Prediction of Creep-Rupture Properties for Austenitic Stainless Steels Undergone Neutron Irradiation at Different Temperatures

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Abstract. Early the physical-and-mechanical model of integranular fracture has been developed that allows the prediction of creep-rupture properties of austenitic stainless steels at different neutron fluxes and temperatures. The model is based on the equations of void nucleation and growth on grain boundaries caused by inelastic deformation (creep and plastic strain) and diffusion of vacancies. Earlier the model has been verified when using available published data for austenitic stainless steels for 18Cr-9Ni and 18Cr-10Ni-Ti grades. The aim of the present work is further verification of the model for austenitic stainless steels under neutron irradiation. For this in-pile tests are carried out for gas-filled tubes at different temperatures (550 ºC and 600 ºC) in RBT-6 reactor with neutron flux equal to $5\cdot 10^{13}$ n/cm^{2}s. Specimens are made from austenitic stainless steels for 18Cr-9Ni and 16Cr-11Ni-3Mo grades. The results calculated by the model are compared with the obtained experimental data, and their good agreement is shown.

1. Introduction

For estimation of the service life of structural components of high temperature fast reactors, material characteristics such as creep-rupture strength and ductility are used. Direct determination of data on creep-rupture strength and ductility over an extended period of time for different operating temperatures is connected with performance of prolonged and costly in-pile experiments. With a long design service life of a structure (for example, hundreds of thousands of hours) tests conducted on a time basis that meets the total design service life become practically impossible. Therefore in order to reduce time and financial expenditures creep-rupture strength is usually predicted by extrapolating the experimental results obtained on comparatively short-term tests (from several thousands to tens of thousands of hours).

At present several empirical dependences have been proposed based on which creep-rupture strength has been predicted. The dependences proposed by Larson–Miller [1], Sherby–Dorn [2], Manson – Haferd [3], Zhurkov [4] and Trunin [5] have received wide acceptance. However the adequate use of the extrapolation dependences is limited by the narrow enough range of thermal-mechanical loading conditions. Besides, there are no approaches that permit predicting creep-rupture strength and ductility of materials subjected to neutron irradiation with different flux levels.

In addition to the mentioned approaches there is the method of determining creep-rupture strength and ductility based on the kinetic equations of a material state that was first proposed by Kachanov [6] and developed in papers [7] and [8]:

$$\xi^c = f(\sigma, \omega, \Phi);$$

$$\dot{\omega} = \varphi(\sigma, \varepsilon^c, \omega, \Phi),$$

where ξ^c is creep strain rate; σ is stress; ε^c is creep strain; ω is a damage parameter; Φ is a neutron flux.

In this case the attainment of a certain value (usually $\omega = 1$) by a damage parameter ω is taken as a criterion of fracture, the relation between ω and the parameters of stress-strain state (SSS) (for example, σ and ε^c) being of an empirical nature, which also does not permit using this approach over a wide temperature–mechanical loading range.

The alternative methods of predicting creep-rupture strength are the approaches based on the physical and mechanical models of damage accumulations in a material [9-16]. In particular, in [9] the dependences were proposed that describe the growth of voids on grain boundaries. The mechanism of void growth caused by diffusion processes and creep was studied in [10, 11]. In [13, 14] the model was developed basing on description of the void nucleation and growth process in special cells that permitted modeling the fracture of a polycrystalline material on grain boundaries. In this model a polycrystalline grain and grain boundary are presented as different materials with special properties. In [15] the model of intercrystalline fracture under creep in conditions of triaxial stress state was proposed. Based on the presented model the investigation was carried out on the influence of stress triaxiality upon void growth determined under creep.

The reported papers provide a more comprehensive understanding of the processes of damage accumulations on grain boundaries; however it is difficult to use these models for predicting creep-rupture strength. Firstly, to describe damage accumulation it is necessary to determine a large enough number of parameters that cannot be obtained from simple mechanical tests. Secondly, the criterion of fracture is defined in the form of the accepted a priori values of critical parameters. For example, the ratio of a void radius to the distance between two neighboring voids or attainment of a certain critical value by a void is often used as a critical parameter.

In [16-18] the model was proposed of intercrystalline fracture under static and cyclic loading, the model being based on the equations of void nucleation and growth, as well as on the so-called criterion of "microplastic collapse" or plastic instability of a unit cell. This criterion does not require introduction of any empirical parameters of fracture.

In this paper the physical and mechanical model of intercrystalline fracture [16-18] was used to predict creep-rupture strength of materials. The model was modified as applied to the peculiarities of damage accumulations under neutron irradiation [19, 20]. In doing so it is accepted that the main mechanism of fracture is damage accumulation on grain boundaries by the mechanism of void nucleation and growth. Also the comparison of the experimental data of creep-rupture strength and prediction by the above model is made.

2. Physical and mechanical model

It is apparent that a detailed describing of the model and presentation of the methods of determination of the model parameters and cannot be given in this paper for reasons of space. Previously, in [21] we described the model and some the approaches to determination of the model parameters.

