THE EFFECT OF INCLUSION ORIENTATION ON DUCTILE FRACTURE

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ABSTRACT

The orientation of elongated inclusions in low strength steels has a large influence on tearing resistance. It is postulated that this results from the strain intensification at the crack tip caused by the inclusions. Experiments on a model system are described, in which the strains between a blunt notch and a void of varying dimensions were measured. These indicate that the inclusion length in the direction of fracture, and the spacing, have a large influence on the strain. A quantitative relationship is proposed which predicts the effect of orientation on both initiation and propagation of tearing. The agreement with measured toughnesses in all six orientations of an EN32B steel is encouraging.

KEYWORDS

Ductile fracture; initiation; propagation; orientation; inclusions; crack tip strains; COD.

INTRODUCTION

Ductile fracture occurs by microvoid coalescence, the voids being initiated at second phase particles. In structural steels the principal void-forming particles are manganese sulphide inclusions, and these are often elongated by hot rolling. It is well known that such an inclusion morphology causes marked anisotropy in resistance to both initiation and propagation of tearing. However, there have been few attempts at a quantitative explanation. The effect of an isolated elliptical void on local stresses and strains has been studied by Inglis [1913] for an elastic matrix, and by Harkegaard [1973] for a perfectly plastic one. Where interactions between a void and a crack tip have been considered, the treatment has either been elastic [Atkinson, 1971] or has been for a spherical void [Rice and Johnson, 1970; Orr and Brown, 1974; Tirosh and Tetelman, 1976]. The effect of inclusion dimensions was studied by Gurland and Plateau [1963] on the basis of a modified elastic solution, and their predictions were later incorporated into the model of Gladman, Holmes and McIvor [1971], which was used to explain the reduction in toughness found in the short transverse orientation. Baker [1971] also developed a model to describe propagation toughness in the two short transverse orientations.

There are six major orientations of cracking with respect to rolling plane and direction, as defined in Fig. 1. Measurements of initiation and propagation toughness have been made for all six orientations of a structural steel [Willoughby, Pratt and Turner, 1980], large effects of inclusion anisotropy being found. Further experiments were therefore undertaken, using a model system, in order to investigate the effect of inclusion dimensions on ductile fracture.

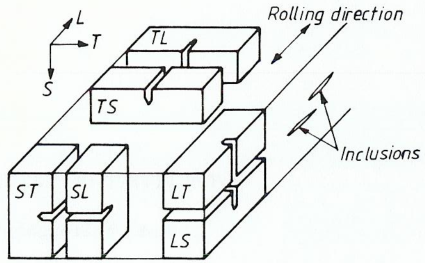


Fig.1. Orientation of cracking with respect to rolling plane and direction.

EXPERIMENTAL STUDY

If it is assumed that ductile fracture is controlled by strains at the crack tip, it is probable that the size, shape and spacing of a void near the tip will influence these strains. Considering a single void and a crack tip as in Fig. 2, it is postulated that several factors will affect the strain in the intervening ligament, for instance

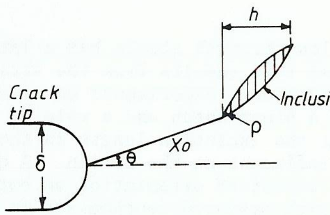


Fig.2. 2-D representation of an inclusion ahead of a crack tip.

(i) the separation, X_o, between the crack tip and the void,
(ii) the frontal radius of curvature, ρ, of the void,
(iii) the length, h, of the void in the direction of fracture,
(iv) the angle, Θ, between the line connecting the tips of the crack and void, and the crack line.

The effect of the first three parameters was investigated by means of experiments on compact tension specimens which contained a blunt crack tip and a hole of varying dimensions [Willoughby, 1979]. Strains were measured directly from the displacements of grids insribed on the specimens. The experimental method and results are summarised below.

