THE EFFECT OF NON-METALLIC INCLUSIONS ON CLEAVAGE FRACTURE

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The effect of inclusions on cleavage in wrought steel has been studied. The cleavage fracture stress is found to exhibit an orientation dependence which is attributed to the morphology of the inclusions. In the short-transverse and transverse orientations, cleavage facets initiate at the edges of elongated inclusions. It is proposed that the inclusions do not themselves act as cleavage nuclei but are internal sites of stress concentration which facilitate carbide-initiated cleavage. Measurements of K_{IC} show no effect of testing orientation. This is attributed to the low probability of encountering inclusions in the crack tip process zone.

INTRODUCTION

The role of non-metallic inclusions in the micro-void coalescence mechanism of fracture is well known and it is recognised that elongated non-metallic inclusions are a major cause of the orientation dependence of fibrous fracture toughness in wrought steels. Whether inclusions can have a significant influence on cleavage fracture behaviour is unclear. For steels having ferrite-pearlite microstructures, it is generally acknowledged that the microstructural feature controlling susceptibility to cleavage fracture is the thickness of iron carbide particles (Curry and Knott, (1). However, recent studies by Tweed and Knott (2) and McRobie and Knott (3) have suggested that in C-Mn weld metals, cleavage fractures can nucleate at brittle non-metallic inclusions.

If inclusions can act as cleavage nuclei in weld metal, the question that arises is whether the inclusions in wrought steels can also act as nucleating sites for cleavage. It is known that sulphide and oxide inclusions can crack when steel undergoes plastic

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deformation (Pickering (4). Since the inclusions are usually thicker than the carbide particles, it might be expected that they would act as more effective cleavage nuclei. Also, in view of the elongated form of most non-metallic inclusions in wrought steel, it might be expected that inclusion-nucleated cleavage fracture would show a pronounced orientation dependence.

The effect of sulphur content on the ductile-brittle transition temperature in a wrought carbon-manganese steel has been studied by Pickering (4). It was found that in both the longitudinal and transverse directions, an increase in the MnS volume fraction first increased the transition temperature and then caused it to decrease at higher volume fractions. It was also reported that for sulphur contents greater than about 0.1%, the transition temperature in the transverse orientation was higher than that in the longitudinal direction. A recent series of measurements on a bainitic steel by Bowen and Knott (5) has also suggested that the microscopic cleavage fracture stress (σ_f) may be lower in the short transverse orientation than in the transverse and longitudinal orientations.

The series of experiments described in this paper was undertaken to determine whether the cleavage fracture behaviour of a wrought C-Mn steel is orientation dependent and, if so, whether this is related to the presence and geometry of the non-metallic inclusions. To facilitate identification of the role of the inclusions, a steel containing a deliberately high sulphur content was employed.

EXPERIMENTAL

The steel selected for the investigation was a resulphurised mild steel, En7A, having the following composition: C 0.18%, Mn 1.25%, Si 0.19%, S 0.15%, P 0.33%. The steel was cast as a full size ingot and then hot rolled and forged to a billet having a cross section of 65 mm x 120 mm. The dimensions of the billet enabled mechanical test specimens of appropriate size to be extracted in the three principal testing directions.

The majority of the inclusions in the steel were type I MnS, but there were also significant numbers of oxide inclusions. The latter were two-phase mixed oxides which were usually larger and more highly elongated than the sulphide inclusions. Typical examples of both types of inclusion are illustrated in figure 1. On the transverse section plane, the average aspect ratio of the inclusions was 2.5; on the longitudinal plane the aspect ratio was 12.1.

The microstructure of the steel in the as-received condition is shown in Fig.2. The ferrite grains were equiaxed but banding of the pearlite was evident. This type of microstructure is typical of hot worked structural steels and one series of tests was undertaken with the steel in this condition. It was recognised that the banding of the pearlite could itself give rise to anisotropy in cleavage behaviour. To explore this possibility, the steel was austenitized and rapidly cooled to produce the Widmanstatten ferrite/bainite microstructure illustrated in Fig. 3. The underlying soluble segregation was of course not removed by the heat treatment, but the alignment of the pearlite which was of main concern with regard to cleavage was eliminated.

