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Structure and Properties of Antifriction Pseudo-Alloys of the Powder Steel–Copper Alloy, Infiltrated with Materials of Various Compositions

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Abstract—The structure and properties of powder steel–copper alloy antifriction pseudo-alloys infiltrated with materials of various compositions are studied, it is shown that mechanical and tribological properties are determined both by the composition and structure of the steel skeleton and, to a large extent, by the composition and structure of the infiltrate. It has been established that the limiting content of lead in the infiltrate, which ensures the absence of lead deposits on the sample surface and a large (10–15%) residual porosity, should not exceed 3%. The use of a mixture of copper powders and alloying additives for infiltration is more technologically advanced than atomized bronze powders. It is shown that the wear resistance of pseudo-alloys with a chromium steel skeleton depends to a lesser extent on the composition of the infiltrate, since the main contribution to wear resistance is made by a hard steel skeleton. The introduction of 3–5% ultrafine aluminum oxide powders into the infiltrate leads to an increase in the seizure pressure by 1.2 MPa and wear resistance by 20–30% due to the refinement of the copper alloy structure and the deceleration of dislocations that arise during deformation due to friction. It is shown that during the wear of pseudo-alloys in the surface layer the structure is refined, martensite is formed in the skeleton, and, accordingly, the microhardness increases by 720–760 MPa.

Keywords: pseudo-alloy, steel skeleton, density, infiltrate, copper alloy, structure, mechanical properties, wear resistance

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INTRODUCTION

Pseudo-alloys combine structural components with sharply different physical and mechanical characteristics, due to which they have important properties—self-lubrication under dry friction conditions, high tribological properties, resistance to intense heat flow, damping capacity under vibration loading, electrical erosion resistance and wear resistance when working in as electrical contacts.

Pseudo-alloys of the system tungsten–cobalt, tungsten–nickel, tungsten–copper, iron–copper and others are obtained by the infiltration method [1].

Iron-copper pseudo-alloys are the most common and are used for the manufacture of structural and tribological parts. The iron phase provides strength and hardness, while the copper phase provides plasticity and thermal conductivity of composites. They consist of inexpensive and non-deficient components produced in large quantities [1, 2].

The properties of iron–copper pseudo-alloys obtained by pressing and sintering are determined by the phase composition and structure morphology that are formed during sintering and depend on technological factors (purity of initial powders and sintering temperature, time, atmosphere), as well as chemical composition, diffusion processes, phase transformations in raw materials. Porous iron–copper pseudo-alloys have good tribological properties, but their high residual porosity (15–20%), low strength, and thermal conductivity makes it difficult their use in heavily loaded friction units [2]. For these conditions, materials must have not only good tribological properties, but also, depending on the operating conditions, sufficiently high strength, thermal conductivity, oxidation resistance at elevated temperatures, and stability of mechanical properties at operating temperatures, that is, materials must be with minimal porosity [3].

A promising process for producing iron–copper pseudo-alloys with low porosity is the infiltration of a pressed or pressed and sintered iron based skeleton with copper or copper alloys [4]. The porosity of pseudo-alloys after infiltration is less than 7%; therefore, they have increased strength, hardness, and corrosion resistance [5].

Table 1. Composition of atomized bronze powders

Material	Composition, %									
	Cu	P	Sn	Pb	Cr	Ni	Mn	Mg	Fe	O_2
CuFe4Mg	Base	–	–	–	–	–	–	0.2–0.5	3.5–4.0	0.9
CuFe4Mn4	Base	–	–	–	–	–	4–4.5	–	3.8–4.2	1.1
CuFe4Cr1	Base	–	–	–	0.5–1	–	–	–	3.5–4.0	0.5
CuFe2Pb60Ni8	Base	–	–	58–60	–	7–8	–	–	1.3–1.8	1.4
CuSn5P	Base	0.25	5–5.5							

The contact angle of wetting iron with copper at a temperature of 1100°C is close to zero, which ensures spontaneous infiltration of the iron skeleton with copper melt due to capillary forces [6, 7]. When iron is infiltrated with pure copper, as a result of active diffusion interaction, the iron skeleton is dissolved in the copper melt and diffusion porosity is formed [8]. To eliminate this disadvantage, the iron skeleton and copper infiltrate are used as filled with each other, and special additives are introduced into the infiltrate [9, 10].

