A possible macro-mechanism for cleavage fracture initiation in mild steel

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Abstract

It is suggested that cleavage fracture in mild steel is initiated when the region of plastic instability ahead of a notch reaches a critical size. The magnitude of the zone of plastic instability is shown to be numerically similar to the crack opening displacement.

The spread of the zone of plastic instability to the surface of the plate causes a transition in fracture mode from cleavage to ductile.

The small size of the critical zone of plastic instability at low temperatures enables low stress fractures to occur in welded structures where the ductility of the steel is exhausted.

Introduction

Fracture mechanics is founded on the first law of thermodynamics. Orowan (1) and Irwin (2) showed that Griffith's work (3) could be applied to metals provided that a plastic work term were included in the energy balance. Many engineers found difficulty in understanding the relevance of an energy balance, that involved a virtual propagation, to the initiation of fracture. However, Irwin (4) has shown that the rate of release of energy is directly related to the stress intensity at the tip of the crack. In the Griffith model the stresses at the tip of the crack are infinite, because the material is assumed to be perfectly elastic and the crack infinitely sharp. The actual sharpness of the notch, although it will affect the fracture stress to some extent (5) is not of prime importance in a real material since yielding always limits the stress. What is important is the size of the highly stressed region, or in other words, the stress intensity factor. If theinitiation stress is high there will be considerable plastic flow around the tip of the crack. Irwin (5) has produced a simple correction to the elastic solution to allow for this flow. This energy approach produces a completely adequate criterion for fracture in high strength materials, but not for mild steel at normal temperatures.

Except at very low temperatures mild steel specimens, even if they contain severe notches, will not fracture until the whole specimen is deforming plastically. However, once initiated, a cleavage fracture can propagate

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at quite low stresses in an unstable manner with very little further plastic deformation. The distinction between initiation and propagation is caused by the strain rate sensitivity of mild steel. Wells (6) has developed a fracture mechanics approach to describe the initiation of cleavage fracture at stresses above the yield. His hypothesis is that cleavage fracture will be initiated when the opening at the tip of a crack reaches a critical value. For wide plates, he showed that the critical crack opening displacement is proportional to the applied strain and the crack length.

If structures behaved similarly to the simple laboratory specimen, brittle fracture would not be a problem for the structural engineer. However, a considerable number of structures (7,8) have failed in a brittle manner at stresses well below the yield. All the service fractures have been initiated at a notch or crack located in steel that has been damaged metallurgically. The incidence of brittle fracture in riveted and welded structures is comparable, but, because the latter are essentially continuous, the fractures in welded structures are more catastrophic and have received most attention. Residual tensile stresses of the order of the yield stress are present along all welds of reasonable length. These stresses do contribute to low stress fracture, in some cases even leading to spontaneous fracture on cooling (9), but they are not the main cause. Mylonas and his co-workers (10,11) have shown that it is possible to produce cleavage fracture at stresses well below the yield, without the presence of residual stress, by prestraining the specimen. The prestrain necessary is very large, but in later work (12) they show that prestrain at temperatures between 400 and 600° F is much more damaging than at room temperatures. A large percentage of the plastic flow caused by welding will take place at these temperatures. Mylonas says that the plastic prestrain "exhausts the ductility" of the steel. This term describes the fact, but not the process.

Krafft (13) has given an interpretation of the mechanism whereby the ductility is exhausted. He found a correlation between the strain hardening exponent and the crack toughness. Because the strain hardening exponent is numerically equal to the strain at which a tensile specimen becomes unstable, he interprets this correlation to mean that initiation of the fracture occurs when plastic instability develops at a certain distance ahead of the crack. To him, the size of the zone of instability appears to be a material constant. Thus any process that decreases the strain hardening exponent or the strain at instability, will cause the steel to fracture at a smaller overall strain. A decrease in temperature, an increase in strain rate, or prestrain, all cause a decrease in the strain hardening exponent.

The initiation of cleavage fracture in mild steel

Since the mechanism of cleavage initiation changes with temperature no one criterion of fracture will necessarily be acceptable at all temperatures. At the very lowest temperatures cleavage fracture is nucleated by twins with only local plastic deformation (14). This paper will not be concerned with fractures at these very low temperatures, but with those fractures that are nucleated in slip bands (14). At high temperatures, ductile tears precede the initiation of cleavage fracture, but these do not appear to cause any abrupt change in the fracture stress. Because ductile fracture is not fracture in the true sense, but only the coalescence of voids opened by plastic flow, it is thought that the presence of a ductile tear does not imply a change in the mechanism of cleavage initiation.

