OBSERVATIONS ON CLEAVAGE INITIATION SITES IN TWO FERRITIC STEELS

R.E. Franklin *

Fracture surfaces from blunt notched fracture stress specimens for two ferritic steels have been looked at in detail. The site of cleavage fracture initiation was located by tracing back characteristic markings such as 'river lines'. The location of these initiation sites with respect to the crack tip or notch root has been recorded, and any microstructural features present at the initiation site identified.

INTRODUCTION

The purpose of this study was to identify the initiation sites of cleavage fracture with the aim of identifying any microstructural features that trigger brittle failure. A large number of fracture surfaces were looked at in a systematic manner so as not to bias the results towards the more interesting specimens.

Two ferritic steels were looked at; a pressure vessel steel (A533B1) and a 3Cr1/2Mo disc steel. Blunt notched specimens (1) were tested in four point bend. The tests were done at a low temperature (-70 °C for the 3Cr1/2Mo steel and -145 °C for the A533B steel) to ensure brittle cleavage failure with no ductile tearing.

METHOD OF LOCATING CLEAVAGE INITIATION SITES

In all of the fracture surfaces examined it was possible to identify a single initiation site from which the cleavage fracture originated, using the same technique

* National Power Technology and Environmental Centre, Leatherhead, Surrey, UK

as Rosenfield and Shetty (2). At low magnifications, regions of shear indicate the general area from which most of the fracture started. At higher magnifications in the SEM, river lines and feather markings indicate the direction of cleavage propagation, and by following these backwards the initiation site can be determined. The river lines and feather markings are fine surface detail and they can therefore be observed more readily in the SEM at low accelerating voltages. The electron beam then penetrates less deeply and more surface detail is resolved. It is particularly important to use low accelerating voltages when looking at the 3Cr1/2Mo steel as the river lines are smaller and more difficult to identify.

It is also possible to identify a number of secondary initiation sites which initiate a region of cleavage fracture which has not propagated from the primary initiation site (Fig.1). In general about 40-95% of the cleavage fracture is observed to have propagated from the primary initiation site, and the rest from secondary initiation sites.

LOCATION OF INITIATION SITES AHEAD OF THE NOTCH.

We expect the fracture toughness of a test specimen to be influenced by the primary initiation site. The location of these primary initiation sites with respect to the notch root has been measured for a large number of specimens of both materials, and the results shown in figures 2 and 3. In these figures the stress and plastic strain plotted correspond to a loading equal to the mean loading at failure, and were obtained from the finite element analysis of Griffiths and Owen (1).

Figures 2 and 3 show clearly that the primary initiation sites are located much closer to the notch root than the position of maximum tensile stress. If the distance of the primary initiation site ahead of the notch root x_0 is compared to the distance of the maximum stress from the notch x_m, it is found that $0.004 < x_0/x_m < 0.7$ for the A533B material, and $0.07 < x_0/x_m < 0.6$ for the 3Cr1/2Mo material.

Reed and Knott (3) have looked at initiation sites within a MnNiMo steel weld-metal and have found the initiation sites to be located much closer to the position of maximum tensile stress ($0.69 < x_0/x_m < 1.49$). However both primary and secondary sites were looked at which will affect the distribution, and the weld metal contained a very large number of inclusions which may affect the initiation mechanism.

Most current theories of cleavage fracture involve a tensile stress ahead of the crack exceeding some critical cleavage fracture stress. This predicts (and assumes) that the initiation site of fracture is located in the region of maximum tensile stress.

The current observations cast doubt on the above assumption, and have implications for the measurement of the cleavage fracture stress parameter σ_f. At present there are two (conflicting) methods used to measure the cleavage fracture stress of a material using blunt notched specimens. The first assumes failure occurs at the position of maximum tensile stress and takes $\sigma_f = \sigma_{max}$. The second determines the position of the primary initiation site and takes σ_f to be the value of the tensile stress ahead of the notch at this position, giving a lower value of σ_f.

Figures 2 and 3 suggest that the location of the initiation sites is dependent upon the effective plastic strain. As the probability of initiation is directly related to the number of initiation sites, these observations suggest that the probability of initiation is related to the local plastic strain.

