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Local Approach to Fracture Based Prediction of Reactor Pressure Vessel Lifetime

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New version of the local approach to fracture is presented. Within the framework of this approach a new methodology is developed, which supposes prediction of radiation life time of a reactor pressure vessel not by ultimate shift of the Charpy critical temperature, ΔT_K, or by reference temperature, ΔT_0, but by the condition of brittle fracture initiation of irradiated metal ahead of a crack tip in reactor pressure vessels.

Keywords: local approach, reactor pressure vessel (RPV) steels, RPV lifetime, fracture toughness, local stress.

Introduction. A critical-temperature-shift-based methodology is used for assessment of irradiation embrittlement of pressure vessel steels. Conventionally, the Charpy temperature shift methodology is utilized. Moreover, the attempts are made to use the Master curve technique [1] to solve this problem. Recently, the local approach to fracture (LAF) has been developed [2], which can be used as a powerful tool for solving this problem [3].

The aim of this study is to present a new version of the local approach to fracture and to exhibit ability of its application to predict pressure vessel lifetime.

Theory. In the general case, the statistical criterion of brittle fracture of a specimen or a structural element with a crack may be presented as

$$F_{\Sigma} = 1 - \prod_{1}^{M} (1 - F_i), \tag{1}$$

where F_{Σ} is the value of tolerance for the probability of fracture of the total cracked body, F_i is the probability of fracture of an elementary volume, and M is the number of such elementary volumes within the "process zone", i.e., within the region where the crack nuclei form.

The value of F_i is usually assessed on the base of the weakest link principle, which gives the approximate equation:

$$F_i \approx 1 - \exp\left[-\rho_i V_i \left(\frac{\sigma_1^i - \sigma_{th}}{\sigma_u} \right)^m \right], \tag{2}$$

where ρ_i is the rate of the crack nuclei (CN) generation within the volume unit of metal at given value of plastic strain, V_i is the elementary volume, σ_1^i is the maximum tensile stress within ith elementary volume, and σ_{th}, σ_u, and m are the parameters of the Weibull distribution.

To ascertain relation between the value of local stress σ_1^i at the moment of fracture and the macroscopic characteristic of loading, for instance, K_{Jc}, a nonlinear boundary value problem for a cracked body should be solved. The finite element method (FEM) enables one to find the value of K_{Jc} with a priori given probability of fracture F_Σ. Such approach is realized in physical (*ab initio*) version of LAF presented in [3]. The difference is that probability of fracture of an elementary volume, F_i, was determined not by the approximate formula (2) but directly by computer simulation of the crack nuclei (CN) formation and instability.

However, analytical expression for the local fracture criterion is more acceptable for engineering calculations. As known for a cracked body, stress and strain distributions ahead of a crack tip are scaled in units J_I/σ_Y, where J_I is the value of J-integral, and σ_Y is the yield strength. It means that at the fixed value of J_I/σ_Y, an unambiguous relation between the maximum value of the local probability of fracture initiation ahead of a crack, $F_i^{\max}$, and the total probability of fracture of a cracked body F_Σ, must exist. It enables one, using (2), to obtain the expression for the value of local strength of metal, σ_f, at given value of general probability F_Σ:

$$\sigma_f = \sigma_{th} + \sigma_u \left[-\frac{\ln(1 - F_i^{\max})}{\rho_i V_i} \right]^{1/m}. \tag{3}$$

Respectively, the criterion of fracture initiation may be presented as

$$\frac{\sigma_f}{\sigma_1} \le 1. \tag{4}$$

In [4], it is shown that the value of the above ratio excess over the unit characterizes stability of ductile state of metal in the crack vicinity, i.e., its remoteness from brittle fracture. Thus, a new characteristic – a parameter of mechanical stability P_{ms} – was proposed:

$$P_{ms} = \frac{\sigma_f}{\sigma_1}. \tag{5}$$

At $P_{ms} > 1$ the metal is relatively stable to brittle fracture, whereas at $P_{ms} \le 1$ it is unstable (which means brittle fracture initiation).

