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ISSN 0543-5846
METABK 42 (3) 159 (2003)
UDC - UDK 539.4:669.285´781´296´71:620.178.3=20

INTERRELATION BETWEEN THE STRUCTURAL STATE OF MATERIAL AND MECHANICAL PROPERTIES OF LOW-ALLOYED MOLYBDENUM ALLOYS

Received - Primljeno: 2002-06-14
Accepted - Prihvaćeno: 2003-02-25
Original Scientific Paper - Izvorni znanstveni rad

As a result of joint analysis of experimental data on the structure and mechanical properties of low-alloy molybdenum alloys of the systems Mo-Al-B, Mo-Zr-B, Mo-Zr-Hf-B and Mo-Re we have established that for considered class of materials over the wide range of temperature there exist close correlations between the structural state, short-term, and low-cycle and high-cycle fatigue strength characteristic.

Key words: *molybdenum alloys, structure of materials, short-term static strength, fatigue strength*

Međusobni odnos strukture materijala i mehaničkih svojstava niskolegiranih molibdenovih slitina. Kao rezultat zajedničke analize eksperimentalnih podataka za strukturu i mehanička svojstva niskolegiranih molibdenih slitina sustava Mo-Al-B, Mo-Zr-B, Mo-Zr-Hf-B i Mo-Re ustanovljeno je da za razmatranu klasu materijala u širokom rasponu temperature postoji uska korelacija između svojstava strukture, kratkoročne čvrstoće, te čvrstoće na niskociklični i visokociklični zamor.

Ključne riječi: *slitine molibdena, struktura materijala, kratkoročna čvrstoća, čvrstoća na zamor*

INTRODUCTION

Low-alloy molybdenum alloys of the systems Mo-Al-B, Mo-Zr-B, Mo-Zr-Hf-B and Mo-Re (obtained by vacuum arc fusion with subsequent hot-deformation into sheets) are widely used in manufacturing practice for welded constructions for domestic purposes operating under conditions of exposure to aggressive gaseous media and high temperatures. Materials of this class distinguished by high purity with respect to interstitial impurities and display a unique combination of physicomechanical and technical characteristics [1-4].

At the present time, rather extensive experimental data have been accumulated on the structure, strength and fracture of low-alloy molybdenum alloys and their welded joints under conditions of short-term, long-term static, low-cycle and high-cycle loading over a broad temperature range. It has been established that the temperature dependences of the strength and plastic characteristics of the indicated materials are similar. We also note an analogy in the occurrence of processes of exhaustion of plasticity reserves in molybdenum alloys upon high-temperature prolonged static and low-cycle loading within the limits of the quasistatic failure region [5-14].

We know that correlations exist between the structure and strength characteristic of heat-resistant and refractory materials for short-term, long-term and cyclic loading. They are of definite scientific and practical interest, since they allow us to estimate the heat resistance and fatigue resistance characteristics of metals and alloys with minimum expense and can be described by quite definite functional relationships based both on empirically and physically grounded approaches. As a rule, various alloys based on the same metal are grouped by the structural criterion using the yield stress or ultimate strength as additional characteristics of metal. It is convenient since the yield stress or ultimate strength values are specified by the same system of obstacles, interfering with the movement of dislocations, on which other poperties of the alloy depend [15-17].

The volume of accumulated information on the mechanical properties and structure of low-alloy molybdenum alloys allows us to analyze them with the goal of establishing the correlations between the structural state, short-term, long-term static, low-cycle, and high-cycle strength characteristics of the given class of materials. Since the considered results of the investigations pertain to the long-term strength region on small bases, in treatment of the data obtained we used the approaches in [18], based

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on the assumption that in certain temperature - force regions (within whose limits the strength of metals and alloys is controlled by the same mechanisms of plastic deformation and fracture), the temperature factor affects the softening rate of the material equally under short-term and long-term static loading conditions. In this case, the experimental data were presented in the form of graphs characterizing the dependencies of the number of cycles to failure of specimen N_p, steady-state creep rate $\dot{\varepsilon}$ and the time to failure τ_f of the material at the investigated structural states or temperatures on the ratio of the applied stresses σ to the conventional yield limit $R_{p0.2}$ or ultimate strength of the material at the corresponding temperature, R_m^T [19].

In interpreting the low-cycle strength characteristics of molybdenum alloys, instead of constant stresses σ we used the equivalent stresses σ_{eq}, using which nonsteady-state mechanical loading is reduced to an equivalent static load [20, 21]. For the materials used in the investigations on low-cycle strength with a trapezoidal load variation cycle, the equivalent stresses were determined using the analytical dependencies in [22].

MATERIALS, TREATMENT, AND TESTING

The chemical composition and the short-term strength and plasticity characteristics of molybdenum alloys at room temperature and high temperatures are presented in Tables 1. and 2. [5-8, 11, 14].

