Antifriction powder bronzes with mechanically alloyed copper-based granules

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Abstract. New antifriction composite materials of matrix-filled type based on tin bronze powder for heavily loaded elements of friction units are presented. As their load-bearing structural component heat – and wear-resistant fillers in the form of copper-based granules with the initial composition Cu-5% Al-2% C-2% MoS2 are used, obtained in the course of the reactionary mechanical alloying of copper powder in the air of attritor by aluminum and lubricating additives in the form of graphite and molybdenum disulfide. Dynamically thermostable particles in the form of $\gamma$–$\text{Al}_2\text{O}_3$ oxides of nanodispersed level, mechanochemically synthesized in the attritor, are evenly distributed in copper-based cold-hardened granules and provide them with a high temperature of softening - up to 08...0.9 of the melting temperature of copper. The addition of such granules to powder bronze with 5 wt% tin allowed to obtain antifriction composite materials, which in terms of mechanical and tribotechnical properties significantly exceed the standard antifriction tin and aluminum bronzes and, in particular, bronze EN CuSn8 and EN CuAl10Ni5Fe4.

1. Introduction

Intensification of work of machines and units and increasing the productivity of technological processes invariably lead to an increase in the level of specific loads on the structural elements of machines and technological tools and increase their temperature during operation. This is especially true for friction units of machines and units: sliding bearings, valve guide bushings, pistons of internal combustion engines and casting machines. For example, the analysis of the boost levels of internal combustion engines for various purposes and the tendency to increase their power show the need to develop new materials for sliding bearings that can withstand specific loads of 100 MPa and higher when heated at least 200 °C [1]. At the same time, as shown by the calculations carried out by the authors of this work, in order to avoid plastic deformations at such a specific load, the bearing material must have a yield strength of at least 280 MPa at compression, and a strength limit of more than 600 MPa, which is consistent with the data given in [1].

Great potential in the creation of antifriction materials has the powder metallurgy technology, which allows, in contrast to casting technology, simply type in the matrix material not only alloying elements but also different, which does not interact with the matrix additives, including friction. Thus, a tin bronze powder containing 27.0 wt %Sn, 2.5 wt %Fe and additives of solid lubricants in the form of graphite (4.0 wt %) and molybdenum disulfide (0.5 wt %), has a sufficiently high hardness, low coefficient of friction (0.035...0.040) and has a wear rate, which is more than 2 times lower than that of compact (cast) tin bronze [2]. However, the ultimate tensile strength of the specified antifriction
powder material with 15 ... 17% porosity does not exceed 180 MPa, which is clearly not enough for this material to be used in friction parts at the above-specified level of specific load and their heating temperature.

Similar approaches to the creation of copper-based antifriction powder materials are also used abroad [3]. Thus, enterprises of the SKF Gruppe company [4] manufacture sintered friction bearings from standard powder bronzes, which additionally contain 1.0 wt % graphite and pores filled under pressure with special oil. Such bearings are used at a specific load of 10...20 MPa, sliding speed of 0.25...5 m/s and the temperature of their heating to 90 °C.

Zollern GmbH & Co. KG [5] for the manufacture of bearings uses bronze SnSb8Cu4, CuPb15Sn8, CuPb20Sn5 and CuPb22Sn, and aluminum-tin alloy AlSn20. To increase the specific dynamic load on the bearings up to 75 MPa, a layer of antifriction material is reinforced with a steel support layer. The same or similar materials are used by other foreign companies (for example, MIBA Gleitlager GmbH, Glyco Metalwerke GmbH, Bleistahl GmbH & Co. KG, Federal-Mogul Italy S. R. L, Daido Metal Co. Ltd, Taiho Kogyo Co. Ltd) producing plain bearings on a metal matrix basis.

One of the ways to improve antifriction composite materials is to create matrix-filled structures [6]. Such materials, for example, sintered tin bronze containing inclusions of ferrochrome FeCr 800 particles with dimensions of 40...50 µm [7,8], have a high complexity of tribotechnical characteristics. However, they are designed to operate at a specific load of not more than 7 MPa. Providing higher contact pressure values for such materials is difficult, due to the weak adhesion between the ductile base and the solid inclusions.

Further development of antifriction composite materials of a matrix-filled type for the elements of heavily loaded friction unit was obtained in [9, 10], where it is especially noted that between a solid wear-resistant phase in the form of a material frame that provides high strength and wears resistance, and a ductile phase in the intergranular space of the frame with a high thermal conductivity and a low friction coefficient, diffusion interaction should be ensured, forming transition layers at the interface.

In the present work, taking into account the above shortcomings, as a solid filler of ductile tin bronze, it is proposed to use mechanically alloyed granules obtained by processing copper powder with additives of alloying elements and solid lubricant in a high-energy ball mill (attritor) in the air medium [11, 12]. It is known [13, 14] that as a result of grinding in a ball mill of copper powder with additives, for example, aluminum powder and graphite in air, conditions are provided for the formation in these granules of aluminum oxide γ-Al2O3, uniformly distributed in a matrix of α-solid Cu(Al) solution. Such strongly cold-hardened granules obtained by reactionary mechanical alloying and containing dispersed particles γ-Al2O3 and graphite with dimensions not exceeding 100 nm have a high hardness and, especially, a high softening temperature reaching 800...850 °C [13-15]. The additional introduction of molybdenum disulfide MoS2 together with graphite should provide these granules, in addition to high heat resistance, also high tribotechnical properties, namely low coefficient of friction, high wear resistance, and high scoring resistance..

