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Relationship between the Tribological Properties of Experimental Aluminum Alloys and Their Chemical Composition

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Abstract—New complex alloying has been designed for aluminum antifriction alloys. Their tribological behavior has been determined, including the running-in ability, scoring resistance, and wear resistance. The interconnection of the tribological properties of experimental alloys with a doping level by different elements has been analyzed. Recommendations on the optimum content of alloying elements for the antifrictionality of the aluminum based alloys have been given.

Keywords: antifriction aluminum alloy, running-in ability, scoring resistance, wear resistance, secondary structures, soft structural component

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INTRODUCTION

Today, special bronze has mainly been used to manufacture monometallic solid cast friction bearings [1, 2]. However, it is expedient to change bronze for aluminum antifriction alloys [1–3]. This change is cost effective because, with the same volume, the part will have 2–2.5 times less weight and mass unit of the aluminum alloy will be two to three times cheaper compared to the bronze mass unit. Taking into account the considerable number of friction bearings made of aluminum alloys scores during the run-in of the engine, alloys should possess sufficient running-in ability and high scoring resistance; this was shown in works [4, 5]. Furthermore, the self-wear resistance and capacity for the minimal wear of the steel counterbody are the efficiency criteria for all antifriction materials. A comparison of the antifriction characteristics of aluminum alloys and bronze, which contain 4% stannum, 4% zinc, and 17% plumbum has been carried out under equal conditions.

Data concerning the mechanical and tribotechnical properties of harder and more tenacious alloys of Al–Sn–Pb–Cu–Si and Al–Sn–Pb–Cu–Si–Bi systems, which are meant for bearings that operate under the conditions of dry friction or in the case of accidental lubricant ingression into the friction zone, are given in works [6, 7]. In recent years, the foreign literature [8–11] has shown increased interest in aluminum friction alloys in combination with the increased alloying level of matrix, solid inclusions, and soft structure inclusions of the structural component. This allows these material to be applied for bearings, which require a combination of high strength with a definite antifriction level.

The aim of the work is to determine the influence of different alloying elements on mechanical and tribotechnical properties of the experimental polyalloyed alloys of the Al–Sn–Pb–Cu–Si–Zn–Mg–Ti system meant for a monometallic friction bearing that operates with lubricant.

MATERIALS AND METHODS

In this work, the chemical composition of experimental alloys is determined by the spectral method on the Spektrolab-S device (Germany). Tribotechnical tests were carried out with an SMZ-2 serial friction machine according to the roller–shoe scheme (rotating steel roller–immobile shoe made of antifriction alloys in friction mode with lubricant).

Rollers were manufactured from normalized steel 45, were 40 mm in diameter, and had widths of 10 mm. The working surface of the rollers was polished. Shoes were manufactured from experimental polyalloyed alloys and had the working surface of 10 mm width and curvature radius of 20 mm. They were used for the scoring resistance and wear-resistance tests and, for the running-in ability, the radius was 22.5 mm.

The rotational frequency of the rollers was 500 rev/min. Oil of $M14B_2$ grade was put on the working surface of rollers by the dropping method at a rate of 2 drops/min (0.002 L/h).

Loading of the initial grip and score based on the value of the dramatic increase in the friction moment and temperature jump of the friction roller surface was

Table 1. Chemical composition of alloys applied for friction tests

Alloy no.	Content of the elements, wt %										
	Sn	Pb	Cu	Si	Zn	Fe	Ti	Ni	Mn	Mg	Al
1	8.65	3.23	3.41	0.53	2.87	0.08	0.03	0.01	0.01	0.38	Remainder
2	10.97	2.59	3.86	0.06	2.63	0.07	0.01	0.01	–	–	Remainder
3	9.82	2.52	4.47	0.64	2.41	0.13	0.03	0.05	0.03	1.23	Remainder
4	9.59	3.15	4.85	0.06	4.39	0.09	0.02	–	0.03	0.31	Remainder

Table 2. Average values of score, contact area for running-in ability, and wearing intensity of experimental alloys

Alloy no.	Score average loading, N	Average contact area, mm^2	Wear intensity, mg/h	
			experimental alloys	steel counterbody
1	2407	50.0	0.060	0.060
2	1650	49.8	0.030	0.015
3	2832	57.8	0.0175	0.0175
4	2107	42.8	0.0525	0.0375

registered during tests for scoring resistance. Friction moments and temperature of the friction surface at each loading step were registered during tests for the running-in ability; the contour area of the friction spot was also measured. The wear resistance was determined by the weight change in the roller and shoe before and after 40 h of testing at a constant load.

RESULTS AND DISCUSSION

Table 1 shows the chemical compositions of four experimental aluminum alloys with the determined tribotechnical characteristics.

Table 2 shows the tests results of four experimental alloys for scoring resistance; the average loading for each alloy by 3 samples with grips and scores was determined.

