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An estimation model for resistance of pressure vessel materials to fracture at different stages of service taking into account actual dimensions of the construction

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ABSTRACT

In the present report a method is proposed for assessment of cracked materials fracture toughness over a wide range of temperautres taking into account the size-effect of structural elements.The procedure proposed was evaluated on specimens of different thicknesses (25...150 mm) and geometries from the parent metal and welded joint metal of the WWER-type nuclear reactor pressure vessels of different classes of strength.

This report presents the results of experimental investigation into fracture toughness characeteristics of primarily, heat-resistant steels 15Kh2MFA and 15Kh2NMFA and their welded joints used in manufacturing WWR-440 and WWR-1000 type pressure vessels. The materials investigated were subjected to different thermal treatments which, on the one hand, simulated the exposure to different doses of radiation and, on the other hand, caused great difference in mechanical properties and fracture toughness characteristics of those materials [σ_{es}=300...1200 MPa]. The results of their investigation especially, in a wide-temperature range give grounds for certain generalizing conclusions.

The investigation of fracture toughness characteristics was performed on 25..150 mm thick compact-tension specimens and 3PB specimens (with a long through crack and a short surface crack) in a temperature range from 293 to 573 K which was the operating one for the given materials.

Since the analysis of the data from the literature revealed that one of the main factors resposponsible for the size effect is a change in the stress state at the crack tip with the change in the body dimensions, to solve the problem stated it was necessary not only to determine the local fracture parameters (criitical cleavage stress σ_c and critical strain ε_f) governing fracture in the so-called "process zone" at the crack tip and providing the basis for prediicting macroparameters, but also to investigate the influence of the stress state upon these parameters. It was also necessary to investigate the influence of plastic prestraining which takes place almost always prior to fracture of metalliic materials and is interrelated with the stress state.

To determine the influence of the stress state on the σ_c and ε_f values smooth cylindrical specimens and with various radii of circular stress concentrator (R = 0.5, 1, 2, 4 mm) were tested for which the stress state triaxiality σ_m/σ_i (σ_m is the hydrostatic stress, σ_i the stress intensity) and the σ_c, ε_f values were calculated by Bridgeman's formulas.

The obtained experimental data [1] on fracture toughness characteristics of structural alloys of a broad class reveal a complex and contradictory character of the size effect which depends primary on the variation range of the specimen thickness and on the material physico-mechanical properties including those defined by the action of technological and service factors. On the whole, the experimental data obtained confirm the possibility of the manifestation of three different characters of fracture toughness dependence on the specimen size noted in various publications (fracture toughness may grow, reduce and remain constant with an increase in the specimen size), which are impossible either to predict or to explain within the framework of the approaches proposed earlier. Especially remarkable it is the opposite character of the size effect for steels 15Kh2MFA(II) and 15Kh2MFA(III) which have close values of yield stress.

At the same time, for the materials studied no essential influence of the specimen geometry, loading scheme, the crack size and shape on fracture toughness was found over the temperature range from 293 to 573 K.

For the alloys studied the critical microcleavage stress is weakly sensitive to the changes in the stress state severity when the test temperature is low enough to allow the ooccurrence of appreciable plastic deformation prior to brittle fracture. Otherwise, an enhancement of the stress state severity results in a change of the critical microcleavage stress and this effect is manifested through the influence of the stress state upon plastic prestraining. Plastic prestraining at the temperature above the brittle-to-ductile transition temperature results in an appreciable increase in the critical microcleavage stress. Processing of the experimental data revealed that in log-log coordinates they are described satisfactorily by a linear equatiuon, i.e. the σ_c plastics strain value ε_i^p relation can be approximated by an exponential equation of the type

$$\sigma_c = \sigma_{co} + H_d(\varepsilon_i^p)^{\lambda_d} \qquad (1)$$

where σ_{co} is critical microcleavage at the nil ductility temperature, H_d and λ_d are material constants.

Compared to the critical microcleavage stress, the critical strain for the steels studied is much more sensitive to the variation of the stress state triaxiality. For all the steels studied the ε_f value is a diminishing function of the stress state triaxiality tending to its asymptotic approximation. In doing this, the intensity of ε_f decrease with an increase in σ_m/σ_i differs for different steels. The σ_m/σ_i variation range within which the ε_f ÿ0value reaches its asymptotic approximation, which varies for different steels, is also different.

