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Physico-mechanical properties of modified antifriction coatings based on babbitt B83

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Abstract. The introduction presents the primary reasons for the decrease in the working efficiency of plain bearing assemblies and suggests key areas for the formation of a stable working capacity of these assemblies.
In addition, the introduction discusses preexisting methods for improving the working efficiency of plain bearings. These methods are based on the use of antifriction coatings and have the drawbacks which are considered in the text. The authors proposed a technology for producing an antifriction coating based on a metal composition. This antifriction coating is produces by high-speed laser processing of powder materials. The technology allows to create antifriction coatings, which have significant wear resistance and the effect of self-lubrication while also provide a minimum run-in time of the bearing assembly.
The methodology validates the choice of materials for the formation of an antifriction coating. An alloy with significant tribotechnical properties based on babbitt B83 was chosen as the basis (matrix). To improve the bearing capacity of the coating, the babbitt base was transformed with MoS2 molybdenum disulfide. The laser radiation usage in the formation of an antifriction coating based on babbitt B83 synthesizes finely dispersed intermetallide phases and forms a porous coating structure due to incomplete melting of the powder material. Molybdenum disulfide is released mainly through the porous structure, which leads to self-lubrication of the bearing assembly during oil starvation.
The results of microstructural and X-ray diffraction analysis are presented to display the structure of the obtained coatings based on antifriction materials. Research value is characterized by the presence of the following intermetallide phases in the structure of the formed coating: Fe_2Sn, SnSb, Cu_3Sn. The dispersivity of the formed phases is much greater than that of standard babbitt coatings, which is determined by higher crystallization rates under conditions of laser radiation processing. The analysis of diffractograms makes it possible to conclude that the distribution of intermetallide phases along the coating depth is uneven. The underlying layers close to the basis (matrix) are more soft and supple due to the presence of α - solid solution. The surface layers are solid and saturated with the finely crystalline Cu_3Sn phase. The research undertaken on formed

coating under conditions of dry friction allows to conclude that the antifriction coating can work without supplying lubricant to the bearing assembly.

Key words: laser radiation, babbitt B83, antifriction coating, plain bearing, working efficiency, wear, intermetallide phases, molybdenum disulfide.

INTRODUCTION

Modern agronomic science is continuously related to the development of innovative machines and mechanisms used in the agricultural production. In order to ensure the reliability and working efficiency of machine components and assemblies, it is necessary to increase the wear resistance of contacting surfaces under severe operating conditions, which include frequent oil starvation, high dynamic and kinematic loads.

Plain bearings are an essential part of modern mechanical engineering. They are used not only at the assemblies where high speeds of linear and rotational motion are needed, but also at the ones the transmission of large dynamic and alternating loads is required.

Wear of friction surfaces in a plain bearing significantly increases the gap clearance between the shaft and the inner surface of the sleeve, which in turn leads to a decrease in the bearing capacity of the oil wedge and causes strong shaft vibration relative to the sleeve. These vibrations provoke uneven wear of the shaft surface and the sleeve inner surface (elliptical shape), which as a result negatively affects the condition of the oil wedge and its bearing capacity. Subsequently, this leads to an acceleration of surfaces wear processes, which results in a bearing assembly failure.

Currently, there is a huge variety of manufacturing processes and restoring methods to prevent the occurrence of the above phenomena. Most of these methods are based on modern technologies for sputtering and surfacing of antifriction coatings with attraction of complex powder compositions on friction working surfaces. Presently known application and restoring methods consider only providing the necessary linear dimensions of the friction surfaces and providing the necessary clearance in the bearing assembly. To extend the working efficiency of bearing assemblies, it is necessary to provide not only coatings with antifriction properties, but also an uninterrupted supply of lubricant or self-lubrication of the coating. An important feature of the created coatings is the fast and high-quality running-in ability of friction surfaces.

