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Using silumin grinding waste for new self-lubricating antifriction composites

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ABSTRACT

The article studies the influence of manufacture technology on the structure and properties of new antifriction self-lubricating composites based on AK12M2 aluminum alloy grinding waste with MoS_2 solid lubricant additives for the contact pairs operating at sliding speeds of 1.0–3.0 m/s and loads of 2.0–4.0 MPa. AK12M2 grinding waste was dried from moisture and cleaned from contamination with abrasive particles. Then the purified metal powders were mixed with non-metallic powders of MoS_2 solid lubricant and pressed at 470–520 MPa at room temperature. The formed briquettes were subjected to hot pressing at a pressure of 300 MPa and a temperature of 400 °C. This technology ensured the formation of the composite's structure consisting of a metallic aluminum matrix with evenly distributed MoS_2 solid lubricant particles. The formed structure contributed to the formation of a high level of mechanical and antifriction properties when working in the self-lubrication mode. Comparative tests showed that the composite based on AK12M2 alloy was not inferior to cast aluminium alloy of the same chemical composition in terms of mechanical properties and exceeds it in tribological properties.

Keywords: grinding waste, silumin, reuse, technology, antifriction composite, solid lubricant, friction, wear, self-lubrication mechanism, post-printing equipment.

INTRODUCTION

Environmental problems related to pollution have gained great importance in the world in recent decades. This is caused by the steadily growing amount of industrial waste, including aluminum alloy waste. Aluminum is one of the most recycled–and recyclable–materials in use today. High-quality and infinitely recyclable, it is valuable for a more circular and sustainable economy [1]. In the world, many enterprises successfully implement large-scale processing of aluminum industrial waste. This is, first of all, processing of beverage and food cans, aluminum scrap, electrical industry waste, etc. [2]. Secondary production is an environmentally sound process that is around 95% more energy efficient than primary production [1]. The increased adoption of recycled aluminum in manufacturing has created significant economic and environmental wins for both industry and consumers. More than 80% of U.S. production today is in making recycled (or secondary) aluminum [3]. No matter the industry, innovators rely on aluminum for greener, more sustainable solutions.

The search for sustainable and ecological solutions fully applies to the printing industry. Printing and post-printing equipment contains many parts made of aluminum alloys, including antifriction ones that work at sliding speeds up to 3.0 m/s and loads up to 4.0 MPa in conditions of liquid lubrication. This is such equipment as automatic machines for the production of paper food bags or devices for gluing polymer windows into the package. The durability of systems, friction units and individual contact parts of such equipment determines the printed products quality. Such parts are often made of cast or plastically deformed aluminum alloys of types EN AB-AlSi9Mg or EN AB-AlSi9Cu1Mg (standard EN 1676: 2020). All such cast aluminium antifriction parts have in common is their unsatisfactory functional properties when working with liquid lubricant (oil). This problem is due to the unstable supply of lubricant to the contact zone, sudden stoppage of the lubricant supply, clogging of the supply devices due to the lubricant polymerization or other emergency situations. In such cases, there is direct contact between the parts, which leads to their rapid scuffing wear [4]. As a result, the printed products quality deteriorates significantly or there are defective products in general. This requires disposal and subsequent recycling, which causes additional financial and material costs. In such a situation, the wear of individual cast aluminum parts leads to the failure of the entire unit or section, and, as a result, the printing machine. This causes equipment stoppages, the need for repair works, replacement and installation of spare parts, etc., which significantly increases the product cost. The described problem requires a solution to stabilize the performance of both individual antifriction aluminum parts and the post-printing equipment as a whole.

For this purpose, one of the sustainable and ecological solutions was the use of powder metallurgy methods to create aluminum antifriction composites [5]. The developed composites had sufficiently high mechanical and tribological characteristics for various working conditions. These composites were recommended for structural applications in the aerospace, automotive and military industries [6, 7]. The authors [8] studied aluminum composites reinforced with steel particles with graphite additives [9, 10] as a solid lubricant. Indeed, it has been shown that the addition of graphite has a positive effect on reducing mass loss. In work [11] it was proved that the hardness and wear resistance of the hybrid nano-composites were increased considerably by increasing the reinforcement content. The material with 5 wt.% SiC and 10 wt.% graphite showed the greatest improvement in tribological performance. Based on [12], the composites with 5 wt% graphite had the lowest wear loss and coefficients of friction because of the self-lubricating effect of graphite.

