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Influence of Production Modes on the Structure and Tribological Properties of Sintered Tin Bronze during Friction with Lubricant in Friction Units

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Abstract—The results of a study on the influence of the modes of obtaining sintered BrO12 bronze on its structure, phase composition and tribological properties during friction with a lubricant are presented. It is shown that the phase composition of BrO12 bronze sintered for 5 min consists of a solid solution of tin in copper and inclusions of intermetallic phases δ-Cu41Sn11 and Cu81nSn22. An increase in the exposure time during sintering leads to an increase in the homogeneity of the solid solution of tin in copper, a decrease in the crystal lattice parameter of copper from 3.69 to 3.68 Å, an increase in the grain size from 2–5 μm at 5 min of sintering to 15–46 μm at 120 min, a decrease in the content of the intermetallic phase δ-Cu41Sn11, and the disappearance of the Cu81nSn22 phase at 60 min of sintering and the virtual absence of intermetallic compounds after sintering for 120 min. Tribological tests have shown that the friction coefficient of bronze sintered for 5 min at a pressure of 4 MPa varies from 0.08 to 0.03, and at 20 MPa, from 0.105 to 0.04, the average wear value at a pressure of 4 MPa and 20 MPa was 2.0 μm. The coefficient of friction at the above pressures of bronze sintered for 60 min was 0.11–0.036 and 0.095–0.023; 0.045 and 0.12–0.5, respectively, wear was 6.3 μm.

Keywords: friction material, friction with lubricant, tin bronze, sintering, structure, sintering time, running-in, steady state friction, friction coefficient, wear

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INTRODUCTION

Most machines and mechanisms contain brake devices with various friction materials. Tin bronze has become widespread as a friction material due to its corrosion resistance, high thermal conductivity, the required friction coefficient, and rapid run-in [1–4].

The copper–tin phase diagram is a combination of several peritectic transformations [5]. The following phases exist in the Cu–Sn system: α-solid solution of tin in copper; tin, since the solubility of copper in tin is less than 0.01%; β-solid solution based on the electronic compound Cu_5Sn; δ-γ-electronic compound $Cu_{31}Sn_8$; γ-a solid solution based on a chemical compound of copper and tin the crystal structure of which has not been established; ε is the electronic compound Cu_3Sn; and η is chemical compound Cu_6Sn_5. The homogeneity of the structure of sintered bronze is determined by the composition and formation conditions.

In the literature there is data on the tribological properties of cast bronze with a homogeneous structure [6–9] but there is no data on the influence of the degree of heterogeneity of the structure in sintered bronze on the level of these properties. Whereas sintered powder materials based on tin bronze are widely used for both antifriction and friction materials. At the same time, the structure of sintered bronze significantly affects its mechanical and tribological properties.

Objective—To study of the influence of the structure of sintered tin bronze on tribological properties during friction with a lubricant.

MATERIALS AND METHODS

Bronze obtained by sintering with 12% tin was used as the object of research. The bronze charge was obtained by mixing powders in the as-delivered state of copper grade PMS-1 with an average particle size of 45 microns and tin grade PO-1 with an average particle size of 20 μm in a mixer for 1 h. From the resulting mixture, samples with a diameter of 20 mm and a thickness of 3 mm were pressed on a hydraulic press at

