Fracture 1977, Volume 3, ICF4, Waterloo, Canada, June 19 - 24, 1977

BLUNTING EFFECTS ON FRACTURE TOUGHNESS OF LOW STRENGTH STEELS

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INTRODUCTION

The fracture toughness of low strength steel decreases considerably with decreasing temperature and increasing strain rate since the fracture micromechanism changes progressively from microvoid coalescence to cleavage. It is proposed [1] that crack initiation by cleavage occurs when σ_{yy}^{max} stress at some distance ahead of the crack tip reaches σ_f, the cleavage strength of the material at the crack tip. It is shown [2] that σ_f changes little with temperature and thus the temperature influences K_{IC} mainly due to the variation of σ_y with temperature wherein the crack tip radius ρ_o remains unchanged [1]. However, K_I (K_{IC}) is an inadequate fracture mechanics parameter when elastic plastic or fully plastic loading situations are encountered such as in low strength steel specimens fractured at higher test temperatures and in such situations the parameter $J(J_{IC})$ should be used more appropriately. Accordingly K_{IC} calculated, from the experimentally measured J_{IC} (or J_Q, which is J_{cr} measured from specimens which do not satisfy requirements of valid J_{IC} measurements) value, is termed as K_{IC} (J) and is obtained from [3,4].

$$K_{IC}(J) = \left[\frac{E.\ J_{IC}}{1 - \nu^2}\right]^{1/2} \tag{1}$$

In the above loading situations, considerable crack tip blunting occurs. It is observed that [5] calculated K_{IC} values based on the achievable $\sigma_{yy}^{max}/\sigma_y$ value [6,7] in the plastic zone ahead of a sharp crack are significantly lower than the experimental K_{IC} (J) values. In addition the achievable $\sigma_{yy}^{max}/\sigma_y$ values were higher than σ_f/σ_y even at room temperature where cleavage micromechanism does not operate as confirmed by fractographic observation [5]. These observations support the contention [8] that the crack tip undergoes blunting. In fact the blunting of the crack tip is physically confirmed and supported by SZW measurement [9,10], COD measurements [11,12] and the results of crack tip profile measurements and observations [9,11,12,13].

RKR [14] used the stress distribution ahead of a crack [8] in conjunction with a two grain model [14] to calculate the K_{IC} values which were compared with the experimental K_{IC} values. However, the change in σ_y/E and n values with change in temperature and strain rate were not taken into account in their calculation.

The present investigation correlates the various elastic-plastic fracture toughness such as δ_c [15], J_{IC} [16,17] and $\bar{G}_{IC}$, the non-linear energy parameter proposed by Liebowitz and Eftis [18] of two different class of low strength steels in the temperature range -196°C to 28°C and crosshead

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speed range 0.5 to 200 mm/minute. In particular the effect of crack tip blunting on K_{IC} (J) is assessed by an examination of the experimental data in the light of the well known theoretical results [6,7,8].

EXPERIMENTAL

The chemical analysis and the other details of the 12.5 mm thick plate materials are reported in Table 1. Three point bend fracture toughness specimens 12.5 x 15 x 75 mm cut with the long axis along the rolling direction were prepared as per ASTM E 399-72. The tests at low temperatures were carried out with the specimens immersed in a low temperature bath. The load, load line displacement and the crack opening displacement were measured as a function of time. Companion tensile test specimens of the two steels were pulled at various temperatures and strain rates.

The load-displacement [16,21] plots were suitably analysed to obtain δ_c [13,19,20], J_{IC} [16,21] and $\bar{G}_{IC}$ [18]. A measure of the crack tip strain rates was obtained, taking into account the tensile yield strength variation with temperature and strain rate [19,20]. The tensile test data were processed to obtain the n and σ_y/E values at various strain rates and temperatures.

RESULTS AND DISCUSSION

Correlation of the Fracture Mechanics Parameters

COD and J relation is given by

$$\text{COD} = \frac{J}{M \cdot \sigma_y}$$

where M takes into account the elevation of the local σ_{yy} stress at which yield occurs at the crack tip. The values of M have been theoretically determined to be 1.63 from deformation theory of plasticity [3], 2.32 using an incremental plasticity theory [24], 2 by finite element analysis [19,25]. Experimental values of M have been reported [26] for three point bend specimens and lie in the range of 0.83 to 1.75 depending upon a/W and W values.

