ISSN 0020-1685, Inorganic Materials, 2016, Vol. 52, No. 15, pp. 1545–1553. © Pleiades Publishing, Ltd., 2016.
Original Russian Text © N.A. Makhutov, E.A. Grin', V.A. Sarkisyan, 2015, published in Zavodskaya Laboratoriya, Diagnostika Materialov, 2015, Vol. 81, No. 11, pp. 44–52.

MECHANICS OF MATERIALS:
STRENGTH, LIFETIME, AND SAFETY

Kinetics of Crack Development in Power Engineering Steels under High-Temperature Creep

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Received July 7, 2015

Abstract—Features of crack development kinetics in steels under creep are investigated from positions of fracture mechanics. It is shown that the creep crack growth rate can be approximated by a power dependence on parameter C^* or on the stress intensity factor. At the same time, exponents of these dependences are a function of characteristics of long-term strength or material creep. For description of the creep crack rate, it is proposed to use the reduced stress intensity factor, which takes into account the character of the stress distribution in the design section and the crack development time. The experiment verifies the advantages of using the reduced stress intensity factor as a correlation parameter describing the creep crack growth rate.

Keywords: steels, creep, temperature, crack development rate, parameter C^*, stress intensity factor (SIF), long-term strength, stress state, crack growth time, kinetic diagram of crack growth resistance

DOI: 10.1134/S0020168516150115

Because the stage of subcritical development of a crack in metal can be a significant part (as high as 50% or more) of the total longevity of a part [1, 2], problems of the interpretation of crack development laws in creep are of critical significance for determination of the lifetime of the safe operation of high-temperature units of equipment [1–5]. On the basis of the analysis of the stress and strain fields in the crack tip, the authors [6, 7] formulated conditions for the application of the stress intensity factor (SIF) as a basic characteristic correlating with the crack growth rate (CGR) during creep. General technical problems of the analysis of stress-strain states in zones and outside zones of cracks for substantiation of the crack growth resistance, lifetime, and safety were widely considered in the journal "Zavodskaya Laboratoriya. Diagnostika Materialov" [8]. Experimental investigations in the given area showed that the SIF (parameter K_1) can satisfactorily describe the creep crack development in the case of small-scale yielding [9, 10], and therefore its utilization as the correlation parameter of the CGR is urgent for materials with low plasticity under creep or for zones with a low structural concentration of stresses, or for relatively short-term processes (tests) which end before transition from creep in the limited volume to conditions of total creep.

In the cases where plastic deformations or creep deformations occur in macrozones behind crack boundaries, criteria K_1 of linear fracture mechanics are found to be insufficient and there is a need to use nonlinear fracture mechanics—deformation or energy criteria [6, 12]. Below, crack development laws are considered under conditions of small-scale creep.

SCIENTIFIC FUNDAMENTALS OF ANALYSIS OF CRACK KINETICS

Theoretical and experimental data demonstrated a fairly satisfactory correlation between the creep CGR and parameter K_1 in the form of the traditional power relation [3, 14]

$$\frac{\mathrm{d}a}{\mathrm{d}\tau} = AK_1^{\beta}, \tag{1}$$

where $\mathrm{d}a/\mathrm{d}\tau$ is the crack growth rate, and A and β are empirical constant of the material.

Along with that, one can observe a substantial "bundle" of CGR curves constructed according to relation (1), which is in the displacement (practically equidistant) of different groups of experimental data relative each other, which are obtained for different types or dimensions of specimens [9–13]. In connection with this, the authors [9, 14] proposed, when describing the CGR under creep conditions, to take into account not only the parameter of fracture mechanics (SIF) but also the level and character of the stress distribution and specimen (section) dimensions. This procedure of normalization of the general correlation parameter (K_1) with respect to the stress state and the scale factor made it possible [9, 14] to decrease significantly the bundle" of CGR curves and practically reduce them in the common array (with a sufficiently wide band of the spread), which corresponded to approximation (1).

However, for full-scale yielding under creep conditions, which is urgent for highly plastic materials, in order to interpret the fracture process, mainly deformation and energy criteria of the nonlinear fracture mechanics were found to be preferential [3, 6, 9–15], in particular, the modified J integral or so-called C^* integral [7, 16]. Parameter C^* ($C^* = \dot{J}$) was determined on the basis of the analysis of deformation rate fields in the crack tip and the crack opening displacement rate [16, 17]. It is experimentally verified that, in the case of plastic materials, the correlation between the creep CGR and parameter C^* is more successful than the similar approximation with respect to parameter K_1 in the form of (1) [9, 10, 17].

