THE INFLUENCE OF THE TYPE OF STRESS STATE ON THE FRACTURE TOUGHNESS OF PRESSURE VESSEL STEELS IN DIFFERENT STATES

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ABSTRACT

A basically new method for the estimation of the fracture toughness of the plastic metal materials has been proposed which is based on the results of special testing of small-size specimens. It allows to give the qualitative and quantitative estimation of the influence of the stress state type on the material fracture toughness characteristics. The test results for the pressure vessel steels used in the reactor construction are discussed.

KEY WORDS

Pressure vessel steels, complete stress-strain diagram, fracture toughness, multiaxial stress state.

PRELIMINARY NOTES

The available methods for the determination of fracture toughness characteristics of plastic materials are generally based on testing specimens whose geometry and dimensions provide plane strain conditions at the crack tip irrespective of the stress state of the subject of investigation as a whole. At the same time a number of home and foreign investigators (Sun, 1987; Sun et al., 1990; Holland et al., 1990; Lebedev et al., 1991 b) testify to the fact that at least such parameter as the severity of the material stress state, which is characterized by the ratio of the first invariant of the stress tensor to the second invariant of the deviator, may influence appreciably its resistance to the crack initiation and propagation. In view of the above-mentioned, in the general problem of the plastic materials fracture toughness one can highlight at least the following two problems that are of fundamental theoretical and great practical importance.

The first problem appears in connection with the lack of physically grounded and reliable methods for the determination of the classical characteristics of the plastic materials fracture toughness by testing small-size specimens. And the second problem is associated with the evident necessity of estimating the relationship between the material fracture toughness and its stress state which depends on the specimen geometry and the features of external effects. Relevant investigations have been carried out at the Institute for Problems of Strength lately (Lebedev and Chausov 1983; Lebedev et al., 1991 a, b) and, in particular, those based on the new method for the estimation of the plastic materials fracture toughness by testing small-size specimens involving complete stress-strain diagrams.

TEST METHOD AND EXPERIMENTAL DATA PROCESSING PROCEDURE

As it was shown previously (Lebedev and Chausov, 1983) complete stress-strain diagrams, i.e. the ones including the second section descending along the abscissa axis, can be obtained using the testing machines of great rigidity only or high accuracy machines fit with high speed feedback device. There are also limitations on the specimens dimensions being used. Those conditions are met in full in the experiments carried out.

Descending branch of the complete stress-strain diagram includes two sections, one of which (the first) corresponds to the period of the accumulation of scattered damages which lead to the formation of a macrocrack in the zone of their highest density. The second section corresponds to the period of the macrocrack propagation through the specimen cross-section by different mechanisms of its growth. It appeared that there is a stable correlation between the parameters of the second section of the complete stress-strain diagram descending branch and the characteristics of the material fracture toughness(Lebedev and Chausov, 1983). In particular, a linear relation is established between the critical stress intensity factor K_{1c} and the coefficient K_λ :

$$K_\lambda = \sqrt{s_k \cdot \Delta \bar{l} p \cdot E}$$

where s_k is the material resistance to tearing, $\Delta \bar{l} p$ is the specimen elongation in the crack growth stage which is normalized on the basis of the initial cross-section area of a standard specimen, E is Young's modulus.

The coefficient K_λ depends also on the severity of the material stress state at the moment of the crack growth onset which can be varied within appreciably wide limits by the formation of a neck of corresponding configuration and dimensions as a result of making a stress concentrator of prescribed geometry on the specimen working section. If parameter $K_\sigma = \sigma_m / \bar{\sigma}$, is assumed to be a characteristic of the stress state severity, where σ_m ,$\bar{\sigma}$ are the average stress and stress intensity, then as it appeared (Lebedev et al., 1991 b) the $K_\lambda (K_\sigma)$ dependence has an asymptote with the ordinate K_{1c}, that gives the possibility to propose a basically new scheme for the estimation of the material fracture toughness by testing small-size specimens taking into account the type of stress state and other factors which influence the fracture toughness.