Mechanical test specimens were obtained from the three principal orientations. For the notched and pre-cracked test pieces, the orientations selected were L-T, T-L and S-T; these are illustrated in figure 4. Testing was carried out in liquid nitrogen at −196 °C and involved measurements of cleavage fracture stress, uniaxial yield stress and plane strain fracture toughness. The cleavage fracture stress was determined from notched 4-point bend specimens using the specimen geometry and finite-element analysis of Griffiths and Owen (6). The uniaxial yield stress was measured using Hounsfield no. 13 tensile specimens which were extracted from the broken halves of the 4-point bend specimens. For the plane strain fracture toughness determinations, 8mm thick fatigue pre-cracked SEN specimens were employed. All the tests gave linear load-displacement plots and the testing procedures and specimen dimensions satisfied the requirements of BS 5447: 1977 for valid K_{IC} determinations.

RESULTS

The results of the fracture tests carried out at −196°C are shown in table 1. The yield strength shows little orientation dependence in

TABLE 1 - Effect of testing orientation on mechanical properties.

Condition	Orientation	Yield stress σ_y MN/m^2	Cleavage fracture stress σ_f MN/m^2	Fracture toughness K_{IC}, $MN/m^{3/2}$
AR	L-T	799	1849	30
		829	1803	31
AR	T-L	821	1594	33
		798	1635	33
AR	S-T	825	1502	32
		824	1515	35
HT	L-T	856	1840	–
		844	1856	–
HT	T-L	810	1567	–
		833	1567	–
HT	S-T	804	1376	–

(AR = as received, HT = heat treated)

either the as-received or heat treated condition. By comparison the measurements of cleavage fracture stress show a pronounced effect of orientation. The highest values are in the longitudinal orientation and the lowest in the short transverse orientation. The results from the heat treated condition are similar to those for the as-received condition. This demonstrates that the anisotropy in cleavage susceptibility is not associated with banding of the pearlite. Only one cleavage stress value is available for the short-transverse orientation of the heat treated condition and it is of note that this is lower than the corresponding value for the as-received condition. Examination of the fracture surface in the scanning electron microscope showed that the low value was associated with the presence of a large oxide inclusion which penetrated the notch root.

In view of the similar cleavage stress values shown by the as-received and heat treated conditions, fracture toughness measurements were carried out only on the as-received steel. The K_{IC} results are shown in Table 1 and it is of note that there is no significant effect of orientation.

The fractographic examination concentrated on the slow notched bend specimens, particular attention being paid to the area of fracture up to 0.5mm ahead of the notch root where the maximum tensile stress would be expected to have developed (6). Examination of the cleavage facets in the scanning electron microscope revealed a region ahead of the notch root from which river markings radiated both back towards the notch surface and forwards through the remainder of the section. A dominant nucleating site could not usually be identified within this region. However, many potential nucleating sites were examined, and particular attention was paid to the participation of non-metallic inclusions.

In the longitudinal testing orientation, no cleavage nucleation sites were identified which could be attributed to the presence of non-metallic inclusions. A nickel-plated section through the cleavage fracture surface of a longitudinal specimen is shown in figure 5 where it can be seen that the interface between the inclusion and the matrix has separated.

On the fracture surfaces from the T-L testing orientation, several cleavage initiation sites were associated with elongated inclusions. A typical example is illustrated in figure 6. The inclusion shown is a fragmented oxide and it was found that these were more commonly associated with cleavage nucleation than were the sulphide inclusions. Another interesting feature of nucleation sites is that they occurred most commonly along the sides of the inclusions. The nickel-plated section through the fracture surface of the T-L specimen is shown in figure 7. Beneath the main fracture surface, an arrested cleavage crack can be seen which appears to have nucleated at a sulphide inclusion.

In the short transverse testing orientation, inclusions frequently appeared to act as nucleating sites for cleavage. A typical example is shown in figure 8. Fragmented oxide stringers were again the preferred sites for cleavage nucleation but sulphides were observed to act in a similar manner.