Table 1. **Chemical composition (mass %) of molybdenum alloys**
Tablica 1. **Kemijski sastav (masa %) slitina molibdena**

Alloy	TsM6	TsM10	TsM12	MI5
System	Mo-Zr-B	Mo-Al-B	Mo-Zr-Hf-B	Mo-Re
Zr	0.20	-	0.03	-
Re	-	-	-	5
Hf	-	-	0.09	-
Al	-	0.02	-	-
B	0.002	0.002	0.003	0.003
C	0.004	0.003	0.003	0.003
O_2	0.002	0.002	0.002	0.002
N_2	0.0004	0.0004	0.0040	0.0040

Semifinished specimens of these alloys were prepared by the method of vacuum-arc melting with subsequent high-temperature step-by-step forging and rolling into 1-mm thick sheets with a level of strain of 90%. In the last stage of the technological procedure, the sheets of TsM-6, TsM-12 and TsM-10, MI-5 alloys were annealed at temperatures of 1420 K and 1220 K, respectively, for 1 h to relieve internal stresses and were subjected to chemical etching to remove scale and the surface layer of the metal with impurities.

Table 2. **Characteristics of short-term strength and plasticity of molybdenum alloys**
Tablica 2. **Svojstva kratkoročne čvrstoće i plastičnosti slitina molibdena**

Alloy	T [K]	Base metal			Weld metal		
		R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]	R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]
TsM-10	290	770	705	19.0	560	550	10.5
	1770	62.5	33	47.5	68	58	32.0
	2020	30.5	20	36.0	25	25	36.0
	2270	9	6	60.0	11.5	6.5	78.0
MI-5	290	745	665	28.5	555	540	14.6
	1770	78	60	31.0	40	34	56.6
	2020	38	30	64.5	-	-	-
	2270	14	10	78.5	-	-	-
TsM-6	290	830	755	24.5	490	420	18.2
	1770	129	85	40.5	155	130	38.0
	2020	60	50	54.5	78	74	43.0
	2270	29	24	61.5	23	21	84.5
TsM-12	290	770	730	25.0	420	335	14.6
	1770	160	150	24.0	160	125	43.0
	2020	86	78	35.0	66	54	55.0
	2270	40	34	35.0	32	28	68.0

Alloy	T [K]	Weld joint		
		R_m [MPa]	Failure site	
TsM-10	290	560	Seam, melted zone	*For determination of the strength characteristic of the base metal, the samples were cut from sheet of thickness 1- 2 mm in the as - supplied state along the direction of the manufacturing deformation* *(the degree of deformation of the sheet was e = 80 - 90 %)*
	1770	70	Seam	
	2020	36	Seam	
	2270	11.5	Base metal	
MI-5	290	545	Seam, melted zone	
	1770	65	Same	
	2020	-	-	
	2270	-	-	
TsM-6	290	380	Seam, melted zone	
	1770	180	Base metal	
	2020	56	Seam	
	2270	24	Seam	
TsM-12	290	515	Seam	
	1770	180	Base metal	
	2020	-	-	
	2270	-	-	

The characteristics of short-term static strength (ultimate strength R_m, conventional yield limit $R_{p0.2}$, relative elongation A, and relative uniform strain A_{un}) were determined according to the results of tensile testing of flat five-fold proportional specimens whose working section was 12 mm in length and 3 mm in width in 1246-R and VTU-2V testing machines [23]. The strain rate was equal to 2 mm/min. This corresponds to relative strain rates of about 2.2×10^{-3} s^{-1}.

Fatigue tests were performed on flat specimens with a cross section of 3 x 1 mm and a length of the working section of 47.5 mm under conditions of rigid alternating bending on a base of $N_p=2\times10^6$ cycles at room temperature [13]. The loading frequency was equal to the resonance frequency of bending vibrations of the specimens and varied within the range 400-450 Hz. The event of fracture was recorded either visually or according to the time of initiation of a fatigue crack detected as a 5% drop in the resonance frequency of natural vibrations of the specimen.

The specimens were cut out from sheets in the direction transverse to the direction of technological deformation and from welded joints (obtained by nonconsumable-electrode arc welding in a controlled atmosphere of helium) along the longitudinal axis of the weld.[1] The procedure of welding was performed at a current strength of 110 A, under an arc voltage of 18.5 V, and at a welding rate of 2.8 mm/s.

The specimens were subjected to heat treatment in an SNVL-1.3.1/16-M2 furnace in a vacuum not worse than 2.6×10^{-3} Pa at temperatures of 1220-1820 K for 1 h.

