CRACK OPENING DISPLACEMENT AND HYDROSTATIC STRESS

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ABSTRACT

The crack opening displacements of shallow cracks at initiation and maximum load are larger than those of deep cracks. By studying the crack opening displacement in V notch bend specimens it is shown that the most significant parameter in determining the difference in behaviour between shallow and deep cracks may be the hydrostatic stress.

INTRODUCTION

It has been established that fractures are more difficult to initiate from shallow cracks than from deep cracks in low strength metals whose fracture properties can be characterised by COD measurements (Chipperfield, 1978; Cotterell et al, 1984). Since in practice defects are often in the form of shallow surface cracks, the use of fracture data obtained from deep notch specimens can lead to over conservative estimates of their significance. There is much less constraint on plastic flow for shallow cracks and the material ahead of the crack deforms rather than fractures. We suspect that the critical fracture criterion depends upon the hydrostatic stress at the tip of a crack which is less for shallow cracks than deep ones. In this paper we examine the effect of hydrostatic stress on the initiation and maximum crack opening displacements for a structural steel 1204-350 by testing three-point V notch bend specimens of differing notch angle.

THE NOTCH BEND SPECIMEN

The theoretical hydrostatic stress (p) at the tip of a deeply notched bend specimen can be determined from the slip line field shown in Figure 1 and is given by:

$$p = k(1 + \pi - 2\beta) \tag{1}$$

where β is the half angle of the notch and k is the yield stress in shear.

The deep notch bend specimen was chosen as the standard for COD tests because the deformation essentially follows the slip line field solution. The two halves of the specimen rotate about a central rigid hinge so the plastic

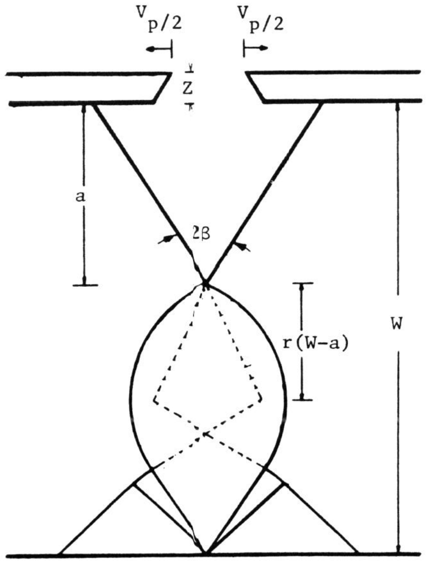

Fig. 1 Slip line field for V-notch bend specimen.

crack opening displacement δ_p is given in terms of the plastic displacement V_p at the tip of the knife edges by

$$\delta_p = \frac{r(W - a)V_p}{r(W - a) + a + Z} \tag{2}$$

where r is the rotation constant.

For the standard COD specimen as given by BS 5762, the slip line field solution indicates that the rotational constant should be 0.50 whereas in the standard 0.4 is used. The rotational constant for specimens with V notches have been calculated from the slip line field for notched bars under 3-point load (Alexander and Komoly, 1962).

We have not established empirical values for r for V notches, but show that the descrepancy introduced by using the theoretical value is small.

The elastic component of the crack opening displacement (δ_e) is given in terms of the stress intensity factor (K) at the tip of the notch by BS 5762: 1979 as:

$$\delta_e = \frac{K^2(1-\nu^2)}{2\sigma_y E} \tag{3}$$

where ν is Poisson's ratio and σ_y is the yield strength. It has been shown (Cook, 1969) that the effective stress intensity factor is virtually independent of the notch angle and thus equation (3) has been used for all notch angles.

EXPERIMENTAL DETAILS

The material used in these tests was 1204-350 steel. The properties of this material are given in Table 1. Three-point bend specimens 25mm deep and 12.5mm wide were machined so that they were orientated in the rolling direction with the notch perpendicular to the plate to simulate a surface defect. The notch angles varied from 0° to 150°. Fatigue cracks were grown from the tips of all the notches which were then remachined so that only a small fatigue crack of about 1mm deep remained. The notches had a depth of 10mm except for two specimens which had shallower notches 5 mm deep. The notches in these last specimens are still technically deep because the yielding did not spread to the surface. All specimens were tested using a span of four times the depth as recommended in BS 5762: 1979.