Indeed it is shown in the work by Lebedev et al., 1991 a, that a decrease in the plastic steel fracture energy, when the severity of the material stress state enhances at the moment of the crack growth onset, is connected with the variation of parameters which characterize the material damage accumulation, in particular, with a decrease in the process zone width where an intensive growth and coalescence of voids and microcracks into a macrocrack occur, and also with changes in the type of damages and their statistical distribution. For this reason (see Fig.1) in the case of the material embrittlement, for instance in the coarse of definite service time, the K_λ (K_σ) curve will shift downwards as the fracture toughness characteristics decrease and to the left since for a more brittle material the plane strain condition is reached at lower severity of the stress state. In the limit the curves contract to a point with the ordinate $K_\lambda = K_{1c}^{br}$ that corresponds to the critical stress intensity factor of the completely embrittled material.

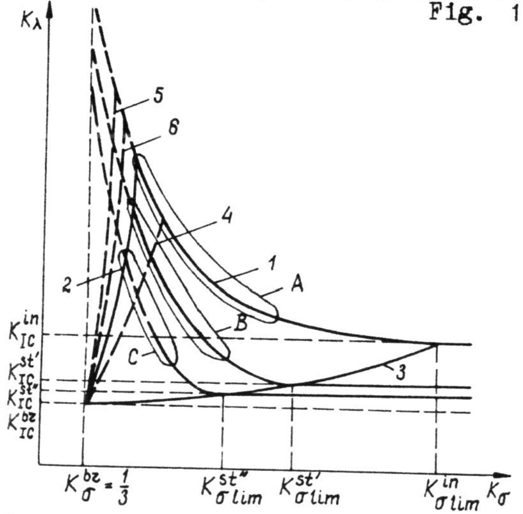

Fig. 1. Dependence of plastic steel fracture toughness characteristics on the stress state severity and accrued service time: 1...3 - see in the text; 4 - for standard specimens with a prescribed notch with different accrued service time; 5 - for smooth specimens with the thickness less thah that of a standard specimen made of the material with different accrued service time; 6 - for specimens with a prescribed notch with the thickness less thah that of a standard specimen with different accrued service time.

One can estimate the severity of the stress state in the specimen neck in different ways. According to the results of special investigations involving the stress-strain state analysis for axially symmetric specimens (including those with different initial stress concentrators) by experimental and calculation methods the most substantiated is Britdgeman's formula

$$K_\sigma = \frac{1}{3} + \ln\left(1 + \frac{r}{2R}\right) \qquad (1)$$

where r, R are the neck geometrical parameters (radius and profile). From relationship (1) in the case of brittle fracture when R = ∞ we get $K_\sigma^{br} = 1/3$.

Thus the whole range of possible values of the material fracture toughness characteristics corresponding to different severity of the stress state and accrued service time in the $K_\lambda - K_\sigma$, coordinates is bounded by a certain curvilinear triangle (see Fig.1), the sides of which offer the dependences of fracture toughness characteristics upon the stress state severity: one side (curve 1) for the initial material with stress concentrators of different severity, the second side (curve 2) for a smooth specimen made of the material after different operation time and the third (curve 3) - for specimens made of the material after different accrued operation time with concentrators which ensure the stress state severity at which the plane strain conditions are reached (quasibrittle fracture occurs).

Naturally, by testing small-size specimens of plastic materials even with an initial stress concentrator in the form of a fatigue crack it is impossible to achieve the strain constraint at the moment of the crack growth onset which corresponds to the plane strain conditions. In similar cases, only a limited range of the K_σ parameter variation at the moment of the crack growth onset is generally covered. Thus for the pressure vessel steel in the initial state the K_σ value that is reached in testing small-size specimens with various stress concentrators does not exceed 2.0, while the maximum possible value of K_σ^{lim} is about 3.5. However, it is important here to determine experimentally the moment when the curve $K_\lambda(K_\sigma)$ reaches the asymptote which corresponds to the material K_{1c} value. Then from the small-size specimen test data the K_{1c} value in regions A, B, C (Fig. 1) can be predicted with sufficient accuracy for a material being in operation during any period of time.

It is interesting to note that the approach mentioned allows the material K_{1c} value to be determined from the test data for specimens whose thickness is smaller than that of standard tensile specimens (with the diameter 8...10 mm), including plane ones. The main condition in those tests is the possibility to register the first linear section on the complete stress-strain diagrams which corresponds to the material fracture by ductile tearing (mode 1) fracture . In this case the K_{1c} parameters correlation is realized with the values of K_λ parameters obtained in the regions to the left of regions A, B, C (see Fig. 1).

