Engineering Science & Technology
http://ojs.wiserpub.com/index.php/EST/

UNIVERSAL WISER PUBLISHER

Research Article

Aluminum Composite Materials Providing Extended Service Life

Yulia A. Kurganova[1*], Alexey G. Kolmakov[1,2], Sergey V. Kurganov[3]

[1]N. Á. Bauman Moscow State Technical University, Moscow, Russian Federation
[2]Baikov Institute of Metallurgy and Materials Science, Russian Academy of Sciences, Moscow, Russian Federation
[3]Research Institute of Electric Coal Products, Elektrougli, Russian Federation
Email: kurganova_ya@mail.ru

Received: 9 July 2021; **Revised:** 22 September 2021; **Accepted:** 28 September 2021

Abstract: Hardness and tribotechnical characteristics were investigated under conditions of dry sliding friction on steel obtained by liquid-phase mixing of Aluminum-Matrix Composite (AMC) materials based on aluminum alloys AK12, D16, V124, AL9, and AL25, reinforced with silicon carbide SiC particles with a size of 28 μm with a content of 5, 10, or 15% by volume. AMC performed better than matrix alloys and the commonly used anti-friction aluminum alloy AOM 2-1. The dry friction coefficient was 1.5-3 times lower on average, and the volumetric wear rate was 5-9 times lower. An increase in the content of SiC particles in the composite from 5 to 20 vol.%, as a rule, leads to an improvement in the tribotechnical characteristics. The composites obtained have shown sufficiently high operational suitability for use in friction units with steels, both under dry friction and friction with lubrication.

***Keywords*:** composite materials, wear resistance, aluminum alloys

1. Introduction

Aluminum Matrix Composite (AMC) materials have been found widely applied in mechanical engineering, instrument making, aircraft engineering, and space technology [1]-[8]. An important advantage of AMC is the possibility of their formation for specific operating conditions, due to the introduction of high-strength high-modulus fillers of various types, fractional composition, and volumetric content into a plastic metal matrix. Recently, there has been a tendency to use nanoscale reinforcing phases to improve the properties of AMC, which makes it possible to obtain a more favorable set of characteristics [9]-[16].

The data of laboratory research and industrial tests have shown that AMC can be effectively used in friction units of various types of equipment [12]-[22]. The advantages of aluminum alloys as matrices of such composites are high thermal conductivity, heat capacity, high technological properties, including the possibility of varying mechanical properties by choosing alloy systems. Particles with hardness sharply different from the aluminum matrix are used as reinforcing fillers, which increase the wear resistance, and also reduce and stabilize the friction coefficients in a wide range of loading parameters. An important requirement for such reinforcing phases is high technological compatibility with an aluminum matrix [1]-[3], [16], [21]. The use of carbide particles, including silicon carbide SiC, has shown to be quite good [16]-[20]. The most developed technology for obtaining anti-friction AMCs is a different version of the method of liquid-phase mixing (introduction of reinforcing particles into the aluminum alloy melt) [14]-[22].

DOI: https://doi.org/10.37256/est.3120221035

For example, in [15], high-strength aluminum alloy AK12M2MgN (wt.%: 11-13 Si, 1.5-3 Cu, 0.3-0.6 Mn, 0.85-1.35 Mg, < 0.5 Zn, 0.05-1.2 Ti, 0.3-1.3 Ni, < 0.8 Fe, < 0.2 Cr, < 0.1 Sn) were reinforced with particles of α-SiC powder with dimensions of 40 and 14 μm with using the method of mechanical mixing at a temperature of 800-850 °C and an impeller rotation speed of 600 min^{-1}. Under conditions of dry sliding friction according to the "bushing (steel 40X)-disk (AMC)" scheme at a speed of 0.39 m/s at specific loads of 0.2-0.7 MPa, the introduction of 10% SiC reduced the wear rate by 1.8 ... 2, 9 times and reduced the coefficient of friction at a load of 0.2 MPa by ≈ 1.2 times. With the addition of 5% SiC, the tribotechnical properties improved to a lesser extent. The bushings of bearings of radial pairs of electric centrifugal pumps of oil refining equipment, made of AMC, have shown themselves well when tested in an aqueous medium and in an environment that simulates formation fluid.

According to [16], AMC obtained by mechanical mixing of 5 wt.% SiC particles 28 μm in size into the melt of aluminum alloys AL2 (wt.%: 84.3-90 Al, 10-13 Si) and D16 (wt.%: 3, 8-4.9 Cu, 1.2-1.8 Mg, 0.3-0.9 Mn), showed in comparison with the matrix material: an increase in the hardness HB from 624 to 712 (for AL2) and from 849 to 1,110 (for D16). Under conditions of dry sliding friction "bushing (steel 40X)-disk (AMC)" at a speed of 200-1,500 min^{-1} at specific loads of 70-215 N for AMS, as compared to the matrix alloy, the load and the speed of transition to the "scuffing" mode increased accordingly from 70 to 180 N and from 600 to 1,500 rpm (for AL2) and from 1,000 to 1,500 rpm at the same load (for D16). The dry friction coefficient, depending on the sliding speed and load, decreased from 0.24-0.39 to 0.13-0.16 (for AL2) and from 0.18-0.25 to 0.14-0.22 (for D16). At sliding speeds of more than 1,100 min^{-1}, the friction coefficient for AMC based on D16, on the contrary, increased in comparison with the matrix alloy to 0.23-0.26. The wear rate for AMS based on AL2 in comparison with the matrix alloy decreased by 2.1-2.2 times. For AMS based on D16, at 300 min^{-1}, the wear rate slightly decreased, and at a speed above 600 min^{-1}, the wear rate, on the contrary, increased by a factor of 1.3-1.35.

