

Article

New Antifriction Composites for Printing Machines Based on Tool Steel Grinding Waste

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Abstract: In this article, we present research results on the structure and properties of new self-lubricating antifriction composites based on 4H4VMFS tool steel grinding waste with solid lubricant additives. The new composites are designed to work in the friction units of offset cylinders in printing machines at rotation speeds up to 7000 rpm and increased loads up to 5.0 MPa. The developed technology formed composites with a fine-grained heterophase structure with a metal matrix base of tool steel 4H4VMFS regenerated grinding waste, consisting of high-alloy α -solid solution and hard grains of alloying element carbides, as well as evenly distributed CaF_2 antiseizure solid lubricant. This structure ensured the formation of composites with favorable functional properties. During the friction process, antiseizure films were formed on the contact surfaces, resulting in a self-lubrication mode. Comparative tests for friction and wear showed significant advantages of the new waste composite compared to cast bronze parts, which are traditionally used in the friction units of offset cylinders of rolled newspaper printing machines. The stable operation of the new composite made it possible to ensure a “wear-free” effect. Studies have shown the importance and prospects of using the wide range of valuable grinding waste in the reproduction cycle to manufacture quality composites. Reuse of such waste would significantly protect the environment from pollution connected with human activity industrial and mitigate negative impacts on ecosystems and the biosphere.

Keywords: grinding waste; tool steel; technology; antifriction composite; microstructure; solid lubricant; tribological properties; antiseizure films; offset cylinder; environment



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1. Introduction

The development of modern technology requires scientists to adhere to a combination of technological, technical, and economic aspects when developing new materials and introducing new parts into production. This applies to the materials of contact pairs operating under severe conditions in the friction units of offset cylinders in printing machines, primarily antifriction (bearing) materials.

Antifriction parts in the friction units of offset cylinders operate at high rotation speeds of 5000 rpm or more and at loads of 3.0–5.0 MPa in air, which causes the working surfaces to heat up to 400–500 °C. A wide range of cast and powder antifriction materials based on iron, copper, etc., have been developed and are currently used for severe working conditions [1–5].

What these antifriction materials have in common is the high wear of the contacting parts, an increase in the friction coefficient under such conditions, and high cost in many cases [1–5].

Bearings based on cast bronze Cu83Sn7Zn3Pb7 or Cu85Sn5Zn5Pb5 (C93200 ASTM Standard, USA) are currently used in the offset cylinders units of rolled newspaper machines such as, the Solna D390 and Solna D480 (Sweden). Such bronze bearings can work when greased with liquid oil [6–8].

Under such conditions, the lubricating oil becomes ineffective at high rotational speeds because it is thrown out of the contact zone by centrifugal forces. As a result, the friction surfaces remain unprotected. Moreover, the contact surfaces are intensively oxidized under the action of the temperatures arising from friction.

The described conditions lead to seizure of the contact surfaces, which causes the complete destruction of the friction unit of offset cylinders in printing machines.

In addition, all cast materials have a significant drawback. They cannot combine substances that differ considerably in nature and composition, i.e., they cannot form a strong matrix that also contains antiseizure additives in the form of sulfides, oxides, chalcogenides, and fluorides to minimize friction and wear [9–15]. Thus, the combination of substances with different natures is impossible when using traditional remelting and casting technology.

This is the reason for the rapid wear of cast parts, the failure of friction units and machines in general, as well as high material expenses.

Powder antifriction materials do not have these disadvantages and possess many advantages. A wider range of materials is possible with powder, as substances can be combined that cannot be combined by casting methods [3,5,16–18].

However, a significant negative factor for powder materials, including high-speed materials, is their high cost due to expensive starting powders and manufacturing equipment, as well as their complexity. These factors have prevented their widespread use.

It is necessary to search for cheap, widely available, economically profitable types of raw materials to create antifriction materials capable of ensuring reliability, durability, and high performance of friction units, especially in difficult working conditions. Moreover, such materials should be made using simple technology and inexpensive raw materials.

In this regard, we paid special attention to the fact that in modern mechanical engineering, large reserves of raw materials are available that are generally not used to manufacture of parts for various purposes [19–21].

Such cheap, accessible, and large quantities of raw materials include grinding waste of non-ferrous and ferrous metals, alloys used for production of machines and instruments. This type of waste is generated daily from the grinding operations of dies, cutting tools, ball bearings, engine pistons, and other structural parts. The waste is taken to dumps or landfills and not used in the production cycle because of abrasive contamination from grinding wheels [19–21].

