Materials Science-Poland, 40(4), 2023, pp. 147-157
http://www.materialsscience.pwr.wroc.pl/
DOI: 10.2478/msp-2022-0051

Tribosynthesis of friction films and their influence on the functional properties of copper-based antifriction composites for printing machines

Kayode Olaleye[1,*], Tetiana Roik[2], Adam Kurzawa[3], Oleg Gavrysh[2], Dariusz Pyka[1], Mirosław Bocian[1], Krzysztof Jamroziak[1]

[1]Department of Mechanics, Materials and Biomedical Engineering, Faculty of Mechanical Engineering, Wroclaw University of Science and Technology, 27 Wyspianskiego str., 50-370 Wroclaw, Poland

[2]National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", 37 Peremogy ave., 03057 Kyiv, Ukraine

[3]Department of Lightweight Elements Engineering, Foundry and Automation, Wroclaw University of Science and Technology, 27 Wyspianskiego str., 50-370 Wroclaw, Poland

This article is devoted to research of the tribosynthesis mechanism of antifriction films and their influence on the functional properties of antifriction composites based on copper alloyed with nickel and molybdenum with the CaF_2 solid lubricant additions for operation at rotation speeds of 3,000–7,000 rph and increased loads of 3.0–5.0 MPa in air. Studies have shown that antifriction films are complex, dynamically changing formations on the surfaces of the composite and counterface, developing according to the bifurcation mechanism. The antifriction layer is decisive in the formation of the friction pair's tribological high-level properties, which provide the self-lubrication mode of the friction unit. The formation and permanent presence of the anti-seize film is associated with a balanced wear rate of the film and its constant formation again on these worn areas at rotation speeds of up to 7,000 rph and loads of up to 5.0 MPa. Due to the steady self-lubrication mechanism, the copper-based composite has significant advantages over cast bronze CuSn5ZnPb, which can only work with liquid lubrication in the friction units of printing machines. The performed studies make it possible to choose rational modes for operation of new high-speed antifriction Cu-composites based on the friction films analysis, predicting their high functional properties.

Keywords: *copper-based composite, antifriction properties, structure homogeneity, rotation speed, tribosynthesis, anti-seize films*

1. Introduction

In large part because of the development of extremely effective production methods and the use of new materials with predefined features, modern printing machines are characterized by higher speeds and loads. The operational characteristics of various parts and components have a significant role in determining the reliability and service life of printing equipment, particularly under conditions of high speeds and higher loads. This directly relates to the use of high-speed printing machinery like the RYOBI 524 GX four-color offset printing machines for the production of a variety of catalog, magazine, and highly artistic products: Solna-D400, Solna-D380 roll printing machine; CityLine Manugraph models for the production of black and white products; and KBA Compacta 213 type roll printing machines for the production of postcards, flyers, advertising catalogs, brochures, magazines, and so on. The equipment and components include plate, printing, and offset cylinders with sliding bearings that are subjected to higher stresses of 3.0–5.0 MPa and rotation speeds of more than 7,000 rph. For example, the maximum rotation speed of the offset cylinders in a Solna-D400 roll printing machine can reach 18,000 rph. As a rule, to minimize the vibration of the offset cylinder, the operating speed is in the range of 3,000–8,000 rph. The dependability and durability

* E-mail: kayode.olaleye@pwr.edu.pl

© Oaleye et al. 2023. This is an open access article distributed under the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License. (http://creativecommons.org/licenses/by-nc-nd/4.0/)

of the specified equipment are directly impacted by the stable operation of such bearings. According to the operating conditions, cast non-ferrous alloys such as bronze or brass are typically used to make these friction pieces. For heavy friction conditions, bearings are made of cast bronzes, BrAGN 10-4-4, Br.OTsS 5-5-5 (DSTU 3474-96, DSTU 3731-98, Kyiv State Standard of Ukraine 1997) which correspond to European and American bronzes, such as Cu80AI10Ni6Fe4, 2. 0971 (WNr DIN 17674-1 Standard, Berlin, Germany) or bronzes Cu80AI10Ni6Fe4, C95500, CuSn5ZnPb, C83800 (ASTM B505, B584 Standard, Oakland USA). The functional characteristics of such parts are unsatisfactory due to their increased wear, which provides satisfactory operation of the unit for only a limited time [1–3]. This is because the friction surfaces are protected by a variety of natural components that cannot be combined by conventional casting procedures. As a result, cast bearings can only be lubricated by liquid oil, and when that supply is cut off, the surfaces begin to seize and heat up to 400°C. In addition, liquid lubrication becomes totally ineffective at high speeds (>100 rpm) and cannot perform the surface lubrication function. At such speeds, liquid lubricant is ejected from the friction zone by centrifugal forces, exposing the contact surfaces, and thus causing seizing and jamming. Therefore, an alternative response to these technological challenges is the use of fundamentally new composite materials capable of ensuring long-term and stable operation of the printing machines' friction units under conditions of high rotation speeds and increased loads. There is no substitute for powder metallurgical techniques to address this issue. The development of antifriction composites based on copper yielded some encouraging results for researchers [4–6]. These composites have alloying components such as Fe, Cr, Ti, and Al, which make it possible to create materials with adequate antifriction qualities for higher speeds and light weights [4–6]. Liquid lubrication is frequently used in copper composites [1, 3, 4]. Other composites contain solid lubricants like MoS_2, Pb, Sn, Bi, or graphite (or its allotropic derivatives) [5–8]. Such composites can function in self-lubrication mode at higher speeds but with lower loads thanks to the solid lubricant. The friction coefficient is between 0.25 and 0.35 and gets lower the more solid lubricant there is [9]. However, an increase in solid lubricant concentration causes a sharp decrease in the mechanical properties and loss of structural strength. High speeds cause significant heating of the surfaces, resulting in instant oxidation of the solid lubricant that penetrates the depth, and consequently the destruction of the composites. The reason for such behavior of composites is not only imperfect production technologies, but also the lack of directed technological influence on the properties during material synthesis.

