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EFFECT OF PRIOR AUSTENITE GRAIN SIZE ON THE FRACTURE TOUGHNESS PROPERTIES OF A533 B STEEL

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INTRODUCTION

The lower yield stress of α-iron is often taken to depend on the inverse square root of the polycrystal ferrite grain diameter according to the Hall-Petch relation [1,2],

$$\sigma_y = \sigma_{oy} + k_y d^{-1/2} \qquad (1)$$

where σ_{oy} and k_y are experimental constants. Hall and Petch independently explained this result in terms of the stress-concentrating character of dislocations within slip bands. Of significance, also, is the earlier observation made by Zener [3] that, based on the continuum shear crack calculations of Starr [4], the yield stress of a polycrystalline material should be expected to be inversely proportional to the square root of the average grain diameter.

The Hall-Petch and Zener analyses for the grain size dependence of the yield stress have an important connection with the fracture mechanics description of the crack size dependence which occurs for the brittle fracture stress of steel and other materials. The fracture mechanics description is normally written, for example, in the Irwin-Orowan equation [5,6]

$$\sigma_f = K_{Ic}(\pi a_e)^{-1/2} \qquad (2)$$

where K_{Ic} is a measure of the level of the crack tip stress-concentration which is reached in plane strain deformation when fast fracture instability occurs. In each case, for yielding or fracture, the critical action of a stress-concentrator is involved and this consideration is the reason for having a reciprocal square root of size dependence for the respective stress.

The yield stress of a crack-free material and the fracture stress for a pre-cracked material have been jointly incorporated into the Dugdale [7] or Bilby-Cottrell-Swinden [8] models for the growth of a crack with an associated plastic zone at the crack tip. For fracture assumed to be controlled by the achievement of a critical plastic zone size, (s) at the crack tip, Armstrong [9] has obtained the result from these analyses that

$$\sigma_f = C\sigma_y\,[s/(a+s)]^{1/2} \qquad (3)$$

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where C is a numerical constant. Equation (3) was shown to be in agreement with results for the grain size (through σ_y) and crack size dependence of the brittle fracture strength measured for 0.04 carbon steel by Yokobori, Kamei, and Kogawa [10]. By combining equations (1) - (3), the grain size dependence of K_{Ic} is obtained as

$$K_{Ic} = \left[C \left(\pi \frac{sa_e}{a + s} \right)^{1/2} \right] (\sigma_{oy} + k_y d^{-1/2}) \tag{4}$$

where, for $(s/a) < 1.0$, $[sa_e/(a+s)]^{1/2} \approx s^{1/2}$. Figure 1 shows, on the basis of equation (4), the trend of these results obtained by Yokobori, Kamei and Kogawa in comparison with more recent results which have been reported by Curry and Knott [11]. Stonesifer [12] has evaluated the constant $C = (8/\pi)^{1/2}$ for plane strain deformation and has shown that s may be matched with twice the radius, r_y, of the plastic zone which was described by Smith, Kies and Irwin [13] as a correction to give a_e in equation (2) in place of a.

Fractographic examination of cleavage failures in pre-cracked ferrous materials appears to substantiate the foregoing description for the influence of grain size on fracture toughness. The size and spacing of cleavage facets may be correlated generally with either the ferrite or prior austenite grain size. The prior austenite grain size is important to consider for cleavage fracture because the crystallographic orientation of the allotropic phases presumably allows an alignment of cleavage planes within the ferrite grains transformed from a single austenite grain. Experience suggests that the fracture toughness of steel, say, as measured by K_{Ic}, is lower when the cleavage facets are larger. The steel employed in this study, A533 B, is one for which the austenite grain size can be changed greatly by heat treatment even though the effective ferrite grain size, say, as measured by the mean free path between carbide particles, is not appreciably altered.

EXPERIMENTAL METHOD AND RESULTS

A description of the particular A533 B steel material which was employed in this study has been given by Stonesifer [12]. The central portion of the plate gave the following chemical composition in weight percent: C - 0.20, Mn - 1.35, P - 0.01, S - 0.017, Ni - 0.66, Mo - 0.56 and Si - 0.22. Three prior austenite (γ) grain sizes were produced, as follows: material A, held for 2 hours at 1255 K in a small laboratory vacuum furnace and furnace-cooled; material B, held for 2 hours at 1366 K and furnace-cooled; and material C, held at 1518 K and furnace-cooled. The A material appeared to have the same prior austenite grain size as was present in the original fine grained material in the quenched and tempered condition. The average grain diameters of the final materials were found to be: 0.015 mm (ASTM 8.5) for A; 0.100 mm (ASTM 4) for B; and, 0.450 mm (ASTM 00) for C. An average ferrite grain size of 0.015 ± 0.005 mm was estimated for all three materials.