In [18], based on the aluminum alloy A359 (wt.%: 9.1 Si, 0.58 Mg), AMC containing 5, 10 and 15 wt.% SiC. The composite melt was compressed in steel molds at 100 MPa. Wear tests were carried out according to the "pin (AMC)-on-disk (steel with a hardness of 62 HRC)" scheme at a speed of 655 min^{-1} (2.75 m/s) at specific loads of 20, 40, and 60 N. SiC particles were relatively evenly distributed in the matrix alloy. It was found that with increasing SiC content, the wear rate decreases. So the wear rate of AMC with 15 wt.% SiC was 2.5-10 times lower than that of the matrix alloy. The friction coefficient with the addition of SiC decreased only at a load of 20 N. At loads of 40 and 60 N, the friction coefficient was: 0.31-0.32 for the matrix alloy, 0.28-0.3 for AMC with 5 wt.% SiC, for AMS with 10 and 15 wt.% SiC 0.34-0.37. The wear surface of the AMC had a smooth, soft layer of iron oxides.

Researchers [20] obtained AMC samples with 5, 10, and 15 wt.% SiC for engineering applications by the method of stirring casting based on the Al 2014 alloy. In this study, the original base and its composites with 5, 10, and 15 wt.% SiC, made by the method of casting with stirring, were subjected to wear testing. Wear tests of matrix alloy and AMC samples with sliding friction according to the pin-on-disk scheme at a speed of 2 m/s at a load of 20 N showed that AMC with 10 wt.% SiC has the best characteristics. Additionally, samples of such an alloy were extruded. Extrusion improved the tribotechnical characteristics, and the sample extruded in a ratio of 8:1 showed the highest wear resistance.

It should be noted that AMCs based on low-alloy cast alloys, reinforced with SiC particles with sufficiently large sizes of 40-68 microns, were mainly investigated. Wear tests were mainly carried out in a narrow range of loads and speeds, and mainly at rather low values. The results on the most favorable (from the point of view of tribotechnical properties) content of SiC particles in AMC samples differ in different works. There is also little data on macrohardness similar to AMC.

In this regard, in this work, we studied AMC obtained by liquid-phase mixing based on fairly representative types of aluminum alloys AK12, D16, V124, AL9, AL25, reinforced with silicon carbide particles SiC 28 μm in size with a content of 5, 10, or 15 vol.%. Sliding friction tests were carried out at sufficiently large values and ranges of speed and load. The hardness HB and the reinforcement hardening efficiency were investigated.

2. Materials and methods

2.1 *Materials*

Standard aluminum alloys AK12, D16, W124, AL9, AL25 were used as materials for the metal matrix. Their chemical composition is shown in Table 1.

Table 1. Chemical composition and mechanical properties of the investigated aluminum alloys

Alloy	Content of elements in wt.%					Mechanical properties		
	Cu	Mg	Mn	Si	Other elements	Conditional yield strength $\sigma_{0.2}$, MPa	Ultimate tensile strength UTS, (MPa)	Elongation δ, %
AK12	≤ 0.6	≤ 0.1	≤ 0.5	10-13	≤ 0.1 Ti, ≤ 0.1 Zr, ≤ 0.3 Zn	80-90	160-170	5-6
D16	3.8-4.9	1.2-1.8	0.3-0.9	-	-	400	540	11
W124	3-4	0.15-0.35	0.1-0.3	8-11	0.1-0.3 Ti, 0.01-0.1 B, ≤ 0.3 Fe	-	400	1-2
AL9	-	0.2-0.4	-	6-8	≤ 0.15 Ti, ≤ 0.1 Be	140-160	200-220	3-5
AL25	1.5-3	0.8-1.3	0.3-0.6	11-13	0.8-1.3 Ni ≤ 0.2 Ti, ≤ 0.2 Cr, ≤ 0.5 Zn	-	190	-

For the reinforcement, we used a standard commercial SiC powder with particles about 28 μm in diameter, having a hardness of HV = 24 ... 28 GPa and an elastic modulus of 350-490 GPa. SiC powder was added in an amount of 5, 10, or 15% by volume. With a higher content of the reinforcing component, the deterioration of the mechanical properties obtained by AMC is possible [2], [23]-[26]. Billets in the form of castings were obtained by the method of liquid-phase mechanical mixing [2], [14]-[16]. SiC particles heated to about 580 °C were fed into a bath with a melt having a temperature of about 820 °C. Mixing was carried out with an impeller speed of 600 rpm for 10 minutes. In some cases, when obtaining model parts, graphite particles with a size of about 400 μm in an amount of 2.5 vol.% were also kneaded into the melt. To obtain prototypes and model parts, the castings were subjected to traditional machining on a lathe using a tool with a diamond insert. Samples for comparison of properties were obtained from the castings of the above-mentioned aluminum alloys, in which the reinforcing particles were not introduced.

2.2 *Research methods*

The microstructure of the obtained AMC samples was studied using an Olympus GX51 metallographic light microscope.

The hardness HB of the studied samples was assessed according to the standard Brinell method on an Emco-test “Dura Vision 20” hardness tester with an indenter in the form of a ball with a diameter of D = 2.5 mm at a load of P = 613 N. At least 5 measurements were carried out on each sample.