In this regard, it is necessary to solve a whole range of problems in the restoration of plain bearing assemblies:

1. Selection and research of efficient materials for shafts; development of technology for creating coatings on the journals of the shafts from the analyzed materials with using the most effective methods (according to the criteria of manufacturability and economy).
2. Development of a balanced composition of materials and optimal technology for their use in the restoration of plain bearings sleeves (providing the best tribological performance).
3. Ensuring high efficiency of plain bearings assemblies due to the quality of the surfaces running-in ability and their increased wear resistance.

The approach to ensuring surface quality should also be changed. The roughness of the restored or created surfaces should correspond to the roughness of the joints that have worked for a long time, and not be limited to the correspondence of the roughness to the allowable accuracy of the part manufacture. When restoring surfaces, it is necessary to make allowance the possibility of ensuring the optimum coating thickness on the surfaces of the joint parts, taking into account the compatibility of the coating materials in accordance with the requirement of tribology.

It should be noted that modern antifriction coatings should have good bearing capacity by virtue of the base material's high strength, a minimum running-in time (due to the protective, supple layer), and also have a greater shear strength due to high adhesive strength (Fig. 1). Usually the transition layer is a nickel or titanium sublayer, which provides high adhesive strength of the main bearing coating with the substrate. This transition layer is also a barrier to prevent the main layer components diffusion deep into the product. Running-in coating is applied by chemical deposition or galvanic synthesis from pure tin.

Creating an antifriction coating with these characteristics is fraught with great difficulties. They arise mainly

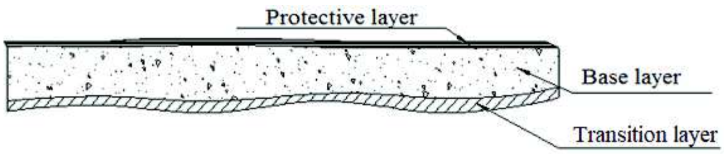

Figure 1. The structure of the modern antifriction coatings.

when it is needed to provide an ultra-small coating thickness (up to 1 mm), the compatibility of the used materials and the complexity of the coating formation technology itself.

This problem is solved by using composite materials made of metals and polymers. The development of this method is carried out in both domestic and foreign mechanical engineering. Bearings made of antifriction materials are based on metals or alloys containing polymer components (Panova, 2014). Lead, stannum, iron, copper and alloys of these metals are used. Polymers (mainly phenoplasts and fluoropolymers) act as alloying components; there are also used some thermosetting resins, which are mostly applied by two methods: impregnation method or rubbing method, both of which are low-tech and ineffective. Tribological properties of these coatings are different, which allows their use in a wide range. A signature feature of the used materials is a rather low coefficient of friction, a minimum running-in time and high anticorrosion properties that determine small amounts of wear. It should not be forgotten that the polymer component has low heat resistance, which leads to the friction coefficient instability, as well as to a decrease in the strength of the base material, which is a serious drawback. To stabilize the temperature within the established limits in the friction zone, it is required to provide an intensive supply of coolant, which in most assemblies is structurally difficult to implement.

It is a difficult task to increase shear strength and in most cases this problem is solved by creating a special layer made of a nickel or copper base, which greatly increases the technology complexity and the cost of manufacturing a plain bearing (Tarelnik et al., 2010).

To simplify the technology of creating coatings based on antifriction materials, you need to strive for the idea of using simple standard and cheap materials with minimal exposure to an energy source, which implies the formation of an antifriction layer in one pass, with ensuring the required coating thickness, properties and roughness (Ločs & Boiko, 2018; Ipatov et al., 2019a; Ipatov et al., 2019b). The use of such technology for coating significantly reduced the cost of plain bearings and as a result improved their quality.

The creation of these coatings is possible while providing 'strict' processing modes. The traditionally used methods of applying many antifriction coatings are based on powder metallurgy technologies (sintering) or casting methods (babbitt coatings). The above methods for creating antifriction coatings have significant drawbacks based on inadequate control of processing parameters and the inability to control them during application, which leads to uncontrolled phase transformations with the formation of unintended phases. These drawbacks result in the limited properties of the created coatings, as well as to a decrease in mechanical properties.

