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Correlation Dependences between Short-Term/Long-Term Static Strength Characteristics and Creep Resistance of Tungsten at High Temperatures

V. A. Borisenko,[a] **V. V. Bukhanovskii,**[a] **and I. Mamuzic**[b]

[a] Pisarenko Institute of Problems of Strength, National Academy of Sciences of Ukraine, Kiev, Ukraine

[b] Faculty of Metallurgy, University of Zagreb, Sisak, Croatia

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Взаимосвязь между характеристиками кратковременной и длительной статической прочности и сопротивления ползучести вольфрама при высоких температурах

В. А. Борисенко[а], **В. В. Бухановский**[а], **И. Мамузич**[б]

[а] Институт проблем прочности им. Г. С. Писаренко НАН Украины, Киев, Украина

[б] Загребский университет, Шишак, Хорватия

Проанализированы механические характеристики технически чистого вольфрама, полученного методами порошковой металлургии, при одноосном растяжении в условиях высоких температур. Установлено, что для вольфрама в высокотемпературной области $\sim(0,5...0,8)T_{пл}$ *существуют корреляционные связи между характеристиками кратковременной и длительной статической прочности и сопротивления ползучести, которые описываются единой функциональной зависимостью.*

Ключевые слова: вольфрам, кратковременная и длительная статическая прочность, сопротивление ползучести, высокие температуры.

Introduction. The progress in a number of branches of modern engineering is related to the use of refractory metals and alloys, which can ensure strength of components and structural elements operating under conditions of extremely high temperatures (up to 2300–3300 K) and mechanical loads. Tungsten and tungsten-based alloys have the most unique range of physico-mechanical characteristics including heat resistance [1–3].

In addition to short-term strength, the characteristics of long-term static strength and creep are the most important factors characterizing serviceability of metals at high temperatures. Complete experimental evaluation of such characteristics for refractory materials presents great difficulties and is unrealistic in many cases.

It is known that temperature dependences of various mechanical characteristics that determine the resistance of metallic materials to deformation are qualitatively similar. Under short-term and long-term static loading, there are correlation dependences between strength characteristics of metals and alloys, which can be described by certain analytical expressions based on both empirical and physically justified approaches. They are undoubtedly of scientific and practical interest, because they make it possible to evaluate heat-resistance characteristics of advanced structural materials at minimum cost [4, 5].

In the present study, based on the analysis of experimental data obtained earlier, a generalized correlation dependence has been established between the characteristics of high-temperature short-term and long-term static strength and creep resistance of commercially pure tungsten produced by powder metallurgy (PM) technique.

Theoretical Background. On the basis of numerous experiments it has been found that temperature dependence of any mechanical characteristics, which determine the resistance of metallic materials to deformation, is described quantitatively by the following equation [4]:

$$M = \sqrt[3]{B\dot{\varepsilon}G^2T}\exp\left(\frac{U}{3kT}\right), \tag{1}$$

which, considering weak influence of preexponential terms as compared to the exponent, is simplified appreciably and takes the form

$$M = c\exp\left(\frac{U}{3kT}\right), \tag{2}$$

where M is the mechanical characteristic of the material, $\dot{\varepsilon}$ is the plastic strain rate, T is the thermodynamic temperature, G is the shear modulus, U is the plastic strain activation energy (enthalpy), k is the Boltzmann constant, B is the material parameters' function involving the entropy term $\exp(-S/k)$, and c is a constant, which is a function of the material parameters and strain rate.

From Eq. (2) it follows that in the absence of physicochemical transformations in the material, the logarithm of the deformation resistance ($\ln M$) should vary depending on the inverse thermodynamic temperature ($1/T$) according to a linear law. In practice, the dependence turns out to be more complex and generally the $\ln M - 1/T$ curve has the form of a broken line. Low- and high-temperature kinks in the logarithm of mechanical characteristic vs inverse thermodynamic temperature curves accompanied by the variation of the slope take place for metals at $\sim 0.2T_{melt}$ and at about $(0.5–0.55)T_{melt}$, respectively. Both types of these kinks are generally related to changes in the dominating mechanism of the material plastic deformation [3, 4].