We see (Table 2.) that molybdenum alloys can be arranged in the following order according to the increase in high-temperature strength: alloy TsM1O of the system Mo-Al-B, which is closest in chemical composition to technical-grade molybdenum; alloy MI5 of the system Mo-Re, containing up to 5 mass % rhenium; alloy TsM6 of the system Mo-Zr-B and alloy TsM12 of the system Mo-Zr-Hf-B, alloyed with up to 0.2 mass % of zirconium as well as zirconium and haf-nium. These alloys can be arranged in a similar order according to the degree of increase in the creep resistance and long-term strength characteristics [7-9, 12, 14].

In the as-delivered state, the microstructure of the investigated molybdenum alloys is formed by fibers placed along the direction of deformation of the sheet. The dislocation structure is cellular with cells of about 2 μm in size and a low density of dislocations. As characteristic features of the structure of welded joints of molybdenum alloys, one can mention the quite large sizes of crystallites (200-500 μm), the presence of large smooth flat boundaries parallel to the axis of the weld, and the formation of segregations of interstitial impurities on the boundaries as a result of the enrichment of a solid solution in the process of nonequilibrium crystallization of the metal in a welding bath and the fast cooling of the welded joint [2, 3].

The process of annealing of the sheets of TsM-10 alloy at a temperature of 1220 K for 2 h is accompanied by a pronounced enlargement of cells caused by the disappearance of some of their boundaries. This leads to a certain increase in the characteristics of strength and plasticity of the material. As the temperature of annealing increases further, the growth of cells becomes more intense. At 1420 K, the process of primary recrystallization is practically terminated.

The process of agglomerative recrystallization occurs in the sheets of TsM-10 alloy within the temperature range 1420-1620 K. At higher temperatures, it transforms into secondary recrystallizalion. An increase in the temperature of annealing within the investigated range is accompanied by a monotonic increase in the grain size to 100 mm and results in a continuous softening of the TsM-10 alloy. This means that, in the process of cooling, the hardening phases either are not segregated at all or are segregated in small amounts.

In the course of annealing of the TsM-6 alloy, its structure improves is in the previous case, but all processes occur at higher temperatures. Thus, after annealing at 1570 K for 1 h, the macrostructure of Mo alloy remains practically unchanged. At the same time, as a result of polygonization, the sizes of dislocation cells increase to 4-6 μm. The process of annealing of the alloy at 1770 K for 1 h is

Table 3. **Grain sizes and characteristics of short-term strength, plasticity, and fatigue resistance of molybdenum alloys subjected to different modes of heat treatment and welding**

Tablica 3. **Veličina zrna i svojstva kratkoročne čvrstoće, plastičnosti i otpornost na zamor slitina molibdena izloženih različitim uvjetima toplinske obradbe i zavarivanja**

Object of investigation	Mode of annealing	D_g [μm]	Structural state of the material	R_m [MPa]	$R_{p0.2}$ [MPa]	A [%]	A_{un} [%]	R_d [MPa]
TsM - 6 alloy								
Base metal	1420 K, 1 h*	2	Strained	830	755	24.5	9.5	620
	1570 K, 1 h	4-6	Polygonized	750	685	27.5	12.5	585
	1770 K, 1 h	40-50	Recrystallized	570	460	43.0	16.5	510
Weld metal	-	200-500	Cast	490	420	18.2	9.2	305
TsM - 10 alloy								
Base metal	1220 K, 1 h*	2	Strained	800	730	19.0	6.8	485
	1220 K, 2 h	2		825	775	19.5	6.9	540
	1320 K, 1 h	4	Polygonized	720	675	21.2	9.7	480
	1420 K, 1 h	10	Recrystallized	615	575	29.5	12.5	415
	1520 K, 1 h	18		565	555	29.8	12.0	395
	1620 K, 1 h	35		545	415	24.6	12.5	335
	1720 K, 1 h	70		522	410	22.3	13.0	315
	1820 K, 1 h	100		516	400	16.9	11.7	295
Weld metal	-	200-500	Cast	550	550	10.5	5.6	415

*As - delivered state

Notation: d_g is the grain size, R_d is the fatigue limit on a base N_p of $2\cdot10^6$ cycles

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[1] Welding was carried out at the Paton Institute of Electric Welding, National Academy of Sciences of Ukraine

accompanied by the recrystallization of the material with an increase in the grain size by 40-50 μm.

The short-term, plasticity and fatigue resistance characteristics of molybdenum alloys TsM-6 and TsM-10 for each structural state of the material at room temperature are presented in Table 3. [13].

RESULTS AND DISCUSSION

As follows from [13] to describe the fatigue resistance of molybdenum alloys in different structural states, each of which is characterized by its own values of short-term static strength and grain size, we plotted four fatigue curves for the TsM-6 alloy and nine fatigue curves for the TsM-10 alloy on the log σ_{max} - logN_p coordinates conventionally used for this purpose. The amount of experimental investigations required significant decreases if the data on the fatigue of alloys is represented via the data on the structure and short-term strength of the material, which can be accumulated much more easily.