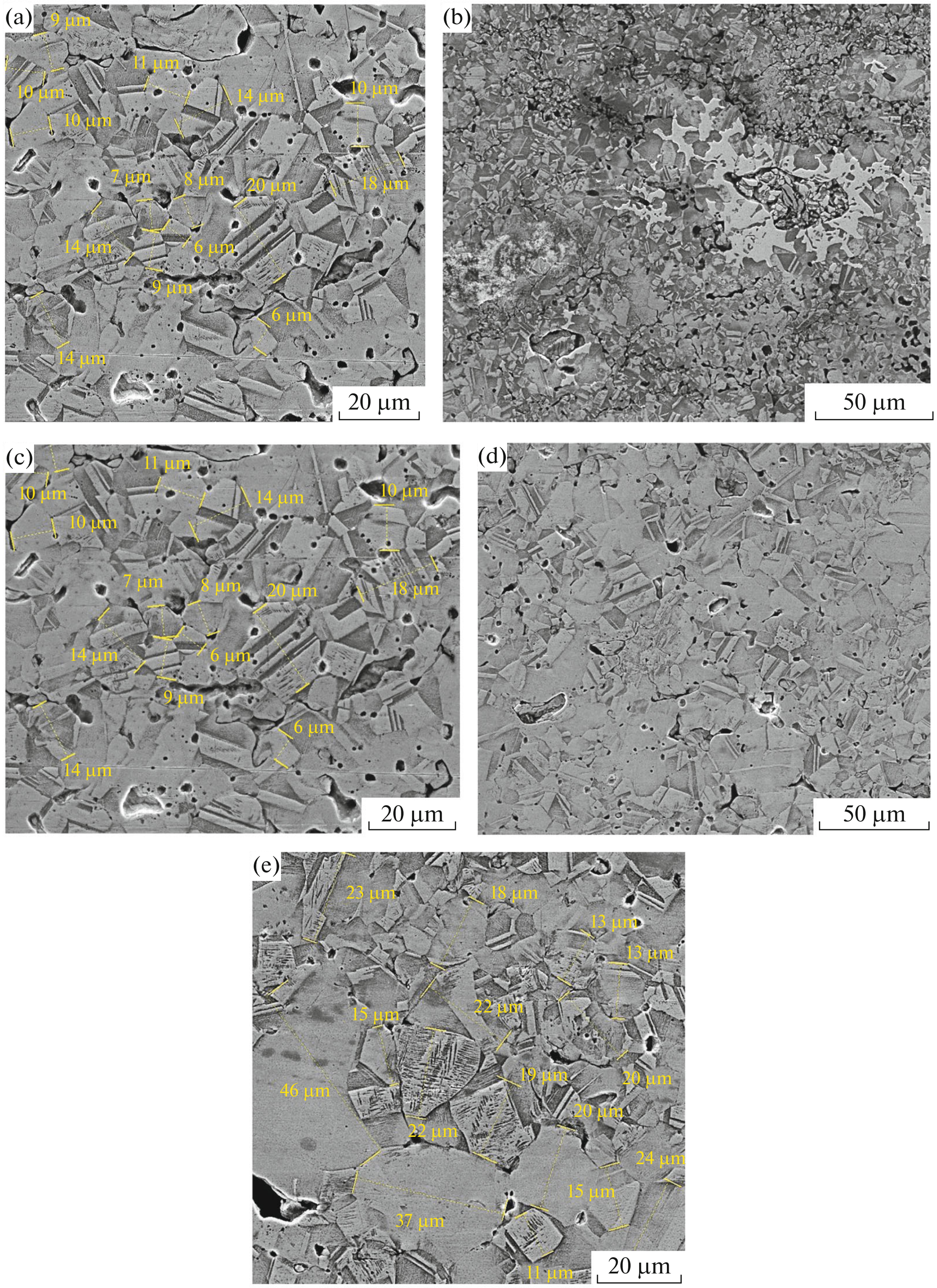

Fig. 1. Structure of BrO12 bronze sintered at different holding times: (a, b) 5; (c, d) 60; (e) 120 min; (a, c, e) ×2000; (b, d) ×1000.

a pressure of 200 MPa. The compressed samples were sintered in a shaft furnace in a protective-reducing atmosphere of dissociated ammonia at a temperature of 780°C for 5, 60, and 120 min.

Tribotechnical properties were determined by testing samples on a MFT-5000 multifunctional tribometer (Rtec Instruments, United States) according to the scheme of reciprocating movement of the sample relative to a stationary steel counterbody made of ShKh15 steel in the form of a cylinder with a diameter of 3 mm, hardness 60–62 HRC, roughness no less than $R_a < 1.6$ µm. Tests were carried out in the presence of I-40A oil at a pressure of 4 and 20 MPa. The sample motion amplitude was 5 mm, the frequency

