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THE EFFECT OF GRAIN BOUNDARY CARBIDES ON FRACTURE TOUGHNESS

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It is well known that fractured carbides at a grain boundary nucleate cleavage fracture in low carbon steels as shown by McMahon and Cohen,[1] and Almond et al.[2] It is of interest to know if some relationship can be determined which might predict the effect of carbide at the grain boundary on impact toughness or the resistance to crack propagation.

In the course of analyzing the cleavage fracture problem with respect to grain size effects, it was discovered that the effect of carbide thickness could also be determined using a relationship developed by Almond et al.[2] describing the effect of carbide thickness on the fracture stress. However, there was little significant data found to test this relationship. Somewhat later, it came to our attention that some data concerning the effect of carbides on impact toughness had been published by Karchner and Stephenson[3] in Mo-B-V steels. The following discussion demonstrates that the proposed theory is indeed compatible with this new information.

II. RESULTS AND DISCUSSION

Gerberich et al.[4] developed a relationship describing the critical region ahead of the crack front in which non-propagating cleavage microcracks occurred before unstable fracture. This is given by

$$K = \pi \, pcf \, \sigma_{ys} \left[\left\{ e^{pcf-1} - 1 \right\} \left\{ \frac{nd}{2} \right\} \right]^{1/2} \qquad (1)$$

where K is the critical stress intensity for unstable cleavage and is related to the plastic flow in the critical microcrack region, nd, d being the grain diameter. The plastic flow in the region, nd, elevates the stress due to plastic constraint, the factor for which is given by $pcf = \frac{\sigma_f^*}{\sigma_{ys}}$ where σ_f^* is the cleavage fracture stress and σ_{ys} is the yield strength. Tetelman, et al.[5] using the microcrack density observed from tensile samples showed that the stress intensity should be some function of a grain size multiple. From the stress wave emission technique[6] used to determine the number of microcracks leading up to the critical cleavage event, the value of nd was determined as a function of grain size which resulted in

$$nd \simeq C_1 [d]^{1/4} \qquad (2)$$

where $C_1 = 0.182 \text{ in}^{3/4}$. Incorporating this with equation (1), the stress intensity can be determined if the cleavage fracture stress and the yield stress are known. The fact that the cleavage fracture stress varies with the thickness of carbide at the grain boundary has been shown by Almond et al.[2] to be given by

$$\sigma_f^* = \left[\frac{k_t^2 d}{4t^2} + \frac{2E\,\gamma_{eff}}{(1+\nu)t}\right]^{1/2} - \frac{k_t d^{1/2}}{2t} \qquad (3)$$

where k_t is 685 psi - $\text{in}^{1/2}$, t is the carbide thickness at the grain boundary, and γ_{eff} is Cotrell's effective surface energy for ferrite being about 0.114 lb/in (20,000 dyne/cm). Thus if the yield stress is known, the stress intensity may be determined from equations (1), (2) and (3).

This development can now be applied to Karchner and Stephenson's data.[3] These Mo-B steels exhibited an increasing carbide size at the grain boundary as the vanadium content was increased from 0% to 0.33%. Also, an increase in the vanadium content resulted in an increase in both the hardness and yield strength as well as a higher transition temperature for a given tempering time and temperature. So that the yield strength was not a variable in the analysis, impact results from Karchner and Stephenson were taken for a constant yield strength at a constant temperature of -50°F. Since this temperature was near or below the ductile - brittle transition for all of the varying amounts of vanadium, sufficiently brittle enough behavior resulted so that a cleavage fracture criterion was reasonable.

In order to compare these impact values to the proposed theory, it was necessary to translate the Charpy impact V-notch values into K_{IC} values. Although several attempts have been made in correlating CVN and K_{IC} data, there is sufficient deviation from material to material to make such correlations suspect. Nevertheless, in order to compare the trend in the data with the theory, an empirical correlation as developed by Rolfe[7] was utilized given by

$$\frac{K_{IC}^2}{E} = C_2[\mathrm{CVN}]^{3/2} \qquad (4)$$

where E is the elastic modulus, K_{IC} is in psi-in$^{1/2}$ units, CVN is in inch-lb units and $C_2 = 0.048$ in$^{-5/2}$ lb$^{-1/2}$. The CVN data are given in Fig. 1, at -50°F. It can be seen that the impact toughness decreases by more than a factor of five (as the carbide thickness increases by about a factor of eight) from 0.5 to 4μ. It may be noted that all of these steels had a similar grain size being about ASTM 11 ± 0.4, which is a given size of about 9.05μ. Hence, this was not a variable in the analysis. Thus, as the carbide thickness approaches an appreciable fraction of grain diameter, there is a drastic decrease in the toughness. Insertion of the CVN data from Fig. 1 into equation (4) allowed experimental estimates of K_{IC} at -50°F to be determined.

