Розроблено антифрикційні композити на основі регенерованих шліфувальних відходів алюмінієвого сплаву АМ4,5Кд з додаванням твердої змащувальної речовини MoS_2, що призначені для роботи у контактних парах постдрукарських машин, таких як фальцювально-клейові машини та машини для вклеювання в пакування.

Аналіз структури нового композиту показав, що легуючі елементи металевої основи утворюють зміцнюючі фази, що рівномірно розподілені в матриці без сегрегаційних скупчень, що сприяє підвищенню конструкційної міцності. Дисульфід молібдену забезпечує ефект самозмащення контактної пари у процесі експлуатації, що обумовлює зниження коефіцієнту тертя і інтенсивності зношування порівняно з композитним матеріалом без твердого мастила. Структурні дослідження засвідчили рівномірність розподілу твердого мастила в усьому об'ємі композиту, що забезпечує підвищення триботехнічних характеристик завдяки формуванню захисних антизадирних плівок тертя при роботі деталі складної геометричної форми в умовах самозмащення.

Аналіз функціональних властивостей дозволяє рекомендувати антифрикційний композит на основі промислових шліфувальних відходів алюмінієвого сплаву АМ4,5Кд з домішками твердого мастила – дисульфіду молібдену MoS_2 для деталей контактних з'єднань складної геометричної форми, що працюють при підвищених дискретних швидкостях ковзання і навантаженнях без змащування рідким мастилом в атмосфері повітря.

Триботехнічні випробування продемонстрували, що новий композитний зносостійкий матеріал, одержаний за розробленою технологією виготовлення, дозволяє форсувати гранично-допустимі режими навантаження і робочі швидкості ковзання при стабільно високих антифрикційних властивостях нових композитних тертьових деталей постдрукарських машин

Ключові слова: шліфувальні відходи, алюмінієвий сплав, тверде мастило, структурні дослідження, антифрикційні властивості, постдрукарські машини

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ANALYSIS OF THE PROPERTIES OF ANTIFRICTION COMPOSITES BASED ON ALUMINUM ALLOY'S GRINDING WASTE

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1. Introduction

The efficiency of operation of equipment in the printing industry depends on stability of operation of contact pairs to a large extent, because contact pairs determine wear resistances of a concrete friction unit and a machine in general.

Wearing of parts of contact joints, particularly antifriction parts, causes misbalance of a unit due to changes in sizes of worn parts, which leads to instability of equipment, loss of productivity and lower quality of products [1, 2]. Authors of papers [3, 4] proved that a number and a term of inter-repair works depends on friction joints by 70 %.

Reasons for failures of brochure and binding equipment, namely folding apparatus, cutting machines, machines for pasting of individual elements into packaging, automatic backing machines, etc. are the same. Post-printing equipment occupies one of the leading places in the printing industry. It is an integral part of the technological process of manufacturing of printed products [1].

Most failures (up to 80 %) of such kind of equipment occur due to the wear of friction parts. The above is a consequence, above all, of imperfections in foundry manufacturing technologies, which causes permanent malfunction of such technologies. Equipment requires a large number of spare parts. It increases material costs of repairs and leads to defects in printed products.

Specialists in operation of the equipment described above state that the main factor, which causes its failure and defects of products, is the wear of antifriction elements of contact pairs [3].

Thus, according to the State Press Publishing House of Ukraine, the State Enterprise Polygraph Combine "Ukraine" and LLC "Factory of Experimental Industrial Technologies" (Kyiv) for 2016–2018 years, the duration of operation of antifriction parts made of cast aluminum alloys such as AK12, AM4.5Kd, AK12MMgN, AK8, D16, etc., lasted 1.5 years only in knife cutting machines of Wohlenberg Trim-tec 560 and Wohlenberg Trim-tec 607 types, in folding apparatus of Heidelberg-IF-50-ST type, in folding-gluing machines of "Bobst Mistral 110 A2" type, in "Heiber & Schroeder wp 800 d" machines for pasting of elements to a package and others, due to imperfection of existing manufacturing technologies, which results in an increase in defects of printed products.

Therefore, the task of the increase of wear resistance and durability of friction parts of post-print machines by creation of new technologies for production of efficient materials of affordable and cheap raw materials is relevant and requires implementation of a complex of studies.

2. Literature review and problem statement

An objective requirement for the further development of the printing industry is a constant improvement of the quality of the printing industry, which definitely depends on the quality of printing equipment [1].