When a material is deformed by a constant load under the action of high stresses (exceeding 10^{-4} of the shear modulus G) in the high-temperature region (above $0.5T_{melt}$), the following relations hold true [6]:

$$\dot{\varepsilon} = A_0\frac{\sigma^n}{T}\exp\left(\frac{-U}{kT}\right), \tag{3}$$

$$\tau = B_0 T\sigma^{-n} \exp\left(\frac{U}{kT}\right), \tag{4}$$

where $\dot{\varepsilon}$ is the steady-state creep rate, τ is the creep-rupture time, σ is the stress, A_0 and B_0 are material constants, and n is a parameter, which characterizes the slopes of the steady-state creep rate and creep-rupture time vs stress curves in the logarithmic coordinate system [5].

At constant temperature, expressions (3) and (4) are transformed to the following equations:

$$\dot{\varepsilon} = A_0^T \sigma^n, \tag{5}$$

$$\tau = B_0^T \sigma^{-n}, \tag{6}$$

where A_0^T and B_0^T are material constants at a given temperature.

Equations (3) and (4) can be reduced to the Monkman–Grant expression. This testifies that the product of the steady-state creep rate and creep-rupture time is a constant value independent of the applied stress and temperature:

$$\dot{\varepsilon}\tau = C_{MG} = \text{const.} \tag{7}$$

Here C_{MG} is the Monkman–Grant constant that usually has narrow margins (between 0.03 and 0.3) for all materials [6–9]. For tungsten, the C_{MG} values range approximately between 0.02 and 0.17 [6, 10–13].

Results and Discussion. The amount of accumulated experimental data on the mechanical properties of tungsten produced by PM technique [10–13] makes it possible to analyze them and establish correlation dependences between the characteristics of its short-term and long-term static strength and creep resistance. The experimental results considered refer to a high-temperature region (above $0.5T_{melt}$) and are obtained for high stresses (higher than 10^{-4} of the Young modulus) at short test time (up to 10^4 s). Therefore, when processing the data, we used the approaches based on the assumption that in certain regions of temperatures and stresses, the strength of metals and alloys under the studied loading conditions is governed by the same mechanisms of plastic deformation and fracture. We considered that the influence of temperature on the material softening under conditions of short-term active and long-term static loading is similar. The results of fractographic examinations, which establish similarity of the PM tungsten fracture modes under conditions of high-temperature creep and static tests, confirm the validity of the hypotheses taken as the basis for our further considerations [10, 11]. The similarity of the mechanisms of plastic deformation under active tension and deformation at the stage of steady-state creep for metallic materials was also noted in [4, 14], where it was mentioned that under conditions of high-temperature uniform tension, the strain rate is equivalent to the steady-state creep rate.

Figure 1 presents experimental data [10–13] on short-term strength of commercially pure PM tungsten (99.97 wt.% W) in the temperature range from

1770 to 2770 K, which corresponds to $\sim(0.5\text{–}0.8)T_{melt}$, in the form of temperature dependences of the ultimate strength R_m and the offset yield stress $R_{p0.2}$. The plots are constructed in the coordinates $\ln(R_m, R_{p0.2}) - 1/T$. This figure also shows the dependences of the tungsten long-term ultimate strength for the test time 10^3 s, $\sigma_{10^3\,\mathrm{s}}$, and stresses corresponding to the steady-state creep rate $10^{-3}\ \%\cdot\mathrm{s}^{-1}$, $\sigma_{10^{-3}\,\%\cdot\mathrm{s}^{-1}}$, on the inverse temperature $1/T$. The two latter curves were obtained from the results, which characterize the variation of the steady-state creep rate with the applied stress, and long-term strength diagrams of tungsten for the temperatures studied (Figs. 2a and 3a). The $\ln\dot{\varepsilon} - \ln\sigma$ and $\ln\sigma - \ln\tau$ curves shown in Figs. 2a and 3a are adequately described by Eqs. (5) and (6). The values of the coefficient n, which characterizes the slope of the curves for PM tungsten, are about 5.3 [11, 13].