Figure 1 shows the correlation between J_{cr}, δ_c and σ_y for the various test temperatures and crack tip strain rates for the two steels. The value of M is about 1.52 and is not unreasonable. It is interesting to note that M has a constant value in spite of the differing amounts of plasticity preceeding fracture in the specimens tested.

Figure 2 shows the relation between J_{IC} and $\bar{G}_{IC}$ for the whole range of small scale to extensive yielding situations. The correspondence between the two is reasonable up to the limits of valid J_{IC} measurements as specified in reference [16].

Stress Induced Fracture - Contribution of Progressive Crack Tip Blunting

An examination [5] of the K_{IC} (J) values in the light of Tetelman and Malkin's [1] anlaysis showed that sharp crack tip radius ρ_o of their analysis depends on temperature and strain rate and increases with increasing δ_c. It has also been shown by earlier investigators that considerable stretching occurs at the crack tip which indicates that crack tip undergoes blunting and the stretched zone width directly relates to δ_c.

It is now proposed that the crack tip undergoes progressive blunting with loading and the radius reaches a critical value ρ_L at the point of crack initiation and that

$$\rho_L = 0.5\ \delta_c \tag{2}$$

Thus the effect of temperature and strain rate on K_{IC} is reflected in two ways - firstly by virtue of their effect on yield strength and secondly through their effect on ρ.

The stress distribution ahead of a blunt crack [8] could not be used to examine experimental results since it is available only for a few σ_y/E values. On the other hand σ_y/E values change continuously in the experimental data obtained. The crack tip blunting effect is therefore assessed in an indirect manner.

The experimentally determined K_{IC} (J) values are suitably processed to calculate hypothetical K_{IC} (J) values as would be obtained if the crack tip were sharp. These hypothetical values are termed as K_{IC} (H). The K_{IC} (H) values are then compared with K_{IC} (NB), the fracture toughness values based on sharp crack stress distribution [6,7] and the two grain model [14]. At low σ_y/E values fracture of three grains is assumed to lead to fracture.

Calculation of $K_{IC}(H)$:

In the case of a blunt crack the stress σ_{yy} reaches a maximum value $\sigma_{yy}^{\max}$ at an approximate distance $X = 1.9\ \delta_t$ [8].

It has been shown [8] that crack opening displacement at the tip can be represented by

$$\delta_t = 0.717\ \frac{K^2}{E\ \sigma_y} \tag{3}$$

Therefore

$$(X)_{\sigma_{yy} = \sigma_{yy}^{\max}} = 1.9\ \delta_t = 1.362\ \frac{K^2}{E\ \sigma_y} \tag{4}$$

It is shown [27]

$$(X)_{\sigma_{yy} = \sigma_{yy}^{\max}} = \rho \left[\exp\left(\frac{\sigma_{yy}^{\max}}{\sigma_y} - 1\right) - 1\right] \tag{5}$$

At crack initiation $\sigma_{yy}^{\max} \rightarrow \sigma_f$, $\rho \rightarrow \rho_L$ and correspondingly $K_I \rightarrow K_{IC}$ (ρ). Combining equations (2), (4) and (5)

$$K_{IC}(\rho) = \frac{E\ \sigma_y\ \delta_c}{2.724} \left[\exp\left(\frac{\sigma_f}{\sigma_y} - 1\right) - 1\right]^{1/2} \tag{6}$$

where $K_{IC}(\rho)$ is the calculated fracture toughness for the different values of ρ_L and ρ_L value changes with strain rate and temperature.

$K_{IC}(\rho)$ can be calculated at various temperatures and strain rates since the experimental δ_c and σ_y are known and σ_f is calculated from the general yield and fracture initiation load as per a procedure reported in reference [1]. The calculated $K_{IC}(\rho)$ is plotted against the experimental $K_{IC}(J)$ values at various temperatures and strain rates in Figure 3. The experimental K_{IC} (J) values as reported in Figure 3 are obtained from equation (1). The $K_{IC}(J)$ values at intermediate strain rates and temperatures are obtained by graphical interpolation. The higher $K_{IC}(\rho)$ values could not be accommodated in the figure but they clearly obey the trend shown in the graph.

Figure 3 shows that $K_{IC}(\rho) = K_{IC}(J)$ up to $K_{IC}(J) = 60$ MPam$^{1/2}$ for the Mn-V steel and 50 MPam$^{1/2}$ for the ship building steel. Above these, the experimental $K_{IC}(J)$ changes linearly with $K_{IC}(\rho)$ and obeys an equation of the form

$$K_{IC}(J) = A + B \cdot K_{IC}(\rho) \tag{7}$$

where the constants A and B can be evaluated from Figure 3.

