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RESEARCH

Depth Dependence of Friction in Self-Lubricating Cu-Based Materials for Highly Demanding Applications

Petya Tabakova[a], Anna Petrova[a,*], Hristo Kolev[b], Feyzim Hodjaoglu[c], Reni Andreeva[c], Ivan Zahariev[c], Georgi Avdeev[c], Snezhana Atanasova[a], Korneli Grigorov[a]

[a]*Space Research and Technology Institute, Bulgarian Academy of Sciences „Acad. G. Bonchev" Str., Bldg. 1, 1113 Sofia, Bulgaria,*
[b]*Institute of Catalysis, Bulgarian Academy of Sciences, „Acad. G. Bonchev" Str., Bldg. 11, 1113 Sofia, Bulgaria,*
[c]*Institute of Physical Chemistry „Rostislaw Kaischew", Bulgarian Academy of Sciences, „Acad. G. Bonchev" Str., Bldg. 11, 1113 Sofia, Bulgaria.*

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* Corresponding author:

Anna P. Petrova
E-mail: ani@phys.bas.bg

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ABSTRACT

The selection of materials with high mechanical and tribological properties defines current trends in modern materials science. In this paper we investigate the use of alloying elements, such as phosphorus (P), manganese (Mn), tin (Sn), antimony (Sb) and lead (Pb), in order to improve tribological characteristics in Cu-based self-lubricating materials. Using structural (XRD, OM) and chemical (EDX, XRF, XPS) analyses we observed distinctive elemental segregation and diffusion towards the surface under mechanical pressure, driven by elevated temperatures. Additionally, we perform GDOES in order to prove the dynamics of element migration towards the surface under working conditions. The latter is very important, because new phases, such as $Pb_{0.8}Sb_{0.2}$, $SnPb_2O_4$, Pb_2O, Cu_3P, *etc. are formed and located near the surface, which improves the tribology in situ. The role of these phases is diverse and differentiated, such as directly lowering the friction coefficient (FC) and as a consequence lowering the temperature, which under operating conditions is over 700 °C. Alloying elements also lead to improved hardness. It was found that the friction coefficient in vacuum dropped as much as 40 times and the wear at load 40 N dropped 4 times in compared the pure copper sample.*

1. INTRODUCTION

Friction and wear of machine parts are major problems in industry. Dry friction is a phenomenon that occurs in contacts where there is no lubricant between the surfaces of the contacting bodies. It also occurs in the aerospace and aviation equipment, in the food, textile and chemical industries, where lubricants are mostly unsuitable for safety and security reasons.

The copper alloys, used as sliding pairs under considerable loads in frictional units of machines and mechanisms - bearings, inserts, bushings and hinges, have poor tribological properties which lead to high wear and consequently to high expenses [1]. That's why these materials are the subject of research to reduce their friction and temperature during operation. By adding alloying elements in amounts less than 15 weight %, the properties of the base material are changed [2].

The composite materials are prepared by casting. At a melting temperature of 1150 °C, the additives are introduced into the Cu-matrix [3] and then cooled to room temperature.

It has been found that at high temperature, in the Cu-Pb-xSn alloy, the lead forms netty-shape from second phase particles on the surface [4]. The described phenomenon is lubrication – it reduces friction by inserting a layer that minimizes wear and lowers temperatures. This process is fundamental to maintaining opperating life of machinery. The structure and properties of composite copper material are discussed in **[5].** The distribution of the alloying elements within the copper matrix is crucial for optimal performance [6].

Introducing a small quantity of Ce into the Cu-matrix increases the wear resistance of the material by 1.5 to 2.0 times and reduces FC by 1.3 to 1.4 times when operating in extreme conditions, such as high pressure, vacuum environment etc. [1,3].

It has been established that materials with additives of Mn, P and Pb, at loads above 10 MPa, are subject to intensive wear, leading to destruction and loss of their working capacity [7]. Phosphorus forms a Cu_3P-solid phase [8]. This phase plays a role as a network [9], which is located along the grain boundaries and increases the wear resistance of the material. Pb plays the role of a natural solid lubricant [10].

Ce together with Pb forms a solid compounds CePb and Ce_2Pb. In this way they increase the mechanical characteristics of the self-lubricating material.

The results of friction and wear tests show FC as low as 0.11 and wear of 30 μg/m, which is explained by the strengthening of the composite due to the presence of the hard-melting compounds CePb and Ce_2Pb, which are located inside the grains of the volume. The positive influence of Ce is maintained up to 1.5 wt. %. Increasing its concentration above this level causes an increase in the FC [3,11].

2. METHODOLOGY

2.1 Materials

We studied a copper alloy with additives (Figure 1). It contains P, Mn, Pb, Sb and Sn. The investigated composite alloy was been produced by copper casting at 1150 °C in atmospheric conditions.