On the whole, the obtaned experimental data confirm the results obtained earlier and the conclusions based on them to the effect-that the critical strain is the diminishing function of the stress state triaxiality and that this function can be taken in the form of an exponential equation of the following type

$$\varepsilon_f = C_f \exp(-k_f\,\sigma_m/\sigma_i) + \varepsilon_{If} \qquad (2)$$

with parameters C_f, k_f and ε_{If} being different for different materials.

Among plenty of phisico-mechanical fracture models proposed by now, some of them being sometimes very complicated, conflicting and insufficiently experimentally substantiated, the choice in the present iunvestigation was made of the models based on the principle of "coalescence" fracture of the material with a macrocrack. In accordance with this principle the macrocrack extension occurs if at some characteristics distance from the crack tip a critical situation is being realized which is governed by critical stress σ_c in the case of brittle fracture and by critical strain ε_f in the case of ductile fracture.

The approach to the prediction of the size effect used in the present work is based on the assumption that the influence of the body size and shape upon fracture toughness characteristics is similar to that on specific stress state parameters (the latter will be shown in what follows).

For the adopted ductile fracture model the fracture condition is described by the following expression:

$$\varepsilon_i^p(x) \Big|_{x=X_c} = \varepsilon_f \qquad (3)$$

where ε_f and $\varepsilon_i^p(x)$ are the critical srain and the intencity of local plastic strains at the crack tip; respectiively; X_c is the characteristic distance.

For a quantitative evalution of the influence of stress state on the intensity of current (corresponding to the applied load) strain, a parameter $\varkappa$ has been used in this present work, which is called the coefficient of approximation to the plain strain conditions.

Parameter $\varkappa$ is defined by solving a three-dimensional elastic problem and its application is based on the valiadity of Neiber-Dikson's equation [2]:

$$\sigma_i\, \varepsilon_i = \sigma_i^e\, \varepsilon_i^e \qquad (4)$$

where σ_i and ε_i are the stress and strain intensities, respectively, at the crack tip in the elasto-plastic region; σ_i^e, ε_i^e are the same when the problem is being solved in elastic formulation.

The determination of parameter $\varkappa$ follows from the following basic relationships of the elasticity theory:

- at plane stress state (PSS) $\qquad \sigma_3 = 0,\ \varepsilon_3 = -\nu(\sigma_1 + \sigma_2)/E;$
- at plaine straine (PS) $\qquad \sigma_3 = \nu(\sigma_1 + \sigma_2),\ \varepsilon_3 = 0;$
- in a general three-dimesional case $\qquad \sigma_3 = \varepsilon_3 E + \nu(\sigma_1 + \sigma_2),\ \varepsilon_3 \neq 0.$

In transition from PSS to PS ε_3 varios from $-\nu(\sigma_1 + \sigma_2)/E$ to 0, i.e. can be rewritten:

$\sigma_3 = \nu(\sigma_1 + \sigma_2)k + \nu(\sigma_1 + \sigma_2) = \nu(\sigma_1 + \sigma_2)(k+1)$

where $-1 < k < 0$.

Assuming $\varkappa = 1 + k$, we finally have

$$\varkappa = \sigma_3 / \nu(\sigma_1 + \sigma_2) \qquad (5)$$

Thus, at PSS $\varkappa = 0$, whereas at PS $\varkappa = 1$.

And in a general three-dimensional case $0 \le \varkappa \le 1$

The determination and the use of parameter $\varkappa$ in the present work is based on the assumption that among the body dimensions it is the crack that has a predominant effect on the parameter and, accordingly, on the plastic strain constraint.