The uncontrollability of synergistic processes, which prevents the system from stabilizing under high friction conditions, is a common characteristic of known copper antifriction composites. As a result, the authors' encouraging findings are only applicable to certain experimental contexts [1, 3, 9]. It is well known that various mechanical, thermal, physical, and chemical processes take place in the surface layers of materials during the friction process, changing the material properties significantly [9–13]. Additionally, the qualities of the surface films that are created, or what are known as secondary structures, influence the material wear resistance in addition to their basic characteristics. Therefore, it is of both scientific and practical importance to research the phenomena as well as the state of the surface layer, which has a significant impact on how well a friction pair operates. The nature and characteristics of the friction films that are generated directly on the contacting surfaces (the so-called secondary structures), as well as the performance of the friction unit, have been demonstrated [6, 9, 11, 12]. When liquid lubricants are ineffective and solid lubricating components are added to the initial charge, secondary structures created by high-speed friction of composites are still unknown. Additionally, there are presently no studies on the relationship between the antifriction behavior and the mechanism of self-lubricating film formation, which are the carriers of tribological properties during friction without liquid lubricant, as well as studies on changes in the tribological properties of materials during production, operation, and the possibility of their predic-

tion.

In [14–18], the authors developed several copper-based antifriction composites for various operating conditions and worked out the technological operations of their production. The developed technological modes made it possible to obtain composites with a high level of functional properties depending on the features of the formed structure. Nevertheless, the mechanisms of stable antifriction film formation (the secondary structures) on the surfaces of copper-based composite materials, which are the carriers of functional properties, remain unclear. This is especially important under conditions of operation without liquid lubrication in the air at high rotation speeds and increased loads. The lack of information about the nature of secondary structure films, which are formed in the friction process of new antifriction copper-based composites, depending on the influence of external factors, does not allow to reasonably choose the rational operating conditions of new bearings for specific types of printing machines and, therefore, to predict their reliable operation. In addition, it was reported that antifriction material damage caused by high-speed temperature or load is a major issue in many industrial domains, such as the power engineering sector. In order to prolong the life of friction units operating in challenging operating conditions, anti-adhesive compounds are included in antifriction composite materials [19–26]. The arguments mentioned above and the complete lack of data on the mechanism of self-lubrication of copper-based composites with solid lubricant became the motivation for carrying out research to determine the features of the self-lubricating films formation on the contact surfaces of antifriction copper-based composites under conditions of high rotation speeds and increased loads. The obtained results will allow to choose reasonable operating conditions of new composite bearings, predicting the formation of high-functional properties considering features of the self-lubrication mechanism. This will provide a significant increase in the reliability and durability of friction units (not less than 4–5 times) and contribute to the higher productivity of high-speed printing machines.

The objective of the work is to establish the specifics of friction films' tribosynthesis and their influence on the functional properties of copper-based antifriction composites for high-speed printing machines working at rotation speeds of 3,000–7,000 rph and increased loads of up to 4.0 MPa in air. This will open up the possibility of purposefully choosing alloying elements and their amount in the initial charge in order to obtain composites with predictable functional properties for specific operating modes.

2. Experimental procedure

2.1. Preparation of powder charge, compaction, and sintering

The subject of the study is copper-based composite doped with nickel and molybdenum, with CaF_2 additions, wt.%: 83Cu–5Ni–3Mo–9CaF_2, developed by the authors of this article [10]. The CaF_2 solid lubricant was selected for the initial charge preparation as a known effective solid lubricant in severe working conditions [19, 20, 27, 28]. Samples were prepared by powder metallurgy methods (Figure 1) according to the technology developed by the authors of this article, which is described in the papers [10, 11, 14–18].

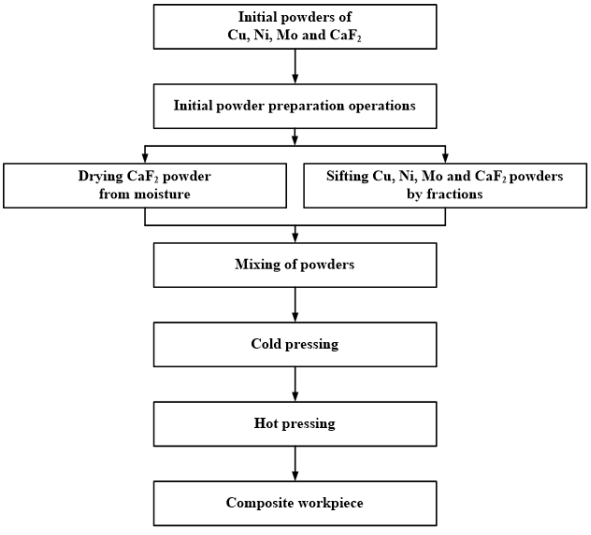


Fig. 1. Technological scheme for manufacturing copper-based antifriction composites

The technological scheme for manufacturing

copper-based antifriction composites demonstrates the sequence of all technological operations (Figure 1), because the formed structure and properties depend on the accuracy of their realization. The starting materials were the following powders: copper (60–63 μm), nickel (10 μm), molybdenum (60–63 μm), and CaF_2 (100 μm). Calcium fluoride powders were drying at a temperature of 120°C for 1 h. Powders Cu, Ni, Mo, and CaF_2 were sifted by fractions. As it is known [4, 11, 14, 15], the different dispersion of powders contributes to better compactibility of the composite during pressing. The mixing operations were followed by cold pressing, then hot pressing to minimize porosity. Cold pressing was carried out at room temperature and at a specific pressure of 350–400 MPa. The porosity of the samples was 12%–14% after cold pressing. Additional hot-pressing operation was carried out at temperatures 820–870°C and specific pressure of 500 MPa in a protective gas atmosphere (H_2). The applied technology used proved to be quite effective [15, 16], which ensured the relative density of the samples in the range of 0.98–0.99 after hot pressing.