DISCUSSION

The present series of experiments has demonstrated that in a steel containing a high volume fraction of inclusions there is a significant orientation dependence of the cleavage fracture stress. The similarity in the behaviour of the as-received and heat treated conditions indicates that the anisotropy is attributable to the presence of the inclusions rather than to any other microstructural feature. This is supported by the fractographic evidence.

The fractographic and metallographic observations indicate that the inclusions can crack in a brittle manner. It could be argued therefore that inclusions in wrought steel may act in a similar manner to grain boundary carbides which are generally regarded as the dominant sites of cleavage nucleation in mild steels. This is the suggestion that has been put forward by Tweed and Knott (2) to account for the participation of fine inclusions in the cleavage fracture of weld metals.

An essential requirement for cleavage fracture in steel is that there must be prior plastic deformation in order to develop the very high local stresses which are necessary for the formation of the crack nucleus. Usually the plastic deformation occurs by a slip mechanism. However, at very low testing temperatures, such as that used in the present series of experiments, deformation can occur by twinning. Both deformation mechanisms are effective in nucleating cleavage.

For slip-initiated cleavage, it has been suggested (1) that the cleavage fracture stress can be related to the size of the crack nucleus by a Griffith equation of the following type:

$$\sigma_f = \left[\frac{\pi . E . \gamma_p}{2\,(1-\nu^2) a} \right]^{1/2} \quad ---------- \quad (1)$$

where E is Young's modulus, γ_p is the effective surface energy of ferrite, ν is Poisson's ratio, and a is the radius of a penny-shaped crack.

If an inclusion were to act as a cleavage nucleus, then the relevant dimension in the short-transverse testing orientation would be the intermediate semi-axis which had an average value of 7.3 µm. Inserting this value in equation (1) together with a value of 210 MNm^{-2} for E, 14 Jm^{-2} for γ_p and 0.3 for ν, gives a calculated σ_f

value of about 830 MNm^{-2}. For the longitudinal testing orientation, the relevant inclusion dimension is the minor semi-axis (2.9 μm) and the corresponding value of σ_f is 1180 MNm^{-2}.

The calculated values of σ_f are lower than the measured values and indicate a greater influence of testing orientation than that observed. Nevertheless it could be argued that the results are not inconsistent with a direct inclusion nucleation mechanism. Although such an explanation is superficially attractive, there are a number of reasons for thinking that it may not be relevant to the steel under investigation. First, if a particle is to act as an effective cleavage nucleus, it must be more brittle than the ferrite matrix. Whilst this is the case for cementite and some oxide inclusions, it is not necessarily so for sulphide inclusions. A second requirement for an effective cleavage nucleus is that the particle should be well-bonded to the matrix in order that a crack can propagate from the particle into the adjacent ferrite. In the case of the manganese sulphide inclusions, the interface with the matrix is extremely weak. The fractographic observations suggest that there is complete decohesion between the sulphide and the matrix prior to the onset of cleavage. Some oxides may be more strongly bonded but this is unlikely to be the case for the duplex oxide stringers in the present steel. These oxides had undergone internal fragmentation during hot working and exhibited an irregular interface with the matrix which separated readily during testing.

An alternative way in which inclusions may influence cleavage behaviour is by modifying the stresses ahead of the notch root. In the absence of inclusions, cleavage initiates at some distance ahead of the notch root when the critical stress for the unstable propagation of a carbide-nucleated crack is attained. This cleavage fracture stress is usually significantly larger than the uniaxial yield stress and is attained by a combination of work hardening and triaxial constraint. If an inclusion is located within the relevant region ahead of the notch root, it may modify the development of plasticity on the local scale and hence facilitate, or even discourage, the normal carbide-nucleated cleavage mechanism.

