CRACK BRANCHING IN A533B STEEL

G. T. Hahn, R. G. Hoagland and A. R. Rosenfield*

INTRODUCTION

Crack branching affects the course and extent of a fracture as well as the size of fragments [1]. It also complicates the task of evaluating G_I, R_{ID}, K_I and K_{ID}, the propagating crack energy release rate, fracture energy, stress intensity, and toughness, which characterize dynamic fracture processes [2].

Yoffe [3] attributed branching to changes in the dynamic stress field obtained at speeds greater than 0.38 Co (Co = bar wave speed), but the branching velocity V_B is frequently lower; for Homalite 100 [4]: V_B = 0.21 Co, plate glass [5]: V_B = 0.28 Co, FK-52 (glass) [5]: V_B = 0.30 Co, and tool steel [6]: V_B = 0.26 Co. In fact, the branching velocity of stress corrosion cracks is as low as $V_B \sim 10^{-12}$ Co [7]. The role of velocity has been clarified by Döll [8] who cites a number of studies which show there is no change in the crack velocity during the branching event. Constancy of velocity is obtained in spite of the fact that the energy release rate and stress intensity requirements are increased by factors of $\sim$ 2 and 1.41, respectively, when two branches form simultaneously as in Figure 1a. Döll notes that this can only occur when the crack is operating on the velocity invariant portion of the K_{ID}-velocity curve (see Figure 2a) and $K_I^B \approx 1.41$ $K_{v,max}$ (K_I^B is the stress intensity for branching and $K_{v,max}$ is the stress intensity that inaugurates the velocity invariant portion of the K_D-velocity curve). The stress intensity for branching is therefore much greater than the fracture toughness: $K_I^B \approx 4$ K_{Ic}, because $K_{v,max} \approx 3$ K_{Ic}, for the materials mentioned above. The results presented by Döll [8] and Irwin, et al [4] in Figure 2a are in reasonably good accord with this picture, considering the subjectivity involved in evaluating $K_{v,max}$.

This paper described observations of branching in the medium strength steel A533B which are quite different: the stress intensity requirements for branching are much lower $K_I^B \approx K_{Ic}$, and the branching velocity $V_B \sim 0.1$ Co is below the maximum velocity. The difference in behaviour is connected to a mechanism of formation involving the interaction of two, originally widely spaced parts of the crack front rather than the simultaneous nucleation of two branches at a point.

EXPERIMENTAL PROCEDURES AND RESULTS

Fast fracture and arrest events were produced in A533B at -12 C (NDT + 17 C) and 1 C (NDT + 30C) by wedge loading 25 mm - and 50 mm - thick, rectangular duplex - DCB specimens [2]. Values of K_{ID} were derived from measurements of K_Q (the stress intensity at the onset of propagation) and the crack

* Metal Science Section, Battelle Columbus Laboratories, 505 King Avenue, Columbus, Ohio 43201, U. S. A.

velocity or the crack length at arrest, using a dynamic analysis. The material (Heat CBI), test procedure and analysis are described elsewhere [9, 10].

The K_D - values and corresponding velocities, shown in Figure 2b define the K_D - velocity curve for the steel, at least approximately. The well-known K_D - velocity curve deduced by Eftis and Krafft [11] for a ship steel is also shown because it gives an indication of the value of maximum velocity for cracks in steel near the NDT (e.g., $V_{max} \geq 1000$ ms^{-1}). Some of the experiments produced large-scale branching events in the A533B steel test section, as shown in Figure 3. The presence of side grooves removing up to 40% of the cross section did not prevent branching (see Figures 3a and 3b). Side grooves comprising 60% of the cross section tend to alter the trajectory of the branches so that one branch is more likely to be left behind (Figure 3c). The K_D^B values for the steel (K_D - values for events accompanied by branching) are identified in Figure 2b. It is apparent that the stress intensity requirements for branching in the steel are much more modest $K_I^B \approx K_{Ic}$, and may not involve a velocity invariant portion of the K_D - velocity curve.

