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Phase Composition, Structure, and Properties of Beryllium Bronze after Thermal and Thermoacoustic Treatment

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Abstract—The influence of thermal and thermoacoustic treatment on the structure and physicomechanical properties of BrNKhK beryllium bronze is considered. Its strength and elasticity may be improved by adjusting the treatment conditions. The influence of treatment before aging and the conditions of aging and thermoacoustic treatment on the structure is described. It is shown that additional improvement in the properties of the bronze wire is possible after thermoacoustic treatment.

Keywords: bronze, heat treatment, thermoacoustic treatment, microstructure, mechanical properties
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Beryllium bronze has the best mechanical properties for use in elastic elements: strength up to 1300 MPa; and yield up to 1200 MPa. Its plasticity is very low, and its relative elongation is no more than 2%. BrNKKh beryllium bronze matches silicon–manganese and tin–zinc bronzes in its strength and exceeds their yield point. Its margin of plasticity remains higher than those of the other bronzes. The sensitivity of the corresponding measuring elements and the accuracy with which the measured parameter is converted to a displacement or force depends largely on the resistance of the material to microplastic deformation, which is responsible for hysteresis, elastic aftereffects, stress relaxation, and creep.

Springs operating at high temperatures must be thermostable and corrosion-resistant. The materials for components of machines and instruments are selected on the basis of the relevant operational, technological, and economic considerations. While the physicomechanical properties of the alloys are of primary importance, technological, economic, and environmental factors are also relevant, especially in large-scale and mass production. Therefore, besides the requirements on the strengthening technology in terms of the needed functional properties, environmental constraints also apply: the environmental impact of alloy production must be minimal. If the resistance of industrial alloys such as BrNKKh 2.5–0.7–0.6 bronze to plastic deformation is improved, their use in the manufacture of elastic elements (springs) may be expanded [1–6].

Strengthening by means of thermoacoustic treatment has been shown to be effective if employed prior to tempering or aging in the case of steel and aluminum and titanium alloys [6]. Accordingly, it is expedient to investigate how thermoacoustic treatment affects the properties of BrNKKh beryllium bronze, which is widely used in the manufacture of components for machines and instruments [1–4].

Elastic elements are manufactured from many alloys of nonferrous and precious metals after strengthening by methods such as aging, dispersional hardening, and thermomechanical and thermochemical treatment. The alloy composition and the strengthening conditions are selected on the basis of the operating conditions of the elastic elements. Copper alloys are of particular interest on account of their distinctive properties: high degrees of strengthening, considerable elastic deformation, high electrical and thermal conductivity, high fracture strength, and corrosion resistance. These alloys are used in instruments, electrical machines, and automatic electrical and mechanical devices; they often serve as strong electrically conducting elastic elements of high precision and reliability [5]. Many copper alloys are used in industry; their structure depends on the strengthening technology employed, which, in turn, depends on the alloy composition.

We investigate BrNKKh 2.5–0.7–0.6 bronze in rod form (diameter 3.5 mm) after heat treatment and subsequent cold plastic deformation (in other words, rods in the state supplied by the manufacturer). BrNKKh bronze may be dispersionally hardened. The rods are characterized by considerable spread in mechanical properties, both in the initial state (after heat treatment and cold plastic deformation) and after aging, which is the final process determining the alloy properties [1–3].

Table 1

Test	Treatment	Additional treatment	σ_u	$\sigma_{0.2}$	$\sigma_{0.05}$	δ, %
			MPa			
1	Initial state (IS)	–	681	460	383	3.2
2		A1	690	602	478	2.9
3		A1 + A1	693	535	425	3.2
4		A2	1100	340	–	5.3
5		A3	676	343	–	9.8
5a	IS	Aging at 440°C, holding for 2 h (standard treatment)	852	803	670	2.4
6		Aging at 440°C, holding for 2.5 h	856	780	650	2.7
7	IS, A1	Aging at 440°C, holding for 2.5 h	865	820	800	3.6
8	IS, A1, aging at 440°C, holding for 2 h	A1	860	819	780	5.9
8a		A1 + A1	890	850	807	7.5
9	IS, A3	Aging at 440°C, holding for 2 h	832	520	–	5.6
10	IS + A3 + aging at 440°C, holding for 2 h	Cold plastic deformation	686	420	–	16
11	Quenching at 900°C	Aging at 440°C, holding for 2.5 h	680	400	–	9

Thermoacoustic treatments A1–A3 differ in the conditions employed and in the temperature to which the sample is heated. Specifically, treatment A1 involves heating to 150–170°C, holding under acoustic pressure for 10–12 min and subsequent cooling in the resonator for 10 min.