2.2. Examination techniques

The structure was studied under a metallographic microscope and raster electron microscope; calcium fluoride in the matrix was identified using scanning electron microscopy (SEM) and analyzed using energy-dispersive X-ray spectroscopy (EDS). SEM observations were carried out using a highly sensitive semiconductor backscattered electron (BSE) detector at an accelerating voltage of 15 kV (analysis mode). The friction films were examined by SEM using a Zeiss-EVO SOXVP microscope, EVO50.04.47 with software.

Tribological tests were performed on a VMT-1 friction testing machine (Figure 2). The VMT-1 friction machine is a dual-purpose testing machine. The VMT-1 tribometric machine can be used for high-speed and high-temperature tests. Tribological test conditions were chosen according to the operating modes of real offset cylinders of high-speed printing machines. To minimize the vibration of the offset cylinder, the operating speed is usually in the range of 3,000–8,000 rph. Therefore, friction and wear tests were performed in the speed range of 3,000–7,000 rph. In addition to high rotational speeds, the offset cylinder is subjected to the maximum total load from the action of the former cylinder, dampening roller of moisturizing apparatus, the drum and roll cylinders of the dampening apparatus, the dampening ductor, the reel rollers, the ink roller, and the reel cylinder, which are tightly pressed against each other under loads from 3.0 to 5.0 MPa. Therefore, during tribological tests, a load of 4.0 MPa was chosen. All friction and wear tests of copper-based composite were performed in comparison with cast bronze specimens, which are traditionally used for bearing bushings in the offset cylinder friction units. The parameters for tribological tests are the following: rotation speed V = 3,000–7,000 rph; load P = 4.0 MPa; the counterface is made of 40Kh steel (C = 0.4%, Cr =1.0), which is an analog of 1.7045, 42Cr4 steel (DIN Standard, Worldwide equivalents of grade 2.0790 (Berlin, Germany: DIN, WNr) or 5140 steel (AISI Standard, 25 Massachusetts Avenue NW, Suite 800 Washington USA), HRC = 53–55; shaft–pin friction pair; liquid lubricant—mineral oil for the comparative tests with the CuSn5ZnPb, C83800 cast bronze samples (ASTM B584 Standard, Roland Way, Suite 224 Oakland, CA 94621 USA). Thus, these test parameters correspond to the operation of bearings in real operating conditions of printing machine offset cylinders.

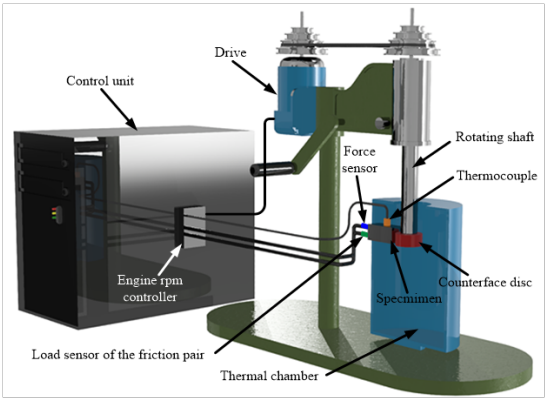
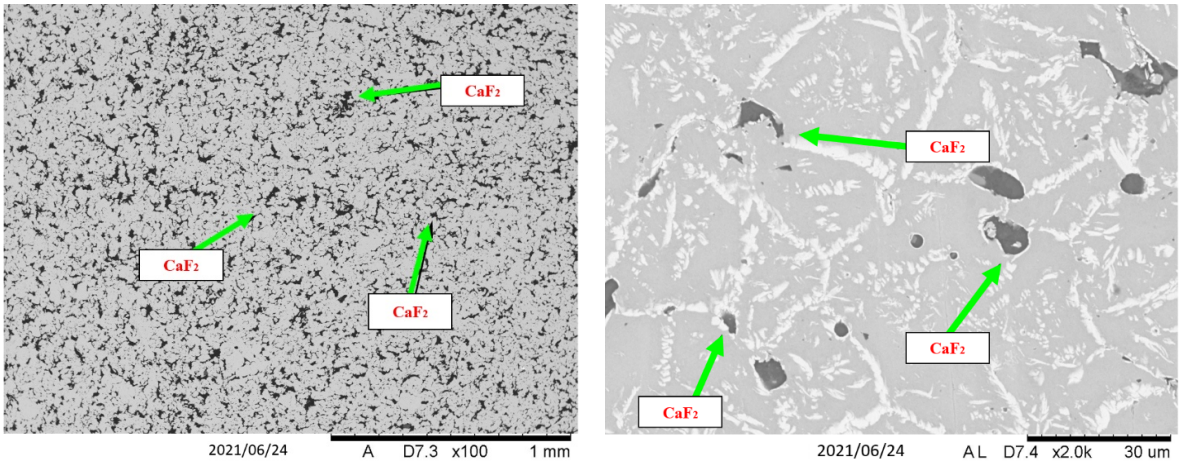


Fig. 2. Schematic setup of VMT-1 friction testing machine



(A) (B)

Fig. 3. Structure of Cu-5%Ni-3%Mo-9%CaF_2 composite: **(A)** optical metallography; **(B)** electron microscopic image

Table 1. Comparative antifriction properties of the studied composite and cast bronze

Composition, wt.%	**Friction coefficient (f)/wear rate (I), μm/km, at load of 4.0 MPa and rotation speed, rph**			**Maximum permissible rotation speed, rph**	**Comments**
	3,000	**5,000**	**7,000**		
Cu + 5Ni + 3Mo + 9CaF_2	0.21/61	0.24/75	0.28/153	7,500	Antifriction films have formed on the contact surfaces
Cast bronze CuSn5ZnPb* [1]	0.37–0.41/388–405	Plastic deformation	800–1,000	Liquid oil smokes and burns	

*Testing with liquid lubricant (mineral oil).

