THE EFFECT OF MICROSTRUCTURE ON THE FRACTURE TOUGHNESS OF STRUCTURAL STEELS

M. HOLZMANN, B. VLACH, Z. BILEK

Institute of Physical Metallurgy, CAS, Zizkova 22, 616 62 Brno, Czechoslovakia

Abstract

Comprehensive research has demonstrated that fracture toughness K_{IC} may be uniquely related to the mechanical properties describing a material's behavior of the crack tip, and microstructure. In the work described in the present paper the behavior of crack in seven weldable low alloy structural steels having tensile strength σ_{TS} in the range of 455-765 MPa was investigated by measurement and observation of plane strain fracture toughness, tensile properties, and microstructure. The information thereby obtained was used to establish a sophisticated K_{IC} calculation model.

Making use of an elastic-plastic finite element program the normal stress distribution ahead of a crack was determined at various levels of work hardening as a function of the applied stress intensity factor and distance from the crack tip. The Tresca yield condition results in somewhat lower stresses than stresses calculated in the literature based on Mises yield condition. Using a critical stress criterion based on the cleavage stress σ_{CF} as the critical stress to be satisfied over some microstructurally significant distance - the process zone R_o ahead of the crack tip - we proposed the functional relationship $K_{IC} = f(\sigma_{CF}, \sigma_y, N, R_o)$ where σ_y denotes yield stress, and N the strain hardening exponent. Existing models predicting the dependence of K_{IC} on temperature are compared to our measurements taken over a wide range of temperature. This comparison clearly shows that the models which do not take into account the crack tip separation process itself do not agree with the experimental data. Therefore, the process zone size is the dominant microstructural factor controlling the fracture toughness and varies from two to six grain sizes depending on the particular microstructure.

The model proposed matches well with the experimental data and may be applied to find an optimum steel microstructure for given brittle fracture design requirements. In addition, the model provided a sound base for the assessment of simple correlations between K_{IC} and dynamic fracture toughness K_{Id}, between K_{IC} and NDT and finally between unirradiated and irradiated fracture toughness.

1. Introduction

The principles of fracture mechanics have provided the design engineer with a logical, quantitative analysis for predicting fracture by using the critical stress intensity factor - fracture toughness. Recently, considerable attention has been given to determining the relationship between uniaxial flow properties and the static fracture toughness K_{IC} [1-10]. The development of a relationship between the properties of uniaxial flow and fracture for a material brings several immediate benefits. First, the present Knowledge of the effects of external and metallurgical variables on the uniaxial flow properties could be used to predict changes in K_{IC}. Secondly, plane-strain values of K_{IC} could be predicted for conditions when laboratory test specimens would be too large for practical testing. Further increases in reliability or efficiency of nuclear power plant components require increases in resistance to the initiation and propagation of brittle cracks characterised by K_{IC} values. Consequently, much effort is being expended in understanding how microstructure affects K_{IC} data. For most structural members, increases in resistance to the initiation of brittle cracks must not be at the expense of the ability to resist fatigue and creep crack growth.

To investigate the sources of static fracture toughness in terms of microscopic and macroscopic mechanical properties, a detailed experimental study of the temperature dependence of K_{IC} and uniaxial flow properties was undertaken for low and intermediate strength steels. The measurements of K_{IC} for a static crack [9] as a function of temperature are reported in this paper on seven structural weldable steels having a room-temperature tensile strength σ_{TS} in the range of 455-765 MPa. The microstructure of the steels showed evidence of polygonal ferrite (or acicular ferrite) grains and ferrite-carbide regions. Because of limited length of this paper only the experimental data for two steels with σ_{TS} = 455 MPa (CSN 11 373 steel) and σ_{TS} = 680 MPa (C-Mn-Mo-Nb-V steel) are presented. The K_{IC} values were measured using the three point bend tests with slow loading rate of $\dot{K}$ = = 2.0 $MPam^{1/2}s^{-1}$ and dynamic loading rate $\dot{K} = 2.5.10^5$ $MPam^{1/2}s^{-1}$; the experimental data were evaluated using the procedure developed by Vlach et al [11]. Specimen design and the testing procedure were in general accordance with the current ASTM recommendations. The K_{IC} data were corrected for a plastic zone size and the J_{IC} path independent integral technique was applied to determine the valid values of K_{IC} at higher temperatures. An initial sharp fatigue crack was produced by cyclic loading with the stress intensity level K_f = 20 $MPam^{1/2}$.