TABLE 1 Composition and Properties of Australian Steel 1204-350

(a) Chemical analysis:

C	P	Mn	Si	S	Ni	Cr	Mo	Cu	Al	Sn	Nb	V
.15	.023	1.3	.28	.014	.20	.20	.005	.025	.040	.005	.026	<.003

Ti	Ce	N	O
<.003	<.005	.0075	.0025

(b) Mechanical properties

Yield strength	402 MPa
Ultimate strength	536 MPa
Elongation to break	26 %
Charpy V-notch impact longitudinal to rolling at 20°C	98 J and 80% fibrous

The crack opening displacements were calculated from clip gauge measurements at the throat of the notches using both the standard rotation factor (r) of 0.4 and the theoretical value calculated from the slip-line fields. A catalytically hardening silicone rubber, Unitek Xantropren Blue dental impression material, was also used to measure the COD directly. After the testing the specimens were heated in a furnace to about 300°C to "blue" any crack growth and then infiltrated with the rubber. Hardening took place in a few minutes and the rubber was removed by breaking the specimen in liquid nitrogen. The replica of the crack was cut into thin sections and the crack opening displacement measured at a number of locations across the specimens. A summary of the estimations of the crack opening displacement from the replicas and clip gauge measurements is given in Table 2. It is seen that the values of the COD calculated from the clip gauge using either the standard or theoretical rotation factor fall within the range of measurements made by the replica technique.

TABLE 2 Comparison of δ_p Values from Replica Measurements and Equation (2)

Notch angle (2β)	r(theoretical)	δ_p		
		Calculated from clip gauge opening		Measured from replica
		r(theoretical) (mm)	r = 0.4 (mm)	min. - max. (mm)
0°[1]	0.50	0.08	0.07	-
		0.13	0.11	-
		0.11	0.09	-
		0.22	0.19	-
		0.25	0.22	-
30°	0.47	0.16	0.14	0.11 - 0.19
		0.14	0.13	0.11 - 0.19
		0.18	0.16	0.12 - 0.18
		0.20	0.18	0.19 - 0.23
		0.20	0.18	0.17 - 0.21
60°	0.43	0.21	0.20	0.18 - 0.19
		0.24	0.23	0.20 - 0.24
		0.25	0.24	0.22 - 0.25
		0.27	0.25	0.20 - 0.27
		0.28	0.27	0.20 - 0.28
90°	0.39	0.28	0.28	0.24 - 0.29
		0.32	0.32	0.26 - 0.31
		0.34	0.34	0.27 - 0.33
120°[2]	-	-	-	0.28 - 0.42
150°[2]	-	-	-	0.32 - 0.47

[1] Replica measurements not made

[2] Only replica measurements - clip gauge displacements too large

RESULTS AND DISCUSSION

The crack opening displacements measured from the rubber replicas with the elastic component added are displayed as a function of the crack growth (measured directly from the fracture surfaces) in Fig. 2. Since a stretch zone forms at the tip of a crack before true crack growth occurs it is difficult to tell whether the crack opening displacement for small apparent crack growths is due to true crack growth. The extent of the stretch zone (s) can be approximately estimated from the crack opening displacement by assuming a semi-circular crack tip geometry and is given by:

$$s = \delta/2 \qquad (4)$$

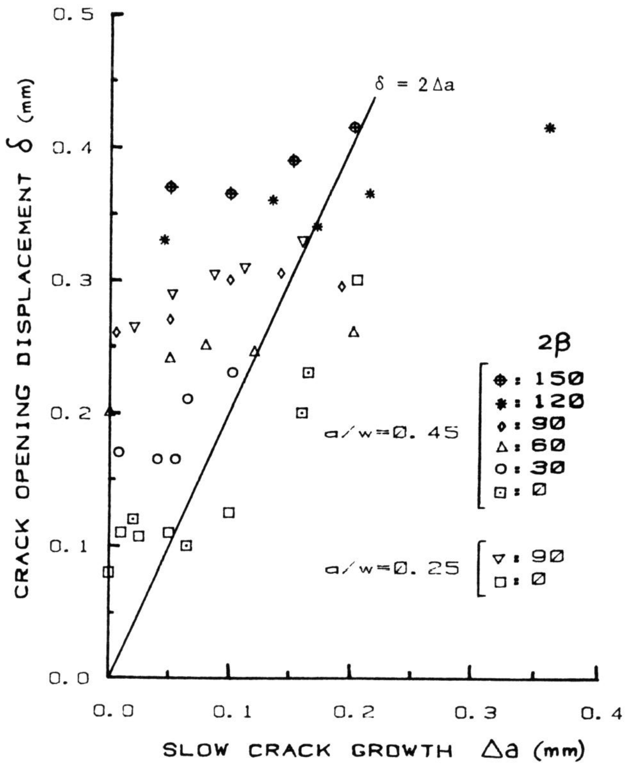

Fig. 2 Variation of crack opening displacement with slow crack growth for V-notch bend specimens with differing included angles.

In Fig. 2 we see that many results come from apparent crack growths less than the stretch zone. Theoretically one would expect the crack opening displacement to tend to zero with decrease in the stretch zone. Since the accuracy in measuring the crack growth is only about 0.05mm we have assumed that these results do in fact represent real crack growths. Hence the crack opening displacement at initiation has been estimated by taking the average of the crack opening displacements for apparent crack growths of less than the stretch zone. The initiation values of the crack opening displacement are shown as a function of the hydrostatic stress in Fig. 3. The crack opening displacement at maximum load is also shown in Fig. 3.

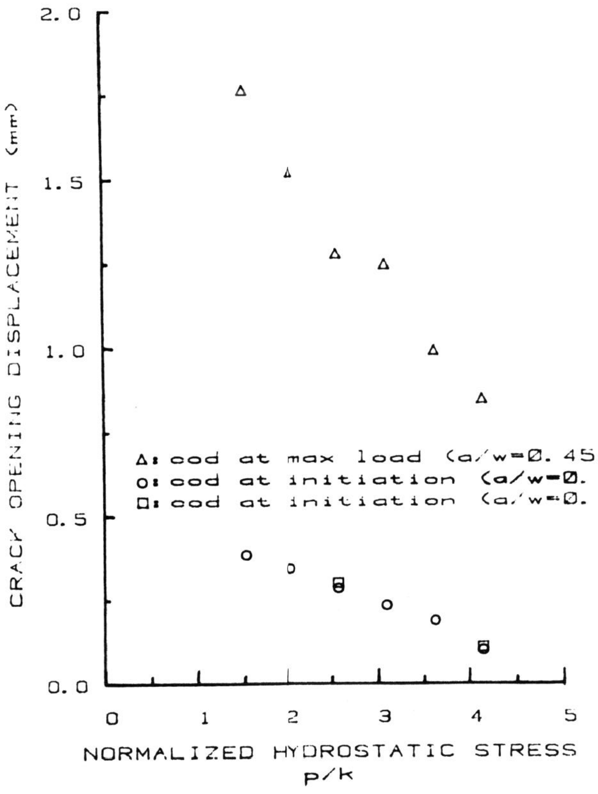

Fig. 3 Dependence of crack opening displacement on hydrostatic stress.

We intend to continue this work with technically shallow cracks and show that their critical crack opening displacements depend on the hydrostatic stress. From previous work we know that the crack opening displacement at initiation for shallow cracks, is about twice that for deep ones (Cotterell et al, 1984), but we have not yet calculated what is the hydrostatic stress for these specimens.

CONCLUSIONS

The crack opening displacement both at initiation and maximum load is clearly a function of the notch angle. We believe that the hydrostatic stress is the most significant variable, though we have not yet demonstrated that the same crack opening displacement can be obtained from a different specimen geometry that gives the same hydrostatic stress.

Our experiments indicate that clip gauges can be used to measure the crack opening displacements of bend specimens with V notches. Further work is necessary, however, to determine the best rotational factor to use in the calculations.

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