Criterion of Fracture

During modeling we use the equations of continuum, which describing visco-plastic deformation of the unit cell [21] under thermal and mechanical loading. The mechanical properties of a cell are taken as identical to the mean mechanical properties of a polycrystalline material. A unit cell is taken to mean a regular fragment of a material volume of size ρ_{uc} equal to a grain diameter d_g, the fragment incorporating grain boundaries. The critical state of a unit cell with voids, i.e. fracture of a cell, is determined as a microplastic collapse that may be written in the form [19]

$$\frac{dF_{eq}}{dæ_p} = (1 - S_\Sigma)\frac{d\sigma_{eq}}{dæ_p} - \sigma_{eq}\frac{dS_\Sigma}{dæ_p} \tag{1}$$

where F_{eq} is equivalent stress, $F_{eq}=\sqrt{\frac{3}{2}S_{ij}S_{ij}}$; $S_{ij}=F_{ij}-F_m\delta_{ij}$; $F_m=F_{ii}/3$; F_{ij} is the tensor of stresses for which the conditions of material volume equilibrium are fulfilled; $\sigma_{eq}=\frac{F_{eq}}{1-S_{\Sigma}}$;

$æ_p=\int d\varepsilon^p_{eq}$; $d\varepsilon^p_{eq}=\sqrt{\frac{2}{3}(d\varepsilon^p_{ij}-d\varepsilon^p_m\delta_{ij})(d\varepsilon^p_{ij}-d\varepsilon^p_m\delta_{ij})}$ is the equivalent plastic strain increment; $d\varepsilon^p_{ij}$ is the tensor of plastic strain increment; δ_{ij} is the Kronecker symbol; $d\varepsilon^p_m=d\varepsilon^p_{ii}/3$; S_{Σ} is a relative void area, i.e. a void area per area unit of a deformed grain face

The values $d\sigma_{eq}$, dS_{Σ} and $dæ_p$ are caused by stress increment dF_{eq} under instantaneous loading.

Void Nucleation on Grain Boundaries

The void nucleation rate α_{int} is defined by $\alpha_{int}=\frac{d\rho}{dæ_{cp}}$, mainly controlled by the equivalent inelastic strain rate $\xi^{cp}_{eq}\equiv\frac{d\varepsilon^{cp}_{eq}}{dt}$ and temperature T; it may be written in the following form [17]

$$\alpha_{int}=\varphi_1\left(\xi^{cp}_{eq},T\right)\cdot(\rho_{max}-\rho), \tag{2}$$

where ρ_{max} is the maximum number of sites of void nucleation per area unit, ρ is the number of voids per area unit of an undeformed grain face.

The function $\varphi_1\left(\xi^{cp}_{eq},T\right)$ at fixed temperature has a maximum and decreases both with decreasing ξ^{cp}_{eq} and with increasing ξ^{cp}_{eq} [17]. Following form of equation of void nucleation rate can be proposed

$$\alpha_{int}=c_{\alpha}(T)\cdot(\rho_{max}-\rho), \tag{3}$$

where $c_{\alpha}(T)$ is the material constant that is temperature dependent in the general case.

The dependence of a void nucleation rate on fluence may be represented as

$$\alpha_F=\varphi_2\left(\alpha_{int},\sigma^F_Y\right), \tag{4}$$

where α_F is the rate of void nucleation under neutron irradiation; σ^F_Y is yield strength under irradiation, it depends on neutron fluence F.

Let us take equation (4) in the form

$$\alpha_F=k_F\cdot\alpha_{int}, \tag{5}$$

where k_F is the coefficient accounting for acceleration of void nucleation due to neutron irradiation, $k_F=\left(1+\frac{\Delta\sigma^F_Y}{\sigma^0_Y}\right)^m$; σ^0_Y is the yield strength at F=0; m is a material constant; $\Delta\sigma^F_Y$ is an increment of yield strength due to irradiation.

Then equation (5) may be rewritten in the form [21]

$$\alpha_F=\left(1+\frac{\Delta\sigma^F_Y}{\sigma^0_Y}\right)^m c_{\alpha}\rho_{max}\cdot\exp\left(-c_{\alpha}\cdot æ_{cp}\right). \tag{6}$$

Growth of Voids

According to [21] the void growth on grain boundaries caused by inelastic strain and diffusion of vacancies may be described by the following dependences

$$\frac{dR}{Rd\varepsilon_{eq}^{cp}} = f_1\left(\frac{\Lambda_q}{R}, q_m\right), \tag{7}$$

where $f_1\left(\frac{\Lambda_q}{R}, q_m\right) = \frac{1}{h(\psi)}\left\{\frac{1}{2}\left[\left(\frac{\Lambda_q}{R}\right)^3 f\left(\frac{\Lambda_q}{R}\right) - \frac{3}{4}\right] + 0.3\cdot(q_m)^r \exp(1.5q_m)\right\}$,