If ρ_L for a sharp crack is known, $K_{IC}(\rho)$ values for a sharp crack can be calculated from equation (6). In these calculations ρ_L corresponding to a sharp crack is assumed to be 2.7 µm since the fatigue crack width and the minimum δ_c value (at -196°C) is 5 to 6 µm. Once $K_{IC}(\rho)$ for a sharp crack is known the corresponding $K_{IC}(J)$ values for a sharp crack can be calculated from equation (7) and these $K_{IC}(J)$ values are termed as $K_{IC}(H)$, the hypothetical $K_{IC}(J)$ value for a sharp crack. The $K_{IC}(H)$ values calculated in this manner are plotted in Figure 4. These $K_{IC}(H)$ values can be compared with $K_{IC}(NB)$ values calculated at the different temperatures and strain rates since both these parameters refer to a sharp crack.

It should be noted that equation (6) and Figure 3 are not based on any microstructural features such as grain size. The change in slope of the lines at various points occur due to various reasons such as: 1) the crack tip becomes too blunt (of the order of the grain size) at higher $K_{IC}(J)$ values, to obey equation (3); 2) the fracture micromechanism changes from a stress induced to a strain induced one; 3) the higher $K_{IC}(J)$ values (>66 MPam$^{1/2}$ for Mn-V steel and >45 MPam$^{1/2}$ for ship building steel) are not derived from valid J_{IC} values and 4) there is a progressive loss of constraint at higher temperatures (i.e. higher $K_{IC}(J)$ values) and lower strain rates. It is interesting however to note that in spite of the above factors, the relation between $K_{IC}(J)$ and $K_{IC}(\rho)$ obeys a linear relationship as given by equation (7).

Calculation of $K_{IC}(NB)$:

The stress distribution ahead of the crack is influenced by n [8]. The result of the previous investigators [28,29] that n depends only on σ_y irrespective of temperature and strain rate was confirmed and the relations between σ_y and n for the two steels investigated were found out [5]. It was also confirmed from the examination [5] of the unnotched and notched tensile test data reported in reference [30,31] that n values are not significantly influenced by triaxiality. Thus n values of the material at the crack tip can be calculated from the σ_y value at a given temperature and crack tip strain rate.

Figure 4 in reference [8] plots σ_{yy}/σ_y versus $X/(K/\sigma_y)^2$ in case of a sharp crack for n values 0, 0.1 and 0.2. An approximate plot for n = 0.15 was generated by graphical interpolation. According to the two grain model [14], X = 2 grain diameter. With σ_f/σ_y and n values known for a given temperature and crack tip strain rate, the value of $X/(K_{IC}/\sigma_y)^2$ is known from the above figure. Since X is known the corresponding K_{IC} can be calculated. This K_{IC} is $K_{IC}(NB)$. The $K_{IC}(NB)$ values are also plotted in Figure 4.

It may be noted that at higher temperatures when σ_y values are low, σ_f is not reached in the very first grain near the crack tip. In these cases based on R_{max} quantity, a value of X=3 grain diameter is assumed and $K_{IC}(NB)$ values are computed.

Comparison of $K_{IC}(H)$ and $K_{IC}(NB)$:

The $K_{IC}(NB)$ values exhibit a somewhat irregular trend since the intermediate n values are appropriately approximated to either 0, 0.1, 0.15 or 0.2 in the calculations. If one were to ignore this irregularity, $K_{IC}(NB)$ values fall reasonably close to $K_{IC}(H)$ values up to a temperature where cleavage mode of fracture operates for a hypothetical sharp crack. The agreement between $K_{IC}(NB)$ and $K_{IC}(H)$ has an interesting consequence. The experimental $K_{IC}(J)$ values contain a contribution due to the crack tip blunting in addition to the contribution due to yield strength. It may be written as

$$K_{IC}(\text{Blunting}) = K_{IC}(J) - K_{IC}(H)$$

where $K_{IC}(H) = K_{IC}(NB)$.

CONCLUSIONS

1. In the specimen geometry investigated, the critical COD is observed to relate to J_{cr} by the relation

   $$\text{COD} = \frac{J_{cr}}{1.53}\ \sigma_y.$$

2. Experimental J_{IC} values show a reasonably good agreement with $\bar{G}_{IC}$ as long as J_{IC} measurements are valid.