To improve the strength of the bronze and reduce its spread, we employ thermoacoustic treatment [5]. In treatment A1, the bronze is heated to 150–170°C and held for 10 min. Some of the samples are cooled in the resonator of a gas-jet sound generator, with simultaneous action of a gas flux and an acoustic field (acoustic pressure 140 dB) for 10–12 min; the others are cooled in air. In treatments A2 and A3, the bronze is at normal temperature, and the acoustic parameters are different.

After thermoacoustic treatment, the samples (length 200 mm) are tested in static tension on a Shumadzu (Japan) AGX-100 kN machine. The microstructure is investigated on a Leica DM2500 (Germany) metallographic microscope and also on a VEGA3 SBH (Czech Republic) scanning electron microscope.

Table 1 presents the mechanical properties of BrNKKh beryllium bronze in the initial state, after aging, and after additional thermoacoustic treatment.

Two types of preliminary treatment are used for the bronze:

(1) quenching + cold plastic deformation (ε = 60%); this is the initial state;

(2) quenching from 900°C, holding for 30 min, and cooling in water.

In the case of preliminary treatment 1 (quenching + cold deformation), the initial mechanical properties depend on the thermoacoustic treatment: for treatment A1 (administered once or twice), σ_u, $\sigma_{0.05}$, and $\sigma_{0.2}$ increase, while the plasticity δ remains unchanged; for treatment A2, σ_u and δ increase, while $\sigma_{0.2}$ declines; and, for treatment A3, δ increases, σ_u remains unchanged, and $\sigma_{0.2}$ declines (Table 1).

The bronze is aged at 380–480°C, with holding for 1.5–3 h. After aging bronze in the initial state at 440°C for 2 h, the strength is significantly greater than for other aging conditions. This is regarded as the standard heat treatment.

If the bronze in the initial state is subjected to thermoacoustic treatment A1 prior to aging at 440°C for 2 h (test 7), all the properties σ_u, $\sigma_{0.05}$, $\sigma_{0.2}$, and δ are greater than after the standard heat treatment. In test 8, with thermoacoustic treatment A1 both before and after aging, the plasticity increases, while $\sigma_{0.05}$ declines somewhat. All the mechanical properties are greater than in other conditions with thermoacoustic treatment A1 after aging [7]. In tests 7 and 8, the use of treatment A1 considerably decreases the spread of the mechanical properties.

In test 9, where the bronze undergoes thermoacoustic treatment A3 before aging (standard heat treatment), we see that the strength (in particular, $\sigma_{0.2}$) is lower than in other cases, but the plasticity is greater. If the treatment in test 9 is followed by cold plastic deformation, the overall gain in strength is lost, but the plasticity increases to δ = 16% (test 10). The loss in strength and gain plasticity after cold plastic deformation is associated with the breakaway of dislocations from the atoms of dissolved impurities of alloying elements.

In the case of preliminary treatment 2 (quenching with subsequent optimal aging), the strength again increases but remains less than for thermoacoustic treatments A2 and A1 (tests 6 and 7).

On the basis of Table 1, thermoacoustic treatment A1 (tests 7 and 8a) may be used to improve the elastic properties of bronze in its initial state (wire with ε = 60%).

In Fig. 1, we show the extension of BrNKKh bronze samples in the initial state and after treatment including quenching, subsequent aging, and thermoacoustic treatment. The diagrams are the same for the samples in the initial state and after quenching (Fig. 1a). For quenched samples, the diagrams remain the same after aging (Table 1); only the parameters change. For samples in the initial state, the diagrams after aging correspond to Fig. 1b.

With any thermoacoustic treatment (Table 1), the diagrams remain the same; only the parameters change (Fig. 1c). These curves include a practically horizontal section corresponding to shear deformation with minimum strengthening. In these conditions, equilibrium is established: the number of dislocations formed corresponds to the number annihilated in transverse slip [9]. Thermoacoustic treatment A1 increases not only $\sigma_{0.05}$ and $\sigma_{0.2}$ but also the plasticity δ. Thus, in the diagrams for bronze after standard heat treatment (aging at 440°C for 2 h), we see that alloy failure begins practically as soon as the stress reaches its peak and localization of the deformation (necking) begins, with minimal deformation (test 5a, Fig. 1b). After thermoacoustic treatment, which increases the plasticity, the deformation that accompanies necking extends over a greater volume than in the case of standard heat treatment alone (Fig. 1c).

