MODELLING OF CLEAVAGE FRACTURE IN MICROALLOYED STEELS WITH MIXED FERRITE-BAINITIC STRUCTURE

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Model of fracture toughness prediction for tempered bainite-ferritic steel with spheroidal carbide particles is presented. The effect of discrete carbide particles and the effect of local relative concentration of carbides on the fracture toughness values are evaluated. Application of the model on microalloyed Nb steel provides a very good conformity of the predicted fracture toughness values with the experimental ones. The relative error in the investigated temperature region is not greater than 10 %.

INTRODUCTION

In the RKR-model of the fracture toughness prediction for the ferritic steels Ritchie et al (1) have assumed the cleavage fracture would originate up to the characteristic distance X^* at the crack tip, where the normal tensile stress $\sigma(X)$ is surpassing the fracture stress of material Σ_f. On the basis of known function of stress distribution at the crack tip under plaine strain conditions:

$$F\left(\frac{X\sigma_y^2}{K_I^2}\right) = \frac{\sigma(X)}{\sigma_y} \qquad (1)$$

where X is distance from the crack tip, K_I is stress intensity factor and σ_y is yield stress, the predicted

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fracture toughness could be calculated as follows:

$$K_{IC} = \sigma_y (X^*)^{1/2} \left\{ F^{-1} \left(\frac{\Sigma_f}{\sigma_y} \right) \right\}^{-1/2} \qquad (2)$$

Curry and Knott (2) presented the statistic model of prediction of fracture toughness for ferritic steels with spheroidal carbides. This model is based on assumption that a cleavage fracture would initiate by microcracks even in the particles of brittle phase as proposed by Guarland (3) . The model has been further developed by Wallin et al (4) also for the bainitic steel of 15Cr2.5MoV type. The microstructural fracture toughness σ_{fB} and/or σ_{fF} indispensable for initiation of a microcrack of the same size as is that of carbide precipitated in bainitic and/or ferritic matrix, can be determined from the Griffith's criterion:

$$\sigma_{fB}(r) = \left[\frac{E \pi \gamma_{effB}}{2(1-\nu^2) r} \right]^{1/2} ; \qquad \sigma_{fF}(r) = \left[\frac{E \pi \gamma_{effF}}{2(1-\nu^2) r} \right]^{1/2} \qquad (3)$$

where E is the modulus of elasticity, γ_{effB} and/or γ_{effF} is the effective surface energy of bainite and/or ferrite, ν is the Poisson's number and r is radius of a carbide particle. While the models (2) , (4) have evaluated fracture toughness from the statistic viewpoint of crack initiation in discrete carbide particles precipitated in the homogeneous matrix of bainite and/or ferrite, attention is devoted in this work to fracture toughness prediction for steel with a mixed bainite-ferritic structure and with spheroidal carbides. Nevertheless, this model is applied for determination of the fracture toughness values based on the size distribution of carbide particle radii and of the distribution of their planar concentration in matrix.

MODEL

When assuming the proportion of bainite and/or ferrite q_B and/or q_F in the microstructure of steel, then the probability density of the spheroidal carbide particle radii in the entire system $\varphi(r)$ can be written as follows:

$$\varphi(r) = q_B \varphi_B(r) + q_F \varphi_F(r) \qquad (4)$$

where $\varphi_B(r)$ and $\varphi_F(r)$ are the probability densities of the carbide particle radii in bainite and in ferrite. Then, for this case the planar density of carbides in bainite N_{AB} and/or in ferrite N_{AF} is expressed as:

$$N_{AB} = \frac{q_B^{-1} N_A}{1 + 1/Q} \quad ; \quad N_{AF} = \frac{q_F^{-1} N_A}{1 + Q} \qquad \dots\dots (5)$$

where N_A is the total planar density of carbides and Q is parameter characterizing the relationship between their planar densities in the individual phases and the proportions of these phases in microstructure of steel:

$$Q = \frac{N_{AB}\, q_B}{N_{AF}\, q_F} \qquad \dots\dots (6)$$

Knowing the function of probability density of the carbide particle radii in bainite $\varphi_B(r)$ and/or in ferrite $\varphi_F(r)$ one can determine the elementary probability of a brittle failure initiation up to the distance X_B and/or X_F from the crack tip in a carbide particle of the size of $r \in (r; r + dr>$ $\psi_B(r)\,dr$ and/or $\psi_F(r)\,dr$ as follows:

$$\psi_B(r)dr = 1 - \exp\left[S\theta_B N_{AB} q_B X_B^2 \ln(1 - \varphi_B(r)dr)\right] \quad \text{and/or}$$

$$\psi_F(r)dr = 1 - \exp\left[S\theta_F N_{AF} q_F X_F^2 \ln(1 - \varphi_F(r)dr)\right] \qquad \dots\dots (7)$$

where S is a factor describing the shape of the plastic zone and θ_B and/or θ_F is a factor characterizing the fraction of the carbide particles taking part in the cleavage failure process. When assuming the processes of a brittle microcrack initiation would not eliminate one another, then the elemental probability of a brittle failure initiation is expressed as:

$$\psi_{B,F}(r)dr = \psi_B(r)dr + \psi_F(r)dr - \psi_B(r)\psi_F(r)d^2r \qquad \dots\dots (8)$$

Under conditions of a cleavage fracture initiation when the total probability set from equation (8) is equal one, by its rearranging, for $\varphi_B(r) = \varphi_F(r) = \varphi(r)$ and $\theta_B = \theta_F = \theta$ and with equations (1) and (3), one obtains the resulting formula for prediction of the fracture toughness $K_{IC}^{B,F}$:

$$K_{IC}^{B,F} = \sigma_y \left\{ S\theta N_A \int_r \left[\left(1 + \frac{1}{Q}\right)^{-1} \left(F^{-1}\left\{\frac{\sigma_{fB}(r)}{\sigma_y}\right\}\right)^2 + (1 + Q)^{-1} \left(F^{-1}\left\{\frac{\sigma_{fF}(r)}{\sigma_y}\right\}\right)^2 \right] \varphi(r)\,dr \right\}^{-1/4} \qquad \dots (9)$$

Evaluation of the fracture toughness based on the distribution of planar concentration of carbides and on assumption that probability of occurrence of the n-carbide particles in the investigated area A, $\xi(n, A)$ would be governed by the Poisson's distribution:

$$\xi(n,A) = \frac{1}{n!}\,(N_A A)^n \exp(-N_A A) \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (10)$$

Then, the concentration c of the n-carbide particles in the area A and/or the mean concentration $\langle c \rangle$ can be defined as follows:

$$c = \frac{n}{A}\int_0^{\infty} \varphi(r)\,\pi r^2 dr \;;\quad \langle c \rangle = \frac{N_A c A}{n} \quad \ldots\ldots\ldots\ldots\ldots \quad (11)$$

By applying of the relative concentration $C = c/\langle c \rangle$ and of equation (11) one can express the local relative concentration of carbides in an area of $1/N_A$ as the limit term:

$$\lim_{A \to 1/N_A} \xi(n,A) = \xi(C) = \frac{1}{eC!} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (12)$$

where e is the base of natural logarithms. When considering $C! = \Gamma(C+1)$, then the probability density of the local relative concentration of carbide particles makes:

$$\tilde{\varphi}(C) = \left\{\Gamma(C+1)\int_0^{\infty} \frac{dC}{\Gamma(C+1)}\right\}^{-1} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (13)$$

where integral is the normalizing factor.