Taking into consideration a high competition in production of polygraph and post-polygraph equipment, specialists pay special attention to high requirements for a functional purpose, accuracy and performance of such machines. The most important are issues of increasing of reliability of units of the indicated equipment and individual components, particularly antifriction parts [2, 3].

Improvement of operation of friction couples is an important issue, because they are responsible for stability of operation of printing equipment in general and post-print in particular [2, 3].

There are tribotechnical studies in works [1–3]. However, they remained the issue of technological features of manufacturing of parts of printing equipment unclear. Papers [4–6] confirmed the above. Specifically, their authors refer to the low level of operational properties of materials developed for friction units.

On the one hand, the widespread use of cast antifriction parts, particularly made of aluminum, is increasing steadily due to significant advantages, as evidenced by studies highlighted in paper [6]. However, casting technology limits the level of antifriction characteristics by almost half due to a use of liquid lubricants. For example, authors of paper [3] presented results of a sharp decrease in fatigue strength of friction parts at operation with liquid lubricants, which contain dissolved organic acids and cause corrosion.

Another approach to development of friction parts is a use of powder manufacturing technology. Authors of works [7, 8] proved possibility of addition of various functional substances to a composition of an initial charge. Substances provide composite operation characteristics, which we can't achieve at application of traditional metallurgical methods. Authors of work [7] found that introduction of a solid lubricant into a friction contact increases the level of antifriction properties due to formation of a lubricating film on a surface of partition. Efficiency of a lubricating action increases at an increase in a load due to a decrease in a displacement stress. Papers [7–9] presented numerous studies on properties of composite materials based on copper, nickel and aluminum with inclusions of different types of solid lubricants. However, data on a use of aluminum alloys for production of new composite components of any purpose are limited due to existing technological difficulties in manufacturing of powder materials and high prices of raw materials (powders) and equipment for its manufacturing. One of the solutions to the mentioned difficulties today is an application of secondary processes for processing of aluminum, as evidenced by technologically and economically substantiated research papers [10–12]. This approach is in line with the European Union's environmental policy in the field of waste management.

As we know, it is possible to use industrial grinding waste metal of machine-building and instrument-making production formed at final operations of grinding of various structural parts and after corresponding processing in a repeated production cycle. However, today there are no studies on a combination of resource-saving technologies with methods of powder metallurgy, which could increase properties of parts under difficult operation conditions and simplify the manufacturing technology.

However, today there is no comprehensive study of a combination of powder metallurgy with resource-saving technology for a use of industrial grinding waste.

However, today there is no research on regeneration of secondary raw materials and introduction of additional compositions due to a lack of advanced technologies of powder metallurgy [11, 12].

All the above suggests that one of the ways to solve the scientific and technical problem is to develop a technology for restoration of grinding waste of aluminum alloys by powder metallurgy methods. This will give possibility to use a valuable refurbished metal base for production of high-quality antifriction components of complex geometric shape, particularly for units of folding-gluing machines and machines for pasting of elements into a package [7, 13].

3. The aim and objectives of the study

The objective of this study was to develop technological modes for manufacturing and to investigate their influence on formation of a structure and functional properties of new composites.

We formulated the following tasks to achieve the objective:

– development of a technology for regeneration of industrial grinding waste and establishment of an influence of new technological modes on formation of a structure and properties of materials;

– substantiation of a use of solid lubricant and conduction of experiments on production of antifriction composites of AM4.5Kd - MoS_2 system with application of new technological modes of consolidation;

– conduction of experimental studies on determination of tribotechnical properties of new materials based on aluminum alloys waste in self-lubrication mode;

– development of recommendations for a use of new materials made of industrial grinding waste of AM4,5Kd aluminum alloy in friction units of printing equipment based on the obtained results of the study on a structure and properties.

4. Materials and methods to study composite antifriction materials

4. 1. Investigated materials and equipment used in experiments

We selected industrial grinding waste of AM4.5Kd aluminum alloy as a basis for antifriction composite materials. Table 1 shows the main percentage of components. The chemical composition of AM4.5Kd alloy corresponds to the AlCu4MgSi alloy in accordance with ISO 209-1:2002 international standard.