The advantages of infiltration in the production of iron-copper pseudo-alloys are a higher and uniform density, improved mechanical properties, the possibility of varying properties by changing the composition of the iron skeleton and infiltrate, eliminating porosity in the surface of products for coating without changes in the state of the internal part of a product, connection of separately pressed different sections in the finished product [11].

To improve the properties of iron–copper pseudo-alloys, alloying of the iron skeleton and copper infiltrate is used as components. A mixture of powders of iron and graphite, manganese, chromium, nickel, vanadium, cobalt, etc. is used as a porous skeleton, and copper alloys with tin, zinc, manganese, lead, aluminum, etc. are used as an infiltrate. Thus, for the manufacture of sliding seals a pseudo-alloy was developed with a skeleton made of a ternary eutectic alloy based on iron with 4–6% phosphorus and 1.5% carbon, infiltrated with copper alloys with 10–50% tin or zinc and 25% manganese [12], for rocket nozzles—as an infiltrate an alloy of copper with zirconium or silver is used [13–15], for valve plates – lead or a copper alloy. The composition of the infiltrate affects the temperature and atmosphere of the infiltration. When infiltrating with copper and copper alloys, the process is carried out in a protective or protective-reducing atmosphere at temperatures of 1100–1250°C, with brass—in a filling of ground refractory clay or in graphite form at a temperature of 1000°C, with lead—in vacuum at a temperature of 400–600°C followed by pressure.

The purpose of the work is to study the influence of the composition of the infiltrate on the structure and properties of powder steel–copper alloy pseudo-alloys.

MATERIALS AND RESEARCH METHODS

Powder steels FeGr0.4, FeGr0.8Ni4, FeGr0.8Cr3 with a relative density of 75 and 85% were used as a steel skeleton. Infiltration was carried out with copper and copper with additives: 5 or 10% tin; 5% tin and 3% lead; 10% lead; 5% tin and 0.5% ultrafine oxide powder. The compositions were obtained by mixing powders of copper grade PMS-1, tin grade PO-1, lead grade PS-1 in the initial state, 3–10% ultrafine aluminum oxide powder with an average particle size of less than 1 μm obtained by grinding corundum powder.

Mixing of the powders was carried out in a mixer of the "drunken barrel" type for 2 h in the presence of balls made of bearing steel with a diameter of 15 mm at a mixture : balls ratio of 1 : 1.

To increase the strength and tribological properties, since the alloying of copper enhances its properties [16], manganese, magnesium, lead, chromium, and phosphorus bronze were used in the form of powders sprayed with air into water at the URG-10 sprayer. When spraying bronze powders, copper of the M1K grade, lead casting of the S2 grade, nickel cathodes of the H2 grade, metallic manganese of the MP0 grade, magnesium metal of the Mg95 grade, and chromium of the X98.5 grade (Cl) were used. Melting was carried out in an induction furnace. The composition of the alloys is given in Table 1.

Prismatic frame specimens 10 mm wide, 12 or 6 mm high, and 55 mm long were pressed from the iron charge in a press-form. Samples of the mass required for infiltration were pressed from the infiltrate using the same press-form.

Infiltration by the contact method was carried out in a protective-reducing atmosphere of endogas at a temperature of 1140°C.

From infiltrated prismatic specimens 12 mm high, cylindrical specimens 10 mm in diameter and 12 mm high were obtained by machining to determine the tribological properties and specimens according to ISO 6892-84 for tensile testing, while specimens 6 mm high were used for three-point bending tests.