A ductile-brittle transition temperature region was determined for the A, B, and C materials by employing standard Charpy V-notched impact tests for triplicate specimens at each test temperature. The results are shown in Figure 2. The ductile-brittle transition was found to occur over the temperature range of 275 - 475 K in the expected order of increasing austenite grain size. The higher "shelf energy" for B material corresponded with an out-of-order greater elongation and reduction in area at room temperature for the B versus A and C materials [12].

Pre-cracked compact fracture toughness specimens [14] were employed for determining K_Q, or conditional K_{Ic}, values at room temperature and at lower temperatures extending to 4.2 K. All specimens were pre-cracked at room temperature using a closed-loop hydraulic machine with an ASTM (E399) type clip gauge inserted into the notch. Between 65 and 75 thousand cycles with $\Delta K = 21.4$ MPa . $m^{1/2}$ were required to extend the original 6.4 mm machined notch to between 7.5 and 10 mm. The K value tests were obtained with a displacement controlled, generated loading ramp profile of 0.079 mm/sec. K_Q values were determined from the load versus displacement records for the first sudden drop in load as described for ASTM test method E399 [14]. In this manner, fracture toughness data were obtained for all three grain sizes at four temperatures mostly well below the 7 J Charpy impact level which is shown in Figure 2.

The fracture toughness measurements are shown versus prior austenite grain size in Figure 3. A $d^{-1/2}$ dependence of the type shown in Figure 1 is observed here also with decreasing values of the intercept and slope measurements occurring for decreasing temperatures. The yield stress and ultimate tensile strength dependences on prior austenite grain size were measured to confirm that these stresses followed the Hall-Petch description given in equation (1). The results agreed, for example, with those results given most recently by Brownrigg [15]. A much lesser Hall-Petch slope dependence occurs for the prior austenite grain size than is normally measured for the ferrite grain size dependence. For A533 B steel at room temperature, $\sigma_{oy} = 572$ MPa and $k_y = 0.11$ MPa . $m^{1/2}$. These measurements may be compared with those measurements of Curry and Knott [11] at 153 K for the ferrite grain size dependence of $\sigma_{oy} = 210$ MPa and $k_y = 0.73$ MPa . $m^{1/2}$.

Yield stress measurements were made for each grain size material at the four test temperatures indicated in Figure 3 so as to allow the plastic zone sizes to be determined for the fracture toughness values according to equation (4). The plastic zone size, s, was estimated to vary from a largest value of 2.0 ± 0.6 mm at room temperature, involving many prior austenite (and ferrite) grains, to a smallest value of 0.035 ± 0.003 mm at 4.2 K, involving approximately two ferrite grains [12]. From microstructural observations, it was determined that the running crack front tended either to pass through or to circumvent *complete* austenite grains leaving behind a predominantly cleavage fracture surface with apparent roughness proportional to the prior austenite grain size. The observations are probably explained, as mentioned earlier, by there being less misalignment of cleavage planes within the ferrite structure of one prior austenite grain than there is between the ferrite crystals of adjacent austenite grains. This should be a major consideration in determining the ability of a prior austenite grain boundary to be seen as an obstacle to the growth of a cleavage crack.

The prior austenite grain size dependence of the fracture toughness for A533 B steel in this study is compared in Table 1 with the ferrite grain size dependence measured for plain carbon steels [10,11] according to equation (4) which is rewritten in the form:

$$K_c = K_{co} + (\Delta K_c/\Delta d^{-1/2})\, d^{-1/2} \, . \tag{5}$$

The comparison shows that the ferrite grain size effect is the larger of the two influences, as expected. In both cases, the strong or weak fracture toughness dependence on grain size matches the counterpart strong or weak effect for the Hall-Petch yield stress-grain size dependence. The fracture toughness values for a ferrite grain size, $d_\alpha^{-1/2} \approx 9\ \mathrm{mm}^{-1/2}$, for the plain carbon steel results of Figure 1 compare reasonably well with the A533 B steel range of values determined at 77 and 200 K.