Considering first the short transverse orientation, it is expected that the weak inclusion-matrix interface would have separated prior to the onset of cleavage. Under these circumstances the inclusion would act a a site of stress concentration. If the inclusion is treated as an oblate ellipsoid, the sites of maximum stress concentration would be at the ends of the transverse semi-axis. For the inclusions in the present steel the radius of curvature at this position was about 0.6 μm. For elastic conditions of loading, the corresponding stress concentration factor would be about 6. In practice this degree of stress concentration cannot be achieved because yielding precedes cleavage nucleation. Thorc would however be a concentration of plastic strain along the edges of the inclusion and this would be reflected in an increase in the value of the local tensile stress due to the development of increased local constraint and increased work hardening. Under these conditions, cleavage fracture is expected to nucleate at a lower nominal stress than would be the case in the absence of the inclusions. This is reflected in the observed reduced value of the cleavage fracture stress. It would also be expected that cleavage would nucleate preferentially along the edges of the elongated plate-like inclusions. The latter is borne out by the fractographic observations. A similar influence of elongated inclusions on brittle fracture nucleation has been demonstrated by Venkatasubramanian and Baker (7) in the hydrogen-assisted cracking of wrought steels in H_2S containing environments.

Because of the dimensions of the forged billet, the width of the inclusions in the transverse direction is not very different from that in the short transverse direction. For the T-L testing orientation, the position of maximum stress concentration is again along the edges of the elongated inclusions, but in this case the relevant radius of curvature is about 9 μm. The corresponding reduction in the degree of stress concentration at the inclusion makes cleavage nucleation less easy than in the short-transverse testing orientation and this is reflected in the observed increase in the measured cleavage fracture stress.

In the longitudinal testing orientation, the inclusions can give rise to no significant stress concentration provided that they do not undergo brittle fracture prior to the onset of cleavage in the matrix. It does not follow that in this orientation the inclusions have no influence on the cleavage process. The fractography has demonstrated that the inclusion/matrix interface is extremely weak and probably decoheres prior to cleavage nucleation. The metallographic evidence suggests that such separated interfaces may arrest and/or deflect a running cleavage crack. As far as the nucleation event is concerned, the separation of the inclusion interfaces which are running at right angles to the fracture plane may lead to a local relaxation of triaxial constraint. The local stress elevation would thereby be reduced and cleavage nucleation hindered. Such an effect would be consistent with the increase in the cleavage fracture stress which was observed in the notched bend tests. A similar effect of weak inclusion interfaces leading to enhanced resistance to hydrogen-induced brittle fracture has been reported previously by Venkatasubramanian and Baker (8).

A feature of the fractographic studies was that oxide inclusions appeared to act as more effective nucleating sites for cleavage than sulphides. A similar observation has frequently been made in relation to inclusion-nucleated fatigue in high strength steels (Murray and Johnson (9). The generally accepted explanation for the fatigue phenomenon is that due to the relative thermal expansion coefficients of the inclusion and matrix, oxide inclusions give rise to a residual tensile stress in the surrounding steel whereas sulphides tend to contract away from the matrix (Brooksbank and Andrews (10). If present, a residual tensile stress would be expected to facilitate cleavage nucleation. In the steel used in the present experiments, the oxides had fragmented during hot working and were no longer fully dense. Consequently it is questionable whether they could give rise to a significant residual stress. There are however two other factors which make the oxides preferred sites for cleavage nucleation. First, the oxides are larger and more highly elongated than the sulphides. As a result they act as more effective local sites of stress concentration. Secondly, the microstructure of the matrix in the vicinity of the oxide inclusions is different from that in the vicinity of the sulphides. When a steel transforms from austenite to ferrite and pearlite, manganese sulphide inclusions act as ferrite nucleating sites. Consequently, as shown in figure 1, the sulphides tend to be surrounded by carbide-free ferrite. By comparison, the oxide inclusions are seen to traverse the carbide rich-regions. If it is assumed that in the presence of the inclusions, cleavage nucleation still occurs by a carbide cracking mechanism, it follows that there is a higher probability of encountering a favourable nucleating site in the vicinity of an oxide inclusion.

A notable feature of the results is that despite the observed anisotropy in cleavage fracture stress there was no significant orientation dependence in the K_{IC} measurements. This is thought to be a consequence of the probability of encountering an inclusion within the crack tip plastic zone. In the blunt notched tests, the maximum tensile stress would have developed at a position approximately 0.25 mm ahead of the notch root (6). Within this region very many inclusions are present and cleavage can nucleate at the most favourable site. In the sharp-crack K_{IC} test, the fracture processes occur within a much smaller zone ahead of the crack tip. At −196°C, the extent of the plastic zone is about 80 μm, and within this zone, the position of maximum tensile stress is located about 10 μm ahead of the crack tip. Under these circumstances there is a low probability that a suitable inclusion would be located within the high stress region of the crack tip plastic zone. It is more likely that cleavage would nucleate at one of the numerous carbide particles present. As a result the inclusion influence is not revealed.