Using eqn (4), the known relation between strain and stress intensities for an elastic solution relation between K_I and J_I and assuming a power approximation of the stress intensity vs strain intensity relation for an elasto-plastic solution, i.e. $\sigma_c = A(\varepsilon_f)^n$, where A and n are the material constants, we get the following relationship:

$$\varepsilon_f = [J_I(1+\nu)/3\pi rA]^{1/(n+1)}(1-2\nu\varkappa)^{2/(n+1)} \qquad (6)$$

As it follow from eqn (6) at a similar loading level J_I for agiven material (with constants ν, E, A, n) the strain value at the crack tip is defined by the parameter $\varkappa$ magnitude. In other words, parameter $\varkappa$ is a quantitative measure of the stress state effect on the deformation process at the crack tip. It should also be noted that relation (6) is analogous to the known relationship for strain distribution at the crack tip which results from the HRR-solution, for a plane problem, though it has been obtained by a quite different method. And which is very much importent, in both dependences the strain singularities coincide. At the same time, an importent distination of relation (6) from the HRR-solution dependence is its capability to take into account the influence of the stress state upon the intensity of elasto-plastic strains using parameter .

From eqns (2), (3) and (6) we get the following equation for prediction of fracture toughness:

$$J_c = [C_f \exp(-k_f \sigma_m / \sigma_i) + \varepsilon_{If}]^{n+1} X_c M_f (1-2\nu\varkappa)^{-2} , \qquad (7)$$

where $M_f = 3\pi A/(1+\nu)$.

Unlike the relationships obtained earlier, eqn(7) includes parameters σ_m / σ_i and $\varkappa$ which take into account the influence of the stress state on both the critical strain ε_f and the deformation process preceding the attainment of this critical strain ε_f , i.e. with the magnitudes of σ_m / σ_i and $\varkappa$ being determined for specific size and shape of a body, one can predict the fracture toughness values for this body from the known material constants A, n, E, ν, C_f, k_f, ε_{If} obtained in uniaxial tensile testing of specimens (smooth and with stress concentrators).

In addition to relation (7) based on the test results for crack-free specimens, we obtain a relationship for predicting fracture toughness of large-size bodies from the results of testing small laborotory specimens with a crack

$$(J_c)_2 = (J_c)_1\{[C_f \exp(-k_f(\sigma_m/\sigma_i)_2) + \varepsilon_{If}]^{n+1}/[C_f \exp(-k_f(\sigma_m/\sigma_i)_1) + \varepsilon_{If}]^{n+1}\}$$
$$[(1-2\nu\varkappa_2)^{-2}/(1-2\nu\varkappa_1)^{-2}], \qquad (8)$$

where $(\sigma_m/\sigma_i)_1, \varkappa_1$ and $(\sigma_m/\sigma_i)_2, \varkappa_2$ are the triaxiality of the stress state and parameter $\varkappa$ for a small specimen and a large-size body, respectively.

The $(\sigma_m/\sigma_i)_1$ and $\varkappa_1$ values for a small specimen can be obtained readily if the specimen dimensions are chosen so that the stress-strain state would approach the plane stress state. In this case $\varkappa_1 \to 0$, and the stress-state triaxiality $(\sigma_m/\sigma_i)_1$ is accurately determined from the HRR-solution.

From eqn (8) it follows that to predict fracture toughness of a large-size body, in addition to fracture toughness $(J_c)_I$ of a small specimen and constants A, n, E, ν, C_f, k_f, ε_{If} one should know the σ_m/σ_i and $\varkappa$ values for this body.

An important feature of the model presented above is, that unlike other models, it given a clear phisico-mechanical explanation of why for different materials the manifestation of the size effect is different, and it predicts the character of the size effect. Thus, in accordance with the model presented the size effect is defined by two factors whose action isopposite.

With an increase in the size of a body on the one hand the stress state triaxiality σ_m/σ_i increases and accordingly, the critical strain ε_f decreases , and on the other parameter $\varkappa$ increases and, accordingly, the coustraint of plastic strain growth, i.e. it becomes more difficult to achieve the critical strain ε_f.

Each material has its own plasticity researve and its own sensitivity of critical strain ε_f to the variation of the stress state triaxiality. For this reason the following three cases may occur.

Case I. With an increase in the specimen thickness plastic strain constraint occurs with less intensity than the decrease of critical strain ε_f, and fracture toughness decreases.

Case II. With an increase in the specimen thickness the intensity of plastic strain constraint growth is higher that the decrease of ε_f, and fracture toughness increases.

Case III. The growth of plastic strain constraint and the decrease of with a change in the specimen size counter balance each other, and the size effect is not observed.