But despite the high level of properties, all powder composites have a high cost [13, 14]. This problem can be solved by using innovative technologies and new materials with high functional properties made from effective raw materials. Such alternative and efficient raw materials are aluminum alloys grinding waste. Large quantities of such grinding waste appear every day in industrial plants. Aluminum grinding waste is generated during grinding operations of cast aluminum parts. These wastes are contaminated with abrasive from grinding wheels and are not used in the recycling cycle. Such grinding waste is taken to landfills, increasing them daily, and poses a threat to the natural ecosystem. However, the authors' scientific works [15–17] have convincingly demonstrated that the substantial volume of aluminum alloys grinding waste after purification can be effectively used for new antifriction parts. They showed high level properties for new antifriction composites from alloy AM4.5Kd grinding waste (analogue is alloy AlCu4MgSi, ISO 209-1:2002 standard), alloy AK12MgN (analogue is alloy AlSi12CuNiMg, EN 1676 standard) and alloy AD35 (analogue is alloy AlSi1MgMn, EN 1676 standard) when working with liquid lubricant (oil). Nevertheless, such studies are still pioneering. They do not cover many grades of aluminum alloys, many technological and scientific issues are not clarified, which does not allow generalizations to be made.

The above arguments became the motivation for carrying out the scientific works to expand the possibilities of using grinding waste of valuable aluminum alloys for their further efficient use, while partially solving the environmental issue of reducing the burden on the ecosystem. The aim of this research is to determine the influence of manufacture technology on the structure and properties of new antifriction self-lubricating composites based on AK12M2 aluminum alloy grinding waste with MoS_2 solid lubricant additives for the contact pairs of post-printing equipment operating at sliding speeds 1.0–3.0 m/s and loads 2.0–4.0 MPa.

Table 1. Chemical composition of the materials based on AK12M2 aluminum alloy grinding waste

Components, [wt. %]									
Si	Cu	Fe	Mg	Zn	Mn	Ni	Ti	Al	MoS_2
11.0–13.0	1.8–2.5	0.6–0.9	0.15–0.20	0.7–0.8	0.3–0.5	0.2–0.3	0.15–0.20	basis	6.0–8.0

EXPERIMENTAL PROCEDURE

Preparatory procedures

The subject of study was new antifriction composite based on AK12M2 aluminum alloy grinding waste with MoS_2 solid lubricant (Table 1).

The AK12M2 alloy grinding waste was formed during the grinding process of cast parts. This waste is contaminated with abrasive particles from grinding wheels and contains components of coolant. Therefore, the purification operations of the AK12M2 alloy waste were the main technological operations for further use of this valuable raw material. The authors [15–17] developed a technology for the regeneration of similar aluminum alloys grinding waste, providing for the performance of two stages: drying from moisture with annealing of the coolant components and separative cleaning from abrasive. The first stage included drying and annealing of AK12M2 alloy waste at 400 °C, followed by air cooling. The second stage involved cleaning aluminium waste from abrasive using the electrodynamic separation method. The abrasive cleaning was performed using the electrodynamic separation method, which is based on the difference in electrical conductivity of metallic and non-metallic particles. Electrodynamic (ED) separation is based on the force interaction of an alternating electromagnetic field with solid conductive bodies with different conductivity values. The special feature of the electrodynamic separation process is that the electrodynamic force acts on the more electrically conductive fraction of the material to be separated. This makes it possible to recover non-ferrous metals with high efficiency, even if their content in low-conductivity waste is low. The electromagnetic separator scheme has been shown in Figure 1.

The rotating magnetic field of the separator (Figure 1) is generated by a multi-pole rotor with an independent rotation drive. The magnetic field of the rotor is excited by a winding powered by a direct current. The rotor is placed in the middle of a stainless steel drum, which serves as a