Therefore, in this work, we propose to use laser radiation as an energy source for obtaining antifriction coatings. Local laser action allows supplying energy to the fusion zone in a graduated way, which make it possible to control the processes of structure formation. High crystallization and recrystallization rates allow to obtain a wide range of intermetallide phases different from the traditional ones (Ipatov et al., 2019a; Ipatov et al., 2019b).

A signature feature of creating a coating technology is not only structural and phase transformations with the formation of intermetallide phases, but also the dendritic structure formation. The dendritic structure is determined by the feature of crystallization and directed growth of dendrites mainly from the substrate surface to the antifriction coating outer surface. Existing methods for applying babbitt coatings provide the chaotic formation of dendrites. The resulting structure is not homogeneous, but heterogeneous with dendritic segregations. To reduce the structure inhomogeneity effect, subsequent heating or pressure shaping of the created coating is used (Potekhin et al., 2006; Potekhin et al., 2010). Other significant drawbacks of babbitt coatings (B83) are intermetallide compounds of the Sn-Sb system - β-phases and acicular particles of the γ-phase (Cu_3Sn) (Table 1).

Table 1. Characteristics of babbit B83 intermetallide compounds

Intermetallide compound	HB phases hardness, kgf mm^{-2}
β-phase (SnSb)	54
γ-phase (Cu_3Sn)	383

The presence of these phases significantly reduces the wear resistance and fatigue strength of babbitt coatings. The striving to quantitatively reduce these phases will obviously lead to an increase in the friction coefficient and a decrease in the hardness and bearing capacity of the coating. The negative influence of these phases is caused by their uneven distribution in the applied coating volume and low dispersion of crystals, which results in the development of microcracks and the formation of dislocations along the boundaries. Some works cite the fact that a decrease in the dimension of these phases (Barykin et al., 2006; Barykin et al., 2000) with a more uniform distribution in the coating volume allows to increase the mechanical properties ofbabbitt coatings. Moreover, all operations to improve the structure and properties are performed on standard finished babbitt coatings, which increases the final cost of production and does not fully provide the intended effect.

At high friction speeds the friction coefficient instability is demonstrated for babbitt coatings. To solve this problem lubricant is intensively supplied to the bearing assembly, but in many of them there is usually no possibility to provide the supply of lubricant due to certain design features. Therefore, self-lubrication is the most relevant issue. Self-lubrication of the antifriction coating is formed in the presence of a lubricant in the porous coating structure (the lubricant fills the pores). The porous coatings creation is impossible when babbitting, therefore, methods for sintering powder materials in the liquid phase are necessary.

To increase the technological effectiveness of creating an antifriction babbitt coating and to lower the product cost while maintaining the necessary tribotechnical and strength properties, we propose the coating formation based on B83 babbitt modified with MoS2 molybdenum disulfide by using laser processing of powder material. This results in the formation of a structure with a finely crystalline intermetallide phase, which is uniformly distributed throughout the entire coating volume; this is facilitated by high crystallization rates, as well as the diffusion kinetics.

The formation of dendritic structures is uniform and contributes to the production of highly dispersed structures, usually formed from the substrate surface to the coating upper layers. However, it should be noted that the coating structure is porous, which is provided by incomplete fusion of powder particles. The molybdenum disulfide powder (modifier) is added into the powder composition. And it is mainly released through the porous structure of the formed coating during its processing.

Methodology for creating coatings

This paper presents a technique for producing modern antifriction coatings by using highly concentrated laser radiation. We use babbitt B83 as an antifriction coating matrix because it has low and stable friction coefficient and relatively high bearing capacity. To maintain the stability of the tribotechnical parameters at high speeds (more than 50 m s^{-1}) and high running-in ability of the coating, as well as to increase the bearing capacity, it is proposed to use the antifriction material molybdenum disulfide MoS2.

Laser processing was carried out in a special chamber made of organic glass in laboratory conditions (in accordance with the technology presented in the paper (Ipatov et al., 2015) (Fig. 2).