When applying equations (7) to (9), for the same preconditions as those considered in previous case, the predicted fracture toughness is expressed in the following terms:

$$\tilde{K}_{IC}^{BF} = \sigma_y\left\{S\,\tilde{\Theta}\,N_A \int_C \left[\left(1+\frac{1}{Q}\right)^{-1}\left(F^{-1}\left\{\frac{\sigma_{fB}(C)}{\sigma_y}\right\}\right)^2 + (1+Q)^{-1}\left(F^{-1}\left\{\frac{\sigma_{fF}(C)}{\sigma_y}\right\}\right)^2\right]\tilde{\varphi}(C)\,dC\right\}^{-1/4} \quad (14)$$

where $\tilde{\Theta}$ is a factor characterizing the elementary areas $1/N_A$ taking part during the failure process and $\sigma_{fB}(C)$ and/or $\sigma_{fF}(C)$ is the microstructural cleavage strength in the region with local relative concentration of carbides C as calculated of equation (3).

MATERIAL AND TECHNIQUE

The investigation was performed on the rolled microalloyed Nb steel having the following chemical analysis (wt%): 0.18%C; 0.95%Mn; 0.25%Si; 0.018%P; 0.018%S and 0.049%Nb. This steel was subjected to heat treatment as follows: 1100°C/1 h/water; 650°C/100 h/air. Jaffe and Hollomon tempering parameter M^* was 20.3 . 10^3. The testing material was taken from thick-walled pipes of Ø168/16 mm in longitunidal direction. The microstructure consists of tempered ferritic zones $q_B = 0.20$ and of tempered bainitic zones $q_F = 0.80$ with spheroidal carbide particles. For the purpose of statistic analysis the testing material was etched in 4 % HNO_3 solution and the carbide particles were measured on surface of etched specimens, by means of SEM with a magnification of 2000 x 1.5. The overall planar density of carbides was calculated as $N_A = 53.8 \cdot 10^{10} m^{-2}$ and the parameter Q was 40. The histogram of relative frequency $\omega(r)$ and the determined distribution function $\tilde{\omega}(r)$ of radii of the carbide particles are shown in Figure 1. Figure 2 shows the function of probability density of local relative concentration of carbide particles $\tilde{\varphi}(C)$; see equation (13).

For the sake of verification of the coincidence of the planar distribution of carbide particles with the Poisson's distribution (equation (11)) the number of carbides was determined on 103 areas a = 10 x 10 mm in size at magnification of 3 000. By a statistic coincidence test at the significance level $\alpha = 0.05$ has found, that mean value of number of carbides on the area a is equal variance of number of carbides on the area a, which is in conformity with the applied preconditions. The temperature dependence of the yield stress of the investigated steel is given in Figure 3. The temperature dependence of the fracture toughness $K_{IC}^{exp}(T)$ was determined from temperature dependence of the notch toughness values as proposed by Barsom (5) and Mazancová et al (6).

RESULTS

The function of stress distribution at the crack tip under the plane strain condition for the yield stress values lying within 500 and 1 000 MPa and for material with strain hardening exponent n = 0.2, which is in conformity with the investigated steel and the temperature dependence of τ_{effB} and/or τ_{effF} were used in present investigation as in case (4). The critical stress $\sigma_{fB}(r)$

and/or $\sigma_{fF}(r)$ was calculated (equation (3)) for given radius (r) of a carbide particle precipitated in the bainitic and/or ferritic matrix. From such stress and with aplication of equation (1) one can calculate the distance X from the crack tip at which a carbide particle with radius r could still initiate a crack. Thus, the critical radius of carbide is expressed by a complex function $r_B(\sigma(X))$ and/or $r_F(\sigma(X))$. The temperature dependence of that function in the site of maximum stress concentration ($X = X_0$) is illustrated in Figure 4. This figure shows simultaneously the temperature dependence of the critical local relative concentration $C_B(\sigma(X_0))$ and/or $C_F(\sigma(X_0))$ determined with application of equations (11), (3) and (1). Figure 5 shows the dependence of the critical value of C_B and/or C_F on the parameter $[X/(K_I/\sigma_y)^2]$ for the temperatures of 57 and 69 K.