$h(\psi) = \left(\frac{1}{1+\cos(\psi)} - \frac{\cos(\psi)}{2}\right)\sin(\psi)$; ψ is the angle between the tangent to a void surface and the grain boundary plane on which a void is located; $\Lambda_q = q^{1/3}\left(\frac{D_\Lambda \sigma_{eq}}{\xi_{eq}^{cp}}\right)^{1/3}$;

$D_\Lambda = \frac{\Omega D\delta_b}{kT_a}$; $f\left(\frac{\Lambda}{R}\right) = \left[\ln\frac{R+\Lambda}{R} + \left(\frac{R}{R+\Lambda}\right)^2\left(1 - \frac{1}{4}\left(\frac{R}{R+\Lambda}\right)^2\right) - \frac{3}{4}\right]^{-1}$; $q = \frac{F_1}{F_{eq}}$; $q_m = \frac{F_m}{F_{eq}}$;

$F_m = \frac{F_{ii}}{3}$; $D\delta_b = D_b\delta_b + d_{F\delta}\cdot\frac{\Phi}{\Phi_0}$; $d_{F\delta} = d_F\delta_b$; $D_b\delta_b = D_{0b}\delta_b \cdot \exp(-Q_b / R_g T_a)$;

$d_F = d_{F0}\exp(-Q_b / 2R_g T_a)$; ξ^{cp} is the rate of inelastic strain; Ω is an atomic volume; d_b is a diffusion thickness of a grain boundary; D_{0b} is the coefficient of grain boundary diffusion; k is the Boltzmann constant; T_a is the absolute temperature; Φ – neutron flux; $\Phi_0 = 10^{12}$ n/cm^{2}c.

Constitutive equations

When defining constitutive equations we will use the following considerations [21]

1. The stress-strain curve relating stress to instantaneous plastic strain is represented in the form

$$\sigma_{eq} = \sigma_Y + a_p(æ_p)^{m_p}, \tag{8}$$

where a_p, m_p are material constants.

2. The full rate of inelastic strain ξ_{ij}^{uc} of a unit cell equal

$$\xi_{ij}^{uc} = \eta(\xi_{ij}^{cp})_b + (1-\eta)(\xi_{ij}^{cp})_g,\ 0 \le \eta \le 1, \tag{9}$$

where $(\xi_{ij}^{cp})_b$ is the rate of inelastic strain in the near boundary zone of a grain; $(\xi_{ij}^{cp})_g$ is the rate of inelastic strain outside the near-boundary zone; η is the parameter depending on void sizes on a grain boundary.

The equivalent inelastic strain rate of a unit cell may be represented in the form

$$\xi_{eq}^{uc} = \eta(\xi_{eq}^{cp})_b + (1-\eta)(\xi_{eq}^{cp})_g, \tag{10}$$

where $\xi_{eq}^{cp} = \xi_{eq}^{c} + \xi_{eq}^{p}$; ξ_{eq}^{c} is a creep rate; ξ_{eq}^{p} is a plastic strain rate;

$$\xi_{eq}^{c} = a_c\left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n_c}(æ_c)^{m_c},\quad \xi_{eq}^{p} = \frac{1}{a_p m_p}\left(\frac{\sigma_{eq}-\sigma_Y}{a_p}\right)^{(1-m_p)/m_p}\dot{\sigma}_{eq};\ \dot{\sigma}_{eq} = \frac{d\sigma_{eq}}{dt}.$$

where a_c, n_c, m_c are material constants, $æ_c = \int d\varepsilon_{eq}^{c}$; σ_0= 100 MPa.

3. The rate of inelastic deformation into the grain boundary

$$\left(\xi_{eq}^{cp}\right)_b = a_c\left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n_c}\left[æ_{cp} - \left(\frac{\sigma_{eq}-\sigma_Y}{a_p}\right)^{1/m_p}\right]^{m_c}\left[1 - \frac{1}{a_p m_p}\left(\frac{\sigma_{eq}-\sigma_Y}{a_p}\right)^{(1-m_p)/m_p}\frac{\sigma_{eq}}{(1-S_\Sigma)}\frac{dS_\Sigma}{dæ_{cp}}\right]^{-1}. \tag{11}$$

4. The rate of inelastic deformation into the grain

$$(\xi_{eq}^{cp})_g = a_c\left(\frac{F_{eq}}{\sigma_0}\right)^{n_c}\left[\text{æ}_{cp}^{g} - \left(\frac{F_{eq}-\sigma_Y}{a_p}\right)^{1/m_p}\right]^{m_c}\left[1-\frac{1}{a_p m_p}\left(\frac{F_{eq}-\sigma_Y}{a_p}\right)^{(1-m_p)/m_p}\frac{dF_{eq}}{d\text{æ}_{cp}^{g}}\right]^{-1}. \tag{12}$$

5. Under neutron irradiation creep rate may be described by the following dependence

$$\xi_{eq}^{c} = a_c\left(\frac{\sigma_{eq}}{\sigma_0}\right)^{n_c}(\text{æ}_c)^{m_c}\left(1+\frac{\Phi}{\Phi_\xi}\exp(Q_\Phi/R_g T_a)\right), \tag{13}$$

where Φ_ξ is a material constant; Q_Φ is the activation energy of radiation creep.