This necessitates the construction of many additional landfills to dispose of such waste material by burying it, which irreparably pollutes the ecosystem and biosphere and is an acute environmental problem on a global scale.

Metal grinding waste contains valuable alloying elements, such as Cr, Mo, W, Si, Ni, V, Al, Co, Ti, Nb, etc.

The presence of these alloying elements in grinding waste in various quantities and combinations make them attractive for further use in order to obtain quality high-alloy antifriction composites and parts [19–21].

The use of industrial grinding waste is important for many reasons. First, it is a cheap raw materials; secondly, it is extremely valuable for its content of alloying elements presence in waste powders; and thirdly, it is available in large quantities.

Using such valuable raw materials in large quantities in the re-production cycle can alleviate the global problem of environmental pollution. Great opportunities are also

created for the use of cheap, affordable, and efficient raw materials, as well as the creation of innovative resource and energy saving technologies.

Such valuable grinding waste includes high-alloy tool steel waste, such as H12, H13 (ASTM A681 International Standard, USA), 1.2365 (X32CrMoV33), 1.2606 (X37CrMoW5-1) (DIN EN ISO 4957, Germany), BH11, BH12 (BS 4659 Standard, UK), SKD6, SKD62 (JIS G4404 Standard, Japan), etc.

Grinding waste is generated during the finishing operations in the manufacture of various parts from ferrous and non-ferrous alloys, namely during the grinding process. Because the grinding process is always carried out using an abrasive tool (abrasive wheels), abrasive particles inevitably mix with the metal microchips. This is a serious obstacle for the further use of metal waste; therefore, such grinding waste is taken to dumps at landfills.

One of the main challenges is to obtain purified raw materials from grinding waste for use in the creation of new materials.

The authors of [19–21] developed a waste recovery technology and obtained the first positive results in the creation of new high-temperature antifriction composites based on regenerated grinding waste steels ShKh15SG, R6M5, and 7HG2VMF (analogue of 52100 ball bearing steel, M2 high-speed steel, and AM6F2 tool steel, respectively; AISI Standard, USA).

Composites based on the waste powders of these steels with the addition of CaF_2 solid lubricant were able to work at elevated temperatures and withstand elevated loads in an oxidizing environment (in air) [19–21].

Nevertheless, many questions remain to be investigated. Among the unstudied issues are the possibility of using a wider variety of grinding waste from various steel grades, the possibility of their application to create effective new composites, the regularities of their structural properties and formation, the behavior of new composites under different operating conditions, etc.

Research in direction is important not only from a scientific but also a practical point of view.

Creating antifriction composites for severe operating conditions is complicated by the wide variety of conflicting theories in the field of friction and wear; the absence of correlations between various properties, phase compositions, and structural and tribological characteristics of composites; limited information on phase composition; and the complete absence of information about the quantitative ratio between the formed phases in the working friction film, especially in the presence of solid lubricants.

These circumstances became the basis for research aimed at creating new antifriction composites based on grinding steel waste for operation at rotation speeds up to 7000 rpm and increased loads of up to 5.0 MPa. Research has also focused on expanding the technological possibility of using a wider range of secondary raw materials to predict and control material functional properties. This would facilitate the task of finding new types of raw materials and the creation of resource saving technologies in addition to alleviating the problem of global environmental pollution.

The aim of this research is to investigate the features of structure formation and their influence on the properties of new antifriction composites based on 4H4VMFS industrial tool steel grinding waste (analogue of tool steel H12, ASTM A681 International Standard, USA) with CaF_2 solid lubricant additives designed for the friction units of offset cylinders in printing machines in self-lubrication mode at rotation speeds up to 7000 rpm and loads of up to 5.0 MPa in air.

2. Experimental Procedure

2.1. Preparatory Procedures

The subject of study was new antifriction composite based on 4H4VMFS tool steel grinding waste with CaF_2 solid lubricant (Table 1).

Table 1. Chemical composition of the materials based on 4H4VMFS tool steel grinding waste.