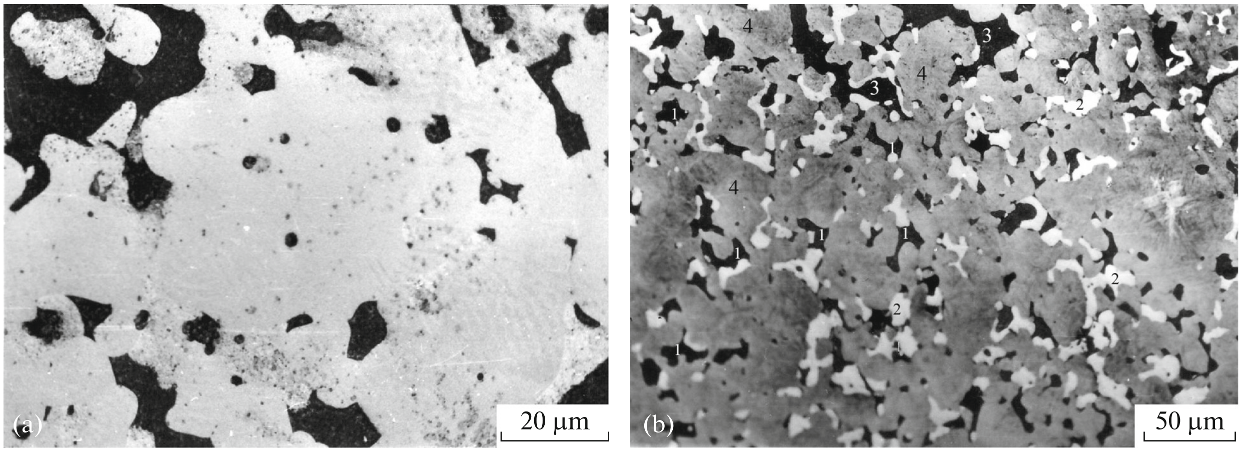

Fig. 1. Structure of a pseudo-alloy with a skeleton made of FeGr0.4 steel infiltrated with atomized powder bronze CuFe2Pb60Ni8: (a) not etched; (b) etched; (1) lead inclusions; (2) solid solution of iron and nickel in copper; (3) pores; (4) areas of the steel skeleton.

Tensile and bending tests were performed on a universal testing machine “Tinius Olsen H150K-U” (England) at a loading speed of 2 mm/min, for Brinell hardness—on a device for measuring hardness according to ISO 410-82, ISO 6506-81 at a load of 7355 N and a ball diameter 5 mm, for friction—on the MT-2 machine according to the “finger-disk” scheme at a sliding speed of 4 m/s. Industrial oil I-20 was used as a lubricant at a flow rate of 6–8 drops/min. The tests were carried out until the moment of seizure. Wear intensity was determined after testing at a load of 3.25 MPa for 1 hour. Wear was determined on an optimeter with an accuracy of 0.001 mm. The fingers were made from the materials under study, and the disks were made from 41Cr4 steel, hardened to a hardness of 55–60 HRC.

The structure was studied using a MEF-3 metallographic microscope (Austria) and a Mira scanning electron microscope (Tescan, Czech Republic) with an INCA 350 X-ray microanalyzer (Oxford Instruments, England). Thin sections were etched with a 4% solution of picric acid in ethanol.

RESEARCH RESULTS AND DISCUSSION

During infiltration with sprayed bronze powders containing 58–60% lead, up to 2% iron and up to 8% nickel (CuFe2Pb60Ni8), due to the almost complete absence of lead solubility in copper and poor wettability of the iron, lead was observed on the surface of the sample, and there was also a residue of non-infiltrated alloy. As a result, the pseudo-alloy had an increased residual porosity, up to 10–15%. The structure of the pseudo-alloy consists of areas of the steels skeleton, an infiltrate in which there are inclusions of free lead, a solid solution of iron and nickel in copper, and pores (Fig. 1). Increased porosity leads to a decrease in the tensile strength of the pseudo-alloy to 270–290 MPa and hardness to 138–148 HB.

Studies of the tribological properties of pseudo-alloys with a skeleton made of nickel and chromium steels, infiltrated with sprayed powders of various bronzes, showed (Table 2) that the maximum wear resistance of the pseudo-alloy is observed when infiltrated with chromium bronze due to its greater hardness.