Laws of crack development kinetics can be substantiated analytically with the use of the Norton stable creep law

$$\dot{\varepsilon} = \dot{\varepsilon}_0(\sigma/\bar{\sigma})^m, \tag{2}$$

the approximation of the long-term creep curve

$$\left(\frac{\tau}{\tau_0}\right) = \lambda\left(\frac{\sigma}{\sigma_0}\right)^{-n} \text{ or } \tau = \bar{\tau}_0\left(\frac{\sigma}{\sigma_0}\right)^{-n}, \tag{3}$$

and a set of Hutchinson–Rosengren–Rice (HRR) equations [6, 18]. In relations (2) and (3), coefficients $\dot{\varepsilon}_0$, $\bar{\sigma}$, σ_0, and $\bar{\tau}_0$ and exponents m and n are the material characteristics. Integrating (2) with respect to time and substituting Eq. (3) into it, we obtain

$$\varepsilon = \dot{\varepsilon}_0\bar{\tau}_0\left(\frac{\sigma}{\bar{\sigma}}\right)^{m-n} = \bar{\varepsilon}_0\left(\frac{\sigma}{\bar{\sigma}}\right)^{m-n}, \tag{4}$$

where $\bar{\varepsilon}_0$ is the deformation during rupture under conditions of uniaxial creep with stress $\bar{\sigma}$.

Subject to relation (4), the HRR equations can be represented in the following form:

$$\begin{aligned} \sigma &= \bar{\sigma}\left(\frac{J}{\bar{\sigma}I_m}\right)^{\frac{\nu}{\nu+1}} r^{-\frac{\nu}{\nu+1}}, \\ \varepsilon &= \bar{\varepsilon}_0\left(\frac{J}{\bar{\sigma}I_m}\right)^{\frac{1}{\nu+1}} r^{-\frac{1}{\nu+1}}, \end{aligned} \tag{5}$$

where $\nu = 1/(m-n)$ and I_m is the multiplayer depending on creep exponent m and long-term exponent n. Functions of geometrical coordinates are omitted in the set of equations (5). Differentiating the second equation of the set with respect to time and multiplying it by the first one, we obtain

$$\sigma\dot{\varepsilon} = \sigma\bar{\tau}_0\frac{1}{\nu+1}\dot{J}r^{-1}. \tag{6}$$

From the last relation subject to (2), it follows that $\dot{\varepsilon} \sim \dot{J}^{1/(m+1)}$ or $\sigma \sim \dot{J}^{1/(m+1)}$.

Within the context of the concept of depletion of long-term plasticity [19], one can accept that crack development occurs by discrete steps as the ultimate creep strain accumulates in the characteristic local volume of metal adjoining the crack tip. Then, subject to relations (2) and (6), we obtain

$$\dot{\varepsilon}\Delta\tau_c = \varepsilon_{cf}, \text{ or } \Delta\tau_c\frac{\bar{\sigma}\varepsilon_0}{\nu+1}\frac{1}{\sigma}\dot{J}\frac{1}{r_c} = \varepsilon_{cf}, \tag{7}$$

where $\Delta\tau_c$ is the duration of the elementary act of fracture; r_c is the dimension of the elementary volume (zone of the accumulated critical damage), in which is the depletion of the long-term plasticity of metal occurs with the following discrete act of fracture; and ε_{cf} is the ultimate fracture strain. From Eq. (7), one can describe

$$\frac{da}{d\tau} = \frac{r_c}{\Delta\tau_c} = \frac{\sigma\varepsilon_0}{\nu+1}\frac{1}{\sigma}\frac{\dot{J}}{\varepsilon_{cf}}, \tag{8}$$

from which

$$\frac{da}{d\tau} \sim (C^*)^{\frac{m}{m+1}}, \tag{9}$$

where C^* is the modified J integral ($C^* \sim \dot{J}$). From the last expression, it is evident that the exponent in kinetic relation $da/d\tau \sim (C^*)$ for the creep CGR corresponds to $\varphi = m/(m+1)$. A similar relation for φ is given in [20]. Its numerical value, which is on the order of 0.7–0.9 for thermally stable steels of the perlite class at a temperature range of 540–550°C, corresponds fairly well to the exponent for parameter C^* [5, 19] in experimental relationships of the creep CGR in form (9). Subject to the relation $\sigma \sim \dot{J}^{1/(m+1)}$, one can see that, with the use of the SIF as the CGR correlating parameter in creep on the basis of the considered model, the exponent in relation (1) corresponds to the exponent of the creep curve, i.e., $\beta = m$. Then, in the case of thermally stable steels, it should be expected that the exponent in the kinetic diagram of relation (1) will be $\beta = 3$–5 at a temperature of about 560°C and a somewhat greater value at smaller temperatures.