To assess the efficiency of strengthening E_h of the obtained AMCs due to the introduction of SiC particles, the following formula is proposed:

$$E_h = (HB_C - HB_M) / \%\ SiC, \quad (1)$$

where HB_C is the hardness of AMC, HB_M is the hardness of the matrix alloy, % SiC is the volumetric content of silicon carbide in the sample. The hardening efficiency Eh shows how much the AMC hardness increased when 1 volume % SiC was added to the material. To assess the uniformity of hardening during mechanical mixing, the distribution of hardness HV over the cross-section of the specimens was assessed by the standard Vickers method using a diamond tetrahedral pyramid as an indenter with an indentation load of 0.098 N and holding the indenter under a load of 30 s. For a sample of each AMC, a series of 10 measurements with a step of 0.5 mm was carried out on a Dura Scan 70 hardness tester. The selected load on the indenter ensured that the size of the diagonal of the indentation was significantly larger than the size of the structural components.

Friction and wear tests were carried out on an MI-1M testing machine of the "Amsler" type according to the "disk-block" loading scheme. Similar test schemes were used in articles [14]-[16], [18]-[20]. A disk made of 40X structural steel (analogue of steels 1.7034, 5140H, 40Cr, 38C4) with a hardness of HRC 45 ... 50 rotated at a speed of $\eta = 300$, 1,000 and 1,500 rpm, and an AMC block was pressed against the end surface of the disk with a constant force F from 70 to 300 N. The test scheme and the main dimensions of the samples and disk are shown in Figure 1. Steel 40X was used since it is the most common contact material. Counterbody materials similar in composition and hardness were used in [15], [16]. The tests were carried out under dry friction conditions and friction conditions lubricated with TM-3-18 machine oil. This oil is a multigrade mineral oil for heavily loaded friction units and meets the following standards: SpiraxEP 90W Mobil, Mobilube GX 90 BP, Gear oil EP SAE 90 Esso. The tribotechnical behavior of the samples was evaluated by the value of the friction coefficient f, the intensity of volumetric wear I_V, and the loss of mass of parts Δm. The value of the friction coefficient is calculated by the formula: $f_{fr} = M_{fr} / (r - N)$, where M_{fr}- the friction moment, r- the disk radius, N- the acting load. Friction tests were carried out following the standards: GOST 27860-88 "Rubbing mating machine parts. Methods of measuring wear", GOST 27640-88 "Engineering materials and lubricants. Methods of experimental evaluation of friction coefficient", GOST 23.301-78 "Products wear resistance assurance. Instruments for evaluating wear by the method of cut notches. Technical requirements". A sample of a typical anti-friction alloy based on Al-AOM 2-1 (Al-2% Sn-1% Mg) was used as a reference sample.

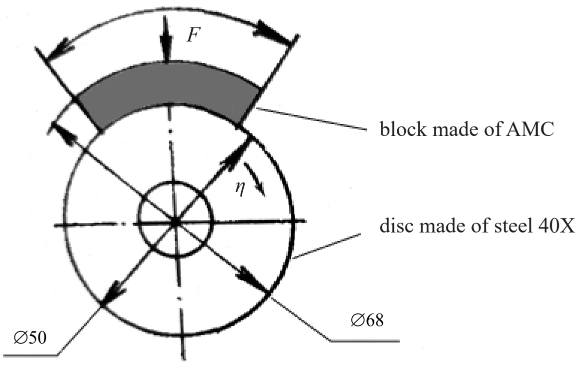


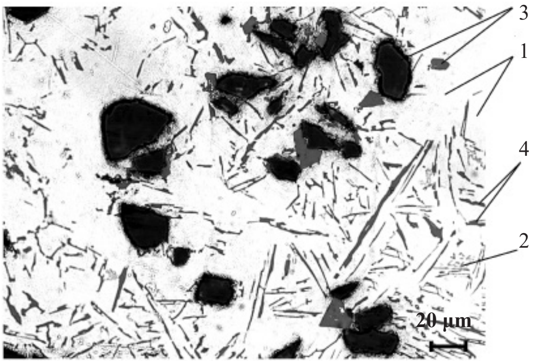
Figure 1. Friction test scheme. Dimensions are in mm.
The diameter of the inner hole in the disk is 16 mm, the thickness of the disk is 12 mm, and the thickness of the block is 10 mm

3. Results and discussion

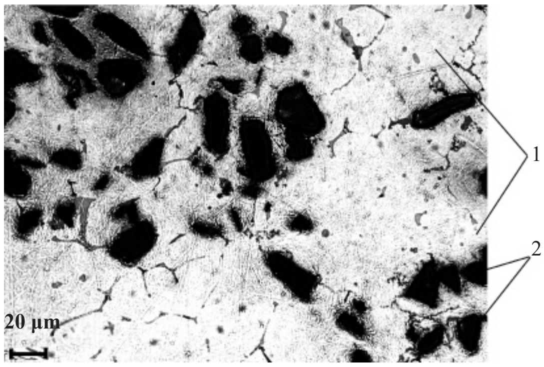
3.1 *Microstructure research*

The microstructures of the studied AMCs obtained using a metallographic microscope have much in common. The most typical microstructures are shown by the example of AMC AK12 + 5% SiC and D16 + 5% SiC in Figure 2.

