DUCTILE FRACTURE IN HIGH-STRENGTH STRUCTURAL STEELS

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Crack opening displacement (C.O.D.) tests have been carried out in two high-strength structural steels, HY80 and HY130. The effects of crack length on toughness in these two steels have been examined and related to the failure mechanisms operating at the crack tips. It is found that the material toughness, as measured by initiation C.O.D. values (δ_i), increases as the crack length decreases. This effect is related to the lower triaxiality at the crack tip associated with short cracks. A semi-elliptical part-through crack was examined in HY130. At the deepest point, the C.O.D. value was found to be similar to that of a short, through-thickness crack, whereas, on the top surface, a much larger value was obtained.

INTRODUCTION

Fracture mechanics is conventionally used to determine material toughness values (K_{Ic} or δ_i) in standard deep-cracked test pieces. These toughness values are subsequently used in engineering design to determine critical crack lengths, below which cracks should not propagate under monotonic loading. This design procedure assumes that toughness is a material constant, independent of crack length. It is, therefore, of importance to determine whether this assumption is valid. Wiltshire and Knott (1) and King and Knott (2) have shown that in very high-strength steels (marageing steels, $\sigma_y \sim$ 2GPa and 300M, $\sigma_y \sim$ 1.8GPa respectively) the crack tip ductility and hence material toughness remains constant with decreasing (a/W) ratios until surface yield occurs. In these steels, plastic zone sizes are small because of the high strength levels and, as a consequence, (a/W) ratios have to be very small before any effect on toughness is seen. On the other hand, Sumpter and McNicol (3) have shown marked effects of crack depth on the toughness of a MnNiMo weld metal in the transition range.

The two steels examined here are quenched and tempered HY80 ($\sigma_y \sim$ 0.7GPa) and HY130 ($\sigma_y \sim$ 1.3GPa) which, in addition to being of different strength levels, exhibit micromechanisms of fracture involving void growth and fast shear in different proportions; HY80 failing by a 'curtailed' void coalescence process (4) and HY130 failing by a rather more shear-dominated process (5). Since void coalescence might be expected to be affected more strongly by a hydrostatic stress field, it was thought that the different balance of void growth and fast shear failure mechanisms in these two steels might give rise to differences in any effect of decreasing crack length on toughness.

The effect of crack shape on initiation is examined in HY130 using specimens containing semi-elliptical part-through cracks. This is of import-

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ance because failure of most service components is generally caused by embedded or surface flaws with semi-elliptical crack fronts rather than by through-thickness cracks (6).

MATERIALS USED AND TEST PROCEDURES

TABLE 1 Chemical analyses of the two steels

Weight % Alloying Element

	C	Mn	Ni	Cr	Mo	Si	V	Cu	S	P
HY80	0.19	0.38	2.80	1.46	0.42	0.23	-	0.09	0.003	0.007
HY130	0.14	0.76	4.90	0.56	0.53	0.22	0.05	0.09	0.007	0.008

Both steels were given an austenitising treatment of one hour at 950°C, followed by tempering for one hour at 650°C for HY80 and one hour at 610°C for HY130. Three crack lengths were examined in each steel, corresponding to nominal (a/W) ratios of 0.5, 0.2 and 0.1.

The steels exhibited significant amounts of crack tip plasticity in standard test configurations and, hence, K_{Ic} values were not valid fracture criteria. Instead, initiation C.O.D. values (δ_i) were used to characterise fracture. The specimens were tested in general accordance with the British Standard for C.O.D. testing, BS5762 (7), with the exception that the specimens were tested in four-point bend rather than three-point bend, as permitted in DD19 (8).

The relation for determining δ in BS5762 is given as

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_y E} + \frac{0.4\,(W-a)\,Vp}{0.4W + 0.6a + Z}$$

where K = stress intensity factor
ν = Poisson's ratio
σ_y = yield stress
E = Young's modulus
W = specimen width
a = crack length
Vp = plastic clip-gauge displacement
Z = knife edge height

This equation separates the C.O.D. into its elastic and plastic components, the latter assuming a hinge-type mechanism in the material ligament under the crack tip. The centre of rotation for this deformation is taken to be at a distance 0.4(W-a) below the crack tip. This assumption is valid for deep through-thickness cracks but is not valid for short cracks where there is interaction of the deformation processes at the crack tip with the top surface of the specimen and the deformation can no longer be described by a hinge mechanism (9,10).