Experimental Details

A 60/40 brass was chosen for the CT specimens because it had sufficient ductility to deform extensively without cracking and could be readily joined by soldering. Dimensions are given in Fig. 3. A grid was scribed on one surface, between the notch and the void, so that tensile strains between the two could be estimated in plane stress. It was also considered desirable to measure these in plane strain (or a state approaching it), so an internal grid was also used on some specimens. This was obtained by scribing relatively coarse lines on one face, and then bonding this face intimately to a similar specimen with silver solder, by heating to 700°C in an inert atmosphere of forming gas. The specimen was then machined to shape, the notch and void inserted and the surface grid scribed. After applying a measured deformation via the loading holes, the tensile strains could be calcula-

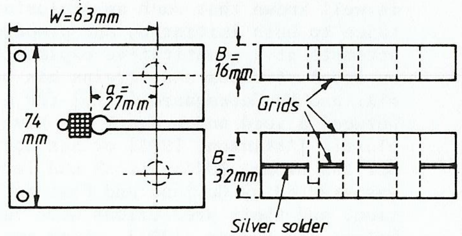
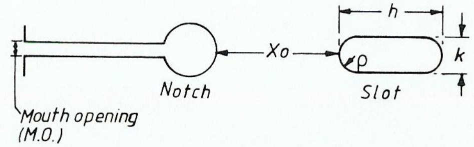


Fig.3. Brass compact tension specimens in single or double thickness.

ted from measurements on photographs of the grids taken before and after deformation. The internal strains were obtained by reheating a specimen to melt the solder, separating the two halves, skimming off excess solder and etching in alcoholic ferric chloride to reveal the grid lines. The void dimensions and spacings examined are given in Table. 1.

TABLE 1 Slot parameters in brass CT specimens.
Notch root radius = 2.4mm



Specimen	X_o mm	h mm	k mm	ρ mm
I*	No slot	-	-	-
II*	7	12.5	3.2	1.6
III*	4	3.2	12.5	∞
IV*	4	3.2	3.2	1.6
V*	7	3.2	3.2	1.6
VI*	4	12.5	3.2	1.6
VII*	7	3.2	1.6	0.8
VIII*	7	3.2	12.5	∞

* Double thickness specimens with centre grid.

Experimental Results

It was intended to deform each specimen to a constant mouth opening (M.O.) of approximately 14mm, but this was not always possible since some specimens began cracking at the centre of the notch before this level of deformation was reached. Where this occurred, the specimen halves were separated, the grids photographed, and the appropriate half then deformed further so that the surface grid could be photographed at the required mouth opening.

Effect of Stress State

Figure 4(a) shows the variation of true tensile strain, ε_{yy}, with distance along the crack plane for Specimen I, which had no "void". At a given mouth opening the strains in the centre are considerably higher than on the surface. The same pattern was found in all other cases, Figs. 4(b)-(d). The distribution of strains, however, appears similar, with surface strains lower by a factor of between 2 and 6. This similarity suggests that the variation of strain pattern with void shape in plane strain may be determined from plane stress measurements, thereby greatly simplifying any future experiments. The difference in magnitude possibly results from the fact that the larger plastic zone size in plane stress means that a given deformation can be accommodated over a larger area.

The predictions of Rice and Johnson's [1970] model are shown in Fig. 4(a), calculated using the measured COD for Specimen I of 2.5mm at M.O. = 9.1mm. The measured strains show a shallower strain gradient, possibly due to the effects of the blunt notch and work hardening, both of which would distribute strains more uniformly.

Effect of ligament width, X_o

Comparing Specimens II and VI (Fig. 4(b)) and IV and V (Figs. 4(c) and (d)) shows that decreasing X_o from 7mm to 4mm increases the average strain in the ligament by a factor varying between approximately 1.5 and 2.5.

Effect of void length, h.

Comparing Specimens II and V (Figs. 4(c) and (d)) shows that, at M.O. ≃ 14.5mm, increasing h by a factor of 3.9, at constant ρ, increases the average strain by a factor of 2.2. The same trend is shown by Specimens IV and VI (Figs. 4(d) and (b)), if it is assumed that strains scale with mouth opening. The dependence is of the