AMC based on casting alloys AK12, W124, AL9, AL25 have a similar matrix alloy microstructure, similar to the base alloy AK12 (Figure 2a), which is an α + Si eutectic. In AMC based on alloy D16 (Figure 2b), weakly defined grain boundaries are observed, and SiC particles are located between grains of the matrix alloy. For all studied AMCs, SiC particles have the form of fragments, but a dark rim is observed along with the particle-matrix alloy boundaries, which contains the reaction products between silicon carbide and an aluminum alloy, which provide a strong bond at the filler-matrix alloy interface and a sufficient level of performance properties.



(a)



(b)

Figure 2. Typical microstructure of aluminum-matrix composite materials obtained by mechanical kneading into the melt: (a) AK12 + 5% SiC (1-α solid solution, 2-eutectic Al-Si (α + Si), 3-SiC particles, 4-needle-shaped Si particles); (b) D16 + 5% SiC (1-matrix alloy D16, 2-SiC particles). Photographs of microstructures were obtained with a light microscope

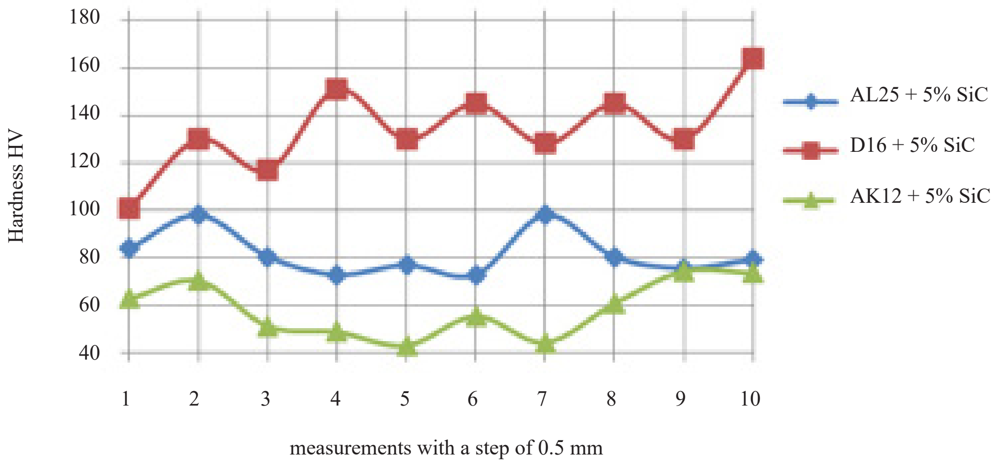
3.2 *Hardness test*

The results of measuring the hardness of the samples by the Brinell HB method are presented in Table 2. It can be seen that the hardness of AMC in all cases exceeds the hardness of the matrix alloy by a factor of 1.1 ... 1.4. The greatest increase in HB values is observed for samples AMC D16 + 5% SiC and W124 + 15% SiC. The hardening efficiency is on average about 2.5 HB units per addition of 1 vol.% SiC. Sample AMC D16 + 5% SiC stands out in particular, for which a weighted value of the hardening efficiency of 6.2 is observed. The high efficiency of hardening for these specimens is since alloys D16 and W124 initially have significantly higher mechanical characteristics in comparison with the rest of the studied matrix alloys. The data on hardness HB very closely coincide with the data of [16].

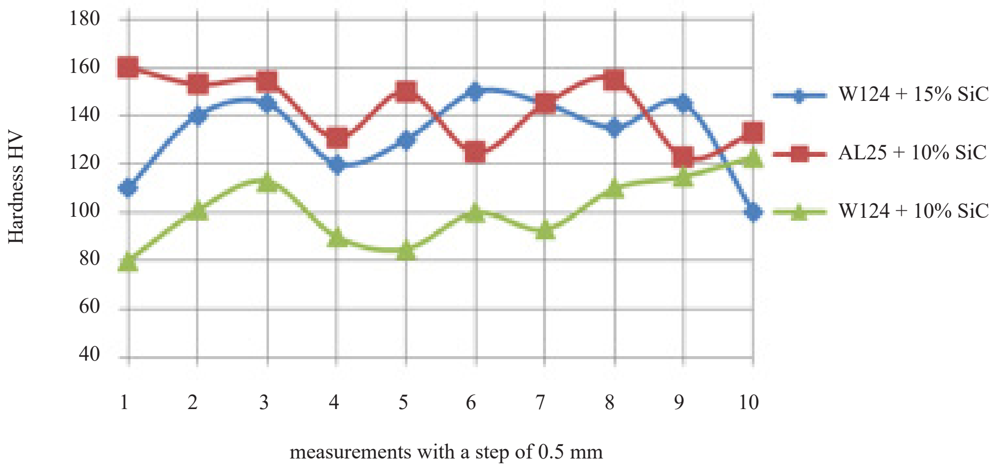
Table 2. Results and analysis of AMC hardness measurements by Brinell method

No	Sample AMC	Matrix alloy hardness HB_M	Composite hardness HB_C	E_h
1	AK12 + 5% SiC	620	710 ± 20	1.8
2	D16 + 5% SiC	850	1160 ± 30	6.2
3	W124 + 10% SiC	880	1130 ± 20	2.5
4	W124 + 15% SiC	880	1240 ± 20	2.4
5	AL9 + 5% SiC	980	1130 ± 20	3
6	AL25 + 10% SiC	980	1240 ± 50	2.6

The results of measuring the hardness HV over the cross section of AMC samples are shown in the form of graphs in Figure 3. It can be seen that for all AMCs the distribution of microhardness over the cross-section is fairly uniform, no sharp peaks are observed. At elevated SiC contents, the distribution is less uniform, there are differences in hardness values depending on the measurement point, which is explained when studying the microstructure studied with a metallographic microscope.