Acknowledging that the modified J integral C^* is a fairly universal parameter controlling the creep crack development, one has to note that its determination in actual structures for purposes of the practical utilization of relations of type (9) entails great difficulties, whereas the calculation of the SIF parameter is well mastered [21] in the presence of data on stresses and the type and dimensions of the crack. Contingencies applied to the application of the SIF as the creep CGR correlating parameter are mainly reduced to the necessity of the consideration of the type of stress state and the degree of metal damage accumulated with time. One of the variants of accounting for the accu-

Characteristics of kinetic diagrams of creep crack resistance of steels

Steel grade	Equipment, units	Temperature, °C	Coefficients of kinetic diagrams of crack resistance	
			A, $(\mathrm{MPa})^{-\beta}\,\mathrm{m}^{1-\beta/2}/\mathrm{h}$	β
12Kh1MF	Steam pipes: pipes, formed components	560	Pipes: 8.97×10^{-12} Bends: 1.90×10^{-11}	3.80 4.20
15Kh1M1F	Steam pipes: pipes, formed components, fittings	560	1.68×10^{-13}	4.50
15Kh1M1FL	Cast products: steam pipe parts, case-shaped parts of turbines, fittings;	560	1.05×10^{-12}	4.75
R2MA	Rotors, steam turbine disk	525	1.13×10^{-15}	5.92
EI-415		525	6.70×10^{-14}	5.40

mulated damage in the metal is the application of the generalized SIF parameter in the form [20, 22]

$$K_{1\mathrm{m}} = \frac{K_1}{1-\omega}, \tag{10}$$

where ω is the damage characteristic. Parameter ω is a temporal function and, as is shown in [10], is

$$\dot{\omega} = f(\sigma_1, \sigma_\Sigma, \tau),$$

i.e., the damage accumulation rate in metal depends on principal stress σ_1, character of the stress state (σ_Σ) in the operating section of a solid with the crack, and duration τ of the thermal force action.

Power relationships of types (1)–(5), (9) are derived from purely strain ones [15] and from energy interpretations [11, 12, 15] of deformation and fracture.

On the basis of considerations of the maximum simplification of calculating procedures both with the approximation of experimental data and with solution of practical problems of the estimation of the survivability of equipment, the present paper gives an account of the approach to the interpretation of fracture kinetics under high-temperature creep by means of using the reduced SIF parameter (K_1^*), which is normalized to the coefficient taking into account the degree of uniformity of the stress state in the design section and to the temporal parameter taking into account the crack development time. The resulting stress σ_r in the design section of the solid with the crack is determined by the membrane (σ_m) and bending (σ_b) components:

$$\sigma_\mathrm{r} = \sigma_m + \sigma_b k_\alpha,$$

where $k_\alpha = r^*/b$ is the relative fraction of the cross section of the part within which bending stress σ_b is positive, i.e., $\sigma_b(x) \geq 0$ at $0 < x \leq r^*$ (b is the length of the net cross section of the part). Taking into account that $\dot{J} \sim (\nu + 1)\sigma\dot{\varepsilon}$, in accordance with (6), we introduce the notion of equivalent stress σ^* being a function of σ_r and parameter ν. For convenience, substituting $1/\chi$ for ν (then $\chi = m - n$), by simple transformations subject to condition $\sigma^* = \sigma_m$ at $\sigma_b = 0$, we obtain

$$\sigma^* = k_\alpha^* \sigma_\mathrm{r},$$

where

$$k_\alpha^* = \frac{\chi}{1+\chi}\left[1 + \frac{1}{\chi}\frac{\sigma_m}{\sigma_m + k_\alpha \sigma_b}\right]. \tag{11}$$

In turn, to take into account the temporal factor, we introduce the parameter (temporal coefficient) which is expressed through the known Larson–Miller (L-M) parameter $P = T(20 + \log\tau) \times 10^{-3}$, where T is the absolute temperature and τ is the time. Coordinating the temporal coefficient with the crack dimension, subject to the functional dependence between the SIF and the crack dimension, we write the expression

$$k_\tau^* = \sqrt{P_i/P_0}, \tag{12}$$

where P_0 and P_i are the L-M parameters, which correspond to the state of metal at the start of the crack growth and in the actual time during its development, respectively. Taking the initial time of the crack growth as an arbitrary unit (for elimination of singularity) and assuming that the temperature in the stationary conditions remains constant, we arrive at the expression

$$k_\tau^* = \sqrt{P_i/P_0} = \sqrt{1 + 0.051\log\tau}. \tag{13}$$

Thus, the proposed variant of the approximation of kinetic diagrams of the crack resistance of material under creep subject to the stress state character and the crack development time is reduced to the use of the reduced SIF parameter K^* in the form