THE RESULTS OF REACTOR STEEL TESTING

The proposed scheme for the estimation of the material fracture toughness by testing small-size specimens with the account taken of the type of stress state has been verified on the specimens made of the pressure vessel steel 15X2MFA after different time of operation. The steel structure state was simulated by thermal treatment. Steels of the type KP60 ($\sigma_{0.2}$= 584 MPa, σ_u= 700 MPa), KP80 ($\sigma_{0.2}$= 782 MPa, σ_u= =1224 MPa), KP100 ($\sigma_{0.2}$= 954 MPa, σ_u= 1069 MPa) were studied. The KP60 steel simulates the metal initial state, the KP100 steel - the state of the metal after radiation - induced embrittlement at the end of the reactor shell service time, the KP80 steel simulates a certain intermediate state after some time of operation. According to the data of the investigations accomplished earlier the critical stress intensity factor K_{1c} of the steel studied varied from 170 to 64 MPa·$\sqrt{m}$ depending on the accrued service time.

Test specimens (Fig. 2) were cut out from the nonworking sections of compact tension specimens, that were subjected to fracture toughness testing at the Institute for Problems of Strength of the Academy of Sciences of the Ukraine. The thickness of compact tension specimens was 150 mm, and that of the KP80 steel specimens - 50 mm.

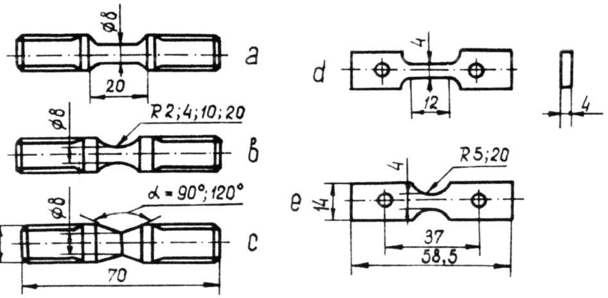

Fig. 2. Test specimens (a...e are types of stress concentrators).

The tests were performed on the test setup with a controlled rigidity of the loading system which was modernized for the second time and was provided with the additional (the third) contour of parallel elastic elements. The limit rigidity of the loading system at this was increased to the level that appeared to be sufficient for the realization of the conditions of equilibrium deformation of specimens with stress concentrators of the 15X2MFA steel in different states.

The S_k, $\overline{\Delta I}p$ values calculated from the test results for smooth specimens with the initial diameter 8 mm and and specimens of steels KP60, KP80, KP100 with stress concentrators are listed in Table 1, as well as the neck geometrical parameters r and R at the moment of macrocrack initiation, parameters K_λ and coefficients K_σ.

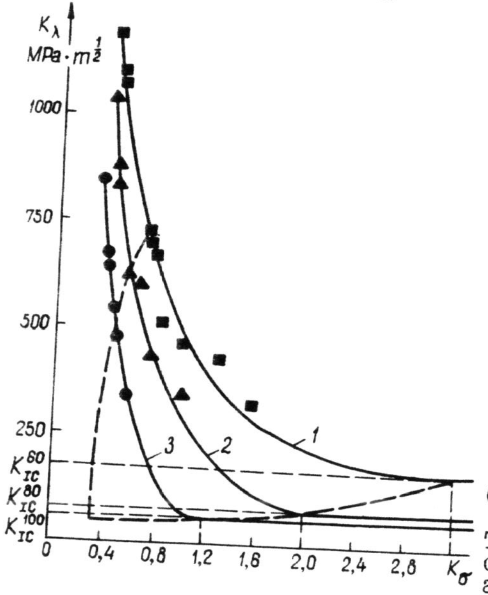

Fig.3.$K_\lambda(K_\sigma)$ dependence for the 15X2MFA steel in different states: 1 - steel of the KP60 type; 2 - KP80 type steel; 3 - KP100 type steel.

Experimentally obtained dependences $K_\lambda(K_\sigma)$ for steels KP60, KP80, KP100 are shown in Fig. 3.

It is of interest to note that for steels KP60, KP80, KP100 the curves $K_\lambda(K_\sigma)$ are described well enough by a common exponential dependence

$$K_\lambda = K_\lambda^{\lim} \cdot \left[1 + \frac{a}{\exp\ (\beta \cdot K_\sigma)}\right] \qquad (2)$$

where a and β are the material constants (for steels KP60, KP80, KP100, a is equal to 15, 90, 120; β is equal to 2.14, 4.28, 6.42, respectively).

