E3S Web of Conferences **376**, 01011 (2023) https://doi.org/10.1051/e3sconf/202337601011
ERSME-2023

Aluminium matrix hybrid composite materials reinforced with carbides and intermetallics

R. Mikheev[1*] and *I.* Kalashnikov[2]

[1]Bauman Moscow State Technical University 5, 2-ya Baumanskaya str., 105005 Moscow, Russian Federation
[2]Baikov Institute of Metallurgy and Materials Science of Russian Academy of Sciences 49, Leninskiy prospect, 119334 Moscow, Russian Federation

Abstract. Composite materials based on aluminum, reinforced with particles of titanium carbide and intermetallic compounds of titanium aluminide, are made by casting technology. Investigations of the structure, mechanical and tribotechnical characteristics of the manufactured composite materials have been carried out. It is shown that the reinforcement of an aluminum matrix with TiC particles, or intermetallic phases of Al_3Ti, formed by introducing reactive titanium powders into the melt, is an effective way to increase the tribotechnical characteristics. It has been established that the reinforcement of the aluminum matrix with TiC particles has a greater effect on the reduction of the friction coefficient and the wear rate, in comparison with the reinforcement with intermetallic phases Al_3Ti, despite the higher volume fraction of the latter. It has been determined that the greatest wear resistance is provided by hybrid reinforcing of an aluminum matrix with TiC particles and intermetallic phases. The additional introduction of stronger TiC particles leads to a decrease in the load on the Al_3Ti intermetallics, thereby preventing their destruction under the action of high external loads. In addition, the presence of a larger number of reinforcing phases in hybrid composite materials than in other composite materials samples provides not only a decrease in the load on each reinforcing particle separately, but also a decrease in the fraction of the matrix in the friction surface, thereby expanding the range of triboloading.

1 Introduction

Aluminum and its alloys are widely used in products of modern technology. Designers are attracted by their low specific weight, high plastic properties, corrosion resistance, and manufacturability. However, due to their low hardness, tendency to seizure, and low wear resistance, they are rarely used in sliding bearings. The introduction into theese materials of a small amount of high-strength ceramic particles (2-10 vol.%) is an effective way to increase wear resistance and scuff resistance in a wide temperature range [1-4]. In addition, particle reinforced aluminium matrix composite materials (CMs) have increased values of specific strength and stiffness while maintaining high damping capacity, electrical and

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[*] Corresponding author: mikheev@bmstu.ru

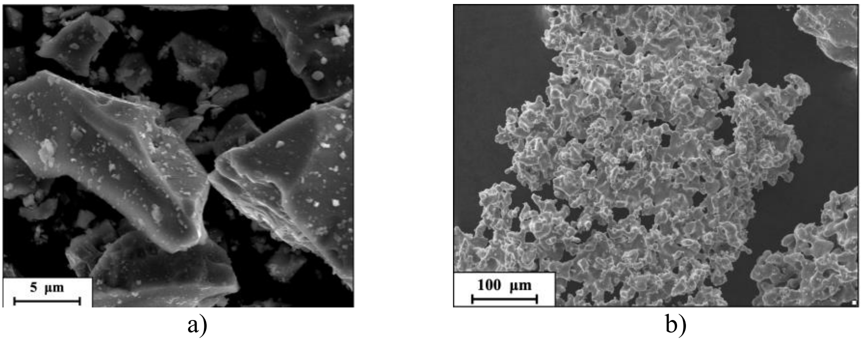
thermal conductivity, and low specific gravity. Ceramic particles or short fibers, such as SiC, TiC, TiB_2, Al_2O_3, B_4C, etc., which have high mechanical properties, are usually used as reinforcements. Increased attention to CMs reinforced with TiC particles is due to the fact that this type of reinforcement, in comparison with other ceramic particles SiC, Al_2O_3, TiB_2, etc., is characterized by greater strength and rigidity, as well as a greater metallic component of the chemical bond [5]. It leads to a stronger interfacial bond and high strength properties of CMs containing such reinforcement. The high hardness of the Al-TiC system CMs ensures low wear rate during sliding friction process [6-8].

