-E 47, eq. (4) gives β = .63, .45, and .43, respectively. Here, ϕ and ν are taken as $\phi = 30^0$, ν = .3, and it is assumed that α = 1. Interpolation of McMeeking's (1977) results leads to β = .54, .36, and .43 for the same materials.

EXPERIMENTAL RESULTS

Figure 3 shows the development of COD as a function of the applied load (expressed in terms of the stress intensity factor) for the three materials considered in this study. The different curves result from the different extrapolation methods and from the optical observation of the crack tip, whereas each solid point represents the result of an infiltration test. The ASTM-limit for small-scale yielding and the onset of stable crack growth (i = initiation) are marked by arrows on the K-axis. It is clear that the methods of Elliot and May (1968), and Hollstein and others (1976) greatly over-estimate the value of COD for all materials. For the high-strength material B, only Venzi's (1972) method approximates the observed COD-values well. Here, the methods of Wells (1971) and Dawes (1979) are within a factor of 2 of the right COD-value whereas all other extrapolation methods are far off. The optical observation of the crack tip yields accurate COD-values for

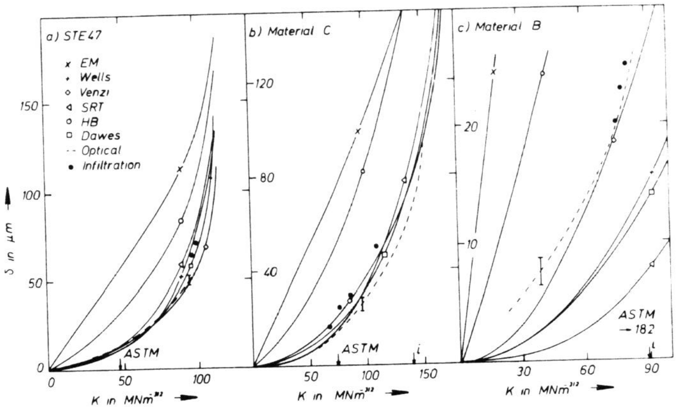

Fig. 3. COD vs. stress intensity factor using different extrapolation methods (EM = Elliot and May, 1968, SRT = Schmidtmann and others, 1974, HB = Hollstein and others, 1976); (a) and (b) are for CT1-, (c) is for CT2-specimens.

the high-strength material, B, and under-estimates COD by about 20 to 30 per cent for the other materials. This corresponds to the result of the infiltration technique which shows that, except for the high-strength material B, COD decreases by some 25 per cent in a region of a few millimeters size near the specimen surface compared to the bulk value. In Fig. 4, the results of the infiltration tests are assembled and compared with the theoretical predictions of McMeeking (1977) for small-scale yielding for the three materials. Obviously, the measured COD-values tend to be larger than the calculated ones. The discrepancy is almost by a factor of 2 for the high-strength material B.

DISCUSSION

If extrapolation methods are to be widely used in fracture mechanics testing it is not sufficient to prove their success in a limited number of tests but they should

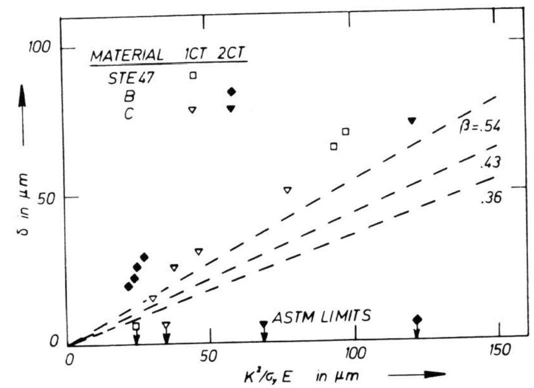

Fig. 4. Comparison of McMeeking's (1977) small-scale yielding calculations (dashed lines) with observed COD-values. The arrows indicate the ASTM-limits for small-scale yielding.

