The Determination of K_{Ic} Values from Measurements of the Critical Crack Tip Opening Displacement at Fracture Initiation

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I. Introduction

The concept of a critical $(COD)_c$, the displacement between the crack faces at the crack tip required for fracture initiation, is an attractive fracture criterion [1-4]. The COD appears to be closely related to the notch root strain, which is, at least for initiation by ductile rupture, the most promising microscopic fracture criterion.

Smith and Knott [5] found that notched bend specimens of mild steel, 0.2", 0.4" and 0.67" thick, all showed the same value of $(COD)_c$ at room temperature. Wilshaw [6] demonstrated that the average degree of transverse constraint at the root of the notch, in a Charpy V bend specimen, is high even well after general yield. From these investigations we believe that it should be possible to obtain COD values under plane strain conditions from measurements at the specimen midsection of small specimens deformed beyond general yield. The use of the theoretical relationships between COD and K_I then allows K_{Ic} to be calculated from measurements of $(COD)_c$ on precracked Charpy specimens 0.4" thick, whereas valid ASTM K_{Ic} values are normally measured on specimens 1" to 12" thick. The use of a reliable method based on a critical plane strain $(COD)_c$ would result in large savings in material, machining time and equipment capacity. The present work was conducted to determine whether a critical $(COD)_c$ approach could be used to obtain K_{Ic} values that were in agreement with values obtained on valid ASTM specimens of A533B and 4340 steel.

II. Experimental details

The program of work was fourfold. First, a set of lines parallel to the specimen axis was printed with Kodak photoresist on the notch root of a sharply notched A533B Charpy V specimen (0.4" thick, 0.002" root radius). The specimen was then loaded in 3 point bending to plastic angles of bend θ up to and beyond that to produce fracture initiation ($\theta = 2\ 1/2^{\circ}$). The grid lines were photographed at intervals of approximately $1\ 1/2^{\circ}$ from $\theta = 0^{\circ}$ to $\theta = 5^{\circ}$. Beyond $\theta = 5^{\circ}$ the grid lines were insufficiently distinct for measurement. It is noted that the degree of transverse contraction in the central third of the specimen is zero (contractions less than 2% could probably not be detected) and consequently plane strain conditions are maintained up to a bend angle of at least $\theta = 5^o$. Figure 1 shows grid lines on a standard Charpy specimen of mild steel bent to an angle $\theta = 20^o$. The lines on this specimen were purposely made coarse so as to be clear on the photograph.

Secondly, a technique was developed whereby the crack tip COD was measured by infiltrating the crack with a catalytically hardening silicone rubber. The rubber was placed in the notch when the specimen was unloaded. A clip gauge was mounted on knife edges attached to the top of the specimen on either side of the notch and the specimen was bent to a particular clip gauge displacement. The specimen was held under load for about 45 minutes until the rubber had set. Bending was then continued until the specimen had broken and the rubber 'casting' could be removed. The 'casting' was sectioned at the midsection and examined in the scanning electron microscope. The COD was measured at the point nearest the crack tip where the crack faces were more or less parallel (Figure 2). This technique allows on-load values of crack tip COD to be measured directly.

The third step was to determine the relation between K and COD. For this, ASTM standard K_{Ic} specimens were required. AISI 4340 steel, quenched and tempered to yield strengths of 175,000 and 190,000 psi, was used so that the valid specimen could be of reasonable size (1" and 1/2" thick respectively). Specimens were loaded up to K values less than K_{Ic} and within the ASTM validity requirements and the COD was measured by the rubber infiltration technique. The results are given in Figure 3 and indicate that COD is proportional to $\left(\frac{K^2}{\sigma_y}\right)$.

The fourth step was to measure $(COD)_c$ on pre-cracked Charpy specimens of A533B that were loaded in slow bending at four temperatures, -55^oC, -31^oC, 0^oC and 24^oC. Below room temperature the increase in viscosity of the silicone rubber renders the use of the infiltration technique difficult. To overcome this problem, measurements of the position of the effective center of rotation at particular values of COD were made at room temperature. The rotational constant r, the

depth below the crack tip at which the center of rotation is located expressed as a fraction of ligament depth, can be calculated from the relationship [2]

$$r = \frac{a + z}{(W-a)\left[\frac{CGD}{COD} - 1\right]} \qquad (1)$$

where W is the specimen width, a is the crack depth, z is the height of the knife edges above the specimen surface and CGD is the clip gauge displacement.

A curve of r versus COD is given in Figure 4. Rearrangement of Equation 1 then allows the central crack tip COD to be calculated from the clip gauge displacement measurements made at the three lower temperatures.

Pre-cracked Charpy specimens of A533B steel were broken in slow bend at the four temperatures selected and examined in the scanning electron microscope to determine the mode of fracture initiation. For those temperatures where fracture initiation was by ductile rupture (0^oC and 24^oC), specimens were deformed in slow bending to a variety of clip gauge displacements at the required temperature and then fractured in impact at liquid nitrogen temperature. Examination of the fracture surfaces in the scanning electron microscope showed whether any ductile rupture was present, which would indicate that fracture initiation, taken as corresponding to 0.001" to 0.002" of crack growth, had occured in the first bending operation. For those temperatures where fracture initiation occurred by cleavage (-31^oC and -55^oC) specimens were deformed to a variety of clip gauge displacements and then ruptured at 100^oC (where fracture is entirely ductile). Any cleavage present indicated fracture initiation in the first bending operation. In all specimens, fracture initiation occured well after general yield. The effect of temperature on $(COD)_c$ values for A533B steel is shown in Figure 5.

