# Mechanical and Metallurgical Factors Influencing the Assessment of Ductile Fracture Resistance

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The study of crack tip behaviour in the ductile-cleavage and ductile-fibrous fracture régimes[1], has made use of direct and empirical measurement methods. Crack opening displacement (COD), as a measure of critical fracture strain, coupled with mechanistic studies of the crack extension process, have been valuable to our understanding. However, COD alone is insufficient to describe the events pertinent to ductile crack extension.

Work on the mechanisms leading to fracture subsequent to yielding has shown that crack extension results from two processes. Initially, 'stretch zone formation' occurs adjacent to the fatigue crack (Fig 1). The stretch zone, inclined at ~45° to the fatigue crack plane exhibits coarse slip bands, in the form of wavy markings. Severe microstructural distortion is seen in grains adjacent to the stretch zone, resulting from the plastic strain ahead of the crack tip. This deformation behaviour is consistent with the well-known mechanism of "alternate slip"[2]. Stretch zone formation represents the creation of new surfaces, whilst a relatively sharp crack profile is maintained.

Ductile extension, leading to either final cleavage fracture or continued ductile fibrous fracture, occurs after stretch zone formation (Fig 2), as a result of void nucleation and growth. In vacuum melted steels, small voids originate at cracks in grain boundary carbides (Fig 3) and pearlite, where the ductility of the ferrite matrix is sufficiently high to impede crack propagation. With commercial steels ductile fibrous fracture is undoubtedly affected by non-metallic inclusions and segregation (eg pearlite banding). For example, large MnS inclusions influence stretch zone formation by producing large shear cusps leading into the fibrous fracture region (Fig 4).

The growth of fibrous fracture has been examined in two C/Mn steels of similar composition, one containing elongated Mn S stringers; the other containing discrete rounded sulphides, produced by rare earth modification. The former steel has very poor fracture resistance since fracture occurs by separation along the incipient crack-like interfaces of the thin, often fragmented, MnS stringers (Fig 6a). Significant improvement in fracture resistance is observed with the modified steel, where fracture is by void nucleation, growth and coalescence around the better distributed inclusion species (Fig 6b).

Fractographic examination of fracture toughness samples confirms that there is a reasonable relationship between stretch zone width and COD up to fibrous fracture initiation (δi) which is apparently unaffected by changes in ferrite grain size, carbon content and test temperature. It is significant that sustained loading in this region does not result in catastrophic fracture. Above δi, crack growth commences at a rate dependent upon the microstructure, anisotropy, starter crack direction and the void nucleation/growth characteristics of the steel, ultimately leading to unstable propagation.

Using an electrical potential technique, it has been found possible to monitor the crack extension processes during loading (Fig 5). It has been suggested that the COD at the initiation of ductile cracking δi, is a significant factor controlling the ductile failure process. However, experiments under the influence of a static force, which result in COD values greater than δi, indicate that crack growth in some cases ceases, on account of a crack blunting mechanism. This suggests that at some higher COD level the crack tip blunting would be insufficient to stop crack growth so that failure would be time dependent and influenced solely by the rate of ductile crack extension. For convenience, this COD value is termed $\delta_f$, see Fig 5. This figure also illustrates a





difficulty encountered in some steels in determining δi, which is dependent upon there being a distinguishable change in gradient of the crack growth curve. In situations of considerable ductile crack growth, it is apparent that, as crack extension can occur at a constant crack tip strain, the elastic and plastic regions will differ according to the testing system, which will result in considerable ambiguity in defining a meaningful δ value above δi.

From the foregoing discussion, it is considered likely that in situations where ductile crack extension constitutes a serious problem, the rate and level of energy dissipated in crack growth will assume a major importance. Crack growth rate data for the two C/Mn steels referred to earlier, which are of similar strength, is shown in Fig 6, as determined from fully instrumented notched bend tests. The data is presented in the form of a resistance curve and clearly illustrates the importance of metallurgical variables, especially inclusion shape, and distribution.

In conclusion, from a microstructural viewpoint, the point beyond which COD is no longer a sole function of stretch zone width, (ie above δi) where ductile fibrous fracture commences, is clearly dependent upon the mechanics of void nucleation and growth. Of significance is the type, size and distribution of second phase particles, along with the matrix properties and the nature of the interface between the phases, since these factors primarily control the events of ductile crack extension through to final fracture.