(a)



(b)

Figure 3. The results of measuring the hardness HV of the samples:
(a) at low values of the SiC content, (b) at the average values of the SiC content

3.3 *Study of tribotechnical characteristics*

The values of the friction coefficients f and the intensity of volumetric wear I_V obtained as a result of the tests for the studied AMC, matrix alloys, and the control anti-friction alloy AOM 2-1 are shown in Table 2.

As can be seen from the test results, AMCs have friction coefficients, as a rule, lower in comparison with antifriction alloy AOM 2-1 and corresponding matrix alloys. At the same time, they keep them in a much wider range of sliding speeds and loads. An increase in the SiC content leads to a noticeable decrease in the friction coefficients f. For example, for AMC based on D16, an increase in the SiC content from 5 to 20% leads to a threefold decrease in f. When compared with the data [16], where other test conditions were somewhat different, the nature of the change in the friction coefficients f for AMC D16 + 5% SiC is quite similar: at a load of 70 N, the values of f are greater than that of the matrix alloy, and at a load of 108 N they become close enough.

Table 3. Results of testing samples for friction without lubrication

No	Sample	Load F, N	f at sliding speed n, rpm			I_V, mm^3/m*
			300	1000	1500	
1	AK12	70	0.5			0.019
2	AK12 + 5% SiC	70			0.34	0.009
3	AK12 + 10% SiC	70		0.68		0.005
		144		0.64		
4	AL25	70		1.02		0.054
		108		0.84		
5	AL25 + 5% SiC	180			0.66	0.006
6	D16	108		1.21	0.61	0.016
7	D16 + 5% SiC	70			0.78	0.007
		108		0.48	0.63	
8	D16 + 20% SiC	300	0.31	0.27	0.20	0.005
9	AOM 2-1	70	0.70			0.047

* I_V determined after tests with a load of 5 kg and n = 180 rpm for 15 minutes

Figure 4 shows the average wear rate for ACM with different SiC content (a) and different matrix alloys (b) to evaluate the contribution made by the properties of the matrix alloy. It can be seen that the intensity of volumetric wear I_V for AMC is 5-9 times lower than for the AOM 2-1 alloy and 2-9 times lower than for the corresponding matrix alloys. An increase in the SiC content in materials leads to a decrease in the I_V value. (Figure 4a). A similar dependence was observed in [18] but under different test conditions and a different matrix alloy. In [20], for AMC with a matrix alloy Al 2014, which is close in composition to the AK12 alloy, a similar picture was also observed: AMC with 10 wt.% SiC had the best wear resistance characteristics. The influence of the composition of the matrix alloy on the value of the volumetric wear is also traced (Figure 3b). Figure 4b shows the average wear rate for AMC with 5% SiC for different matrix alloys to evaluate the contribution made by the properties of the matrix alloy. Smaller values of I_V were observed for AMC based on the AL25 alloy with a higher content of Si, Ni, Cr, and Zn in comparison with the matrix alloys AK12 and D16. At the same time, the lowest values of volumetric wear IV were shown by AMC D16 + 20% SiC and AK12 + 10% SiC, which have high values of hardness.

Figure 5 shows the values of the mass loss Δm for AMC parts, counterbody made of 40X steel, and the total mass loss for both parts under conditions of friction without lubrication and with lubrication. Analysis of the behavior of a friction pair in which one part is made of AMC (light parts of the columns in Figure 5), and the counterpart is made of structural steel (dark parts of the columns in Figure 5), makes it possible to assess the compatibility of these materials based on the value of the total wear of the friction pair, which will demonstrate the functioning of the material in the product, since it is important to evaluate the behavior of not only the material under study but also the material of the counterpart paired with which the operation is supposed to be. In general, all AMCs have shown sufficiently high compatibility in pairs with steel, which shows the serviceability of these AMCs for work in friction units with steel. The most balanced ratio of Δm for parts made of AMC and steel, as well as lower values of Δm for AMC, were shown by materials 1-AL25 + 5% SiC, 2-D16 + 20% SiC, which have high hardness values. Also, AMC with such matrix alloys, as shown above, are distinguished by a lower wear rate, especially with an AL25 matrix. Taking into account the above-considered dependence of the AMC wear intensity on the SiC content, it is recommended to use composites with a SiC content of about 20% for friction units with a pair of “AMC-steel”.