III. Discussion

From linear elastic fracture mechanics,

$$K^2 = \frac{EG}{1-\nu^2} \qquad (2)$$

From the theoretical treatment of, for example, Bilby et al [4],

$$G = n\,\sigma_y\,COD \tag{3}$$

where σ_y is the yield stress and n is a constant. From Equations 2 and 3

$$COD = \frac{K^2\,(1-\nu^2)}{\sigma_y\,n\,E} \tag{4}$$

The data of Figure 3 confirms the relationship in Equation 4 between COD and $\left(\frac{K^2}{\sigma_y}\right)$. The value of n has been theoretically estimated as $\frac{\pi}{4}$ (Wells [3]) and 1.0 (Bilby et al [4]). A least squares fit to the data of Figure 3 gives an experimental value of n equal to 0.93, thereby confirming theoretical estimates. The measurement of COD values is accurate within 10%. Rearranging Equation 4 and using n = 1 for simplicity, we find

$$K_{Ic} = \sqrt{\frac{E\,\sigma_y\,(COD)_c}{1-\nu^2}} \tag{5}$$

Values of K_{Ic} for A533B at the various temperatures were calculated using Equation 5 from the $(COD)_c$ values of Figure 5. The results are shown in Figure 6, superimposed on the scatter bend for the HSST "valid" K_{Ic} results. It is noted that the agreement between the K_{Ic} values obtained from $(COD)_c$ measurements and valid ASTM tests is good.

IV. Conclusion

1. The central region of a Charpy specimen in 3 point bend remains in plane strain until well after general yield.
2. Plane strain values of $(COD)_c$ can be determined from infiltration measurements at the midsection of pre-cracked Charpy specimens, even under conditions where a valid ASTM K_{Ic} specimen would be more than an order of magnitude larger.
3. The COD is directly proportional to $\frac{K^2}{\sigma_y}$, as theoretically predicted.
4. These values of $(COD)_c$ from small specimens can be used to accurately predict K_{Ic} values for A533B steel.

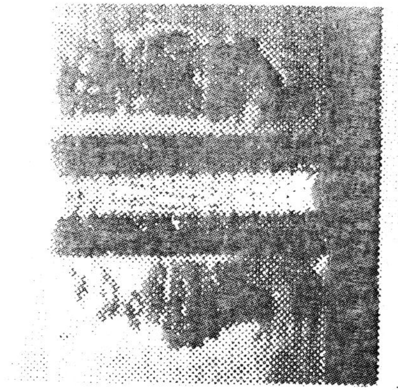

Figure 1. Grid Lines Across Notch of Mild Steel Standard Charpy Specimen, $\theta = 20°$

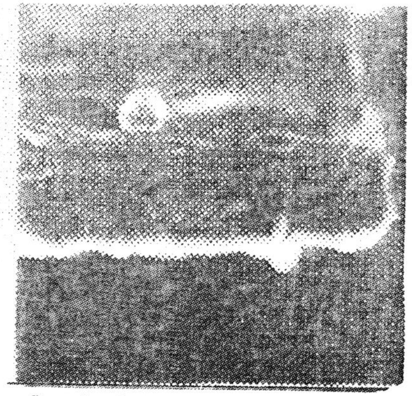

Figure 2. Rubber 'Casting' of Crack Tip in 4340 Steel Sectioned at the Center of the Specimen x 500

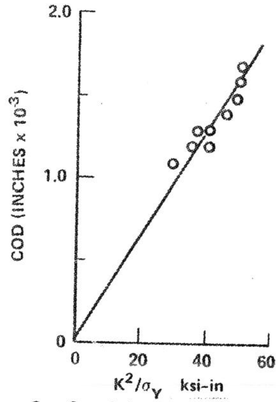

Figure 3. Correlation Between K and COD for 4340 Steel Quenched and Tempered

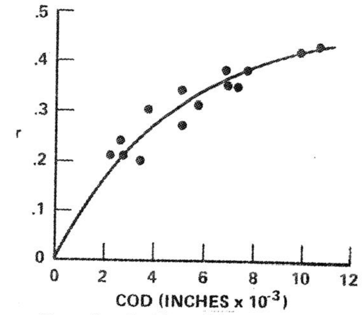

Figure 4. Position of Center of Rotation Versus COD for A533B

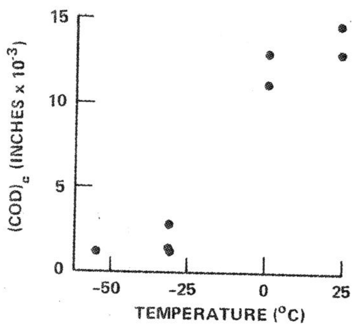

Figure 5. Critical Crack Tip COD Values for A533B

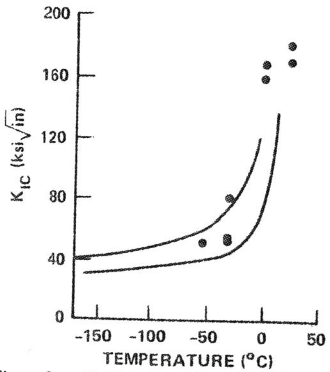

Figure 6. K_{Ic} Calculated from $(COD)_c$ for A533B Superimposed on the Scatter Band for HSST Valid K_{Ic} Results

V. References

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