As the load on a specimen containing a crack is increased, a zone of plasticity will grow outwards from the crack. At some stage in the loading, the strain hardening rate of the material at the tip of the crack, will no longer be large enough to compensate for the reduction in area and a region of plastic instability will develop. The strain energy stored in this region decreases with further deformation and the associated plastic work is very small. It is suggested that a failure in this region could build up sufficien momentum to carry it through the rest of the specimen as a cleavage fracture. Fractures originating in slip bands without any previous ductile tears will be considered first. The initial stages of these fractures are very difficult to detect (14,18). Microcracks do form before the main fracture, at some distance below the root of the notch, but quickly coalesce. The presence of microcracks alone cannot cause cleavage fracture. Microcracks exist ahead of an arrested fracture and yet the plate still has to be yielded as a whole to reinitiate cleavage (9). However, if these microcracks suddenly form in a region of plastic instability, the load previously carried by those grains that have cracked must be redistributed. But the material is unstable and cannot support any extra load. The ligaments between the microcracks will start to deform rapidly and may tear before the load shed by the microcracks is transmitted to the stable plastic region. If the zone of plastic instability is of sufficient size then it is suggested that the fracture will gather speed increasing the strain rate sufficiently to enable cleavage fracture to propagate. Very few microcracks can be detected in an unbroken specimen strained to the point of fracture (15). Thus the conditions for the formation and propagation of the microcracks must be very similar. The above suggestion gives a necessary mechanism for the initiation of cleavage, but it is not sufficient in itself. Therefore the size of the zone of plastic instability observed in any fracture tests may be some what larger than the critical size necessary for the mechanism described above.

The zone of plastic instability will increase with applied strain, if there is no fracture, until a ductile tear develops. Ahead of the crack voids form at inclusions (13) or from microcracks formed in iron carbide plates contained within the pearlite grains (16). These voids open under the applied stress and a ductile tear is formed when the voids coalesce (see fig. 1). The mechanism for the initiation of cleavage is suggested to be similar to that when there is no ductile tear. If one of the ligaments located somewhere near the centre of the zone of plastic instability suddenly cleaves, then the adjacent ligaments, which cannot withstand the redistributed load, rapidly deform and shed the load still further. The resulting fracture will multiply rapidly and gather sufficient speed to propagate as a cleavage fracture, if the zone of plastic instability is sufficiently large.

Ductile tearing limits the size of the zone of plastic instability. In plate specimens with notches through the thickness, the ductile tear is at first transverse, but soon develops into a 45° mode. Successive positions of a purely ductile fracture are shown in fig. 2. Krafft et al. (17) has shown that the resistance to propagation increased with the growth of shear lips and thus there will be some increase in the size of the zone of plastic instability until the 45° fracture mode is fully developed. However, such a mechanism does not seem applicable to fracture in circumferentially notched round bar specimens which are essentially in a state of plane strain. There is a tendency for the length of the ductile tear to be greater the higher the temperature, although there is considerable scatter in results. If the probability of any one grain or ligament cleaving under a certain strain increases as the temperature decreases, then the most probable length of the ductile tear before a favourable grain is found will also decrease.

The critical size of the zone of plastic instability

Krafft (13) has estimated the critical size of the zone of plastic instability from the expression for the elastic strains using an experimental correlation of strain hardening rate with crack toughness. The estimate is extremely small (9 microns). Would this not imply that cleavage fracture were highly dependent on the radius of the tip of the notch, unless it were small compared with 9 microns ? In Krafft's work fatigue cracks were used, which presumably would have a fairly constant tip radius. However, only if the radius of the tip of the notch is large will cleavage fracture of mild steel be affected to any degree. Wells (6) argues that the radius of the tip of the notch is not important unless it is comparable to the crack opening displacement which at low temperature is of the order 0.02 in.

An infinitesimal elastic solution seems completely inadequate for the plastic conditions near the tip of a crack. Knott and Cottrell (14) have measured strains of the order of 100% in this region. Since no complete analysis exists, it is necessary to make some quite crude assumption in order to produce an estimate of the size of the zone of plastic instability. The most easily measured quantity is the crack opening displacement (6).