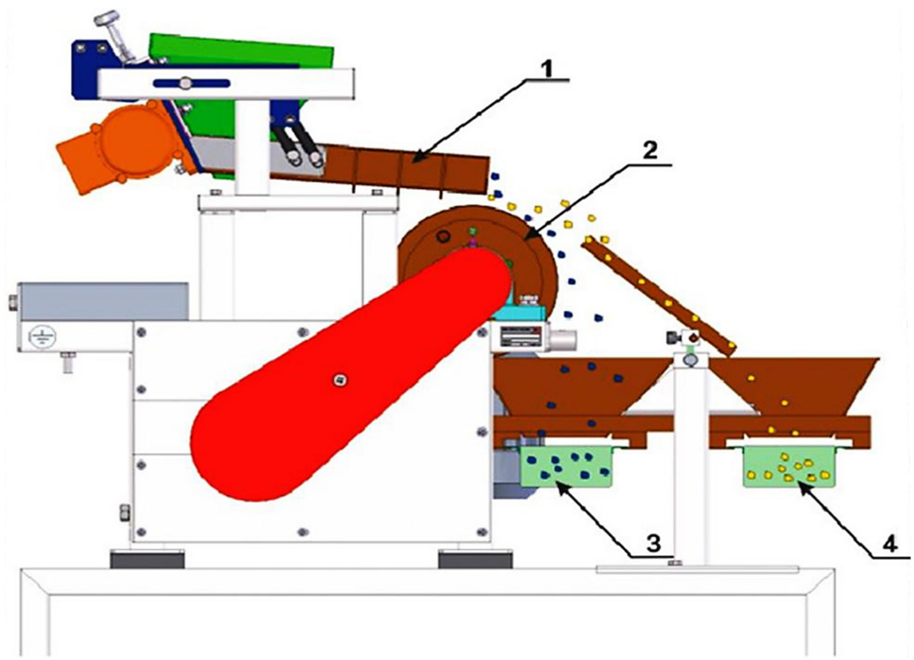

Figure 1. The electromagnetic separator scheme: 1 – receiving hopper with vibrating feeder; 2 – drum with magnetic rotor; 3 – receiving tray for non-electrically conductive fraction (abrasive particles); 4 – receiving tray for electrically conductive fraction (AK12M2 alloy particles)

means of transporting the material to be separated within the rotating magnetic field. The drum (2) rotates under the influence of electrodynamic forces interacting with the rotor field. The eddy currents are induced in the electrically conductive particles of the AK12M2 alloy, which interact with the rotor field that sets them in motion. The material to be separated is evenly fed to the separator drum, from where the electrically conductive particles of AK12M2 grinding waste are thrown by the rotor field into the far receiving hopper (4), and the non-conductive abrasive particles fall freely from the drum into the nearer hopper (3). The use of electrodynamic separation to remove abrasives from AK12M2 grinding waste has proven to be effective in obtaining high-quality raw materials for the manufacture of new antifriction composites. These operations resulted in almost pure AK12M2 alloy powders with residue of abrasive particles content of up to 2%. These particles were present after grinding with abrasive wheels, however, it makes material suitable for further use, since the role of solid lubrication is decisive.

Charge preparation and consolidation

The regenerated powders of AK12M2 alloy with a size of 60–180 μm prepared in the above-described way were used to make the initial charge. In many post-printing machines, aluminum parts are in direct contact with printed products such as postal envelopes, letterheads, transparent windows for cardboard packaging, etc. Therefore, the use of liquid lubricant (oil) is unacceptable in such cases, as this can contaminate the products.

With this in mind, the MoS_2 solid lubricant was added to the composition of the initial charge in the amount of 6.0–8.0 wt.%. The well-known MoS_2 solid lubricant is effective when working in medium-severe friction conditions [15]. The solid lubricant amount was determined based on the following considerations: a MoS_2 content of less than 6 wt.% is insufficient for effective lubrication of the contact surfaces, and more than 8.0 wt.% leads to a decrease in the composite's mechanical properties [18]. Thus, regenerated metal powders of AK12M2 aluminum alloy were mixed with non-metallic powders of MoS_2 solid lubricant. As a result, the initial charge was prepared with the following composition: AK12M2+(6.0–8.0)% MoS_2.

The operating conditions of friction units in post-printing machines are associated with the action of loads and speeds, which requires a high structural strength of the parts. This can be achieved by minimizing porosity. For this purpose, a two-stage composite consolidation process was used. In the first stage, the briquettes were cold pressed at 450–500 MPa, and in the second stage, the previously obtained briquettes were additionally subjected to hot pressing at 270–300 MPa and a temperature of 400 °C.

Examination techniques

Structural studies of the composite material were performed using a metallographic microscope Optika B1000 MET and scanning EVO 50XVP electron microscope (SEM).

The mechanical properties of aluminium cast alloy and the new composite were determined according to standard procedures using standard equipment. A UIT GTM 500 testing machine and a UIT HBW-1 stationary Brinell hardness tester were used in the study. Samples were made from the studied composite with MoS_2 solid lubricant and AK12M2 cast alloy in the amount of 20 pieces of each material. The AK12M2 cast alloy samples were not subjected to additional heat treatment. Tests were performed according to standard methods by ASTM D7264, ISO 6506/ASTM E10, (ISO 4498-1-90).

Tribological tests were performed according to the end-friction scheme; the friction track was 5 km. Friction and wear tests were carried out on a VMT-1 friction machine under the following operating conditions: sliding speed 1.0–3.0 m/s, load P = 2.0 – 4.0 MPa in air, counterface made of cast steel 45. Cast steel 45 corresponds to the actual material of the contact pair that works in pair with the antifriction aluminum part in the post-printing machine. The chemical composition is as follows, wt.%: 0.42–0.50 of carbon, 0.17–0.37 of silicon, 0.50–0.80 of manganese, < 0.25 of chromium, < 0.25 of nickel, < 0.04 of sulphur, < 0.035 of phosphorus, and iron as the base.

