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CLEAVAGE BEHAVIOR IN STRUCTURAL STEELS

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Abstract—A consistent understanding of the initiation, spreading and arrest of cleavage in structural steels is possible only when the role of very high local-region strain rates is taken into account. Cleavage initiates only when the local strain rate is high enough to force a rigid (cleavage) response in the ferrite matrix. Run-arrest bursts of cleavage through regions comparable with the prior austenite grain size correspond to fracture appearance and assist understanding of variation of general cleavage crack speed. Measurements of toughness based upon cleavage arrest are of special value. These measurements can be obtained using relatively small specimens, show no influence of constraint and provide lower bounds for measurements of cleavage initiation toughness.

INTRODUCTION

In order to assist understanding and efficient use of fracture toughness measurements for nuclear vessel steels, a number of fractographic studies have been made. Cleavage behavior in the transition temperature range from near NDT to the loss-of-cleavage temperature is discussed. In addition, viewpoints are presented which are supported both by what is seen, with scanning electron microscopy (SEM) and optical fractography, and by results from theoretical analysis.

EXPERIMENTAL

Figure 1 shows general features of a running cleavage crack in a simplified manner. Although strain rates within the cleavage crack front are too high for significant plastic straining, the strain rates further ahead are lower, permitting an advance plastic zone of moderate size. The smallness of plastic straining in the region containing the cleavage crack "front" is assisted by the diffuse scattering of the partly connected cleavage facets, crudely pictured in Fig. 1. The stretch and rupture of the late breaking connections between cleavage facets is represented by diagonal lines behind the crack front. Essentially the leading cleavage facets rapidly pre-crack the material ahead, making the separation process rapid.

The varied orientations in an array of connected cleavage facets is illustrated in Fig. 2(a). In a Charpy specimen of A508 steel ($\sigma_{ys} = 620$ MPa) broken at room temperature, two cleavage cracks started from the notch. The section plane is normal to the notch. The dominant crack, out of view below, stress relieved and arrested the small crack shown. A light etch was used to indicate microstructure. The main tension direction was apparently altered by the dominant crack so that many of the facets intersected the section plane at

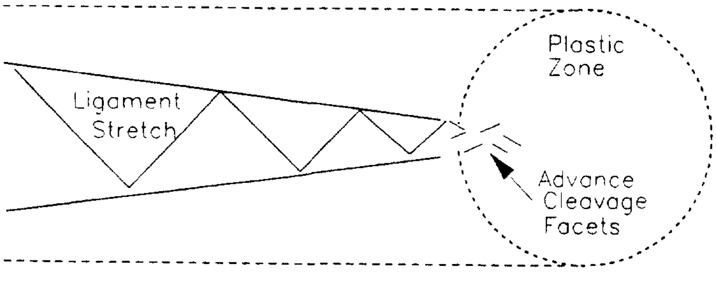


Fig. 1. Schematic of regions near the front of a rapid cleavage crack.

small angles, causing the opening sizes to appear to be larger than they actually are. Although unbroken regions extending to about 1.5 mm from the tip of the array can be seen, all facets are connected at some position in front of or behind the section. Enlargements of two areas are shown in Figs 2(b,c). In Fig. 2(b), cleavage on more than one cleavage plane is shown in a large ferrite grain. In the higher magnification views, one can see that the section plane was intersected by some facets which are nearly normal to it. These have a straight-line appearance with no visible indications of plastic deformation.

