Cleavage fracture prediction in pressure vessel steels

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1 INTRODUCTION

The fracture instability of the tempered ferrite-bainitic steels with precipitated carbide particles may be caused by two micromechanisms of cleavage failure (Strnadel et.al. 1986a,b).When the normal tensile stress $\sigma(x)$ exceeds the microstructural cleavage strength σ_{fB}, the microcracks initiated in carbide particles start to extend into matrix (Curry and Knott 1978):

$$(1)\quad \sigma_f = \left[\frac{\pi \cdot E \cdot \gamma_{effB}}{2(1-\nu^2)r}\right]^{1/2}$$

where E is Young's modulus, γ_{effB} is the effective surface energy of bainite, ν is the Poisson's ratio and 2r is diameter of the carbide particle. Mutual interaction of the moving dislocations in the ferritic matrix under the tensile stress $\sigma(x)$ leads to the formation of cleavage dislocations. The coalescence of such dislocations is associated with microcrack initiation (Cottrell 1958). The microscopic cleavage strength σ_{fF} is in this case expressed as follows:

$$(2)\quad \sigma_{fF} = \frac{2G\gamma_{effF}}{k_y^2\ d^{1/2}}$$

where G is the shear modulus, k_y^s is the Hall-Petch shear constant and d is the size of a ferrite grain.

The propagation and linking of the initiated microcracks lead to the initiation of a main crack and to the final failure (Rawall and Gurland 1977). The maximum probability of coalescence of the microcracks is delimitated by the active volume in front of a precracked specimen (Evans 1983):

$$(3)\quad f(x) = \pm \mathcal{S} \cdot x^{\varkappa}$$

where $\varkappa \leq 1$ determines the shape of active volume and $\mathcal{S}$ is coefficient characterizing the prevailing orientation in propagation of main crack. The initiated microcracks, situated outside the active volume, remain stationary. Because of the local character of initiation of the cleavage microcracks and their random distribution, the fracture path has stochastic character.

The presented study is an attempt to predict the cleavage fracture path and the cleavage fracture toughness of steels with tempered ferrite-bainitic structure being used for manufacture of the pressure componts of the primary circuit of the nuclear power plants.

2 MODELLING OF THE FRACTURE PATH AND OF FRACTURE TOUGHNESS

Modelling of the fracture path and of fracture toughness of the steel grade in question is going out from the assumption that the microcracks would be initiated in the carbide particles, precipitated in bainite (Curry and Knott 1978) and in the ferrite grains by a coalescence of dislocations (Cottrell 1958). The effect of fine carbide particles precipitated in ferrite on the fracture path was neglected (Strnadel et.al.1986a, Strnadel et.al.1986b).

Knowing planar density of carbide particles in the bainitic matrix, and/or of ferrite grains N_{AB}, and/or N_{AC} and application of eqn (3) one can calculate the expected number of carbide particles, and/or ferrite grains m_B (x_r, x_s), and/or m_c (x_r, x_s) in an element of active volume given by the coordinates x_r, x_s, (Figure 1).

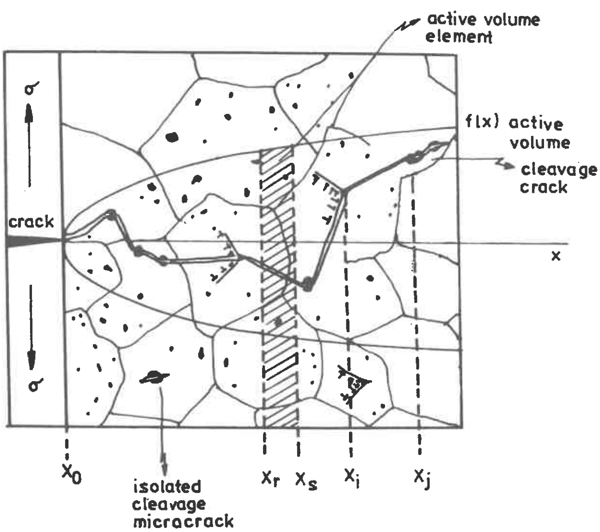

Figure 1. Scheme of initiation of microcracks and the fracture path.

In the k^{th} element of the active volume only the carbide particle, and/or the ferrite grain of maximum size take part in the fracture process. If ϕ_B (2r), and/or ϕ_C(d) is the distribution function of the sizes of carbide particles, and/or ferrite grains, then the distribution function of maximum size of the carbide particle, and/or ferrite grain in the considered element of active volume is expressed as follows:

$$(4)\quad \phi_{max,B}\left[2r, m_B(x_{r_k}, x_{s_k})\right] = \sum_{p_B=1}^{\infty} Q_B\left[m_B(x_{r_k}, x_{s_k}), p_B\right] \phi_B^{p_B}(2r),$$