In order to understand our experimental findings, we have had to set up a detailed theoretical description of stress field ahead of crack by finite element method [9] for the power hardening material. The values of K_{IC} are calculated with the aid of a critical stress criterion [9,10] which has a sound theoretical basis. The model is seen to predict well the experimentally determined variation of K_{IC} with temperature and makes it possible to find an optimum steel microstructure for given brittle fracture design requirements, although the stress analysis near crack is based on a number of simplifying assumptions about the fracture process at a crack tip.

2. Relationship Between Fracture Toughness and Microstructure

Fracture toughness is the critical stress intensity factor for significant crack growth to occur at the tip of an existing crack. It represents the inherent ability of the material to withstand the stress intensity near the crack tip, but does not characterize the separation process itself. The fracture process initiates deep in the plastic zone that encompasses the crack tip. The materials in this zone yields, flows, and finally fractures. Consequently, fracture toughness must be determined partly by the mechanical properties of the material near the crack tip on a microstructural scale. The scope of this paper is restricted to a discussion of transgranular, cleavage fracture modewhich occurs when the level of the maximum local tensile stress (Fig. 1) will reach a value of the critical cleavage stress σ_{CF}, required to propagate nuclei in cracked specimens of low alloy steels [10,11]. The values of σ_{CF} have been obtained from studies made on test pieces containing blunt notches (σ_{CF} = 1 150 MPa for CSN 11 373 steel and σ_{CF} = 1 450 MPa for C-Mn-Mo-Nb-V steel).

Empirical and theoretical models have been devised which incorporate the mechanical and metallurgical parameters affecting the toughness of metals.

2.1 Empirical Models

The empirical correlations for cleavage fracture between the plane strain crack toughness, σ_{CF} and yield stress σ_{Kt} were suggested in [1-3]

$$\frac{K_{IC}}{\sigma_{Kt}} = 2.5\ (\frac{\sigma_{CF}}{\sigma_{Kt}} - 1) \qquad (1)$$

$$\frac{K_{IC}}{\sigma_{Kt}} = (\alpha\ \frac{\sigma_{CF}}{\sigma_{Kt}})^{\beta} \qquad (2)$$

where α, β are empirical constants having average values of $\alpha = 1.38$ and $\beta = 3$ according [2]. Furthermore, Gerberich et al [3] developed a fracture model which gives

$$\frac{K_{IC}}{\sigma_{Kt}} = C\ (\frac{\sigma_{CF}}{\sigma_{Kt}} - 0.4)^{2} \qquad (3)$$

where $C \approx 1$.

2.2 Theoretical Models

Tetelman et al [4,5] have developed a simple model to determine K_{IC} in terms of the cleavage stress σ_{CF} and yield stress σ_{Kt} using Hill's rigid-plastic solutions for notched bars loaded in plane strain bending

$$\frac{K_{IC}}{\sigma_{Kt}} = 14.45 \left(e^{\frac{\sigma_{CF}}{\sigma_{Kt}} - 1} - 1\right)^{1/2} \sqrt{\rho_0} \qquad (4)$$

where ρ_0 is a critical value of the root radius ρ. For $\rho < \rho_0$ K_{IC} is independent of ρ. By examining a number of representative sets of experimental data eq. (4) was slightly modified [3]

$$\frac{K_{IC}}{\sigma_{Kt}} = \frac{\sigma_{CF}}{\sigma_{Kt}} \pi \left[\left(e^{\frac{\sigma_{CF}}{\sigma_{Kt}} - 1} - 1\right) \left(\frac{nd}{2}\right)\right]^{1/2} \qquad (5)$$

where nd represents an entire multiple of grain size d. Derivation of eq. (5) assumes that σ_{CF} is achieved over the distance nd in difference to eq. (4) which implicitly assumes that the value of σ_{CF} is reached only at one point on elastic-plastic boundary.

Applying Rice's small scale yielding stress and strain distribution [7] Krasovski [6] has suggested a correlation

$$\frac{K_{IC}}{\sigma_{Kt}} = \sqrt{\pi R_0} \left(\frac{\sigma_{CF}}{\sigma_{Kt}}\right) \left(\frac{\sigma_{CF}}{\sigma_{Kt}}\right)^{\frac{1-N}{2N}} \qquad (6)$$

similar to a relationship

$$\frac{K_{IC}}{\sigma_{Kt}} = p(N) \sqrt{R_0} \left(\frac{\sigma_{CF}}{\sigma_{Kt}}\right)^{\frac{1+N}{2N}} \qquad (7)$$

proposed by Bilek [9] using the same stress analysis [7]. R_0 is the process zone size over which a value of σ_{CF} is reached and N denotes the strain hardening exponent N defined by the well known power function.