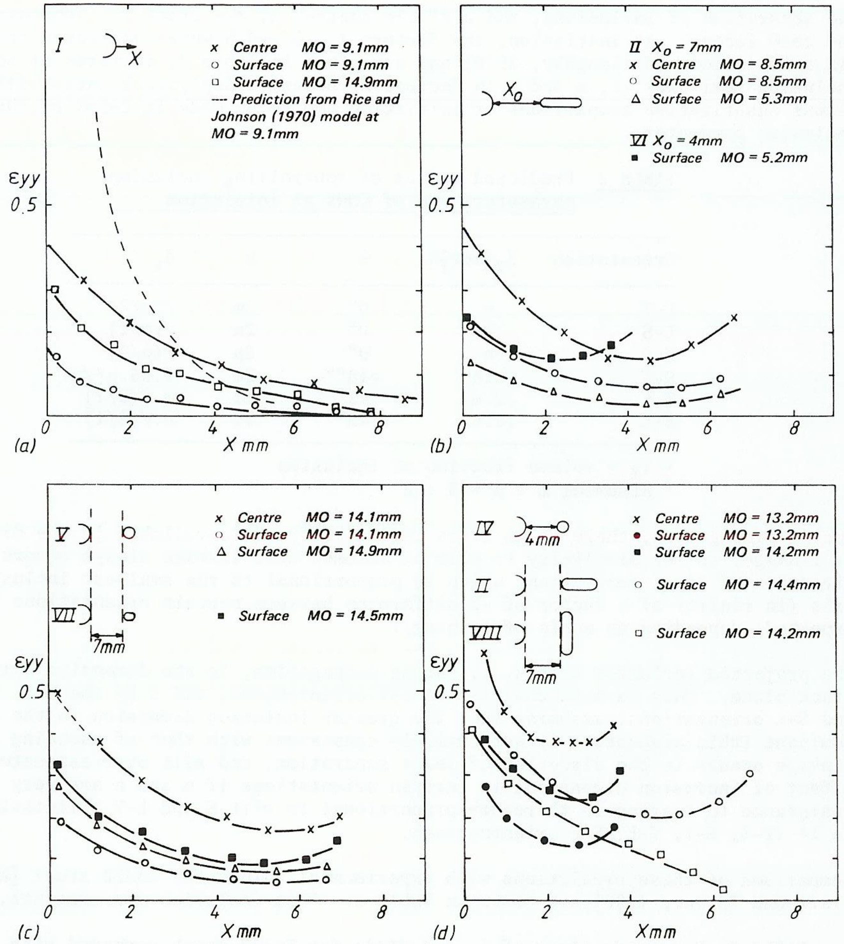


Fig.4(a-d). Distribution of true strains between the notch tip and void.

same order as that predicted by Inglis [1913] for an elastic matrix, where the stress is proportional to $(h/\rho)^{\frac{1}{2}}$.

Effect of frontal radius of curvature, ρ.

Comparison of Specimens V and VII (Fig. 4(c)), where a factor of two difference in ρ was achieved, shows a small change in average strain. However, Specimen VIII (Fig. 4(d)), where $\rho \simeq \infty$, had a higher average strain than that for Specimen V at M.O. $\simeq$ 14mm. No firm conclusion can therefore be drawn as to the effect of ρ on strains, except that the variation appears to be less marked than that predicted by Inglis [1913] for elasticity.

DISCUSSION

These experiments show that the strains between a notch tip and a void are strongly influenced by certain void parameters. The strain increases as the separation decreases (in agreement with the observations of Tirosh and Tetelman [1976]), as the void length in the direction of fracture increases, and possibly as the frontal radius of curvature decreases. The dependence on angular position, Θ, of the void was not investigated here, but an inverse relationship, such that the strain is greatest when $\Theta = 0$, and least when $\Theta = \pi/2$, might be expected.

The dependence of the average strain in the ligament on void parameters may be written

$$\varepsilon' = \varepsilon(1 + F) \qquad [1]$$

where ε' is the average true tensile strain in the intervening ligament, ε is that strain in the absence of the void, and F is a "strain intensification" factor, and is a function of void parameters. It is postulated that F varies which each of the void parameters separately,

$$\text{ie.}\quad F = f_1(\rho)\ .\ f_2(\Theta)\ .\ f_3(X_o)\ .\ f_4(h) \qquad [2]$$

Quantitative expressions for f_1 - f_4 cannot be deduced rigorously from these experiments. The following simple relationships, which are consistent with the experiments will, however, be assumed in order to develop a model to describe the effect of inclusions on tearing resistance:-

(i) $f_1(\rho)$ = constant, since the dependence on ρ was found to be rather weak.

(ii) $f_2(\Theta) \propto \cos\Theta$, which satisfies the requirements that f_2 should be zero at $\Theta = \pi/2$, and maximum at $\Theta = 0$. This dependence was postulated by Baker [1971].

(iii) $f_3(X_o) = 1/X_o$, since f_3 was found to be inversely dependent on X_o.

(iv) $f_4(h) = (h)^{\frac{1}{2}}$, since this reflects the fairly strong dependence on inclusion length, and is also consistent with the elastic solution.