Figure 2. Application of an antifriction coating in a shielded chamber.

The pulsed laser radiation was generated by a fiber-optic laser machine LRS AUTOMATIC manufactured by OKB ‘Bulat’. To protect the coating from oxidation, fusion was carried out in a medium of chemically pure argon. The processing modes were specially selected to ensure the fact that the structure remelting occurred over the entire thickness of the antifriction coating. Scanning speed v_{sc} (mm s^{-1}), pulse energy ε (W), and pulse frequency λ (kHz) were taken as main processing parameters. The processing conditions values were adopted on the basis of exploratory researches (presented in the paper (Ipatov et al., 2019)) and had the following indicators: v_{sc} - 25 mm s^{-1}, ε - 60W, λ -50 Hz.

X-ray diffraction studies were conducted on the DRON-6 automated diffractometer to determine the coating phase composition. The survey was performed by using the constant time method in monochromatic Co-Kα radiation with a wavelength of λ = 1.7902 Å, with the angle step of 0.05° and an exposure time of 5 s at each point. To research the structural and phase composition of the resulting coating as well as to determine the porosity and dimensionality of the structural components metallographic studies were conducted by using a Neophot-32 microscope. Micrographs in the cross section of coating were prepared in order to conduct a metallographic analysis. The micrographs were preliminarily pickled in the conditions of nitric acid. The dimensionality of the structural components was determined by the micrometer scale installed in the microscope eyepiece. Wear tests were carried out under dry and liquid friction conditions on an SMT-2070 friction machine. The following values were taken as the modes of tribo-loading: the friction speed was 2 m / s; the loading mode was varied in the range from 5 to 20 mPa. The cycle time under one load was 5 minutes.

RESULTS AND DISCUSSION

In the process of producing antifriction coatings, priority was assigned to the appearance of the resulting coating; also such parameters as the absence of delamination from the substrate, the presence of incomplete fusions and flaws, as well as the uniformity of the applied coating over the thickness were controlled (Fig. 3). The resulting coatings have a uniform structure. There are no visible defects. The uniform coating thickness is on average 0.45–0.5 mm.

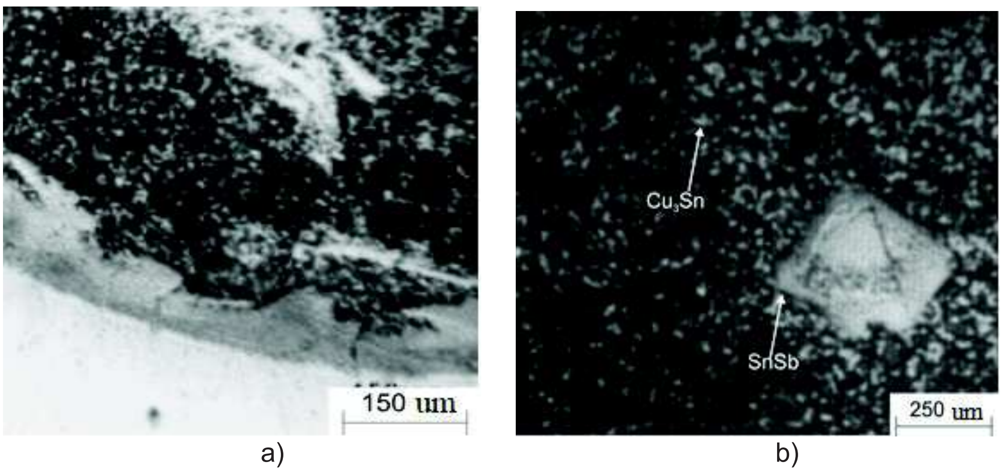

Figure 3. The microstructure of the cross section of the analyzed coating.

The coating top layer is dark in color, with the presence of subtle pores filled with molybdenum disulfide. The surface is oily and layered to the touch.