3. Results and discussion

The use of the developed technology by the authors of this article [15, 16, 18], which includes the operation of hot pressing, provides completeness of the studied composite's diffusion homogenization, which is shown in Figure 3. The process of structure homogenization minimizes porosity, eliminates segregation phenomena, and enhances the material's properties.

The structure of the Cu–5%Ni–3%Mo–9%CaF_2 composite is finely dispersed (Figure 3A) and is an alloyed α-solid solution based on copper, in which CaF_2 solid lubricant particles are uniformly distributed (Figures 3A and 3B).

The metal matrix is an α-solid solution based on copper, alloyed with nickel and molybdenum. It is known [4, 10, 17] that the alloying elements Ni and Mo do not form chemical compounds with copper; they strengthen the copper solid solution. However, nickel and molybdenum form intermetallic compounds of Ni_3Mo type, which are effective hardeners of copper matrix [4, 10, 17]. The formation of the Ni_3Mo intermetallic phase was studied in detail by the authors of this article in [10]. Therefore, when preparing the initial charge, 5% of nickel and 3% of molybdenum were added to its composition. The presence of a hardened metal matrix can reduce the deformation degree of the material at the increased loads and speeds during the operation process. As can be seen from Figure 3, photographed at different magnifications, the structure of the studied composite is fine-grained. It is also seen that use of the developed technology provided a uniform distribution of CaF_2 solid lubricant over the entire volume of the material, which is a positive factor for the composite of antifric-

tion purpose. As can be seen from Figure 3, the manufacturing technology showed its effectiveness and provided the formation of a uniform structure throughout the composite volume, without negative segregation phenomena.

The finely dispersed and homogeneous structure of the composite contributed to a high level of functional properties compared with cast bronze, which is traditionally used for bearing bushings in the friction units of many printing machines (Table 1).

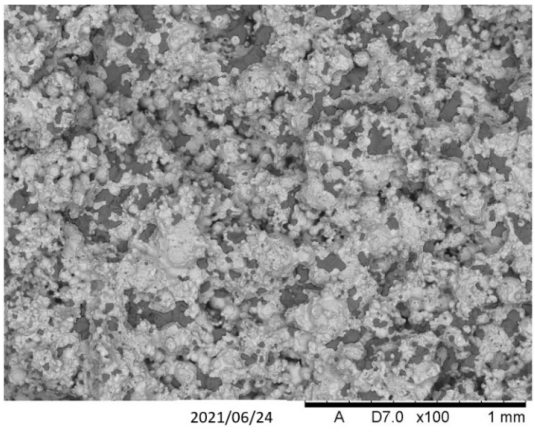
The data in Table 1 show that the studied composite has significant advantages in terms of tribological properties compared with cast bronze [1].

Cast bronze exhibits poor operating characteristics due to the ineffectiveness of lubricating oil at high rotational speeds combined with the load on the friction pair. The liquid lubricant is under the simultaneous action of two external factors—increased loads on the friction pair and high rotation speeds. As a result, the liquid lubricant is simultaneously squeezed out under load and ejected by centrifugal forces from the friction zone due to high rotation speeds. In this case, the contact surfaces remain unprotected, the friction surface heats up, and the oil smokes and begins to burn, starting at a rotation speed of 3,000 rph. As the rotation speed increases, plastic deformation of the cast bronze and irreversible loss of geometric characteristics are observed. Such phenomena lead to a catastrophic increase in wear, seizure of the contacting surfaces, and final loss of the friction pair functionality.

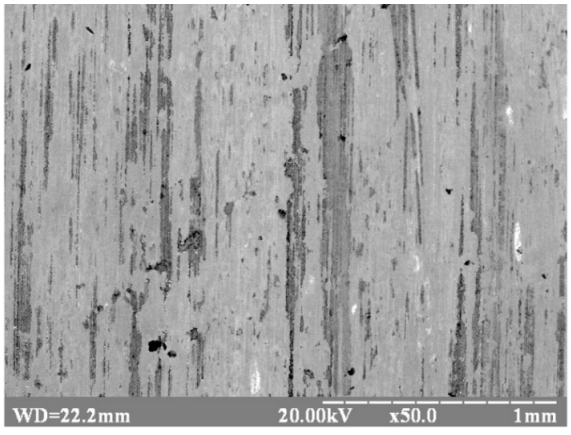
In contrast to cast bronze, the studied copper-based composite demonstrates high tribological characteristics and is able to work under increased loads and high rotation speeds.

Such frictional behavior of the composite is associated with the antifriction film formation on the contact surfaces (Figure 4). It becomes the third and equally important participant in the friction process along with the studied composite and counterface.

Therefore, the next step in the research was to study the formed friction films and the mechanism of their lubricating effect under specific test conditions.



(A)



(B)

Fig. 4. Antifriction film on friction surfaces: **(A)** examined composite Cu+5%Ni+3%Mo+9%CaF_2; **(B)** counterface of 40Kh steel (analog of 1.7045, 42Cr4 steel, DIN standard, Germany)

Figure 4 shows an image of the formed friction film on both contact surfaces. It can be seen that the film is crushed on the surface of the composite (Figure 4A) due to the harder counterface tightly adjoining it. As a result, the film is smeared on the surface of the counterface (Figure 4B). In this case, the friction mechanism is associated with the permanent effect of mutual mass transfer of both solid lubricant CaF_2 and other elements of the friction pair (composite and steel counterface), which form an anti-seize film. This is evidenced by the data of the micro-X-ray spectral analysis from the selected sections of the film (spectra 1, 2, and 3, Figures 5 and 6; Tables 2–4). Separately, it should be noted

that during the formation of the friction film and its simultaneous wear, very fine wear products are formed (many small particles can be seen in Figure 5).