Ritchie, Knott and Rice [8,10] have presented an analysis which related σ_{CF} to K_{IC}. The analysis is based on accurate numerical elastic-plastic solutions for the stress distribution ahead of a sharp crack. Unstable fracture was found to be consistent with the attainment of a stress intensification close to the tip such that the maximum tensile stress σ_{yy} exceeds σ_{CF} over a characteristic distance termed as process zone size R_0. It is possible to calculate K_{IC} directly from a knowledge of R_0, σ_{Kt}, N, σ_{CF} and from stress distribution in Fig. 2. Essentialy this approach was adopted in this paper however Rice's stress analysis [7,8] was replaced by our finite element computations [9] shown in Fig. 2. From this figure we can determine R_0 for given material knowing σ_{CF}, σ_{Kt} and K_{IC} at the same temperature and loading rate. Therefore from known temperature dependence of σ_{Kt} and σ_{CF} we find out dependence of K_{IC} on temperature assuming R_0 is temperature insensitive.

2.3 Results and Discussion

The data of Fig. 3 indicate that a unique relation exists between

K_{IC}/σ_{Kt} and σ_{CF}/σ_{Kt} for all investigated steels. The experimental points are bounded by the results for 11 373 and C-Mn-Mo-Nb-V steels for which further data are shown (Figs. 4-7) in various coordinates. The coordinate systems were chosen in such a way that eqs. (1-5) give linear relationship between $\sigma_{CF}/\sigma_{Kt} \sim K_{IC}/\sigma_{Kt}$. It is seenthat the eqs. (1-5) when applied to our steels do not explain the measured temperature dependence of K_{IC} in the particular form of Figs. 4 to 7 over a wide range of testing temperatures. The disagreement between experiment and eqs. (1) - (7) observed namely at low values of K_{IC}/σ_{Kt} (Fig. 3) suggests that some materials parametr identified later in [8,9] as the process zone size R_0 is missing in eqs. (1-5). On the other hand the procedure developed by Ritchie et al [8] when combined with our stress analysis - Fig. 2 matches well our experimental findingsas demonstrated in Fig. 8.

3. Conclusions

The results of an investigation to develop a correlation between K_{IC} and crack tip mechanical properties of steels having widely different strength levels may be briefly summarized as follows.

1.) The values of K_{IC} are a unique function of the crack tip yield stress σ_{Kt} - Fig. 3.
2.) The accurate correlation of K_{IC} with σ_{CF}, σ_{Kt}, N and R_0 is derivable from crack tip stress analysis and critical tensile stress criterion for transgranular cleavage fracture.
3.) The approach applied in this paper predicts K_{IC} values which are in better agreement with the experimental measurements than K_{IC} values predicted by methods developed up to now.
4.) The established functional relationship $K_{IC} = f(\sigma_{CF}, \sigma_{Kt}, N, R_0)$ makes possible to derive relation between K_{IC} and dynamic fracture toughness K_{Id} [11] and also explains the temperature shift of irradiated K_{IC} data [12].

References

[1] HAHN, G. T., ROSENFIELD, A. R., "Relations between Microstructure Toughness of Metals," Trans. ASM 59, pp. 909-920, (1966).

[2] HAHN, G. T., HOAGLAND, R. G., ROSENFIELD, A. R., "The Variation of K_{IC} with Temperature and Loading Rate," Metallurgical Trans. 2, pp. 537-541, (1971).

[3] GERBERICH, W. W., ZACKAY, V. F., PARKER, E. R., PORTER, D., "The Role of Grain Boundaries on Crack Growth," In: Ultratine Grain Metals, Sagamore, USA, (August 19-22), 1969.

[4] MALKIN, J., TETELMAN, A. S., "Relation between K_{IC} and Microscopic Strength for Low Alloy Steels," Engineering Fracture Mechanics 3, pp. 151-167, (1971).

[5] TETELMAN, A. S., WULLAERT, D., IRELAND, D., "Prediction of Variation in Fracture Toughness from Small Specimen Tests", Proc. Practical Application of Fracture Mechanics to Pressure-Vessel Technology London, England, (May 3-5, 1971).

