# Correlation between the Fracture Toughness and Material Ductility

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## I. INTRODUCTION

For metals and alloys, fracture toughness, the work required to form a unit area of new crack surface is principally the plastic work in the volume ahead of the crack associated with crack growth and therefore has to be a function of the flow stress of the material and a critical fracture strain. This is also reflected in the many relationships proposed e.g. by Wells[1], Beeuwkes[2], Krafft[3], Hahn and Rosenfield[4] and Barsom[5]. Since the stress state ahead of a crack tip is biaxial or triaxial it is necessary to determine the critical parameters for this condition. The flow stress can readily be obtained from the Tresca or the von Mises criterion. For the effect of stress state on fracture strain Marin[6] proposed a critical maximum stress criterion. Recent studies at Syracuse[7], however, have shown that this criterion does not apply to any of the aluminum alloys, titanium alloys and steels studied; rather the effect of stress state on fracture strain is best expressed by a critical mean stress failure criterion which yields

$$\frac{\bar{\varepsilon}_{F,\alpha\beta}}{\bar{\varepsilon}_{TF}} = \left[\frac{1}{1+\alpha+\beta}\{(1+\alpha+\beta)^2 - 3(\alpha+\beta+\alpha\beta)\}^{1/2}\right]^{1/n} \qquad (1)$$

where $\alpha = \sigma_2/\sigma_1$, $\beta = \sigma_3/\sigma_1$, $\bar{\sigma} = K\bar{\varepsilon}^n$, $\bar{\sigma}$ and $\bar{\varepsilon}$ are the effective stress and strain, $\bar{\varepsilon}_{F_{\alpha\beta}}$ the effective fracture strain under multiaxial conditions and $\bar{\varepsilon}_{TF}$ the tensile fracture strain. Thus, for plane stress conditions the minimum effective fracture strain is obtained under balanced biaxial tension, $\alpha = 1$ and not for $\alpha = 1/2$ as predicted by Marin.

A correlation between fracture ductility and fracture toughness is developed which is in good agreement with experimental evidence.

## II. EFFECTS OF BIAXIAL STRESS STATE ON DUCTILITY

Biaxial fracture tests on flat smooth specimens were performed on 300 M steel (0.4C, 1.8Ni, 1.6Si, 0.9Cr, 0.4Mo, + V) and D6AC steel (0.46C, 1.0Cr, 1.0Mo, 0.55Ni), each heat treated to three hardness levels. Figs. 1a to d show the design of the test specimens and the test fixtures. The fracture ductility is obtained by measuring the effective strain $\bar{\varepsilon}_F$ at fracture. The results, plotted in Fig. 2, are in good agreement with the predictions of the mean stress fracture criterion, as expressed in Eq. 1. The ductility minima occur for balanced bi-axial tension (bulge test).

## III. CORRELATION BETWEEN FRACTURE TOUGHNESS AND DUCTILITY

Fracture toughness, defined as

$$G_c = \frac{dW}{dA}; = \frac{K_c^2}{E} \text{ for plane stress}; = \frac{K_{Ic}^2}{E}(1-\nu^2) \text{ for plane strain} \quad (2)$$

where W is the plastic work associated with crack growth and A the crack area, can be related to fracture ductility and flow stress if W can be expressed as a function of these parameters. From the strain distribution in the plastic zone

$$\varepsilon = \varepsilon_F \left(\frac{\rho^*}{\rho^*+2r}\right)^{\frac{1}{n+1}} \quad (3)$$

where $\rho^*$ is the Neuber microsupport effect constant[8] and r the distance from the crack tip, one obtains for the plastic work in a crack sheet of thickness t and crack length 2a

$$dW = S \frac{\sigma_Y}{n} \rho^* \varepsilon_F \left[\left(\frac{\varepsilon_{F\alpha\beta}}{\varepsilon_Y}\right)^n - 1\right] t \cdot da \quad (4)$$

and hence

$$K_c^2 \simeq S \frac{\sigma_Y^2}{n} \rho^* \left[\frac{\varepsilon_{F\alpha\beta}}{\varepsilon_Y}\right]^{n+1} \quad (5)$$