Metallographic sections of the crack profile in a second heat of A533B that is also prone to branching [9] displayed numerous microbranches as shown in Figure 4a. Such microbranches have also been observed but on a smaller scale on crack profiles in A517F steel which does not branch (see Figure 4b). Direct observations of the fractured surfaces of the steel revealed that the branches do not form simultaneously but sequentially by the interaction of portions of the crack front that are originally coplanar as shown in Figure 1b.

DISCUSSION

One possible reason for the invariance of crack velocity during branching in Homalite - 100 and glasses is that the branching attempt is otherwise unsuccessful. For the case where the two branches nucleate simultaneously at a single point, the K_I - value sensed by one branch is about 40% less than the main crack, and depends on its orientation and its portion relative to the other branch. Consequently, if the velocity varies with K_I, the branch nucleus is likely to be overtaken by the main crack front. Alternatively, a small fluctuation is likely to cause one branch to be left behind by the other as in Figure 3c. Consistent with this idea, the microbranches observed in the two steels can be looked upon as unsuccessful attempts of the simultaneous mode of branch nucleation.

The relative ease of branching in the A533B steel and in lower strength ship steels [12] is attributed to a number of factors. One is the presence of microbranches. These make it easy to deflect a portion of the crack front from the plane of symmetry. When the microbranches are small as in the A517F steel, or absent as in 4340 steel, branching is not observed even at much higher crack velocities. A contribution from microbranches of a size related to the microstructure can also help to explain heat-to-heat variations in the branching tendency. A second possible factor is the relative instability of the plane-of-symmetry crack path in the DCB - specimen caused by bending stresses. These two factors make it possible to activate the sequential mode of branching (Figure 1b) which does not involve a significant change in K_I, therefore does not occasion changes in velocity even when K_I is velocity sensitive, and is further less sensitive to velocity because the two nucleation points are separated. Efforts

are currently underway with SEN test pieces to test the idea that the branching is more difficult when the crack path is more stable.

REFERENCES

1. WEIMER, R. J. and ROGERS, H. C., Proc. 2nd Int. Conf. Mech. Behaviour of Materials, Federation of Materials Societies, 1976, 1473.
2. HOAGLAND, R. G., ROSENFIELD, A. R., GEHLEN, P. E. and HAHN, G. T., Fast Fracture and Crack Arrest, (ASTM-STP, to be published).
3. YOFFE, E. H., Phil. Mag., 42, 1951, 739.
4. IRWIN, G., DALLY, J. W., KOBAYASHI, T. and ETHRIDGE, J. M., Report NUREG-75/107, U. of Maryland, 1975.
5. DOLL, W., Private Communication, 1976.
6. CONGLETON, J., Dynamic Crack Propagation, G. C. Sih, Editor, Noordhoff, Leyden, 1973, 427.
7. ANTHONY, S. R., CHUBB, J. P. and CONGLETON, J., Phil. Mag., 22, 1970, 1201.
8. DOLL, W., Int. J. Fract., 11, 1975, 184.
9. HAHN, G. T., HOAGLAND, R. G., KANNINEN, M. F. and ROSENFIELD, A. R., ASTM-STP 601, 1976, 209.
10. HAHN, G. T., HOAGLAND, R. G., KANNINEN, M. F. and ROSENFIELD, A. R., Proc. 2nd Int. Conf. Pressure Vessel Tech., II, ASME, N. Y. C., 1973, 981.
11. EFTIS, J. and KRAFFT, J. M., Trans. ASME, 87D, 1964, 257.
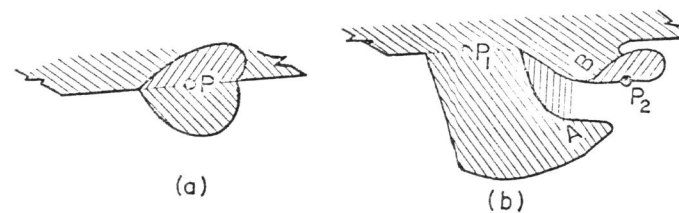12. HAHN, G. T., HOAGLAND, R. G. and ROSENFIELD, A. R., Report SSC-256, Ship Structure Comm., 1976.