Fig. 1. Sample of copper alloy**.**

The additives were mixed until homogenisation was achieved. Copper and its alloys form a supporting part (matrix). Lead is present in the form of conglomerates, which practically do not interact with copper.

2.2 Methods

The chemical composition, phase identification and quantification were analysed using X-Ray Fluorescent Analyses (XRF). The XRF equipment includes a Zetium spectrometer with a mapping module, manufactured by Malvern-PANalytical.

The crystalline structure was revealed by XRD in θ-2θ configuration with step size [°2θ] = 0.02 and scan step = 1 [s] with a Philips PW1050 diffractometer from 10 to 90° using a Cu-cathode λ = 1.54060 [Å].

X-ray photoelectron spectroscopy (XPS) of samples 1 and 2 were conducted using an ESCALAB MkII electron spectrometer equipped with a twin-anode MgKα/AlKα non-monochromatic X-ray source. The instrumental resolution was approximately 1eV. The obtained data were analysed using SpecsLab2 CasaXPS software (Casa Software Ltd). Spectral processing included subtraction of X-ray satellites and Shirley-type background correction [12]. Peak positions and areas were evaluated using symmetrical Gaussian-Lorentzian curve fitting. The relative concentrations of different chemical species were determined by normalizing peak areas to their photoionization cross-sections, calculated by Scofield [13].

GDOES is an analytical technique that provides both the surface/depth profile and the bulk elemental composition of materials and layers.

The hardness and coefficient of friction of the samples were measured using a Tribometer UMT-2 by Bruker Inc. (Billerica, MA, USA), with an AISI 52100 steel ball (radius of 5 mm) serving as a counter body. The tests were conducted on a dry surface and comprised two stages. The first stage involved a reciprocating linear movement with a stroke length of 4 mm and a linearly controlled load ramp from 0 to 10 N, applied over a duration of 1 h. The second stage was performed under a constant load of 10 N for 4 h. Thus, FC represents the ratio of the tangential force to the normal force, as measured by the equipment.

3. EXPERIMENTAL

The main technological principle in the creation of self-lubricating materials is the achievement of optimal parameters: low friction and high load capacity while reducing the formation of abrasive centres at the contact during operation. Thus, addition of lead is essential for enhancing the antifriction performance under heavy loads [10]. The lead and its oxide phases usually form conglomerates and do not interacts with the copper matrix.

In our research, we have mainly studied the changes on the surface of the alloy (Figure 2).

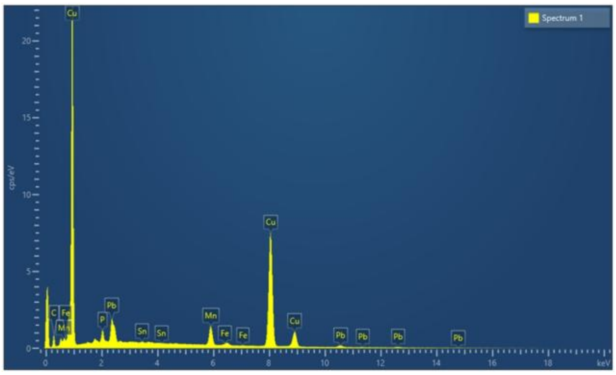


Fig. 2. EDX spectrums alloyed sample.

The elemental composition of the sample taken from the tribometer trace was determined by Energy-Dispersive X-ray spectroscopy (EDX) and is presented on Table 1.

To improve the properties of the matrix and to protect the friction surface from scratching, scoring and abrasion, the elements like P, Mn, Sn and Sb were used. In these materials, a eutectic is formed, consisting of an α-solid solution of Mn, Sn or P in copper (Figure 3).

Table 1. Chemical composition of sample in 2 points.

Element	Spectrum 1 [wt.%]	Spectrum 2 [wt.%]
P	1.74	1.91
Mn	5.94	6.06
Fe	0.22	0.29
Cu	81.59	84.23
Sn	0.47	0.49
Pb	10.04	7.00
Total	100.00	100.00

The molten eutectic is arranged along the grain boundaries of the solid solution in the form of a fragmented network. The solid phase Cu_3P limits plastic deformation in the surface layer and protects the surface from the formation of scratches and welding centres at the contact interface.