In Fig. 2, we show the microstructure of BrNKKh bronze in the initial state and after heat treatment. In the initial state, the microstructure consists of deformed grains of the solid solution and intermetallides deposited on solidification (Fig. 2a). The quantity of intermetallides increases further on aging, as a result of decomposition of the solid solution (Figs. 2b and 2c). In other words, we observe phase aging, characterized by small difference between the yield point and the strength: $\sigma_{0.2}/\sigma_u$ = 0.8–0.95. That is consistent with Table 1 (test 5a, for example). On aging, the number of twins in the alloy also increases. The structure of the aged alloy depends not only on the chemical composition but on factors such as the type of preliminary treatment and the treatment temperature.

In Fig. 3, we show the microstructure of BrNKKh bronze in the initial state and after thermoacoustic treatment A1. The thermoacoustic treatment results in smaller structural components. That ensures retardation of the dislocations by the elastic stress field in the matrix around the inclusions and also improves the mechanical properties of the bronze as the dislocations move around the disperse particles [8].

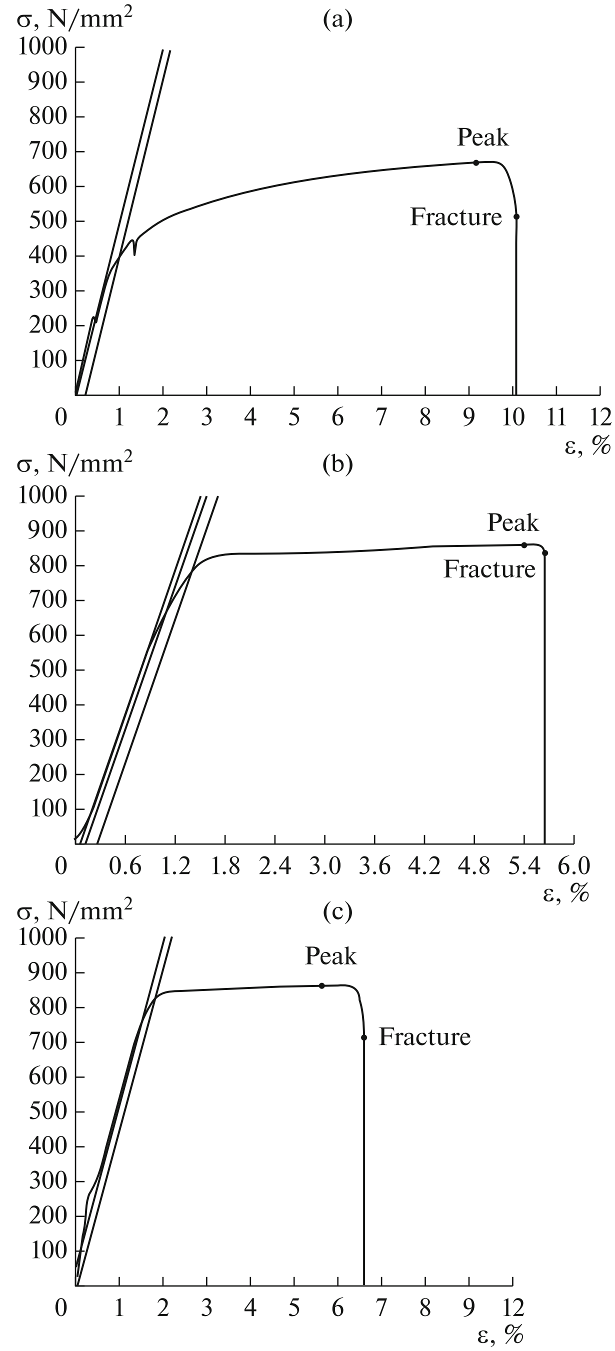

Fig. 1. Extension of bronze after the following treatments: (a) quenching at 900°C with 30-min holding + aging at 440°C for 3 h (test 11); (b) standard heat treatment (aging at 440°C for 2 h) of alloy in the initial state (test 5a); (c) thermoacoustic treatment A1 and standard heat treatment of alloy in the initial state, followed by thermoacoustic treatment (test 8).

Table 2 presents the chemical composition of the particles deposited from the solid solution of the