The surface roughness was measured according to the standard method (ISO 4287:1997) using a ProfilControl 7S Tube profilometer [19]. Visual evaluation of the surface was performed using an EVO 50XVP electron microscope. Measurements on the profilometer were carried out along 20 measuring tracks of 220 μm length perpendicular to the direction of friction.

Roughness measurements were carried out on the following parameters: RSm – mean width of the profile, Rv – maximum profile valley depth, Rp – maximum profile peak height, Ra – arithmetic mean deviation of the profile, Rz– maximum height of the profile, Ir – sampling length- roughness profile.

RESULTS AND DISCUSSION

The structure of the composite based on AK-12M2+7%MoS_2 grinding waste that was formed after hot pressing technological operation is shown in Figure 2. The microstructure is composed of a metal matrix and uniformly distributed MoS_2 solid lubricant particles. Its metal matrix consists of an alloyed α-solid solution based on aluminum and hardening phase particles [20]. In turn, the Al solid solution is a eutectic that forms at a silicon content of 11.6 wt.%, which corresponds to the Al-Si phase diagram.

As can be seen from Figure 3, the structure of the new composite is homogeneous, which indicates the effectiveness of the developed manufacturing technology. Such structure of the new material provided better tribological properties with respect to the base material (Table 2).

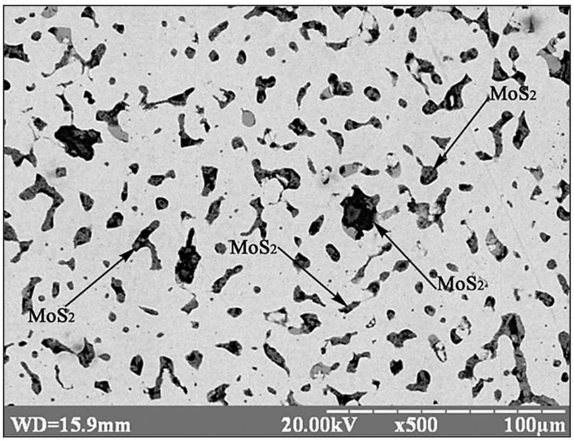

Figure 2. The structure of the composite based on grinding waste AK12M2+7%MoS_2, unetched state

As can be seen from the Table 2, the composite based on AK12M2 alloy waste is not inferior to cast aluminum alloy in terms of mechanical properties, and it exceeds cast alloy in terms of tribological properties, when friction takes place without liquid lubricant. This is due to the presence of MoS_2 solid lubricant in the composite volume, which is constantly smeared on the contact surfaces and minimizes wear. Under such friction conditions, an antifriction film is permanently formed at the wear areas on the contact surface. The product of wear is then dust (powder with micrometer-sized particles), causing a superlubricating effect, which reduces the value of the coefficient of friction and prevents the occurrence of dry friction.

In this case, the value of the coefficient of friction is 0.19–0.21 and 0.47–0.61, respectively, in the case of contact between the counterface and new aluminium composite with molybdenum disulfide and cast aluminium alloy, which in the latter case is consistent with the data available in the literature [24]. Thus, it should be concluded that the addition of MoS_2 results in a nearly threefold reduction in the value of the coefficient of friction determined during tribological tests conducted under a load of 2.5 MPa. Moreover, with the increase of the load to 4.0 MPa, the value of the coefficient of friction is only slightly higher and amounts to 0.22–0.24. The coefficient of friction and wear cannot be determined for a cast aluminium alloy specimen due to the seizure and adhesion of the contact surfaces under friction conditions of 2.5 MPa and more without lubrication. The cast alloy cannot operate without lubrication. Based on this, it should be concluded that the maximum allowable sliding speed is 3.0 m/s under a load of 4.0 MPa for the composite sample with molybdenum disulfide additive and 1.0 m/s under a load of 2.5 MPa for the sample of cast alloy. In this case, the slight reduction in

Table 2. Comparative mechanical and tribological properties of the studied composite and cast alloy

Composition, [wt. %]	Bending strength, R_{tr}, [MPa]	HBS 2,5/31,25/15	Friction coefficient (f) and wear rate (I), [μm/km], at load, [MPa]				Maximum allowable sliding speed, [m/s]	Maximum allowable load, [MPa]
			2.5		4.0			
			f	I	f	I		
AK12M2 + (6–8) MoS_2	180–185	62–65	0.19–0.21	36–41	0.22–0.24	48–56	3.0	4.0
AK12M2 cast alloy [19]	186–190	64–68	0.47–0.61	>600	adhesion of surfaces		1.0	2.5

Note: friction without liquid lubricant.

mechanical properties caused by the reduction in the size of the active cross-section, including the bending strength R_{tr} from 186–190 MPa for the base material to 180–185 MPa for the material with the addition of molybdenum disulfide, is quite acceptable in terms of increasing the tribological properties of the new aluminium composite based on waste.