Here S is a shape factor. A very simple approximate and intuitively useful relationship is obtained for n = 1, which is not unreasonable since most measurements[9] of the strain distribution within the plastic zone are well approximated by Eq. 3 with n = 1, namely

$$K_c = E\sqrt{S\rho^*} \cdot \varepsilon_{F_{\alpha\beta}} \quad (6)$$

Fig. 3 shows a plot of $K_c$ vs $\varepsilon_{F_{\alpha=1,\beta=0}}$, the fracture ductility obtained from a bulge test. The fracture toughness values were obtained with the compact tension specimen shown in Fig. 1e. From previous tests $\rho^* \simeq$ 0.0017 inch for high strength steels. Fig. 3 shows a remarkably good correlation with $K_c=900.\varepsilon_{F_{\alpha=1,\beta=0}}$ ksi $\sqrt{in}$ or $K_c=31{,}000.\varepsilon_{F_{\alpha=1,\beta=0}}$, $N.mm^{-3/2}$ which yields for $S\rho^*=0.9.10^{-3}$ inch or 0.023 mm which is quite reasonable.

To further check the validity of the proposed correlation for steels a bulge test was conducted on HY-80 steel. From the measured ductility $\varepsilon_{F_{\alpha=1,\beta=0}}=0.92$, $K_c=830$ ksi $\sqrt{in}$ (28,884 $Nmm^{-3/2}$) which is remarkably close to the experimentally determined[9] $K_c$ value for the same material, namely 800 ksi $\sqrt{in}$ (27,840$Nmm^{-3/2}$). Finally it should be pointed out that Eq. 6 offers the opportunity of obtaining an estimate of $K_{IC}$, namely

$$K_{IC} \simeq 0.34\, E\sqrt{S\rho^*}\,\varepsilon_{F_{\alpha=1,\beta=0}} \text{ ksi } \sqrt{in}$$

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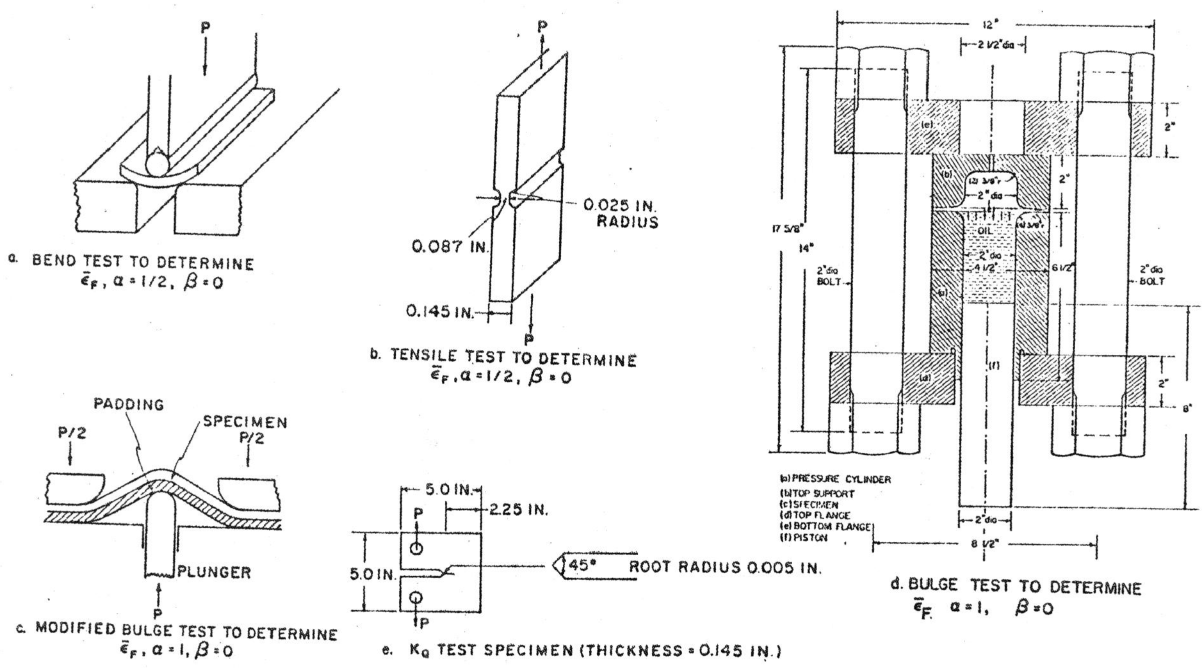