2. Materials and methods of research

The initial chemical composition of the granular powder mixture (charge), from which the studied materials were obtained, is presented in Table 1. The mixture included electrolytic copper powder of the PMS-1 brand, tin powder of the POE brand, and mechanically alloyed granules Cu-5% Al-2% C-2% MoS2.

The studied materials on the composition can be attributed to the powder composite materials «tin bronze – inclusions (granules)». They differ in their different content of granules.

The granules were obtained by treating in the attritor of PMS-1 copper powder, PP-1 aluminum powder, GK-3 graphite and DMI-7 molybdenum disulfide mixture within 90 min. For the production of samples of the studied composite materials, the obtained granules were sieved through a sieve with a mesh size of 0.05 mm. The yield of granules with dimensions not exceeding 0.05 mm was not less than 95 % of the total number of granules obtained.
For comparison, samples of tin bronze powder with the symbol 100M were also made (see Table 1) with a tin content of 5 wt%.

Table 1. Initial chemical composition of the studied materials.

| Material symbol | The initial content of components in the granular powder mixture, wt% |
|-----------------|---------------------------------------------------------------|
|                 | Copper powder | Tin powder | Granules |
| 100M            | 95           | 5         | -        |
| 85M/15G         | 80           | 5         | 15       |
| 80M/20G         | 75           | 5         | 20       |
| 70M/30G         | 65           | 5         | 30       |

The technology of manufacturing cylindrical samples of the studied materials with a diameter of 13 mm and a height of 10...12 mm included the following operations:
- production of working charge by mixing the components of the granular powder mixture in a «drunken barrel»;
- cold pressing of the working charge in the mold at a pressure of 500 MPa;
- heat treatment of pressed preform in a solid carbonizer (or nitrogen) at 700 °C for 1 h;
- heating of pressed preform in technological capsules with a solid carbonizer and their subsequent post-compaction at a pressure of 500 MPa with an exposure of 2 minutes in a heated 500 °C mold.

On the obtained samples, the Brinell hardness was determined by a 2.5 mm diameter ball at a load of 187.5 kg with exposure under a load of 30 s. The density was determined by weighing the samples on the WLR-200 scales with an accuracy of ±0.00015 g. The volume of samples was calculated based on the results of measuring their diameter and height with an accuracy of ±0.01 mm.

The limit of compressive strength $\sigma_c$ and the relative sediment before the destruction of the specimen $\varepsilon_c$ was determined by compressive testing on a universal tensile machine. In determining these characteristics for samples heated to 200 °C, a special chamber with an annular electric furnace was used, in which the samples were heated.

The structure of the samples was investigated on a metallographic microscope Altami Met. The micro-sections were etched with a saturated solution of ammonia.

Tribotechnical tests of samples of the studied materials were carried out on the upgraded friction machine SMZ-2 under the scheme «pad - roller» with abundant lubrication (engine oil SAE 10W-40), heated to 90 °C. The sliding speed of the roller relative to the pad of the studied materials was 5.2 m/s, and the pressure between them varied from 10 MPa to 100 MPa. The roller material was EN 41Cr4 type steel with the hardness of 52...53 HRC. Contact pressure was increased stepwise by 10 MPa. The duration of the test at each pressure stage was 15 minutes unless there was a sharp increase in the coefficient of friction and scoring.

During the tests in real time recorded the moment of friction, the speed of the roller, the force of its pressing to the pad. With the help of a thermocouple sealed into the pad, the heating temperature of the pad was fixed. Wear of the pad was determined by weight method with an accuracy of 0.00015 g. For the intensity of wear, pads took the ratio of linear wear, recalculated according to the weight of wear, to the distance traveled. Wear of the roller was determined by the method of prints [13]. Prints were applied to the friction surface of the roller by Vickers indenter on the PMT-3 microhardness tester.

For comparison, under the same conditions, tribotechnical tests of similar samples from standard antifriction bronzes EN CuSn8 and EN CuAl10Ni5Fe4 were carried out.

3. Research results and discussion

The results of the measurement of hardness and density of samples of the studied materials are presented in Table 2.
Table 2. Mechanical properties of samples of the studied materials depending on the composition.

| Material symbol | Density, kg/m³ | HB hardness | Compression strength, σвс, MPa | Relative sediment, εz, % |
|-----------------|----------------|-------------|--------------------------------|--------------------------|
|                 | 20 °C | 20 °C | 20 °C | 200 °C | 20 °C | 200 °C |
| 100M            | 8250±20 | 68±5 | 935±45 | 875±45 | 50±4 | 55±4 |
| 85M/15G         | 8120±20 | 120±2 | 1245±45 | 1175±45 | 40±3 | 45±4 |
| 80M/20G         | 8060±20 | 127±3 | 1145±45 | 1090±45 | 34±5 | 40±4 |
| 70M/30G         | 7760±20 | 140±2 | 660±45 | 625±45 | 22±5 | 28±4 |

The density of the studied samples with inclusions of granules is less than the initial density of the samples of tin bronze powder with the symbol 100M, which is due to the significantly lower density of fillers in the form of granules compared to the ductile base of tin bronze, the density of which is 8250 kg/m³.