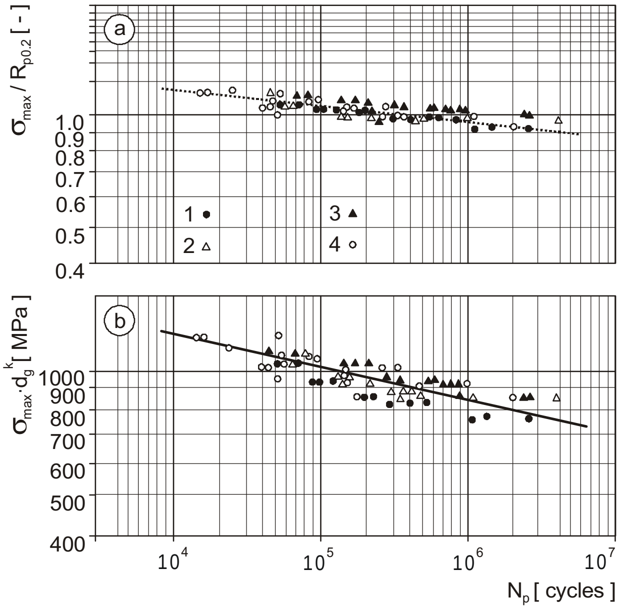

Figure 1. **Generalized fatigue curves of the TsM-6 molybdenum alloy on the log(σ_{max}/ $R_{p0.2}$) - logN_p (a) and log($\sigma_{max} d_g^k$) - logN_p (b) coordinates. (1-3 sheets, 4 weld metal). Anneal-ing for 1h at different temperatures: 1) T = 1420 K (as-delivered state), 2) T = 1570 K, 3) T = 1770 K**

Slika 1. **Uopćene krivulje zamora slitine molibdena TsM-6 na koordinatama log(σ_{max}/ $R_{p0.2}$) - logN_p(a) i log($\sigma_{max} d_g^k$) - logN_p (b). (1-3 limovi, 4 - zavar metala). Žarenje tijekom 1 sata na različitim temperaturama: 1) T = 1420 K (u isporučenom stanju), 2) T = 1570 K, 3) T = 1770 K**

In Figures 1a. and 2a., we present the generalized fatigue curves of the TsM-6 and TsM-10 alloys plotted on the logarithmic coordinates in the form of dependences of the number of cycles to failure N_p on the ratio of the maximum stresses in a cycle to the conventional yield limit of the material in a given structural state σ_{max}/ $R_{p0.2}$. The analysis of the accumulated results shows that, despite the significant difference between the structure and characteristics of short-term strength of the investigated molybdenum alloys in the strained, polygonized, recrystallized, and cast states, all available experimental data on the fatigue of these alloys can be described by equations of the same form, namely

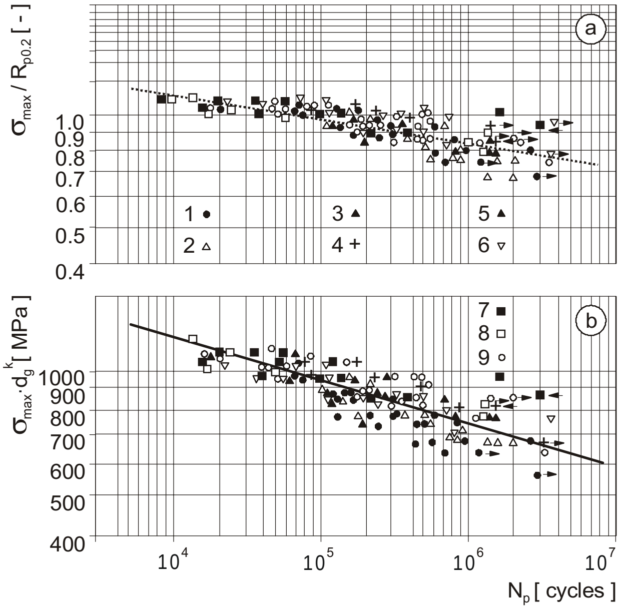

Figure 2. **Generalized fatigue curves of the TsM-10 molybdenum alloy on the log(σ_{max}/ $R_{p0.2}$) - logN_p (a) and log($\sigma_{max} d_g^k$) - logN_p (b) coordinates. (1-8 sheets, 9 weld metal). Annealing for 1h at different temperatures: 1) T = 1220 K (as-delivered state), 2) T = 1220 K, 2h, 3) T = 1320 K, 4) T = 1420 K, 5) T = 1520 K, 6) T = 1620 K, 7) T = 1720 K, 8) T = 1820 K**