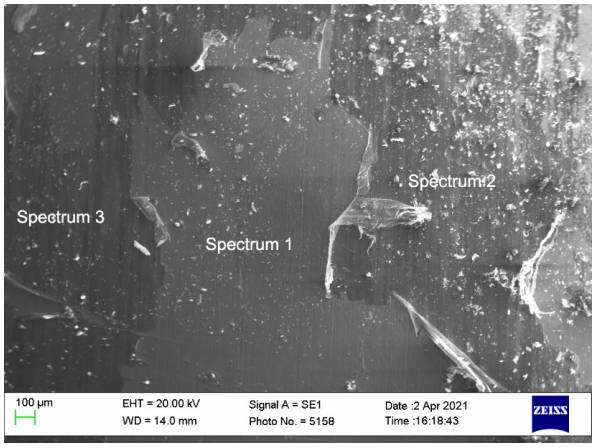


Fig. 5. Antifriction film with places for micro-X-ray spectral analysis (spectra 1, 2, and 3)

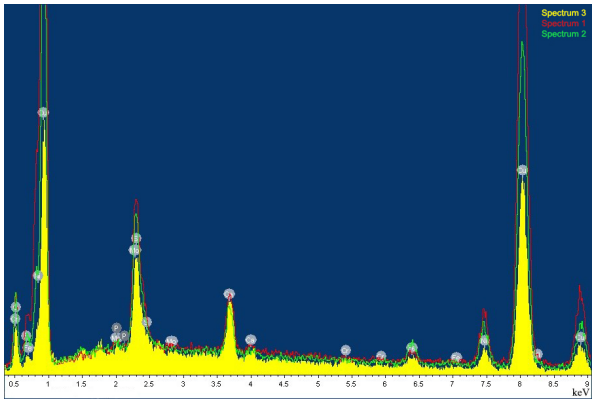


Fig. 6. Micro-X-ray spectral analysis of film sections

Table 2. Chemical composition of spectrum 1

Element	Intensity	Weight%	Weight%, σ	Atomic%
CK	2.0816	12.57	0.71	39.81
OK	0.7860	4.71	0.25	9.91
FK	0.5422	1.82	0.25	3.54
SK	0.8207	0.23	0.22	0.31
CaK	1.0503	1.47	0.09	1.35
FeK	1.1168	0.47	0.11	0.30
NiK	0.9799	4.58	0.22	2.80
CuK	0.9441	66.84	0.80	39.23
MoL	0.6776	7.31	0.64	2.75
Result		**100.00**		**100.00**

Table 3. Chemical composition of spectrum 2

Element	Intensity	Weight%	Weight%, σ	Atomic%
CK	3.1867	49.38	0.57	77.22
OK	0.5512	5.61	0.29	7.44
FK	0.4215	1.02	0.22	1.03
PK	0.9402	0.06	0.04	0.04
SK	0.7728	0.53	0.12	0.23
CaK	1.2703	1.03	0.07	0.52
FeK	0.9234	0.98	0.11	0.31
NiK	0.7966	2.74	0.14	0.91
CuK	0.8837	35.27	0.52	11.68
MoL	0.6979	3.38	0.29	0.62
Result		**100.00**		**100.00**

Table 4. Chemical composition of spectrum 3

Element	Intensity	Weight%	Weight%, σ	Atomic%
CK	4.7439	67.59	0.57	89.30
OK	0.4207	3.78	0.34	3.71
FK	0.3612	0.63	0.27	0.53
SK	0.8711	0.36	0.09	0.13
CaK	1.0372	1.56	0.08	0.58
CrK	0.9261	0.38	0.06	0.05
FeK	0.8968	0.44	0.06	0.11
NiK	0.8198	1.54	0.12	0.38
CuK	0.8246	21.59	0.40	4.99
MoL	0.7734	2.13	0.22	0.22
Result		**100.00**		**100.00**

As can be seen from Figures 5 and 6 and Tables 2–4, the chemical elements of the composite and steel counterface are present in all spectra at the analysis areas, which confirm the mutual mass transfer phenomena. In addition, oxygen is visible in each spectrum, indicating the formation of oxides and the oxidative nature of the wear process. The following phenomena are observed in the friction process.

Anti-seize films (secondary structures) as dissipative structures are complex, dynamically changing formations on the composite and counterface surfaces, developing according to the bifurcation mechanism [6, 7, 9]. Due to self-organization, such structures can stay in one of two relatively long-term states, in other words, in one of two attractors.

According to the principle of bifurcation [29], the friction film can have abrasive properties or be a permanent antifriction lubricant. This depends directly on the external loading factors (load, speed, etc.). Thus, development of the bifurcation mechanism can lead to only one relatively stable attractor, where the film is either an abrasive or an antifric-