From other studies, the prior austenite grains ranged in size from ~ 30 to ~ 160 μm. Picturing the general cleavage in structural steels as a sequence of cleavage bursts, of comparable size, is not new and seems necessary. Extension velocities of general cleavage in structural steel plates have been reported by Krafft and Irwin (1965), which range from ~ 180 to ~ 1700 m s^{-1}. From the upper velocity, cleavage must be able to move through a ferrite grain at a velocity above half the shear wave speed, c_2 (3×10^3 m s^{-1}). Freund and Hutchinson's theoretical studies (1985) dealt with rapid plastic straining in the plastic zone ahead of a fast moving cleavage crack tip. The results indicated that, within a small zone enclosing the crack tip, only elastic straining would occur. Using assumptions appropriate for mild steel, the analysis suggested a cleavage crack speed of near $0.5c_2$ as probable. Correspondingly, fractographic studies have shown no general plastic strain within cleavage facets other than warping near facet boundaries due to post-cleavage separation of late breaking connections. This is observed across the transition temperature range as well as at lower temperatures. Evidently the spreading velocity of cleavage across a ferrite grain is always near or above $0.5c_2$. It seems necessary therefore to picture general cleavage as a sequence of quick local bursts of cleavage separated by time periods of "pause". With this assumption, conditions which lower the extension speed, decrease driving force or increase plate temperature, can do that by lengthening the "pause" times.

If we assume that the time needed to advance the crack front by a distance comparable with the average prior austenite grain size is the time for the run-arrest burst plus the pause time (t_p), then

$$t_p = \frac{L}{C} - \frac{L}{C_f},$$

where L is the size of an average run-arrest burst (100 μm), C is the general cleavage crack speed and C_f is the crack speed through ferrite grains. A rough estimate of maximum pause time is obtained if we assume C_f is half the shear wave speed and that C is 200 m s^{-1}, the lowest observed cleavage velocity prior to crack arrest. From these assumptions, the pause times near crack arrest are no larger than 0.5 μs and a small strain of 1% correspond to a strain rate above 2×10^4 s^{-1}. Figure 3, from Freund and Hutchinson's results (1985), indicates that an increase in the strain rate to above 2×10^4 s^{-1} is accompanied by a rapid increase of resistance to plastic straining. Evidently the strain rates of main interest for run-arrest cleavage behavior in steels are all above 10^4 s^{-1}, a region where the sensitivity of plastic flow stress to strain rate is relatively high. Obviously, spreading of cleavage from a local cleavage initiation should not occur unless the crack front K value is larger than the K_{Ia} for cleavage arrest. Correspondingly, Irwin *et al.* (1992) obtained cleavage initiation K values similar to those for cleavage crack arrest using a drop-weight loading method. Loading times smaller than 200 μs were impractical and it was necessary to enhance the notch severity by pre-compression in order to obtain useful results.

In small-specimen wedge-loaded tests for crack arrest K_{Ia} values, rapid stress wave damping and the relatively small specimen size limit the dynamic stress elevation following crack arrest to an unimportant size. When the specimen is heat tinted, chilled and broken open, no indication of a crack front stretch zone is visible. When the specimen is large, a substantial amount of dynamic reloading may occur. The post-arrest plastic straining will then produce a crack front stretch zone and may reinitiate cleavage. In the wide-plate tests at NIST, a series of cleavage arrests occurred, each followed by plastic stretch at the crack front and reinitiation of cleavage. The K for reinitiation was computed using a dynamic

Fig. 2. (a) A section normal to the notch in a broken CVN specimen showing a small arrested cleavage crack. The lower view connects to the upper view. The dominant crack is out of view above. This branch crack is connected to the notch about 1 mm to the upper left. A508 steel tempered at 613 C, tested at −40 C.

Fig. 2b. A region containing a large ferrite grain.