Images of the surfaces subjected to tribological tests are shown in Figure 3. According to the attached microscopic documentation, the main mechanism of wear of aluminium alloy is delamination of the surface layer, and the film delamination has been shown in Figure 4a. According to [21], in the case of aluminium alloys, the above type of wear is caused by plastic deformation of the surface layer, followed by the initiation and propagation of cracks, resulting in the formation of wear debris and their subsequent separation from the substrate. This type of wear is caused by different properties of the surface layer compared to the core - the surface layer, which often contains oxides on its surface [22], is characterized by lower ductility, making its main wear mechanism micro-cracking and delamination [23], [24]. In addition, it should be noted that the exit of MoS_2 from the middle to the surface leads to the formation of microgeometric notches, which contribute to the formation of microcracks on the friction film's surface with subsequent delamination of the fragments.

The mass transfer effect is observed during friction of a new Al-composite with molybdenum disulfide on a counterface made of steel 45. The formed friction film covers both contact surfaces.

The effect of mass transfer is demonstrated by the transfer of molybdenum disulfide and other components of the aluminium composite to the surface of the steel 45 counterface.

The main mechanism of wear is the microploughing of the contact zones in accordance with the direction of friction [29, 30]. The friction surface film is deformed, cracked and peeled off on both contact surfaces. The wear products are pulverised at the same time. Since the formed friction film is very mobile, its detachment and crushing leads to localisation of plastic deformation in a thin surface layer without affecting the deeper layers. As mentioned earlier, the friction film contains MoS_2 and oxides of the friction pair's elements. Thus, in this case the character of wear is oxidative without abrasive phenomena leading to scratching of contact surfaces and their subsequent seizure.

The new waste-based aluminium composite demonstrates high antifriction properties under specified friction conditions precisely due to the formation of a complex and multi-component friction film, which wears and re-forms again on both surfaces. This is how the self-lubrication mode is realised.

The results of roughness measurements confirmed the presence of friction film. They agree with the microphotographs of the surfaces subjected to wear tests (Figure 4), where the presence of friction film is evident. The friction film on the counterface's surface appears as a layer with a striped structure that follows the direction of the abrasive wear line. This layer forms the parameters that characterize the roughness. The average values of roughness measurements before and after tribological tests of the counterface have been summarized in Table 3. The results of roughness measurement before and after tribo-tests show that a layer of lubricating film was formed on the

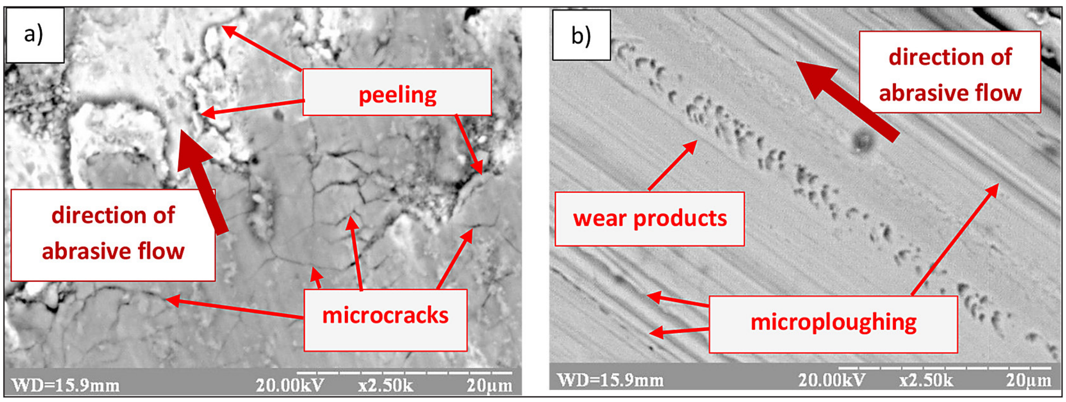

Figure 3. Friction surfaces: (a) sample, (b) counterface after tribological tests at sliding speed of 2.5 m/s and load P = 3.0 MPa in air