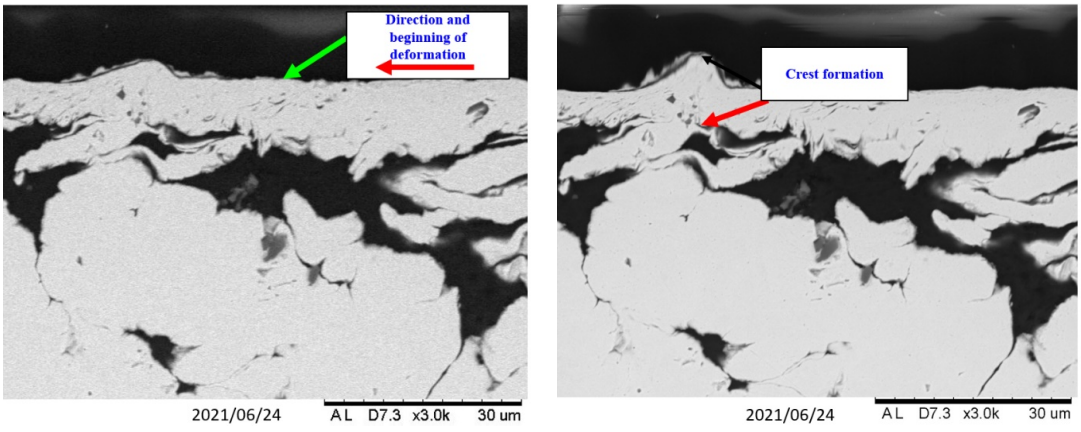


Fig. 7. Deformation and wear process of the antifriction film area: **(A)** beginning of deformation; **(B)** forming a crest before peeling off the area

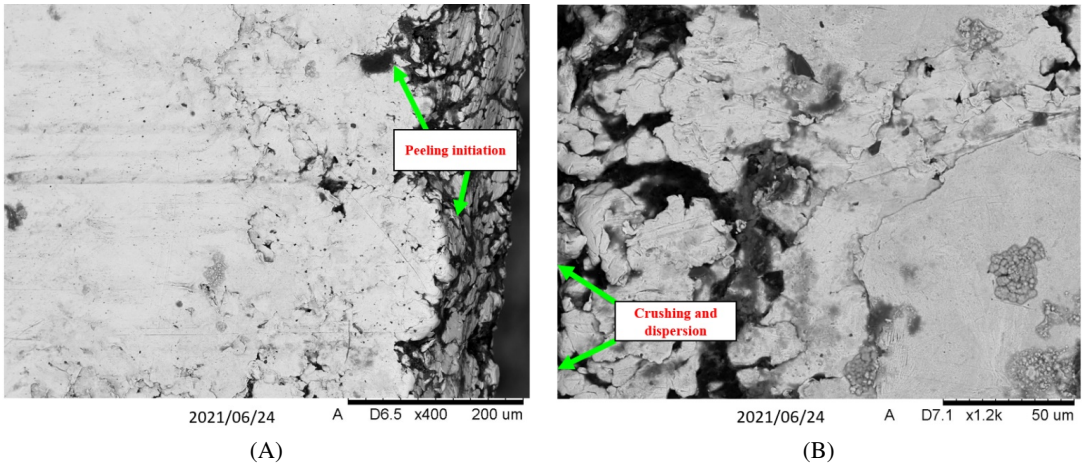


Fig. 8. Wear of the film section: **(A)** peeling; **(B)** crushing and dispersion

tion lubricant. In this case, working conditions of the friction pair become the determining factors.

In our case, the range of operating conditions resulted in the formation of an attractor that was relatively stable, that is, the anti-seize film formation that reduces the friction coefficient and protects the surfaces from wear.

The secondary structure film has a smoother microtopography without spalling spots, severe fractures, or fatigue damages. It is the smoothed relief of the friction surfaces that contribute to minimizing the friction coefficient and wear rate [30]. The formation and permanent presence of the anti-seize film is related to the balance of the following phenomena, namely, the film wear during the friction process and its continuous formation again on the worn areas under these friction conditions.

The high rotation speed and increased load make sections of the film more mobile and cause it to peel and crush locally. Thus the level of rotation speeds and loads (V = 3,000–7,000 rph; load P = 3.0–4.0 MPa) established during the research lead to the appearance of a positive attractor in terms of antifriction properties. It can be seen from Table 1 that the investigated composite shows the best antifriction properties.

When the rotational speed increases up to 7,500 rph the antifriction properties of the composite significantly decrease (Table 1). This means that the formed friction film starts to work as an abrasive, and the system (composite) passes to the negative attractor according to the bifurcation principle [29, 31]. In this case, areas of the formed film wear out faster than new ones are formed. There is an imbalance in the system.

The system is in the positive attractor in the range of rotation speeds and loads determined by us (V = 3,000–7,000 rpm; load P = 3.0–4.0 MPa). The active antifriction layer has a fine-dispersed structure and the maximum localization of surface deformation under friction will occur in it.

The development of the wear process, dispersion, and peeling of the film is shown in Figures 7 and 8.

In Figure 7, the relief areas are due to an artifact of the surface geometry, that is, the appearance of crests in the anti-seize film's embrittlement places in response to external influences. It can be seen that this process is dynamic. Figure 7 illustrates the stages of the film's crest formation and before its detachment during wear.

Figure 8A shows a general picture of the permanent friction film grinding process, and Figure 8B allows us to evaluate the details of this process at higher magnification.

The high degree of active layer dispersion during the friction process is one of the relief's distinguishing characteristics. The crushing of the film structure increases the role of its plastic deformation, and the increased loads promote the effect of smoothing the microgeometry of the anti-seize layer relief, which reduces its wear.

The formation of a smooth microgeometry of the film relief stabilizes the friction pair operation. This promotes the friction process and prevents seizure in combination with the action of the thermally and chemically stable solid lubricant CaF_2 present in the composite.

Experimental results confirmed the fine-dispersed structure of the antifriction layer and the maximum localization of surface deformation in it during friction. Microplastic deformation of such a layer occurs as a result of attraction and displacement of its microvolumes.

Due to the appearance of many elementary shear directions in the microvolumes, multiple layer microdistortions predetermine a high elastic deformation resource in the anti-seize film and, consequently, its high wear resistance.

Additional shear formation in the film is also provided by internal adsorption of oxygen into the deformed volumes.