Table 1

Chemical composition of AM4.5Kd alloy (DSTU 2839-94)

Percentage content of components, % by weight						
Si	Cu	Mn	Mg	Zn	Sn	Cr
0.3–0.8	4.5–5.1	0.35–0.80	0.03–0.05	0.06–0.1	0.01–0.02	0.1–0.3
Percentage content of components, % by weight						
Ni	Na	Fe	Ti	Cd	Zr	Al
0.1–0.2	0.05–0.1	0.1–0.15	0.15–0.35	0.07–0.25	0.10–0.15	rest

AM4.5Kd alloy contains a large number of valuable alloying elements (Table 1). In addition to a high-alloy α-solid solution based on aluminum, they form a series of reinforcing phases in double and triple Al-Cu, Al-Mn, Al-Ni, Al-Ti, Al-Cu-Mn systems and Cd and Zr separate inclusions. Such phase composition of the matrix basis can enable a high level of physical-mechanical properties of a composite and to determine its structural strength. This is an important factor for operation of a part under medium loaded friction conditions. And this is a substantiation for selection of AM4.5Kd alloy as a basis for an antifriction composite.

Any liquid lubricant doesn't work under mid-heavy conditions of a friction pair, when there is an effect of increased sliding rates and, as a result, an occurrence of elevated temperatures on operation surfaces. That is why it is necessary to use impurities. They act as solid or dry lubricants.

Introduction of composite sintered materials has the following advantages:

– ensuring of specified properties in the process of manufacturing and systematic reproduction in the process of exploitation;

– continuous restoration of a produced separating layer, which determines stability and duration of a friction unit;

– simplification of maintenance of a bearing unit, etc.

The mechanism of lubricating action of a substance, which acts as a lubricant, depends on operation conditions of a friction pair. Structural properties determine lubricity of a substance, mainly, in cases where temperature is insignificant. A transition from light modes to medium friction modes changes a mechanism of lubrication. We know [3, 7] that activation of solids particles the mechanism of lubrication due to destruction of bonds inside a crystalline lattice of particles material. The destruction of solids particles affects the friction mechanism, and, in this case, the most important factors, which determine the mechanism of lubrication action of solid lubricants, will be structural properties (type, shape and size of a crystalline solids lattice) and adhesion ability [7–10].

Finally, intense deformation of layers of powdered oils and a friction metal layer, as well as a rise in temperature accompany the transition to heavy friction modes. As a result, the rate of chemical reactions and diffusion processes in material of a part and a counterpart increase. Chemically modified thin, superficial layers, which provide lubricating performance under difficult conditions, appear.

Compositions of material of a friction pair, lubricant and the medium where friction occurs determine composition of layers [14–16].

We can explain the selection of MoS_2 molybdenum disulfide solid lubricant and its amount by several reasons. First, we know that it is a solid-lubricant [17, 18] chemically and thermally stable to 600 °C, which guarantees its unobstructed presence in a composite as in the manufacturing process, and in the process of exploitation of material. Second, molybdenum disulfide is an effective lubricant in the air under not difficult or medium-difficult conditions of operation of a part [7]. Third, the amount of MoS_2 added to the initial charge was 9.0–12.0 % by weight. Authors [7, 16, 18] found that the amount of MoS_2 less than 9.0 % was insufficient to perform a surface lubrication function. Mechanical properties of composites, particularly plastic characteristics, and a structural strength of material decreases significantly with MoS_2 content larger than 12.0 %. The above-mentioned circumstances became a basis for formation of the hypothesis about possibility of obtaining of a complex structure of a new composite based on AM4.5Kd alloy with presence of MoS_2. Such a structure of a new composite will be able to provide a high level of complex properties of parts in medium loaded units of friction, especially at operation in self-lubricating mode.

The next step in the study was development of technology and adjustment of new production modes in the following sequence.

The first stage of compacting and consolidation was regeneration of output grinding waste of AM4.5Kd alloy by the developed technological modes [11, 17]. First of all, there were cleaning of grinding waste from abrasive crumb by electrodynamic separation. The residual amount of abrasive was 3 % after the electrodynamic cleaning.

The next step in the process of regeneration of grinding waste was an operation of drying of powders from residual moisture. Further, we mixed metal powders with non-metallic solids of powders of molybdenum disulfide MoS_2 in the amount of 9.0–12.0 % by weight, and compressed at pressures of 450–500 MPa at room temperature.

Subsequently, formed presses go to a hot-pressing process operation at pressures of 280–300 MPa and the heating temperature of 400 °C to minimize porosity [7]. The use of a hot-pressing process provides complete diffusion homogenization of a composite. This minimizes porosity, and, as a result, increases a structural strength of antifriction material based on AM4.5Kd alloy powder-waste. The relative density of composites was 0.98–0.99 after manufacturing according to the worked out technological modes.