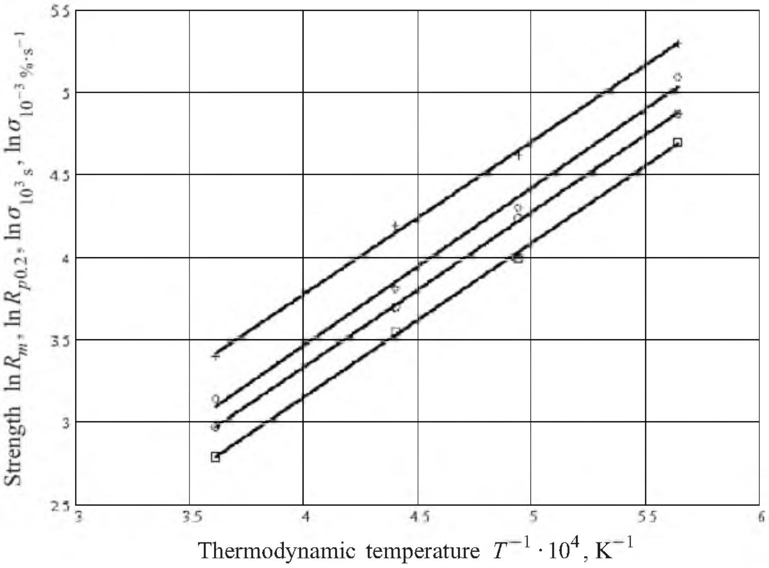
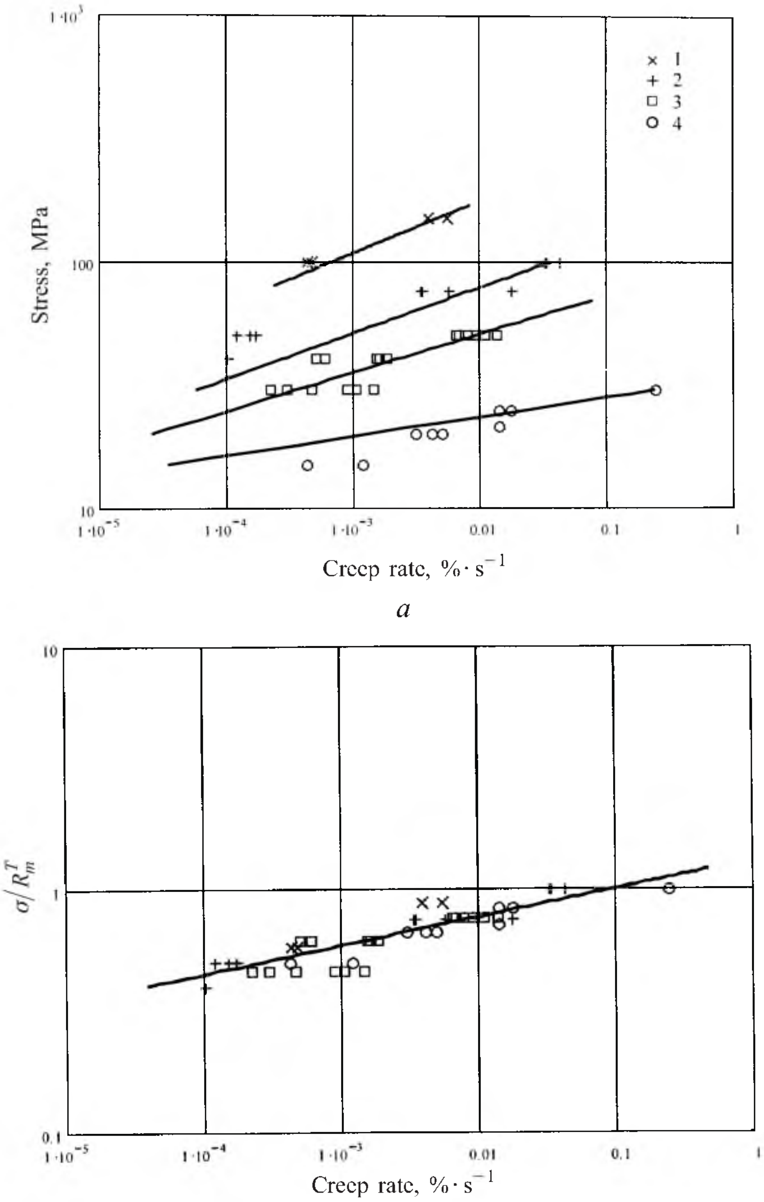