Figure 1 Schematic Representation of Branching Mechanisms:
(a) Simultaneous Nucleation of 2 Branches at the point P, and
(b) Sequential Nucleation Involving (i) Veering of the Crack Front at P₁, (ii) Sidewise Growth at A and (iii) Interaction with the Main Crack Front at B Leading to Veering at P₂
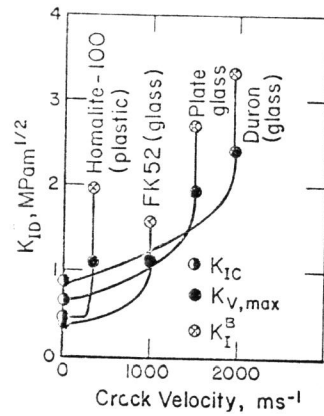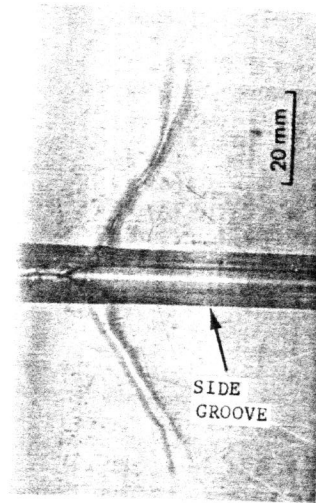
(a)
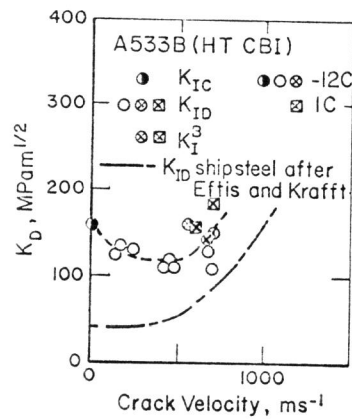
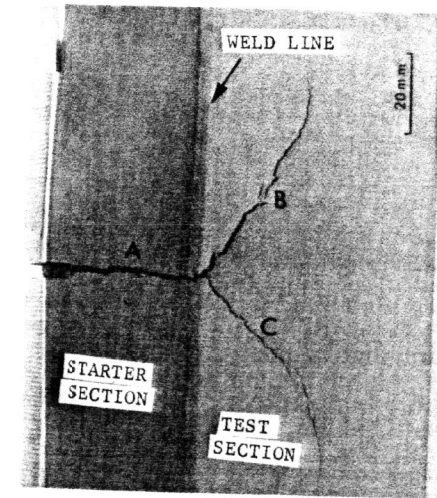
(b)

Figure 2   Variation of the Propagating Crack Toughness, K_{ID}, with Crack Velocity Showing the Stress Intensity Required for Branching K_I^B:
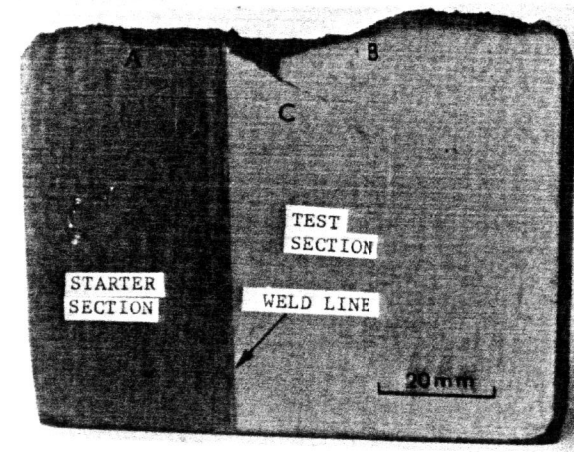
(a) Homalite 100 [4] and Glasses [8] and,
(b) A533B Steel and Ship Plate [11]

(a) Surface, 40% Side Grooved Specimen

(b) Midsection, 40% Side Grooved Specimen Shown in (a)

(c) Midsection of 60% Side Grooved Specimen

Figure 3   Examples of Branching Events in Rectangular, AISI 4340/A533B Duplex DCB Specimens

(a) and (b) A40% Side Grooved Specimen (DA-13) Tested at -12°C,
(c) A60% Side Grooved Specimen (DA-19) Tested at 1°C.