Components, wt. %										
C	W	Cr	Mo	Si	Mn	V	S	P	Fe	CaF ₂
0.37–0.44	0.8–1.2	3.2–4.0	1.2–1.5	0.60–1.0	0.2–0.5	0.6–0.9	0.02–0.03	0.02–0.03	basis	4.0–6.0

4H4VMFS steel is the closest analogue of H12 tool steel (ASTM A681 International Standard, USA), 1.2606 (X37CrMoW5-1) (DIN EN ISO 4957, Germany), BH12 (BS 4659 Standard, UK), or SKD62 (JIS G4404 Standard, Japan).

Grinding powder waste of 4H4VMFS tool steel is formed during the grinding process of various cast tools and contaminated with abrasive particles from the grinding wheels. This grinding waste is in the form of microchips. However, this steel contains valuable alloying elements (Table 1). The microchips used in this study had initial sizes ranging from 70 to 250 μm immediately after the grinding process.

Cleaning the grinding waste of 4H4VMFS steel by magnetic separation [19–21] decreased abrasive particles to 2 wt.%, which corresponds to 1.6 vol. %, taking into account their density. This residual amount of abrasive particles had no effect on the composite's antifriction properties. In addition, a small amount of abrasive can act as a kind of framework when combined with hard inclusions in a soft matrix, according to the well-known principle of creating antifriction materials.

Steel grinding waste is formed during the finishing process of cast parts in industrial plants. This waste is highly oxidized due to the high temperatures generated by the friction of the abrasive wheel against the part. Therefore, an obligatory operation was performed to reduce the total oxygen content in the grinding waste because such powders are oxidized in the grinding process. Reductive high-temperature annealing at 900–1000 $^{\circ}\text{C}$ provided a twofold decrease in the total amount of oxygen. Recovery annealing was carried out for 2 h in an atmosphere of continuous hydrogen supply. Hydrogen was found to be a strong reducing agent of oxides in 4H4VMFS steel waste powders. After annealing, the formed conglomerates were crushed in a crushing machine and sifted through a sieve into fractions.

Regenerated powders (microchips) of 4H4VMFS steel (125–160 μm in size) prepared by this method were used as the initial charge for subsequent manufacture of antifriction composites.

The presence of variously dispersed powder particles improves further compaction and minimizes porosity.

The new antifriction composite was designed to operate at high rotational speeds. A solid lubricant was added to the original powder charge. Calcium fluoride was chosen as a solid lubricant due to its stable performance under severe operating conditions (Table 1), such as high temperatures, loads, or rotational speeds [6–8,19].

2.2. Charge Preparation and Consolidation

The initial charge had a composition of 4H4VMFS steel + (4–6) wt.% CaF₂ after the mixing of metal powders (4H4VMFS steel regenerated waste) and nonmetallic powders (CaF₂ solid lubricant). The powders were mixed in a can mixer for 4 h with the addition of ethyl alcohol to avoid density segregations. Subsequently, the powder mixture was pressed at $P = 850\text{--}900$ MPa and sintered at $T = 1100\text{--}1150$ $^{\circ}\text{C}$ for 4 h in a hydrogen environment. The criteria for the selection of the above pressing and sintering parameters were the values of the samples' mechanical properties, as described in [19], where similar results were obtained. Maximum values of the mechanical properties were achieved with the abovementioned pressing and sintering parameters. Particular attention was paid to the change in volumetric shrinkage ($\Delta V/V$). The maximum value of volumetric shrinkage was achieved at a temperature of 1150 $^{\circ}\text{C}$ and amounted to ~18%. Sintering temperatures of 1100–1150 $^{\circ}\text{C}$ have been found to afford the maximum density [21]. After sintering, porosity was in the range of 10–12%.

2.3. Examination Techniques

Structural studies were performed using electron microscopy (SEM). The mechanical properties of the new composites were determined according to standard procedures using standard equipment. For comparative tests, we used 20 samples of the studied composite and cast bronze C83600 unhardened by heat treatment. Tests were performed according to standard methods by ASTM D7264, ISO 6506/ASTM E10. Tribological tests were performed according to the end-friction scheme with a 5 km friction track. Friction and wear tests were carried out on a VMT-1 friction machine under the following operating conditions: rotation speed, 7000–8000 rpm; load, $P = 5.0$ MPa in air; a counter face made of 9H2 cast steel, which is an analogue of I3 (10I30) alloyed roll steel (AISI standard, USA, hardness 55–58 HRC). 9H2 cast steel corresponds to the shaft material of an offset cylinder in a printing machine, with a chemical composition as follows: wt.%: 0.85–0.95 carbon, 0.25–0.5 silicon, 0.2–0.7 manganese, 1.7–2.1 chromium, 0.5 nickel, 0.03 sulfur, 0.03 phosphorus, and iron as the base.