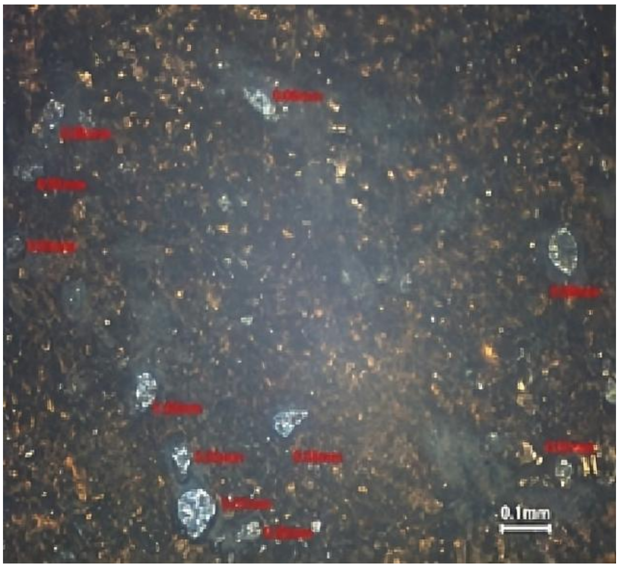


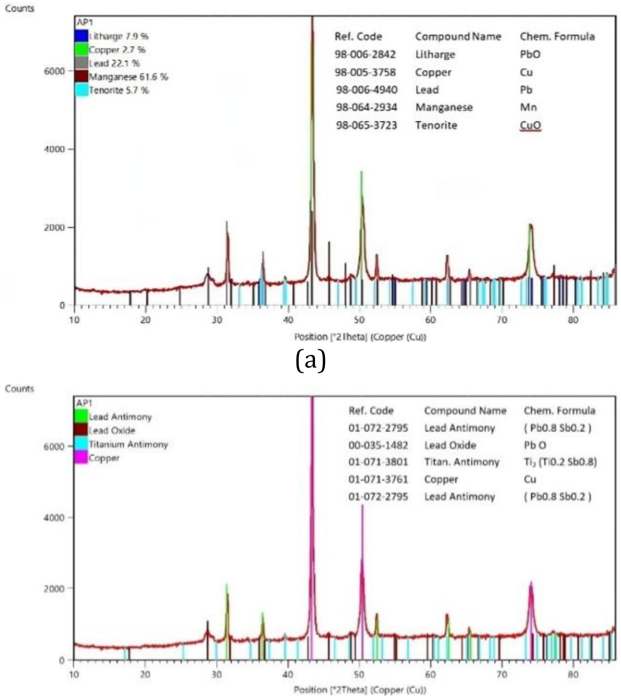
Fig. 3. Metallographic image of the alloy microstructure.

The microstructure is made up of solid solutions of tin and partially of phosphorus in copper. The remaining part of phosphorus forms a copper phosphide phase, which, in the form of a discontinuous network, is located around the grains of the solid solutions. The presence of this network increases the wear resistance of the material. Alloying with tin improves the mechanical and antifriction properties. The copper phosphide phase strengthens and reduces plastic deformation of the composite under dry friction conditions in vacuum [6,8]. The constituent components have differentiated functions.

Antimony is used to improve alloy properties such as hardness and strength, on the one hand and to enhance thermal and electrical dissipation, on the other.

4. RESULTS

The XRD spectra of the alloyed sample show well-pronounced crystalline phases of Cu-matrix, as well as those of the additives. As we observed five different phases, for clarity, we have divided them in two graphics (Figure 4a, b). The relative phase and elemental compositions displayed in Figure 4a is as follow: 12% metallic Pb, 13% Pb_2O, 5% Mn, 5% SnO_2 and 65% Cu.



(a)

(b)

Fig. 4. XRD spectrums of alloyed sample, including all observed phases.

The formation of the solid phase Pb0.8Sb0.2 (Figure 4b) strengthens the structure and increases the microhardness.

The samples were analysed also by X-ray fluoresce (XRF) to determine the elemental composition and the results are shown in Table 2 and Figure 5. Processes of migration, diffusion and segregations were observed.

Table 2. Surface chemical composition of the alloyed sample.

Chemical composition	[wt. %]
Cu	81.81
Pb	12.81
Mn	5.00
Fe	0.43
Sb	0.50

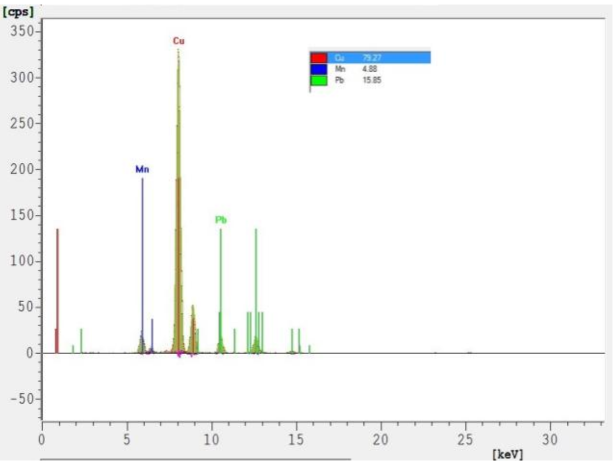


Fig. 5. XRF spectrum of alloyed sample.