[6] KRASOVSKI, A. J., NADĚŽDIN, G. N., "Physical Aspect of Plasticity in Linear Fracture Mechanics," Proc. the III. Int. Conf. on Fracture Munich, Germany, (March 15-18, 1973).

[7] RICE, J. R., ROSENGREN, G. F., "Plane Strain Deformation Near a Crack Tip in a Power Law Hardening Material," J. Mech. Phys. Solids 16, pp. 1-12, (1968).

[8] RITCHIE, R. O., KNOTT, J. F., RICE, J. R., "On the Relationship between Critical Tensile Stress and Fracture Toughness in Mild Steel", J. Mech. Phys. Solids 21, pp. 395-410, (1973).

[9] HOLZMANN, M., VLACH, B., BILEK, Z., MAN, J., "Relationship between Microscopic and Macroscopic Fracture Properties, Res. Rep. UFM CSAV, Brno, (December 1975).

[10] KNOTT, J. F., "Micro-Mechanisms of Fracture and the Fracture Toughness of Engineering Alloy," Proc. Conf. on Fracture ICF4 Waterloo, Canada, (June 19-24, 1977).

[11] VLACH, B., MAN, J., HOLZMANN, M., BILEK, Z., "The Relation between Static and Dynamic Fracture Toughness of Structural Steels," Proc. Conf. on Fracture ICF4 Waterloo, Canada, (June 19-24, 1977).

[12] BILEK, Z., "On the Influence of Irradiation on Fracture Toughness", Engineering Transactions 29, (1980) in press.

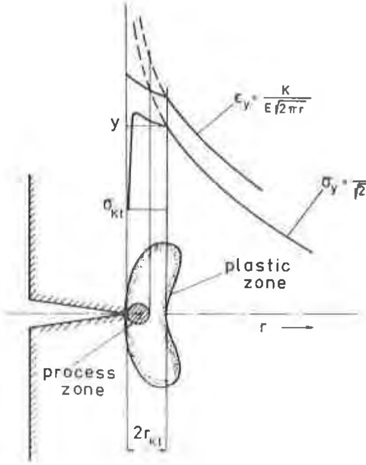

Fig. 1: Schematic illustration of stress and strain distribution at a crack tip.

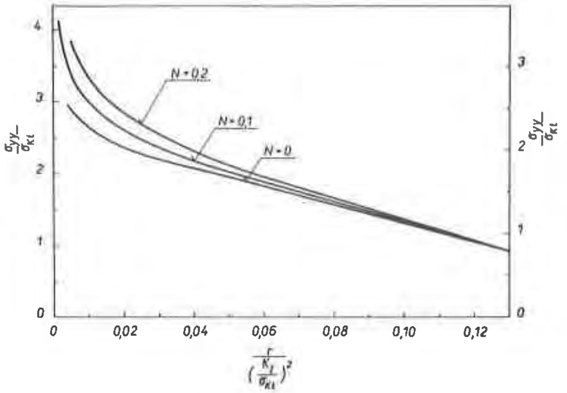

Fig. 2: Distribution of longitudial tensile stress σ_{yy} acting directly a head of a sharp crack in plane strain for power work-hardening material from finite-element computer solution due to Bilek [9]. The left hand side scale is for Mises material and the right hand side scale is for Tresca material.

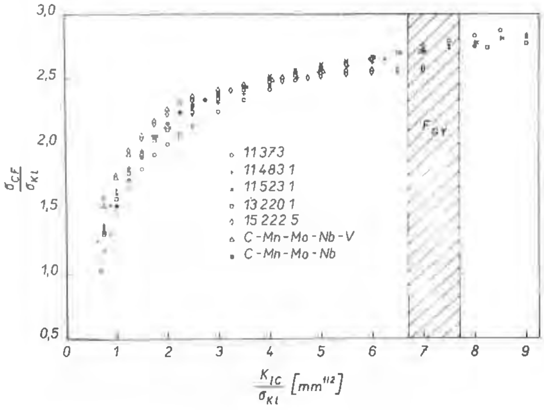

Fig. 3: Experimentally determined dependence σ_{CF}/σ_{Kt} on K_{IC}/σ_{Kt}.