In terms of mathematics and according eqn. (7) the above three cases of the size effect manifestation are deseribed by the following relationship:

I $\quad d(1-2\nu\varkappa)^{-2}/d\varkappa < d[C_f \exp(-k_f\,\sigma_m/\sigma_i) + \varepsilon_{If}]^{n+1}/d(\sigma_m/\sigma_i)$ -
fracture toughness decreases

II $d(1-2\nu\varkappa)^{-2}/d\varkappa < d[C_f \exp(-k_f\,\sigma_m/\sigma_i) + \varepsilon_{If}]^{n+1}/d(\sigma_m/\sigma_i)$ -

fracture toughness increases

III $d(1-2\nu\varkappa)^{-2}/d\varkappa < d[C_f \exp(-k_f \sigma_m/\sigma_i) + \varepsilon_{If}]^{n+1}/d(\sigma_m/\sigma_i)$ - fracture toughness does not change.

The model developed makes it possible, in particular, to explain such phenomenon as different character of the size effect for steels 15Kh2MFA(II) and 15Kh2MFA(III) which have close values of yield stress.

Steel 15Kh2MFA(III), whose yild stress is even somethat lower than that of steel 15Kh2MFA, has critical strain ε_f which is much lower and its limiting value of ε_{If} is reached even at low triaxiality of the steels state σ_m/σ_i, i.e. 25 mm and 150 mm thick specimens have critical strains which are virtually similar. For this reason in 25 mm thick specimens with lower constraint of plastic strain growth, the intensity of plastic deformation is higher and the critical state is reached earlier than in 150 mm thick specimen.

Steel 15Kh2MFA(II) has a higher critical strain ε_f and higher sensitivity to the stress state triaxiality σ_m/σ_i than steel 15Kh2MFA(III) and for the former the size effect is manifested according to scheme I, i.e. it leads to fracture toughness reduction with in increase in the specimen thickness.

The basis for the model for taking into account the size effect at brittle fracture is the assumption that the size effect influence th e fracture toughness as much, as the change in the stress state caused by it affects plastic deformation preceding the brittle fracture by cleavage.

According to the adopted model of brittle fracture and the distributuion of the principal stress in crack tip, taking into account eqn(1) we get the systems of eqns. for the prediction of the fracture toughness:

$$K_c = [\sigma_{co} + H_d(\varepsilon_i^p)^{\lambda_d}]\sqrt{2\pi X_c}\ , \quad \varepsilon_i^p(\varkappa, T, K_I) < \varepsilon_f(\sigma_m/\sigma_i), \tag{9}$$

$$\varepsilon_i^p = [K_I^2(1+\nu)/(3\pi X_c E A)]^{1/1+n}(1-2\nu\varkappa)^{2/n+1} - \\ - 2(1+\nu)(1-2\nu\varkappa)K_I/(3E\sqrt{2\pi X_c}) \tag{10}$$

As it follows from eqns (9), (10), the influence of the stress state on the critical SIF at brittle fracture is taken into account via parameter $\varkappa$ as in the case of ductile failure.

The above of brittle fracture which takes into account the influence of the stress state is simple enough and at the same time enables the formulation of the conditions for the brittle-to-ductile transition according to which at the instant of such transition the following relationships are valid:

$$\sigma_I = \sigma_c(\varepsilon_i^p), \quad \varepsilon_i^p(\varkappa, T, K_I) = \varepsilon_f(\sigma_m/\sigma_i), \tag{11}$$

From them considering (9) we obtain an expression for the critical SIF at which the brittle-to-ductile transition occurs:

$$K_c^{b-t} = [\sigma_{co} + H_d(\varepsilon_i^p)^{\lambda_d}]\sqrt{2\pi X_c}. \tag{12}$$

According to the model devised in the present work, depending on the material properties the size effect leads to two different schemes of variation of temperature and force parameters of the brittle-to-ductile transition (Fig.1). According to the first scheme, with an increase in the specimen thickness t and, accordingly, in the stress state triaxiality σ_m/σ_i, the critical strain ε_f does not change (it has reached saturation), and the size effect leads to a shift of the brittle-to-ductile transition temperature T^{b-t}. According to the second scheme, with an increase in the specimen thickness t and a corresponding growth of the value σ_m/σ_i, the critical strain ε_f decreases and in this case the size effect leads to a shift of the temperature T^{b-t} and to a reduction of the critical SIF.