The main tasks of the analysis were to determine the phase composition and phase dispersion, as well as to reveal the adhesion pattern of the coating to the substrate. The microstructures research showed the presence of a coating soft matrix (α is a solid solution), solid inclusions consisting of Sn-Sb intermetallide compounds of β-phase and acicular inclusions of γ-phase - Cu_3Sn.

As expected, the size of the obtained phases is smaller than that of the babbitt coatings obtained by the traditional method, which is explained by high crystallization rates, especially in the γ phase. Micrometric analysis showed a decrease in the size of intermetallide compounds by 65%. The dimensionality of the obtained phases was determined by using a micrometer scale applied on the microscope eyepiece.

Adhesion zone with the substrate is characterized by a lighter shade, which indicates the presence of additional phases. The fusion zone has no pores or incomplete fusions, which proves that the optimal processing conditions were selected and the necessary joint strength was attained. In this work there were no researches devoted to the adhesion strength determination, but it is worth mentioning that the impact force did not lead to the coating delamination from the substrate.

X-ray diffraction researches were carried out to determine the phase distribution uniformity in the coating volume (Fig. 4). To provide a more detailed analysis of the phase distribution in the cross section, the coating was divided into three layers by diamond grinding method at every 20 μm interval: 1st layer characterizes the adhesion zone of the coating with the substrate, 2nd layer characterizes the phase state of the coating at a distance of 20 μm from the adhesion zone, 3^{d} layer characterizes the surface condition.

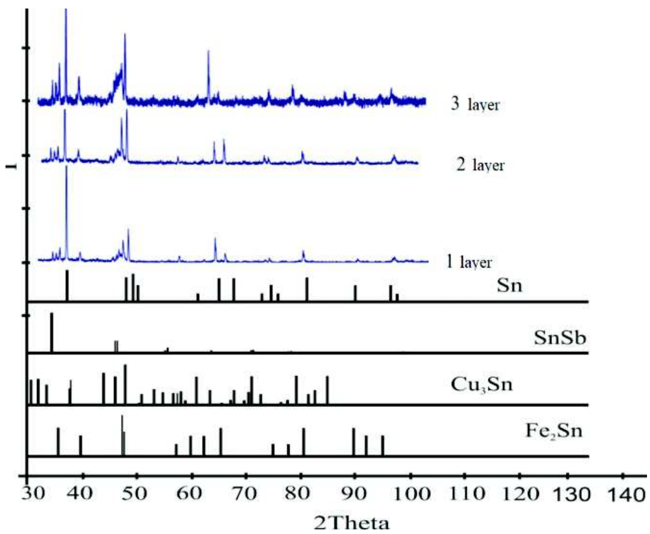

Figure 4. Diffractograms of the coatings with increasing thickness of the applied babbitt coating.

According to the results of the experiment, the formation of the 'standard' intermetallide compounds mentioned above and Fe_2Sn compounds was revealed. The producing of this compound mainly occurs in the underlying layers close to the substrate, which characterizes the processes of mixing the metals volumes of the substrate and the applied composite during laser processing. The presence of this phase in the microstructural analysis is no indicated, which characterizes its fine-crystalline structure. Intermetallides have a relatively high strength, which in return provides high adhesion strength of the created coating to the substrate. In order to determine the thickness of the phases quantitative composition, an X-ray diffraction analysis was carried out, in which the conditionally formed coating was divided into three layers. The main data of quantitative analysis are presented in Table 2. The table shows the intermetallide compounds formed under equilibrium crystallization conditions.