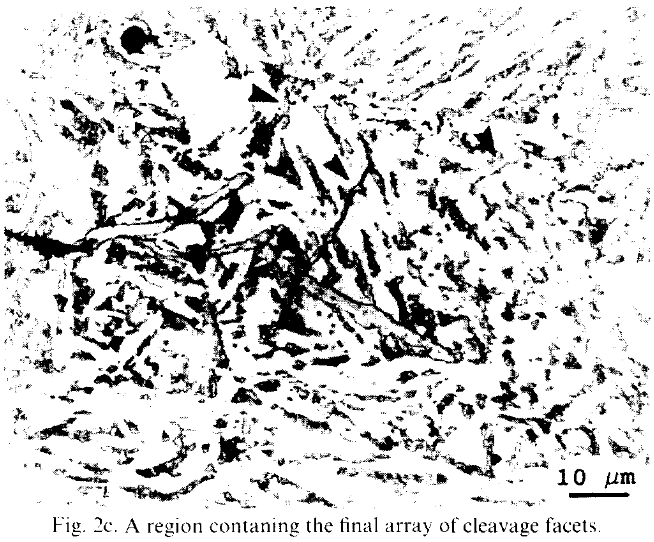
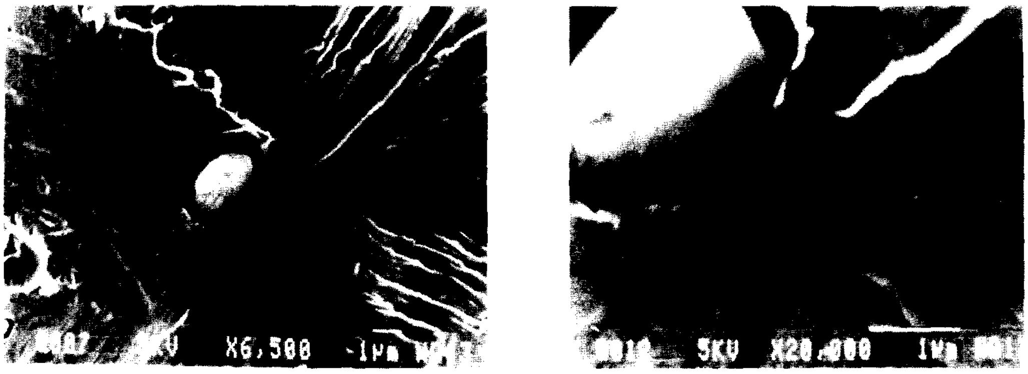
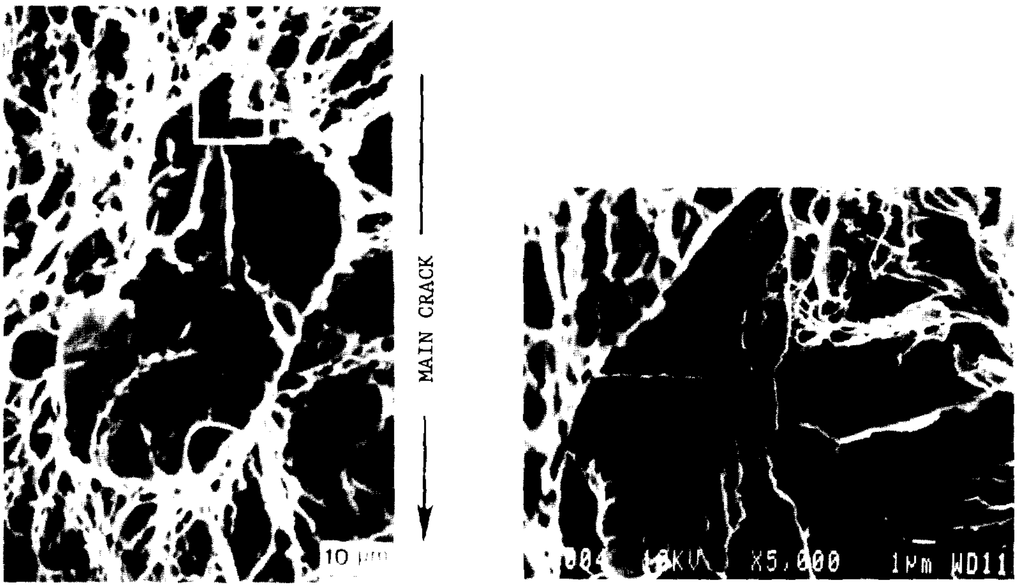


Fig. 2c. A region contaning the final array of cleavage facets.



(a) (b)

Fig. 5. (a) A cleavage origin region of an ICR found on a Charpy specimen of low carbon weld metal fractured at 79 C. (b) The particle fracture and the region adjacent to it.



(a) (b)

Fig. 6. (a) General view of a typical ICR in A508 steel which started from a particle clump. (b) The enlargement of the box area in Fig. 6(a).