As shown in [4], the value of the metal local strength, σ_f, can be expressed via R_{mc} – the minimum value of fracture stress of a standard specimen under uniaxial tension within the ductile-to-brittle-transition temperature range:

$$\sigma_f = k_v R_{mc}, \tag{6}$$

where coefficient k_v is the measure of the scale effect related to excess of the value of fracture stress σ_f of the local volume V_i over the minimum stress of brittle fracture of standard tensile specimen ($V_0 \approx 1000$ mm^3), R_{mc}. According to (3), the expression for k_v is

$$k_v = \frac{\sigma_{th}}{R_{mc}} + \frac{\sigma_u}{R_{mc}} \left[-\frac{\ln(1 - F_i^{\max})}{\rho_i V_i} \right]^{1/m} . \tag{7}$$

The tensile stress level ahead of the crack tip, σ_1, may be presented as follows:

$$\sigma_1 = j\sigma_Y \left(\frac{e_f}{e_Y} \right)^n , \tag{8}$$

where j is the coefficient of local overstress ($j = \sigma_1 / \overline{\sigma}$, where $\overline{\sigma}$ is equivalent stress), e_f is the value of local plastic strain within the local region where $F_i = F_i^{\max}$, e_Y is plastic strain at yield strength, and n is strain-hardening exponent.

Accounting for (6) and (8), the expression for P_{ms} is

$$P_{ms} = \frac{K_{ms}}{q_{cr}} , \tag{9}$$

where K_{ms} is the coefficient of mechanical stability of metal under uniaxial tension:

$$K_{ms} = \frac{R_{mc}}{\sigma_Y (e_c / e_Y)^n} , \tag{10}$$

q_{cr} is the force equivalent of the embrittlement effect due to both triaxial tension and localization of fracture initiation ahead of the crack tip,

$$q_{cr} = \frac{j}{k_v} \left(\frac{e_f}{e_c} \right)^n , \tag{11}$$

K_{ms} characterizes the level of stability of the metal plastic state under uniaxial tension, and is unambiguously determined by the mechanical properties obtained under uniaxial tension: R_{mc}, σ_Y, and n. Parameter q_{cr} shows how will this initial level of stability decrease if this metal is placed at the macrocrack tip [4]. For typical pressure vessel steels $\sigma_Y = \sigma_{0.2}$ ($e_Y = 0.002$), and critical strain is $e_c \approx 0.02$, therefore, $K_{ms} = R_{mc} / (\sigma_{0.2} \cdot 10^n)$.

According to (10), radiation-enhanced hardening of pressure vessel steel must result in the reduction of it mechanical stability level, K_{ms}. Using Eqs. (9) and (10) and well-known dependence yield strength increment $\Delta\sigma_{Y_s}$ vs. fluence value Φ ($\Delta\sigma \approx B_h(\Phi/10^{22})^{m_\Phi}$, where $m_\Phi \approx 0.33$–0.51 [5]), and the expression for the parameter of mechanical stability of irradiated steel, P_{ms}^{ir}, can be obtained

$$P_{ms}^{ir} = \frac{K_{ms}}{E_m}, \tag{12}$$

where E_m is the general force equivalent of the embrittlement which characterizes the total embrittlement due to both stress-strain field ahead of a crack tip and radiation-enhanced hardening of metal:

$$E_{ms} = q_{cr} q_{ir}, \tag{13}$$

where coefficient q_{ir} characterizes the degree of radiation embrittlement of steel due to it radiation-enhanced hardening [4]:

$$q_{ir} \approx 1 + \frac{B_h}{\sigma_Y}\left(\frac{\Phi}{10^{22}}\right)^{m_\Phi}. \tag{14}$$

Dependences (12) and (14) enable one to predict the value of critical fluence Φ_c, at which the cracked pressure vessel fails ($P_{ms}^{ir} = 1$) at the given value of load J_I/σ_Y.

When solving this problem, the scale effect is critical. According to (11) and (7), this effect governs the embrittling force value of a crack (parameter q_{cr}).

In the first approximation, the value of an elementary volume V_i can be expressed as

$$V_i = Bh_i, \tag{15}$$

where B is the crack front length and h_i is parameter characterizing the width of an elementary volume, for which σ_f is determined. The upper limit of h_i is determined from the condition that stress and strain variations within h_i limits may be neglected. The lower limit of h_i characterizes the minimum size of the region required for the CN formation. In the first approximation, this size must be of the true grain size order.

Accounting for (15) and (7), the expression (11) for q_{cr} will be the following:

$$q_{cr} = \frac{j(e_f/e_c)^n}{\left\{\dfrac{\sigma_{th}}{R_{mc}} + \dfrac{\sigma_u}{R_{mc}}\left[-\dfrac{\ln(1-F_i^{\max})}{\rho_i h_i B}\right]^{1/m}\right\}}. \tag{16}$$

According to (16), susceptibility of the value of embrittling force of a crack q_{cr} to change in the crack front length B, depends on the value of parameter m. For typical pressure vessel steels, m is determined, above all, by the inhomogeneity of distribution of carbide sizes.