and/or

$$(5)\quad \phi_{max,C}\left[d, m_C(x_{r_k}, x_{s_k})\right] = \sum_{p_C=1}^{\infty} Q_C\left[m_C(x_{r_k}, x_{s_k}), p_C\right] \phi_C^{p_C}(d)$$

where p_B, and/or p_C is the number of carbide particles, and/or ferrite grains in the considered element and Q_B, and/or Q_C are the probabilities of realization of the given number of carbide particles, and/or ferrite grains. The probability of propagation of the microcrack initiated in the element of active volume is given by the probability of overpassing the critical size of the considered microstructural components:

$$(6)\quad R^{B,C}\left[\sigma(x_k), x_{r_k}, x_{s_k}\right] = 1 - q_B\, \phi_{max,B}\left[2r_B(\sigma(x_k))\right] - q_C\, \phi_{max,C}\left[d_C(\sigma(x_k))\right]$$

where q_B, and/or q_C is the volume fraction of the bainitic, and/or ferritic matrix and $2r_B\,(\sigma(x_k))$, and/or $d_C(\sigma(x_k))$ is the critical size of the carbide particle, and/or ferrite grain calculated of eqn (1), and/or eqn (2). The microcracks initiated in carbide particles and in ferrite grains determine orientation of the segment of a cleavage crack during its propagation from the starting site x_o to the site x_n at the elastic-plastic interface of the precracked specimens. The probability of crack propagation from site x_i to site x_j (eqn (6)) can be written as follows:

$$(7)\quad P_{i,j}^{B,C} = \prod_{k=i+1}^{j} \left\{\delta_{k,j} \cdot R^{B,C}\left[\sigma(x_k), x_{r_k}, x_{s_k}\right] + (-1)^{\delta_{k,j}}\left[1 - R^{B,C}(\sigma(x_k), x_{r_k}, x_{s_k})\right]\right\}$$

for $i < j$

$$(8)\quad P_{i,j}^{B,C} = 0 \qquad \text{for } i > j$$

$$(9)\quad P_{i,i} = \prod_{k=i+j}^{n+1} \left\{1 - R^{B,C}\left[\sigma(x_k), x_{r_k}, x_{s_k}\right](\delta_{k,(n+1)} - 1)\right\}$$

where $i, j = 0, 1, 2 \,.....\, n$ and $\delta_{k,j}$ is the kronecker delta. The values $P_{i,j}^{B,C}$ are the elements of matrix $\mathbf{P}^{B,C}$ with a dimension of $(n+1).(n+1)$, in which the line vector $\mathbf{P}_i^{B,C}$ represents the probability of all the possible pathes of a crack propagating from the site x_i to site x_j. The probability of crack stability in the active volume can be expressed as follows:

$$(10)\quad U=\sum_{i=0}^{n-1} V_i \prod_{\substack{j=0\\ j\neq i}}^{n-1}(1-V_j)$$

where V_i represents the elementary probability of propagation of a crack from site x_o to site x_i and its arrest in this site. In view of the fact that the fracture toughness is a controling parameter of crack stability, it can be approximated in the simplest form as follows:

$$(11)\quad K_{IC} = const\ U$$

By assuming the $Q_B\,[m_B(x_{r_k}\,,\,x_{s_k})],\ p_B$ value is conforming to the Poisson's distribution, then

$$(12)\quad Q_B\left[1/N_A\,,\,p_B\right]=\lim Q_B\left[m_B(x_{r_k}\,,\,x_{s_k}),p_B\right]=\frac{1}{e\,C!}$$

where $(1/N_A)$ is the area allocated per one carbide, -e- is the base of natural logarithms and C is the local relative concentration of carbide particles expressed as:

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

The probability of cleavage failure initiation in carbide particle, and/or in ferrite grain within a distance of x from the precrack is expressed as:

$$(14)\quad \xi_B(C)dC=1-\exp\left\{S\cdot\tilde{\theta}_B\cdot N_{AB}\cdot q_B\, x^2\, \ln\left[1-\tilde{\psi}(C)dC\right]\right\},$$

and/or

$$(15)\quad \xi_C(d)dd=1-\exp\left\{S\cdot\tilde{\theta}_C\cdot N_{AC}\cdot x^2\cdot \ln\left[1-\varphi_C(d)dd\right]\right\}$$

where S is a factor describing the shape of the plastic zone and $\tilde{Q}_B$, and/or $\tilde{Q}_C$ is factor characterizing the fraction of carbide particles, and/or ferrite grains taking part in the cleavage fracture process. When assuming the two processes would not eliminate one another, then the predicted fracture toughness can be written as follows:

$$(16)\quad \tilde{K}_{IC}^{B,C}=\sigma_y\Big[S\cdot\tilde{\theta}_B\cdot N_{AB}\cdot q_B\int_{C_B(\sigma(x_o))}^{C_B(\sigma(x_n))}\left\{F^{-1}\left[\sigma_{fB}(C)/\sigma_y\right]\right\}^2\psi_B(C)dC+ + S\cdot\tilde{\theta}_C\cdot N_{AC}\int_{d_C(\sigma(x_o))}^{d_C(\sigma(x_n))}\left\{F^{-1}\left[\sigma_{fC}(d)/\sigma_y\right]\right\}^2\varphi_C(d)dd\Big]^{-1/4}$$

where C_B is the critical local relative concentration of carbide particles calculated according eqn (1)), σ_y is the yield stress of investigated steel and F^{-1} is the inverse function of stress distribution at the crack tip.