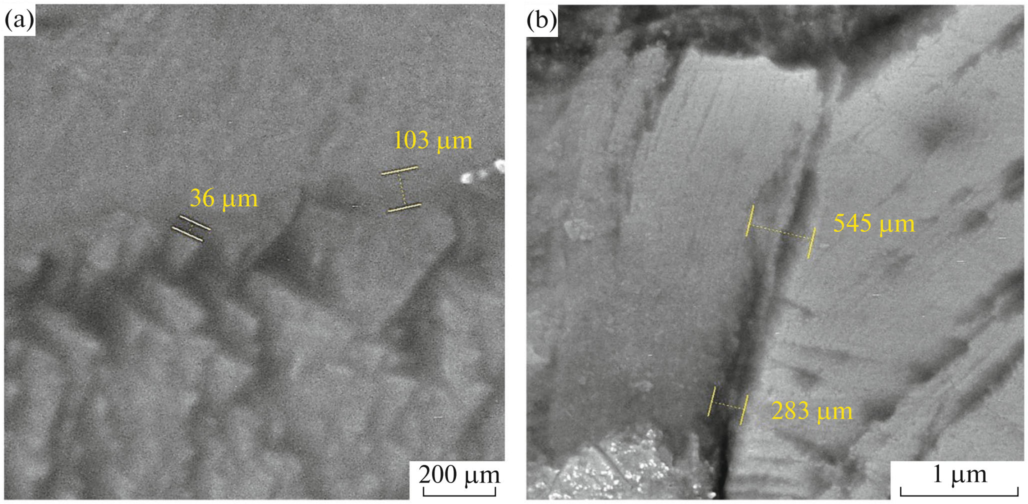

Fig. 2. Grain-boundary region in the structure of bronze BrO12 sintered at different holding times: (a) 60; (b) 120 min.

was 10 Hz, and the duration of tests in the loaded state was 30 min. Based on the test results, the coefficient of friction (COF) was determined. Before testing, the friction pair was run-in for 30 min using sandpaper of various grain sizes (P400, P600, P1000) at a pressure of 7 MPa.

The amount of linear wear was determined by changes in the position of the load sensor. In case of material wear, a negative reading is noted, while in the case of material transfer to the surface of the counterbody, a positive reading is noted. The position of the load sensor was monitored and values were recorded automatically during the entire test period.

The homogeneity of the structure and morphology of the friction surface was analyzed using a Mira high-resolution scanning electron microscope (SEM) from Tescan (Czech Republic) with a micro-X-ray spectral analyzer from Oxford Instruments Analytical (United Kingdom). The phase composition was determined on an Ultima IV X-ray diffractometer (Rigaky) in CuK_{α}-radiation at a voltage across the X-ray tube of 40 kV, anode current of 40 mA. For phase analysis, a standard PDF file was used.

RESULTS AND DISCUSSION

SEM Studies and Phase Composition

The sintering time significantly affects the structure and phase composition of sintered bronze. Figure 1 shows the structures of BrO12 bronze sintered at various exposures. The grain size in bronze sintered for 5 min is 2–5 μm (Fig. 1a), there are light inclusions in the form of individual particles or a discrete mesh up to 100 μm in size (Fig. 1b). As X-ray diffraction analysis has shown, the basis of the structure is a solid solution of tin in copper, the inclusions are intermetallic compounds δ-$Cu_{41}Sn_{11}$ or $Cu_{81}Sn_{22}$.

When the holding time during sintering increases to 60 min, due to diffusion, tin is redistributed in the copper base, and a more uniform structure with a grain size of 10–12 μm is formed (Fig. 1c), accordingly, the lattice parameter decreases, so if after 5 min of sintering the lattice parameter is 3.6999 Å, then after 60 min, it is 3.6904 Å. Even greater grain growth and a decrease in the lattice parameter are observed after sintering for 120 min, 15–46 μm (Fig. 1e) and 3.6889 Å, respectively.

When sintering for 60 min, the number of inclusions of the intermetallic phase δ-$Cu_{41}Sn_{11}$ is sharply reduced (Fig. 1b), and after sintering for 120 min, the intermetallic phase δ-$Cu_{41}Sn_{11}$ was recorded in the form of traces. The $Cu_{81}Sn_{22}$ phase was not detected either after sintering for 60 min or 120 min.

The holding time during sintering also affects the width of the grain boundaries; if after 5 min the width of the grain boundary zone is 50–80 nm, then after 120 min, it is more than 250 nm (Fig. 2).

X-ray microanalysis confirmed the significant heterogeneity of the tin structure in bronze sintered for 5 min (Fig. 3a). The light areas of intermetallic compounds contain 24–36% tin; in a copper base, 11–14 and 3%. The interval for varying the tin content in bronze sintered for 60 min is 7–13% (Fig. 3b), 120 min, 10–12% (Fig. 3c).