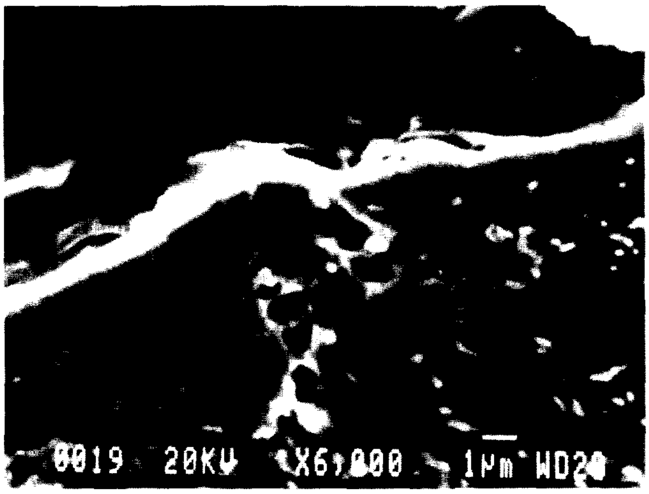


Fig. 7. A section normal to the fracture surface plane of Fig. 6 and 1 μm from the origin region of cleavage. Particles clinging to cavity sides are visible. The holes are incompletely joined.

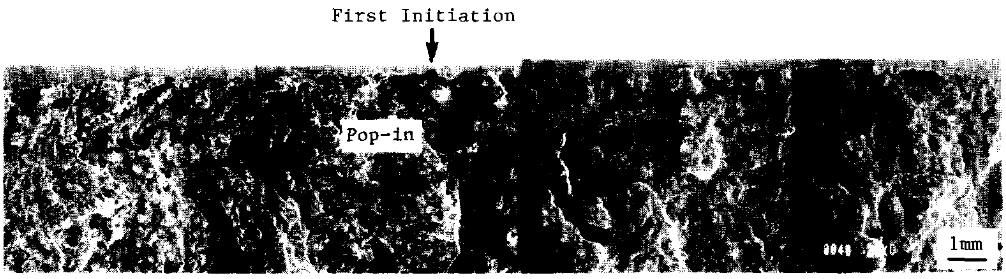


Fig. 8. Regions of cleavage initiation at the border of a fatigue pre-crack are marked. The extent of a small pop-in event is also marked. The material was A508 steel, as in Figs 6 and 7.

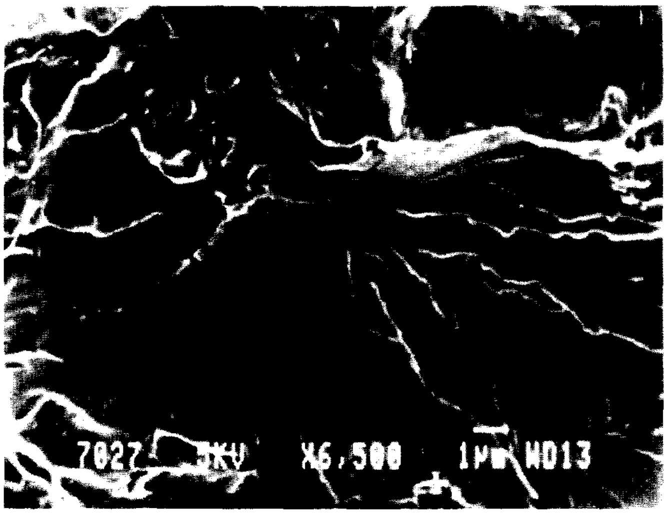


Fig. 9. The cleavage initiation region judged likely to be the first initiation event. Cleavage on two levels started from a nest of cavities.