3. Experimental Results and Discussion

A heterophase structure was formed in the 4H4VMFS- CaF_2 composite after sintering (Figure 1).

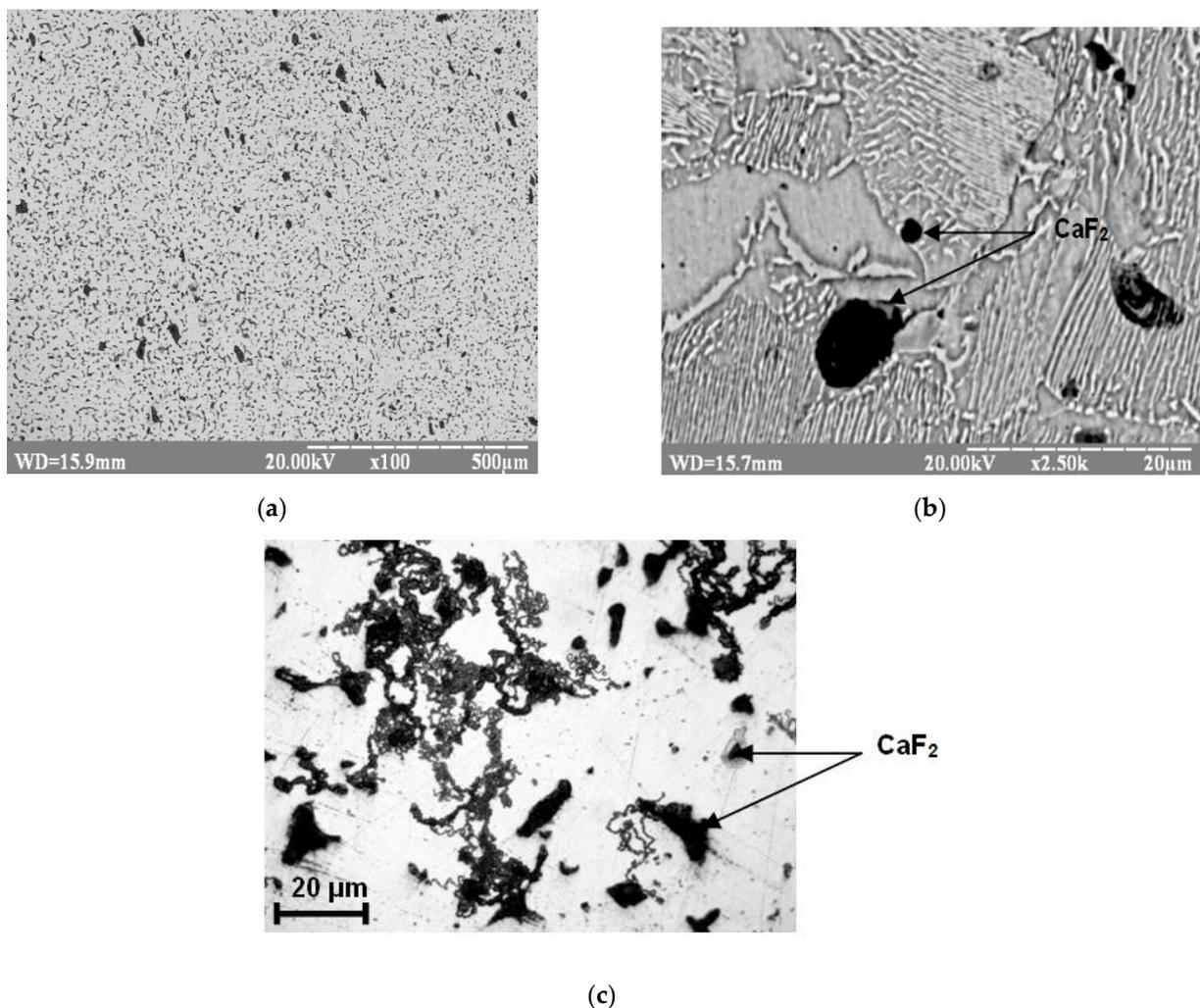


Figure 1. Microstructure of the 4H4VMFS + 5% CaF_2 composite. Dark inclusions— CaF_2 ; (a) electron microscopy; (b) a fragment of perlite in a metal matrix, electron microscopy; (c) CaF_2 distribution, optical microscopy (the section is not etched).