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Table 1 A533 B steel fracture toughness dependence on prior austenite grain size and, for mild steel, on ferrite grain size

Material	Grain Size Variation	Temperature	K_{Co} (MPa · m$^{1/2}$)	$\frac{\Delta K_C}{\Delta d^{-1/2}}\left(\frac{\mathrm{MPa \cdot m^{1/2}}}{\mathrm{mm^{-1/2}}}\right)$	K_C at $d_\alpha^{-1/2} \approx 9\mathrm{mm}^{-1/2}$
A533 B Steel	Prior Austenite	4K	22	0.1	23
A533 B Steel	Prior Austenite	77K	26	0.8	28-33
A533 B Steel	Prior Austenite	200K	40	1.1	42-49
A533 B Steel	Prior Austenite	300K	63	4.0	68-96
.04 C Steel*	Ferrite	(Brittle)	~13	~2.9	~45
Mild Steel**	Ferrite	153K			

*Yokobori, Kamei, Kogawa, 1973 [10]
**Curry and Knott, 1976 [11]

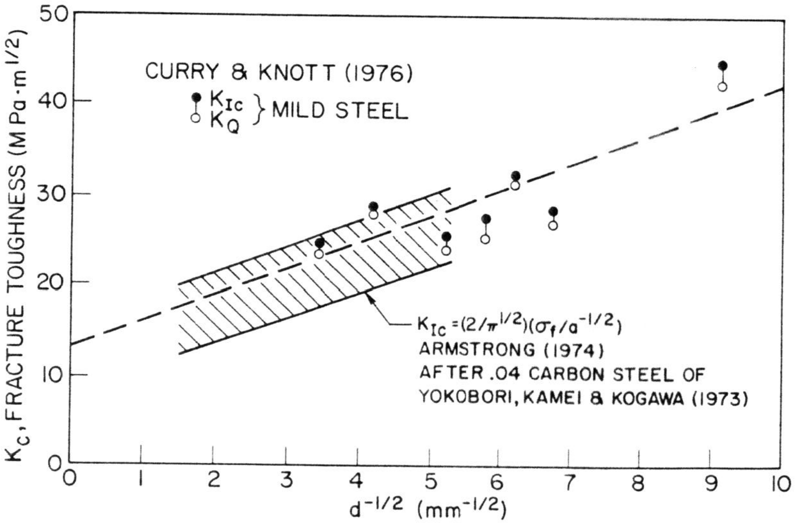

Figure 1 Fracture toughness of several plain carbon steels versus reciprocal square root of ferrite grain size

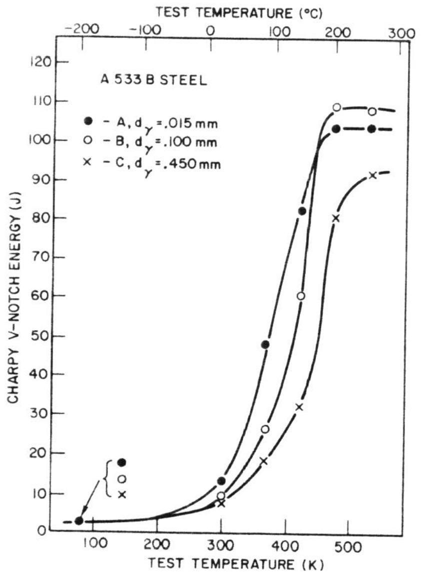

Figure 2 Charpy V-notch impact results showing the ductile-brittle transition behavior for three prior austenite grain sizes

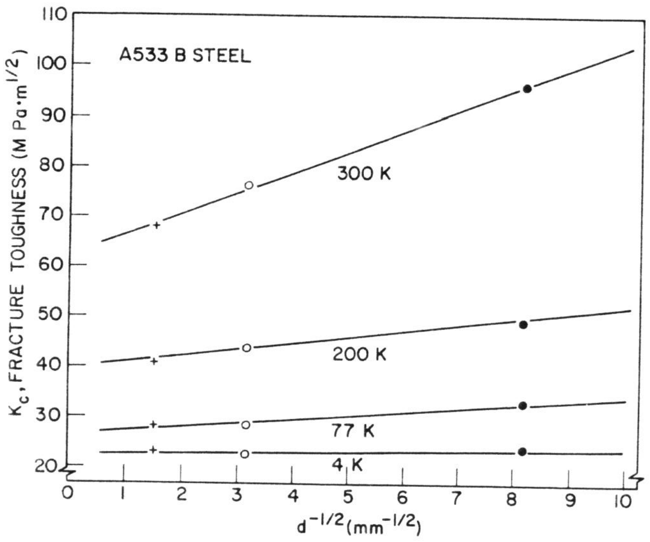

Figure 3 Prior austenite grain size dependence of the fracture toughness at different temperatures