Along with the introduction of ceramic particles of the same type into the aluminum matrix, hybrid reinforcing opens up significant possibilities for the purposeful control of CM properties, i.e. simultaneous reinforcing of matrices with particles of different nature and size. Hybrid reinforcing can be carried out both by introducing a mixture of fundamentally different reinforcing particles into the matrix melt, and by introducing mixtures of reinforcents and reactive elements (Ti, Ni, Fe, Zr, etc.), leading to the formation of intermetallics directly in the matrix melt in as a result of chemical reactions (so-called in-situ processes) [9-11]. The melt temperature increasing associated with the exothermic effect of the intermetallic phases formation chemical reactions promotes better wetting of the reinforcing particles by the matrix melt. Intermetallic phases formed in-situ are characterized by a high level of bonding along the reinforcement / matrix interfaces due to a small mismatch between the crystal lattices of the new phases and the matrix, as well as high thermal stability, which ultimately provides a higher level of mechanical and special properties of CMs.

This article presents the results of studying the Al-Ti-TiC system CMs, namely the effect of reinforcing components on the structure and tribological properties of CMs.

2 Materials and methods

CMs were manufactured using casting technology by mechanically mixing TiC reinforcing particles and titanium powders into an aluminum matrix melt A99 (GOST 11069). Single-crystal titanium carbide particles, obtained by the chemical hydride-calcium method, had a size of no more than 20 μm (Fig. 1 a). The reaction-active element was titanium particles of TPP 5 grade (TU 1794-449-05785388-99), 630-1000 μm in size (Fig. 1 b). The charge composition of the investigated CMs is given in table 1.



a) b)

Fig. 1. Powders of titanium carbide (a) and titanium (b) in the initial state.

Table 1. Charge composition, intermetallics predicted content and the manufactured samples hardness.

Sample number	Composition, wt.% (vol.%)	Al_3Ti, wt.% (vol.%)	HB, MPa
1	Al	-	150
2	Al + 2 (1.14) Ti	5.4 (4.3)	180
3	Al + 2 (1.1) TiC	-	200
4	Al + 2 (1.2) Ti + 2 (1.1) TiC	5.4 (4.2)	240

Mechanical mixing of the reinforcements into the matrix melt was carried out at an impeller rotation speed of 600 min-1. The matrix melt temperature was 1073-1123 K. In the manufacture of hybrid CMs, a mixture of TiC and Ti powders was introduced into the melt. The initial components were processed in an attritor for 2 minutes to obtain a powder mixture. After mixing the powders and holding the composite melt at a temperature of 1073-1123 K for 20 minutes, the oxide film was removed from its surface, re-mixed, and the composite melt was poured into graphite molds.

The structure of the manufactured samples was investigated on Neophot and Leica DMILM microscopes using the Qwin software for image analysis. The Brinell hardness of the samples was measured using a Wilson Wolpert 930 N universal device by indenting a ball with a diameter of 2,5 mm at a load of 620 N.

Tests for dry sliding friction were carried out on an MTU-01 equipment (TU 4271-001-29034600-2004) according to the scheme: a rotating sleeve (counterbody made of 40X steel, HRC> 45) over a disk (CMs) at loads from 18 to 60 N and a speeds of 0,39 m/s. Steel sleeve dimensions: inner diameter 11,8 mm, outer diameter 15,8 mm. CMs disk size: diameter 40 mm, thickness 6 mm. During the test, the friction moment and the change in weight were recorded by weighing each sample before and after the test with an accuracy of ± $0{,}5\times10^{-3}$ g. The behavior of the samples during dry sliding friction was evaluated by the friction coefficient (f), the coefficient of the friction process stability (α_{st}), and the value of the volumetric wear rate (I_v):

$$f=\frac{M}{R_{av}\cdot F_a} \tag{1}$$

$$\alpha_{st}=\frac{f_{av}}{f_{max}} \tag{2}$$

$$Iv=\frac{\Delta m}{\rho\cdot L} \tag{3}$$

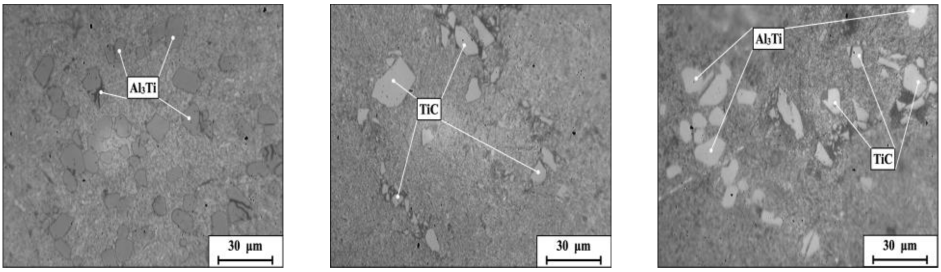
where Δm is the mass loss of the sample; ρ is the density of the sample, L is the friction lenght; M is the frictional moment; R_{av} - the average radius of the sleeve; F_a - axial load, f_{av} - average friction coefficient value, f_{max} - maximum friction coefficient value.