Determination of the model parameters

It is seen from previous section that for practical implementation of the presented model it is necessary to determine a large enough number of parameters entering the equations of nucleation and growth and also the equations describing the material properties. These parameters were determined for steel 18Cr-9Ni (the Russian analog of steel 304) and for steel 18Cr-10Ni-Ti (the Russian analog of steel 321) [21]. The average creep-rupture strength can be predicted on the basis of these parameters [21].

3. In-pile tests

We carried out the creep–rupture tests for steels in initial condition and in-pile tests in Russian RBT-6 reactor. Tests were carried out for gas-filled tubes at the temperatures 550 ºC and 600 ºC. Gas-filled tubes were made of 18Cr-9Ni and 16Cr-11Ni-3Mo steels. Chemical compositions of these steels are given in Table 1. The drawing of gas-filled tubes is shown in Fig. 1.

TABLE 1. CHEMICAL COMPOSITION OF 18Cr-9Ni AND 16Cr-11Ni-3Mo STEELS

Steel	C, %	Mn, %	Si, %	S, %	P, %	Cr, %	Ni, %	Cu, %	Mo, %	Ti, %	V, %	N_2, %
18Cr-9Ni	0.09	1.47	0.43	0.006	0.011	18.00	9.01	0.03	0.01	0.01	0.02	0.02
16Cr-11Ni-3Mo	0.08	1.32	0.70	0.003	0.011	16.15	10.98	0.03	2.26	0.01	0.01	0.01

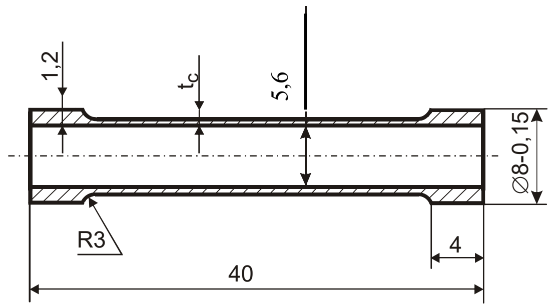


FIG. 1. Drawing of the gas-filled tubes for in-pile tests (t_c ≈ 0.495 mm)

For creating stress in the tube specimen inertial gas was injected into it at the room temperature. After heating the pressure in the tube specimen increases to a given value. Specimens were tested at two different temperatures. The first group of specimens were tested at 550ºC; the second – 600 ºC. Neutron flux in RBT-6 reactor was $\Phi=5.0\cdot10^{13}$ $n\cdot cm^{-2}s^{-1}$ (E>0.1 MeV). Each specimen is connected to recording device. The time to rupture is determined accurate to one minute due to changing of pressure in recording device. Temperature of specimens was sustained accurate to ±2 % of a given value in reactor and ±1

Celsius degree in furnace. Time to rupture is measured accurate to ±1 minute. Stresses in specimen are measured accurate to ±2 %.

In Figs. 2 and 3 experimental data on the creep-rupture strength for 18Cr-9Ni steel in initial and irradiated conditions are represented at 550 °C and 600 °C. In Figs. 4 and 5 experimental data on the creep-rupture strength for 16Cr-11Ni-3Mo steel in initial and irradiated conditions are represented at 550 °C and 600 °C. Also we were carried out creep-rupture test for steels in initial condition for uniaxial specimens, which were made of 18Cr-9Ni and 16Cr-11Ni-3Mo steels. Results of this test are presented in figs 2 and 4.

4. Calculation

In this section the calculation of the average dependences of creep-rupture strength is presented on the basis of the above model at various temperatures for steels 18Cr-9Ni and 16Cr-11Ni-3Mo (the Russian analog of steel 316) in initial and irradiated conditions. The comparison of these dependences and experimental data is made.

18Cr-9Ni steel

Initial condition. The parameters entering in the equations of void nucleation and growth on grain boundaries differ a little for steels of the same class. Therefore these parameters were taken as the parameters for 18Cr-10Ni-Ti steel. The parameters entering into the equation of creep rate were obtained by processing the creep curves for 18Cr-9Ni steel that are presented in [22, 23] and are given in Table 2.

The value of yield strength σ_Y is taken as in [24], the constants a_p and m_p were calculated for different temperatures in accordance with [25] and are given in table 2.