Durometric analysis showed that the hardness of the light areas of intermetallic compounds is 76–83 HV, the base with a tin content of 7–13% is 40–46 HV, and 10–12% is 31–38 HV. The hardness of bronze sintered for 60 min is 63.8–72.5 HV, for 120 minutes, 71.3–84.1 HV.

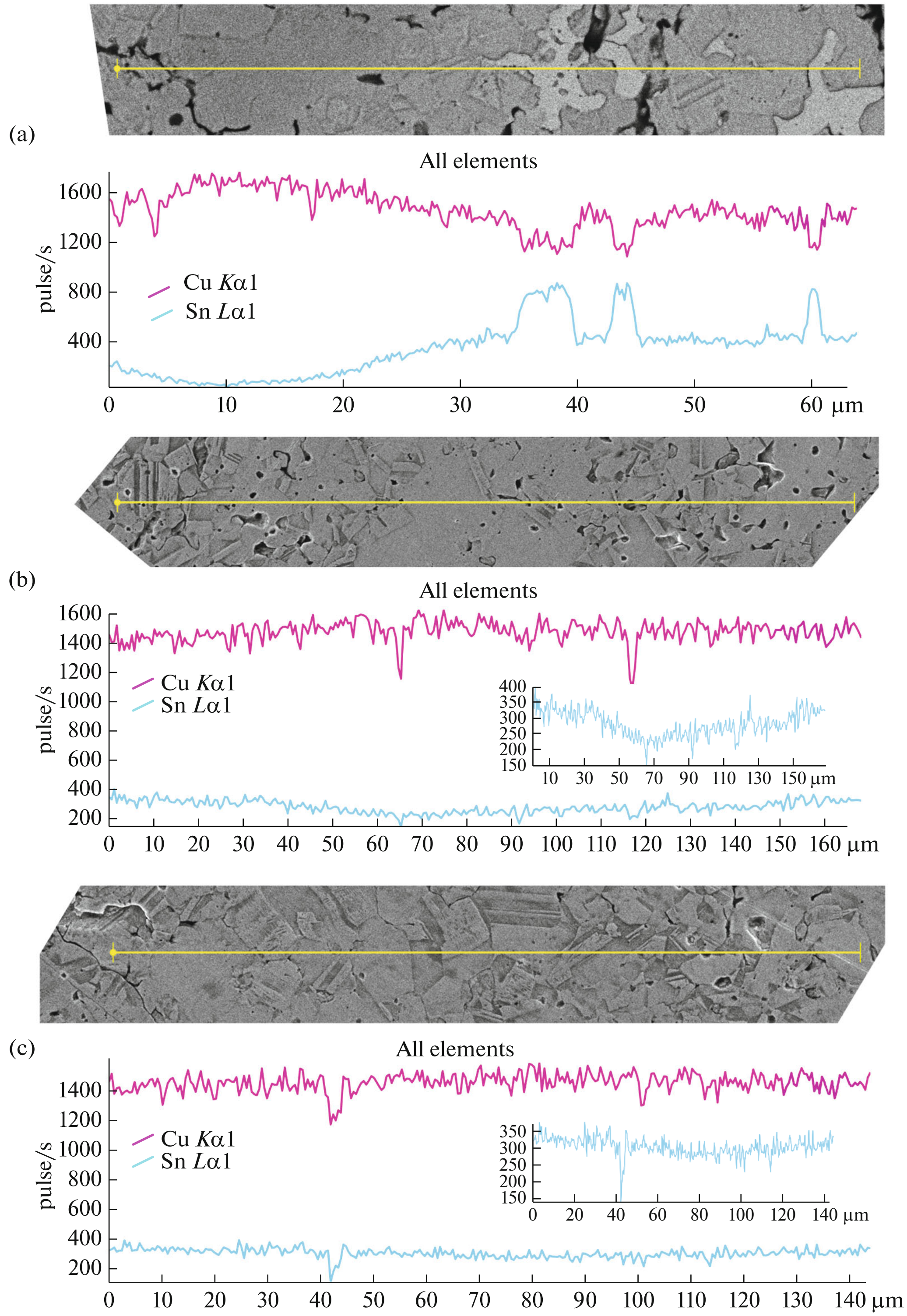

Fig. 3. Distribution of copper and tin in the structure of BrO12 bronze sintered at different holding times: (a) 5; (b) 60; (c) 120 min.