Table 2. Wear resistance (length of the wear pit, mm) of pseudo-alloys with a skeleton with a relative density of 75 and 85%, infiltrated with atomized powder bronzes and microhardness of the infiltrate

Composition of infiltrate	Skeleton composition, %						Microhardness of infiltrate, MPa
	FeGr0.8Ni4		FeGr0.8Cr3		FeGr0.4		
	75	85	75	85	75	85	
CuFe4Cr1	2.8	4.3	4.0	5.2	–	–	1240
CuFe4Mn4	3.6	5.5	4.0	4.8	–	–	1210
CurFe4Mg	3.5	5.3	3.3	5.1	–	–	1100
CuSn5P	–	–	–	–	6.2	6.5	1050
Copper	3.8	5.7	4.2	5.5	6.9	7.4	990

Table 3. Mechanical properties of pseudo-alloys with a skeleton made of nickel and chromium steels with a relative density (θ) of 75 and 85%, infiltrated with atomized powder bronzes

Skeleton material	Infiltrate	Tensile strength, MPa		Bending strength, MPa		Impact strength, кJ/m^2	
		θ = 75%	θ = 85%	θ = 75%	θ = 85%	θ = 75%	θ = 85%
FeGr0.8Ni4	CuFe4Cr1	680	760	1370	1410	135	127
	CuFe4Mg	610	700	1160	1270	138	130
	CuFe4Mn4	720	780	1320	1380	135	134
	Copper	650	730	1210	1320	147	138
FeGr0.8Cr3	CuFe4Cr1	480	570	890	930	135	128
	CuFe4Mg	380	520	700	790	128	119
	CuFe4Mn4	430	560	750	830	132	124
	Copper	420	550	810	920	134	127
FeGr0.4	CuSn5P	380–410	–	Hardness, HB 170–200	–	–	–
	Copper	320–340	–	138–140	–	–	–

The wear resistance of pseudo-alloys with a chromium steel skeleton depends to a lesser extent on the composition of the bronze used for infiltration, since the main contribution to wear resistance is made by a hard steel skeleton containing wear-resistant inclusions of chromium carbide and chromium-alloyed iron carbide, as well as chromium-alloyed ferrite and perlite.

A pseudo-alloy with a mild carbon steel skeleton infiltrated with copper has minimal wear resistance.

The mechanical properties of pseudo-alloys infiltrated with sprayed bronze powders are also higher than those infiltrated with copper: tensile strength by 50–290 MPa, bending strength by 20–30 MPa, impact strength by 5–8 kJ/m^2 (Table 3), and as well as wear resistance, the highest properties are provided by infiltration with chromium bronze. Thus, a pseudo-alloy with a nickel steel skeleton infiltrated with chromium bronze has a tensile strength of 680–760 MPa, a relative elongation of 4–5%, a relative narrowing of 5–6%, magnesium bronze – of 610–700 MPa and 1–2%, of manganese bronze – 720–780 MPa and 1–3%, respectively.

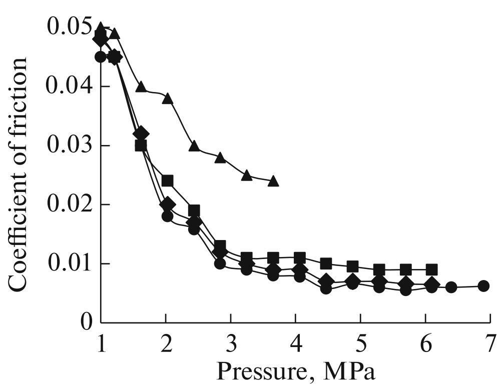

Fig. 2. Dependence of the coefficient of friction (*k*) of a pseudo-alloy with a skeleton with a relative density of 85% made of steel FeGr0.8 on the pressure (*P*) and composition of the infiltrate: (◆) Cu with 5% Sn and 3% Pb; (■) Cu with 5% Sn; (●) Cu with 10% Sn; (▲) Cu.

The low properties of pseudo-alloys obtained by infiltration with magnesium bronze are explained by the presence of oxides in them, which are formed due to the increased tendency of magnesium to oxidize, as well as by increased porosity due to the high viscosity of bronze at the experimental temperature, and by incomplete infiltration of the steel skeleton.

It should be noted that sprayed bronze powders are not technologically advanced, as they have poor compressibility due to the spherical shape, therefore it is advisable to apply the infiltrate mixed from components. It is not possible to obtain magnesium, chromium and manganese bronze with a homogeneous structure by mixing, since these elements cannot be introduced in elemental form due to their high affinity for oxygen, and the introduction of chromium and manganese in the form of ferroalloys leads to an increased content of iron. In this regard, it is advisable to carry out infiltration with materials obtained by mixing copper powders with tin and lead.