We studied the structure of the antifriction composites with a use of metallographic and raster electron microscopes, we identified molybdenum disulfides in the matrix by scanning electron microscopy (CEM) and analyzed it with a use of the method of energy-dispersive X-ray spectroscopy (EDX) [19, 20].

In addition, we used CEM image for quantitive description of MoS_2 in the antifriction composite. We evaluated MoS_2 content with a use of micrometric software [20, 21].

We performed physical-and-mechanical tests according to the standard methods given in publications [22].

We carried out tribotechnical tests at the testing VMT-1 friction machine in the air at a sliding velocity of 1.0–3.0 m/s, loads per friction pair of 2.0–4.0 MPa in pairs with a counterpart of steel 45 (HRC 45-48) without lubricating with liquid lubricant (under self-lubrication) according to the authors' original method [21]. A counterpart made of steel 45 had a surface roughness parameter Ra=0.94–1.32 μm after final machining processing with lever grinding wheels.

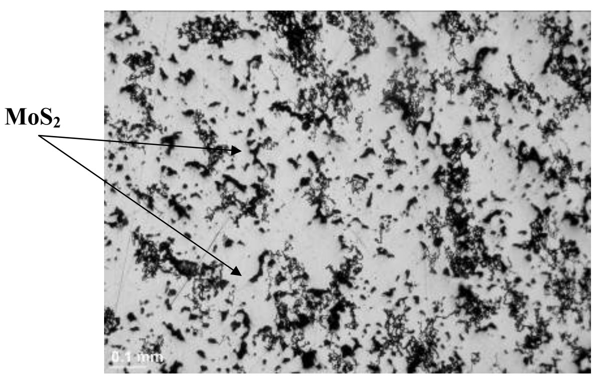
We selected the range of tribological research parameters based on conditions of operation of frictional connections of post-printing machines.

5. Results of studying the operational properties of composites based on grinding aluminum alloy waste

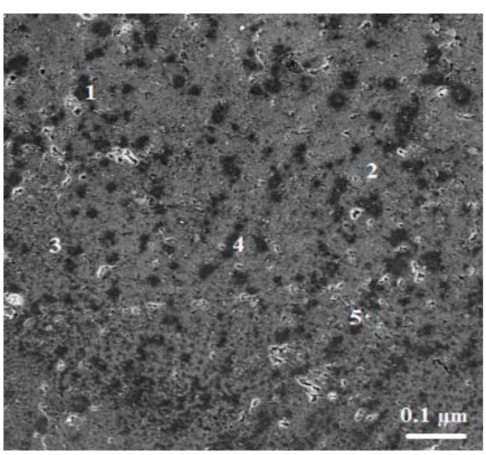
Developed technological methods for production of workpieces of regenerated grinding wastes of AM4.5Kd alloy consist of a combination of resource-saving technologies and powder metallurgy techniques. As a result, we obtained a complex heterogeneous structure of a new material based on grinding waste with impurities of MoS_2 solid lubricant (Fig. 1).

Studies showed that MoS_2 solid lubricant does not form segregations in the sample volume and is evenly spaced in a structure of the investigated composite (Fig. 1). This fact indicates the correctness of the applied manufacturing operations.

The structure of the investigated composite is an aluminum base in the form of a cast α-solid solution with evenly spaced particles of a solid lubricating component – molybdenum disulfide (Fig. 1).



a



b

Fig. 1. Structure of AM4.5Kd+10 % MoS_2: *a* – distribution of MoS_2 indicated by arrows, there is a section not etched; *b* – is an image of intermetallic (1 – $CuAl_2$, 2 – $MnAl_6$, 3 – $NiAl_3$, 4 – $TiAl_3$, 5 – Al_2CuMn), there is a section etched (NaOH). We obtained the image from a metallographic microscope

MoS_2 molybdenum disulfide has a thermal stability to temperatures of 550–600 °C, which guarantees its presence in a constant initial state in material, both in the manufacturing process and under operation conditions [3, 7]. Fig. 1, *a* shows the distribution of MoS_2 in the metal matrix of the test material.

The indicated phenomenological peculiarities of distribution and dispersion of MoS_2 solid lubricant (Fig. 1, *a*) are a positive factor. Continuous lubrication of it on both contacting surfaces of the friction pair, namely, on the surface of the antifriction part and the combined counterpart during operation proves this [21].

Phases of $CuAl_2$ formed at the stage of production of AM4.5Kd alloy are effective reinforcers – $NiAl_3$, $TiAl_3$ intermetallics together with $MnAl_6$, Al_2CuMn phases strengthen solid aluminum-based solution and increase mechanical properties of composite material [22, 23].