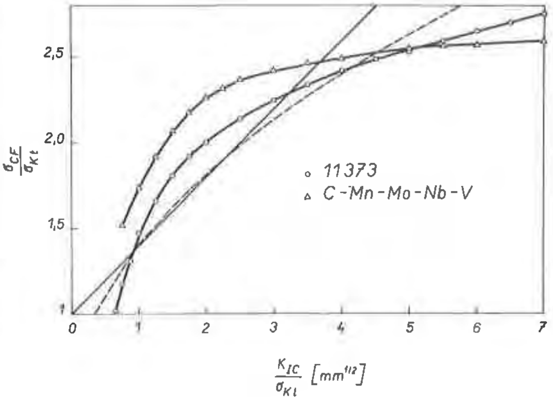

Fig. 4: Comparison of experimental data with eqs. (1) —— and (3) ----

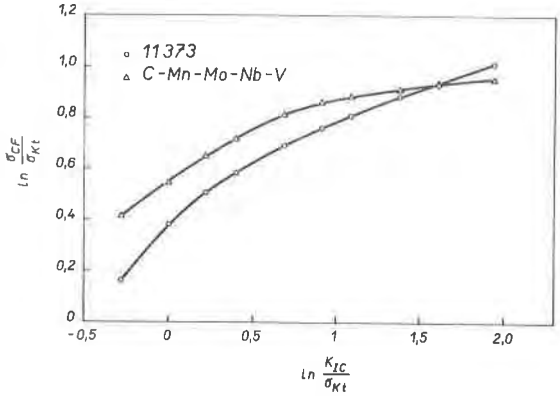

Fig. 5: Comparison of experimental data with eqs. (2), (6) and (7).

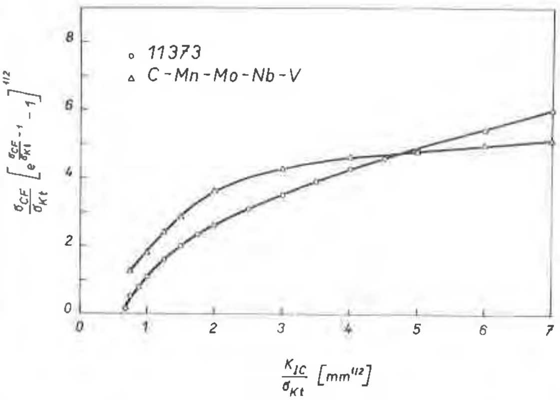

Fig. 6: Comparison of experimental data with eq. (4).

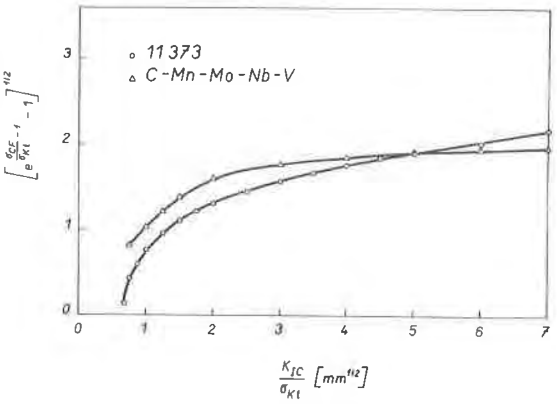

Fig. 7: Comparison of experimental data with eq. (5).

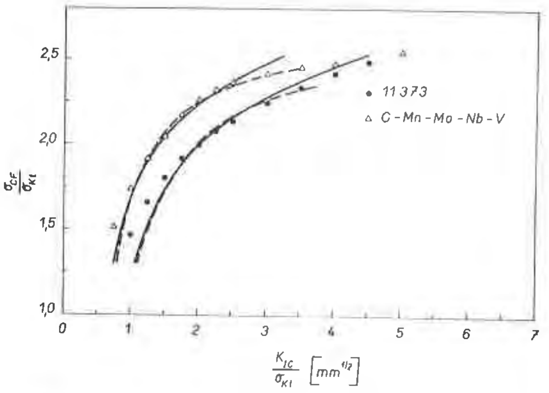

Fig. 8: Comparison of experimental data with the models proposed in [8,9] applying the stress analysis of Fig. 2 for Tresca material N = 0.1, R_0 = 5D for CSN 11 373 steel and R_0 = 7D for C-Mn-Mo-Nb-V steel. Dashed line shows Ritchie et al prediction [8] with R_0 = 6D for CSN 11 373 steel and R_0 = 8D for C-Mn-Mo-Nb-V steel, N = 0, D is average grain size.