3. Significant amount of crack tip blunting occurs during elastic-plastic loading situation and this contributes considerably to the toughness. The contribution can be evaluated from a relation of the type

   $$K_{IC}(\text{Blunting}) = K_{IC}(J) - A - B\sqrt{\rho_s}\ E\ \sigma_y \left[\exp\left(\frac{\sigma_f}{\sigma_y} - 1\right) - 1\right]^{1/2}$$

   where the value of ρ_s corresponds to the critical crack tip radius at the initiation of a sharp crack and A and B are numerical constants.

REFERENCES

1. MALKIN, J. and TETELMAN, A. S., Engng. Fracture Mech., 3, 1971, 151.
2. KNOTT, J. F., JISI, 204, 1966, 104.
3. RICE, J. R., J. Appl. Mech., 35, 1968, 379.
4. BEGLEY, J. A. and LANDES, J. D., ASTM STP 514 (II), 1972, 1.
5. PANDEY, R. K., Ph.D. Thesis, IIT-Bombay, 1976.
6. HUTCHINSON, J. W., J. Mech. and Phys. Solids, 16, 1968, 13.
7. RICE, J. R. and ROSENGREN, G. F., J. Mech. and Phys. Solids, 16, 1968, 1.
8. RICE, J. R. and JOHNSON, M. A., "Inelastic Behavior of Solids" (ed. Kanien, et al), McGraw Hill, New York, 1970.

9. TANAKA, J. P., PAMBILLO, C. A. and LOW, J. R., ASTM STP 463, 1970, 191.
10. PANDEY, R. K. and BANERJEE, S., Engng. Fract. Mech., 5, 1973, 965.
11. SPITZIG, W. A., ASTM STP 453, 1969, 90.
12. BROTHERS, A. J., et. al., ASTM STP 493, 1971, 3.
13. BATES, R. C., CLARK, W. G. and MOON, D. M., ASTM STP 453, 1969, 148.
14. RITCHIE, R. O., RICE, J. R. and KNOTT, J. F., J. Mech. and Phys. Solids, 21, 1973, 395.
15. Methods for COD Testing, DD19:1972, British Standards Institution, London.
16. BEGLEY, J. A. and LANDES, J. D., Westinghouse Scientific Paper 73-1E7-FMPWR-P3, October 1973.
17. BEGLEY, J. A. and LANDES, J. D., ASTM STP 514, 1972, 1.
18. EFTIS, J. and LIEBOWITZ, H., Engng. Fract. Mech., 7, 1975, 101.
19. HAYES, D. J., and TURNER, C. E., Int. J. Fract., 10, 1974, 10.
20. VEERMAN, C. C. and MULLER, T., Engng. Fract. Mech., 4, 1972, 25.
21. LANDES, J. D. and BEGLEY, J. A., "Guidelines for J_{IC} Tests", Report of ASTM Task Group E.24.01.09, 1974.
22. SHOEMAKER, A. K. and ROLFE, S. T., Trans. ASME, 91D, 1969, 512.
23. PANDEY, R. K., HARIDAS, J. D. and BANERJEE, S., Engng. Fract. Mech., 6, 1974, 105.
24. LEVY, N., et al., Int. J. Fract., 7, 1971, 143.
25. BOYLE, E. F. and WELLS, A. A., Report on 'Finite Element Study of Plane Strain Fracture Criteria Under Elastic Plastic Condition', June 1973, Queens Univ., Belfast.
26. DAWES, M. G., The Welding Institute Research Report, E/65/75, March 1975.
27. HILL, R., Mathematical Theory of Plasticity, Oxford Press, London 1950.
28. ROSENFIELD, A. R. and HAHN, G. T., Trans. ASM, 59, 1966, 962.
29. HOLLOMAN, J. H. and ZENER, C., Trans. AIME, 158, 1944, 283.
30. HAYDEN, H. W. and FLOREEN, S., Acta Met., 17, 1969, 213.
31. COX, T. B. and LOW, J. R., Met. Trans., 5, 1974, 1457.

