FRACTURE TOUGHNESS PREDICTION OF STRUCTURAL FERRITE-BAINITIC STEELS

B. Strnadel*, E. Mazancová**, K. Mazanec***

A statistical model for fracture toughness prediction of a steel having mixed ferrite-bainitic microstructure with precipitated spheroidal carbide particles is presented. The model provides a rational relationship between statistical distribution of cracked carbide particles and fracture toughness. The predicted temperature trend in fracture toughness agrees with the results of measurements.

INTRODUCTION

The carbides of the ferritic (Curry and Knott (1)),and/or bainitic (Wallin et al (2)) steels have been evidenced to be sites for nucleation of the transgranular cleavage failure. The propagation of a carbide particle microcrack into the matrix is assumed to occur at the critical stress characteristic of the carbide strength σ_f. For a spheroidal particle containing a penny-shaped crack, σ_f is related to the particle size 2r as: $\sigma_f = \{\pi E \gamma_{eff} / [(1-\nu^2) 2r]\}^{1/2}$, where γ_{eff} is the effective surface energy of the matrix, E is Young's modulus and ν is Poisson's ratio. The propagation and linking of the initiated microcracks lead to the formation of a main crack and to the final fracture instability (Figure 1). The origin of the cleavage fracture path x_o needs not to be fallen in the fatigue crack tip.

* Vítkovice, Steel and Engineering Works, 70602 Ostrava
** Research Institute, The New Metall. Works, 70702 Ostrava
*** Technical University, 70833 Ostrava-Poruba, Czechoslovakia

Propagating fatigue crack is blunted by slip mechanism and so called stretched zone is formed.

The fracture instability state given by the critical value of the stress intensity factor was predicted in relation with the cleavage strength σ_f and the effective limiting crack sharpness ϱ_o, in the following form (Malkin and Tetelman (3)):

$$K_{IC}(\sigma_f) = 2{,}89\,\sigma_y\,[\exp(\sigma_f/\sigma_y - 1) - 1]^{1/2}\sqrt{\varrho_0} \qquad \ldots\ldots(1)$$

where σ_y is the yield stress. The parameter ϱ_0 is determined by some microstructural feature, such as grain size or interparticle spacing and by statistical nature of cleavage fracture. The statistical models for fracture toughness prediction based on the evaluation of initiated carbide microcracks and the main crack propagation have been proposed. However, application of such models is limited to tempered ferritic (1), and/or bainitic steels (2). The present work deals in detail with the conditions of prediction of fracture toughness in the case of steel with tempered mixed ferrite--bainitic microstructure.

STATISTICAL MODEL

From the analysis presented in introduction follows the carbide size 2r to be microstructural parameter controlling microcrack initiation. Taking into account the probability density of carbide sizes precipitated in bainite, and/or ferrite $\varphi_B(2r)$, and/or $\varphi_F(2r)$ and using stress criterion for carbide microcrack initiation, the probability density of "microscopic" cleavage fracture stress can be expressed in the following form:

$$\varphi_B(\sigma_{fB}) = \left(\frac{2\pi E\,\gamma_{effB}}{(1-\mu^2)\,\sigma_{fB}^3}\right)\varphi_B\left(\frac{\pi E\,\gamma_{effB}}{(1-\mu^2)\,\sigma_{fB}^2}\right) \qquad \ldots\ldots\ldots(2)$$

where γ_{effB} is the effective surface energy of bainite. Using eqn. (1) and transforming eqn. (2) the probability density of the "microscopic" fracture toughness K_{IC}^B can be found in form of:

$$\psi_B(K_{IC}^B) = \frac{4hq_B K_{IC}^B}{[1+h(K_{IC}^B)^2][1+\ln(1+h(K_{IC}^B)^2)]}\,\varphi_B\left(\frac{q_B}{[1+\ln(1+h(K_{IC}^B)^2)]}\right) \qquad \ldots\ldots\ldots(3)$$

where $h = (2{,}89\,\sigma_y\sqrt{\varrho_0}\,)^{-2}$ and $q_B = \pi\cdot E\cdot\gamma_{effB}/[(1-\mu^2)\,\sigma_y^2]$. In the same manner one can determine the function of probability density of the "microscopic" fracture toughness $\psi_F(K_{IC}^F)$.