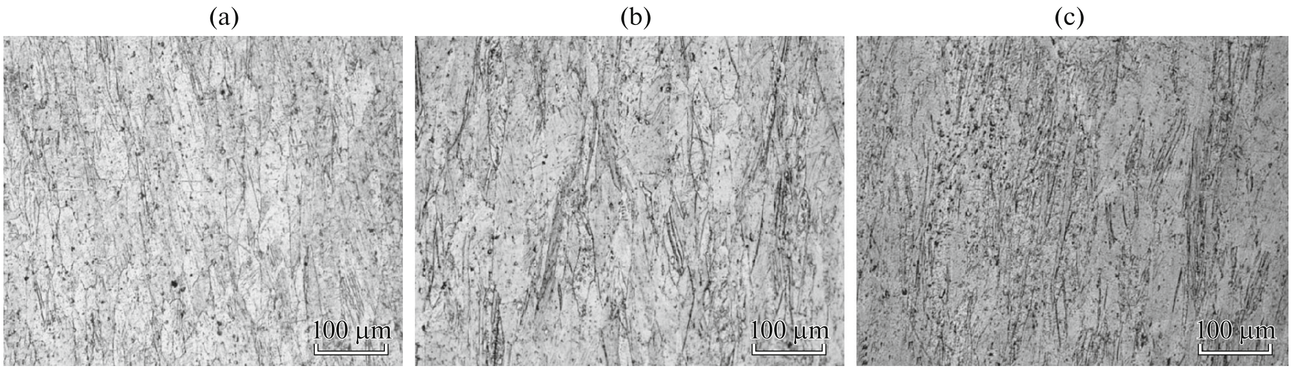

Fig. 2. Microstructure of BrNKKh bronze in the initial state (a), after aging at 440°C for 2 h (b), and after subsequent tensile testing (c).

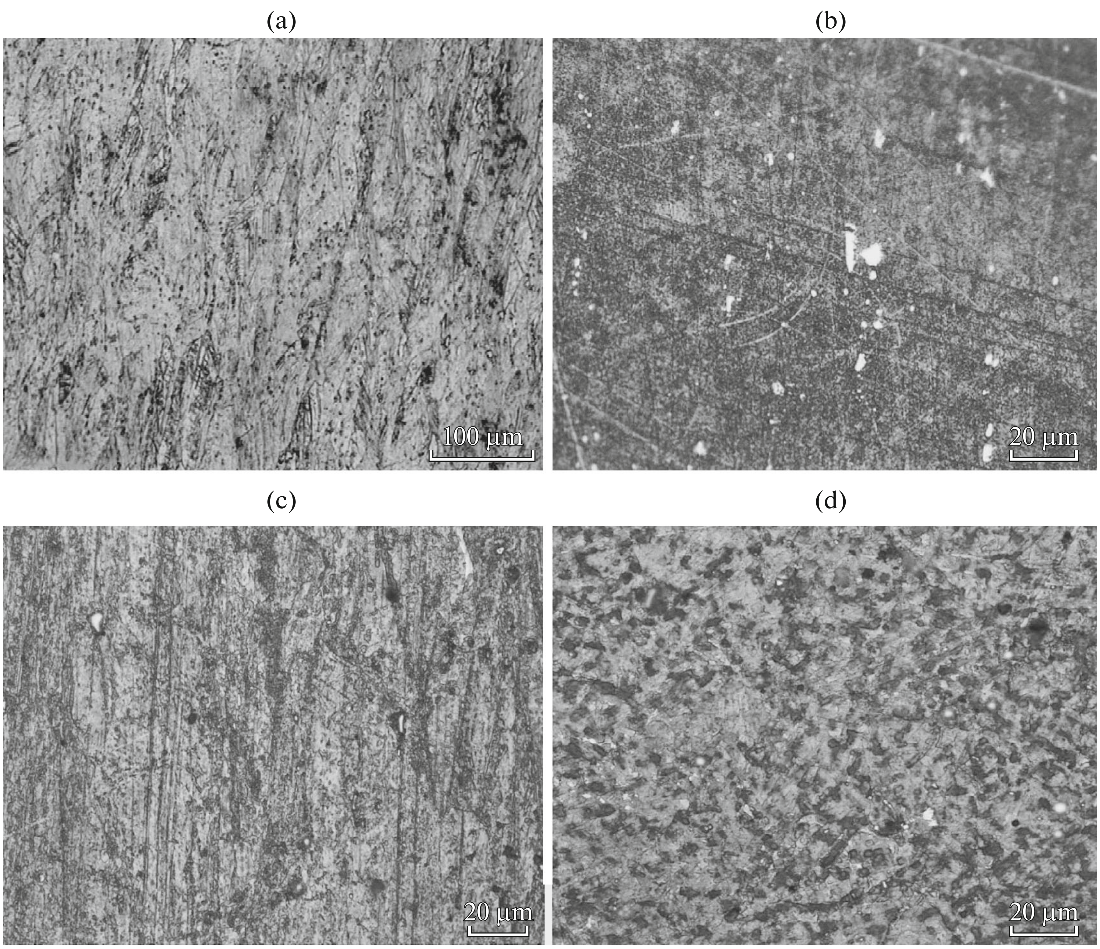

Fig. 3. Microstructure of BrNKKh bronze in the initial state (a, b) and after additional thermoacoustic treatment (c, d).

bronze matrix on alloy solidification and on aging at 440°C for 2.5 h. According to microspectral analysis, the large round particles are compounds of chromium with silicon (Cr_3Si), additionally alloyed with copper and a small quantity of nickel. The inclusions may contain iron (Table 2). These intermetallides are formed on solidification. The extended plates contain less chromium; their composition is closer to Cr_2Si. However, they include considerable quantities of copper and some nickel.