In the present work, values of C.O.D. for (a/W) $\sim$0.5 were determined by the British Standard test procedure. For the shorter cracks, however, this is not appropriate and instead the procedure adopted was as follows:

1) The crack was infiltrated off-load with araldite resin and sectioned to reveal the crack profile (Figures 1,2). The displacement of the parallel crack

faces was measured as δ_1.

2) When a specimen is unloaded, the crack closes up by an amount determined by reverse plasticity at the crack tip (δ_2) which may be estimated as a first approximation, following Rice (11), as

$$\frac{K^2 (1 - \nu^2)}{4\sigma_y E}$$

which is half the elastic component of δ which would be determined from BS5762. The C.O.D. values quoted are then the sums of δ_1 and δ_2.

Alternative techniques were also investigated - these being determinations of C.O.D. values from stretch zone width measurements and from direct measurements of sectioned replicas, made from an elastomeric material infiltrated into the crack with the specimen held on-load.

RESULTS

TABLE 2 δ_i values for different (a/W) ratios in HY80 and HY130 (mm)

	a/W	0.5	0.2	0.1
HY80		0.22	0.43	0.58
HY130		0.12	0.15	0.33

The δ_i values tabulated above are results obtained from extrapolation of δ vs Δa curves to zero crack growth ($\Delta a = 0$). The values of δ for (a/W) ratios of 0.5 were obtained from BS5762 calculations, but were compared with the metallographic technique used for the smaller (a/W) ratios. These two methods appear to correlate well for these higher (a/W) ratios (Figure 3).

Values of δ_i measured from stretch zones were obtained from random sampling along the crack front, but these were found to have rather poor agreement with the metallographic technique used. An average value of stretch zone width determined by measurement along the whole crack front would clearly be more satisfactory but the measurements would be extremely tedious to make. An example of the irregularity of the crack front may be seen in Figure 4.

Infiltration of cracks under load with elastomeric material, which has proved to be a useful technique for C.O.D. determination, agreeing reasonably well with BS5762 (12), was attempted but it was found that the silicone rubber material did not penetrate into the fibrous crack growth region in these steels, and it was uncertain as to whether or not it actually reached the crack tip.

Failure Micromechanisms

In testpieces containing deep cracks, HY80 has been observed (13) to fail by a void-coalescence process, which may be curtailed by shear decohesion between the opened voids when the hardening capacity of the material is exhausted. A similar mechanism appears to operate in testpieces containing short cracks, although the C.O.D. values are increased (Figure 1). The higher strength steel, HY130, however, fails in a manner more dominated by shear. Voids formed around inclusions are linked together by shearing between them to produce a 'zig-zag' fracture profile (Figure 2), where distinct shear 'steps' are apparent. It was found that the length of these steps was of the same magnitude as the inclusion spacing in the material, i.e. 200μm.

DISCUSSION

Despite a general similarity in the appearance of the fracture profiles in the two steels, (Figures 1,2) the δ_i values differ by a factor of two (Table 1), indicating greater localisation of flow in HY130.

In both steels, it is clear that δ_i increases with decreasing (a/W) ratios. This effect may be explained generally by consideration of the deformation processes in the specimens. In deep-cracked specimens, deformation may be described by a hinge-type rotation of 'rigid' blocks of material in the ligament under the crack tip. A high hydrostatic component is maintained here. In the shallow-cracked specimens, when this deformation begins to interact with the top surface of the specimen, the hydrostatic stress state is relaxed and therefore allows greater crack opening before propagation.

The difference between δ_i for deep and shallow cracked specimens in both HY80 and HY130 is a factor of three. This correlates well with results obtained by Hancock and Cowling (14) where a decrease in constraint by variation of specimen geometry produces an effect on δ_i of the same magnitude. However, it is seen that the difference between δ_i for (a/W) ratios 0.5 and 0.2 is not as marked in HY130 as it is in HY80. This is presumably due to the plastic zone in HY80 interacting with the specimen top surface for (a/W) $\sim$ 0.2 whereas in the higher-strength HY130 this interaction does not occur significantly until (a/W) ratios of 0.1 are reached. There is therefore a similar general effect of crack length on δ_i in both HY80 and HY130, despite the differences in the proportion of void growth and fast shear in the micromechanisms of failure. There is however, an indication that the 'critical' (a/W) ratio is smaller for HY130 than for HY80.