TABLE 2. VALUES OF TEMPERATURE DEPENDENT PARAMETERS FOR 18Cr-9Ni STEEL

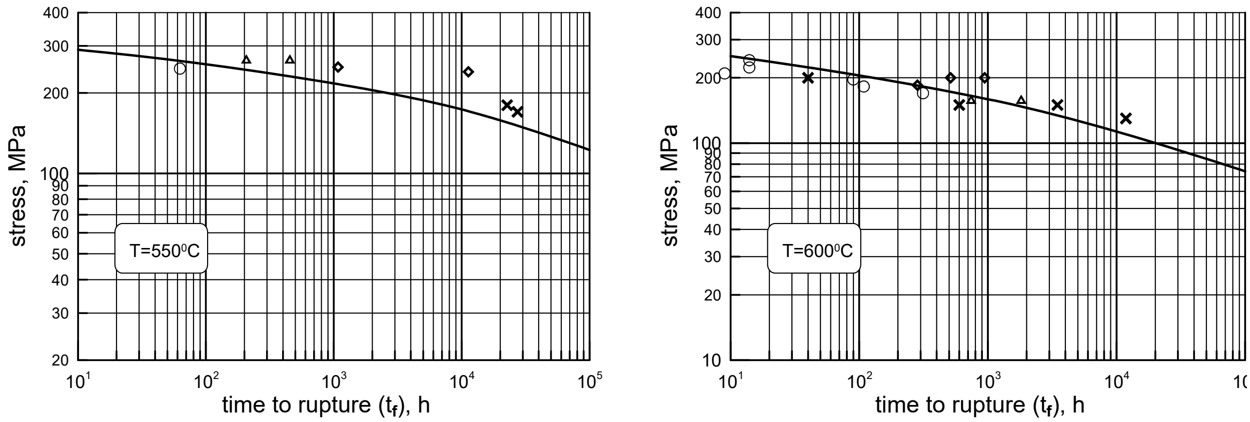
T_a, K	σ_Y, MPa	a_p, MPa	m_p, MPa	a_c, $(\text{MPa})^{-n_c}/\text{h}$	n_c	m_c
773	169	950	0.585	$4.82{\cdot}10^{-13}$	13.5	-1.5
823	155	638	0.585	$2.46{\cdot}10^{-9}$	9.5	-0.7
873	150	568	0.558	$1.20{\cdot}10^{-7}$	8.2	-0.63

Based on the physical and mechanical model and obtained parameters the calculation was performed of creep-rupture strength of steel 18Cr-9Ni in the initial condition at the temperatures 550 and 600 °C. These dependences at the temperatures 550 and 600°C, as well as the experimental data on steels 18Cr-9Ni are given in Fig. 2. It is seen from the figure that the physical and mechanical model provides adequate enough predictions.

Irradiated condition. The dependences of creep-rupture strength were calculated for steel 18Cr-9Ni with neutron flux Φ equal $5{\cdot}10^{13}$ n/cm$^2{\cdot}$s (E>0.1 MeV). These dependences, as well as the experimental data are presented in Fig. 3. It is seen from the figure that the physical and mechanical model provides adequate enough predictions.

16Cr-11Ni-3Mo steel

Initial condition. The parameters entering into the equation of a creep rate were obtained by processing the creep curves of steels 16Cr-11Ni-3Mo that are presented in [22, 23] and are given in Table 3. The value of yield strength σ_Y is taken as in [24], the constants a_p and m_p were calculated for different temperatures in accordance with [25] and are given in Table 3.



a b

FIG. 2. Creep-rupture strength of 18Cr-9Ni steel in initial condition at temperatures T=550°C (a) and T=600°C (b): (——) – calculation by the model; (O) – experimental data of gaz-tube specimen; (◊) – experimental data of uniaxial specimens; (X) – experimental data of uniaxial specimens [26]; (Δ) – experimental data of uniaxial specimens [27].

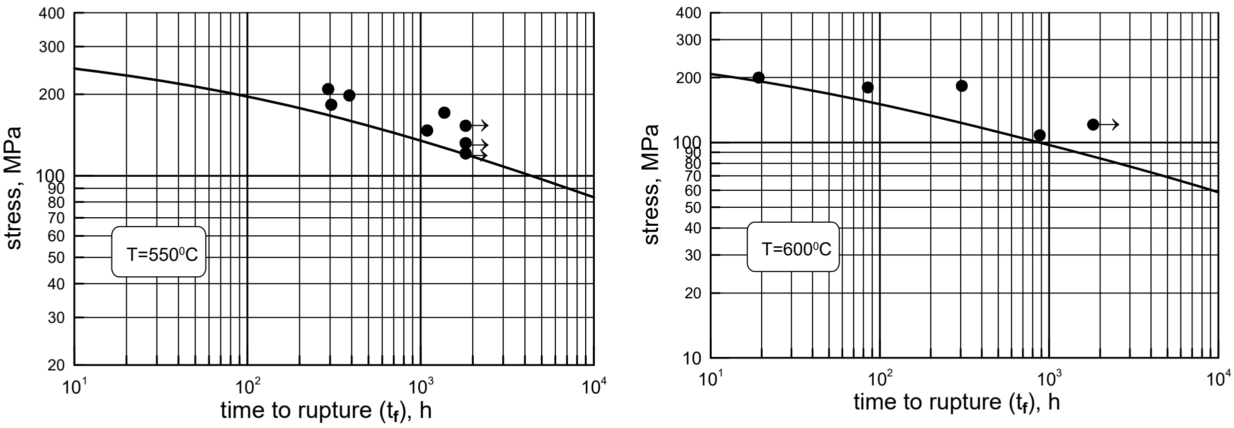


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FIG. 3. Creep-rupture strength of 18Cr-9Ni steel in irradiated condition ($\Phi=5\cdot10^{13}$ n/cm²s (E>0.1 MeV)) at temperatures T=550°C (a) and T=600°C (b): (——) – calculation by the model; (●) – experimental data, → - specimen didn't rupture.