CONCLUSIONS

1. The cleavage fracture stress in a resulphurised wrought mild steel has been shown to be orientation dependent. The orientation dependence of the cleavage fracture stress is attributed to the presence of elongated non-metallic inclusions.

2. In the transverse and short-transverse testing orientations, cleavage facets initiate at the edges of elongated inclusions. It is proposed that the inclusions act as internal sites of stress concentration and encourage carbide-initiated cleavage in the adjacent matrix.

3. In the longitudinal testing orientation, decohesion of the inclusion-matrix interface leads to a local reduction in stress triaxiality which inhibits cleavage nucleation.

4. No effect of testing orientation on K_{IC} is observed. This is attributed to the low probability of encountering inclusions in the crack tip process zone.

SYMBOLS USED

σ_f = cleavage fracture stress

σ_y = yield stress

K_{IC} = plane strain fracture toughness

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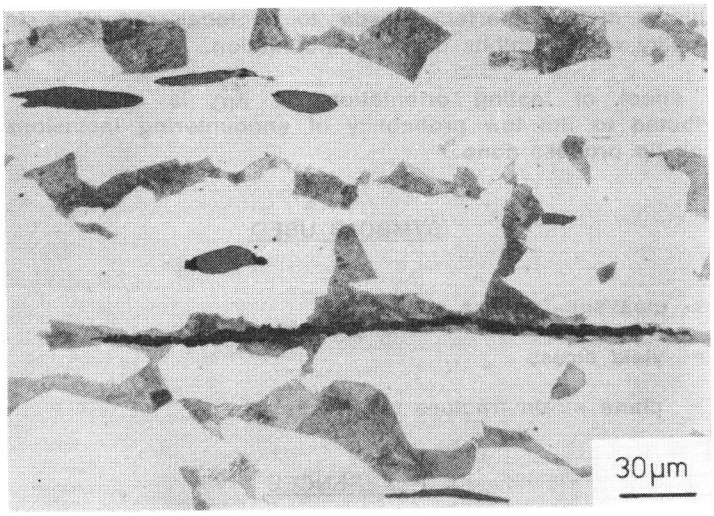