FIGURE 1. TEST SPECIMENS FOR BIAXIAL FRACTURE STRAIN AND FRACTURE TOUGHNESS MEASUREMENTS.





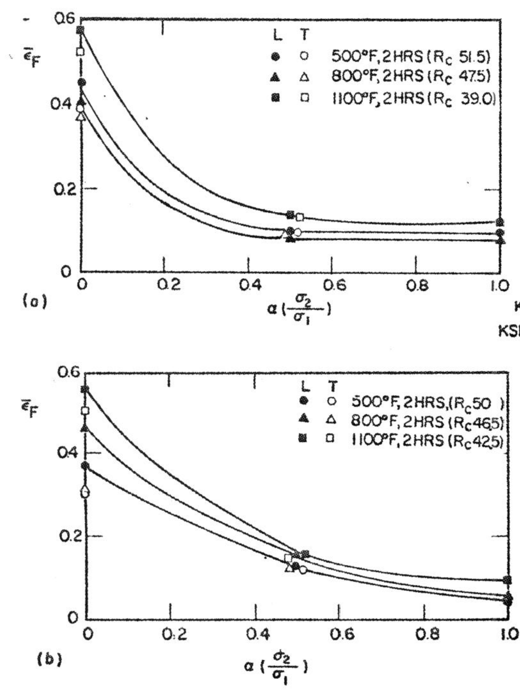


FIG. 2 EFFECT OF STRESS BIAXIALITY ($\sigma_3$=0) ON $\bar{\epsilon}_F$ FOR (a) 300M STEEL (b) D6AC STEEL.

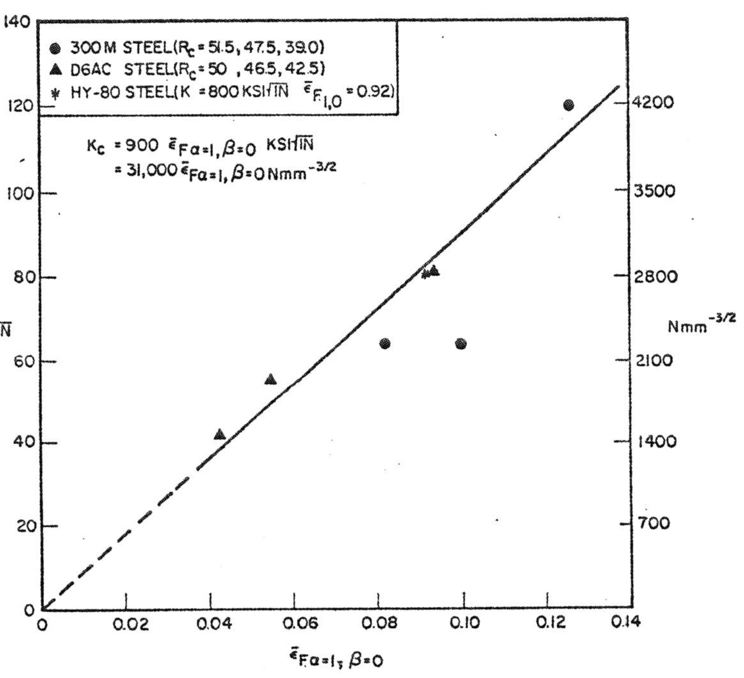


FIG. 3 FRACTURE TOUGHNESS PLOTTED AS A FUNCTION OF BALANCED BIAXIAL DUCTILITY ($\bar{\epsilon}_{F_{\alpha=1,\beta=0}}$), t = 0.145 inch.