$$K^* = k_\alpha^* k_\tau^* K_1. \tag{14}$$

EXPERIMENTAL INVESTIGATIONS OF CRACK DEVELOPMENT LAWS AND ANALYSIS OF RESULTS

Kinetic diagrams of the crack resistance under conditions of high-temperature creep were obtained for thermally stable steels of the perlite class, which are widely used for the manufacture of power equipment. Grade 12Kh1MF and 15Kh1M1F(L) steam pipe steels and grade 25Kh1M1FA(R2MA) and 20Kh3MVFA(EI-415) rotor steels were investigated. Grade 12Kh1MF steel was represented by cuts from a straight pipe and a roll-formed branch in the initial state and from a roll-formed branch after an operating time of ~120 000 h at a temperature of 550–560°C, and grade 15Kh1M1F and 15Kh1M1FL steels were represented by cuts from gate bodies stamp-welded and cast, respectively (metal of both gates is in the initial state). The chemical composition and mechanical properties of grade 12Kh1MF and 15Kh1M1F steels corresponded to requirements of TU (Standard) 14-3-460-75, and for grade 15Kh1M1FL steel, TU 108.961.03-79.

Grade R2MA rotor steel was investigated using cuts from high-temperature zones of high- and medium-pressure rotors of steam turbines (K-200-130) operating for different periods in thermal power plants (~50000–55000 and 200000 h). Grade EI-415 steel is represented by the cut from the combined high- and medium-pressure rotor dismantled from the K-160-130 turbine after operation for ~140000 h. It belonged to the first rotor batch of grade EI-415 steel, and the standard thermal treatment accepted at that time provided the highest level of strength properties of the metal, but lower plastic characteristics and viscosity. The plastic properties and viscosity of steel were enhanced at a later time because of the enhancement of the thermal treatment conditions. The chemical composition and mechanical properties of grade R2MA steel, as a whole, corresponded to requirements of TU 108.1029-81, whereas grade EI-415 steel showed a lower level of plastic properties relative to the given TU, which was due to the above-mentioned causes. In connection with this, grade EI-415 steel investigated most likely had conservative characteristics of crack resistance.

Eccentric tension tests were carried out using compact specimens with a nominal thickness of 25 mm (ST-1 type). They were produced in such a way that the notch plane was oriented in the radial-axial section of a cylindrical units (pipe, shaft). Specimens of roll-formed branches were cut from the expanded zone of the bend. The specimen faces were treated for surface side notches (grooves or slots) with the triangle profile in the continuation of the basic notch of the specimen. Because of that, the creep crack grew in the plane of side grooves, i.e., in the continuation of the plane of the basic notch of the specimen. In this case, the deformation constraint in the plane of side grooves provided conditions closed to the plane-strain condition. All specimens tested were equipped with initial fatigue cracks in accordance with stated requirements [23].

Specimens were tested using AIMA 5-1 serial testing machines at different levels of temperatures. Steampipe steels were investigated in a temperature range of 540–594°C, and rotor steels were investigated in a temperature range of 505–540°C. To provide the given temperature conditions of tests, muffle furnaces manufactured on the basis of serial electric furnaces from the complete set of the AIMA 5-1 testing machine were used in the three-section design with autonomous control of voltages in every section. The existing control circuit of heating the furnace of the AIMA device was improved for enhancement of the accuracy and smoothness of the temperature condition control in tests. The furnace contained a chain of two specimens included sequentially in the force chain of the machine. To record the specimen opening displacement along the axis of the force action, a special accessory was mounted on pinchers that provided the possibility for measuring the opening displacement parameter behind the hot zone.

In the tests, the specimen displacements (opening displacement of notch edges) along the force action were measured with a periodicity of 2–4 h. The partial unloading (~15–20% of the given load) of the specimen with the following loading to the given level was performed at the initial step of tests to fix the time of crack initiation. When the slope ratio of the load–displacement diagram deviated by more than 5% of the initial value, further periodic unloading was stopped, and the given time was considered as the crack growth initiation under creep conditions. The maximum test duration was about 26000 h. With the attainment of the given displacement value, the specimen was removed from the tests and destroyed completely at room temperature on a vibratory device. Initial fatigue crack length $\bar{a}_0$ and finite crack length $\bar{a}_c$ were measured by the fracture of the specimen using a toolmaker's microscope. Measurements were carried out along nine points equally spaced from each other (with an interval of ~2 mm) over the specimen thickness. The averaged value of the crack regrowth for the test time was determined as $\overline{\Delta a} = \bar{a}_c - \bar{a}_0$. The SIF for the compact specimen with side grooves (slots) was calculated by the formula [24]

$$K_1 = K_s (B/B_N)^{0.68},$$

where K_s is the SIF for the compact specimen in the standard make [23] and $(B/B_N)^{0.68}$ is the term considering the effect of side grooves (B and B_N are specimen thicknesses in the gross and net sections, respectively). The SIF was determined by the standard formula using average values of crack length for its every regrowth