Figure 1 Oxide and sulphide inclusions on longitudinal section

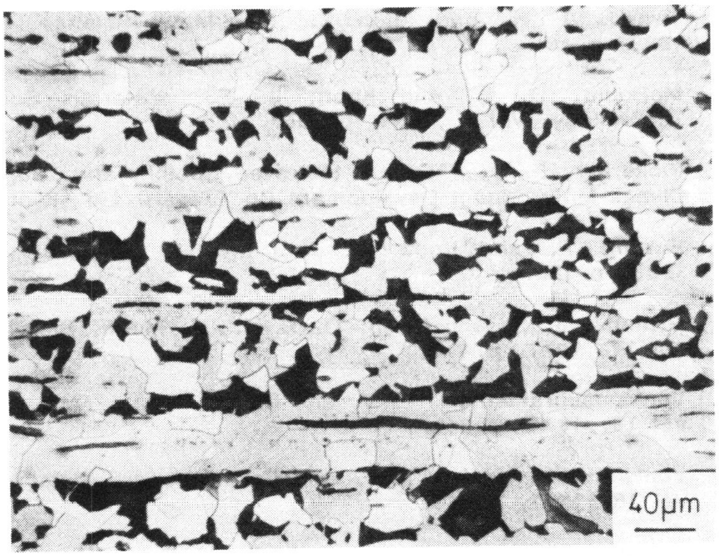

Figure 2 Banded pearlite in as-received steel

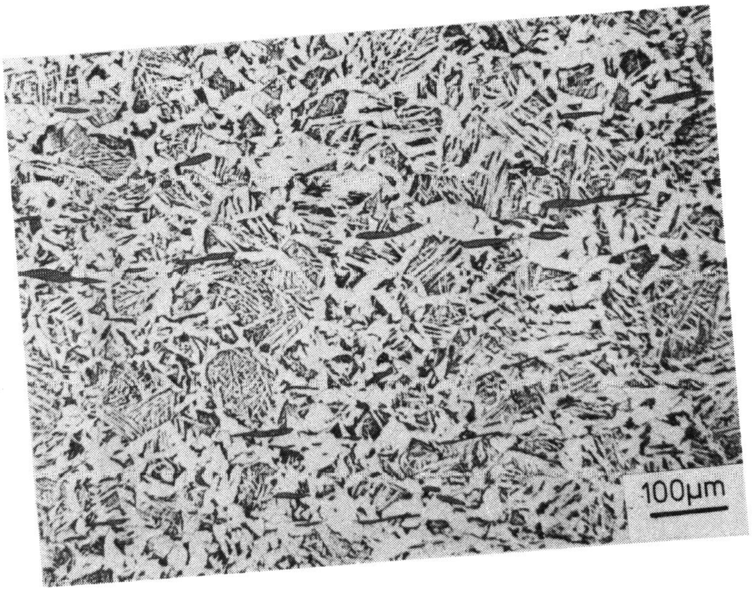

Figure 3 Heat treated microstructure

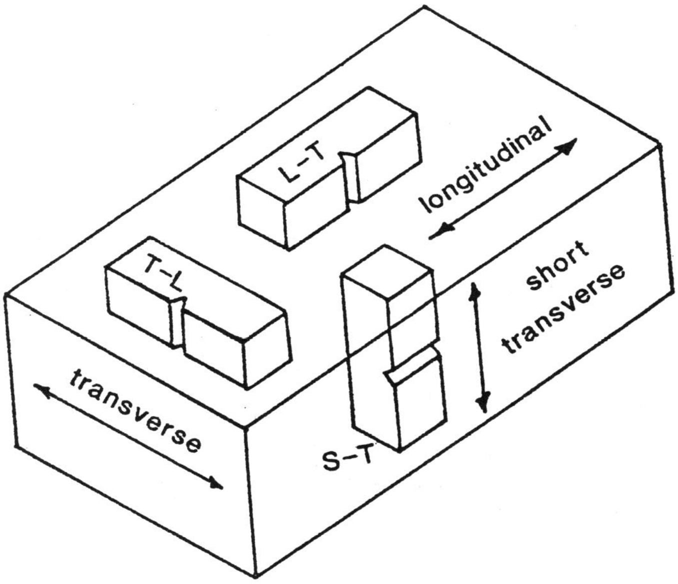

Figure 4 Test piece orientation

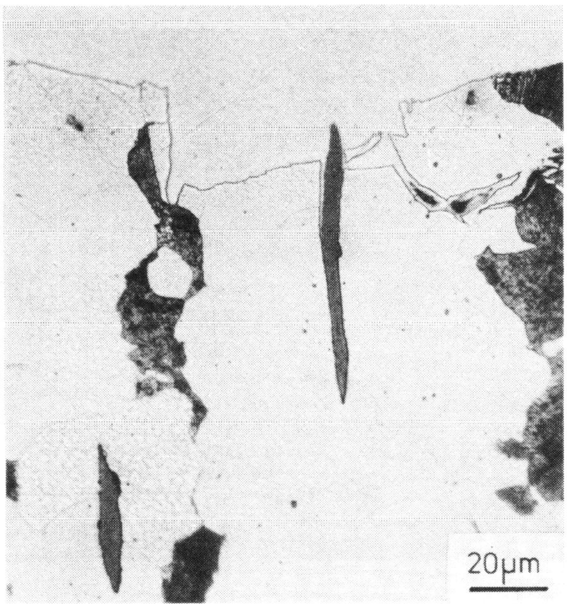

Figure 5 Nickel plated sections through fracture surface of L-T orientation