Fig. 1. Temperature dependences of the tensile ultimate strength, R_m, offset yield stress, $R_{p0.2}$, creep-rupture strength for the test time 10^3 s, $\sigma_{10^3\,\mathrm{s}}$, and stresses corresponding to the steady-state creep rate $10^{-3}\ \%\cdot\mathrm{s}^{-1}$, $\sigma_{10^{-3}\,\%\cdot\mathrm{s}^{-1}}$, for PM tungsten in the temperature range from 1770 to 2270 K. Designations: (+) R_m; (◇) $R_{p0.2}$; (○) $\sigma_{10^3\,\mathrm{s}}$; (□) $\sigma_{10^{-3}\,\%\cdot\mathrm{s}^{-1}}$.

The interrelation between the creep-rupture time τ and the steady-state creep rate $\dot{\varepsilon}$ for PM tungsten in the temperature and stress ranges studied, which was plotted in logarithmic coordinates, is shown in Fig. 4. From this figure it follows that, in the general form, this relation is adequately described by the exponential equation proposed in [11]:

$$\dot{\varepsilon}\tau^d = D, \tag{8}$$

where d and D are the material constants.



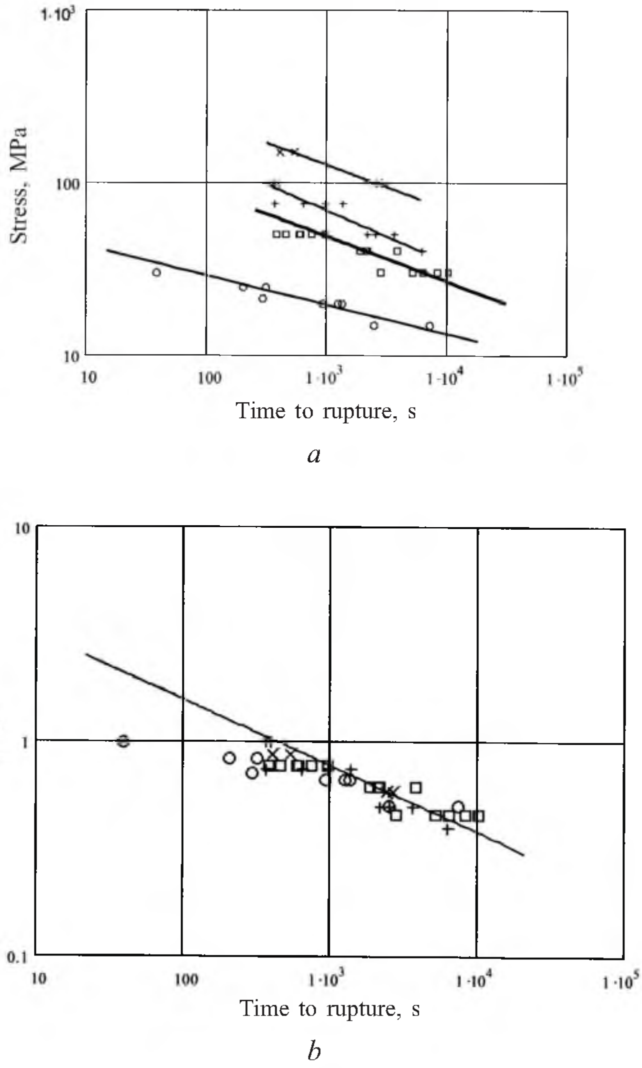
a

b

Fig. 2. Dependences of the steady-state creep rate on the stress σ (*a*) and on the ratio σ / R_m^T (*b*) for PM tungsten at temperatures of 1770 (*1*), 2020 (*2*), 2270 (*3*), and 2770 K (*4*). (Here and in Figs. 3–5, the designations are the same.)