The factor describing the shape of the plastic zone was chosen, in conformity with (2); for the case in question as S = 8, which refers to the shape of double lobe. The factor characterizing the fraction of the carbide particles θ and/or of the investigated elements (with area $1/N_A$) $\tilde{\theta}$ taking part in the process of brittle failure initiation was chosen the same as elsewhere (2), (4), say $\theta = \tilde{\theta} = 0.01$.

Figure 6 shows the summary comparison of the predicted temperature dependence of $K_{IC}^{B,F}$ and/or $\tilde{K}_{IC}^{B,F}$-values (equation (9) and/or (14)) with the K_{IC}^{exp}-values found experimentally. This figure is completed simultaneously by the temperature dependence of the $(K_{IC}^{B,F} \cdot M_{B,F}^{-1})$ and/or $(\tilde{K}_{IC}^{B,F} \cdot \tilde{M}_{B,F}^{-1})$ parameter. The parameter $M_{B,F}$ and/or $\tilde{M}_{B,F}$, representing the relation between the predicted $K_{IC}^{B,F}$ and/or $\tilde{K}_{IC}^{B,F}$-values and the microstructural parameters, can be defined as follows (2):

$$M_{B,F} = \frac{K_{IC}^{B,F}\,\Omega^{1/4}}{\sigma_y} \; ; \quad \tilde{M}_{B,F} = \frac{\tilde{K}_{IC}^{B,F}\,\tilde{\Omega}^{1/4}}{\sigma_y} \qquad \text{.....................} \quad (15)$$

where $\Omega = \frac{N_A}{q_B}\left(1+\frac{1}{Q}\right)^{-1}\int_{r}\left(F^{-1}\left\{\frac{\sigma_{fB}(r)}{\sigma_y}\right\}\right)^2 \varphi(r)\,dr + \frac{N_A}{q_F}(1+Q)^{-1}\int_{r}\left(F^{-1}\left\{\frac{\sigma_{fF}(r)}{\sigma_y}\right\}\right)^2 \varphi(r)\,dr$

In similar manner one can determine the value of $\tilde{\Omega}$. As can be seen the two parameters $M_{B,F}$ and $\tilde{M}_{B,F}$, in the temperature region of the transcrystalline cleavage fracture, are practically independent of temperature, and they reach $M_{B,F} = \tilde{M}_{B,F} \cong 2.00$, as found even elsewhere (2). This parameter $M_{B,F}$ and/or $\tilde{M}_{B,F}$, however, does not present exact conformity of the predicted and experimentally measured fracture-toughness values and thus, the parameter $\bar{M}_{B,F}$ and/or $\tilde{M}_{B,F}$:

$$\bar{M}_{B,F} = \frac{K_{IC}^{exp} M_{B,F}}{K_{IC}^{B,F}} \; ; \quad \bar{\bar{M}}_{B,F} = \frac{K_{IC}^{exp} \tilde{M}_{B,F}}{\tilde{K}_{IC}^{B,F}} \qquad 16$$

should be used here. The parameter $\bar{M}_{B,F}$ and/or $\bar{\bar{M}}_{B,F}$ reveals decreasing tendency with rising temperature and it varies, at the investigated temperature region, from 2.5 to 1.8 and/or from 2.8 to 1.8.

DISCUSSION

This presented model of the fracture toughness prediction for steels with a mixed bainite-ferritic structure with spheroidal carbide particles was realized from the viewpoint of both the statistic distribution of carbide particle radii (equation (9)) and the statistic distribution of the local relative concentration of carbide particles. It takes into account the effect of carbide particles precipitated both in the bainitic and in ferritic matrix, on the process of initiation of a cleavage microcrack. While in the former the critical size of a carbide particle $r_B(\sigma(X))$ and/or $r_F(\sigma(X))$ is the criterion for initiation of a cleavage microcrack, in the latter the critical value of the locally relative concentration of carbides, $C_B(\sigma(X))$ and/or $C_F(\sigma(X))$ is of utmost significance. Thus, a cleavage failure can initiate, according to the second model, at the crack tip in the plastic zone, where radius of any carbide does not surpass the critical value of $r_B(\sigma(X))$ and/or $r_F(\sigma(X))$, however, the local relative concentration of carbides is higher than $C_B(\sigma(X))$ and/or $C_F(\sigma(X))$.