Table 1 Chemical Analyses, Tensile Properties and Grain Size of Steels Investigated

Steel	C	Si	P	S	Mn	V	YS MPa	UTS MPa	E%	Average Grain Size in µm
Mn-V (TISCO)	0.20	0.235	0.032	0.027	1.60	0.12	434	600	38	18
Ship Building (Lloyds Grade A)	0.16	0.03	0.009	0.019	0.80	-	234	365	36	27

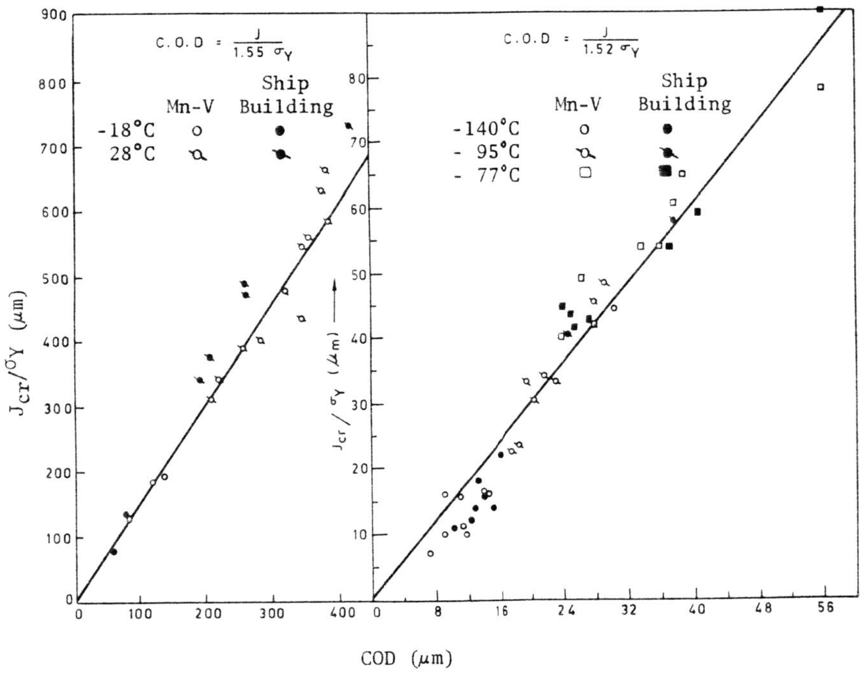

Figure 1 Relation Between Critical COD and J_{cr}/σ_Y

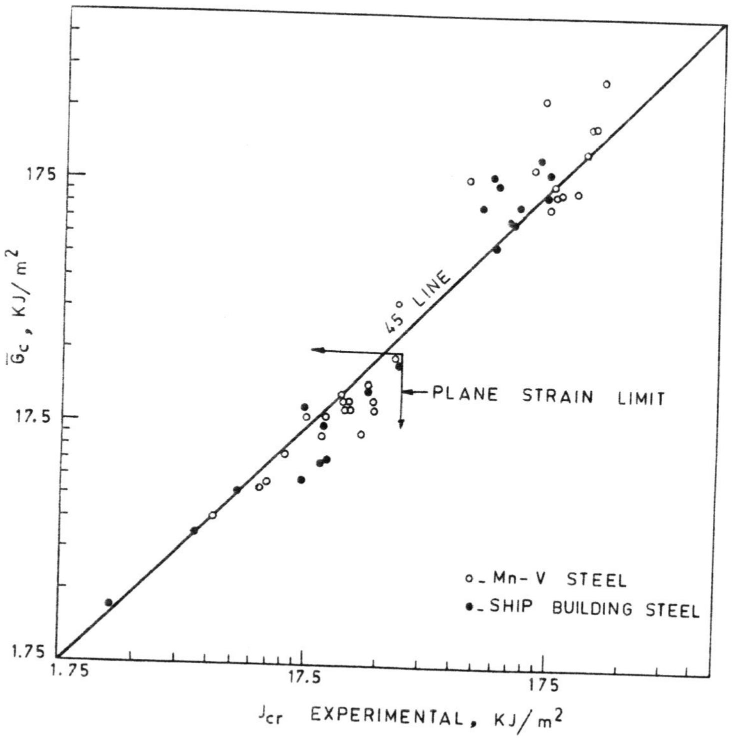

Figure 2 Comparison Between Experimental J_{cr} Values and $\bar{G}_c$ Values of Liebowitz and Eftis