Hence Equation [1] may be expressed approximately at

$$\varepsilon' = \varepsilon(1 + C\ .\ \cos\Theta\ .\ h^{\frac{1}{2}}/X_o) \qquad [3]$$

where C is a constant. Since C is not dimensionless, quantitative estimates which might be deduced from the model could not be readily applied to the real situation, where the inclusion dimensions are several orders of magnitude smaller, without some scaling factor. However, for materials where the volume fraction and the length h are sufficiently large for the inclusions to exert a strong influence on fracture, ie. where $h^{\frac{1}{2}}/X_o \gg 1$, the dependance of the average strain on inclusion parameters becomes approximately

$$\varepsilon' \propto \varepsilon\ \cos\Theta\ h^{\frac{1}{2}}/X_o \qquad [4]$$

A MODEL TO DESCRIBE THE INFLUENCE OF ELONGATED INCLUSIONS ON DUCTILE TEARING RESISTANCE

In applying these considerations to ductile fracture in low-strength steels it will be assumed that, (i) manganese sulphide particles are weakly bonded and therefore act as voids (hence no nucleation strain is required), (ii) crack extension occurs on the attainment of a critical strain over a critical distance ahead of the crack tip, (iii) the critical strain is determined by the flow properties of the matrix, and is the same for all orientations, (iv) the critical distance is of the same order as the inclusion spacing, (v) in the absence of voids the average true strain (ε in Equation [4]) ahead of the crack is proportional to the COD, δ, prior to initiation and to the crack tip flank angle, $d\delta/da$, during tearing (where a is the crack length).

If fracture occurs when ε', averaged over the critical distance, reaches a critical value, ε_c, then the criterion for crack initiation or propagation becomes, from Equation [4]

$$\delta_i \text{ or } \frac{d\delta}{da} \propto \frac{\varepsilon_c X_o}{\cos\Theta \, . \, h^{\frac{1}{2}}} \qquad [5]$$

This expression would seem to imply that the effect of inclusion dimensions, and hence orientation, is the same for both initiation and propagation. This is not so, because the appropriate inclusion parameters are different in each case. Figure

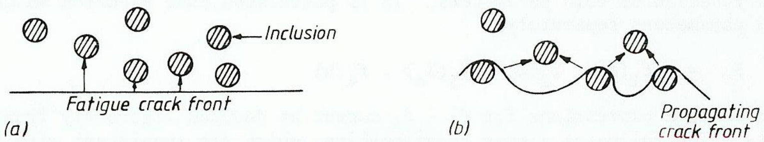


Fig.5. Interaction between crack tip and inclusions: a) Prior to initiation; b) during propagation.

5(a) shows a plan view of the crack plane prior to initiation. As the COD increases, the fatigue crack blunts through the formation of stretch zone. The greatest strain intensification would occur where the distance between inclusions and the crack tip is least. This will be on planes normal to the crack front, and there will be no tendency for blunting to occur in a lateral direction. It follows that only the inclusion dimensions in the plane perpendicular to the crack front (the plane of Fig. 2) need be considered. By contrast, propagation occurs in three dimensions, as illustrated in Fig. 5(b). The crack front is irregular, being composed of voids which have coalesced. Subsequent propagation will occur in whatever happens to be the direction of greatest strain intensification, and therefore inclusion dimensions both parallel and perpendicular to this direction are equally important.

Baker [1971] showed that the separation of inclusions in any direction is proportional to their dimension in that direction, assuming a random dispersion. Linkage between elongated inclusions will not therefore take place along the rolling direction, where dimensions and therefore spacings are greatest. Where this is the macroscopic direction of fracture, linkage on the micro-scale occurs by "zig-zagging" or oblique shear between inclusions. For rod-like inclusions the factor $X_o/\cos\Theta$ is similar, within a factor of $\sqrt{2}$, for all six orientations, and the inclusion length h in the direction of fracture becomes the parameter which governs toughness. At initiation, therefore, the lowest toughness is predicted for the T-L and S-L orientations, when the inclusions are elongated in the macroscopic direction of fracture. During propagation the T-L, S-L, S-T and T-S orientations are predicted to give equally low resistances (given by $d\delta/da$), since inclusions now lie in the macroscopic crack plane. The L-S and L-T orientation, where the inclusions are oriented normal to the crack plane and direction, are predicted to show high resistances to both initiation and propagation.