Technique for Prediction of Critical Fluence Φ_c. The essence of technique proposed is to obtain the dependence of the parameter of mechanical stability P_{ms} on the fluence value Φ, and to find critical value Φ_c, at which $P_{ms}=1$ (i.e., brittle fracture is initiated ahead of a crack-like defect tip in a pressure vessel) grounded on the findings of tests of surveillance specimens. According to (12), it is necessary to know the value of K_{ms} for steel in the initial (non-irradiated) state and then to estimate the degree of irradiation embrittlement of steel (q_{ir}) grounded on the findings of tests of surveillance specimens under uniaxial tension as well as to find the value of q_{cr} for a cracked non-irradiated metal.

As it follows from (10), brittle strength of metal, R_{mc}, determined as the minimum fracture stress over the ductile-to-brittle-transition temperature region under uniaxial tension [4] is the key characteristic for K_{ms} determination.

Figure 1 presents the dependences of K_{ms}^{ir} and q_{ir} on fluence for pressure vessel steel 15Kh2NMFA (Table 1).

T a b l e 1

Mechanical Properties of Pressure Vessel Steel 15Kh2NMFA in the Initial and Irradiated States

Steel	R_{mc}, MPa	Non-irradiated state			Irradiated state		
		$\sigma_{0.2}$, MPa (20°C)	n (20°C)	T_0, °C	$\sigma_{0.2}^{ir}$, MPa (20°C)	n (20°C)	T_0, °C
15Kh2NMFA	1400	595	0.06	−167	663	0.05	−130

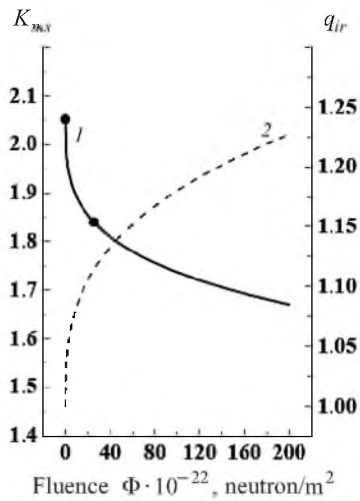

Fig. 1. Effect of the fluence value Φ on the coefficient of mechanical stability K_{ms} (*1*) and the parameter q_{ir} (*2*) of RPV steel 15Kh2NMFA.

The essence of technique of experimental determination of q_{cr} value for a crack in non-irradiated steel is shown in Fig. 2. It consists in the ascertainment of critical temperature T_c, at which fracture of specimen occurs at specified value of $J_{\rm I}/\sigma_Y$. The point of intersection of the temperature dependences of fracture toughness of non-irradiated steel, K_{Jc}, and stress intensity coefficient K_{IL} for the given value J_I/σ_Y determines the above temperature. In this case:

$$K_{IL} = \sqrt{\frac{E\sigma_Y}{1-\nu^2} bL}, \tag{17}$$

where L is the dimensionless loading parameter:

$$L = 1/M = J_I/(b\sigma_Y), \tag{18}$$

M is the dimensionless parameter in ASTM E1921, b is the ligament size, E is the Young modulus, and ν is Poisson's ratio.

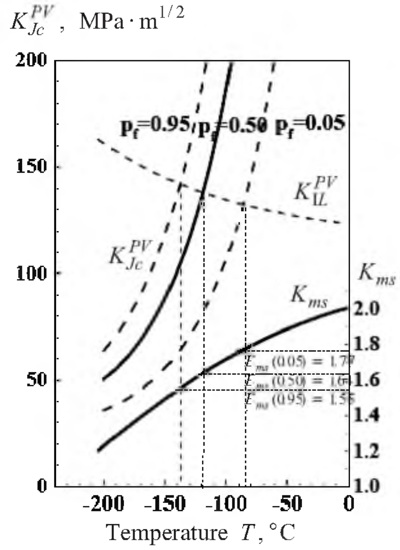

Fig. 2. The temperature dependence of the coefficient of mechanical stability of pressure vessel steel, K_{ms}, and the value K_{Jc}^{PV} for proof crack in a reactor pressure vessel.

The value of parameter q_{cr} is quantitatively equal to the magnitude of K_{ms} at this critical temperature T_c. It follows from the dependence (9), according to which condition $q_{cr} = K_{ms}(T_c)$ holds at the moment of fracture ($P_{ms} = 1$). The values of q_{cr} for fracture probabilities 0.05 and 0.95 are ascertained similarly.

Knowing the coefficient of mechanical stability in the initial state, K_{ms}, the value of parameter, q_{cr}, and the relation between q_{ir} and Φ, the dependence of parameter of mechanical stability of irradiated steel, P_{ms}^{ir}, on the fluence value can be plotted (Fig. 3). The value of fluence, at which $P_{ms}^{ir} = 1$, is the critical value of $\Phi = \Phi_c$.