Slika 2. **Uopćene krivulje zamora slitine molibdena TsM-10 na koordinatama log(σ_{max}/ $R_{p0.2}$) - logN_p(a) i log($\sigma_{max} d_g^k$) - logN_p (b). (1-8 - limovi, 9 zavar metala). Žarenje tijekom 1 sata na različitim temperaturama: 1) T = 1220 K (u isporučenom stanju), 2) T = 1220 K, 2h, 3) T = 1320 K, 4) T = 1420 K, 5) T = 1520 K, 6) T = 1620 K, 7) T = 1720 K, 8) T = 1820 K**

$$N_p = B\cdot(\sigma_{max}/R_{p0.2})^{-\beta} \tag{1}$$

where B and β are constants of the material independent of its structural state.

The results of statistical processing of the experimental data on short-term strength and fatigue (combined with their regression analysis and performed separately for the TsM-6 and TsM-10 molybdenum alloys) are presented in Table 4. The quite high values of the coefficients of correlation r between logN_p, and log(σ_{max} /$R_{p0.2}$) obtained for the investigated materials enable us to conclude that, for all structural states of low-molybdenum alloys, there exist common functional relationships between the characteristics of fatigue resistance and the conventional yield limit under the conditions of short-term tension. In this case, the slope of generalized fatigue curves characterized by the value of the coefficient β and the spread of the experimental data for the TsM-6 alloy alloyed with small amounts of zirconium are somewhat lower for the commercially pure molybdenum.

The dependencies established in the present work enable one to perform accelerated evaluation and prediction of the characteristics of fatigue resistance of molybdenum alloys on the basis of the available data on the parameters of short-term strength and, in particular, on the conventional yield limit of the material in the analyzed structural state.

The values of the fatigue strength of the molybdenum alloys obtained as the lower bounds of the 95% confidence interval of the generalized fatigue curve described by equation (1) for $N_p = 2\cdot10^6$ cycles are equal to 0.86 (for the TsM-6 alloy) and 0.72 (for the TsM-10 alloy) of the conventional yield limit of the material in the corresponding structural state.

The verification of the hypothesis that the mechanical characteristics of the analyzed molybdenum alloys presented in Figures 1a. and 2a. belong to the same general population showed that this assumption does not contradict the experimental data. However, it seems unreasonable to integrate these data into a common experimental sample with the aim of their subsequent joint statistical processing and regression analysis because this would lead to a decrease in the accuracy of prediction of the characteristics of fatigue of these alloys according to the results of short-term tests.

It is known that the characteristics of short-term strength of metals and alloys are connected with their structural parameters by power dependences described by the Hall-Patch equation [24]. In particular, we established the following relationship between the conventional yield limit and the grain size:

$$R_{p0.2} \sim d_g^{-k} \tag{2}$$

where $k = 0.13$ for the TsM-6 alloy and $k = 0.176$ for the TsM-10 alloy.

This formula establishes a direct correlation between the characteristics of fatigue resistance of molybdenum alloys and their structural parameters. In Figures 1b. and 2b., we present the fatigue curves of the TsM-6 and TsM-10 alloys plotted on the $\log(\sigma_{\max} d_g^{\,k})$ - $\log N_p$ coordinates according to the results of testing of these materials in different structural states. It is easy to see that these curves can be quite satisfactorily described by equations of the form

$$N_p = B' \cdot (\sigma_{\max} d_g^k)^{-\beta'} \tag{3}$$

where B' and β' are constants of the material independent of its structural state.

The empirical values of the parameters B' and β' and the coefficients of correlation r' between $\log N_p$, and $\log(\sigma_{\max} d_g^{\,k})$ obtained as a result of statistical processing of the experimental data on the high-cycle strength and structure of the TsM-6 and TsM-10 alloys are presented in Table 4.

Relation (3) enables one to perform an accelerated evaluation and prediction of the characteristics of fatigue resistance of molybdenum alloys on the basis of the available data on the structure of the material and, in particular, on its grain size.

Table 4. **Results of joint statistical processing of structural parameters and the characteristics of short-term strength and fatigue resistance of molybdenum alloys**

Tablica 4. **Rezulati zajedničke statističke obrade strukturalnih parametara i svojstva kratkoročne čvrstoće i otpornosti molibdena na zamor**

Alloy	Sampling volume	r	β	B	r'	β'	B'
TsM-6	65	-0.850	9.05	1 036 988.5	0.815	11.30	$1.336\cdot10^{39}$
TsM-10	133	-0.743	6.93	426 033.6	0.721	8.61	$4.847\cdot10^{30}$

Note: Structural states of the investigated alloys are as follows: strained, polygonized, recrystallized, and cast; r is the coefficient of correlation between $\log N_{\mathrm{p}}$ and $\log(\sigma_{\max}\, d_g^{\,k}/R_{p0.2})$ and r' is the koefficient of correlation betwen $\log N_{\mathrm{p}}$ and $\log(\sigma_{\max}\, d_g^{\,k})$

Thus, as a result of the joint analysis and statistical processing of the experimental data on fatigue, short-term static strength, and structure of low-molybdenum alloys in the strained, polygonized, recryslallized, and cast slates, we deduced empirical correlation relations between the characteristics of fatigue resistance, conventional yield limit, and the grain size of the investigated materials.