The diffusion rate is proportional to the contact area, the type of chemical elements, the temperature, thermal and electrical conductivity of the materials. The number of atoms, which diffuse to the surface, is proportional to the square root of time. Under structural rearrangement in the diffusion layers and during the saturation process, a zone with reduced porosity is formed on the surface of the samples.

The formation of Pb-based new phases is a result of processes which took place in the matrix under increasing temperature. Atoms and molecules are redirected towards the surface, freeing up space for those beneath to participate in the migration. Those above atoms and molecules have already free space for movement, and the larger this area is, the greater the opportunity for the particles to move and, consequently, the faster they orient themselves upwards.

This process is related to the material's density- it is denser in the lower regions, while towards the surface the density decreases, although we demonstrate through XRD that the phases are crystalline. The decrease in the density of the examined samples leads to an increase in the diffusion rate during the formation of the lubricating layer. In this layer, the Pb content increases, leading to the formation of an amorphous coating as a result of the slipping of several tribological layers. There is also another fact -the diffusion velocity of small molecules and atoms is higher than that of larger particles.

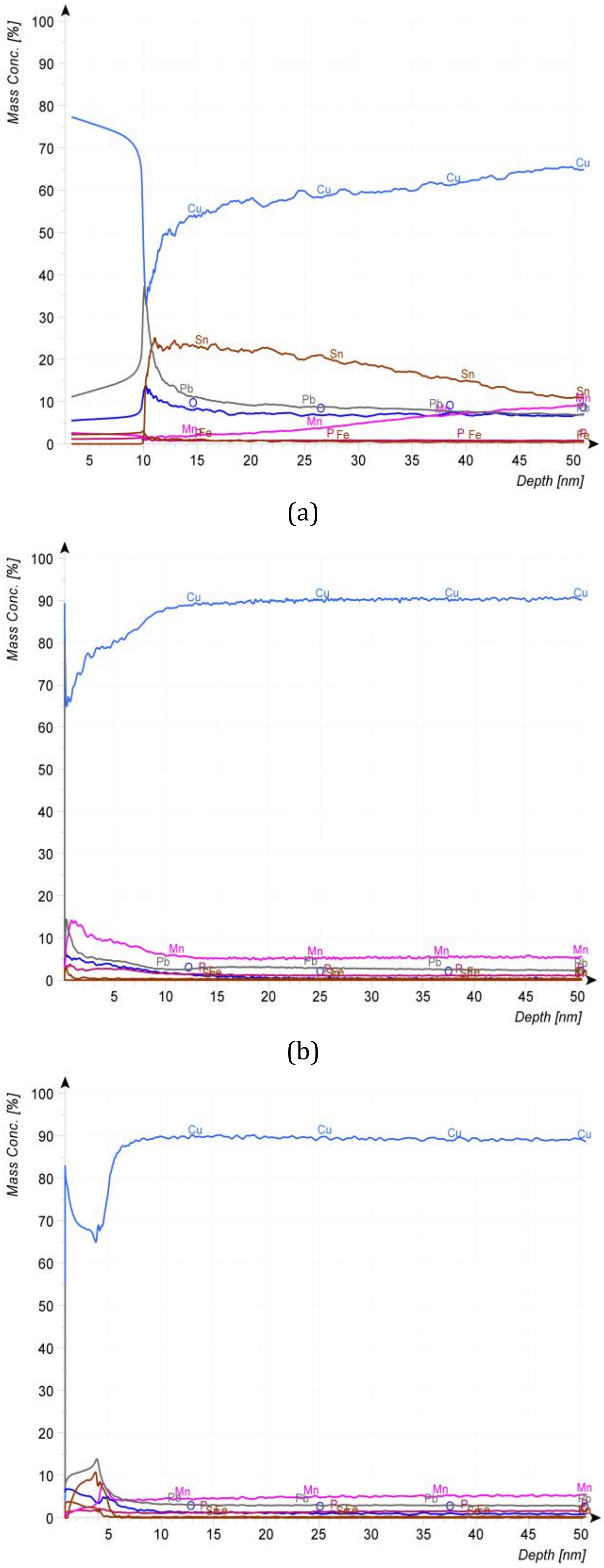
Further, Glow-Discharge-Optical-Spectroscopy (GDOES) was used to follow up the constituent dynamics to and from the surface the surface at work conditions. The latter is important as far as new elements and oxides are formed which significantly improve the tribology properties in situ.