During infiltration with a mixture of copper powders with 10% lead, lead on the sample surface and increased residual porosity of the pseudo-alloy were observed. Reducing the lead content to 3% made it possible to avoid the presence of lead on the surface of the infiltrated sample, so the maximum content of lead in the infiltrate should not exceed 3%.

The coefficient of friction of a pseudo-alloy infiltrated with a mixture of copper with 5% tin and copper with 5% tin and 3% lead is almost three times less, and the seizure pressure is two times higher than that infiltrated with copper (Fig. 2).

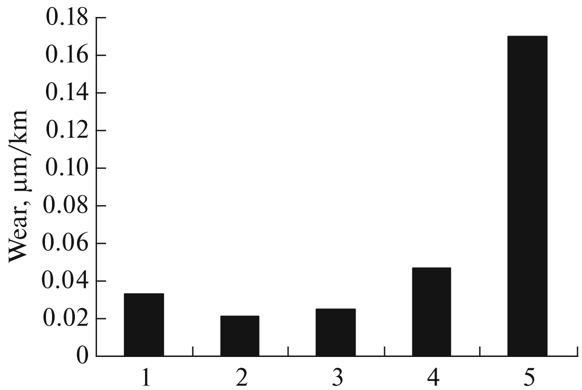

Fig. 3. Wear of a pseudo-alloy with a skeleton with a relative density of 85% made of steel FeGr0.8, infiltrated with various compounds: (1) Cu with 5% Sn; (2) Cu with 5% Sn and 3% Pb; (3) Cu with 10% Sn; (4) Cu; (5) CuAl9Fe4.

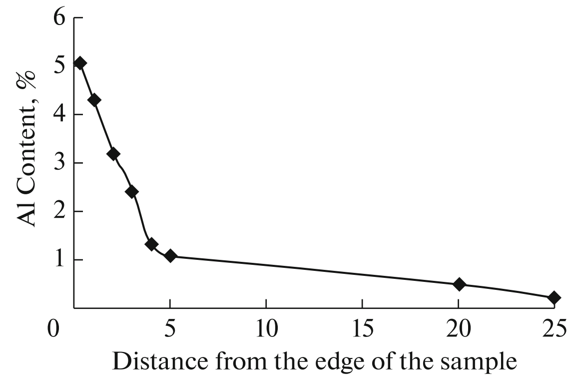

Fig. 4. Distribution of aluminum in the copper phase of a pseudo-alloy obtained by infiltration of Cu with 5% Sn and 5% Al_2O_3 at different distances from the surface.

An increase in the tin content in the mixture up to 10% has practically no effect on the level of the friction coefficient of the pseudo-alloy, the seizure pressure increases by only 1 MPa.

Infiltration with alloys of copper with 5% tin, copper with 5% tin and 3% lead, copper with 10% tin provides an increase in the wear resistance of the pseudo-alloy by 1.8–2 times compared with infiltration with copper and by almost 6 times compared with the wear resistance of compact bronze CuAl9Fe4 (Fig. 3).

Since an increase in the tin content in the infiltrate from 5 to 10% has practically no effect on the tribological properties of the pseudo-alloy, and tin is an expensive element, it is not advisable to increase its content in the infiltrate above 5%.

The higher tribological properties of pseudo-alloys obtained by infiltration with a mixture of copper powders with tin and lead compared to copper infiltration are explained by the greater hardness and strength of the bronze infiltrate, and, accordingly, the lower degree of its deformation during friction.

Unlike cast materials, in which wear resistance is determined mainly by the hardness of the material [17–20], in pseudo-alloys it is determined not only by the hardness of the constituent phases and thermal conductivity, but also by the wear mechanism. In the process of wear of pseudo-alloys obtained by infiltration, studies have shown that the copper phase is smeared on the steel, protecting it from wear, and due to the high thermal conductivity in the friction zone, the temperature is lower, respectively, the deformation of the material is less [21]. In addition, the study of the structure of the surface layer of samples from pseudo-alloys before and after wear showed that during wear, the structure becomes smaller, martensite is formed in the skeleton, and, accordingly, microhardness is increased. Thus, the microhardness of the surface of specimens made of a pseudo-alloy with a FeGr0.8 steel skeleton infiltrated with Cu with 5% tin increased from 1820–1920 to 2540–2680 MPa.