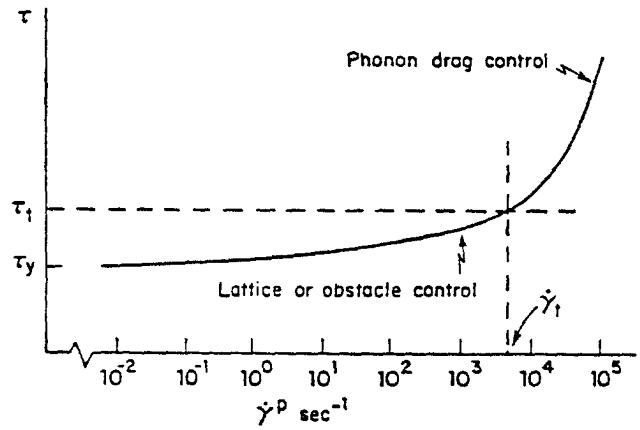


Fig. 3. Relation of stress to strain rate at given temperatures showing the transition between a high strain rate regime and a low to intermediate strain rate regime; from Freund and Hutchinson (1985).

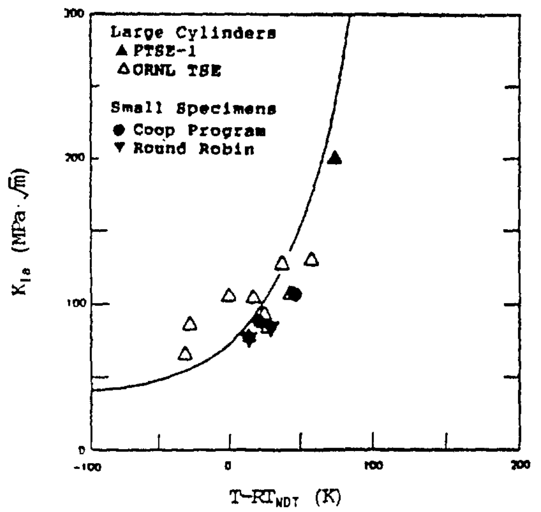


Fig. 4. K_{Ia} as a function of temperature from data shown in Fig. 6.1 of Naus *et al.* (1990).

calculation fitted to the time and crack position observations at the end point of the arrest period. The K value for cleavage arrest was the lower value of K at the beginning of the crack arrest time period. The reloading time leading to reinitiation was rather small. According to results from Naus *et al.* (1990), the time values range from 1 to 10 ms; however, for the abrupt crack arrest event, a time longer than 10 μs would be unlikely.

Figure 4 from Barker *et al.* (1988) shows a collection of values of crack arrest toughness, K_{Ia}, obtained with small test specimens and with thermal shock loadings of large cylinders. These results do not show a significant influence of constraint upon the K_{Ia} value. This is quite plausible because the stress elevation by constraint is associated with plastic yielding. The times closely associated with the crack arrest event are too small to permit a significant amount of plastic straining.

Initiation of a general cleavage event differs importantly from crack arrest in that the loading rate, prior to onset of cleavage, permits various degrees of plastic flow stress elevation by constraint which can be estimated in a macroscopic fashion using elastic–plastic calculations. As will be illustrated, cleavage initiation occurs only when rapid separations of certain features of microstructure induce a very large elevation of strain rate and tension within a micrometer-size region. Several features of microstructure, associated with cleavage initiation, have been noted by Irwin (1987) and Zhang *et al.* (1989, 1990), and will be reviewed briefly. In heavy section nuclear vessel steels and their weld metals, rapid hole-joining fractures, produced at temperatures close to and above loss-of-cleavage temperature, contained small islands of cleavage. From fractographic studies, each of these seemed to have a single origin location from which cleavage spread through a number of ferrite grains without visible indications of arrest at the ferrite boundary passageways. These isolated cleavage regions will be termed ICRs.

In the low-carbon weld metals, the spreading of cleavage emanated either from a broken silicate particle in the 2–3 μm size range or from a "clump" of smaller silicate particles which debonded. Figure 5(a) shows SEM views of an ICR containing a particle fracture cleavage origin in weld metal. Figure 5(b) shows the cleavage surface region, adjacent to the particle fracture, within which cleavage initiated and spread. Irwin (1987) estimated a plausible strain rate in the ferrite close to the particle crack as about 10^6 s^{-1}. From Freund and Hutchinson's study (1985), plastic strain rates that high can elevate tensile stress to values near $E/40$.