3 Results and discussion

Typical CMs structures are shown in Figure 2. The samples obtained by adding a reactive component to the matrix melt are characterized by the presence of Al_3Ti intermetallics formed in the in-situ reaction between the matrix material and titanium [12, 13]:

$$Al+Ti=Al_3Ti\ (\Delta G^\circ=-52503+21{,}484\cdot T,\ \text{where } T=[298 - 1400]\ K).$$

Intermetallic compounds in CMs samples poured after a 20-minute exposure of the melt are predominantly in the form of block crystals, which indicates the completion of the exothermic reaction of their formation and thermodynamic stability [14]. Due to the epitaxial correspondence, the titanium aluminide particles become crystallization centers and are fairly uniformly distributed in the aluminum matrix. Due to good wettability, TiC particles introduced into the melt ex-situ are not pushed aside by α-Al crystals into intergranular spaces, but are distributed randomly (Fig. 2b). The distribution of intermetallic phases and TiC particles in polyreinforced samples can be determined as random (Fig. 2c) [15].



a) b) c)

Fig. 2. Structure of manufactured samples: Al + 2 wt.% Ti (a), Al + 2 wt.% TiC (b), Al + 2 wt.% Ti + 2 wt.% TiC (c).

The results of the samples hardness measuring (Table 1) show that the introduction of reactive titanium powders or reinforcing particles of titanium carbide into the aluminum matrix increases the hardness in comparison with the matrix alloy by ΔHB = 30 MPa and 50 MPa, respectively. Despite the higher content of Al_3Ti intermetallics in the CMs composition as compared to TiC particles (4,3 vol.% and 1,1 vol.%, respectively), the highest degree of hardening is achieved due to the introduction of the latter. This is due to the higher strength characteristics of TiC particles (3200 HV) in comparison with Al_3Ti (400-700 HV) [1, 8]. The highest hardness (ΔHB = 90 MPa) is characteristic of hybrid CMs, which is associated with the presence in its composition of a larger amount of reinforcing particles (up to 5,3 vol.%).

Figure 3 shows the wear rate of samples made of matrix material and CMs under dry sliding friction conditions. It is seen that the axial load increasing leads to an increase in the wear rate for all samples. Unreinforced samples have the maximum wear rate. The wear rate is significantly reduced when the Al_3Ti intermetallics are formed in the matrix alloy by the in-situ method or the ex-situ introduction of TiC reinforcing particles. Comparison of CMs containing only intermetallic compounds or only titanium carbide particles shows that the latter are characterized by lower wear rates. The differences are especially noticeable with increasing axial loads above 50 N. This can be explained by the fact that, under such loads, TiC particles still play the role of bearing supports, while Al_3Ti intermetallic particles, which have lower strength characteristics than TiC particles, begin to break down and lose the ability to protect the matrix from fatigue (delaminate) wear and adhesive mechanisms [16, 17].

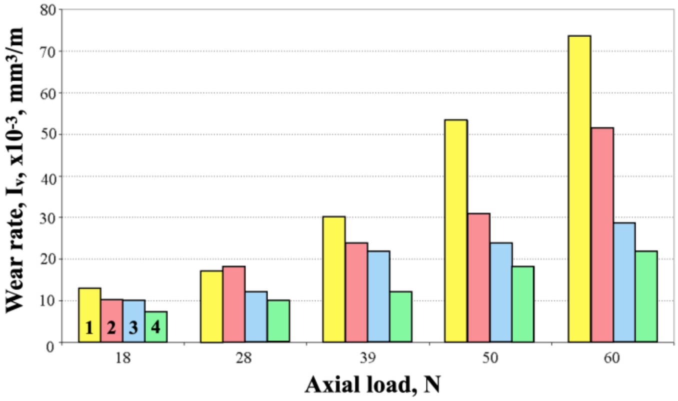


Fig. 3. Dependence of the wear rate on the applied axial load. Samples compositions, wt.%: 1 — Al; 2 - Al + 2 Ti; 3 - Al + 2 TiC; 4 - Al + 2 Ti + 2 TiC.