The structure unites a metal ferritic-perlite matrix (Figure 1b) and distributed particles of CaF_2 solid lubricant (Figure 1c).

The metal matrix structure of the composite based on 4H4VMFS steel waste significantly differs from that of 4H4VMFS cast steel. In particular, it does not suffer the disadvantages of cast tool steels, such as carbide segregation. This is due to the fact that the composite material is formed from individual particles of metal waste, which are essentially micro-ingots. This feature excludes the appearance of carbide segregation, which has a positive effect on the properties of the composite material.

The carbide phase in perlite (Figure 2) is presented in the form of carbides of alloying elements (Figures 3 and 4).

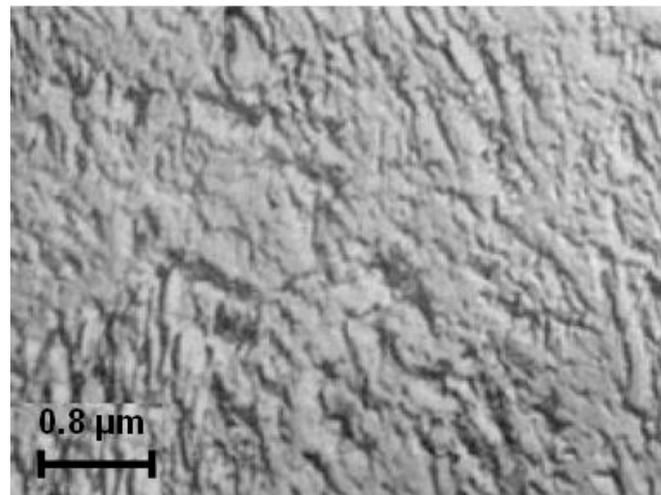


Figure 2. Fine-grained structure of perlite phase.

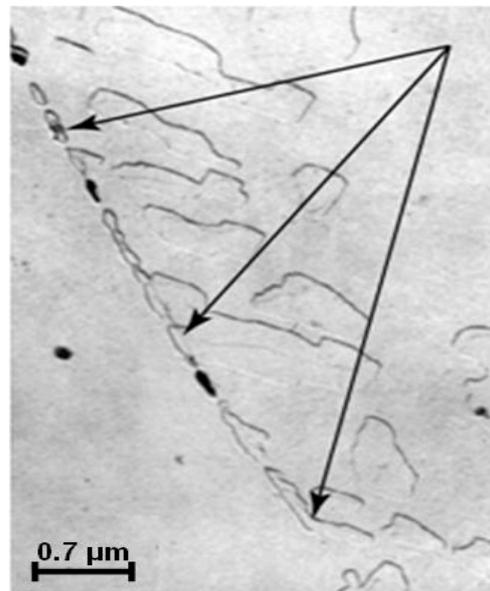


Figure 3. The $(\text{Cr, Fe, Mo, W, V})_{23}\text{C}_6$ carbides, shown by arrows (direct coal replica).

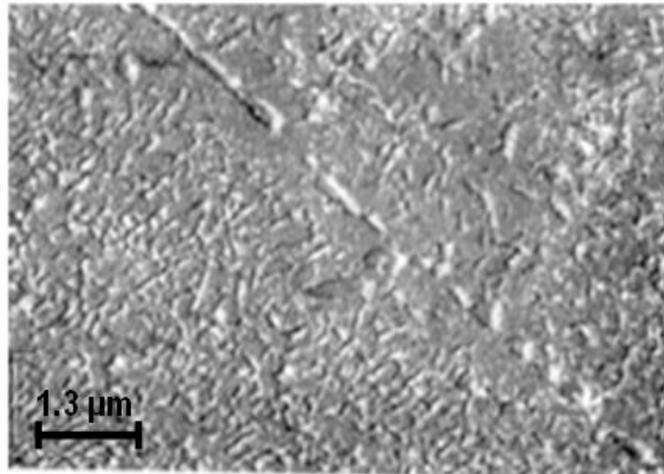


Figure 4. Particles of the $(\text{Fe, Mo, W})_6\text{C}$ fine-grained carbides.