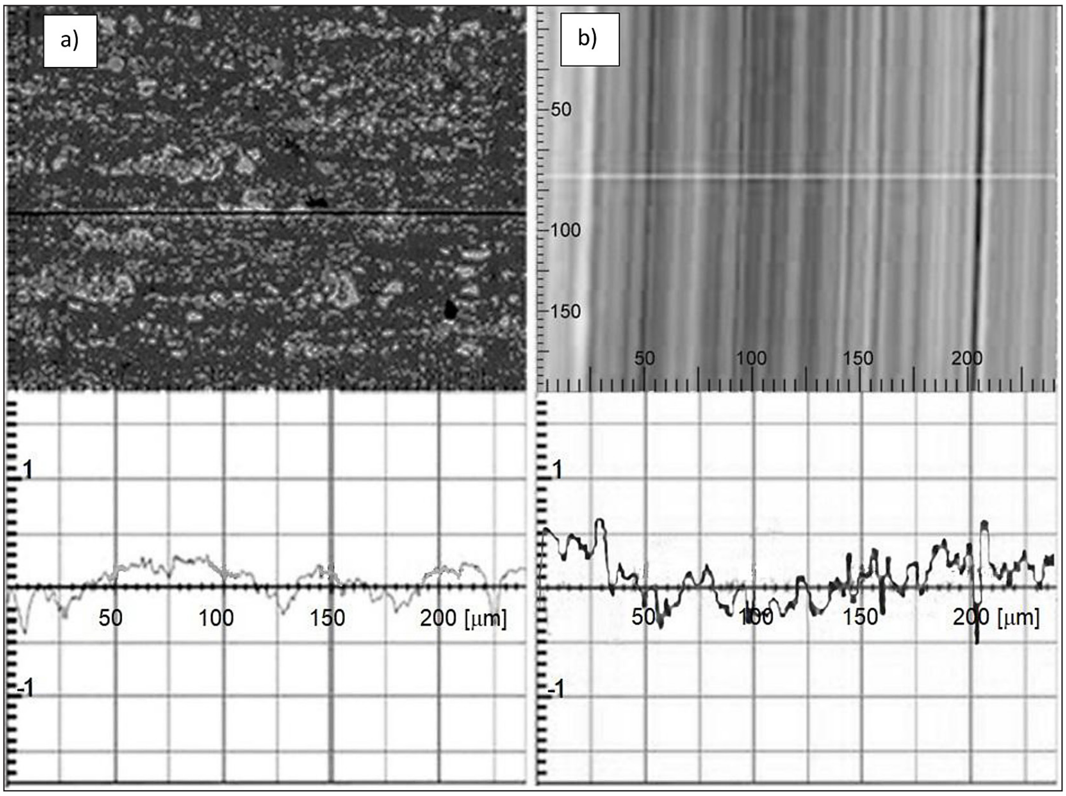

Figure 4. Measurement of counterface's surface roughness before tribo-testing (a) and after tribo-testing (b)

Table 3. Roughness parameters of the counterface before and after tribological tests

Counterface	Roughness parameters, [µm]					
	RSm,	Rv,	Rp,	Ra,	Rz,	Ir
Before tribo-tests	35.01	0.79	0.61	0.16	1.81	220
After tribo-tests	23.31	0.96	0.87	0.22	2.21	220

Note: Tribological tests at V = 2.5 m/s, load P = 3.0 MPa.

counterface's surface. The arithmetic mean value of Ra parameter after testing increases by more than 27% and the profile height Rz increases by more than 18% compared to the surface of the counterface before tribo-testing.

For softer materials, high surface roughness can also lead to failures and outages. The Rv parameter shows a strong correlation with hardness - according to [25], an initial increase in the hardness of Hardox 500 steel led to a rise in the Rv parameter, followed by its decrease. This is due to the detachment of fragments of the material, without its plastic deformation, which in the case of materials with higher hardness leads to deeper valleys. In this case, the low value of the parameter Rv of 0.96 µm and Rp = 0.87 µm indicates a smooth surface after the test and ensures the stability of the contact pair, with a maximum profile height Rz of 2.21 µm. The parameters Rv, Rp, Ra and Rz in each case show lower values compared to high strength steels [26, 27], and the value of Rsm - the only parameter describing the horizontal size of the section – at 23. 31 µm indicates that the resulting valleys are narrow, yielding a height-to-width ratio (Rz/Rsm) of 0.09. According to Wolf's roughness shape indices [25], Ra/Rz and Rv/Rp ratios of 0.10 and 1.10, respectively, indicate that indentations predominate over protrusions in the surface topography. In [28], the results of tests on several aluminum alloys subjected to tribological testing based on friction with sandpaper were summarized. In this case, only alloy A339 with SiC addition obtained a lower Ra value (0.18 µm) compared to the results presented in this manuscript. During pin-on-disc tests, the Al 7075 aluminum alloy, depending on the test conditions (changes in the applied load and the size of the abrasive particles), shows an Ra value in the range of 0.38–1.11 μm [29]. The above differences increase especially with regard to the surface roughness of aluminum alloys after machining. The obtained value is also lower compared to the 7075 alloy with 10% SiC, in which the lowest surface roughness Ra = 3.37 μm was obtained at a cutting speed above 220 m/min using a PCD tool [30]. In [31], it was shown that during cutting, the surface of the AW-2024 T3 aluminum alloy is characterized by the lowest Ra value of 0.30 μm, which is also a less favorable result compared to the presented test results.