The analysis of the results obtained reveals that according to the scheme proposed for the material after a certain service time when the signs of embrittlement appear (steel KP80) the $K_\lambda(K_\sigma)$ curve is situated below the one for the material in the initial state (steel KP60) and is shifted to the left. With an increase in the accrued service time (steel KP100) the corresponding $K_\lambda(K_\sigma)$ curve is really transformed in such a way that in the limit it degenerates into a point with the ordinate K_{1c}^{br} corresponding to the

critical stress intensity factor of the completely embrittled material (K_σ^{br} being equal to 1/3).

The whole area of possible values of the material fracture toughness characteristics, which correspond to different stress state severities and accrued service time in the coordinates K_λ-K_σ is really bounded by a certain curvilinear triangle marked by dashed lines in Fig. 3. The experimental points obtained by testing plane specimens of steels KP60, KP80, KP100 are marked on the corresponding curves $K_\lambda(K_\sigma)$.

It is necessary to emphasize that the character of the $K_\lambda(K_\sigma)$ curve is determined by the features of the micromechanisms of mode I macrocrack initiation and growth which in their turn depend on the severity of the stress state. For this reason, it is possible to judge about the slope of the $K_\lambda(K_\sigma)$ dependences by the rate of the process zone width w decrease (Lebedev et al., 1991 a) with an increase in the severity of the material stress state.

Table 1. Mechanical and geometrical characteristics of the test specimens made of the pressure vessel steel 15X2MFA in different states (steels of the types KP60, KP80, KP100).

Steel state	Specimen type	$\overline{\Delta I}p$, m×10^{-3}	S_k, MPa	r, m×10^{-3}	R, m×10^{-3}	K_σ	K_λ MPa×m$^{1/2}$
KP60	Smooth	1.560	1510.9	2.120	2.32	0.706	708.3
	R20	1.800	1388.3	2.390	2.60	0.693	729.2
	R10	1.765	1257.0	2.647	2.78	0.722	687.1
	R4	0.983	1240.1	3.147	2.61	0.809	521.9
	R2	0.805	1290.9	3.400	1.86	0.982	470.4
	∠120°	0.692	1300.0	3.040	0.96	1.280	437.5
	∠ 90°	0.420	1232.6	3.173	0.67	1.547	331.7
KP80	Smooth	1.116	1672.0	2.965	6.28	0.542	630.1
	R10	1.010	1567.2	3.390	4.67	0.640	609.7
	R4	0.590	1524.1	3.637	3.67	0.732	437.8
	R2	0.284	2060.0	3.780	1.93	1.010	353.1
KP100	Smooth	0.752	1842.9	1.625	7.12	0.438	543.0
	R10	0.640	1639.4	1.865	6.40	0.466	481.3
	R4	0.346	1574.3	2.050	4.12	0.552	340.4

Figure 4 shows as an example changes occurring in the width w of the process zone, where pores and microcracks coalesce into a macrocrack, in the tests of KP100 steel plane specimens with different stress concentrators (see Fig. 2 d, e).

We must note in the conclusion that the elaborated scheme for the estimation of the pressure vessel steels fracture toughness taking into account the material stress state and different accrued service time running may appear to be very promising for predicting fracture toughness of the nuclear reactor elements material taking into consideration real time of operation.

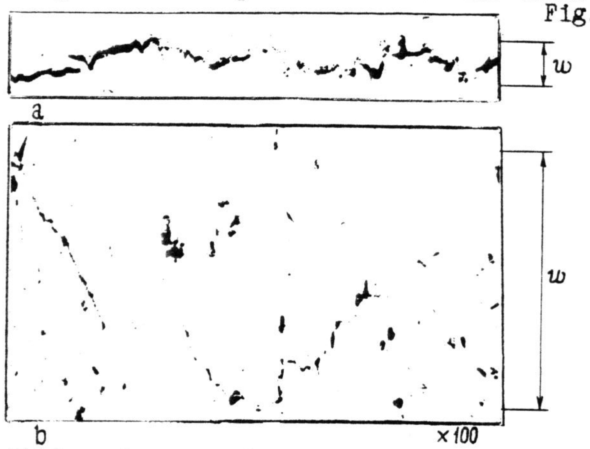

Fig.4. The influence of the stress state severity on the width *w* of the zone where the pores and microcracks coalescence into a macrocrack occurs for plane specimens of pressure vessel steel 15X2MFA of the KP100 type: a - specimen with initial radius R5; b - a smooth specimen.

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