The brittle failure initiation arises when acting stress in the distance x from the cleavage fracture path origin $\sigma(x) \geq \sigma_{FB}$, and/or σ_{FF} . Therefore, the probability of brittle fracture initiation in bainite, and/or in ferrite can be written as follows:

$$P_B(x) = 1-\int_0^{K_{IC}} \psi_B(K_{IC}^B)\,dK_{IC}^B \quad \text{and/or} \quad P_F(x) = 1-\int_0^{K_{IC}(\sigma(x))} \psi_F(K_{IC}^F)\,dK_{IC}^F \qquad \text{.........(4)}$$

Providing that the processes of microcrack initiation in bainite and in ferrite do not eliminate mutually, then probability of cleavage failure initiation in the microstructural system in question is expressed by the following relationship:

$$P_{B,F}(x) = 1-\int_0^{K_{IC}(\sigma(x))} \psi_B(K_{IC}^B)\,dK_{IC}^B \int_0^{K_{IC}(\sigma(x))} \psi_F(K_{IC}^F)\,dK_{IC}^F \qquad \text{.......(5)}$$

Considering the probability of cleavage failure initiation is given by the probability density of "macroscopic" fracture toughness $\psi_{B,F}(K_{IC})$ in the form:

$$P_{B,F}(x) = 1-\int_0^{K_{IC}(\sigma(x))} \psi_{B,F}(K_{IC})\,dK_{IC} \qquad \text{.......(6)}$$

then the distribution function of predicted "macroscopic" fracture toughness in given as follows:

$$\Psi_{B,F}(K_{IC}) = \Psi_B(K_{IC})\,\Psi_F(K_{IC}) \qquad \text{.......(7)}$$

where $\Psi_B(K_{IC})$, and/or $\Psi_F(K_{IC})$ is the distribution function corresponding to the probability density $\psi_B(K_{IC})$, and/or $\psi_F(K_{IC})$. Using the temperature dependence of the yield stress and the effective surface energy of bainite, and/or ferrite (2), the lower bound of K_{IC} on the chosen level $(1-\alpha)$ can be obtain in the following form:

$$K_{IC}(1-\alpha) = \Psi_{B,F}^{-1}(\alpha) \qquad \text{.......(8)}$$

where $\Psi_{B,F}^{-1}(\alpha)$ is the inverse function of $\Psi_{B,F}(K_{IC})$.

MODEL APPLICATION

Evaluation was made for Nb microalloyed low carbon steel having the following chemical composition in wt%: 0,16%C; 0,95%Mn; 0,26%Si; 0,018%P; 0,018%S; 0,049%Al and 0,043%Nb. The material in question was treated as follows: 1100°C/30min/water; 650°C/100h/air.

The microstructure of investigated steel consisted of a mixture of tempered bainite ($q_B = 0{,}80$) and of ferrite ($q_F = 0{,}20$) with precipitated spheroidal carbide particles. The probability density of carbide sizes was found by the maximum likelihood method in the Weibull's form:

$$\varphi_B(2r) = \varphi_F(2r) = \frac{\beta}{\ell}\left(\frac{2r}{\ell}\right)^{\beta-1} \exp\left[-\left(\frac{2r}{\ell}\right)^{\beta}\right] \qquad \ldots\ldots\ldots(9)$$

where $\beta = 2{,}71$ and $\ell = 0{,}44$. The probability density functions $\varphi_B(2r)$, $\varphi_F(2r)$ and corresponding distribution functions are depicted in Figure 2. The obtained temperature dependence of the yield stress is given by following Table 1.

TABLE 1 - Temperature dependence of the yield stress of the investigated steel

T [K]	57	69	78	87	97	107	119	133
σ_y [MPa]	1000	900	850	800	750	700	650	600

The envelope curve of the experimental values of fracture toughness K_{IC}^{exp} derived from the values found in the three-point bending test is illustrated in Figure 3. The effective limiting crack sharpness ϱ_0 was considered as temperature independent. It was experimentally confirmed $\varrho_0 \approx 4\ \mu m$. The predicted lower bound of fracture toughness on $(1-\alpha)$ level was obtained using eqns. (8) and (9) as:

$$K_{IC}(1-\alpha) = \left[h^{-1} \exp\left\{\left[-\left[\left(\frac{q_B}{\ell}\right)^{\beta} + \left(\frac{q_F}{\ell}\right)^{\beta}\right]^{-1} \ln\alpha\right]^{-1/2\beta} - 1\right\} - 1\right]^{1/2} \ldots\ldots(10)$$

For $\alpha = 0{,}05$ and $0{,}10$ temperature dependences of $K_{IC}(1-\alpha)$, $K_{IC}^{B}(1-\alpha)$ and $K_{IC}^{F}(1-\alpha)$ are shown in Figure 3.