LOCATION OF INITIATION SITES WITH RESPECT TO SECOND PHASE PARTICLES

One of the main objectives of the detailed fractographic examination was to identify any unusual microstructural features that may have been associated with the triggering of the brittle fracture. However the microstructure of the steel at the initiation sites did not appear unusual or unique when observed in the scanning electron microscope. This is consistent with other observations in the literature (4).

When making observations on features visible at initiation sites it is easy to bias the reporting towards the interesting and more visible but perhaps more unusual features. Systematic observations have therefore been made on the fracture surfaces for both materials.

A small number of the primary initiation sites looked at (3 out of 29) appear to be coincident with either an inclusion or a visible carbide, and one site is close to a small carbide. At the other sites, if an initiating particle is present (as most theories assume) it must be very small (<0.5μ) as it is not visible. Often much larger carbides are visible on the fracture surface near the initiation site. This is surprising since carbide cracking models would predict the larger carbides to preferentially initiate cleavage fracture.

Comparison of predicted size of microcracks with observed inclusions and carbides.

Using a Griffith crack propagation criteria for a penny shaped crack, Curry and Knott (5) have shown that the cleavage fracture stress can be related to the crack size by the following expression

$$\sigma_f = \left\{ \frac{\pi E \gamma_p}{2(1-\nu^2) r} \right\}^{1/2}$$

where γ_p a surface energy term and r is the radius of the penny shaped crack. Fracture will occur if $\sigma_{yy}(\sigma_y, K_1, x) > \sigma_f$. If we know the stress field ahead of the notch, then it is possible to predict the required size of microcrack at any position ahead of the notch for cleavage fracture to occur. The critical radius, r_0, is given by

$$r_0(x) = \frac{\pi E \gamma_p}{2(1-\nu^2)\sigma_y(x)}$$

where σ_y is determined from the stress analysis of Griffiths and Owen (1), at a distance $x = x_0$ where x_0 is the distance of the primary initiation site from the notch root.

Estimates for γ_p in the literature vary from 2 Jm^{-2} to 190 Jm^{-2} depending on the method of determination. The theoretical absolute minimum value for the surface energy term is 2 Jm^{-2} . Using this value we obtain a lower limit on the critical carbide radius of 0.3-0.9 μm . This is sufficiently large for any inclusion, carbide, or hole (from which a particle has been dislodged) to be clearly visible in the SEM. (It is possible to identify features of 0.2 μm diameter without difficulty).

In one specimen examined initiation clearly occurred at a Mg/Ca/Ti inclusion of diameter 9 μm , and in two others at or near titanium carbides of diameter 1.0 μm and 0.5 μm respectively. The absence in general of initiating particles suggests that a dislocation mechanism such as that proposed by Cottrell (6) is the most likely mechanism for the formation of cleavage initiation sites.

CONCLUSIONS

In each specimen it is possible to identify one unique primary initiation site from which most of the fracture originated. In blunt notched specimens the primary initiation sites are located closer to the notch root than the position of maximum tensile stress. The probability of initiation is apparently related to the effective plastic strain.

Initiation generally does not occur at an inclusion or carbide, although there are a few exceptions to this. This suggests the initiation sites are formed by a dislocation mechanism such as that proposed by Cottrell (6).

ACKNOWLEDGEMENT

This work was carried out at the National Power Technology and Environmental Centre and the paper is published with permission of National Power PLC.

SYMBOLS USED

E = Youngs modulus (MPa)
r_0 = Critical radius (m)
x_0 = Distance of primary initiation site from crack (m)
x_m = Distance of maximum tensile stress from notch (m)
γ_p = Surface energy term (J)
σ_f = Fracture stress (MPa)
σ_{max} = Maximum tensile stress ahead of notch (MPa)
ν = Poissons ratio

REFERENCES

(1) Griffiths, J. R. and Owen, D. R. J., J. Mech. Phys. Solids. Vol.19., 1971, pp.419-431.

(2) Rosenfield, A. R. and Shetty, D. K., Metall. Trans. A Vol.19., 1983, pp.1934-1937.