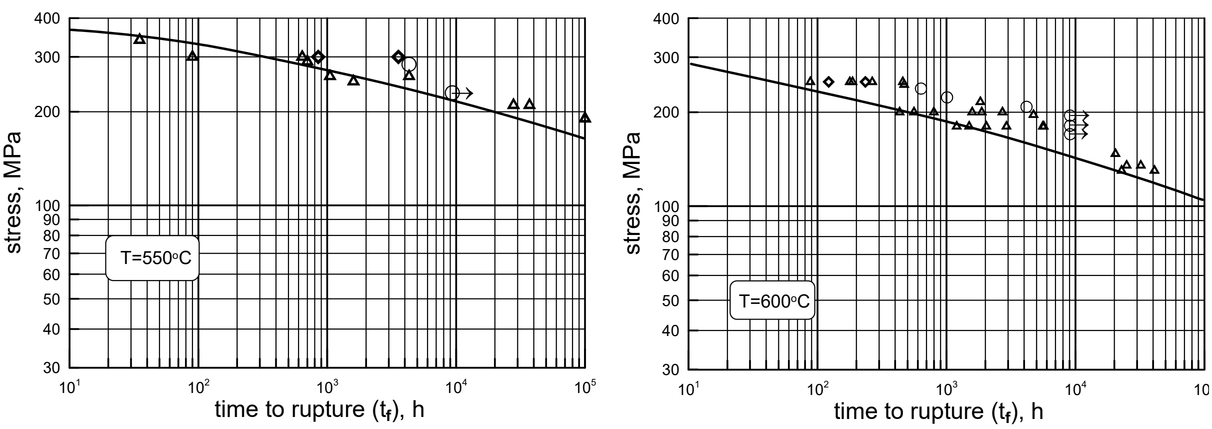

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FIG. 4. Creep-rupture strength of 16Cr-11Ni-3Mo steel in initial condition at temperatures T=550°C (a) and T=600°C (b): (——) – calculation by the model; (O) – experimental data of gaz-tube specimen; (◊) – experimental data of uniaxial specimens; (Δ) – experimental data of uniaxial specimens [27]; → - specimen didn't rupture

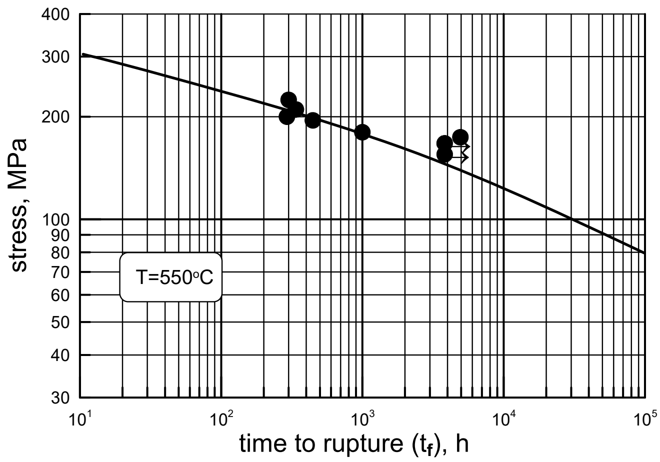

FIG. 5. Creep-rupture strength of 16Cr-11Ni-3Mo steel in irradiated condition ($\Phi=5\cdot10^{13}$ n/cm²s (E>0.1 MeV)) at temperature T=550°C: (——) – calculation by the model; (●) – experimental data, → - specimen didn't rupture.

TABLE 3. VALUES OF TEMPERATURE DEPENDENT PARAMETERS FOR 16Cr-9Ni-3Mo STEEL

T_a, K	σ_Y, MPa	a_p, MPa	m_p, MPa	a_c, $(\mathrm{MPa})^{-n_c}/\mathrm{h}$	n_c	m_c
773	168	1045	0.585	$7.3445\cdot10^{-14}$	13.8	-1.5
823	165	702	0.585	$1.3433\cdot10^{-11}$	12.5	-1.1018
873	160	625	0.558	$1.1984\cdot10^{-8}$	11.2	-0.6484

Based on the physical and mechanical model and obtained parameters the calculation was performed of creep-rupture strength of steel 16Cr-11Ni-3Mo in the initial condition at the temperatures 550 and 600 °C. These dependences at the temperatures 550 and 600 °C, as well as the experimental data on steels 16Cr-11Ni-3Mo are given in Fig. 4. It is seen from the figure that the physical and mechanical model provides adequate enough predictions.