Tribotechnical Research

As friction tests have shown, the structure of bronze sintered at different exposures affects its tribological properties. It was found that when running-in samples sintered for 5 min at a pressure of 4 MPa, the friction coefficient increases to 0.080, and at 20 MPa, to 0.105. The running-in time was 380 s. In the steady period of friction, the friction coefficient at a pressure of 4 MPa is 0.032 (Fig. 4, line *1*), at 20 MPa, instability

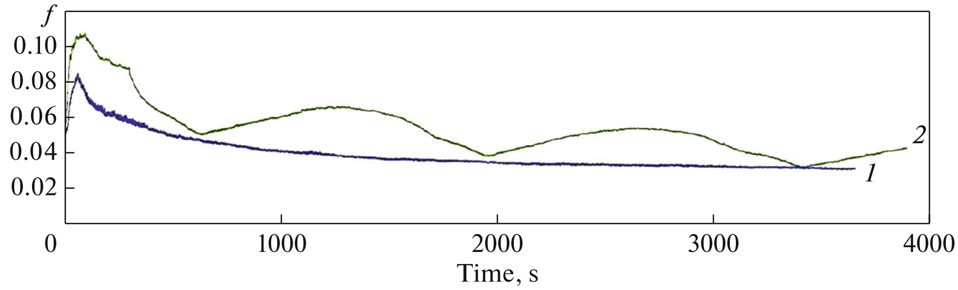

Fig. 4. Change in friction coefficient during friction of BrO12 bronze sintered for 5 min: (*1*) 4; (*2*) 20 MPa.

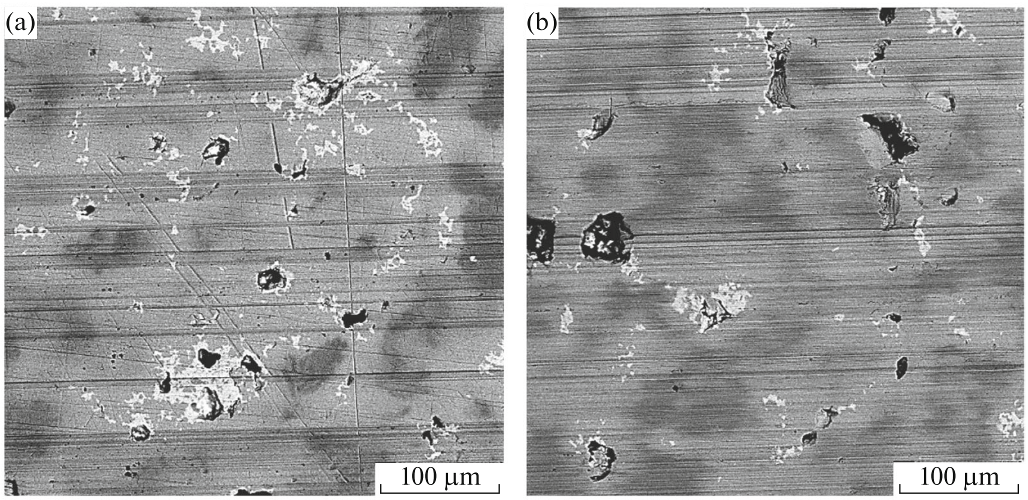

Fig. 5. Morphology of the friction surface of BrO12 sintered for 5 min (test time 4000 s): (a) 4; (b) 20 MPa.

of the friction coefficient is observed (Fig. 4, line *2*), it varies from 0.08 to 0.04.

The wear of bronze at both a pressure of 4 MPa and 20 MPa is 2.0 μm.

Analysis of the morphology of friction surfaces showed that an increase in pressure does not lead to a change in the wear mechanism; the presence of traces of abrasive wear is noted (Fig. 5), which can be formed during the destruction of a solid intermetallic compound.

Increasing the bronze sintering time to 60 min led to a decrease in the running-in time at a pressure of 4 MPa to 260 s and an increase in the friction coefficient to 0.11, and at 20 MPa, to a slight decrease to 0.095 (Fig. 6). At the stage of steady wear at a pressure of 4 MPa, the friction coefficient is 0.043; at 20 MPa, the friction coefficient fluctuates in the range of 0.03–0.04 only at the initial stage for 1500 s, then the friction coefficient is 0.023.

Wear at 4 MPa does not exceed 0.5 μm, at 20 MPa, 1.1 μm, and the depth and width of the formed wear tracks on the friction surface increases (Fig. 7).