also fullfil certain requirements of theoretical consistency. The extrapolation methods relate the COD-value to the notch opening, V, measured by a clip gauge. In the small-scale yielding range, V increases in linear proportion to the load. More precisely is $V = g(a/W)K\sqrt{W}/E$, where W is specimen width, and g is a dimensionless geometry function. On the other hand, COD must be related to K as in eq. (3), i.e., in small-scale yielding the extrapolation formulae must be compatible with

$$\delta = \frac{\beta E V^2}{g^2 \sigma_y W} . \tag{5}$$

In the fully-yielded limit, theory predicts a linear relation, $\delta = h(a/W, N) \cdot V$ where h is again a dimensionless geometry function. Of the extrapolation methods considered in the present paper, only the methods of Wells (1971), Venzi (1972) and Dawes (1979) exhibit the required quadratic dependence $\delta \propto V^2$ or $\delta \propto K^2$ for small values of V. The formulae of Wells and Dawes in addition contain E and σ_y correctly if the slight dependence of β in eq. (4) on E/σ_y is ignored. The factor of proportionality in the relation $\delta \propto V^2$ is determined empirically by Venzi and Wells, whereas Dawes uses eq. (3) setting $\beta = .5(1-\nu^2)$. The methods of Wells, Venzi, and Dawes also express the linear relation, $\delta \propto V$, in the fully-yielded limit correctly using an estimate for the geometry function h(a/W, N) based on slip line theory. An improved estimate could certainly be drawn from the finite element analyses of the fully-yielded case in power-law hardening materials (e.g. Shih and Kumar, 1979).

The method of Elliot and May (1968), if applied with a fixed rotation center, enforces a linear relation, $\delta \propto V$, which is clearly inadequate in the small-scale yielding case. The relation given by Schmidtmann and others (1974) leads to $\delta \propto K^{2H} \cdot V$ or $\delta \propto K^{2H+1}$ (with $H \approx 0.8$ for CT-specimens) in small-scale yielding. This method also fails to describe the fully-yielded limit correctly, and can therefore be fitted to the observed COD-values at best in an (unspecified) intermediate range. The same can be said of the method of Hollstein and others (1976).

Thus, of the extrapolation methods based on a single clip gauge measurement, only the methods of Wells (1971), Venzi (1972), and Dawes (1979) are theoretically well founded. According to the experimental results of the present study the methods of Wells and Dawes work about equally well, but Dawes' method is preferred for its greater theoretical clarity in the small-scale yielding limit. The methods due to Venzi and Dawes almost coincide for the materials C and St-E 47. For the high-strength material B, Venzi's method yields higher COD-values than Dawes' method. This is because Venzi's formula neglects the dependence of COD on the yield stress which is required by theory but is not found to the predicted extent in experiments. Therefore Venzi's method is more successful than Dawes' method for the high-strength material although Dawes' method appears to be theoretically better founded.

CONCLUSIONS

A comparative study on different methods to measure COD has been carried out. The infiltration technique is considered to provide the most reliable results. Extrapolation methods are judged in relation to the infiltration technique and to theoretical viewpoints. The following is concluded:

(1) Of the extrapolation methods considered, only the methods of Wells (1971), Dawes (1979) and, partly, Venzi (1972) are compatible with certain basic theoretical requirements. The method of Daves is preferred to that of Wells for theoretical clarity.

(2) The method of Venzi (1972) successfully describes the COD versus load curves for all strength levels, although it neglects the theoretically required dependence of COD on the yield stress in small-scale yielding.

(3) Associated with this observation is the finding that the measured COD-values in small-scale yielding are larger than the theoretically predicted values. The relative difference is larger for higher strength levels (Fig. 4). This remains an unclarified problem.

(4) The most practical way of precisely defining where COD is to be measured, is to draw two lines inclined by $\pm 30^0$ to the crack plane backward from the crack tip and measure COD where the lines intersect the crack profile.

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