The presence of large amounts of carbides in 4H4VMFS tool steel is due to the presence of alloying elements V, W, Mo, and Cr [22,23]. Vanadium, tungsten, molybdenum, and chromium are known to be strong carbide-forming elements [22–25].

Such carbides are of varying composition and nature. Carbides of chromium, molybdenum, tungsten, and vanadium increase mechanical properties and expand the normal wear zone during friction. Carbides Me_6C and Me_{23}C_6 are the main strengthening phases in the metal matrix of the composite based on 4H4VMFS steel waste and were detected using extraction replicas (Figures 3 and 4).

The following complex carbides are present in the metal matrix of the material:

- Me_{23}C_6 type— $(\text{Cr, Fe, Mo, W, V})_{23}\text{C}_6$ is a complex chromium carbide; it has a size of 3–5 microns and retains a high dispersion due to a low coagulation tendency;
- Me_7C_3 type— $(\text{Cr, Fe, Mo, W, V})_7\text{C}_3$ is complex chromium carbide in which V, W, and Mo are dissolved; it increases the resistance of 4H4VMFS steel against softening during heating. This carbide was found to significantly increase wear resistance [22,23,26], which also contributes to an increase in antifriction properties during operation under severe friction conditions.
- Me_6C type— $(\text{Mo, Fe, Cr, W, V})_6\text{C}$ is complex carbide with high hardness that increases wear resistance and decreases the friction coefficient value;
- Me_2C and MeC types are Mo and W carbides (Mo_2C , W_2C), as well as VC carbides. These carbides contribute to increased hardness.

Silicon in the pearlite of 4H4VMFS tool steel increases the $\alpha \rightarrow \gamma$ transformation temperature and thereby contributes to an increase in heat resistance. In addition, silicon contributes to the preservation of fine grains, making self-diffusion difficult. Silicon strengthens ferrite, increasing the hardness of the material after sintering [22,26].

Therefore, alloying elements in waste powders contribute to the formation of phases in composites that are responsible for the formation of operational properties.

Furthermore, almost all alloying elements in 4H4VMFS steel waste increase the maximum allowable loads. The greatest maximum load is provided by carbon, tungsten, molybdenum, and vanadium [22,26,27]. This allows for an intensification of the new material's operation modes.

Therefore, the main strengthening phases in the material matrix based on 4H4VMFS steel grinding waste are carbides Me_6C , Me_7C_3 , Me_{23}C_6 , Me_2C , and MeC . Molybdenum and tungsten play similar roles; they make it difficult for carbides to be precipitated at grain boundaries [22,25–27].

All carbides improve the resistance of the composite against abrasive wear and increase its resistance against plastic deformation.

Thus, a heterophase fine-grained structure was formed in the process of sintering composites using 4H4VMFS steel waste powders with CaF_2 additives. The structure comprises a metal matrix consisting of a high-alloy α -solid solution and solid grains of complex alloying-element carbides, as well as evenly distributed CaF_2 inclusions of antiseizure solid lubricant.

Such a material-bearing structure results in the most favorable combination of mechanical and antifriction characteristics, the values of which are given in Table 2. In our case, the composite has an optimal combination of hardness and bending strength.

Table 2. Properties of composite based on 4H4VMFS tool steel grinding waste.

Composition, wt.%	Bending Strength, σ_s , MPa	Hardness, HB, MPa	Friction Coefficient, V = 7000 rpm	Wear Rate, $\mu\text{m}/\text{km}$, V = 7000 rpm	Wear Rate, $\mu\text{m}/\text{km}$, V = 8000 rpm
4H4VMFS + 5CaF ₂	320–360	800–820	0.18–0.22	64–67	340–420
Bronze cast alloy C83600 * (Cu85Sn5Zn5Pb5), C93200 Standard ASTM, USA	147–240	380–400	0.30–0.42	490–520	980–1036

* Friction without lubrication.

Analysis of the results (Table 2) shows the new composites have much higher mechanical (approx. 1.5–2.0 times) and antifriction properties (approx. 3.0–7.0 times) and are able to operate at higher rotational speeds and loads in self-lubrication mode compared to bronze C83600 (ASTM C93200 Standard, USA), which is currently used in high-speed offset cylinder units. Self-lubrication mode occurs as a result of the formation of antiseizure lubricating films. These films possess the high antifriction properties of the composites (Figure 5).