The predicted $\tilde{K}_{IC}^{B,F}$-values in the temperature region of transcrystalline cleavage failure are approx. by 2 MPa m$^{1/2}$ smaller than those of the prediction of $K_{IC}^{B,F}$ (Figure 6). The accordance between the predicted fracture toughness ($K_{IC}^{B,F}$ and/or $\tilde{K}_{IC}^{B,F}$) and the experimentally determined K_{IC}^{exp}-values seems to be quite good here and the relative error is not greater than 10 %.

Comparison of the temperature dependence of minimum carbide particle radius taking part at cleavage failure, i. e. $r_B(\sigma(X_o))$ and/or $r_F(\sigma(X_o))$ with temperature dependence of the minimum local relative concentration of carbide particles $C_B(\sigma(X_o))$ and/or $C_F(\sigma(X_o))$ shows the same character for the two dependences as it follows from Figure 4. The dependence of the critical value of local relative concentration of the carbide particles C_B on the $[X/(K_I/\sigma_y)^2]$ -value (Figure 5) for selected temperatures shows that with increasing temperature and increasing distance from the crack tip, the local relative concentration is increasing too, which is necessary for initiation of cleavage fracture.

CONCLUSION

The presented results confirmed the possibility of application of that model for the fracture toughness prediction in structual steels with mixed microstructure, which provides good preconditions for application of that model at numerous types of steels. A certain precisioning of the existing modes for the fracture toughness prediction was reached at evaluation based on knowledge of the relative carbide particle concentration.

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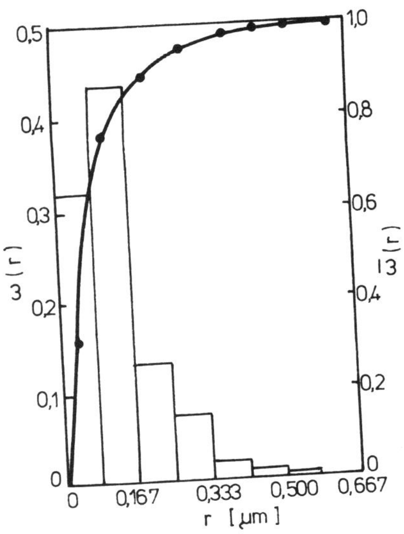