$$\bar{a} = \bar{a}_0 + \overline{\Delta a}/2.$$

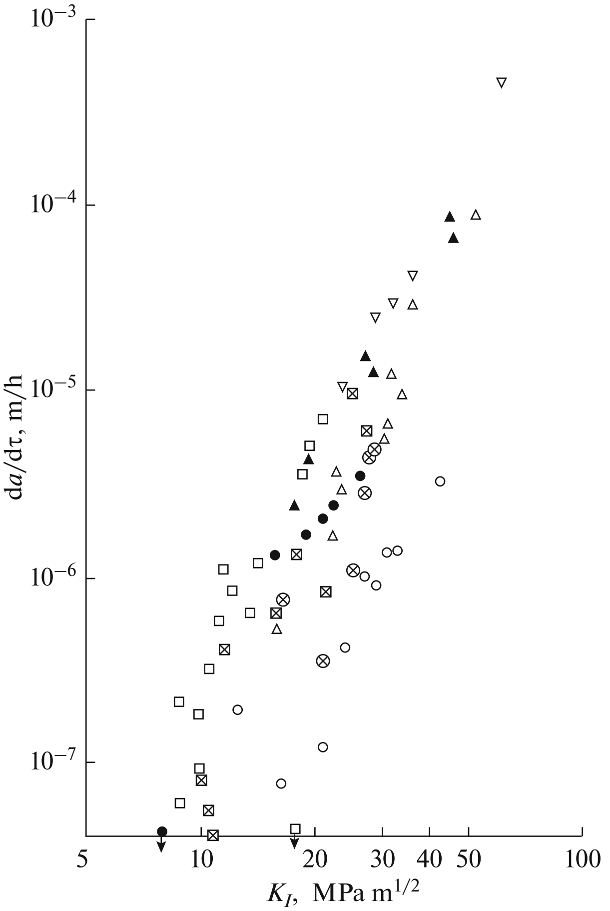

Fig. 1. Characteristics of the creep crack resistance of grade 12Kh1MF steel: (○, ⊗, ●) pipe in the initial state at temperature $T = 560$, 583, and 594°C, respectively; (△, ▲, ⊠, □) bend in the initial state: (△, ▲) compact specimens at 560 and 583°C; (⊠, □) cylindrical specimens at 540 and 560°C; and (▽) bend after operating time of ~120000 h ($T = 560$°C).

The results of investigations in the form of kinetic dependences of the CGR on the value of the SIF (K_1) under creep conditions (relations of type (1)) for aforementioned steels are given in Figs. 1–3.

The fairly wide scatter of experimental data attracts our attention especially in cases where the metal of a particular grade is represented in different states (see Figs. 1 and 3). An increase in the temperature results in an expected increase in the CGR in steels for every considered state. The metal of the stretched part of the bend, which is made of grade 12Kh1MF, is characterized by higher CGRs (i.e., lower crack resistance) in comparison with the metal of the straight pipe (see Fig. 1). This is due to the fact that the stretched zone of the branch during bending forms a field of intense residual deformation affecting substantially the properties of the metal. The effect of the long-term operation of the metal is revealed in a decrease in the resistance to development of cracks under creep (see Figs. 1, 3), which in principle corresponds to the concept of the effect of metal microdamage on creep crack kinetics, which is accumulated during the long-term thermal force action [20, 22], according to relation (10).

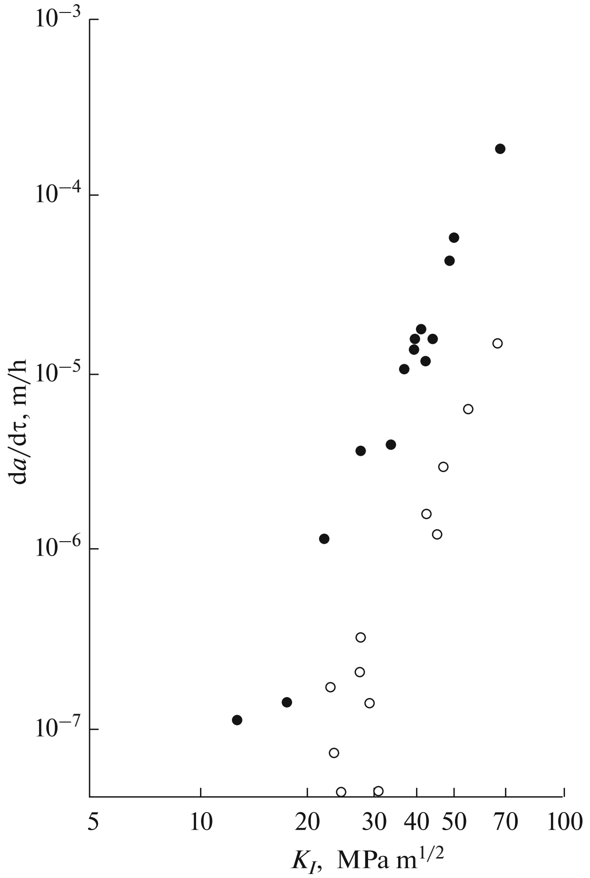

Fig. 2. Creep crack resistance of grade 15Kh1M1F steel in (○) rolled-stamped and (●) cast makes at a temperature of 560°C (initial metal).