We see in Table 2 that the solid solution is significantly depleted in chromium after aging. On aging, the largest particles (of both round and plate type) increase in size (to 5.85 μm). The small particles are

Table 2

Phases	Composition, %				
	Si	Cr	Ni	Cu	Fe
Large rounded particles	15.72	74.92	0.83	4.98	–
	15.89	76.49	–	4.69	–
	8.62	43.35	–	5.45	10.05
Plates	8.72	29.18	5.57	24.47	–
Small rounded particles	5.94	14.98	3.07	46.4	–
	9.91	29.31	4.83	32.8	–
	4.27	20.95	4.15	63.57	–
Solid solution	1.58	–	2.95	94.07	–
	1.12	–	3.3	93.39	–

enriched in nickel, corresponding to the formula $Si(Cr,Ni)_3$, and also in copper (Table 2). For both small inclusions and plates, the nickel content increases to 5.57%, while the chromium content decreases to 11.19–43.35%. The smaller $Si(Cr, Ni)_3$ particles are formed mainly on aging and result in considerable strengthening [8]. The chemical composition of the phases in Table 2 largely agrees with the data in [2].

CONCLUSIONS

If BrNKKh 2.5–0.7–0.6 bronze is subjected to thermoacoustic treatment A1 prior to optimal aging or after aging, its mechanical properties are improved, with increase in its resistance to slight plastic deformation. The spread of the mechanical properties is decreased. Accordingly, such bronze may be used to produce elastic elements (springs). After thermoacoustic treatment, the mechanical properties (σ_u, $\sigma_{0.05}$, $\sigma_{0.2}$, and δ) of the bronze are such that, in some cases, it may be used in place of more expensive alloys, including BrB2 bronze.

Additional cold plastic deformation of BrNKKh bronze after thermoacoustic treatment A1 improves its plasticity, while maintaining the required strength.

The use of thermoacoustic treatment to strengthen alloys has practically no environmental impact. The system may be connected to the enterprise's compressed-air supply lines.

REFERENCES

1. Kareva, N.T., Koryagin, Yu.D., and Medvedeva, G.I., Effect of various aging modes on properties of Br-NKhK alloy, *Izv. Vyssh. Uchebn. Zaved., Tsvetn. Metall.*, 1985, no. 6, pp. 64–68.
2. Kareva, N.T. and Koryagin, Yu.D., Effects of heat treatment on the structure of BrNKhK bronze, *Vestn. Yuzh.-Ural. Gos. Univ., Metall.*, 2015, vol. 15, no. 4, pp. 84–88.
3. Nikolaev, A.K., Dispersion hardening as an effective trend of the synthesis of constructional alloys, *RITM Mashinostr.*, 2011, no. 3, pp. 31–35.
4. Pastukhova, Zh.P. and Rakhshtad, A.G., *Pruzhinnye splavy tsvetnykh metallov* (Spring Alloys from Nonferrous Metals), Moscow: Metallurgiya, 1983, 2nd ed.
5. Remshev, E.Yu., Danilin, G.A., Vorob'eva, G.A., and Silaev, M.Yu., Ensuring the operational reliability of elastic elements by acoustic methods, *Metallurgist*, 2015, vol. 59, nos. 3–4, pp. 225–228.
6. Vorob'eva, G.A. and Uskov, V.N., *Aerotermoakusticheskaya obrabotka stalei i splavov* (Aerothermoacoustic Treatment of Steels and Alloys), St. Petersburg: Balt. Gos. Tekh. Univ., 2012.
7. Remshev, E.Yu., Vorob'eva, G.A., Bespalov, D.A., Olekhver, A.I., and Silaev, M.Yu., RF Patent 2691823, *Byull. Izobret.*, 2019, no. 17.
8. Novikov, I.I., *Teoriya termicheskoi obrabotki metallov* (Theory of Heat Treatment of Metals), Moscow: Metallurgiya, 1986.
9. Zolotorevskii, V.S., *Mekhanicheskie svoistva metallov* (Mechanical Properties of Metals), Moscow: Mosk. Inst. Stali Splavov, 1998.

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