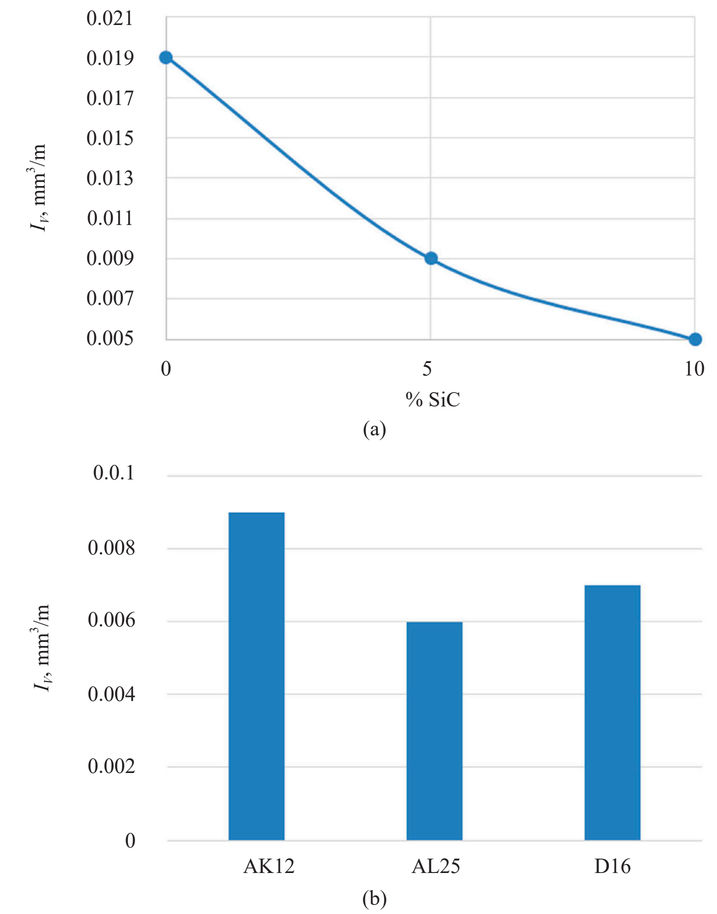


Figure 4. Influence of various factors on the wear rate of I_V AMC under dry friction conditions: (a) the effect of the SiC content in the AK12 matrix alloy; (b) I_V values for AMC with different matrix alloys at the same SiC content of 5 vol.%

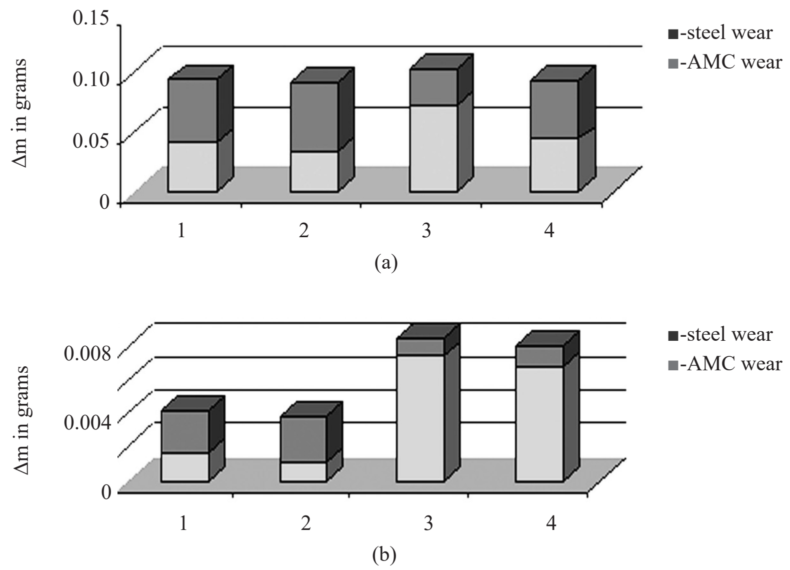


Figure 5. Loss of mass of parts Δm in grams for parts made of steel 40X and the total loss of mass for both parts along the friction path of 9,432 m under friction conditions: (a) with dry friction with a load of F = 0.8 MPa; (b) with friction with lubrication at F = 15 MPa. The numbers indicate AMC: 1-AL25 + 5% SiC, 2-D16 + 20% SiC, 3-AK12 + 5% SiC, 4-D16 + 5% SiC

3.4 *Research in some industrial friction units replacing parts from traditional materials with parts from AMC*

From the obtained AMCs, some model parts for real friction units were obtained and the results of replacing parts from traditional materials with parts from AMC were analyzed. The results of these studies are shown in Table 3.

The data in Table 3 demonstrate, using the example of some real products in service, the clear advantages of the AMC of the group in question, compared to replaceable materials. Quotas of superiority in terms of durability, service life, weight, and cost have been reached. All presented units have passed bench and field tests. Thus, in practice, it has been shown that parts made from AMC have higher performance characteristics. In all the examples presented, due to the replacement of the material, a significant increase in the service life has been achieved by 1.4 ... 1.5 times. A threefold reduction in part weight can be achieved. According to the economic factor, the gain is usually 2 to 10 times. These results are in good agreement with the literature data. In particular, works [27], [28] also indicated a decrease in the weight and cost of products made of similar AMCs, and articles [18], [23]-[24], [28]-[32] indicated an increase in the service life of parts from AMCs with similar composition. It should be noted that AMC, thanks to an aluminum-based matrix, is resistant to chemical corrosion, including in seawater. In general, it can be noted that the introduction of AMC is most promising for parts of friction units in the automotive, aerospace, shipbuilding, and oil-producing industries, where, along with high tribotechnical characteristics, weight reduction and good corrosion resistance are required.

4. Conclusions

Many composites are based on aluminum alloys AK12, D16, W124, AL9, AL25, reinforced with silicon carbide SiC particles in an amount from 5 to 20 vol.% obtained by the technology of liquid-phase mechanical mixing. The developed composites in comparison with the initial matrix alloys had 1.1 ... 1.4 times higher values of hardness, with a fairly uniform distribution of their values over the cross-section of the sample.