Hybrid CMs have the lowest wear rates over the entire triboloading. The additional introduction of stronger TiC particles leads to a decrease in the load on the Al_3Ti intermetallic compounds, thereby preventing their destruction under the action of high external loads. In addition, the presence of a more reinforcing particles in hybrid CMs than in other CMs samples provides not only a decrease in the load on each reinforcing particle separately, but also a decrease in the fraction of the matrix in the friction surface, thereby expanding the range of triboloading.

Figure 4 allows to compare the friction coefficients of samples made of CMs and matrix alloy (f_{CM} / f_M) depending on the applied axial load. It is seen that CMs have lower friction coefficients than the matrix. The in-situ formation of Al_3Ti intermetallics in an aluminum matrix leads to a decrease in the friction coefficient by 30-60%. The friction coefficient decreases even more noticeably for CMs reinforced with TiC particles or hybrid CMs. The friction coefficients values of theese samples are close in magnitude over the entire range of tested loads. This is probably due to the formation, under conditions of stable sliding friction, of a transition layer, or “third body,” which protects the sample from wear. According to [17-19], the transition layer is a mechanical nanostructured mixture of the material of the counterbody and the test sample, as well as their oxides, which provides low friction coefficient and wear rate values.

Samples made of CM in the entire triboloading are characterized by the coefficients of the friction process stability close to unity (Table 2), which indicates the stable friction mode.

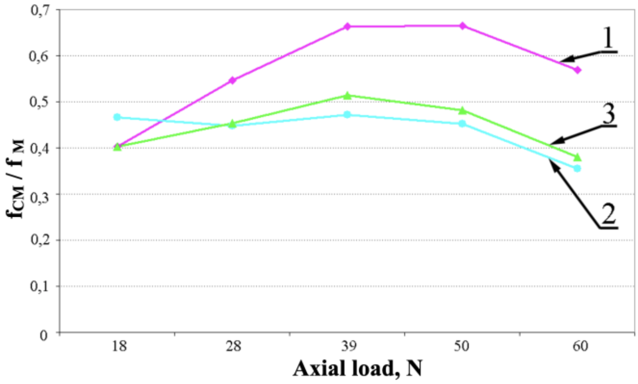
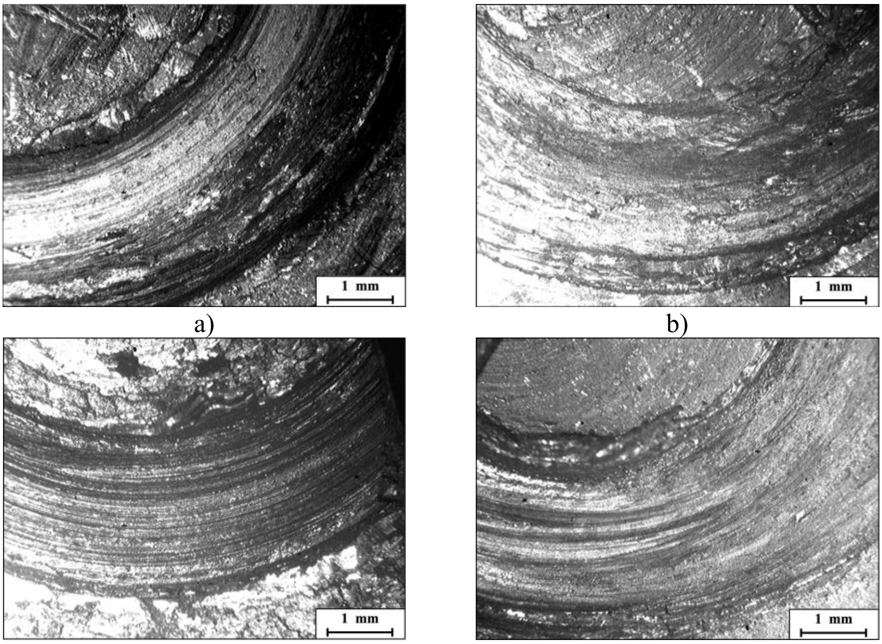


Fig. 4. Dependence of the friction coefficients of samples made of CMs.