Relations (2) and (3) which describe the dependence of short-term strength and fatigue resistance of molybdenum alloys on grain size are true for quite a narrow range of room and high temperatures at which structural stability of material appears. They are evidently untrue for high temperatures at which the transformation of material and alloy structure appears due to thermally activated processes of polygonisation and recrystallisation.

In Figures 3., 4. we present graphs characterizing the dependence of the steady-state creep rate and durability of low-alloy molybdenum alloys under long-term static and low-cycle loading conditions on the ratio σ / R_m^T in the temperature range 1770-2270 K. Analysis of the results presented suggests that in the high-temperature region (for temperatures higher than 0.5 T_{mp}), all the experimental data obtained on the heat resistance of low-alloy molybdenum alloys [6-12], despite the very substantial

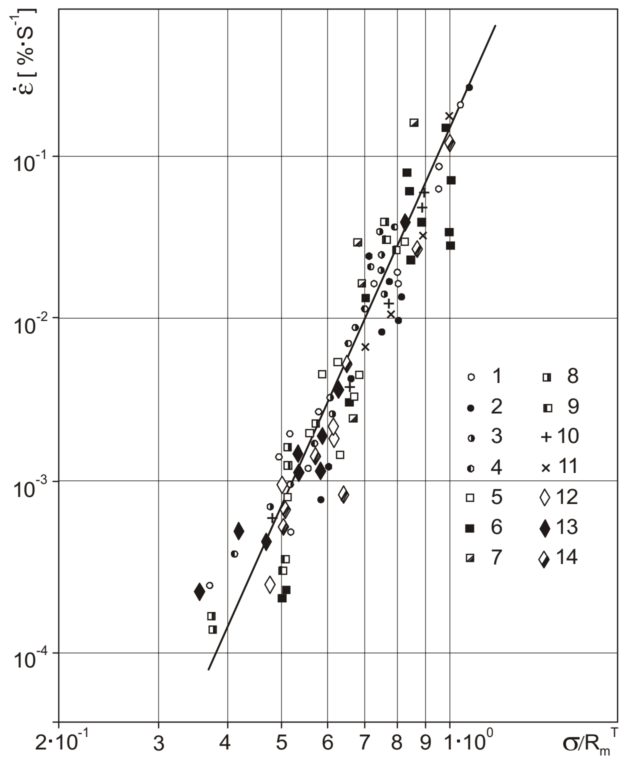

Figure 3. **Dependence of the steady-state creep rate of the base metal for low-alloy molybdenum alloys TsM-10 (1-4), TsM-6 (5-9), MI5 (10-11), TsM-12 (12-14) on the value of σ/R_m^T: 1, 2, 5-7, 10-14) static creep; 3, 4, 8, 9) cyclic creep; 1, 3, 5, 8, 10, 12) T = 1770 K; 2, 4, 6, 9, 11, 13) T = 2020 K; 7, 14) T = 2270K**

Slika 3. **Ovisnost brzine puzanja osnovnog materijala za niskolegirane slitine molibdena u stacionarnom stanju TsM-10 (1-4), TsM-6 (5-9), MI5 (10-11), TsM-12 (12-14) o vrijednosti σ/R_m^T: 1, 2, 5-7, 10-14) kod statičkog puzanja; 3, 4, 8, 9) kod cikličkog puzanja; 1, 3, 5, 8, 10, 12) T = 1770 K; 2, 4, 6, 9, 11, 13) T = 2020 K; 7, 14) T = 2270K**

differences in short-term strength (Table 2.), are described by common equations of the form

$$\dot{\varepsilon} = A''\cdot(\sigma/R_m^T)^{\alpha''} \tag{4}$$

$$\tau_f = B''\cdot(\sigma/R_m^T)^{-\beta''} \tag{5}$$

where α″, β″, A″ and B″ are coefficients, constant for the given class of materials in the considered temperature range, which depend on the structural state of the material.