For the theoretical determination of K_{IC}, several constants had to be determined. A σ_{ys} value of 120,000 psi was obtained by Karchner and Stephenson[3] at room temperature. For the -50°F analysis, this σ_{ys} value was adjusted to 130,000 psi by taking into account an additional 10,000 psi due to an increase in the thermal component of the yield strength as suggested by the data of Wessel[8] on similar steels. The size of the critical microcrack region, nd, found by applying equation (2) and a grain size of d = 9.05μ gives a value of nd = 0.0103 inches. The values of the parameters k_t and γ_{eff} are known from Almond's[2] data and Poisson's ratio, ν, was taken to be approximately 0.3. Using equation (3), the cleavage fracture stress was calculated and is tabulated in Table I, for varying carbide thicknesses and vanadium content.

Table I.

Calculated Values of σ_f* Using Equation (3).

Carbide Thickness at grain boundary t, μ	Percentage Vanadium % V	Cleavage fracture stress σ_f*, ksi
0.05	0	282
1	0.04	236
2	0.09	189
4	0.33	146

The stress intensity values as a function of carbide thickness were then calculated using the cleavage fracture stress values in equation (1). The resulting curve of stress intensity, K_{IC}, versus carbide thickness, t, shown in Fig. 2 is seen to agree well with the experimental data. The fact that the data is nearly in perfect quantitative agreement is undoubtedly fortuitous because of the many assumptions and uncertainties involved. The important factor to be accentuated is that the trend in the data is almost exactly predicted, which lends support to the theoretical interpretation of the effect of carbide boundary thickness on crack propagation resistance.

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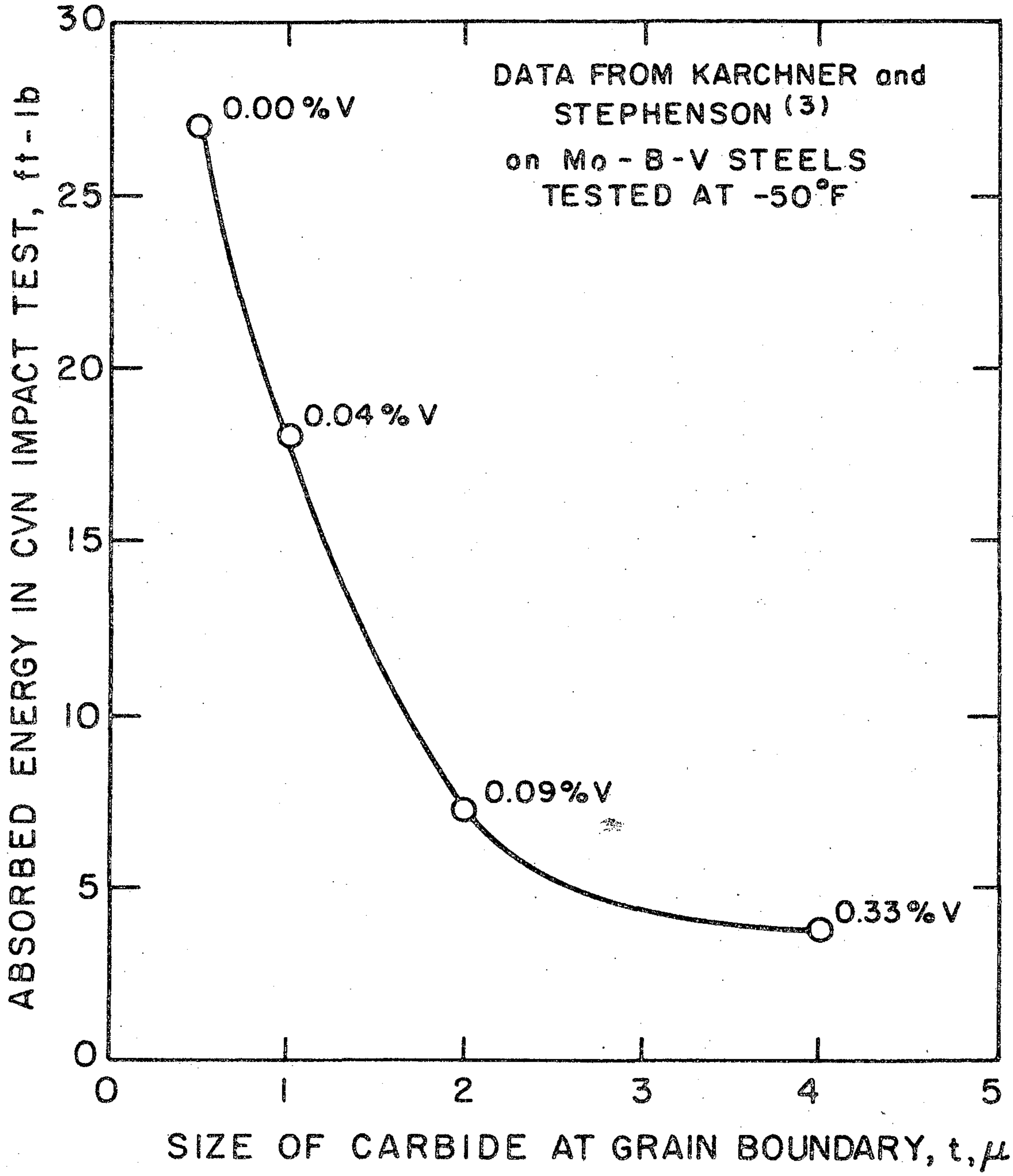