CONCLUSIONS

The research results proved the fundamental possibility of using aluminium alloys grinding waste in the repeated production cycle. Studies have shown the high efficiency of using industrial aluminium alloy grinding waste to manufacture new high-quality composites. The use of valuable waste in the repeated production cycle opens up broad prospects not only for the production of new high-quality materials, but also minimizes the number of hazardous wastes landfills and significantly reduces the impact on the global ecosystem.

The developed technology ensured the formation of the composite's structure consisting of the metallic aluminum matrix with evenly distributed MoS_2 solid lubricant particles. The formed structure contributed to the formation of a high level of mechanical and antifriction properties when working in the self-lubrication mode. Comparative tests showed that the composite based on AK12M2 alloy waste is not inferior to the cast aluminum alloy in terms of mechanical properties and exceeds it in tribological properties under friction conditions without grease. This is due to the MoS_2 solid lubricant in the composite volume, which is constantly smeared on the contact surfaces and minimizes wear. This permanent self-lubrication mode eliminates the possibility of the contact surfaces' seizure, adhesive phenomena and failure of both the individual friction units. The antifriction film of MoS_2 solid lubricant ensured stable operation under friction conditions at sliding speeds of 1.0–3.0 m/s and loads equal to 2.0–4.0 MPa.

Summarizing the results, it can be stated that the technological approach used by the authors to the utilization, cleaning from contamination and further use of recovered valuable industrial grinding metal waste is very important on the way to the creation of new effective materials and parts made from them. Moreover, this approach will provide further steps towards protecting the environment from contamination and will contribute to the reduction of landfills.

REFERENCES

1. https://www.aluminum.org/sites/default/files/2021-11/KPI_Report_2021.pdf
2. Lenka. Muchová and Peter. Eder, End-of-waste criteria for aluminium and aluminium alloy scrap : technical proposals. Publications Office, 2010.
3. https://www.cancentral.com/wp-content/uploads/2023/01/Metabolic_Report_RecyclingUnpacked.pdf
4. Lawrowski Z., Tribologia. Tarcie, zużywanie i smarowanie. Warszawa: Wydawnictwo Naukowe PWN, 1993.
5. Prasan K. Samal and Joseph W. Newkirk, Ed., ASM Handbook, Volume 7: Powder Metallurgy. ASM International, 2015.
6. Jasiński R. and Chruścielski G. Possibilities to modify the properties of the AW7075 aluminum alloy for the automotive industry," Combustion Engines, Jan. 2024, https://doi.org/10.19206/CE-170711
7. Jankauskas V., Žunda A., Katinas A., and Tučkutė S., Wear study of bulk cargo vehicle body materials used to transport dolomite, Coatings, Feb. 2025, 15(2), 227, https://doi.org/10.3390/coatings15020227
8. Alaneme K. K., Fajemisin A. V., and Maledi N. B., Development of aluminium-based composites reinforced with steel and graphite particles: structural, mechanical and wear characterization, Journal of Materials Research and Technology, Jan. 2019, 8(1), 670–682, https://doi.org/10.1016/j.jmrt.2018.04.019
9. Zemlik M., Dziubek M., Pyka D., Konat Ł., and Grygier D., Case study of accelerated wear of brake discs made of grey cast iron characterized by increased thermal stability, Combustion Engines, Mar. 2022, https://doi.org/10.19206/CE-146698
10. Podgornik B., Kosec T., Kocijan A., and Donik Č., Tribological behaviour and lubrication performance of hexagonal boron nitride (h-BN) as a replacement for graphite in aluminium forming, Tribol Int, Jan. 2015, 81, 267–275, https://doi.org/10.1016/j.triboint.2014.09.011