Figure 1 gives results of creep crack investigations performed previously at the All-Russia Thermal Engineering Institute on cylindrical specimens with a circular crack. It is evident that, in the case of the same material, cracks develop faster (at comparable values of the SIF) under uniform stress state conditions than under nonuniform stress field conditions with the presence of the bending component (compact specimen). The similar character of the effect of the stress state type on the creep crack resistance of the metal agrees with the results of research [9], in which it is shown that the CGR under creep conditions is controlled not only by the SIF parameter but also by the character of the stress distribution in the specimen section. The similar pattern is traced in the approach to the analysis of the resistance of steels to development of cracks under creep proposed in [22]. Its essence is in the necessity to consider both the singular component of the metal damageability in the local

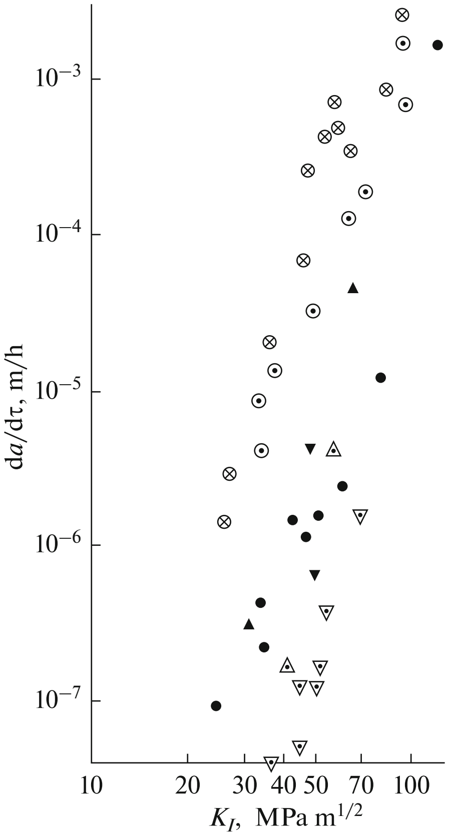

Fig. 3. Creep crack resistance of rotor steels: grade R2M(A) at temperature $T =$ (●, ▲, ▼) 525–530°C and (△, ▽) 505°C (operating time of (▼, ▽) ~50000 h; (●) ~55000 h); and (▲, △) ~20000 h); grade EI-415 at $T =$ (⊗) 540 and (⊙) 525°C (operating time of 140000 h).

zone of the crack tip and of the regular component of the damageability, which, in particular, depends on the stress state in the section of the unit (or specimen).

In the case of grade 15Kh1M1F steel, the creep crack resistance of cast metal is lower than that of metal in the rolled-stamped make (see Fig. 2). From comparison of the diagrams in Figs. 1 and 2, it follows that grade 15Kh1M1F steel in the rolled-stamped make differs in a somewhat higher resistance to creep crack development in comparison with the less heat-resistant grade 12Kh1MF steel in the similar make at the same test temperature. This can mean that the crack resistance of steels under high-temperature creep depends on heat-resistant properties, which in turn also explains the difference in crack resistance characteristics of the cast and rolled metal of a single grade of steel (see Fig. 2). Meanwhile, test results for grade 15Kh1M1FL steel in two structurally contrasting states (bainite and ferrite with carbides) showed [5] that the resistance to development of creep cracks of the metal with higher heat-resistant properties and reduced plasticity (bainite structure) is lower than that for the less heat-resistant but more plastic metal (ferrite) in the region of relatively low SIFs. At the same time, the tendency changes at a sufficiently high level of the SIF, and now steel with the ferrite structure reveals lower creep crack resistance than steel with the bainite structure (less plastic, but more heat resistant). On the basis of this, one should assume that the crack growth resistance of metal under high-temperature creep is determined by the set of its properties, in particular, by parameters of the long-term strength curve and the creep curve, which is actually supported by the structure of relations (8) and (9).