On the whole, the model of the present investigation were put to an evalution testing when predicting the fracture toughness of 150 mm thick specimens of steels 15Kh2MFA(II) and 15Kh2MFA(III) on the lower and upper shelves of the fracture toughness temperature dependence. The data presented in Fig.2 indicate a satisfactory agreement between the experimental values of the fracture toughness and those calculated by the models.

References

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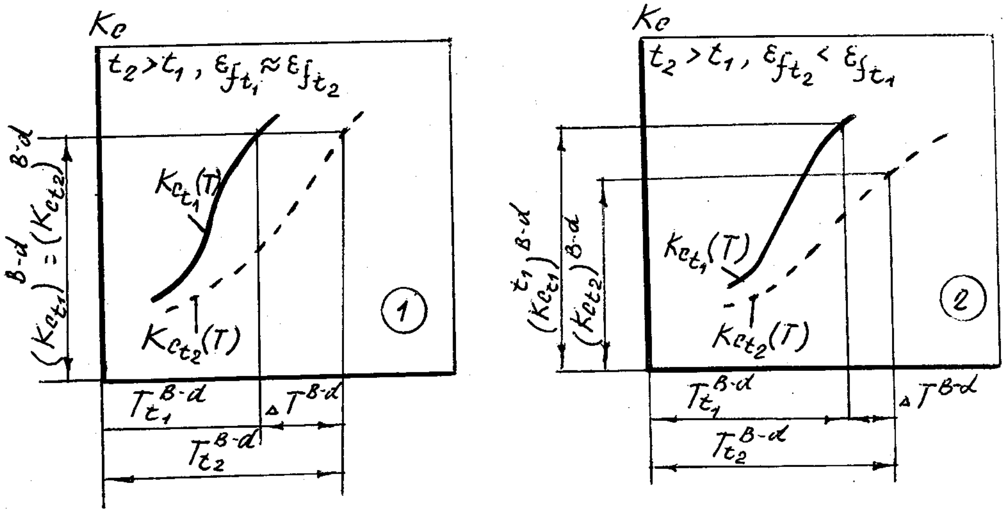

Fig. 1. Scheme of the influence of the specimen dimensions on the brittle-to-ductile transition temperature.

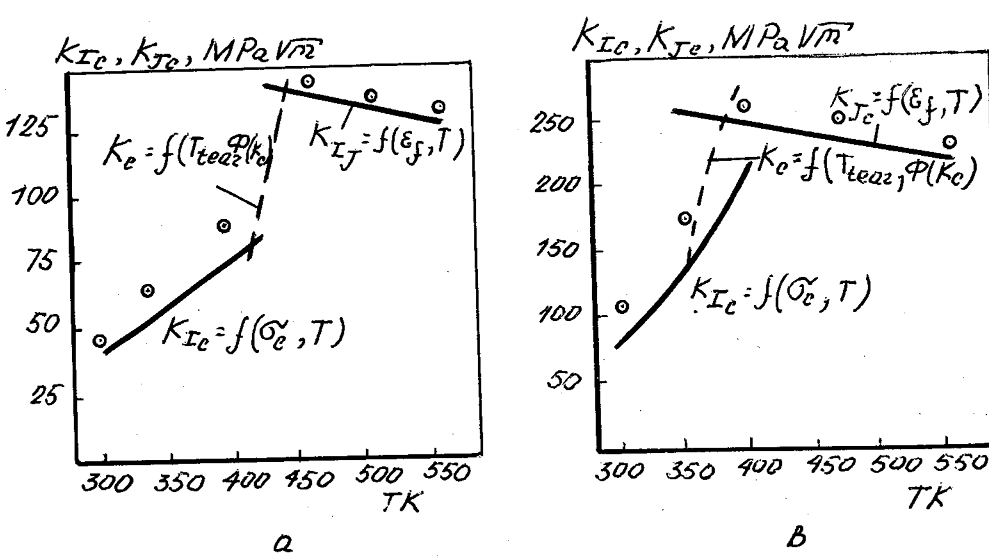

Fig. 2. Comparison of calculated (solid lines) and experimental (symbols) data on fracture toughness temperature dependences for 150 mm thick specimens of steels 15Kh2MFA(III)-a and 15Kh2NMFA(II)-b.