Bronze sintered for 120 min has a minimum running-in period of 200 s. Friction coefficient *f* at a pres-

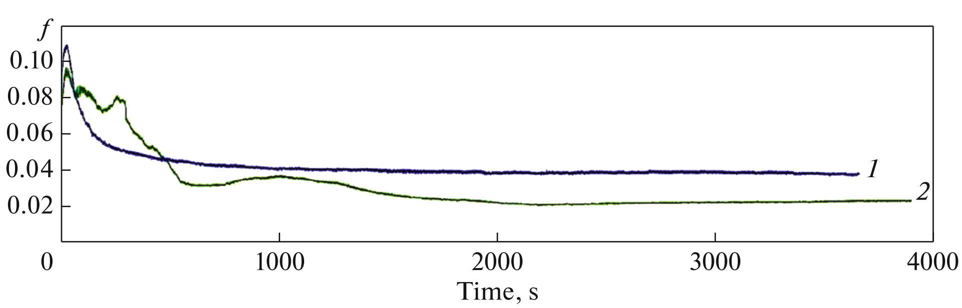

Fig. 6. Change in friction coefficient during friction of BrO12 bronze sintered for 60 min: (*1*) 4; (*2*) 20 MPa.

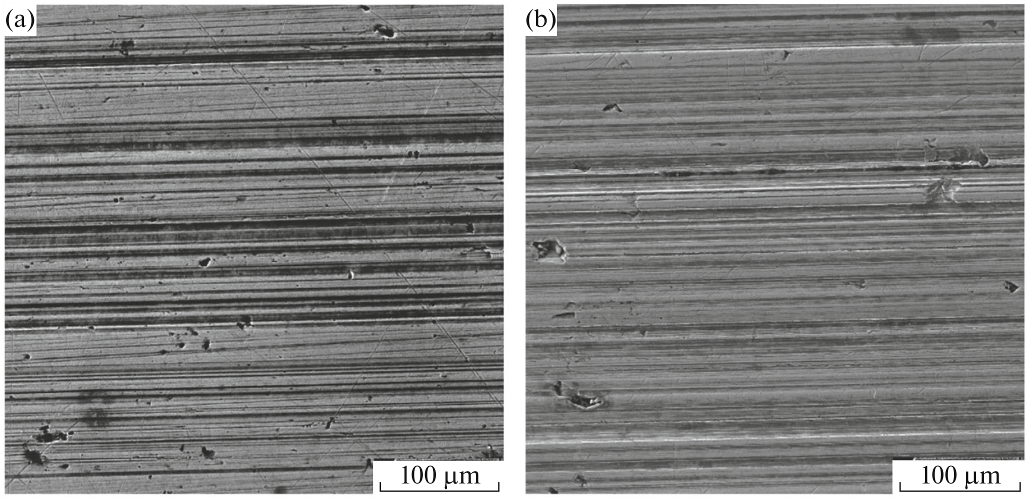

Fig. 7. Morphology of the friction surface of BrO12 sintered for 60 min (test time 4000 s): (a) 4; (b) 20 MPa.

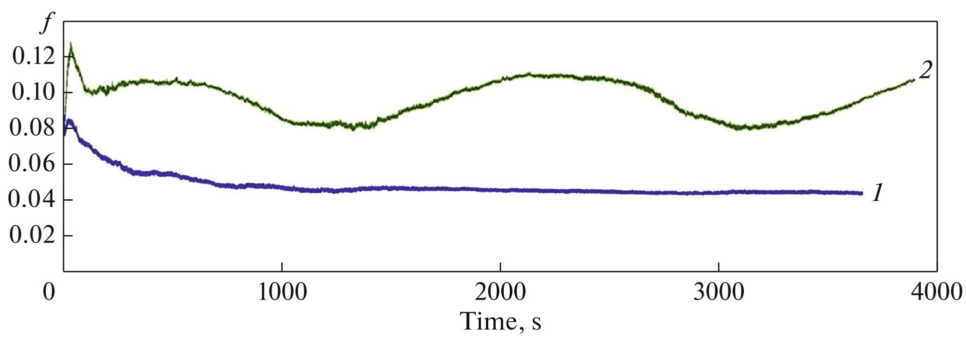

Fig. 8. Change in friction coefficient in time for BrO12 bronze sintered for 120 min: (*1*) 4; (*2*) 20 MPa.

sure of 4 MPa was 0.085, at a pressure of 20 MPa, it increased to 0.125 (Fig. 8). In the steady-state friction mode, the friction coefficient is higher than after sintering for 60 min, at a pressure of 4 MPa, 0.045, and at a pressure of 20 MPa, 0.095–0.110.