Fig. 1, *b* shows distribution of the strengthening phases in the structure of the investigated material. We detected it with using the JDX-MAPI X-ray micro diffractometer (Japan).

The presence of the stable Al_2CuMn compound stable at elevated temperatures in the metal matrix, as well as the presence of $CuAl_2$, $NiAl_3$ and $TiAl_3$ intermetallics, causes alloy's ability to maintain high mechanical properties [24]. The presence of cadmium and zirconium, which form their own phases in the structure of material, in the aluminum matrix contribute to formation of a complex heterophase structure of the antifriction material.

Cadmium is almost insoluble in aluminum in the solid state. It lies in a metal matrix as individual crystals. It slows down the movement of holes to grain boundaries and promotes formation of loop dislocations and strengthens a connection between discharges of hardening phases and a metal matrix of a solid solution [7, 16, 18].

We know from papers [7, 2] that a chemical element, zirconium, is almost insoluble metal in an aluminum-based alloy. Zirconium forms intermetallic inclusion of $ZrAl_3$ type at the stage of foundry of AM4.5Kd alloy. They play a role of strong grain shredders and help to increase recrystallization temperature of material. This is a positive factor for maintenance of a structural strength of a composite at moments of an unexpected increase in operational loads.

In addition, the presence of tin in the metal matrix of material, which gets into AM4.5Kd alloy in the process of foundry, contributes to an increase in plasticity of a composite [1, 9]. This fact positively affects ability of parts to run in fast in start-up and adjustment periods of equipment. In addition, tin, as a soft metal, makes an additional contribution to the process of mass transfer during operation of a contact pair due to its property to be distributed along boundaries of grains in the volume of metal [9, 16]. This is especially important in operation of a component of a complex semi-circular form in medium loaded operation modes under the conditions of discrete application of external loads.

The formed structure of the investigated composite provided formation of a complex of physical-mechanical and tribotechnical properties. Tables 2 and 3 show them.

Analysis of data of Tables 2 and 3 shows that the composite made on the basis of grinding wastes of AM4.5Kd alloy with MoS_2 solid lubricant is almost inferior to cast alloy by mechanical characteristics [1–3, 7]. At the same time, the material developed exceeds the cast analogue at friction without liquid lubricant significantly by antifriction properties.

Such behavior of the investigated material lies in significant differences in the structure of the composite and

AM4.5Kd base cast aluminum alloy, which arise from various principles of synthesis of materials.

The essential disadvantages of the cast alloy are liquidation and segregation phenomena of AM4.5Kd alloy, which are inherent to alloys obtained by traditional foundry technology.

Table 2

Physical-mechanical properties of the studied antifriction composites and cast alloy

No.	Material, % by weight	Tensile strength, MPa	Hardness, HB, MPa	Impact viscosity, kJ/m^2
1	Composite material AM4.5Kd + +(9.0–12.0) MoS_2	179–184	570–590	0.22–0.28
2	Cast alloy AM4.5Kd [14]	187	630	0.30–0.40

Table 3

Tribotechnical characteristics of the studied composites

Composition of material, % by weight	Boundary permissible load, MPa	Coefficient of friction (f) and intensity of wear (I), μm/km, at loads MPa				Boundary permissible speed of sliding, m/s
		2.5		4.0		
		f	I	f	I	
AM4.5Kd+ +(9–12)MoS_2	4.0	0.11–0.12	22.38–22.42	0.14–0.16	23.66–23.69	3.0
AM4.5Kd [11, 13]	2.5	0.27–0.31	39.82	0.39–0.42	69.18	1.0

A number of alloying elements, primarily such as cadmium and zirconium, which do not dissolve in the aluminum matrix in solid state, are present in the form of independent formations – crystals. This leads to formation of a coarse-heterogeneous structure of cast alloy with segregational clusters, which causes increased wear of a contact pair.

We can observe similar phenomena in the uneven distribution of other strengthening phases, intermetallics.

Liquidation and segregation phenomena are completely absent in the composite material based on AM4.5Kd alloy waste. In it, the structural formation of independent phases of Cd and Zr, solid intermetallic compounds are in microparticles of raw material (waste) and thus they are initially uniformly arranged in the structure of the material without creation of segregations. The above phenomena influence on the integral component in increasing of antifriction properties of the material.