DISCUSSION

The proposed method of fracture toughness evaluation applied for evaluation of a tempered microalloyed steel with a mixed ferrite-bainitic microstructure enables to predict the lower bound of $K_{IC}(1-\alpha)$ values on the chosen level $(1-\alpha)$. The predicted temperature dependence of $K_{IC}(1-\alpha)$ for $\alpha = 0{,}05$ and $0{,}10$ is in good conformity with temperature dependence of experimentally determined lower bound of $K_{IC}(1-\alpha)$ values (eqn. (10)) as it is shown in Figure 3. In Figure 4 is depicted the dependence of predicted $K_{IC}(1-\alpha)$ values for α = 0,05 and 0,10 on the experimental values. It is obvious that the zone between the predicted and experimentally determined K_{IC} values with increasing temperature, and/or fracture toughness is widening. While for the temperature of 60 K this difference is about 2 MPa $m^{1/2}$, for 130 K this difference is 7 MPa $m^{1/2}$. The dependence of predicted values of K_{IC} (0,90) and K_{IC} (0,95) on the experimental K_{IC}^{exp} values is not linear as it was found (2) but it has a hyperbolic character.

CONCLUSION

The proposed solution of fracture toughness prediction of steel with tempered mixed ferrite-bainitic microstructure enables to determine the distribution of "macroscopic" values of fracture toughness and their lower bound on the chosen level. The maximum difference between experimental and predicted values is in average 3 MPa $m^{1/2}$ which can be considered as very good conformity.

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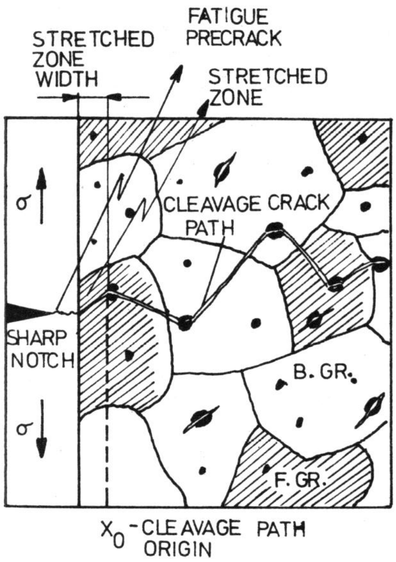

Figure 1 Scheme of crack propagation

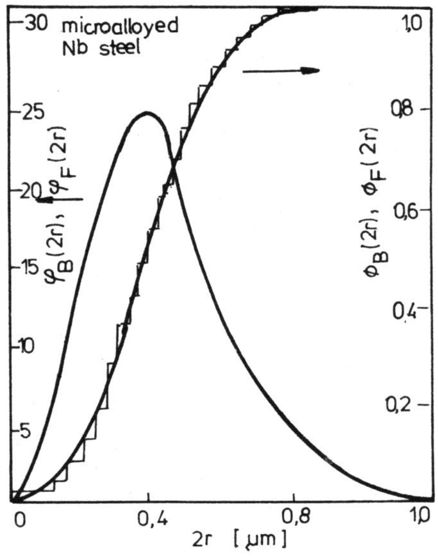

Figure 2 Distribution function of carbide sizes

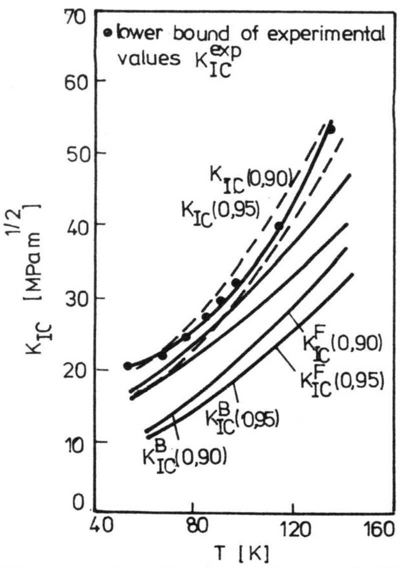

Figure 3 Exp. and pred. K_{IC} values vers. temperature

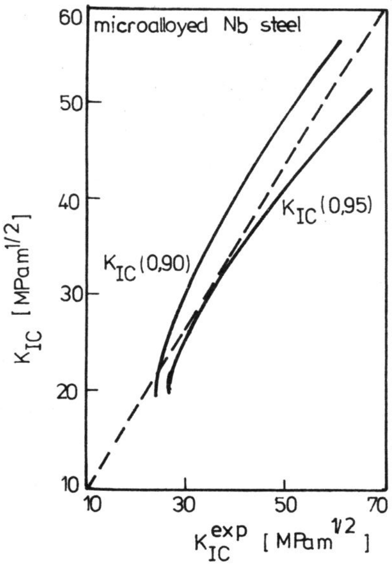

Figure 4 Relationship between K_{IC} exp. and pred.