Selected values of the coefficients d and D for PM tungsten, as well as the coefficient of correlation r between $\ln \dot{\varepsilon}$ and $\ln \tau$ are listed in Table 1. The value of d approaching unity indicates that the relation between the steady-state creep rate and creep-rupture time of tungsten can be described by a classical inversely proportional Monkman–Grant dependence (7).

From Fig. 1 one can see that within the temperature range studied the characteristics of short-term and long-term static strengths and creep resistance of tungsten vary monotonically with increasing temperature. The temperature dependences of the aforementioned mechanical characteristics in the coordinates $\ln M - 1/T$ are linear and satisfy Eq. (2). On the basis of experimental data on strength and creep resistance of tungsten in the temperature range $\sim (0.5\text{–}0.8)T_{melt}$, the authors determined the values of the plastic strain activation energy listed in Table 2. This table also presents the values of the plastic strain activation energy for PM tungsten obtained in [4] for *HV* hardness.



a

b

Fig. 3. Long-term strength diagrams of PM tungsten in the coordinates $\ln\sigma - \ln\tau$ (*a*) and $\ln(\sigma/R_m^T) - \ln\tau$ (*b*) at temperatures of 1770 (*1*), 2020 (*2*), 2270 (*3*), and 2770 K (*4*).

Analysis and comparison of the experimental values of the plastic strain activation energy of tungsten calculated using different strength characteristics and the results of theoretical and experimental works at studying the processes of deformation, internal friction, creep, and self-diffusion of tungsten generalized in [4], allowed us to make the following conclusions.

Table 1

Results of Joint Statistical Treatment of the Heat-Resistance Characteristics of Tungsten at High Temperatures

T, K	N	r	d	D	r_1	α	A	r_2	β	B
1770–2770	41	−0.92	1.14	15.1	0.917	5.75	0.099	−0.86	4.98	419.6

Note. N is sampling volume, r is coefficient of correlation between $\ln\dot{\varepsilon}$ and $\ln\tau$, r_1 is coefficient of correlation between $\ln\dot{\varepsilon}$ and $\ln(\sigma/R_m^T)$, and r_2 is coefficient of correlation between $\ln\tau$ and $\ln(\sigma/R_m^T)$.

Table 2

Plastic Strain Activation Energy of PM Tungsten Calculated Based on Different Characteristics of Strength

Strength characteristics	U (eV) in the temperature range from 1770 to 2770 K
R_m	2.41
$R_{p0.2}$	2.48
$\sigma_{10^3\,\mathrm{s}}$	2.42
$\sigma_{10^{-3}\,\%\cdot\mathrm{s}^{-1}}$	2.43
HV [4]	2.5±0.1

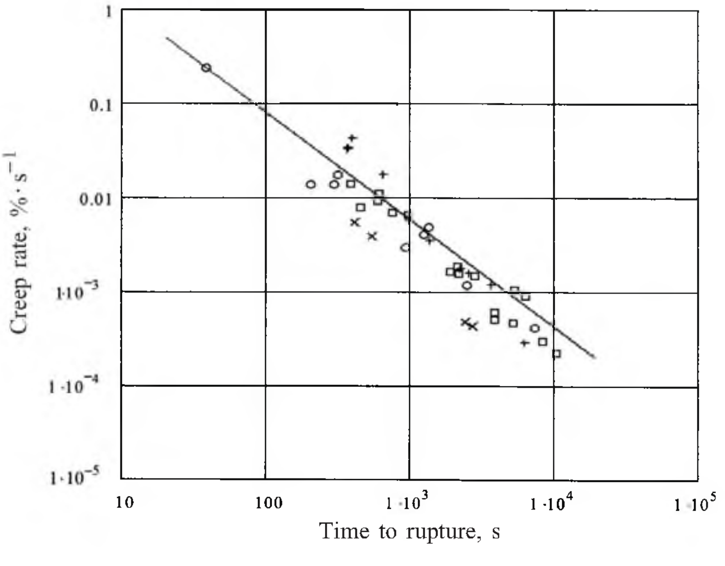


Fig. 4. Creep-rupture time vs steady-state creep rate of PM tungsten in the temperature range from 1770 to 2770 K.