Authors of [13–15, 17] established that a multicomponent oxide film located on regenerated powders of the AM4.5Kd alloy consists of Al_2O_3 and oxides of alloying elements. It protects wear-resistant material from oxidation at operation in air. The soft metal base powders of AM4.5Kd alloy waste promotes a quick run in of composite wear-resistant material during its operation. Data presented in Table 3 show that the presence of MoS_2 molybdenum disulfide in the investigated composite obtained of grinding waste of AM4.5Kd aluminum alloy is a determining factor. This provides a significant reduction in friction and wear parameters under conditions of medium loaded operation modes compared with material of a similar composition, but without solid lubricant. This material is satisfactory only if it is lubricated with liquid lubricant.

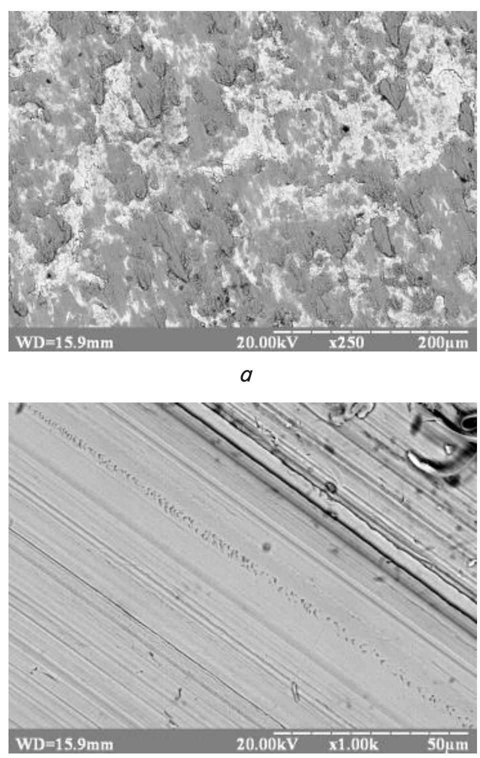
We should emphasize separately that, in the presence of MoS_2, there is a self-lubricating, multiphase antifriction film of friction formed on both contact surfaces. It is a carrier of high tribotechnical properties under such conditions of operation. Probably it consists of solid lubricant, separate elements and phases formed by both parts of a friction pair [21, 22].

During operation of material under an influence of external load factors, MoS_2 is evenly distributed on operation contact surfaces. It creates a continuous and uniform lubricating layer that wears out and restores simultaneously during operation of a part. Moreover, a rate of wear of an antifriction film coincides with a rate of recovery of a lubricating layer on contact surfaces under such conditions of operation.

We obtained the image of contact surfaces of the friction pair – the composite of AM4.5Kd + MoS_2 alloy and the counter part of steel 45, after tribotechnical tests. Fig. 2 shows it.

Due to the presence of MoS2, the anti-extinguishing layer is a lubricating antifriction film that minimizes the friction coefficient and the wear rate of the material under the specified operating conditions.

Sliding contact surfaces of friction pair, as Fig. 2 shows, are of high quality. A lack of areas of destruction, grappling, etc. evidences this on both friction surfaces. Such a relief of friction tracks on surfaces is a prerequisite for reliable and stable operation of contact pairs of a post-printing machine unit.



a

b

Fig. 2. Surfaces of the friction pair: *a* — AM4.5Kd+MoS_2 composite; *b* — the counter part of steel 45

6. Discussion of results of studying the influence of structure on tribotechnical characteristics of friction parts

Studies showed that the developed technology of regeneration of industrial grinding waste in combination with subsequent manufacturing operations makes possible to obtain a fundamentally new material with a high level of properties. The formed structure of AM4.5Kd – MoS_2 composite is a complex heterophase system. It is a combination of a metal matrix based on aluminum and reinforced with doping elements with evenly distributed inclusions of solid lubricant (Fig. 1).

Such structure of the material provided a high complex of mechanical and tribotechnical characteristics, which contributes to increasing of wear resistance of friction units of post-printing equipment, and hence the quality of printed products in general.

However, today there are difficulties in obtaining of grinding waste on the basis of aluminum in Ukrainian enterprises due to a lack of additional equipment. In addition, it is necessary to know the brand of aluminum alloy for the application of the developed technology as a choice of solid lubricant depends on it. This is not always possible in serial production. However, authors of study [24] showed that mixing of close alloys does not reduce operational properties of friction parts.

We will aim further research at a thorough analysis of a composition of antifriction films of new materials based on industrial grinding waste of AM4.5Kd aluminum alloy with impurities of solid lubricants.