Under conditions of dry friction on steel according to the “disk-block” loading scheme in the range of rotation speeds of 300-1,500 rpm and loads of 70-300 N, the composites showed better efficiency compared to matrix alloys and the frequently used anti-frictional aluminum alloy AOM 2-1. The dry friction coefficient was 1.5-3 times lower on average, and the volumetric wear rate was 5-9 times lower. An increase in the content of SiC particles in the composite from 5 to 10-20 vol.% usually leads to an improvement in tribotechnical characteristics. The composites obtained have shown a sufficiently high operational suitability for work in friction units with steels both in dry friction and in friction with lubrication.

Of the composites studied, the best performance characteristics and consequently, the greatest promising application in the industry were shown by the materials D16 + 20% SiC and AL25 + 10% SiC. Composites W124 + 15% SiC and AK12 + 10% SiC also have a potential for use.

Full-scale tests on replacing parts made of traditional anti-friction materials with parts made from obtained composites in real friction units have shown that such a replacement makes it possible to improve the performance, increase the service life, and reduce the cost of products by 2-10 times.

Conflict of interest

The authors declare no conflict of interest.

References

[1] D. B. Miracle, “Metal matrix composites-from science to technological significance,” *Composites science and technology*, vol. 65, no. 15, pp. 2526-2540, 2005.

[2] V. V. Berezovskii, A. A. Shavnev, Y. O. Solyaev, S. A. Lur’e, A. V. Babaitsev, and Y. A. Kurganova, “Mechanical

properties of a metallic composite material based on an aluminum alloy reinforced by dispersed silicon carbide particles,'' *Russian Metallurgy (Metally)*, vol. 2015, no. 10, pp. 790-794, 2015.
[3] Y. A. Kurganova, T. A. Chernyshova, L. I. Kobeleva, and S. V. Kurganov, ''Service properties of aluminum matrix precipitation hardened composite materials and the prospects of their use on the modern structural material market,'' *Russian Metallurgy (Metally)*, vol. 2011, no. 7, pp. 663-666, 2011.
[4] T. A. Chernyshova, L. I. Kobeleva, P. A. Bykov, L. K. Bolotova, I. E. Kalashnikov, A. T. Volochko, and A. Y. Izobello, ''Nanostructuring of dispersion-reinforced aluminum-matrix composite materials,'' *Inorganic Materials: Applied Research*, vol. 4, no. 3, pp. 247-255, 2013.
[5] Y. A. Kurganova, S. P. Shcherbakov, I. Chen, and S. D. Karpukhin, ''Technology for producing a promising aluminum-matrix composite material with discrete Al_2O_3 fibers,'' *Russian Metallurgy (Metally)*, vol. 2020, no. 13, pp. 1531-1536, 2020.
[6] W. Moćko and Z. L. Kowalewski, ''Mechanical properties of the A359/SiC_p metal matrix composite at wide range of strain rates,'' *Applied Mechanics and Materials*, vol. 82, pp. 166-171, 2011.
[7] P. A. Vityaz, A. F. Ilyushchenko, A. G. Kolmakov, M. L. Heyfets, and I. N. Chernyak, ''Manufacture of composites based on aluminum and shungite under high pressure conditions,'' *Inorganic Materials: Applied Research*, vol. 7, no. 7, pp. 478-481, 2016.
[8] R. S. Mikheev, I. E. Kalashnilov, L. K. Bolotova, and A. G. Kolmakov, ''Research of the intermetallics formation mechanism during the synthesis of functionally graded layered steel-aluminum compositions,'' *IOP Conference Series: Materials Science and Engineering*, vol. 848, no. 1, pp. 012056, 2020.
[9] M. Jagannatham, P. Chandran, S. Sankaran, P. Haridoss, N. Nayan, and S. R. Bakshi, ''Tensile properties of carbon nanotubes reinforced aluminum matrix composites: A review,'' *Carbon*, vol. 160, pp. 14-44, 2020.
[10] A. Mazahery and M. Shabani, ''Characterization of cast A356 alloy reinforced with nano SiC composites,'' *Transactions Nonferrous Metals Society of China*, vol. 22, pp. 275-280, 2012.
[11] P. A. Vityaz, V. T. Senyut, M. L. Kheifetz, A. G. Kolmakov, and E. O. Nasakina, ''Designing and synthesis of alumo-matrix composite material modified by nanostructured cubic boron nitride,'' *Nonlinear Phenomena in Complex Systems*, vol. 22, no. 2, pp. 128-134, 2019.
[12] A. D. Breki, T. S. Kol'tsova, A. N. Skvortsova, O. V. Tolochko, S. E. Aleksandrov, A. G. Kolmakov, A. A. Lisenkov, A. E. Gvozdev, Y. A. Fadin, and D. A. Provotorov, ''Tribotechnical properties of composite material 'Aluminum-Carbon Nanofibers' under friction on steels 12Kh1 and ShKh15,'' *Inorganic Materials: Applied Research*, vol. 9, no. 4, pp. 639-643, 2018.
[13] G. V. N. B. Prabhakar, L. Dumpala, and N. Ravikumar, ''Mechanical, machining and corrosion properties of Al5083-carbon nanotubes composite produced by friction stir processing,'' *Materialwissenschaft und Werkstofftechnik*, vol. 52, no. 5, pp. 520-528, 2021.
[14] I. E. Kalashnikov, L. K. Bolotova, L. I. Kobeleva, P. A. Bykov, and A. G. Kolmakov, ''Wear products that form during tribological tests of aluminum-matrix composite materials,'' *Russian Metallurgy (Metally)*, vol. 2015, no. 4, pp. 285-289, 2015.
[15] I. E. Kalashnikov, L. K. Bolotova, and T. A. Chernyshova, ''Tribological characteristics of cast aluminum-matrix composites modified by nanosized refractory powders,'' *Nanotechnologies in Russia*, vol. 6, no. 1-2, pp. 144-153, 2011.
[16] T. A. Chernyshova, L. I. Kobeleva, L. K. Bolotova, and I. E. Kalashnikov, ''Tribological characteristics of the matrix-alumina composites strengthened with nano-fillers,'' *Trenie i Iznos*, vol. 26, no. 4, pp. 446-450, 2005.
[17] L. Stanev, M. Kolev, and L. Drenchev, ''Enhanced tribological properties of an advanced Al-Al_2O_3 composite infiltrated with a tin-based alloy,'' *Journal of Tribology*, vol. 143, no. 6, pp. 064502, 2021.
[18] E. A. M. Shalaby, A. Y. Churyumov, D. H. Besisa, A. Daoud, and M. A. El-khair, ''A Comparative study of thermal conductivity and tribological behavior of squeeze cast A359/AlN and A359/SiC composites,'' *Journal of Materials Engineering and Performance*, vol. 26, no. 7, pp. 3079-3089, 2017.
[19] T. A. Chernyshova, R. S. Mikheev, I. E. Kalashnikov, I. V. Akimov, and E. I. Kharlamov, ''Development and testing of Al-SiC and Al-TiC composite materials for application in friction units of oil-production equipment,'' *Inorganic Materials: Applied Research*, vol. 2, no. 3, pp. 282-289, 2011.
[20] S. Dhanalakshmi, K. ShanmugaSundaram, T. R. Tamilarasan, and R. Rajendran, ''The role of ceramic particle loading and the influence of hot extrusion on the tribological behaviour of aluminium alloy-SiCp composites,'' *Journal of Composite Materials*, vol. 55, no. 5, pp. 687-701, 2021.
[21] B. N. Sarada, P. L. S. Murthy, and G. Ugrasen, ''Hardness and wear characteristics of hybrid aluminium metal matrix composites produced by stir casting technique,'' *Materials Today: Proceedings*, vol. 2, pp. 2878-2885, 2015.