Table 2. Phase and quantitative composition of the coating

Phase	The amount of phase in layer 1, %	The amount of phase in layer 2, %	The amount of phase in layer 3, %
Sn	6.29	19.74	0.25
SnSb	44.48	6.04	14.14
Cu_3Sn	43.91	68.24	84.94
Fe_2Sn	5.32	5.98	0.67

The quantitative phase composition of the formed coating (Table 2) shows that when the thickness of the applied layer is increasing, the amount of the Sn phase tends to zero, and the amount of the Cu_3Sn intermetallide phase significantly increases, which is attributed to the increase in laser processing time. The decrease in the amount of the Fe_2Sn phase close to the surface layer is associated with an increase in the coating thickness and the absence of iron in the upper layers. Thus, the features of phase transformations during laser processing have resulted in a quantitative change in the phase composition over the thickness. Based on the data in Table 1, it can be concluded that the coating has optimal mechanical properties: in particular, the underlying layers are softer and more flexible due to the presence of the α – solid solution and β – phase (SnSb), and the upper layers are harder due to the increase in the amount of γ – phase (Cu_3Sn), which has a higher solidness. Under operating conditions high surface hardness resists intense wear, and a soft, flexible base resists dynamic, alternate loads, increasing the fatigue and cyclic strengths of the coating. Thus, the presented results fully meet the requirements of modern antifriction coatings.

The main tribotechnical indicators of coatings were presented in the work (Ipatov et al., 2015), which examined the effect which the structure of the created coating has on its wear under dry friction conditions (Fig. 5).

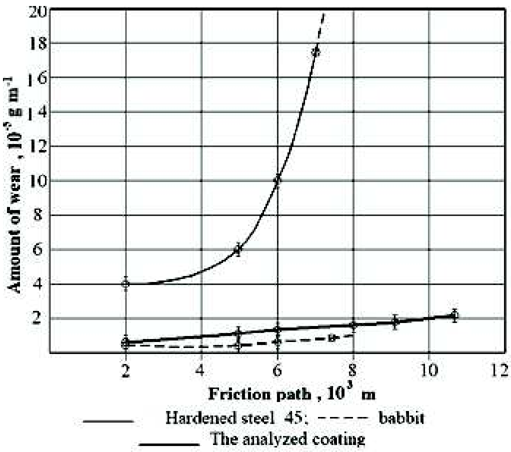

Figure 5. Dry friction wear characteristics (Ipatov et al., 2015).

During wear tests the operation of plain bearing was simulated under dry friction conditions as the most aggressive operating conditions possible. The following parameters were accepted as the research modes: friction speed of 2 m s^{-1}, specific load of 20 mPa in dry lubrication conditions (the modes were determined on the basis of averaged empirical parameters of internal combustion engines operation under medium load). To compare the amount of wear, we considered the wear of standard materials in the following joints: 'hardened steel - hardened steel 45', 'hardened steel - babbitt B83 coating obtained by casting method', 'hardened steel - analyzed coating'. Test modes for all coatings were the same. All surfaces were running-in under conditions of hydrodynamic friction, after which the surfaces of the samples were wiped dry.

The research showed the smallest wear for a standard babbitt coating. The porosity lack of the molded babbitt coating gives it a high cohesive strength, which recfects in a decrease in the surface damage probability. The high density of the coating material gives good thermal conductivity, which reduces the setting process of micro unevenness of friction surfaces. This affects the coating wear rate reduction. However, the work duration of the babbitt coating in conditions of dry friction is limited and the setting process of friction surfaces occurs when the path length is 7,500 m. Setting moment for hardened steel 45 occurs even earlier, but significant wear is observed over the entire range of the friction path. During the research, the process of setting surfaces has never been seen in the coating forming, which shows the effective coating ability of self-lubrication. The formed surface has porosity filled with molybdenum disulfide, which results in friction surfaces separation and ensuring uninterrupted operation of the assembly under dry friction conditions.

Therefore, the presented results of comparative wear tests clearly illustrate the following idea: in the conditions of emergency wear (lack of intensive lubrication) the analyzed coating has a higher resistance to wear and to seizing of friction surfaces.

CONCLUSIONS

The developed technology for producing antifriction coatings is feasible. The structure formation of the created coatings differs from the standard ones and is characterized by the presence of finely dispersed intermetallide phases. The research devoted to the distribution of these phases over the thickness indicates the optimality of the mechanical properties the coating has, which confirmed the expected results.

The results of wear tests make it possible to conclude that the proposed antifriction coating is functional even in dry friction conditions, which corresponds to the research objectives.

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