11. Ravindran P., Manisekar K., Vinoth Kumar S., and Rathika P., Investigation of microstructure and mechanical properties of aluminum hybrid nano-composites with the additions of solid lubricant, Mater Des, Oct. 2013, 51, 448–456, https://doi.org/10.1016/j.matdes.2013.04.015
12. Ravindran P., Manisekar K., Narayanasamy R., and Narayanasamy P., Tribological behaviour of powder metallurgy-processed aluminium hybrid composites with the addition of graphite solid lubricant, Ceram Int, Mar. 2013, 39(2), 1169–1182, https://doi.org/10.1016/j.ceramint.2012.07.041
13. Dasgupta R., Aluminium alloy-based metal matrix composites: a potential material for wear resistant applications, ISRN Metallurgy, Oct. 2012, 2012, 1–14, https://doi.org/10.5402/2012/594573
14. Venkata Siva S. B. et al., Preparation of aluminum metal matrix composite with novel in situ ceramic composite particulates, developed from waste colliery shale material, Metallurgical and Materials Transactions B, Aug. 2013, 44(4), 800–808, https://doi.org/10.1007/s11663-013-9832-x
15. Roik T., Gavrish O., Oliynik V., and Vitsiuk I., Analysis of the properties of antifriction composites based on aluminum alloy's grinding waste, Eastern-European Journal of Enterprise Technologies, Aug. 2018, 4, 12 (94), 16–22, https://doi.org/10.15587/1729-4061.2018.140984
16. Roik T. A., Gavrysh O. A., and Vitsiuk Yu. Yu., The functional properties acquired by antifriction composites produced from silumin grinding waste, Powder Metallurgy and Metal Ceramics, Jan. 2019, 57(9–10), 526–532, https://doi.org/10.1007/s11106-019-00011-0
17. Roik T. A., Gavrysh O. A., and Vitsiuk Iu. Iu., Composite antifriction material based on wastes of aluminum alloy for items of post-printing equipment, Powder Metallurgy and Metal Ceramics, Sep. 2020, 59(5–6), 282–289, https://doi.org/10.1007/s11106-020-00160-7
18. Ouyang J.-H., Li Y.-F., Zhang Y.-Z., Wang Y.-M., and Wang Y.-J., High-temperature solid lubricants and self-lubricating composites: A critical review, Lubricants, Aug. 2022, 10(8), 177, https://doi.org/10.3390/lubricants10080177
19. Roik T., Brovkyn A., and Dubolazov O. V., Analysis of the parts' roughness parameters of high-speed printing equipment by optical profilometry, in Fifteenth International Conference on Correlation Optics, O. V. Angelsky, Ed., SPIE, Dec. 2021, 52. https://doi.org/10.1117/12.2615584
20. Haimann R., Metaloznawstwo. Wrocław: Wydawnictwo Politechniki Wrocławskiej, 1980.
21. Deuis R. L., Subramanian C., and Yellup J. M., Dry sliding wear of aluminium composites—A review, Compos Sci Technol, Jan. 1997, 57(4), 415–435, https://doi.org/10.1016/S0266-3538(96)00167-4
22. Olaleye K. et al., Tribosynthesis of friction films and their influence on the functional properties of copper-based antifriction composites for printing machines, Materials Science-Poland, Dec. 2022, 40(4), 147–157, https://doi.org/10.2478/msp-2022-0051
23. Wang J., Zhou X., Thompson G. E., Hunter J. A., and Yuan Y., Delamination of near-surface layer on cold rolled AlFeSi alloy during sheet forming, Mater Charact, Jan. 2015, 99, 109–117, https://doi.org/10.1016/j.matchar.2014.11.011
24. Zhang J. and Alpas A. T., Delamination wear in ductile materials containing second phase particles, Materials Science and Engineering: A, Jan. 1993, 160(1), 25–35, https://doi.org/10.1016/0921-5093(93)90494-Y
25. Zemlik M., Białobrzeska B., Stachowicz M., and Hanszke J., The influence of grain size on the abrasive wear resistance of Hardox 500 Steel, Applied Sciences, Dec. 2024, 14(24), 11490, https://doi.org/10.3390/app142411490
26. Pawlak K., Białobrzeska B., and Konat Ł., The influence of austenitizing temperature on prior austenite grain size and resistance to abrasion wear of selected low-alloy boron steel, Archives of Civil and Mechanical Engineering, Sep. 2016, 16(4), 913–926, https://doi.org/10.1016/j.acme.2016.07.003
27. Zemlik M., Konat Ł., and Białobrzeska B., Analysis of the possibilities to increase abrasion resistance of welded joints of Hardox Extreme steel, Tribol Int, 2025, 201, https://doi.org/10.1016/j.triboint.2024.110271
28. García-Cordovilla C., Narciso J., and Louis E., Abrasive wear resistance of aluminium alloy/ceramic particulate composites, Wear, Mar. 1996, 192(1–2), 170–177, https://doi.org/10.1016/0043-1648(95)06801-5
29. Sardar S., Karmakar S. K., and Das D., High stress abrasive wear characteristics of Al 7075 alloy and 7075/Al2O3 composite, Measurement, Oct. 2018, 127, 42–62, https://doi.org/10.1016/j.measurement.2018.05.090
30. Bhushan R. K., Kumar S., and Das S., Effect of machining parameters on surface roughness and tool wear for 7075 Al alloy SiC composite, The International Journal of Advanced Manufacturing Technology, Sep. 2010, 50(5–8), 459–469, https://doi.org/10.1007/s00170-010-2529-2
31. Doluk E., Rudawska A., and Miturska-Barańska I., Investigation of the surface roughness and surface uniformity of a hybrid sandwich structure after machining, Materials, Oct. 2022, 15(20), 7299, https://doi.org/10.3390/ma15207299