In fig. 3 it is assumed that the material at the tip of a crack can be treated as fibres wrapped round the notch. At the tip of the crack these fibres are almost semi-circular. Under an applied strain the tip of the crack opens an amount δ and the fibres take up positions shown by the dotted lines which are still assumed to be arcs of circles. With these assumptions it can be shown that the natural strain is

$$\epsilon = \log\left\{\frac{2}{\pi} q \sin^{-1} \frac{p}{q}\right\} \qquad (1)$$

where $p = \dfrac{(\frac{\delta}{r} + 2)}{2}$

$q = \frac{1}{2}(p^2 + 1)$

The strain distribution given by the above expression is shown in fig. 4. If it is assumed that the radius of the root of the notch is small compared with the crack opening displacement δ, r can be measured from the notch tip. An elastic strain solution is matched at$(\frac{r}{\delta}) = 1$ and is less steep than that obtained from equation (1). It is not assumed that the present distribution is any more accurate than the elastic solution. However, the magnitude of the strains is now linked to a measurable quantity. The strain for plastic instability in a normal tension test on mild steel is of the order of 20%, thus the size of the zone of plastic instability will be of the order of the crack opening displacement (see fig. 4). From Wells' measurements of crack opening displacements (6,18) the size of the zone of plastic instability can be estimated to be of the order of 0.02 in. and reasonably constant below -20°C. There is a marked increase in the crack opening displacement above -20°C and at +20°C it is of the order of 0.2 in. The order of the magnitude of the zone of plastic instability can be found by direct experiment with circumferentially notched round bar specimens. If the diameter is small enough, these specimens develop general instability before fracture. Although the specimen as a whole may be unstable, the zone of plastic instability does not necessarily envelop the whole notched section. General instability in circumferentially notched round bar mild steel specimens whose reduced diameters are 0.25 in. develops before cleavage fracture when the temperature is above -30°C. Thus from this observation the size of the zone of plastic instability must be of the order 0.1 in. at temperatures above -30°C.

It is interesting to estimate the size of specimen in which it would be possible to produce cleavage fracture in mild steel without yielding the whole specimen. Goodier and Field (19) using the model of Dugdale (20) have shown that the crack opening displacement in an elastic perfectly plastic specimen containing a central crack of length ℓ small compared with the width of the specimen is, if Poisson's ratio is assumed to be 1/3

$$\frac{\delta}{\ell} = \frac{4}{\pi}\frac{Y}{E} \log \sec\beta \qquad (2)$$

where $\beta = \frac{\pi}{2}\frac{T}{Y}$, T is the applied stress and Y is the yield stress. For fracture at 80% of the yield stress assuming that the critical size of the zone of plastic instability is 0.02 in., the initial crack length pedicted by equation 2 is approximately 10 in. The plastic zone associated with this zone of plastic instability can be calculated from Dugdale's expression

$$\frac{p}{\ell} = \frac{1}{2}\left[\sec\beta - 1\right] \qquad (3)$$

where p is the length of the plastic zone. For this particular example p is approximately 25 in. Thus it is not surprising that no cleavage fractures have been initiated at stresses below the yield in laboratory tests.

When the fracture stress is above the yield, Wells' (6) expression for the crack opening displacement,

$$\frac{\delta}{\ell} = \pi\epsilon \quad , \tag{4}$$

can be used as an approximation to the size of the zone of plastic instability. This equation is applicable only to cracks that are very small compared with the specimen width.

Fracture mode transition

In materials, such as aluminium alloys, whose metallurgical mechanism of fracture shows no change, the fracture mode changes with plate thickness. Fracture in thick plates is predominantly transverse with shear lips at the edges of the plate. As the plate thickness is reduced so that the amount of transverse fracture decreases; the size of the shear lips remain almost constant. When the size of the plastic zone ahead of the crack is greater than the plate thickness, the transverse fracture vanishes and the shear lips fill the specimen (21). Mild steel presents two distinct metallurgical mechanisms of failure - ductile tearing and cleavage. Since even cleavage fracture cannot be initiated at stresses below the yield, there must be some other mechanism whereby cleavage changes to ductile fracture in mild steel.

In a zone of plastic instability deformation can take place with very little work, since the energy stored decreases. If the zone is smaller than the plate thickness its deformation is restricted, but if it spreads to the plate surface there is little restriction on deformation. Thus ductile tearing can take place before the zone of plastic instability has grown to a size large enough to promote cleavage fracture. Wells (22) has tested a series of geometrically similar notch-bend mild steel specimens at room temperature. The fractures were completely ductile in specimens 0.221 in. thick and less. This thickness can be compared with the crack opening displacement of 0.18 in. measured at the same temperature in a tension test on mild steel (6). It will be remembered that the crack open displacement is postulated to be of the same size as the critical zone of plastic instability.