Grade R2MA and EI-415 rotor steels differ from steampipe steels (12Kh1MF and 15Kh1M1F) in the higher strength and, as consequence, reduced plasticity. In connection with this, the SIF parameter for them is preferred to describe the CGR under high-temperature creep conditions [5, 9]. This is supported by the fairly moderate spread of experimental data (see Fig. 3) for a specific batch of metal and the same test temperature. The lower resistance to growth of creep cracks of grade EI-415 steel in comparison with grade R2MA steel attracts our attention. The long-term plasticity factor is probably predominant for rotor steels with respect to the effect on resistance of the metal to growth of creep cracks. An increase in the test temperature results in an increase in the CGR (see Fig. 3), supporting that the steel fracture process under high-temperature creep conditions is thermally activated. The crack resistance of grade R2MA steel has the tendency to decrease under creep conditions with a substantial increase (to ~200000 h) of the initial operating time of the metal. As a whole, the character of experimental data in Fig. 3 indicates that an increase in the CGR with an increase in the SIF in grade R2MA steel occurs more intensely than in grade EI-415 steel, which results in the convergence of corresponding kinetic relationships for the given steels in the region of sufficiently high SIFs. As was mentioned above, a similar tendency was stated by results of investigations of grade 15Kh1M1FL steel represented by two structurally contrasting states [5].

In the context of the approach proposed here, which is in the consideration of the degree of uniformity of the stress state and the time of the crack development during the determination of the SIF, the obtained experimental data were processed additionally with the determination of the reduced SIF (K^*) according to relation (14) and the corresponding reconstruction of kinetic diagrams. Values of coefficient k_a^* obtained as a result of data processing in accordance with Eq. (11) varied in a range of 0.69–0.89, and values of coefficient k_τ^*, calculated by formula (13) were from 1.04 to ~1.11. Experimental dependences of the CGR on the reduced SIF (points) for the investigated steels are shown in Figs. 4–6.

It is evident that the realization of the proposed method noticeably decreased the experimental data

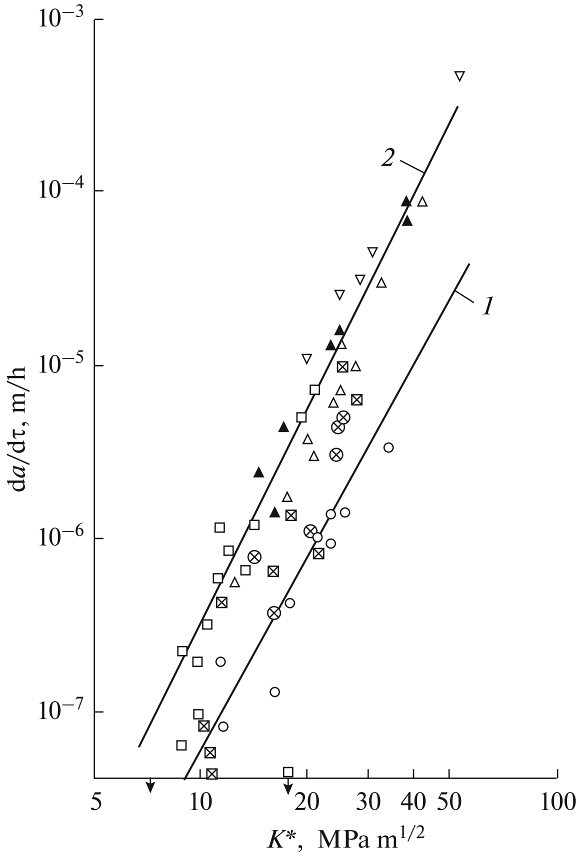

Fig. 4. Dependences of the creep crack growth rate on the reduced SIF (K^*) in grade 12Kh1MF steel: designations of experimental point are the same as that in Fig. 1: (*1*) and (*2*) are kinetic diagrams for metal of the straight pipe and the bend, respectively.

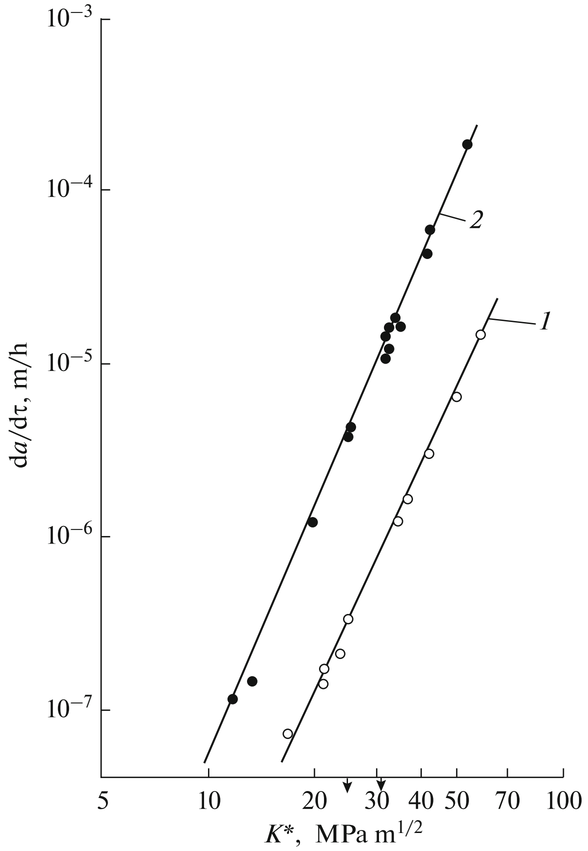

Fig. 5. Dependences of the creep crack growth rate on the reduced SIF (K^*) in grade 15Kh1M1F steel in (*1*) rolled-stamped and (*2*) cast makes at 560°C (initial state).