All of the cleavage initiation sites identified in A533B and A508 steels were associated with groups of debonded carbide particles which we termed particle "clumps". The particles were small, 0.1–0.2 μm. Figure 6 shows general views of a typical ICR in A508 steel. Figure 7 shows a section nearly normal to the cleavage fracture through the initiation region. Portions of the clump of cavities, from which cleavage spread, are barely visible about 1 μm behind the section plane. The appearance of debonding beneath the fracture surface is of special interest. Some of the particles are visible within cavities, which were incompletely joined when deformation was arrested by rapid cleavage above them. This section view indicates that particle debonding, when forced by a high local stress, can be very rapid. Progressive debonding is the expected behavior when particle debonding forms a cavity. This is supported by the adhesion with which a particle clings to the "bottom" of a cavity. It is suggested that, near the front of a rapid debonding separation, strain rate and stress can be elevated to the same high levels as would pertain near a rapid particle fracture.

The investigations of cleavage initiation at temperatures below the loss-of-cleavage temperature centered attention on A508 steel at temperatures near to and moderately below the RT-NDT temperature. The yield strength was 620 MPa (90 ksi) and RT-NDT was near 60 C. Figure 8 shows a region within which cleavage started in pop-in fashion from a fatique pre-crack. A large number of closely spaced cleavage initiations occurred along the border of the fatigue pre-crack. Although independent (nearly simultaneous) initiations are possible, most of these indications of cleavage initiation occurred by rapid re-initiations, spreading in lateral fashion from a first-cleavage event. Positions of cleavage initiation and the estimated extent of the pop-in event are marked on the figure. Obviously lateral spreading is more rapid than spreading in the forward direction. This pattern is favored by the stress elevation near the pre-crack. Figure 9 shows the cleavage initiation site which was selected as the probable start of the pop-in event. At the location of this event, the forward extension of the pop-in was largest. Debonding within a cluster of particles started two cleavage separations; one moving (in the figure) downward and to the left; the other, at a higher level, moving forward and to the right. This behavior exposed a group of carbide particles similar to the particle clumps observed at cleavage origins within ICRs at loss-of-cleavage temperature.

In other examinations of cleavage initiation and reinitiation sites, the particle appearances differed considerably. At locations judged to be reinitiation locations, particularly within general cleavage regions, it seemed that debonding of single particles or particle pairs could be assisting the reinitiation event. The particle clumps associated with ICRs near the loss-of-cleavage temperature would be expected also to initiate cleavage at lower temperatures. However, smaller particle arrays are more probable and can dominate as cleavage origins when either temperature reduction or high strain rate make their cleavage initiation severity adequate.

Non-uniformities which can cause a large elevation of local stress and local strain rate are present in heavy section nuclear vessel materials. Examples are carbide banding, grain size variations and grain boundary segregation. In addition, the pre-crack in a test specimen has crack front irregularities which increase in size when hole-joining separation occurs prior to cleavage initiation. The cleavage initiation regions observed within ICRs were

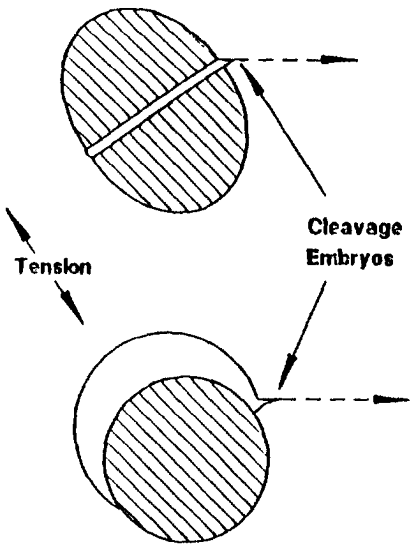


Fig. 10. Schematic pictures of cleavage embryo formation.