A correlation between the accumulations of lead on the surface of the studied sample in the friction layer is observed, Figure 6a. At higher roughness, copper peaks are first visible, after which the Cu concentration drops sharply, and the amount of lead and tin increases. The change in lead concentration passes through a maximum at about 10 nm and then normalizes to typical values for the studied alloy.

After treatment with sandpaper of 3-5 μm grain size, the peaks of Pb and Sn are shifted are found to be closer to the surface by 0.5-2 nm (Figure 6a). The highest concentration of Pb and Sn are located near the surface and then gradually decrease (Figure 6b and 6c).

From the obtained results, it can be concluded that the smoother the surfaces of the rubbing samples, the better the lead performs its function as a lubricant.

The oxidation state and the surface atomic concentrations of the elements in the sample were investigated by X-ray Photoelectron Spectroscopy (XPS). Two points of each sample were examined - pristine surface and the scratched one. The scratching process was carried out in vacuum with SiC (P2000) sandpaper to remove the very top layer without breaking chemical bonds.



(a)

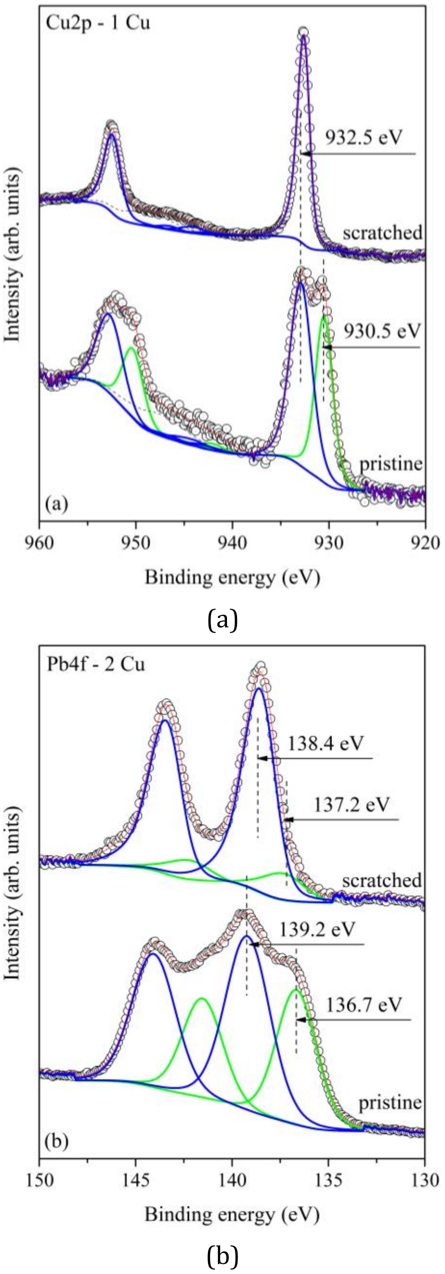
(b)

(c)

Fig. 6. Depth elemental composition in measured on samples with different roughness using GDOES: (a) The roughness were obtained after grinding with P150 (grain-sized 80-100 um); (b) R2500 (grain-sized 3-5 um); (c) Pristine sample.

Sample 1 (pure Cu)

The pristine surface shown in Figure 7, (lower spectrum) indicates an enrichment of Cu^{2+} ions, as evidenced by a peak at 933.2 eV, accompanied by a pronounced shake-up satellite in the 937-948 eV range. This signature is comparable to that observed by Yoshida (1979) in XPS studies of 2-mercaptobenzothiazole metal complexes [14]. The presence of nitrogen and sulphur traces suggests that the Cu^{2+} species may be part of a complex.



(a)

(b)

Fig. 7. High-resolution XP spectra of: (a) Cu2p and (b) Pb4f core levels of pristine and scratched surfaces of 1 sample. Open circles are used for experimental data, red line is the envelope of curve fitting procedure, coloured thick lines representing the different constituents of the peaks (oxidation states).

The blue-marked peak at 932.2 eV, with a low-intensity satellite in the 940-950 eV range, is indicative of Cu^{1+} oxidation state [15].

Following the same scratching procedure as used for sample 1, the Cu2p spectrum of scratched sample 1 exhibits a significant shift. The main Cu2p peak is now at 932.8 eV, with a low-intensity satellite in the 940-950 eV range, confirming the presence of Cu^{1+} ions (39.49 at. %). The shift of 0.7 eV suggests the removal of Cu_2O species formed due to oxidation upon air exposure. The uncovered surface consists of a C-H-N-O complex bound to the copper substrate, consistent with previous findings [16].

Sample 2 (Cu-alloy with additives)

Figure 7 represents the core-level spectra of the pristine surface compared to the scratched surface of sample 2. The pristine sample exhibits multiple doublet peaks in the core-level spectra of Cu2p (Figure 7a) and Pb4f (Figure 7b), indicating different oxidation states (blue and green curves).