In order to make these predictions more quantitative, relative inclusion dimensions must be considered. For ellipsoidal inclusions, Baker [1971] showed that the factor $X_o/\cos\Theta$ is obtained from the point of intersection of an ellipse, representing

the separation of inclusions, and a circle centred at the crack tip representing the $\cos\Theta$ factor. At initiation, the factors X_o, Θ and h were calculated for the six orientations [Willoughby, 1979] and are given in Table 2, in terms of the inclusion semi-axes (l, m and n in decreasing order). Applying Equation [4] then allows quantitative comparisons of initiation COD to be made in terms of the inclusion parameters.

TABLE 2 Predicted ratios of controlling inclusion parameters and of CODs at initiation

Orientation	$X_o(x6V_f^+)$	Θ	h	δ_i
L-T	m	0°	2m	$\sqrt{(m/2)}$
L-S	n	0°	2n	$\sqrt{(n/2)}$
T-S	n	0°	2n	$\sqrt{(n/2)}$
S-T	$\sqrt{2}$.n	≈18°*	2m	1.05.$n/\sqrt{m}$
T-L	$\sqrt{2}$.m	45°	2l	m.$\sqrt{(2/l)}$
S-L	$\sqrt{2}$.n	45°	2l	n.$\sqrt{(2/l)}$

+ V_f = volume fraction of inclusion
* Assuming m : n = 3 : 2

During propagation, there is an extra degree of freedom available in the direction of linkage, so for simplicity it will be assumed that linkage always occurs in the direction of least separation, which is proportional to the smallest inclusion semi-axis (in reality of a factor of $\sqrt{2}$ difference between certain orientations may be expected, depending on angle of joining).

The projected inclusion length, h, during propagation, is the dimension lying in the crack plane. This is m in the L-S and L-T orientations, and l in the T-S, S-T, T-L and S-L orientations, assuming that the greater inclusion dimension in the plane is dominant (this assumption is not entirely consistent with that of assuming that the linkage occurs in the direction of least separation, and will over estimate the effect of inclusion dimensions in certain orientations if m and n are very different). Resistance to tearing is therefore proportional to $m^{\frac{1}{2}}$ (L-S and L-T orientations) and to $l^{\frac{1}{2}}$ (T-S, S-T, T-L, S-L orientations).

Comparison of these predictions with experimental values for En32B steel [Willoughby, Pratt and Turner, 1980] are shown in Table 3. From inclusion measurements, the

TABLE 3 Measured values of δ_i and $d\delta/da$ for En32B steel, compared with predictions, assuming that l : m : n = 15 : 1.5 : 1

	L-T	L-S	T-S	S-T	T-L	S-L
Measured δ_i - actual (mm)	0.13	0.10	0.09	0.06	0.04	0.04
- fraction of L-T	1	0.77	0.69	0.46	0.31	0.31
predicted ratio	1	0.82	0.82	0.98	0.62	0.31
Measured $d\delta/da$ - actual (mm)	0.70	0.69	0.21	0.18	0.15	0.17
- fraction of L-T	1	0.99	0.30	0.26	0.21	0.24
predicted ratio	1	1	0.32	0.32	0.32	0.32

ratios of l:m:n were taken as 15:15:1. Despite the many assumptions, agreement is reasonable, particularly for propagation resistance. For initiation CODs, agreement is poorest for the S-T and T-L orientations, where the predictions are too high. This could be due to the fact that strain localisation encourages easier initiation, or possibly to the neglect of the frontal radius of curvature. In qualitative terms, however, the T-S and S-T orientations illustrate the prediction that the effect of inclusion orientation on toughness is not identical at initiation and during propagation.

CONCLUSIONS

1. The crack tip strains were found to be influenced strongly by void separation and length in the direction of fracture, and only weakly by frontal radius of curvature.

2. Initiation of tearing is a 2-D process on the micro-scale, whereas propagation occurs in 3-D. Therefore the influence of elongated voids on initiation is not necessarily the same as on propagation.

3. Predictions as to the effect of inclusion orientation on tearing resistance were applied to a structural steel. Agreement with experiment is reasonable, particularly during propagation.

ACKNOWLEDGEMENTS

The authors wish to thank the Science Research Council for financial support, and Professor J.G. Ball for the provision of research facilities at Imperial College.

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