The results of statistical treatment of the experimental data and their regression analysis (Figures 3., 4.) carried out for the base metal of all investigated molybdenum alloys, are contained in Table 5. The values of the correlation coefficients r_1'' and r_2'' rather close to unity obtained for the investigated materials in the temperature range 1770-2270 K allow us to judge whether general functional relations exist between the characteristics of resistance to long-term failure and the short-term strength indices in the high-temperature region for the low-alloy molybdenum alloys, independently of their chemical composition.

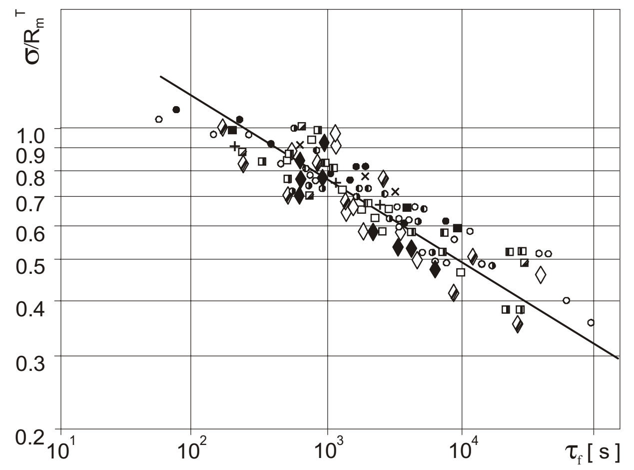

Figure 4. **Long-term strength diagrams for base metal of low-alloy molybdenum alloys in $\ln(\sigma/R_m^T)$-$\ln\tau_f$ coordinates. (The symbols mean the same as in Figure 3.)**

Slika 4. **Dijagrami dugoročne čvrstoće za osnovni metal niskolegiranih slitina molibdena u koordinatama $\ln(\sigma/R_m^T)$-$\ln\tau_f$. (Značenja simbola su ista kao na slici 3.)**

We know that there is an interdependence between the rate of steady-state creep, as a kinetic characteristic of the failure process, and the durability of the metallic materials [16]. For all the investigated molybdenum alloys, this dependence is general in character (Figure 5.) and can be described by a power-law expression of the type [25]

$$\tau_f\cdot\dot{\varepsilon}^{0.73} = 44.05 \tag{6}$$

Table 5. **Results of joint statistical treatment of the heat-resistance characteristics of low-alloy molybdenum alloys at high temperatures**

Tablica 5. **Rezulati zajedničke statističke obrade svojstava toplinske obradbe niskolegiranih slitina molibdena na visokim temperaturama**

T [K]	Object of investigation	Sampling volume	r_1'' between $\ln\dot{\varepsilon}$ and $\ln(\sigma/R_m^T)$	α′′	A′′	r_2'' between $\ln\tau_p$ and $\ln(\sigma/R_m^T)$	β′′	B′′
1770 2270	Base metal	113	0.976	7.09	0.102	-0.917	5.45	207.9

Analysis of the correlations between the short-term, long-term static, and low-cycle strength characteristics of low-alloy molybdenum alloys allows us to hypothesize that for the given class of materials in the high-temperature region, there exists a general functional relationship connecting the three characteristics: the ratio of operative stresses to the ultimate strength of the material at the specified temperature σ/R_m^T, the rate of steady-state creep $\dot{\varepsilon}$, and the time to failure τ_f corresponding to the indicated stress level under long-term static or low-cycle loading conditions. In Figure 6., this dependence, describing the behavior of the considered alloys at the temperatures 1770-2270 K, is illustrated graphically in the three-dimensional coordinate system XYZ, along the axes of which are plotted, respectively, the logarithms of $\dot{\varepsilon}$, τ_f and σ/R_m^T. The functions are plotted using the experimental points obtained for base metal of the molybdenum alloys TsM-6, TsM-10, TsM-12, and MI5 at temperatures of 1770, 2020, and 2270 K, and generally represent a straight line in three-dimensional space. The projections of this function on the coordinate planes XOZ, YOZ, and XOY (marked by the dashed lines in Figure 6) are described by expressions (4), (5), and (6), respectively. The dependence itself can be described analytically by the system of equations proposed in [19]:

$$A_1 \ln \dot{\varepsilon} + B_1 \ln \tau_f + C_1 \ln(\sigma / R_m^T) + D_1 = 0 \tag{7}$$

$$A_2 \ln \dot{\varepsilon} + B_2 \ln \tau_f + C_2 \ln(\sigma / R_m^T) + D_2 = 0 \tag{8}$$

where A_1, B_1, C_1, D_1, A_2, B_2, C_2, and D_2 are coefficients depending on the structural state of the material and are constant for the given class of materials in a certain temperature-force region, within the limits of which the resistance to plastic deformation and fracture is controlled predominantly by the same physical processes and mechanisms.