The same mechanism will also account for the transition from cleavage to ductile fracture in circumferentially notched round bar specimens. Unrestricted plastic flow will occur in this case when the zone of plastic instability completely envelopes the specimen before fracture.

Low stress brittle fracture in welded structures

Low stresses fractures in welded structures invariably originate in the heat affected zone alongside the weld. This zone has been plastically worked at high temperature, which as Mylonas (12) has shown, significantly exhausts the ductility of the steel. The strain hardening rate is much higher than that for the unaffected steel and much less strain is required to produce instability. Thus if the critical size of the zone of plastic instability is less than the thickness of the heat affected zone, fracture may be possible at low stress. A much larger applied strain will be necessary if the critical size of the zone of plasticity is appreciably greater than the heat affected zone. Thus the sudden increase in crack opening displacement observed in mild steel should correspond to the change from low to high stress fracture observed in welded steel plate. Direct comparison is possible in the work of Wells (23). The fracture stress of welded wide plates changes from low to high values at -10 °C and there is also a marked increase in the crack opening displacement at this same temperature for either notch bend or tension tests in the same material (6,18).

Conclusions

Except at very low temperatures cleavage fractures can only be initiated when the zone of plastic instability reaches a critical size. The magnitude of the critical zone of instability can be identified with the crack opening displacement and although it is not a material constant there is a considerable temperature range in which it is reasonably constant.

At high temperatures there is a considerable increase in the critical size of the zone of plastic instability and if this critical size is greater than the plate thickness the ductile tear does not change to cleavage.

It is also suggested that the increase in the critical size of the zone of plastic instability causes the observed change from fracture below to fracture above the yield stress in welded steel plate containing a notch in the weld. The transition in behaviour occurs when the critical size of the zone of plastic instability exceeds the size of the heat affected zone.

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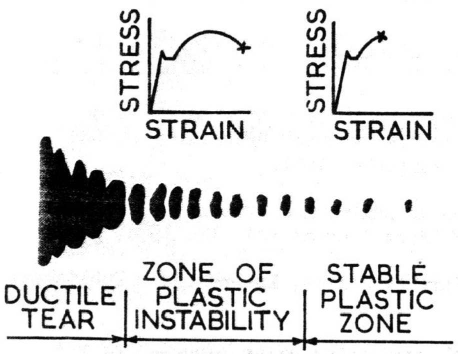

FIG. 1 SCHEMATIC DIAGRAM OF A DUCTILE TEAR

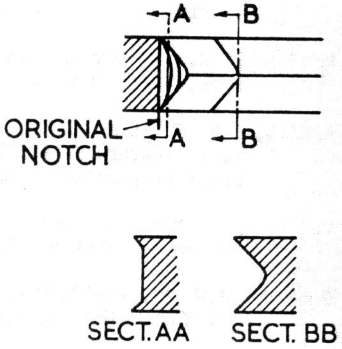

FIG. 2 DEVELOPMENT OF A DUCTILE TEAR IN A PLATE

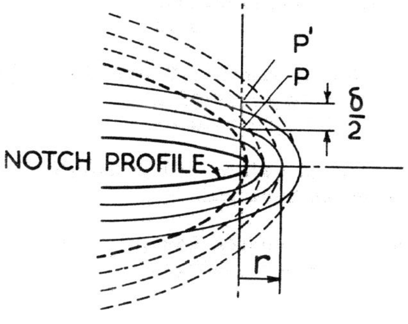

FIG. 3 THE CRACK OPENING DISPLACEMENT

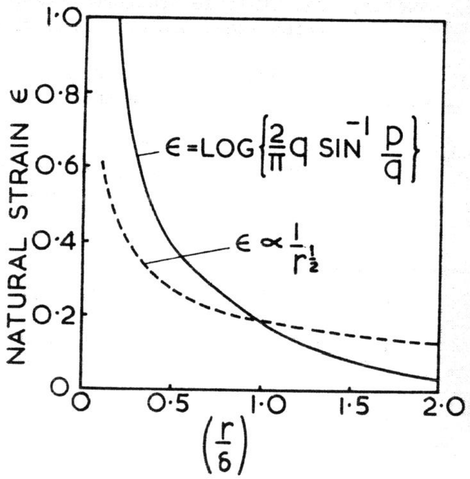

FIG. 4 STRAIN DISTRIBUTION AT THE TIP OF A CRACK