C.O.D. values at the deepest point in semi-elliptical cracks in HY130 were found to be of the same order ($\delta \sim 0.42$mm) as those for specimens containing short through-thickness cracks for an equivalent amount of crack extension ($\delta \sim 0.4$mm) and it is observed that the fracture profiles in both cases appear to be similar. (Compare Figure 5 with Figure 2). On the top surface, however, the C.O.D. values obtained are significantly larger ($\delta \sim 0.5$mm) for a smaller amount of crack extension and the fracture profile reveals a macroscopic shear-type failure (Figure 6) with shear cracks emanating from the original crack tip at angles of 45°. This is equivalent to the failure of a centre-cracked panel under uniform tension.

In conclusion, the effect of increased δ_i values for short crack lengths and for part-through cracks in structural steels implies a high margin of safety (up to a factor of three) in engineering applications where failure assessment is based entirely on results obtained from δ_i values measured for deep through-thickness cracks.

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SYMBOLS USED

δ = crack opening displacement (C.O.D.)

δ_i = initiation crack opening displacement

K_{Ic} = critical stress intensity factor

σ_y = yield stress

a = crack length

W = specimen width

ν = Poisson's ratio

E = Young's modulus

V_p = plastic clip-gauge displacement

Z = knife edge height

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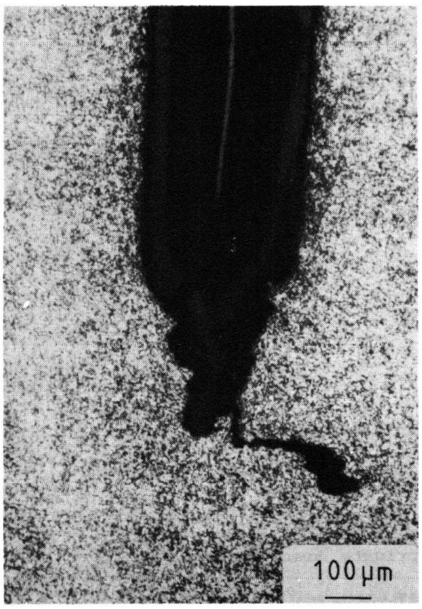