The obtained results of operational properties (Tables 2, 3) gave possibility to develop recommendations for the effective use of the investigated composites for manufacturing of antifriction parts of folding and gluing machines and machines for pasting of elements into a package.

7. Conclusions

1. Our study has proven that the developed technology for the regeneration of industrial grinding waste with the subsequent manufacturing of material provided formation of heterogeneous structure of a new wear-resistant composite based on AM4.5Kd alloy with the addition of molybdenum disulfide solid lubricant.

2. This study has shown that the presence of MoS_2 ensures run in of wear-resistant material on the basis of grinding waste of AM4.5Kd alloy. That makes it possible to apply the composite in a wider range of loading factors (loads up to 4 MPa and sliding speeds up to 3 m/s) for units of different types of post-printing machinery, and to maintain stable high antifriction characteristics (friction coefficient of 0.14–0.16 and intensity wear of 23.66–23.69 μm /km).

3. Possibility to use grinding waste of aluminum alloys of a wide range of brands, for example, AK12M2, AMg5Mts, AK12MMgN, for production of quality composite parts that operate under friction and wear in self-lubrication mode proves the effectiveness of the study results. This eliminates a need to use lubricating oils and simplifies a design of units due to the removal of complex lubricate-supplying systems.

4. Analysis of functional properties give possibility to recommend antifriction composite made on the basis of industrial grinding waste of AM4.5Kd aluminum alloy with impurities of solid lubricant - MoS_2 molybdenum disulfide for parts of contact joints of complex geometric shapes. Conditions of operation of such parts are increased discrete sliding speeds, loading and friction without lubricating with liquid lubricant in the air. In such modes work Contact pairs of a number of post-print machines, such as folding and gluing machines, machines for pasting elements into packaging, etc., operate in such modes, where we can use the developed composites.

References

1. Gordon N. J. Essentials of Polygraph and Polygraph Testing. CRC Press, 2016. 304 p. doi: https://doi.org/10.1201/9781315438641
2. Novitni kompozytsiini materialy detalei tertia polihrafichnykh mashyn / Kyrychok P. O., Roik T. A., Havrysh A. P., Shevchuk A. V., Vitsiuk Yu. Yu. Kyiv: NTUU KPI, 2015. 428 p.
3. Sviridenok A. I., Myshkin N. K., Kovaleva I. N. Latest developments in tribology in the journal Friction and Wear // Journal of Friction and Wear. 2015. Vol. 36, Issue 6. P. 449–453. doi: https://doi.org/10.3103/s106836661506015x
4. Material properties of graphene/aluminum metal matrix composites fabricated by friction stir processing / Jeon C.-H., Jeong Y.-H., Seo J.-J., Tien H. N., Hong S.-T., Yum Y.-J. et. al. // International Journal of Precision Engineering and Manufacturing. 2014. Vol. 15, Issue 6. P. 1235–1239. doi: https://doi.org/10.1007/s12541-014-0462-2
5. Fabrication of a new Al-Al 2 O 3 -CNTs composite using friction stir processing (FSP) / Du Z., Tan M. J., Guo J. F., Bi G., Wei J. // Materials Science and Engineering: A. 2016. Vol. 667. P. 125–131. doi: https://doi.org/10.1016/j.msea.2016.04.094
6. Manufacturing of high strength aluminium composites reinforced with nano tungsten particles for electrical application and investigation on in-situ reaction during processing / Dixit S., Kashyap S., Kailas S. V., Chattopadhyay K. // Journal of Alloys and Compounds. 2018. Vol. 767. P. 1072–1082. doi: https://doi.org/10.1016/j.jallcom.2018.07.110
7. Kostornov A. G., Fushchich O. I. Sintered antifriction materials // Powder Metallurgy and Metal Ceramics. 2007. Vol. 46, Issue 9-10. P. 503–512. doi: https://doi.org/10.1007/s11106-007-0078-5
8. Bocian M., Jamroziak K., Kulisiewicz M. An identification of nonlinear dissipative properties of constructional materials at dynamical impact loads conditions // Meccanica. 2014. Vol. 49, Issue 8. P. 1955–1965. doi: https://doi.org/10.1007/s11012-014-9931-z
9. Shevchuk Y. F., Roik T. A., Varchenko V. T. Antifriction composite materials for friction joints of centrifugal equipment // Powder Metallurgy and Metal Ceramics. 2007. Vol. 46, Issue 7-8. P. 404–407. doi: https://doi.org/10.1007/s11106-007-0063-z