A detailed examination suggests the presence of at least one top layer that has a different charge than the bulk sample, and this could be associated with the presence Pb_2O at the surface. Based on the binding energy and peak shapes, copper in the pristine sample is predominantly in the Cu^{1+} (1.60 at. % in one of the layers and 2.15 at. % for the other layer) oxidation state (Figure 7a). This assignment is further supported by the presence of a low-intensity shake-up satellite in the 938-948 eV energy range.

The lead component appears to be a mixture of Pb^0, Pb^{2+}, and Pb^{4+} oxidation states, although their precise proportions cannot be determined.

An estimation based on a curve-fitting procedure reveals lead contents of 4.90 at. % and 7.10 at. % in the two non-contacting layers, respectively.

Upon mechanical removal of the top layer, the Cu2p and Pb4f spectra undergo significant changes (Figure 7b, scratched spectrum). The Cu2p peak is now observed at 932.5 eV, with a low-intensity satellite structure in the 940-950 eV range, characteristic of the Cu^{1+} (6.80 at. %) state [14].

The Pb4f spectrum changes significantly, enabling a more precise determination of lead oxidation states. The curve-fitting analysis reveals two doublets with BEs of 137.2 eV and 138.4 eV, corresponding to Pb^{3+} (0.48 at. %) and Pb^{4+} (2.77 at. %) oxidation states.

Based on XPS analysis, the surface of the sample 1, Cu sample consists primarily of hydrocarbon-oxygen-containing species, with minor amounts of Cu^{1+} and Pb^{4+}. After mechanical removal of the top layer, the surface composition shows a higher concentration of Cu^{1+}.

Table 3 summarizes the atomic concentrations, binding energies, and oxidation states of the elements detected in samples before and after removing the top contaminated layer. The results confirm that the pristine surface of sample 2 is composed predominantly of hydrocarbon-oxides-containing species with minor amounts of Cu^{1+} and Pb^{4+} ions. After scratching, the surface becomes rich in Cu^{1+} and Pb^{4+}, metallic copper and oxidized lead (Pb_2O). Sample 2 deserves more attention due to the interesting discovery, namely, migration processes towards the film surface as a result of elevated temperature. The study focus on the atomic concentration of lead in both the pristine and the scratched surfaces. The oxidized lead in the pristine sample is 7.1 at. %, while in the scratched sample the same phase has decreased to 2.77 at. %, which corresponds to a reduction by a factor of 2.56 in the Pb_2O phase. In contrast, the metallic component of Pb4f has decreased 10 times by more than an order of magnitude (bold in Table 3).

Table 3. Atomic concentration (at. %), binding energies (eV), obtained after curve fitting procedure of the C1s, O1s, Pb4f and Cu2p core levels and oxidation states of elements on the surface of 1Cu sample.

Sample 2 - pristine									
	C 1s				**O 1s**	**Pb4f**		**Cu2p**	
[at. %]	56.80				27.43	12.00		3.75	
[at. %]	7.84	42.95	-	6.01	27.43	4.90	7.10	1.60	2.15
BE [eV]	282.5	285.0	-	288.8	529.2 531.7	136.7	139.2	930.5	932.9
Sample 2 - scratched									
[at. %]	57.63				32.31	3.25		6.80	
[at. %]	-	36.10	14.92	6.61	32.31	0.48	2.77	-	6.80
BE [eV]	-	285.0	286.5	288.9	530.0 531.5 533.1	137.2	138.4	-	932.5
Ox. state		C-C H-C	C-O	C=O H-C=O		Pb^{3+}	Pb^{4+}		Cu^{1+}

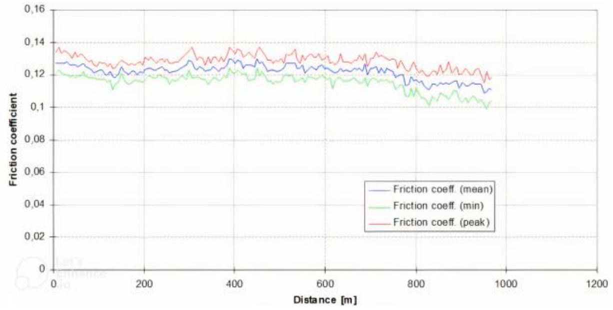
These results clearly show pronounced migration of the oxidized lead to the hot surface. Therefore, approximately 60% of the lead content of the sample has floated to the surface. The latter immediately rises the tribological significance of this alloy. On the surface, the lead-oxides (Pb_2O) concentration is almost 3 times greater than the metallic state - Pb. However, for the scratched sample, this ratio is about 8 times, which suggest that the main culprit for the low FC is the lead oxides, in particular - Pb_2O, as shown in XRD (Figure 4b).