Oxygen is adsorbed in microcracks, micro voids, at the grain boundaries, and in other defective places in the films. In addition to chemical interaction, oxygen can significantly reduce the strength of the formed surface layer and thereby facilitate the wear products grinding during high-speed friction.

Thus, for the first time the studied mechanism of self-lubrication of a new composite based on copper was performed. The formation of antifriction films of secondary structures, as the main factor in friction with solid lubricant, should be interpreted as the emergence of dissipative systems due to the implementation of self-organization processes that provide a self-lubrication mode. It was shown that in the ranges of rotational speeds and loads determined for a copper-based composite, the formation of antifriction films occurred by such a bifurcation mechanism that provided the appearance of a favorable attractor in which the highest antifriction characteristics are demonstrated. A stable balance between the antifriction film's wear rate and the rate of the new film area formation ensures high antifriction properties of composite under certain operating conditions. The formation of the film relief's smoothed microgeometry stabilizes the operation of the friction pair. In combination with the high thermal and chemical stability of calcium fluoride, this facilitates sliding and prevents adhesion.

4. Conclusions

- For the first time a study of the tribosynthesis features of antifriction films showed that an anti-seize fine layer is formed on

the contact surfaces of Cu + 5%Ni + 3%Mo + 9%CaF_2 composite and 40Kh steel counterface during friction at rotation speeds 3,000–7,000 rph and increased loads 4.0 MPa in air. Antifriction films are complex, dynamically changing formations on the Cu-based composite and steel counterface surfaces, developing according to the bifurcation mechanism.

- The friction conditions contributed to the formation of a relatively stable attractor due to their self-organization. This led to the formation of an anti-seize film protecting the surfaces from wear and minimizing the friction coefficient. Such a film contains chemical elements of both the investigated copper-based composite and steel counterface, as well as the solid lubricant CaF_2 due to the effect of mutual mass transfer.
- This antifriction layer is decisive in the formation of a high level of tribological properties, which provides self-lubrication mode of the friction unit at rotation speeds of up to 7,000 rph and loads of up to 4.0 MPa.
- For the first time it is shown that the wear process occurs by shredding the structure of the anti-seize layer and localization of plastic deformation in it under influence of the external factors. Formation and permanent presence of the anti-seize film is associated with the balanced wear rate of the film and its constant formation again on these worn areas under these friction conditions.
- Due to the sustainable self-lubrication mechanism, copper-based composite Cu + 5%Ni + 3%Mo + 9%CaF_2 has significant advantages over the cast bronze CuSn5ZnPb, which can only work with liquid lubricants in printing machine assemblies.
- The studies conducted allow to choose rational modes of operation for new high-speed antifriction composites based on friction films analysis, predicting their high functional properties. This provides a significant increase in the reliability and durability of friction units (not less than 4–5 times), and therefore contributes to the stability of high-speed printing machines.
- It was shown that the most rational modes of operation for new antifriction composites based on copper are rotation speed V = 3,000–7,000 rph and load P = 3.0–4.0 MPa.
- Further studies will be directed at determining the phase composition and quantitative ratio of phases in the anti-seize film, and influence of the friction pair's chemical elements and oxygen on the functional properties. This will allow to choose purposefully the alloying elements and their quantity in the initial charge for the possibility of making composites with predetermined properties for specific modes of operation.

Conflict of interest

The authors declare no competing interests.

References

[1] Neale MJ. *The tribology handbook*. 2nd ed. Elsevier Ltd. All rights reserved, editor. Oxford: Butterworth-Heinemann; 1996. https://doi.org/10.1016/B978-0-7506-1198-5.X5000-0.

[2] Simmons CH, Maguire DE, Phelps N. 35 - Bearings and applied technology. In: *Simmons CH, Maguire DE, Phelps NBTM of ED*. 5th ed. Oxford: Butterworth-Heinemann; 2020. p. 519–45. https://doi.org/10.1016/B978-0-12-818482-0.00035-9.

[3] Guangrong H XT. *Copper-based alloy sliding-bearing material and preparation method thereof*. Patent. China; CN103602849A, 2016. https://patents.google.com/patent/CN103602849A/en.

[4] Samal P, Newkirk J. *Powder Metallurgy*. ASM International; 2015. https://doi.org/10.31399/asm.hb.v07.9781627081757.

[5] Liu Q, Castillo-Rodríguez M, Galisteo AJ, Guzmán de Villoria R, Torralba JM. Wear behavior of copper–graphite composites processed by field-assisted hot pressing. *J Compos Sci.* 2019; 3(1): 29. https://doi.org/10.3390/jcs3010029.

[6] Wu G, Xu C, Xiao G, Yi M. Recent progress in self-lubricating ceramic composites. In: Menezes PL, Rohatgi PK, Omrani E, (eds.) *Self-lubricating composites.* Berlin, Heidelberg: Springer Berlin Heidelberg; 2018. p. 133–54. https://doi.org/10.1007/978-3-662-56528-5_5.

[7] Li R, Yin Y, Zhang K, Song R, Chen Q. Effects of ball milling and load on transfer film

formation of copper-based composites. *Ind Lubr Tribol.* 2022;74(9):1056–62. https://doi.org/10.1108/ILT-04-2022-0119.

[8] Hoganas Handbook for Sintered Components: *Material and Powder Properties*. 1997. https://books.google.pl/books?id=wl9OtAEACAAJ.

[9] Stojadinović S, Tadić N, Vasilić R. Plasma electrolytic oxidation of hafnium. *Int J Refract Met H.* 2017;69:153–7. https://doi.org/10.1016/j.ijrmhm.2017.08.011.

[10] Konopka K, Roik TA, Gavrish AP, Vitsuk YY, Mazan T. Effect of CaF_2 surface layers on the friction behavior of copper-based composite. *Powder Metall Met Ceram*. 2012;51(5):363–7. https://doi.org/10.1007/s11106-012-9441-2.