Irradiated condition. The dependences of creep-rupture strength were calculated for steel 16Cr-11Ni-3Mo with neutron flux Φ equal $5\cdot10^{13}$ n/cm²·s (E>0.1 MeV). These dependences, as well as the experimental data are presented in Fig. 5.

Also the dependences of creep-rupture strength were calculated for steels 16Cr-11Ni-3Mo and 18Cr-9Ni with different values of neutron fluxes Φ that varied through a range between $2\cdot10^{12}$ and $1\cdot10^{14}$ n/cm²·s (E>0.1 MeV). These dependences are presented in Fig. 6. From this figure it is seen strong influence of flux level on creep-rupture strength.

5. Conclusions

1. In-pile tests for gas-filled tubes were carried out at various temperatures (550 °C and 600 °C) in RBT-6 reactor with neutron flux equal to $5\cdot10^{13}$ n/cm²s for austenitic stainless steels of 18Cr-9Ni and 16Cr-11Ni-3Mo grades. Moreover creep-rupture tests for gas-filled tubes and uniaxial specimens were carried out for above steels in initial condition.

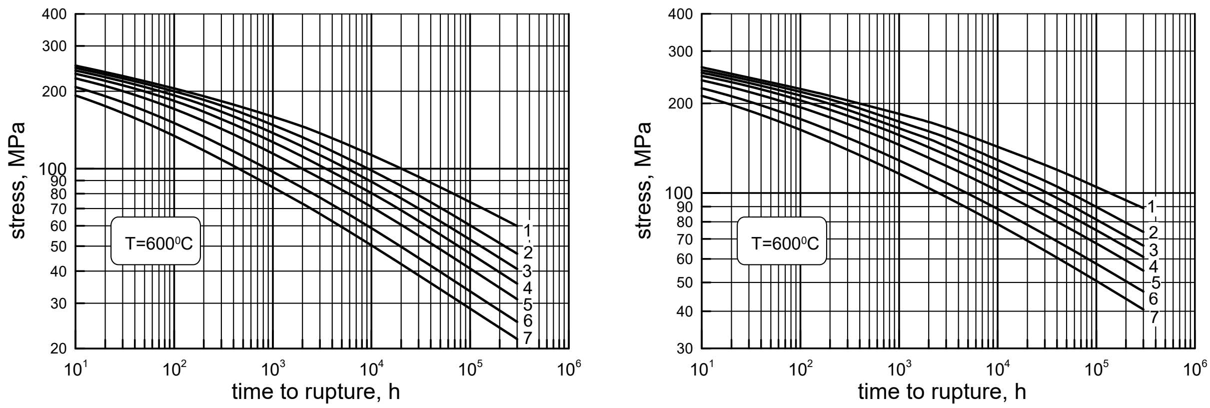

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FIG. 6. Dependence of creep-rupture strength on time to rupture at T=600ºC for different neutron flux levels (a – 18 Cr-9 Ni steel, b – 16 Cr-11 Ni- 3 Mo steel): 1 – initial condition; 2 – $\Phi=2\cdot10^{12}$ n/cm²s; 3 – $\Phi=5\cdot10^{12}$ n/cm²s; 4 – $\Phi=1\cdot10^{13}$ n/cm²s; 5 – $\Phi=2\cdot10^{13}$ n/cm²s; 6 – $\Phi=5\cdot10^{13}$ n/cm²s; 7 – $\Phi=1\cdot10^{14}$ n/cm²s (E>0.1 MeV).

2. The calculation of creep-rupture strength are made at temperatures 550 and 600 ºC on the basis of the physical-mechanical model integranular fracture for 18Cr-9Ni and 16Cr-11Ni-3Mo steels in initial and irradiated conditions. The calculated dependences and experimental data for gas-tubes specimens (reactor RBT-6) made are compared. It is shown good agreement between the experimental data and the calculated dependences of creep-rupture strength.

3. The predictions of creep-rupture strength are carried out at temperature 600 ºC for 18Cr-9Ni and 16Cr-11Ni-3Mo steels for different neutron fluxes over a range from $2\cdot10^{12}$ to $1\cdot10^{14}$ n/cm$^2\cdot$s (E>0.1 MeV).