Wear at 4 MPa does not exceed 0.5 μm, at 20 MPa, 6.3 μm. The wear surface at a pressure of 4 MPa practically does not change (Fig. 9); at a pressure of 20 MPa, areas of setting with tears are noted (Fig. 9c).

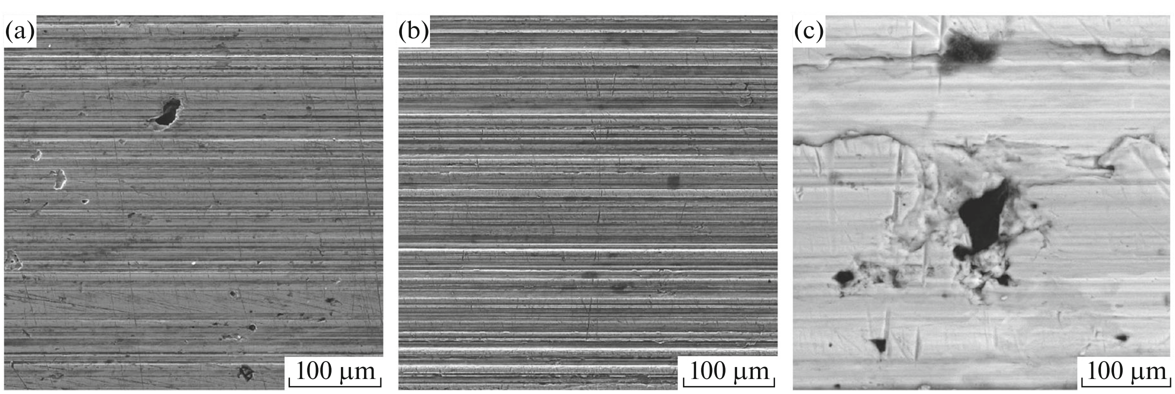

Fig. 9. Morphology of the friction surface of BrO12 bronze sintered for 120 min (test time 4000 s): (a) 4; (b, c) 20 MPa; (b) ×500; (c) ×5000.

CONCLUSIONS

Sintering time has a significant impact on the structure, phase composition, and tribological properties of sintered bronze. The phase composition of BrO12 bronze sintered for 5 min consists of a solid solution of tin in copper and inclusions of intermetallic phases δ-$Cu_{41}Sn_{11}$ and $Cu_{81p}Sn_{22}$. An increase in the holding time during sintering leads to an increase in the homogeneity of the tin solid solution in copper, a decrease in the crystal lattice parameter of copper from 3.6999 to 3.6889 Å, and an increase in the grain size from 2–5 μm at 5 min of sintering to 15–46 μm at 120 min, reducing the content of the intermetallic phase δ-$Cu_{41}Sn_{11}$ and the disappearance of the $Cu_{81p}Sn_{22}$ phase at 60 min of sintering and the virtual absence of intermetallic compounds after sintering for 120 min. The tin content in bronze sintered for 5 min varies from 3 to 14%, in areas of intermetallic compounds 24–36% tin, in bronze sintered for 60 min, the range of varying tin content is 7–13%, for 120 minutes, 10–12%.

Friction tests revealed the abrasive nature of wear, regardless of the test pressure, and the influence of the structure of bronze, sintered at various exposures, on its tribological properties. The running-in time decreases with increasing sintering time, the friction coefficient at the running-in stage at a pressure of 4 MPa, depending on the sintering time, changes from 0.08 to 0.11, at a pressure of 20 MPa, from 0.095 to 0.125, and at the stage of steady-state friction at a pressure of 4 MPa, the friction coefficient increases from 0.032 to 0.04 with increasing holding time from 5 min to 60 min, and to 0.045 up to 120 min. At a pressure of 20 MPa, the friction coefficient in time ranges from 0.08 to 0.04 after 5 min of sintering, from 0.03 to 0.04 at the initial stage for 1500 s, after 60 min of sintering, and from 0.095 to 0.11, after 120 min of sintering. Bronze wear increases from 2 to 6.3 μm with increasing sintering time.

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CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

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