The hardness of tin bronze powder 100M after heat treatment at 700 °C for 1 h is 68 HB 2.5/187.5/30. The introduction of high-hard granules Cu-5%Al-2%C-2%MoS2 in the composition of the studied composite materials increases their hardness. The highest hardness was observed in the test sample 70M/30G with a granule content of 30 wt %.

As studies of the microstructure of samples with granule inclusions show, the process of forming the structure of the samples under study occurs in several stages. When heated samples obtained by cold pressing of the charge to a temperature of 450...500 °C in these samples as a result of the interaction of tin with copper are formed, in accordance with the state diagram of the system Cu-Sn [9], light inclusions with a bluish tinge, which are eutectoid α + δ [17]. Upon exposure of 1 h at the temperature of 700...750 °C in the microstructure of samples enable eutectoid not observed, which can be explained by dissolution δ-phase with the formation of α-solid solution Cu(Sn). As a result, the microstructure of the studied composite material is formed, consisting of a base in the form of a solid solution of tin in copper and inclusions in the form of granules (Figure 1). The microhardness of the granules in the samples was 3.85...4.15 GPa.

The results of the compression tests (see Table 2) showed that the samples of material with the designation 85M/15G and 80M/20G had the highest compressive strength, both normal and at elevated test temperatures. Therefore, further tribotechnical tests were performed on samples of composite materials 85M/15G and 80M/20G.

Figure 1. Microstructure of antifriction composite material with the symbol 85M/15G. x300.

As shown by tests of composite materials 85M/15G and 80M/20G for friction (Figure 2), the introduction into the sintered tin bronze of dispersed (less than 50 microns) high-hard
granules Cu-5% Al-2% C-2% MoS$_2$ containing in addition to nanoparticles aluminum oxides γ – Al$_2$O$_3$ also particles of graphite and molybdenum disulfide, improves the tribotechnical characteristics in comparison with standard antifriction bronzes and, in particular, with EN CuSn8 and EN CuAl10Ni5Fe4 bronzes.

As shown in Figure 2, the contact pressure limit for tin bronze EN CuSn8 is 80 MPa. If this value is exceeded, the coefficient of friction increases significantly (10 times), which leads to an increase in the intensity of wear, an increase in temperature and eventually to scoring. For aluminum bronze EN CuAl10Ni5Fe4, which in the entire investigated range of contact pressures has higher values of the coefficient of friction compared to bronze EN CuSn8, the maximum pressure is 90 MPa.

The studied composite material 80M/20G has lower values of the friction coefficient at contact pressures from 10 MPa to 40 MPa compared with the composite material 85M/15G, and in the pressure range 40...100 MPa they have approximately the same values of the friction coefficient.

Especially high tribotechnical characteristics of the studied composite materials 85M/15G and 80M/20G in a pair with steel EN 41Cr4 are observed at high contact pressures (60...100 MPa). Compared with standard bronzes, the developed antifriction powder bronzes with inclusions in the form of high-hard granules Cu-5%Al-2%C-2%MoS$_2$ have lower friction coefficient values reaching 0.01 in the area of high contact pressures. There have not been any phenomena of the seizure of the sample (pads) with counterbody (roller).

The wear intensity of the samples of the developed composite materials 85M/15G and 80M/20G at a contact pressure stepwise increasing to 100 MPa is $1.9 \times 10^{-11}$ and $1.85 \times 10^{-11}$, respectively. At the same time, the wear intensity of the steel counterbody EN 41Cr4 hardness 52...53 HRC - almost two orders of magnitude less.

The wear intensity of samples from standard bronzes EN CuSn8 and EN CuAl10Ni5Fe4 under the same test conditions was $4.0 \times 10^{-10}$ and $4.3 \times 10^{-9}$, respectively.
4. Conclusions

New antifriction composite materials of a matrix-filled type based on powder tin bronze have been developed, which contain heat- and wear-resistant fillers in the form of copper-based granules with the initial composition Cu-5%Al-2%C-2%MoS₂, obtained by reactionary mechanical alloying of powdered copper in air of an attritor with aluminum and lubricating additives in the form of graphite and molybdenum disulfide. The addition of such granules to powder bronze with 5% tin allowed obtaining antifriction composite materials, which in terms of mechanical and tribotechnical properties significantly exceed the standard antifriction tin and aluminum bronzes and, in particular, bronze EN CuSn8 and EN CuAl10Ni5Fe4 and can be recommended for the manufacture of sliding bearings operating at pressures of at least 100 MPa and a heating temperature of at least 200°C.

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