The pattern of the temperature dependences of the tungsten strength, hardness, and creep resistance under conditions of short-term and long-term static loading in the range ~(0.5–0.8)T_{melt} is similar. They obey the general law of variation of their values with increasing temperature.

Rather close values of activation energy calculated from various strength characteristics are indicative of the identity of major mechanisms of plastic deformation governing the short-term and long-term static strength, hardness, and creep resistance of tungsten within the temperature and stress ranges under investigation.

If we represent the results obtained for the long-term strength and creep of tungsten (Figs. 2a, 3a, and 4) in a three-dimensional spatial coordinate system *XYZ*, along the axes of which $\ln\dot{\varepsilon}$, $\ln\tau$, and $\ln\sigma$ are plotted, all experimental data turn out to belong to a single common surface (Fig. 5a and 5b). Figure 5b shows this surface plotted by the experimental points with a Mathcad 2000 software package. It is seen that this surface is in close proximity to the plane perpendicular to the coordinate plane *XOY* In the adopted spatial coordinate system, the generalized dependences of the steady-state creep rate and creep-rupture time on the value of the applied stress $F(\dot{\varepsilon},\tau)=f(\sigma)$ represent a set of curves that are parallel to each other and are equally sloped to the plane *XOY* (Fig. 5a). Each of these curves corresponds to a certain test temperature. The generalized dependences can be analytically described by a set of equations proposed in [15]:

$$A_1^T\ln\dot{\varepsilon}+B_1^T\ln\tau+C_1^T\ln\sigma+D_1^T=0, \tag{9}$$

$$A_2^T\ln\dot{\varepsilon}+B_2^T\ln\tau+C_2^T\ln\sigma+D_2^T=0, \tag{10}$$

where A_1^T, B_1^T, C_1^T, D_1^T, A_2^T, B_2^T, C_2^T, and D_2^T are constants for the given material and temperature.

Projections of the generalized spatial curves on the planes *ZOX* and *ZOY* represent the dependencies of the steady-state creep rate on the stresses and the diagram of long-term strength of the PM tungsten shown in Figs. 2a and 3a, respectively. The projection of the generalized curves on the plane *XOY* is nothing but the Monkman–Grant dependence (Fig. 4) described by Eq. (7).

Based on the hypothesis that the characteristics of short-term and long-term static strength and creep resistance of tungsten in the temperature-load range studied are governed by the same system of obstacles in the path of dislocation motion, we have made an attempt to find a general dependence relating all the experimental data obtained. Figures 2b and 3b show the plots characterizing the variation of the steady-state creep rate and life of PM tungsten under conditions of long-term static loading in the temperature range from 1770 to 2770 K with the magnitude of the generalized load, i.e., the ratio of the acting stress σ to the ultimate strength of the material at a corresponding temperature R_m^T [15].

The analysis of the given curves testifies that in the high-temperature range $\sim(0.5–0.8)T_{melt}$, all the experimental data obtained on the tungsten heat resistance are described quite satisfactorily by the unified equations of the form:

$$\dot{\varepsilon}=A(\sigma/R_m^T)^{\alpha}, \tag{11}$$

$$\tau=B(\sigma/R_m^T)^{-\beta}, \tag{12}$$

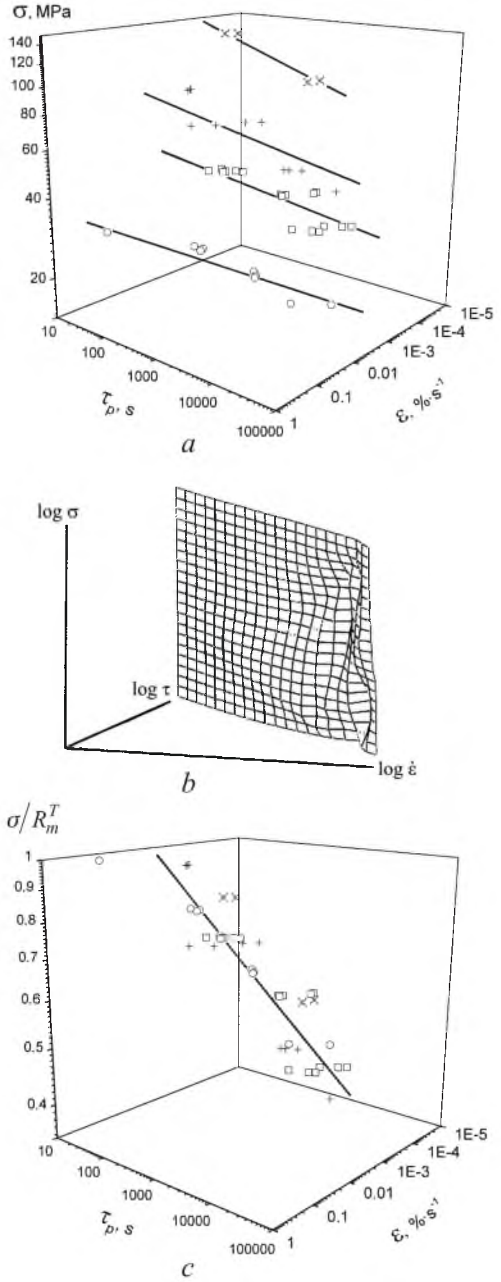


Fig. 5. Generalized dependence of the steady-state creep rate and creep-rupture time of PM tungsten on the stress σ (a, b) and the value of the ratio σ/R_m^T (c).

where α, β, A, and B are constants for the material in the temperature and stress ranges under investigation.

The values of the constants in Eqs. (11) and (12) obtained as a result of statistical treatment and regression analysis of experimental data are listed in Table 1. The values of the coefficients of correlation r_1 between $\ln \dot{\varepsilon}$ and $\ln(\sigma/R_m^T)$ and r_2 between $\ln \tau$ and $\ln(\sigma/R_m^T)$, which are close to unity, indicate that in the high-temperature region, there are general functional relations between the characteristics of creep resistance, long-term static and short-term strengths of tungsten.

Figure 5c presents the dependences between the investigated mechanical characteristics of PM tungsten in the temperature range $\sim(0.5\text{–}0.8)T_{melt}$ in the most general form. It relates three characteristics: the generalized load σ/R_m^T, steady-state creep rate $\dot{\varepsilon}$, and creep-rupture time τ corresponding to the indicated temperature and stress level under conditions of long-term static loading. This function has been plotted by the experimental points in the *XYZ* coordinate system, with logarithms of $\dot{\varepsilon}$, τ, and σ/R_m^T plotted respectively on its axes, and has the form of a straight line in a 3D space.

To analytically describe the proposed generalized relationship, which characterizes the mechanical behavior of PM tungsten in the temperature and stress ranges studied, we propose a system of Eqs. (9) and (10) in the following form:

$$A_1 \ln\dot{\varepsilon} + B_1 \ln\tau + C_1 \ln(\sigma/R_m^T) + D_1 = 0, \qquad (13)$$

$$A_2 \ln\dot{\varepsilon} + B_2 \ln\tau + C_2 \ln(\sigma/R_m^T) + D_2 = 0, \qquad (14)$$

where A_1, B_1, C_1, D_1, A_2, B_2, C_2, and D_2 are constants for the investigated material in a certain temperature and stress range within which the resistance of the material to plastic deformation and fracture is mainly governed by the same dominating physical processes and mechanisms.

Conclusions

1. As a result of the joint analysis of experimental data on the strength of PM tungsten under conditions of short-term active and long-term static loading in the temperature range $\sim(0.5\text{–}0.8)T_{melt}$, the authors established the existence of close correlation dependences between the characteristics of its short-term and long-term static strengths and creep resistance.

2. To analytically describe the obtained correlation dependences, a generalized empirical relation has been proposed, which represents the mechanical behavior of tungsten in the temperature and stress ranges studied.

Резюме

Проаналізовано механічні характеристики технічно чистого вольфраму, що отриманий методами порошкової металургії, за одновісного розтягу в умовах високих температур. Установлено, що для вольфраму в області високих температур $\sim(0{,}5...0{,}8)T_{\text{пл}}$ існують кореляційні зв'язки між характеристиками короткочасної та тривалої статичної міцності й опору повзучості, що описуються єдиною функціональною залежністю.

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