spread for every specific batch of tested specimens, i.e., for the same state of the metal, same temperature, etc. In addition, the results of tests which were carried out for the same material (metal of the bend of grade 12Kh1MF steel) on specimens of different types drew closer together, and one can conclude that they were in the common spread band (Fig. 4). This verifies that the degree of uniformity of the stress state and the accumulated damage in the section of specimens are taken into account owing to the use of the reduced SIF as the CGR parameter, because of which the difference in kinetic diagrams of the crack resistance, which is caused by the effect of these factors, levels. It is significant that all the above-mentioned tendencies with respect to the effect of the metal state and the test temperature on creep crack growth kinetics remain with the interpretation of kinetic dependences by the reduced SIF parameter (Figs. 4–6).

The kinetic diagram of the crack resistance in coordinates da/dT–K^* was constructed for every investigated material at the specifically selected test temperature which was the most relevant in view of the operating conditions for products of the given material. At the same time, test results for different states (operating time) of the metal of a particular steel were combined into a total array of experimental points and processed by the least-squares procedure with the construction of the diagram in the form of the upper boundary of the 95% confidence interval. For grade 12Kh1MF and 15Kh1M1F(L) steampipe steels, the kinetic diagrams are constructed for a temperature of 560°C, and for grade R2MA and EI-415 rotor steels, they are constructed for a temperature of 525°C. The resultant kinetic curves $da/d\tau$–K^* for the steel crack resistance are depicted in Figs. 4–6. The values of the coefficients of power equation (1) for the creep CGR corresponding to these curves are listed in the table. Power equipment units produced from the investigated steel grades are listed here as well.

Our results indicate that exponent β in kinetic relation (1) of the crack resistance for steampipe (vessel) steels is approximately 4–5, and for rotor steels, it is 5.5–6.0, which agrees with above-stated analytical relations (8) and (9). It should be noted that grade 15Kh1M1F in the context of the given investigation was represented in the rolled-stamped make, i.e., it more corresponds to the material of a rolled pipe. It can be expected that, with the transition to the metal

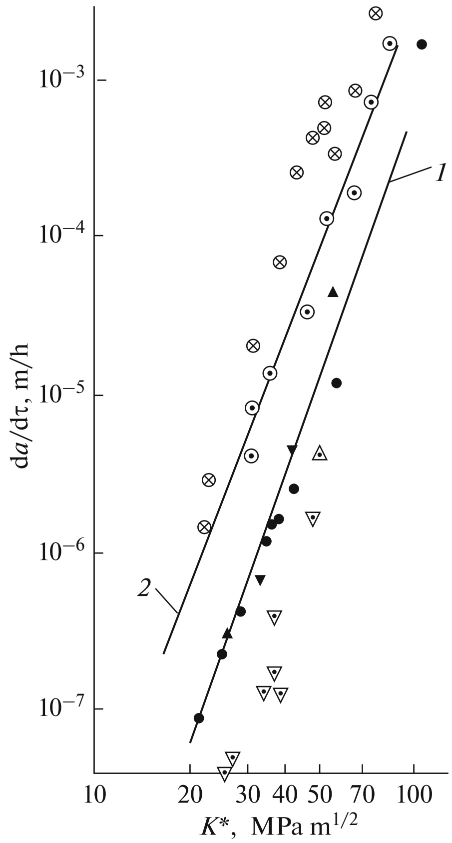

Fig. 6. Dependences of the creep crack growth rate on the reduced SIF (K^*) in rotor steel: designations of experimental point are the same as that in Fig. 3: (*1*) and (*2*) are kinetic diagrams for grade R2MA and EI-415 steels, respectively.

of the stretched part of bent branches, the crack-resistance characteristics of this steel will be lower (similarly as for grade 12Kh1MF), approximating the crack-resistance diagram of cast metal.

Generalizing the given material, one can conclude the following. The possibility of the approximation of the creep crack growth rate in the form of a power dependence on the stress intensity factor is experimentally verified for heat-resistant steels applied in power-plant engineering. The use of the reduced CGR, which takes into account the features of the stress state in the operating section and the metal damage accumulated during the crack growth, makes it possible to reduce noticeably the spread of experimental data in the mentioned approximation and to construct a kinetic diagram of the crack resistance acceptable for practical calculations of the equipment life under creep conditions.

ACKNOWLEDGMENTS

This study was supported by the Ministry of Education and Science of the Russia Federation (sponsorship agreement no. 14.576.21.0048).

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Translated by S. Ordzhonikidze