Results and Discussion. Pressure vessel steel 15Kh2NMFA in the irradiated and initial states was employed as the subject of study (Table 1).* Figure 1 presents dependences of the coefficient of mechanical stability K_{ms}^{ir} and q_{ir} on

* Mechanical tests were conducted by Senior Researcher, Ph.D. V. N. Revka.

the value of fluence at the temperature 20°C. To approximate the experimental data, the value $m_\Phi = 1/3$ was used. Figure 2 demonstrates the technique of determination of the parameter q_{cr}. Temperature dependence of K_{Jc} was plotted based on the test data on three-point bending of precracked surveillance Charpy specimens. The value of K_{Jc} was adjusted to $B = 150$ mm by the Master curve technique (ASTM E1921 standard). This B value is approximately equal to the front length of a proof elliptic crack of depth $a = 25$ mm ($0.125S$, where S is a thickness of the reactor pressure vessel wall). To simplify calculations, curvilinearity of the crack front was neglected. Calculations were executed for $J_\mathrm{I}/\sigma_Y = 0.13$ mm.

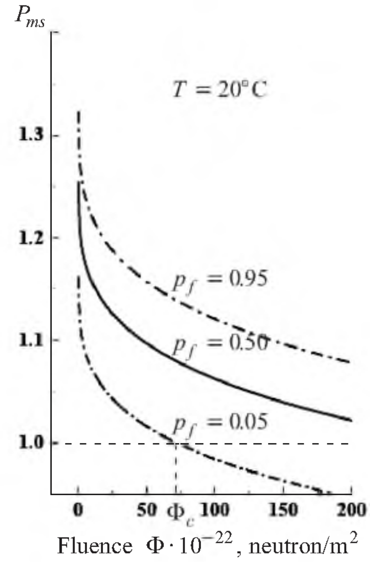

Fig. 3. Effect of the fluence value, Φ, on the parameter of mechanical stability of steel, P_{ms}, ahead of a crack tip in a reactor pressure vessel wall.

According to calculation results, at this loading level ($J_\mathrm{I}/\sigma_Y = 0.13$ mm) the effect of the crack embrittlement parameter for given values of probabilities 0.05; 0.50, and 0.95 amounts to $q_{cr}^{0.05} = 1.765$, $q_{cr}^{0.50} = 1.635$, and $q_{cr}^{0.95} = 1.550$, respectively. Data presented in Figs. 1 and 2 enable one to plot the dependence of the mechanical stability parameter P_{ms} on the fluence value and to ascertain the critical magnitude of the fluence (Fig. 3). Calculation results clearly manifest the essential effect of the probability of critical event under consideration on the critical fluence value. Thus, at the probability of unstable equilibrium of a crack-like defect in a pressure vessel $p_f = 0.5$, the value of critical fluence exceeds $\Phi_c > 200 \cdot 10^{22}$ neutron/m^2, and at $p_f = 0.05$, the critical fluence value amounts to $\Phi_c = 72 \cdot 10^{22}$ neutron/m^2, which is much closer to the standard value of 57 neutron/m^2 for pressure vessels of WWER-1000 reactors. Noteworthy is that option of determination of the critical fluence value with a priori probability makes possible a quantitative prediction of the reliability of safe operation of a reactor pressure vessel.

Conclusions

1. A new approach to prediction of reactor pressure vessel lifetime is proposed; within the framework of this approach, the critical value of fluence is determined not by the ultimate shift of Charpy critical temperature, ΔT_K, or by ΔT_0 according to the Master curve technique, but by the condition of instability of the ductile state (initiation of brittle fracture) of irradiated metal ahead of a crack tip in a reactor pressure vessel.

2. The condition of ductility exhaustion (initiation of brittle fracture) of the irradiated metal within the local region ahead of a crack tip can be described by two new mechanical characteristics, namely:

(i) the coefficient of mechanical stability K_{ms}, which characterizes ability of metal to resist transition from ductile to brittle state in laboratory conditions of uniaxial tension; it is determined unambiguously by such structure-sensitive characteristics as brittle strength R_{mc}, yield strength $\sigma_{0.2}$, and strain-hardening exponent n $(K_{ms} = R_{mc}/(\sigma_{0.2} \cdot 10^n))$;

(ii) force equivalent of embrittlement E_m, which demonstrates how much is this initial (laboratory) level of mechanical stability, K_{ms}, decreased by the effect of both radiation strengthening of steel (parameter q_{ir}) and inhomogeneous force field ahead of a crack tip (parameter q_{cr}) $(E_m = q_{ir} q_{cr})$.

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