[11] Roik TA, Gavrish AP, Kirichok PA, Vitsyuk YY. Effect of secondary structures on the functional properties of high-speed sintered bearings for printing machines. *Powder Metall Met Ceram*. 2015;54(1):119–27. https://doi.org/10.1007/s11106-015-9688-5.

[12] Kurzawa A, Roik T, Gavrysh O, Vitsiuk I, Bocian M, Pyka D, Zajac P, Jamroziak K. Friction mechanism features of the nickel-based composite antifriction materials at high temperatures. *Coatings*. 2020; 10(5): 454. https://doi.org/10.3390/coatings10050454.

[13] Mohan S, Anand A, Arvind Singh R, Jayalakshmi S, Chen X, Konovalov S. Friction and wear study of Fe-Cu-C-CaF_2 self-lubricating composite at high speed and high temperature. *IOP Conf Ser: Mater Sci Eng.* 2020;834(1):12010. https://dx.doi.org/10.1088/1757-899X/834/1/012010.

[14] Roik TA, Gavrish OA, Vitsiuk II. The phase composition and structure of the antifriction copper-based composite and their influence on tribological properties. *Powder Metall Met Ceram*. 2021;60(3):191–7. https://doi.org/10.1007/s11106-021-00227-z.

[15] Jamroziak K, Roik T, Gavrish O, Vitsiuk I, Lesiuk G, Correia JAFO, De Jesus A. Improved manufacturing performance of a new antifriction composite parts based on copper. *Eng Fail Anal*. 2018;91: 225-233. https://doi.org/10.1016/j.engfailanal.2018.04.034.

[16] Roik TA, Gavrysh OA, Vitsiuk II, Khmiliarchuk OI. New copper-based composites for heavy-loaded friction units. *Powder Metall Met Ceram*. 2018;56(9):516–22. https://doi.org/10.1007/s11106-018-9924-x.

[17] Roik T, Jamroziak K, Lesiuk G, Gavrish OA, Vitsiuk J. *Copper based anti-friction composite material*. Patent. Poland: PL237229, 2019. https://api-ewyszukiwarka.pue.uprp.gov.pl/api/collection/7b74f34630c6a414f465b09b7beb407a.

[18] Roik TA, Gavrysh OA, Vitsiuk II. *Antifriction composite material based on copper*. Patent. Ukraine: UA135076 IPC, 2019.

[19] John M, Menezes PL. Self-lubricating materials for extreme condition applications. *Materials*. 2021; 14(19): 5588. https://doi.org/10.3390/ma14195588.

[20] Ouyang JH, Li YF, Zhang YZ, Wang YM, Wang YJ. High-temperature solid lubricants and self-lubricating composites: A critical review. *Lubricants*. 2022;10(8):177. https://doi.org/10.3390/lubricants10080177.

[21] Kyrychok PO, Roik TA, Gavrish AP, Shevchuk AV VY. New composite materials for friction parts of printing machines. Kyiv: NTUU KPI, Ukraine; 2015.

[22] Bhushan B. *Introduction to tribology*. 2nd Editio. John Wiley & Sons, Ltd; 2013. https://onlinelibrary.wiley.com/doi/book/10.1002/9781118403259.

[23] Migranov MS, Mukhamadeev VR, Migranov AM, Mukhamadeev IR, Khazgalieva AA. The improvement of the tribotechnical properties of materials and coatings for metal cutting tool. *IOP Conf Ser Mater Sci Eng*. 2018;447(1):12083. https://dx.doi.org/10.1088/1757-899X/447/1/012083.

[24] Purushotham G, Hemanth J. Action of chills on microstructure, mechanical properties of chilled ASTM A 494M grade nickel alloyreinforced with fused SiO_2 metal matrix composite. *Proc Mat Sci*. 2014;5:426–33. https://doi.org/10.1016/j.mspro.2014.07.285.

[25] Olaleye K, Roik T, Kurzawa A, Gavrysh O, Vitsiuk I, Jamroziak K. Structure formation in antifriction composites with a nickel matrix and its effect on properties. *Materials*. 2022;15(9):3404. https://doi.org/10.3390/ma15093404.

[26] Avram V, Csaki I, Mates I, Stoica NA, Stoica AM, Semenescu A. The effect of Ca and Mg on the microstructure and tribological properties of YPbSn10 antifriction alloy. *Materials*. 2022;15(9):3289. https://www.mdpi.com/1996-1944/15/9/3289.

[27] Su L, Gao F, Han X, Chen J. Effect of copper powder third body on tribological property of copper-based friction materials. *Tribol Int*. 2015;90:420–5. https://doi.org/10.1016/j.triboint.2015.05.003.

[28] Rodrigues ACP, Yonamine T, Albertin E, Sinatora A, Azevedo CRF. Effect of Cu particles as an interfacial media addition on the friction coefficient and interface microstructure during (steel/steel) pin on disc tribotest. *Wear*. 2015;330–331:70–8. https://doi.org/10.1016/j.wear.2015.02.006.

[29] BergeṔ, Pomeau Y, Vidal C, Ruelle D, Tuckerman LS. *Order within chaos: Towards a deterministic approach to turbulence*. New York, Paris SE: Wiley; Hermann; 1984.

[30] Bowden FP. Introduction to the discussion: the mechanism of friction. *Proc R Soc Lon A*. 1952;212:440–9. http://doi.org/10.1098/rspa.1952.0093.

[31] Wang Z. A universal bifurcation mechanism arising from progressive hydroelastic waves. *Theor Appl Mech Lett*. 2022;12(1):100315. https://doi.org/10.1016/j.taml.2021.100315.

Received 2023-02-09
Accepted 2023-03-18