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Fig. 1

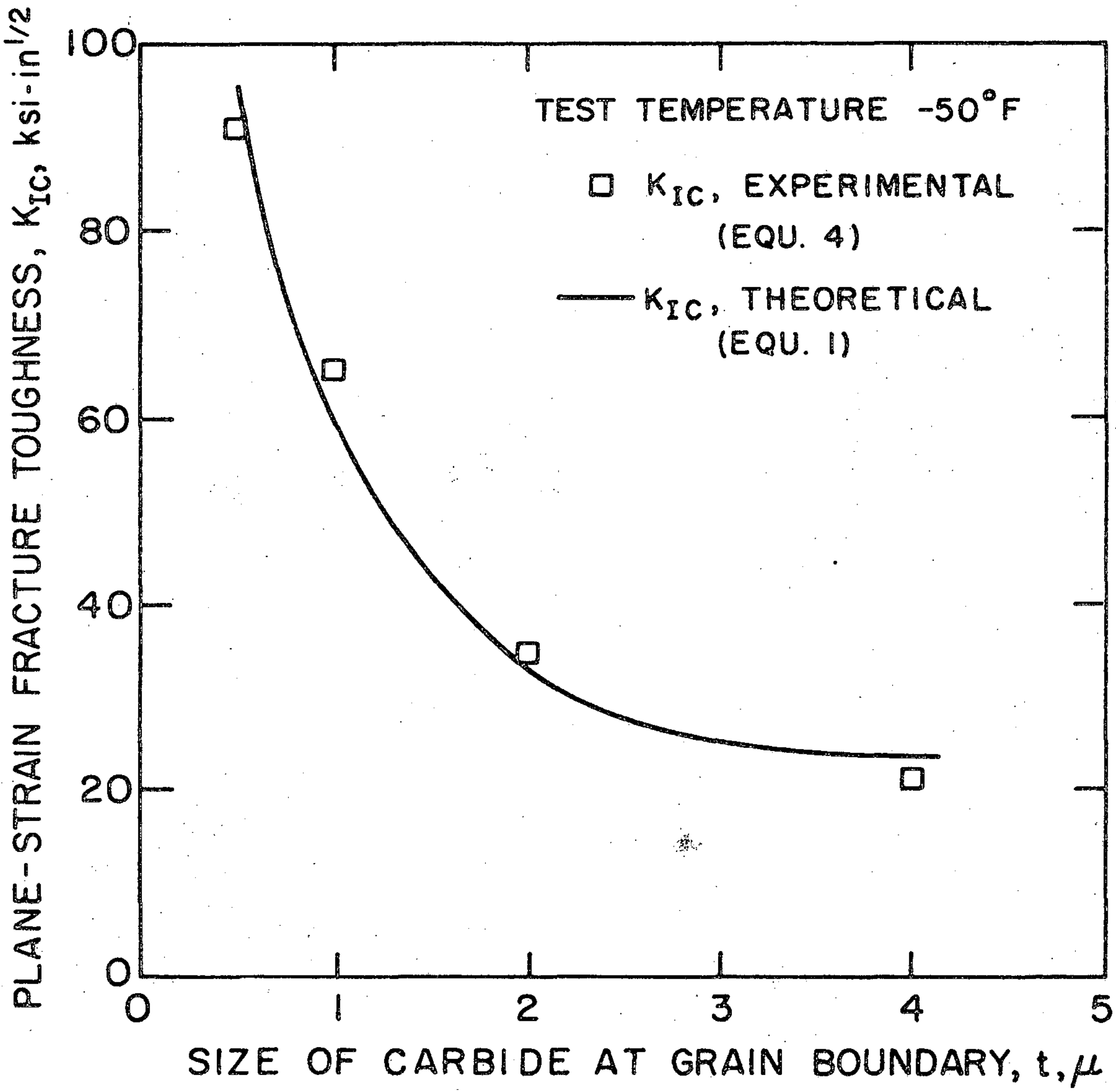

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Fig. 2

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