The infiltration process makes it possible to further increase the wear resistance of pseudo-alloys and to slow down the processes of plastic deformation in the soft copper phase due to the introduction of ultrafine oxide powders into the infiltrate.

Using X-ray microanalysis, it was found that, under the action of capillary pressure, during infiltration, ultrafine particles of aluminum oxide rise with a copper alloy and penetrate into the pores of the steel skeleton to a height of 7–20 mm, but individual inclusions are also identified at a height of up to 25 mm (Fig. 4).

The introduction of ultrafine aluminum oxide particles into the infiltrate led to a slight (by 0.02) increase in the friction coefficient, but an increase in the seizure pressure by 1.2 MPa (Fig. 5) and wear resistance by 20–30%.

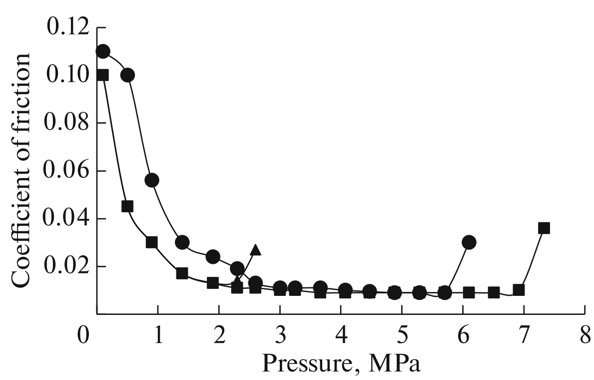

Fig. 5. Influence of pressure and aluminum oxide content in the Cu infiltrate with 5% Sn on the coefficient of friction of the pseudo-alloy with a skeleton with a relative density of 75% made of FeGr0.8 steel: (●) without additive; (■) 5% aluminum oxide; (▲) 10% aluminum oxide.

Aluminum oxide particles lead to a refinement of the structure of the copper alloy, as well as to the deceleration of dislocations that have arisen due to friction deformation. An increase in the content of aluminum oxide in the infiltrate above 3–5% causes a sharp decrease in the properties of the pseudo-alloy, since due to a significant increase in the viscosity of the infiltrate, its rise in pores decreases, so the residual porosity in the pseudo-alloy is 9–12%.

CONCLUSIONS

The mechanical and tribological properties of iron-copper alloy pseudo-alloys obtained by infiltration are determined both by the composition and structure of the steel skeleton and, to a large extent, by the composition and structure of the infiltrate. It has been established that infiltration both with sprayed powders and with a mixture of copper and lead powders with a content of more than 3% leads to the formation of lead on the surface of the sample and a large (10–15%) residual porosity, which causes a decrease in properties.

When infiltrating skeleton made of nickel and chromium steels with sprayed bronze powders, the maximum wear resistance and mechanical properties are achieved using chromium bronze powders, and the minimum is achieved with copper infiltration. The wear resistance of pseudo-alloys with a chromium steel skeleton depends to a lesser extent on the composition of the infiltrate, since the main contribution to wear resistance is made by a solid steel skeleton.

When infiltrating with a mixture of copper with 5% tin and copper with 5% tin and 3% lead, the friction coefficient of the pseudo-alloy is almost three times lower, and the seizure pressure is two times higher than with copper infiltration and almost 6 times compared to wear resistance compact bronze CuAl9Fe4. In the process of wear of pseudo-alloys in the surface layer, the structure is refined, martensite is formed in the skeleton, and the microhardness increases by 720–760 MPa.

The introduction of ultrafine aluminum oxide powders into the infiltrate leads to an increase in seizure pressure by 1.2 MPa, wear resistance by 20–30% due to the refinement of the structure of the copper alloy and the deceleration of dislocations that occur during friction deformation. An increase in the content of aluminum oxide in the infiltrate by more than 3–5% causes a sharp decrease in properties due to an increase in the viscosity of the infiltrate, respectively, a decrease in the height of its rise in the pores, so the residual porosity in the pseudo-alloy is 9–12%.

CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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