The fractures propagated from left to right and the photos show the main crack (A) and the two branches (B) and (C). In the 60% side grooved sample in (c), branch (B) continued to propagate and branch (C) arrested.
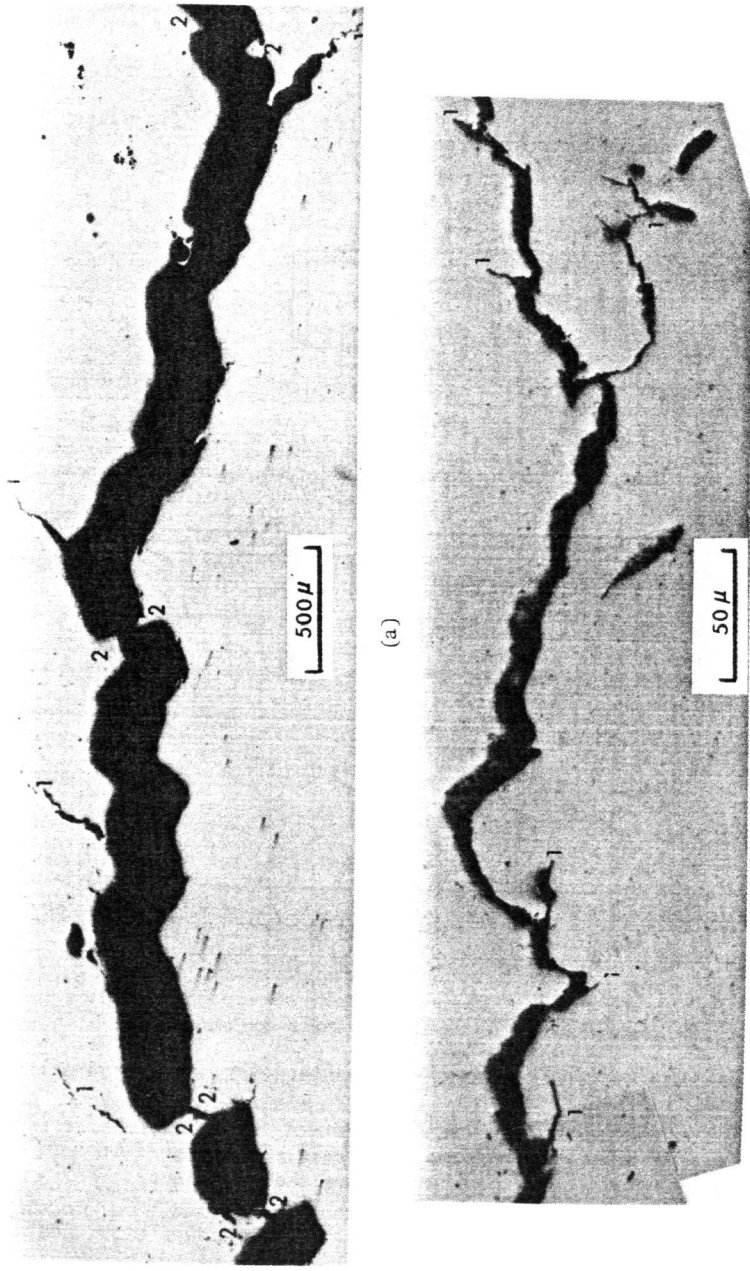
500 μ

(a)

50 μ

(b)

Figure 4 Examples of Microbranches: (a) A533 Steel, (b) A517F Steel. The numeral 1 identifies microbranches left behing by the running crack.