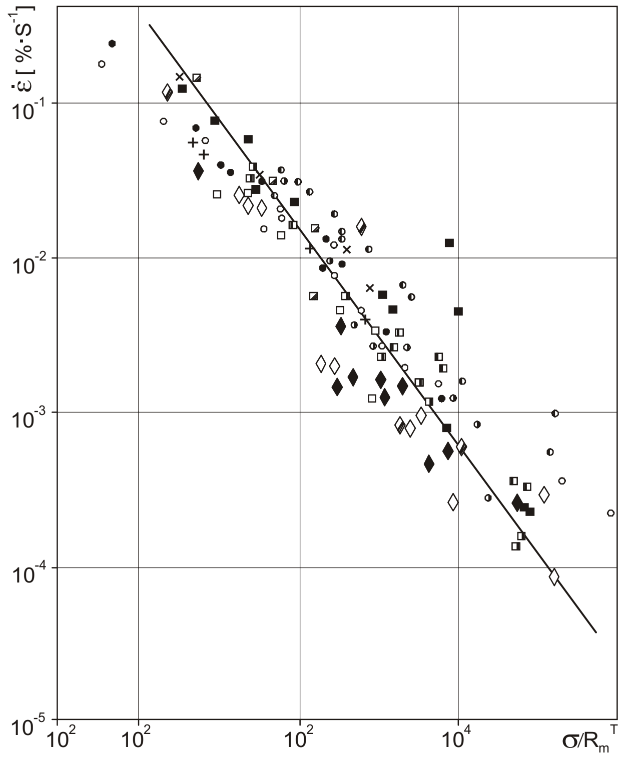

Figure 5. **Dependence of the time of failure for base metal of low-alloy molybdenum alloys on the steady creep rate. (The symbols mean the same as in Figure 3.)**

Slika 5. **Ovisnost vremena nastajanja greške na osnovnom metalu niskolegiranih slitina molibdena o konstanti brzine puzanja. (Simboli su isti kao na slici 3.)**

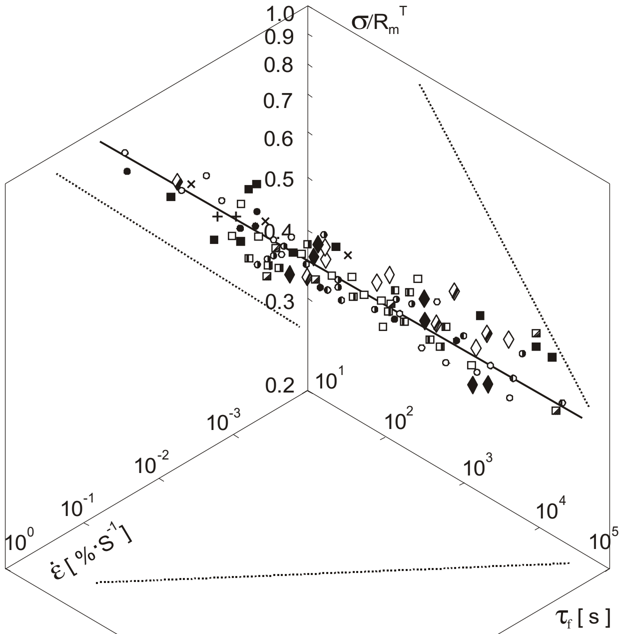

Figure 6. **Dependence of the steady-state creep rate and time to failure for base metal of low-alloy molybdenum alloys on the value of σ/R_m^T in the temperature range 1770 - 2270 K. (The symbols mean the same as in Figure 3.**

Slika 6. **Ovisnost brzine puzanja u stacionarnom stanju i vremena nastajanja greške na osnovnom metalu niskolegiranih slitina molibdena o vriednosti σ/R_m^T unutar temperaturnog područja od 1770 - 2270 K. (Značenje simbola je isto kao i na slici 3.)**

Thus we have established that in the high-temperature region for low-alloy molybdenum alloys, correlations exist between the short-term, long-term static, and low-cycle strength characteristics, which are described by functional depend-ences which are common to all the materials of the indicated class.

By virtue of the fact that most molybdenum alloys are obtained by introducing the alloying elements in small amounts, not exceeding their solubility limit (up to 1 mass %), the practical importance of the results obtained becomes obvious for accelerated assessment of the heat-resistance characteristics of existing and newly created molybdenum alloys during their development and investigation of weldability.

CONCLUSION

1. As a result of joint analysis of extensive experimental data on the mechanical properties and structure of low-alloyed molybdenum alloys for different type of loading we established empirical correlation relations between the characteristics of fatigue strength, conventional yield limit of the material, and its grain size.
2. We have established analytical expressions, which are described generalized empirical correlation dependence between short-term, long-term static, low-cycle strength and creep resistance characteristics of low-alloyed molybdenum alloys over the wide range of high temperatures.

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