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REFERENCES

[1] F.R. Larson, J. Miller. A time-temperature relationship for rupture and creep stress. *Trans. ASME,* 1952, V. 74, No.5.
[2] J.E. Dorn. Some Fundamental Experiments on High temperature Creep. *NPL,* 1956, 89.
[3] S.S. Manson, A.M. Haferd. A liner time-temperature relation for extrapolation of creep and stress rupture data. *NACA TN 2800*, Washington, D.C., March 1953.
[4] S.N. Zhurkov, T.P. Sanfirova. Temperature and time dependence of strength of pure metals. *DAN USSR,* 1955, V. 101 (in Russian).
[5] I.I. Trunin, Ya.F. Fridman and I.M. Perets.Parametric method of evaluating the long-term strength and creep limit of metal lots. *Strength of Materials*, 1979, V.11, No. 10, 97-100.
[6] L.M. Kachanov. About the rupture time under creep. *Izv. AN USSR, OTN,* 1958, No. 8, 3-10.
[7] A.A. Chizhik, Yu.K. Petrenya. About kinetic equations of damage at intercrystalline fracture. *Proceedings of CKTI,* Saint Petersburg, 1978, No. 169, 42-44 (in Russian).
[8] V.N. Kiselevsky. Strength of structural materials of nuclear reactors. Kiev: NaukovaDumka, 1990 (in Russian).

[9] R. Raj, M.F. Ashby. Intergranular fracture at elevated temperature. *Acta. Met.,* 1975, V. 23,653-666.
[10] A. Needleman, J.R. Rice. Plastic creep flow effects in the diffusive cavitation on grain boundaries. *Acta Met.,* 1980, V. 28, 1315-1332.
[11] V. Tvergaard. On the creep constrained diffusive cavitation on grain boundary facets.*J. Mech. Phys. Solids,* 1984, V. 32,373-391.
[12] H. Riedel. Fracture at High Temperatures. Springer Vergal, Berlin, 1987.
[13] Van der Giessen, V. Tvergaard. Development of final creep failure in polycrystalline aggregates. *Acta Metall. Mater.,* 1994, V. 42, 959-973.
[14] Van der Giessen, V. Tvergaard. Micromechanics of intergranular creep failure under cyclic loading. *Acta Metall. Mater.,* 1996, V. 44, 2697-2710.
[15] A.C.F. Cocks, M.F. Ashby. Integranular fracture during power-law creep under multiaxial stresses. *Metal Science,* 1980, V. 8-9,395-402.
[16] G.P. Karzov, B.Z. Margolin. and V.A. Shvetsova. Physical and mechanical modelling for fracture process. Saint Petersburg: Polytechnica, 1993 (in Russian).
[17] B.Z. Margolin, G.P. Karzov, V.A. Shvetsova and V.I. Kostylev. Modelling for transcrystalline and intercrystalline fracture by void nucleation and growth. *Fatigue & Fracture of Engineering & structures*, 1998, V. 21, 123-137.
[18] B.Z. Margolin, A.G. Gulenko. Lifetime prediction for intercrystalline fracture under cyclic loading with various strain rates. *International Journal of Fatigue*, 1999, V. 21, 497-505.
[19] B.Z. Margolin, A.G. Gulenko, I.P. Kursevich, A.A. Buchatsky. Modeling fracture for long-term static loading under creep and neutron irradiation. Report 1. Physical and mechanical model. *Problemyprochnosti*, 2006, No.3, 5-22 (in Russian).
[20] B.Z. Margolin, A.G. Gulenko, I.P. Kursevich, A.A. Buchatsky. Modeling fracture for long-term static loading under creep and neutron irradiation. Report 2. Prediction of the creep-rupture properties. *Problemyprochnosti*, 2006, No.5, 5-16 (inRussian).
[21] B.Z. Margolin, A.G. Gulenko, A.A. Buchatsky, in: *Proceedings of ASME 2009 Pressure Vessels and Piping Division Conference PVP2009 July 26-30, 2009*, Prague, Czech Republic (2009), PVP2009-77084
[22] Rules and regulations in nuclear power engineering. Regulations for strength analysis in nuclear power plants equipment and piping (PNAE G-7-002-86). Moscow: Energoatomizdat, 1989 (in Russian).
[23] ASME Boiler and Pressure Vessel Code. N-47-32. ASME, Three Park Avenue New York, NY 10016-5990, 1976.
[24] Data sheets on the elevated temperature properties of 18Cr-8Ni stainless steel for boiler and heat exchanger seamless tubes (SUS 304H TB). NRIM creep data sheets No. 5B, National research institute for metals, Tokyo, Japan, 1986.
[25] I.P. Kursevich, B.Z. Margolin, O.U. Prokoshev, V.I. Kohonov. Mechanical properties of austenitic steels under neutron irradiation: The effect of various factors. *Voprosymaterialovedenia*, 2006, No.4(48), 55-68 (in Russian).
[26] The effect of long-term aging on the creep-rupture properties of 18Cr-9Ni austenitic steels. Margolin B.Z., Gulenko A.G., Buchatsky A.A., Nesterova E.V., Kashtanov A.D. – Voprosy materialovedeniya, 2010, N4(64), p. 118-127.
[27] A. S. Kudryavtsev, V. G. Markov, R. N. Grishmanovskaja. Assessment of changing in properties of 304 steel by 130 thousand hours service in super heater of plant BN-600. *Proceedings of The Ninth International Conference "Material Issues in Design, Manufacturing and Operation of Nuclear Power Plants Equipment"* Saint Petersburg, 2006, V. 2, 290-298 (in Russian).