It is important to report the hardness measurements of the pure copper sample and the treated one with the already discussed alloying elements.

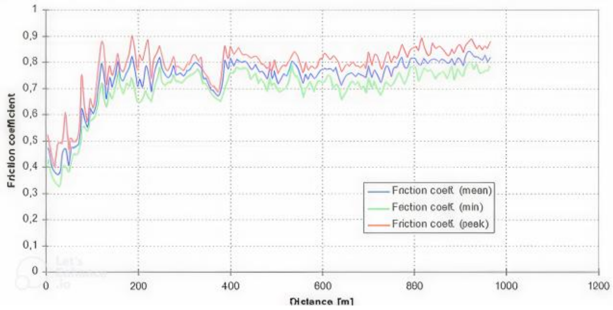
We found HV75 for the pure one, and HV150 for the treated one. These increase is due to the copper phosphide (Cu_3P) which is a harder phase and the role of the Sn forming Cu_3Sn and $SnPb_2O_4$. The latter phase is known to form open network on the film surface, and possibly into the bulk. This results in even better hardness and wear resistance under heavy loads. In Table 3, the mean values of the Friction Coefficients (FCs) are compared at equal conditions, in vacuum and in air.

In Figure 8a and 8b the FC's are given for samples measured in vacuum and on air at 2N load and speed of 1 m/s.

The friction depends not only on the mechanical irregularities of both contacting surfaces, but also is a consequence of molecular and atomic forces, which are inherent characteristics of each material. Under working conditions, the FC behave dynamically because processes of diffusion and new phase formations take place, and thus structural changes occur.



(a)



(b)

Fig. 8. Friction coefiecient at 2N load in: (a) Vacuum; (b) Air [7].

As a consequence, a secondary layer is formed. Due to the additives, the wear of the materials is improved, but external factors could change the chemical and structural state of the surface.

Table 4. FC of raw Cu sample and reinforced one in vacuum and in air.

FC μ	Copper	Copper alloy	Δμ* [%]
on air	0.5	0.76	+52↑
vacuum	4.8	0.12	-97.5↓
$\Delta\mu_{a/v}$ [%]	+860↑	-533↓	

5. LIMITATIONS AND FUTURE SCOPE

In this study we present only one load and speed when tracing the FC. Using only one speed as a variable could be considered as a strong limitation of the experimental setup. Speed variations can impact the wear and FC, respectively of the composite material, particularly in hard and dynamic applications. It is suggested that future research should explore the effect of different sliding and rotational speeds. Such an investigation would provide a more comprehensive understanding of the wear mechanisms under varying operational conditions and enhance the applicability of the material in real environments, both in air and in vacuum.

In aerospace engineering, materials with good strength properties at low temperatures (alloys and steels) are widely used. In mechanical engineering, self-lubricating composite materials, applicable to high loads in air, vacuum or inert environments, are sought.

Green technologies that do not have a harmful impact on service personnel and the environment are also preferred.

6. DISCUSSION

Dry friction is a phenomenon that occurs between contacting surfaces in the absence of lubricant in space and rocket equipment. Hereafter, 4-cases are described about phase formations and their influence on the friction behavior in respect air or vacuum media for pure Cu-samples and Cu-alloys, Table 4.

Pure copper in air: the nascent copper surface quickly oxidizes. While these oxides can be somewhat protective against severe adhesion, they are also abrasive. When two pure copper surfaces slide in air, these brittle oxide layers are constantly formed, fractured, and abraded, contributing to higher friction.

Pure Copper in vacuum: In vacuum, there are no air-formed oxides or adsorbed gas layers to separate the sliding surfaces. This leads to nascent (clean, bare) metal surfaces coming into direct contact. Metals, especially soft, ductile ones like pure copper, have a strong tendency to cold weld (adhere) to each other under normal load in vacuum. This cold welding and subsequent shearing of welded junctions results in high friction and severe adhesive wear (material transfer, prow formation). This is a well-known phenomenon for many metals in vacuum.

Copper alloy in air: Tin forms stable oxides (SnO_2) that are generally harder and more protective than copper oxides. The presence of tin can lead to the formation of intermetallic compounds (e.g., Cu_3Sn) and contribute to a more robust and wear-resistant surface oxide layer that is less prone to breaking off and acting as abrasive debris. Antimony also forms oxides (Sb_2O_3, Sb_2O_5). These, along with tin oxides, can further enhance the stability and protective nature of the tribo-oxide film formed on the surface in air. Antimony is known to improve hardness and wear resistance in these alloys. Lead, being softer and largely insoluble in copper, tends to segregate at grain boundaries or form dispersed particles. In air, lead oxides (PbO, PbO_2) can form. PbO is a solid lubricant with a low shear strength. In air, if these oxides form and are continuously regenerated, they can act as a boundary lubricant, reducing metal-to-metal contact and thus reducing friction and wear compared to pure copper.