Fig 1 Crack profile in HY80 1mm cracked testpiece

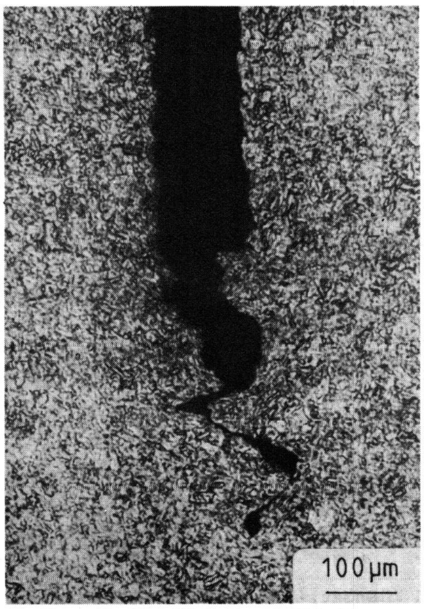

Fig 2 Crack profile in HY130 10mm cracked testpiece

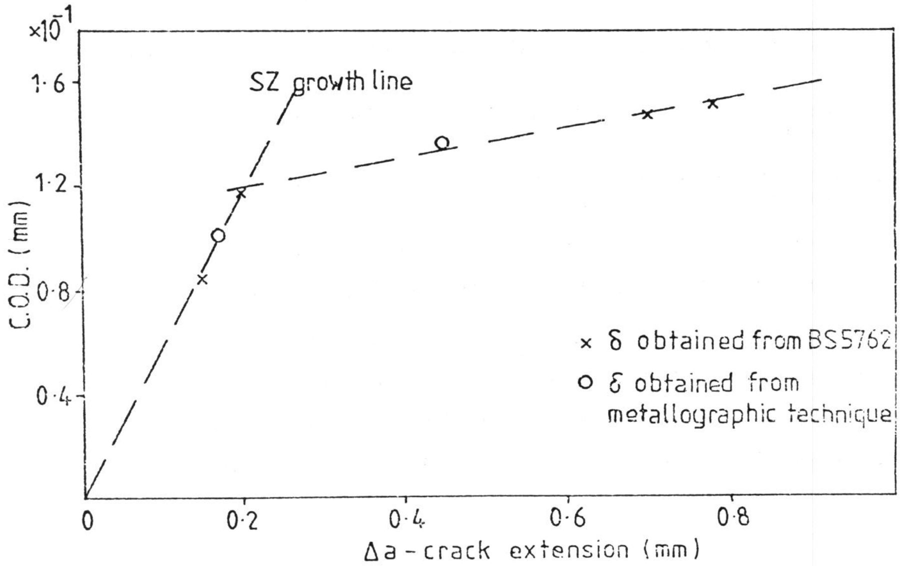

Fig 3 R-curve for 10mm cracked specimens in HY130 showing δ values obtained from BS5762 and from the metallographic technique used, yielding δ_i value of 0.12mm.

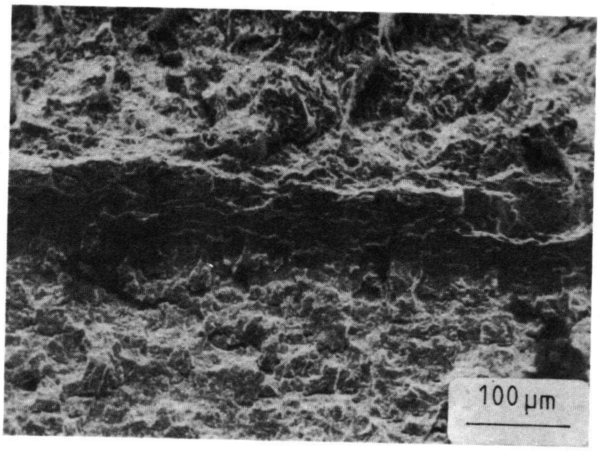

Fig 4 Typical stretch zone in HY80

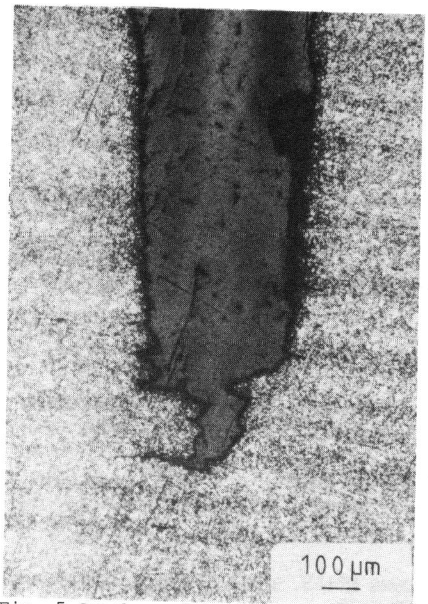

Fig. 5 Crack profile at deepest point in HY130 semi-elliptical cracked specimen.

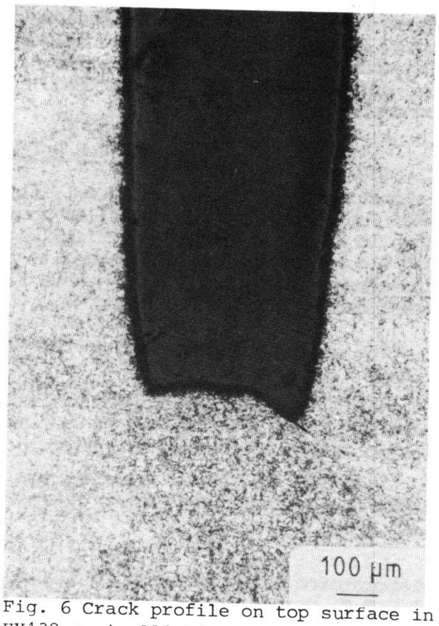

Fig. 6 Crack profile on top surface in HY130 semi-elliptical cracked specimen.