These observations are of direct relevance to structural steel development, in particular the use of controlled processing to achieve adequate strength with microstructural improvement, coupled with clean steel production, where the number of inclusions have been suitably reduced and possibly modified in shape.

In acknowledging the need for a simple laboratory test able to realistically select materials in terms of the conditions for fibrous fracture initiation and risk of propagation, it is suggested that some form of dual criterion is required, preferably based on an energy measurement and a geometry factor, akin to the R-curve concept, with loading variables considered. Such an approach should help to resolve the contradictory property requirements based on energy and fracture appearance. Finally, any attempt to evolve a meaningful fracture criterion, must take into account both metallurgical and mechanical aspects of the failure process.

References

1. A. H. Cottrell, Trans. AIME 212, 1958, p.192.
2. H. C. Rogers in "Ductility" ASM Ohio, 1968, p.37





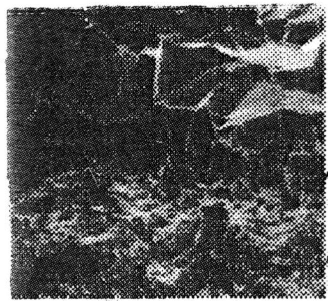


FIG 1. STRETCH ZONE FORMATION (x 290)

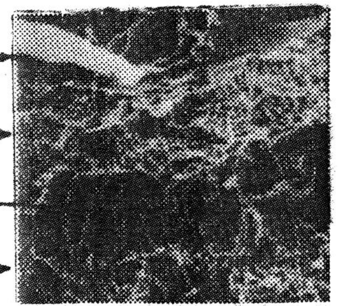

FIG 2. FIBROUS FRACTURE REGION (x410)

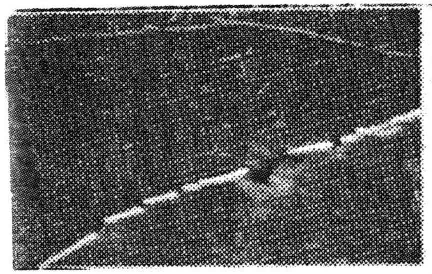

FIG 3. CARBIDE CRACKING & VOID FORMATION (x3760)

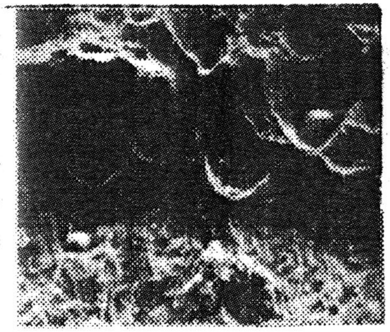

FIG 4. INFLUENCE OF MnS INCLUSIONS ON CRACK EXTENSION (x310).

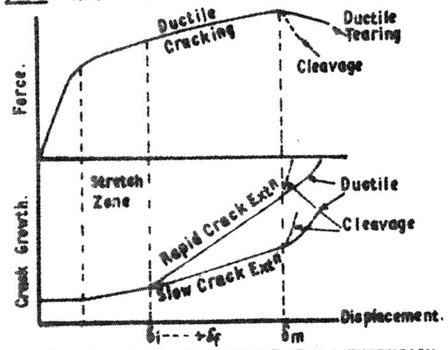


FIG 5. SCHEMATIC PICTURE OF CRACK EXTENSION PROCESSES DURING LOADING.

(b) DUCTILE FRACTURE - Good Resistance (x310)

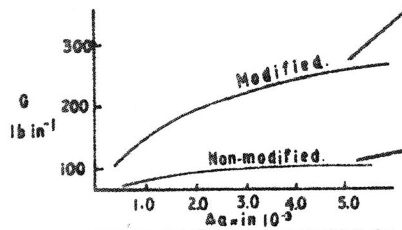


FIG 6. EFFECT OF SULPHIDE MODIFICATION ON THE RESISTANCE TO DUCTILE CRACK EXTENSION.

(a) SEPARATIONS - Poor Resistance (x 520)