And matrix alloy (f_{CM} / f_M) on the applied axial load. Samples compositions, wt.%:

1 - Al + 2 Ti; 2 - Al + 2 TiC; 3 - Al + 2 Ti + 2 TiC

The surface relief of the samples after dry sliding friction testing was analyzed by viewing with an optical microscope and SEM. At the initial stages of testing at low axial loads, grooves of plastic shear are formed on the samples surface in the sliding direction under the action of the roughness of the counterbody. A certain number of grooves and scratches parallel to the sliding direction may be associated with the predominance of the abrasive wear mechanism at the early stages of running-in, caused by the scratching and cutting action of solid reinforcing particles [20]. Further, at the stage of oxidative wear, the relief of the friction surface practically does not change. However, after testing at an axial load of 60 N, cavities and craters with a size of 1-1,5 mm, elongated along the sliding direction, are found on the friction surfaces of the matrix and the sample from the CMs of the Al-Ti system (Fig. 5 a, b). This morphology of the worn surface is the result of a change in the wear mechanism and its transition to an adhesive type. The characteristic features of adhesive wear are the seizure and transfer of the matrix material to the surface of the counterbody. The resulting high levels of deformations and stresses in the subsurface layer lead to significant damage to the friction surface, but there are no traces of damage along the intermetallic-matrix interface (Fig. 6).



a) b)

c) d)

Fig. 5. Macrophotographs of friction surfaces of samples after testing under 60 N axial load. Samples compositions, wt.%: a — Al; b - Al + 2 Ti; c - Al + 2 TiC; d - Al + 2 Ti + 2 TiC.

Table 2. Coefficient of the friction process stability (α_{st}) of manufactured CMs samples.

Sample composition. wt.%	**α_{st} depending on the applied axial load (P. N)**				
	18	**28**	**39**	**50**	**60**
Al — 2 Ti	0.91	0.86	0.75	0.78	0.73
Al — 2 TiC	0.95	0.89	0.88	0.9	0.93
Al — 2 Ti — 2 TiC	0.91	0.89	0.84	0.89	0.9

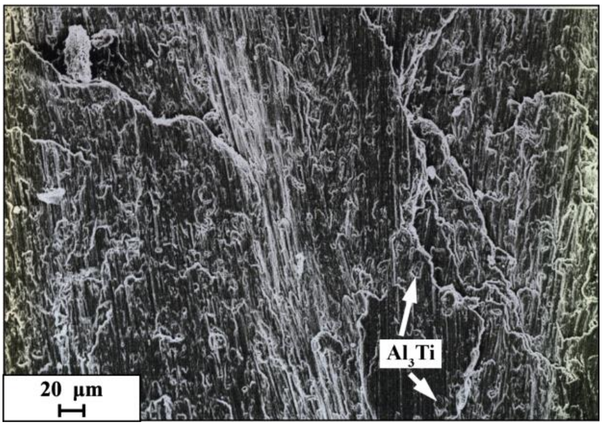


Fig. 6. The typical structure of the friction surface of a sample made of Al + 2 wt.% Ti composition.

Sufficiently smooth friction surfaces of CMs reinforced with TiC particles or hybrid CMs reinforced with Al_3Ti and TiC particles (Fig. 5 c, d) after tests at an axial load of 60 N, as well as low values of the wear rate and friction coefficient of these samples indicate moderate wear, which occurs by the oxidative mechanism. It is with this type of wear that a transition layer is formed on the friction surface, which prevents direct contact of the rubbing surfaces, and therefore protects the sample from destructive adhesive wear [19].

4 Conclusion

The studies carried out show that the reinforcing of the aluminum matrix with TiC particles, or intermetallics Al_3Ti, formed by introducing reactive titanium powders into the melt, is an effective way to increase the tribological characteristics. Reinforcing of an aluminum matrix with TiC particles has a greater effect on reducing the friction coefficient and the wear rate, in comparison with reinforcing with intermetallic phases Al_3Ti, despite the higher volume fraction of the latter. The best wear resistance is provided by hybrid reinforcing of the aluminum matrix with TiC particles and Al_3Ti intermetallic phases.

Acknowledgement

The research results were partially obtained within the framework of Russian Science Foundation № 22-29-00366, https://rscf.ru/project/22-29-00366/ «Functionally organized composite layers on steel friction units for improving their performance: development of compositions, formation and surface modification processes».

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