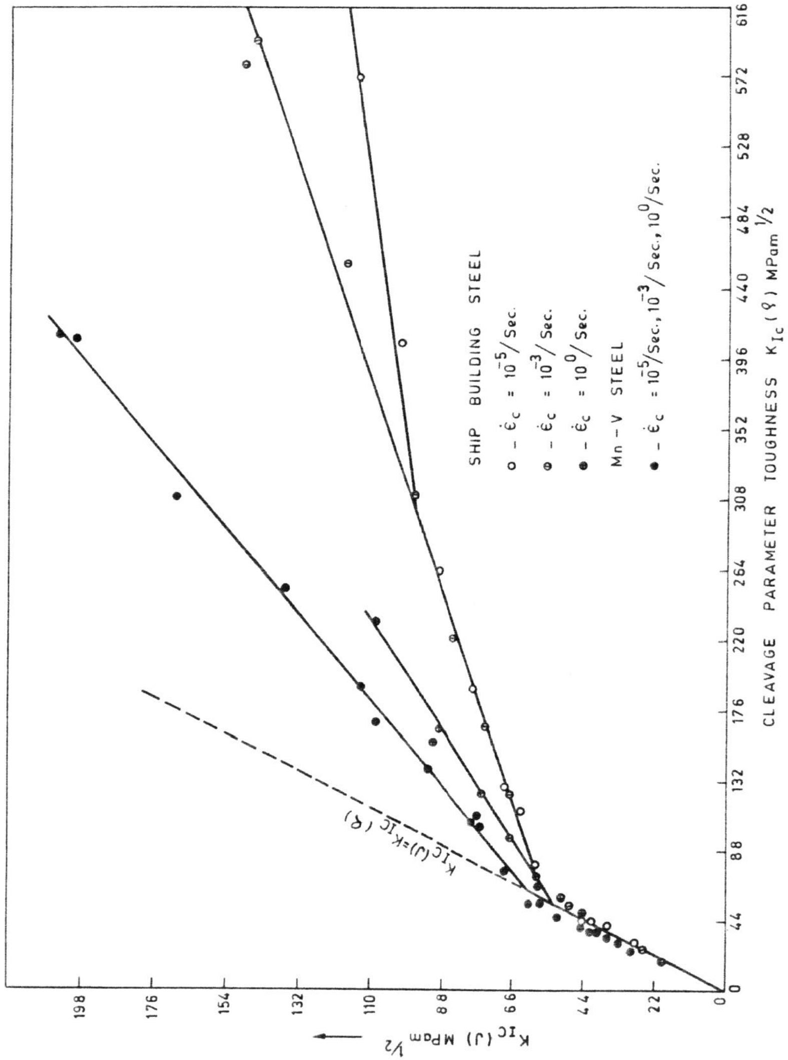

Figure 3 $K_{IC}(J)$ as a Function of Cleavage Parameter Toughness

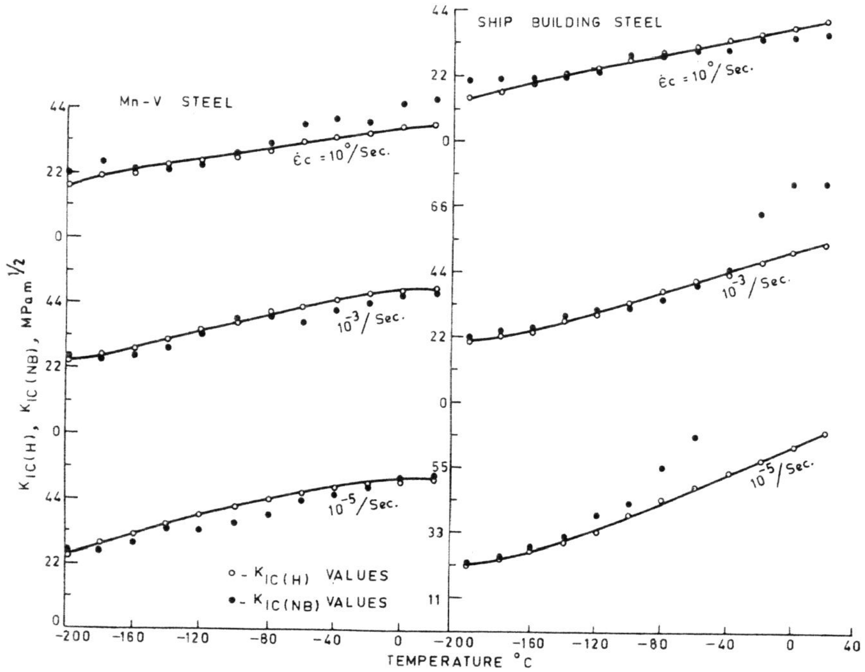

Figure 4 Temperature Variation of $K_{IC(H)}$ and $K_{IC(NB)}$