Lower-Energy-Shelf Plane-Strain Fracture Behavior. The lower-energy-shelf brittle-fracture behavior of structural steels has received the most attention from quantitative approaches to fracture problems. The small plastic-zone sizes and large constraint enable this brittle behavior to be analyzed by applying linear-elastic fracture mechanics concepts. Previous studies with these same steels gave fracture toughness, K_{Ic}, values and yield strengths for both static and dynamic-loading conditions [2]. These data can now be compared with the impact data, since the crack-tip strain rates associated with impact loading are within an order of magnitude of the dynamic-strain rates obtained in the K_{ID} studies of these steels.

The relationship among lateral contraction, crack opening, and K_{Ic} can now be examined for dynamic loading. Burdekin has shown that even for brittle behavior the lateral contraction at the crack tip is equal to the crack opening, δ [12]. Therefore, for the brittle-fracture behavior associated with the lower-energy shelves of these steels, the crack opening, δ, in equation (3) is replaced by the lateral contraction and must be proportional to

$$\text{impact lateral contraction} \propto \frac{K_{ID}^2}{\sigma_{YD} E} \qquad (4)$$

where K_{ID} = dynamic K_{Ic} value at the test temperature
σ_{YD} = dynamic yield strength at the test temperature

The application of equation (4) to four of the structural steels is shown in Fig. 15. Crack-toughness values were not previously obtained for the A36 steel, and lateral-contraction measurements were not made for the HY-80 steel. For each steel the data include the temperature range from −320 deg F to the NDT temperature, since plane-strain K_{ID} values were obtained in 1 in. thick specimens for temperatures up to the NDT temperature. The results for the four steels indicate a linear proportionality between the lateral contraction and K_{ID}^2/σ_{YD}E; the HY-130 results have the greatest deviation from this proportionality. From Fig. 15 it is apparent that the lateral contraction is 20 times greater than the value calculated from the quantity K_{ID}^2/σ_{YD}E. For all the steels examined, a constant lateral contraction of about 0.030 in. occurred at the NDT temperatures. A constant lateral contraction or crack opening at the NDT temperature is consistent with previous results which showed that the NDT temperature is the upper boundary for dynamic plane-strain fracture in 1 in. thick sections [2].

If the thickness is insufficient to measure plane-strain K_{Ic} values, the same lateral contraction and crack opening will give K_c values greater than the K_{Ic}. If, in fact, equation (3) is correct for ductile behavior, it should be possible to obtain plane-stress K_c values as large as $\sqrt{20}$ or about 4.5 times the K_{Ic} value. Such an estimate of crack-toughness increase due to lack of constraint in thin sections, points out the high degree of conservatism that is adopted when calculations of critical stress and flaw size are made on the basis of K_{Ic} behavior for plate thicknesses that are much less than those required for the constraint of plane strain.

Summary

The notch-ductility transition of six structural steels ranging in yield strength from 36 to 137 ksi was studied with the use of V-notch and fatigue-cracked Charpy specimens, $^5/_8$ and 1 in. thick dynamic-tear (DT) specimens, and previously reported dynamic-fracture-toughness, K_{ID}, values. The results of this study may be summarized as follows:

1 For temperatures in the range of the upper shelf in the DT and Charpy specimens, the energies absorbed in fracture can be related through the plastic volume, giving a constant average plastic energy density for fracture in each steel. The plastic-volume ratio between $^5/_8$ in. thick DT and CVN specimens for full-shear behavior was about 8.8, whereas the ratio between the 1 and the $^5/_8$ in. thick DT specimens was about 6.8.

2 The lateral contraction increased linearly with temperature, independent of thickness, as an exponential function up to a maximum plateau value that was dependent on the thickness.

3 The maximum lateral contraction increased with increasing thickness, an indication that K_c values should increase with thickness.

4 From geometry considerations, the crack-opening displacement $\left(\delta = \frac{K_c^2}{\sigma_Y \mathrm{E}}\right)$ should be equal to the lateral contraction. However, for the brittle lower-energy-shelf behavior, the measured lateral contraction was 20 times greater than that estimated from the plane-strain fracture-toughness values and K_{ID}^2/σ_{YD}E, an indication that K_c values may be as much as 4.5 times larger than the K_{Ic} values.

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DISCUSSION

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The author has provided a wealth of information concerning the fracture resistance characteristics of six commercial steels of high interest. The source of the many problems encountered when criteria for toughness are based upon Charpy test results is clearly displayed in Figs. 1–6. A comparison of the temperature transition curves for C_v energy and DT energy for the different materials shows that there is no fixed displacement for the transition region of the C_v energy curve. This requires a separate calibration for C_v energy for each steel to adjust the transition region to that for a sharp notch or crack.

In the "Discussion" section of this paper, an hypothesis concerning the plastic volume for full shear behavior is proposed that is not substantiated experimentally. The proposed model intimates that plastic strain is uniform in the plastic zone, and that the plastic zone is limited to a zone with a square cross section bounded by the plate surfaces. This assumption leads

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to an expression for the effects of size on fracture resistance that is not confirmed experimentally.

A study of the effects of geometry on plastic fracture resistance as measured in the DT test has been conducted at NRL using a variety of steels including A537A, A537B, and A517F. Specimens of various shapes, including net ligament length-to-thickness ratios from 1:1 to 3:1, were used and thicknesses from $^1/_4$ in. to 2-$^1/_2$ in. The data obtained from these DT tests, which were conducted at temperatures in the ductile region, were reduced to the following equation which provides a general expression for the material and mechanical aspects of plastic fracture resistance:

$$\mathrm{DTE} = P_r(d)^2(B)^{1/2}$$

where DTE is the dynamic tear (DT) energy, P_r is the plastic instability resistance factor (PIRF), d is the ligament or crack run distance, and B is the thickness. This equation was accurate within ±15 percent for all specimens with thickness greater than $^3/_8$ in. Plastic fracture resistance of metals in thin sections requires modification of the formula due to limitations in thickness strain.

The foregoing equation proposes a significantly different relationship for size effects on plastic fracture resistance than those proposed in the paper ($\mathrm{DTE} \sim B^2$), and caution is, therefore, recommended concerning the material characterization analysis and the structural design implications discussed in this paper.

Author's Closure

The author certainly agrees with the difficulties encountered in attempting to relate fracture energies of specimens of different sizes, let alone different configurations. In fact, the paper points out an apparent consistency in lateral-contraction measurements and includes a discussion of quantitative fracture-toughness estimates (K_{Ic} and K_c) which indicates how much more potential significance there is to ductility measurements, such as lateral contraction, than to energy measurements. However, the upper-shelf fracture energies were examined using models previously proposed in the literature in references [7, 8, and 9] and more recently described by Gavigan, Liu, and Ke.[3]

This author is not aware of models or information in the published literature which would substantiate the values of the exponents of the terms in the equation given by the discusser. It will be quite informative to see a plastic flow model consistent with this equation, since there are still many unanswered questions concerning this type of ductile fracture behavior.

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