Copper alloy in vacuum: This is the most critical component for friction reduction in vacuum. Lead is a soft, low shear strength metal that is largely insoluble in the copper matrix. In vacuum, with no oxygen to form hard oxides, the finely dispersed lead particles can be smeared across the contact interface, forming a continuous, low-shear solid lubricating film. This film prevents direct copper-on-copper cold welding, effectively reducing the coefficient of friction significantly. This self-lubricating mechanism is highly effective in vacuum because there are no gaseous contaminants to interfere with the lead's ability to spread and adhere to the surfaces. Sn (Tin) and Sb (Antimony): While tin and antimony primarily increase hardness and wear resistance (important for supporting the soft lead phase and preventing bulk deformation), their *oxides* are not formed in vacuum. However, their presence contributes to the overall microstructure of the alloy, which helps in the stable smearing of lead. The alloy's greater hardness compared to pure copper also helps to support the contact load without excessive plastic deformation, facilitating the formation and maintenance of the lead film.

It is important to compare the hardness measurements of the pure copper sample and the treated one with the already discussed alloying elements. We found HV75 for the pure one, and HV150 for the treated one. In Table 4, the mean values of the FCs are compared under identical conditions, in vacuum and in air. These increase is due to the copper phosphide (Cu_3P) which is a harder phase, and the addition of Sn, which is forms Cu_3Sn and $SnPb_2O_4$. The latter phase is known to form an open network on the film surface, and possibly into the bulk. Antimony is alloyed with lead and other metals to improve their hardness and strength. Real improvement (lowering) of the FC is observed in vacuum.

This results in even better hardness and wear resistance under loads.

The reduction in the FC and wear (Figure 9) with increasing friction speed is atypical for machine parts operating in a vacuum. This is achieved by combining he material’s structure, composition and processing technology to enable self-lubrication at the contact interface. The indicator for this is the constant value of the friction coefficient, measured during continuous operation with increased load.

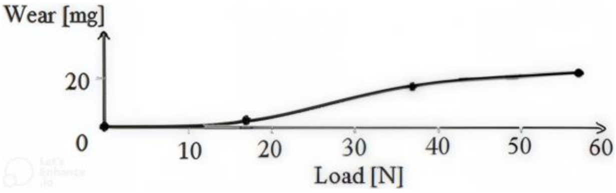


Fig. 9. Dependence of wear resistance under different loads for the tested cast copper sample.

Here, two factors, such as temperature and oxidation determine the compositional dynamics and new phase formations. We observed the formation of oxide clusters which migrate to the surface and are participated in the sliding friction process. As a matter a fact, in the course of wear of these lubricants, a new supply of those molecules is provided from the bulk. The processes listed below occur in a dynamic way and they are governed by a steady-state mechanism, which depends on numerous factors, such as:

- Oxidation, resulting from the interaction of the affected surfaces with the gaseous environment;
- Diffusion or redistribution of elements in the surface layer from the interior of the material to the surface;
- Selective migration of chemical elements due to heating;

- Phase and structural transformations, such the formations of new phases and structures;
- Redistribution of stresses, primarily in the initial stages of friction, followed by its gradual decrease;
- Appearance of cubic phases, which proves crystallization of the surface layer.

7. CONCLUSION

In the present work, Cu-based alloys with addition of reinforcing elements are considered to improve their tribological and mechanical properties. The alloying elements are P, Pb, Sn and Mn. Both materials, the raw one and the Cu-alloy are studied with respect to their structure, morphology and chemical composition in the intact and the worn surfaces.

The samples were thoroughly quantified by XRF, XRD and XPS analyses to investigate the elemental dynamics. Processes of migration, diffusion and segregations were also noted. The formation of new phases, such as Pb_2SnO_4, Cu_3P and Cu_3Sn was detected and is largely responsible for the significant improvement in friction. It has been shown that the treated sample exhibits approximately a 40-fold reduction in the FC lowering in vacuum and 2-fold increase in hardness.

In this way, the material increases its strength without reducing its ductility and adapts in the friction process.

The metallographic images reveal surface Pb segregation, later confirmed by XPS and XRD analysis as Pb_2O.

All mentioned and studied processes describe, in a complex way, the in-situ phase dynamics, surface migration, and oxidation of these competitive solid lubricants. They are applicable in machine parts, including MEM's, and in vacuum installation, where Cu with low oxygen content is essential.

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