With regard to the value of the average score loading, all four experimental aluminum antifriction alloys are considerably superior to the reference bronze of the BrO4Z4S17 grade, which had the same value under identical conditions at a level of 1081H [6].

During the determination of the dependence of the scoring resistance of alloys on the content of alloying elements, three groups of elements may be specified as follows:

—the tendency of the scoring resistance to increase at an increased content of these elements in alloys is observed for most of the alloying elements, i.e., plumbum, silicon, magnesium (Table 3), ferrum, and titanium;

—influence on scoring resistance is not observed for copper within 3.40–4.85%;

Table 3. Score loadings, wear intensity of alloys, and steel counterbody on alloying elements content

Element	Mg			
Element content, wt %	0	0.31	0.38	1.23
Score loading, N	1650	2832	2407	2832
Alloy wear intensity, mg/h	0.03	0.0525	0.06	0.0175
Element	**Sn**			
Element content, wt %	8.65	9.59	9.82	10.97
Wear intensity of the steel counterbody, mg/h	0.06	0.0375	0.0175	0.015
Element	**Cu**			
Element content, wt %	3.41	3.86	4.47	4.85
Alloy wear intensity, mg/h	0.06	0.03	0.0175	0.0525
Wear intensity of the steel counterbody, mg/h	0.06	0.015	0.0175	0.0375

—linear tendency for three out of four alloys concerning the decrease in the score resistance with the increased content of these elements in the experimental alloys is observed during alloying by zinc and stannum.

The obtained data contradicts the general notion about score resistance increase with the increase in the stannum content. Big influence is exerted by plumbum and zinc contained in the low-melting soft structural component. The positive influence on score resistance of the elements forming fine solid inclusions in the alloy structure capable of cutting seizure bridges has been proved. Silicon, ferrum, and titanium are among these elements.

It has been considered that more solid alloys have a better resistance to scores; this is why magnesium, which considerably increases the hardness of alloys and exerts a positive influence on the score resistance. Copper, which has a lower increase in hardness, did not show an evident influence on the score resistance.

The average contact area of the contact after friction tests with the loading progressive steps of 304—1058 N, which operate for 10 min at each step was taken as a criterion for the run-in. Test results are given in the Table 2 [5].

As concerns average contact area after the run-in test all four experimental aluminum antifriction alloys are considerably superior the reference bronze of the BrO4Z4S17 grade which had this value at the level of 39.2 mm^2 under identical conditions. Furthermore, the difference in values of four experimental alloys was 35%. The considerable influence of their concentration on the alloy run-in has not been found for most of the alloying elements.

One may talk about the tendency of the run-in to increase with an increase in the alloying elements content with regard to silicon and to a smaller degree with regard to ferrum.

Alloy run-in decreases with an increase in the zinc and plumbum content. It is considered that running-in improves with an increase in the soft structural content [1, 3]. However, for these experimental alloys, the amount of stannum does not exert a considerable influence, and the increase in the amount of plumbum and zinc even deteriorates the running-in of alloys. This is probably connected with the fact that plumbum and zinc make the soft structural component stronger and more solid.

The wear intensity of the antifriction material and wear intensity of the steel counterbody that operates in a pair under constant load for 40 h (Table 2) were determined among the wear characteristics of the experimental alloys. As for the weight wear, all four experimental aluminum alloys are considerably superior to the reference bronze of the BrO4Z4S17 grade, which, under identical test conditions, had the value at the level of 0.0675 mg/h. However, taking into account the difference in specific weights of bronze and aluminum alloys, alloy no. 3 only has less linear wear and the wear of alloy no. 2 equals the bronze wear.

It is considered that alloys with increased hardness have a lower level of wear. However, the dependence of the wear intensity of the alloy on the stannum content demolishes this view. Stannum decreases the alloy hardness, but for three out of four alloys, there is a tendency of the wear to decrease with an increase in the stannum content. On the other hand, the same tendency is found for ferrum; however, unlike stannum, it increases the hardness of the alloys. The reverse tendency, i.e., an increase in the alloy wear with an increase in the content of the alloying element is observed for plumbum and titanium. That is why it is required to limit this additive content.

For the remaining alloying elements, this dependence is of a complex character. In the interval of 3.4—4.5%, copper decreases the alloy wear (Table 3); however, after 4.5%, steep jump wear is observed. This may be explained by the structural changes in the Al—Cu system taking place at the copper content exceeding 4.5%. Therefore, it may be recommended to restrict the copper content in the aluminum antifriction alloys at the level of 4.0—4.5%.

Two zones are indicative for dependence on zinc. With an increase in the zinc content from 2.5 to 3.0%, there is a steep increase in the wear intensity of the alloys; then, the wear intensity decreases (from 3.0 to 4.5% Zn). Most likely, it is connected with the influence of zinc on the properties of the soft structural components, where zinc with plumbum hardens stannum and makes this phase considerably harder.