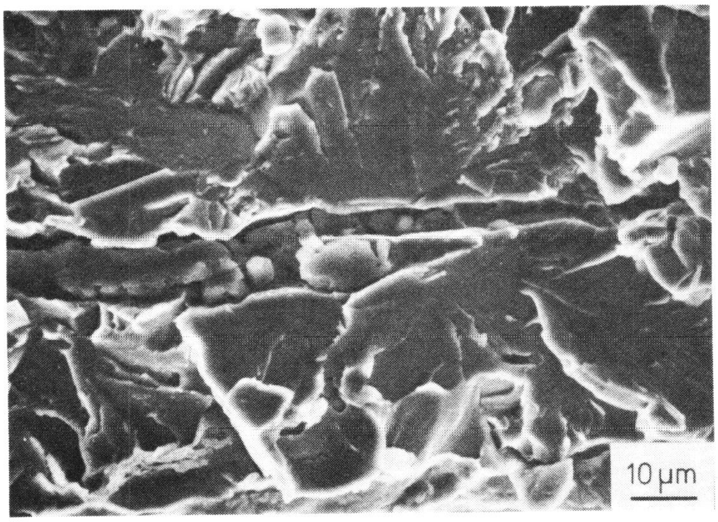

Figure 6 Fracture surface from T-L orientation showing cleavage nucleation adjacent to oxide inclusion

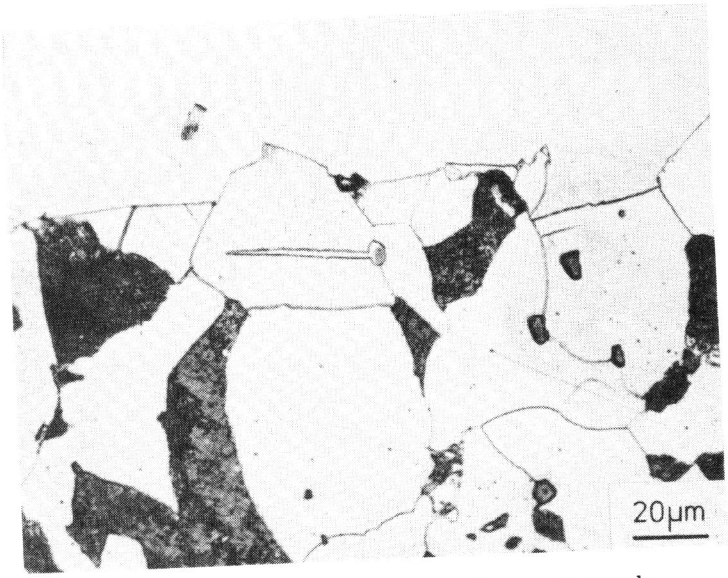

Figure 7 T-L orientation showing cleavage crack associated with sulphide inclusion

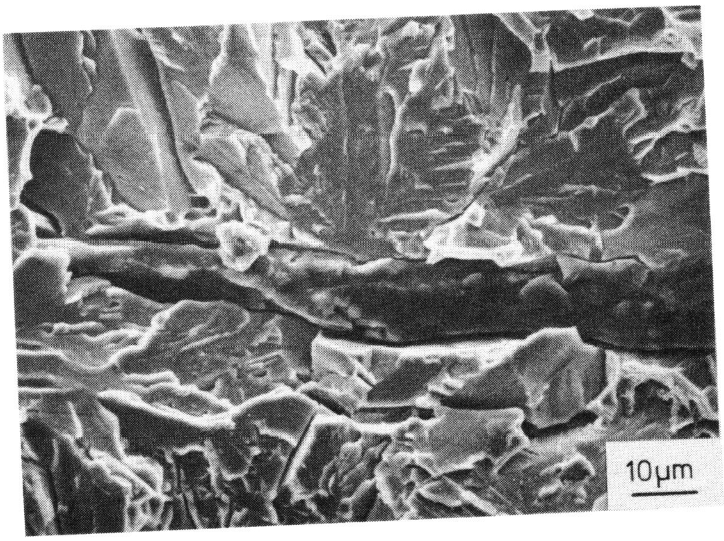

Figure 8 S-T testing orientation showing cleavage nucleation at oxide inclusion