[22] J. F. Liu, L. Qi, G. L. Li, and Y. D. Qu, ''Microstructure, mechanical properties and wear resistance performance of TiCp/7075 matrix composite by vacuum stirring,'' *Materials Reports (Cailiao Daobao)*, vol. 35, no. 6, pp. 6114-6119, 2021.
[23] P. B. Li, T. J. Chen, and H. Qin, ''Effects of mold temperature on the microstructure and tensile properties of SiCp/2024 Al-based composites fabricated via powder thixoforming,'' *Materials & Design*, pp. 112, pp. 34-45, 2016.
[24] P. Liu, A. Q. Wang, J. P. Xie, and S. M. Hao, ''Characterization and evaluation of interface in SiCp/2024 Al composite,'' *Transactions of Nonferrous Metals Society of China*, vol. 25, no. 5, pp. 1410-1418, 2015.
[25] T. Dou, H. G. Fu, Z. L. Li, X. Ji, and S. S. Bi, ''Prediction model, simulation, and experimental validation on thrust force and torque in drilling SiCp/Al6063,'' *The International Journal of Advanced Manufacturing Technology*, vol. 103, no. 1-4, pp. 165-175, 2019.
[26] S. T. Kumaran, T. J. Ko, M. Uthayakumar, M. A. Khan, and I. Muhammad, ''Some experimental investigations on drilling AA (6351)-SiC-B4C composite,'' *Materials and Manufacturing Processes*, vol. 32, no. 13, pp. 1557-1564, 2017.
[27] D. B. Miracle, ''Aeronautical applications of metal matrix composites,'' *ASM handbook-Composites*, vol. 21, pp. 1043-1049, 2001.
[28] N. Chawla and K. K. Chawla, *Metal Matrix Composites*. New York: Springer Science + Business Media, 2013, pp. 370.
[29] B. N. Sarada, P. S. Murthy, and G. Ugrasen, ''Hardness and wear characteristics of hybrid aluminium metal matrix composites produced by stir casting technique,'' *Materials Today: Proceedings*, vol. 2, no. 4-5, pp. 2878-2885, 2015.
[30] J. H. Bae, K. C. Jung, S. H. Yoo, S.H. Chang, M. Kim, and T. Lim, ''Design and fabrication of a metal-composite hybrid wheel with a friction damping layer for enhancement of ride comfort,'' *Composite Structures*, vol. 133, pp. 576-584, 2015.
[31] A. J. Knowles, X. Jiang, M. Galano, and F. Audebert, ''Microstructure and mechanical properties of 6061 Al alloy based composites with SiC nanoparticles,'' *Journal of Alloys and Compounds*, vol. 615, pp. S401-S405, 2014.
[32] X. Yao, Y. F. Zheng, J. M. Liang, and D. L. Zhang, ''Microstructures and tensile mechanical properties of an ultrafine grained AA6063-5 vol.% SiC metal matrix nanocomposite synthesized by powder metallurgy,'' *Materials Science and Engineering: A*, vol. 648, pp. 225-234, 2015.