The influence of magnesium (Table 3) and silicon on the wear resistance of alloys is given by the curve with the expressed maximum. The alloy with 1.2% Mg and 0.64% Si has the minimum wear.

Wear of the steel shaft is the main criterion for the antifriction alloy adequacy to be used as material for friction bearings. The less is the steel wear the higher is the service life of the shaft— the most expensive part of the engine. It is easier and cheaper to change a bearing than a steel shaft. That is why the decreased shaft wear is more important for antifriction alloys, even by decreasing the wear resistance.

It is considered that the main criterion for steel counterbody wear is the number and hardness of the soft structural component. This thesis is proved by the dependence of the steel wear intensity on the stannum content (Table 3); the tendency of the wear to decrease with the increase in the stannum content is clearly seen. Plumbum, which increases the hardness of the soft structural component, increases the steel wear.

No univocal tendency of the influence on the steel wear for zinc, silicon, titanium, and ferrum was found. Copper in different concentrations influences the steel wear in different ways (Table 3). The steep decrease in steel wear intensity takes place within the interval of 3.4—3.9%. Steel wear remains at a stable minimum level in the interval of 3.9–4.5% Cu. Growth in the steel wear takes place with an increase in the copper content up to 4.9%. Therefore, the introduction of copper into aluminum antifriction alloys in the amount of 4.0–4.5% may be recommended.

The influence on the magnesium of the wear resistance of steel is not explicit. Minimal wear is found with alloy no. 2; magnesium is not contained in its composition. An increase in its content to 0.3–0.4% increases the steel wear; however, an increase to 1.2% leads to a decrease in the wear intensity of steel. Because magnesium exerts a positive influence on score resistance and the alloy with 1.23% Mg has the maximal wear resistance, alloying aluminum antifriction alloys at a level that does not exceed 1.0% Mg can be recommended.

It is necessary to mention that the influence of each alloying element is considered to be a whole system. That means that the influence of any element on the tribotechnical properties is more complex compared to double alloys with aluminum down to the opposite effect.

CONCLUSIONS

The studies have shown the possibility of influencing the tribotechnical properties of aluminum antifriction alloys by varying the content and concentrations of different alloying elements. Tendencies of the influence on alloy properties of eight alloying elements have been revealed.

Stannum within concentrations ranges of 8.5–11 wt % decreases the score resistance and increases the wear resistance of the material and decreases the wear intensity of the steel counterbody. No influence of stannum on the run-in ability has been found. Taking into account the high cost and deficiency of stannum and the determination of optimal content for this element should be taken from the operational conditions of every individual part.

Plumbum within concentration ranges of 2.5–3.2 wt % increases the score resistance, but decreases the run-in ability and wear resistance of aluminum antifriction alloys. The increase in the plumbum content by more than 2.5% leads to an increase in the steel counterbody wear. That is why, for parts with the increased requirements to score resistance, it is necessary to increase the plumbum content by more than 2.5% and, for parts taken out of service because of wear, it is recommended not to exceed the limit of 2.5% Pb.

Zinc was introduced into the composition of the studied allows in amounts of 2.41–3.39%. In this range, zinc decreases the score resistance, running-in ability, and wear resistance of both alloys and the steel counterbody. Zinc exerts a more favorable influence zinc on mechanical properties. That is why it may be recommended not to wave zinc alloying of aluminum antifriction alloys, but rather to limit its concentration to 2.5%.

Copper in the range of 3.4–4.85% did not show an influence on score resistance and running-in ability. Furthermore, it considerably decreases the wear intensity of the material and steel counter body with an increase in concentration from 3.4 to 4.5% Cu. The following increase in the copper content is not expedient due to the increase in the wear of both components of the friction pair.

Silicon increases the score resistance and running-in ability of aluminum antifriction alloys. Influence of silicon on wear resistance of steel counterbody is not found. Wear of the antifriction material increases with the increase in the silicon content up to 0.5% and decreases with the increase in the silicon content to 0.8%.

Magnesium increases the score resistance of alloys and hardly influences the running-in ability. It was found that alloy with 1.23% Mg possesses a higher wear resistance and the counterbody experiences less wears than alloys with 0.3–0.4% Mg. That is why alloys with 1.0–1.5% magnesium may be recommended.

Ferrum is considered to be additive in aluminum antifriction alloys. However the tendency score resistance, running-in ability, and wear resistance of alloys to increase with an increase in the ferrum content to 0.13% has been found. The influence of ferrum on the steel counterbody wear has not been found. That is why the ferrum content in alloys with concentrations of up to 0.13% may be considered not only allowable, but desirable.

Titanium is modifier of the II-d type for aluminum alloys and exerts a determining influence on the grain size and the formation of hot cracks during the crystallization of alloys. The tendency of an increase in the score resistance with a decrease in the wear resistance of alloys and the steel counterbody. It was found that titanium did not influence the running-in ability. The amount of titanium in the alloy is not determined by tribotechnical properties, but rather by its modifying ability.

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