3 APPLICATION OF THE MODEL

To apply this model the steel of 10MnNi2Mo grade (Strnadel et.al. 1986a), whose microstructure consits of a mixture of tempered bainite (q_B = 0,5) and ferrite (q_F = 0,5), was used. The sizes of carbide particles precipitated in bainitic matrix were measured on a strongly etched surface(SEM). The sizes of ferrite grains were determined by means of a light microscopy. The statistical distribution of sizes of the two microstructural components was found to agree with the Weibull´s distribution (Figure 2). The statistical test of

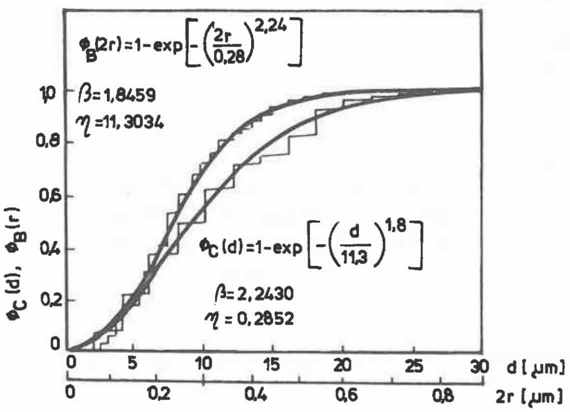

Figure 2. The distribution function of the carbide particles and of the ferrite grains.

conformity showed that Q_B and Q_C values correspond to the Poisson´s distribution. The function of stress distribution at the crack tip for yield stress from 500 to 1000 MPa and for the of strain hardening exponent of 0,2 was considered according to (Wallin et.al.1984). The effective surface energy of the bainitic, and/or ferritic matrix γ_{efFB}, and/or γ_{efF} was considered as a temperature dependent value (Wallin et.al.1984). The elements of matrix $P^{B,C}$(eqns (7)--(9)) were calculated using the $R^{B,C}[\sigma(x_k)\ x_{rk}\ ,\ x_{sk}]$ values. The probability determination of crack stability in the active volume (eqn(12)) was approximated for $V_i = P^{B,C}_{ii}$, $P^{B,C}_{oi}$. The active volume at the tip of crack was considered in shape of a wedge for the parameters of ϑ= 0,05 and $\varkappa$= 1, see eqn (3).

The temperature dependence of U-value, together with the temperature dependences of the experimental and of the predicted values of the fracture toughness K_{IC}^{exp} and K_{IC} (eqn (11)) for const.=3,6 x 10^5, are illustrated in Figure 3. The dependences of the critical local relative concentration C_B on the $(x\sigma^2/K_{IC}^2)$ parameter for the temperatures of 153 and 160 K are shown in Figure 4.

The temperature dependences of the predicted K_{IC}, and/or $\tilde{K}_{IC}^{B,C}$ values(eqn(11) and eqn(16)) demonstrate good conformity

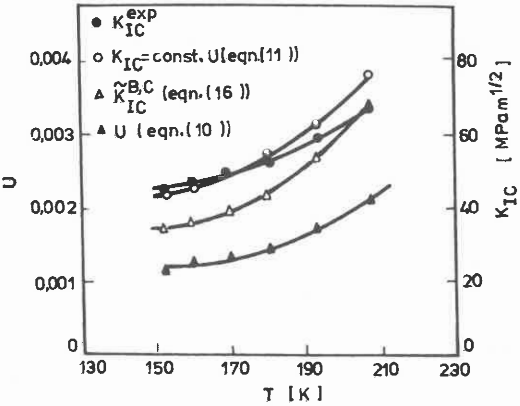

Figure 3. The temperature dependences of the predicted and experimental K_{IC} values and of the probabilities of crack stability U in the active volume.

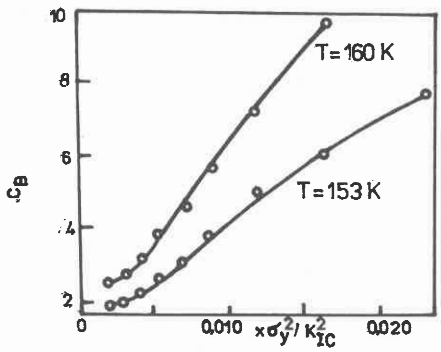

Figure 4. Dependence of the critical relative concentration on the $(x\,\sigma_y^2/K_{IC}^2)$ parameter.

with the temperature dependence of the experimental K_{IC}^{exp} values (Figure 3).

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