10. Pickens J. W. Assuring the Benefits of Aluminum Recycling: Engineering Economical Environmental Solutions to the Issues of Black Dross & Saltcake // Recycling of Metals and Engineercd Materials. 2013. P. 1195–1207. doi: https://doi.org/10.1002/9781118788073.ch105
11. Process Control in Aluminum Foam Production Using Real-Time X-ray Radioscopy / Stanzick H., Wichmann M., Weise J., Helfen L., Baumbach T., Banhart J. // Advanced Engineering Materials. 2002. Vol. 4, Issue 10. P. 814–823. doi: https://doi.org/10.1002/1527-2648(20021014)4:10<814::aid-adem814>3.0.co;2-5
12. Banhart J. Aluminium foams for lighter vehicles // International Journal of Vehicle Design. 2005. Vol. 37, Issue 2/3. P. 114. doi: https://doi.org/10.1504/ijvd.2005.006640
13. Muchová L., Eder P. End-of-waste Criteria for Aluminium and Aluminium Alloy Scrap // Technical Proposals. 2010. 69 p.
14. Kompozytsinyi pidshypnykovyi material na osnovi aliuminiu: Pat. No. 34407 UA. MPK (2006) C22C 21/02 / Roik T. A., Havrish A. P., Kholiavko V. V., Havrysh O. A., Prokhorenko O. M. No. u200803173; declareted: 12.03.2008; published: 11.08.2008, Bul. No. 15.
15. Improved manufacturing performance of a new antifriction composite parts based on copper / Jamroziak K., Roik T., Gavrish O., Vitsiuk I., Lesiuk G., Correia J. A. F. O., De Jesus A. // Engineering Failure Analysis. 2018. Vol. 91. P. 225–233. doi: https://doi.org/10.1016/j.engfailanal.2018.04.034
16. Effect of CaF2 surface layers on the friction behavior of copper-based composite / Konopka K., Roik T. A., Gavrish A. P., Vitsuk Y. Y., Mazan T. // Powder Metallurgy and Metal Ceramics. 2012. Vol. 51, Issue 5-6. P. 363–367. doi: https://doi.org/10.1007/s11106-012-9441-2
17. Effect of Secondary Structures on the Functional Properties of High-Speed Sintered Bearings for Printing Machines / Roik T. A., Gavrish A. P., Kirichok P. A., Vitsyuk Y. Y. // Powder Metallurgy and Metal Ceramics. 2015. Vol. 54, Issue 1-2. P. 119–127. doi: https://doi.org/10.1007/s11106-015-9688-5
18. New Copper-Based Composites for Heavy-Loaded Friction Units / Roik T. A., Gavrysh O. A., Vitsiuk I. I., Khmiliarchuk O. I. // Powder Metallurgy and Metal Ceramics. 2018. Vol. 56, Issue 9-10. P. 516–522. doi: https://doi.org/10.1007/s11106-018-9924-x
19. Wejrzanowski T. Computer program Micrometer // Material Science. 2005. Issue 23. P. 28–34.
20. Huliaev A. P. Metallovedenye. Moscow: Metallurhyia, 1986. 544 p.
21. Structure and mechanical properties of mechanically alloyed Al/Al-Cu-Fe composites / Kaloshkin S. D., Tcherdyntsev V. V., Laptev A. I., Stepashkin A. A., Afonina E. A., Pomadchik A. L., Bugakov V. I. // Journal of Materials Science. 2004. Vol. 39, Issue 16/17. P. 5399–5402. doi: https://doi.org/10.1023/b:jmsc.0000039253.28721.3f
22. Tribological Studies of Al-based Composite / Venkata Siva S. B., Sreenivasa Rao G., Sahoo K. L. // Developed from a Waste Material. 3-rd International Conference on Mechanical, Automotive and Materials Engineering (ICMAME'2013). Singapore, 2013. 10 p.
23. Zhang J. Z. Research of Composite Material Properties Based on Waste Glass and Scrap Aluminum // Advanced Materials Research. 2012. Vol. 468-471. P. 2868–2871. doi: https://doi.org/10.4028/www.scientific.net/amr.468-471.2868
24. A novel powder metallurgy-based method for the recycling of aluminum adapted to a small island developing state in the Pacific / Kumar S., Mathieux F., Onwubolu G., Chandra V. // International Journal of Environmentally Conscious Design & Manufacturing. 2007. Vol. 13, Issue 3 (4). P. 1–22.