Table 1. Cleavage embryo size estimates for several values of local stress, σ, and resistance to spread, R

σ/E	a (μm) (for $R = 20$ J m^{-2})	a (μm) (for $R = 40$ J m^{-2})
1/40	0.12	0.24
1/60	0.27	0.55
1/80	0.48	0.97

$G = 4/\pi(\sigma^2 a/E)$.

often close to an ICR border with an adjacent region of hole-joining at the same level which had a relatively brittle appearance. The local stress elevating events which cause a silicate particle to fracture, rather than debond, or cause a sufficient rapidity of debonding within a particle clump, are not completley revealed by SEM. However, varied degrees of assistance of that kind seem essential to an understanding of the "rare event" nature associated with cleavage initiation test results. Zhang *et al.* (1990) reported that silicate particles (2–3 μm in size) in low carbon weld metal and particle clumps in the heavy section steels are not rare. The likelihood of them being present, per average ferrite grain volume, is substantial. Cleavage initiations become "rare" because particle fracture, rather than debonding, as well as an adequately high speed of debonding, occur only with the aid of local stress elevations provided by other non-uniformities.

Among the features associated with cleavage behavior in steels, the spreading of cleavage through ferrite grains is of major importance. For this nearly crystallographic event to occur, cleavage must start and spread from a nearly crystallographic cleavage embryo produced in some manner. Figure 10 shows potential origin locations for formation of cleavage embryos. For plausibility of occurrence, such an embryo must be quite small; however, it must be large enough that the crack extension driving force, G, is as large as the resistance to spreading. Table 1 shows estimates of this size corresponding to assumed values of tensile stress, σ, and of the resistance to spreading, R. In the clumps of debonding carbide particles, which were cleavage origin locations, the particle size was in the range 0.1–0.2 μm. A cleavage embryo size larger than the particle size seems unlikely. From the table, the size corresponding to the smallest R and the largest σ seems best. Figure 11, from Freund and Hutchinson (1985), shows values of plastic flow stress across a wide range of strain rates for α-iron. Since the steels of interest are stronger and since local region strain rates applicable to Fig. 10 may be larger than 10^5 s^{-1}, a local region stress high enough for the 0.12 μm embryo size in Table 1 is plausible.

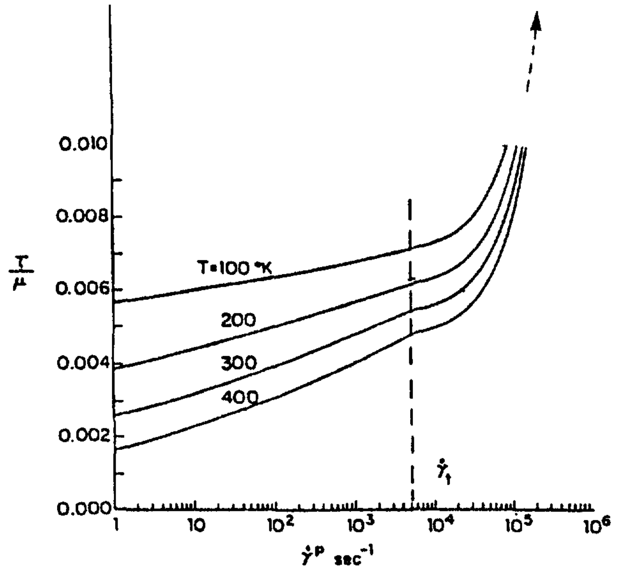


Fig. 11. Stress as a function of plastic strain rate at several temperatures for α-iron; from Naus *et al.* (1990).

SUMMARY

In summary, a consistent understanding of the initiation, spreading and arrest of cleavage in steels is possible only when the role of very high local strain rates is taken into account. Cleavage initiates only when the local strain rate is high enough to force a rigid (cleavage) response. The run-arrest bursts of cleavage through regions comparable with the prior-austenite grain size correspond to fracture appearance and provide an explanation for variations of general cleavage crack speed. Cleavage crack arrest toughness values are of special interest. They can be obtained using relatively small specimens, show no influence of constraint, and provide lower bounds for measurements of cleavage initiation toughness.

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