Figure 1 Statistics of carbide particles

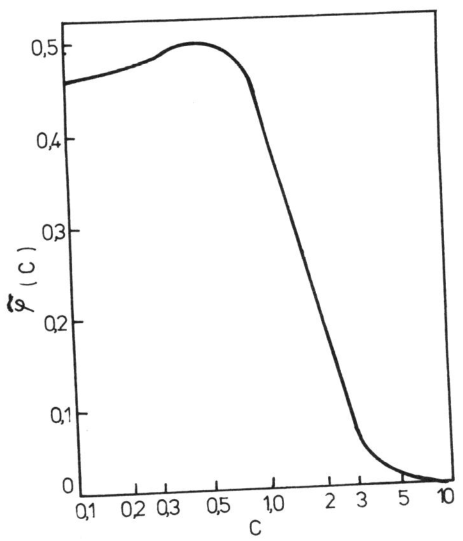

Figure 2 Local concentration of carbide particles

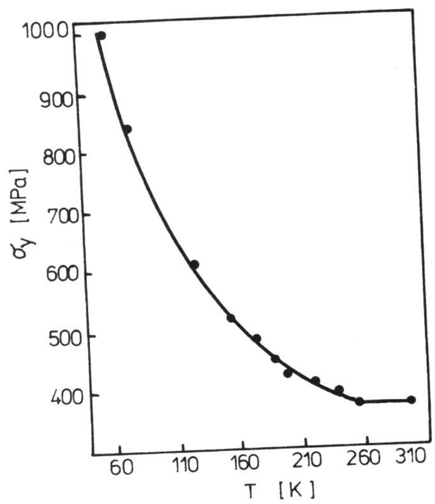

Figure 3 Yield stress of the investigated steel

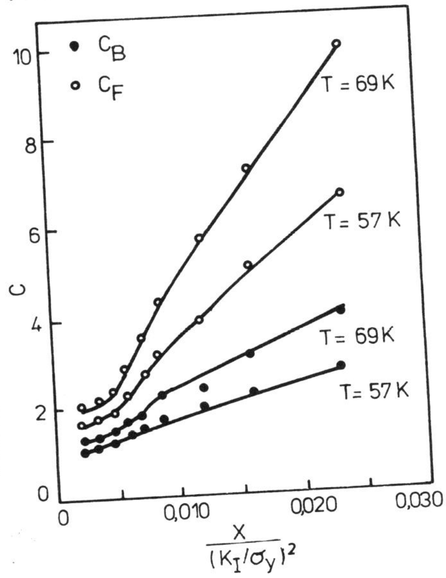

Figure 5 Critical carbide concentration at crack tip

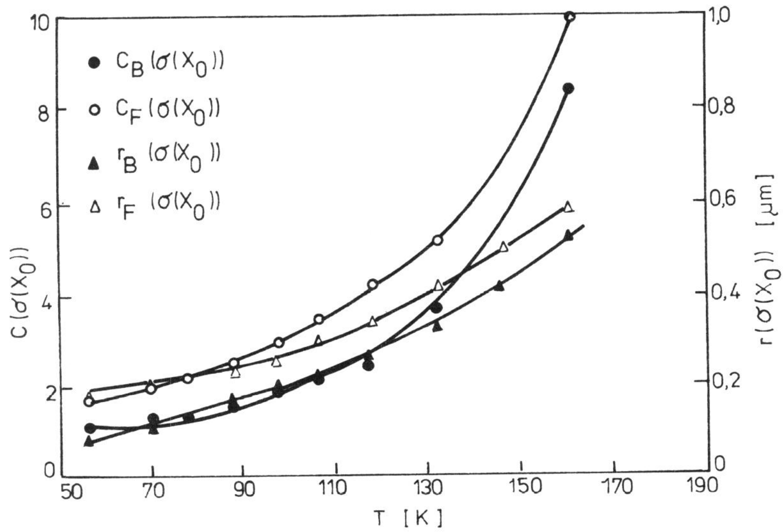

Figure 4 Minimum radii, local carbide concentration

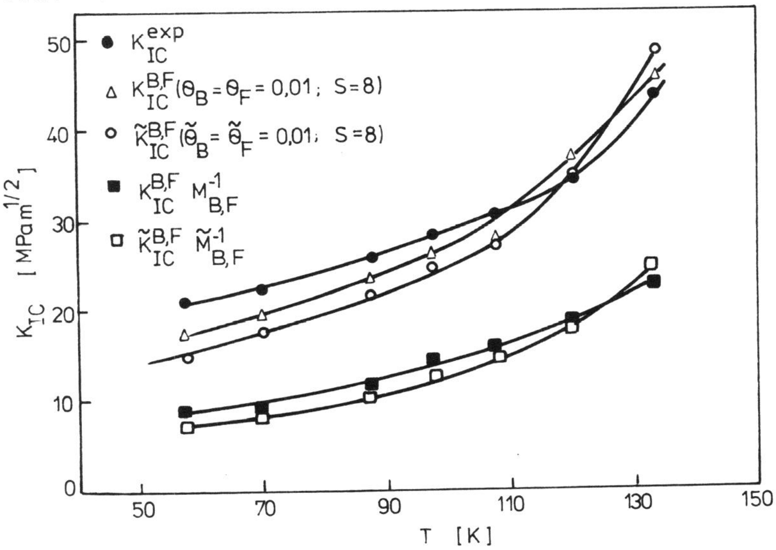

Figure 6 Predicted and experimental K_{IC} -values