(3) Reed, P. A. S. and Knott, J. F., Proc. ICF7. Houston, Texas Vol.4., 1989, pp.2583-2593.

(4) Rosenfield, A. R. and Shetty, D. K., Engineering Fracture Mechanics, Vol.17., 1983, pp.461-470.

(5) Curry, D. A. and Knott, J. F., Metal Science. Vol.12., 1978, pp.511-514.

(6) Cottrell, A. H., Trans. ASME, Vol.212., 1958, p.192.

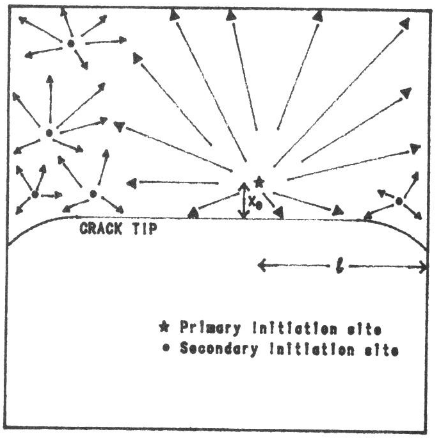

Figure 1 Schematic diagram of fracture surface

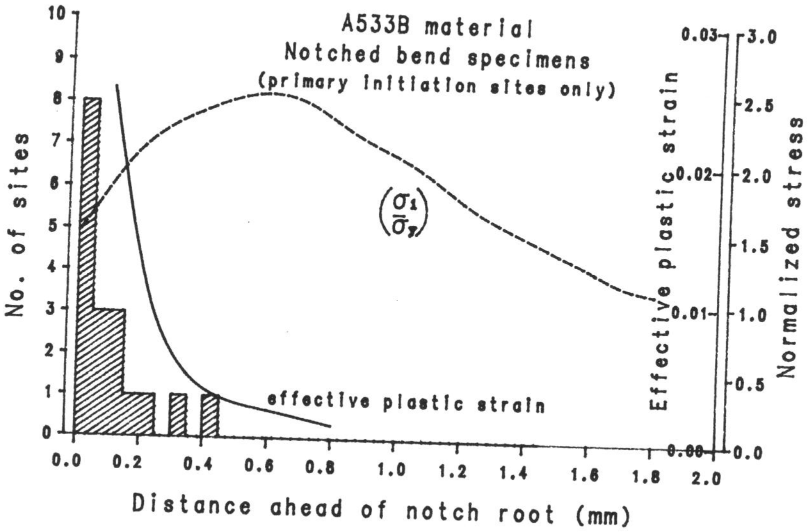

Figure 2 Distribution of initiation sites ahead of notch root

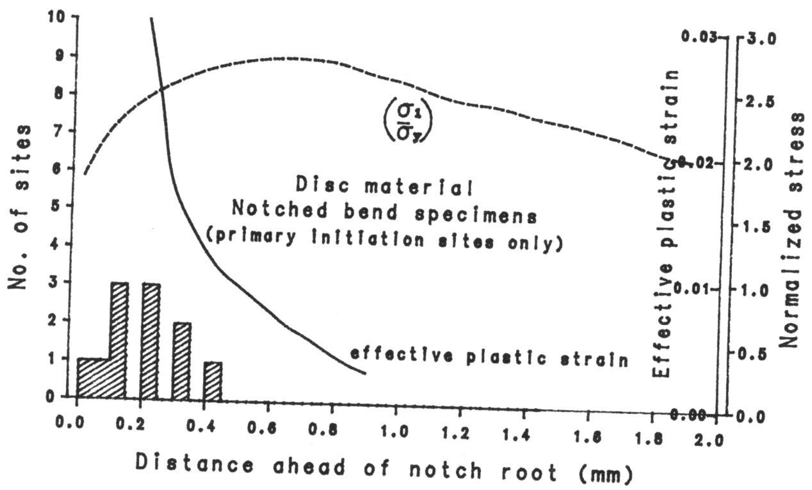

Figure 3 Distribution of initiation sites ahead of notch root for disc steel