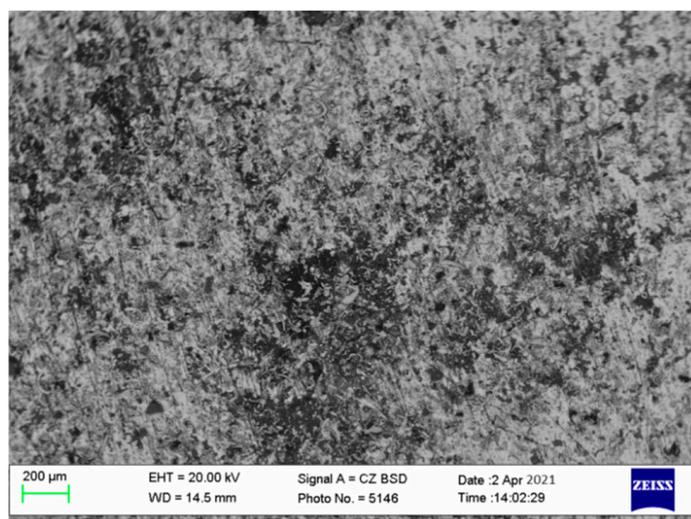


Figure 5. Antifriction film (white).

The white films formed during friction (Figure 5) completely cover the contact surface area and protect the friction unit from intense wear.

Under such operating conditions, an equilibrium state is observed between the formation and wear of antiseizure films at rotational speeds up to 7000 rpm.

However, this balance is disturbed when the speed is increased to 8000 rpm. This is due to the fact that the friction films are worn out before they can be formed again at such speeds. Such friction conditions lead to an intensification of the wear process and failure of the friction unit of the offset cylinder.

Antifriction films formed at speeds up to 7000 rpm (Figure 5) are dense and smooth, with a thickness of 20–30 μm . They are formed in two stages: first, individual white spots (CaF_2) appear on the surface, which are then “smeared”, forming a homogeneous smooth surface. As a result, a “wear free” effect is realized, which stabilizes the work of the friction unit.

The presence of alloying elements that form a heterophase structure reduces the wear intensity and friction coefficient, especially in the presence of CaF_2 solid lubricant. Therefore, the new composite is able to operate stably at higher speeds compared to cast bronzes currently used in the friction units of rolled newspaper printing machines.

Reducing the friction coefficient and wear intensity causes an increase in the stability of the contact pair due to less intense heat generation during friction and prevents deformation of the unit elements.

4. Conclusions

In this study, we developed a new and effective self-lubricating antifriction composite based on 4H4VMFS steel grinding waste. This composite showed high tribological properties at rotation speeds up to 7000 rpm and increased loads of up to 5 MPa, which is typical in the operation of friction units of offset cylinders in printing equipment.

Comparative tests have showed the significant advantages of the new waste composite compared to cast bronze parts, which are traditionally used in the friction units of rolled newspaper printing machines.

Previous studies have demonstrated the technological possibilities of controlling the structure and functional properties of antifriction composites based on valuable grinding waste.

To achieve this, it is necessary to select the appropriate type of ferrous or non-ferrous grinding waste depending on the intended use, vary the amount of solid lubricant, and apply rational manufacturing modes to obtain the predicted structure and functional properties.

Our results convincingly demonstrate the usefulness of a wide range of alloy steels in valuable grinding waste for use in the repeated production cycle to manufacture high-quality antifriction composites for severe operating conditions.

Future research will be devoted to expanding the assortment of grinding waste of ferrous and non-ferrous metals for use in the manufacture of composites for various operating conditions.

Such developments are important not only from a scientific but also a practical point of view, as they facilitate the effective use of cheap, valuable, and affordable raw materials and help to mitigate environmental problems.

In this study, we addressed a number of important issues, including the functional behavior of composites from waste under the action of heavy loads, temperatures or speeds in combination with the action of atmospheric oxygen, the interaction of individual chemical elements and phases in friction films, and the control of the formation process of self-lubricating films.

Solving these issues will not only present opportunities to obtain effective composites with specified characteristics but will also alleviate environmental problems, such as pollution connected to human industrial activity, mitigating negative impacts on ecosystems and the biosphere [28–30]. Reuse of industrial metal waste on a large scale is a step towards sustainable development as a global process of change to maintain ecological and economic balance [31].

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