TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX NANOCOMPOSITES

Sandra Veličković [1*], Slobodan Garić [1], Blaža Stojanović [1], Aleksandar Vencl [2]

[1] Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, 34000 Kragujevac, Serbia
[2] Faculty of Mechanical Engineering, University of Belgrade, Kraljice Marije 16, 11120 Belgrade, Serbia

Abstract:
The paper provides an overview of tribological properties of nanocomposites with aluminium matrix. Nanocomposites represent a new generation of composite materials with better properties than conventional composite materials. The paper presents and explains the most common methods of nanocomposites production. In addition, the overview of tribological properties is presented through the equipment used for testing; amount, size and type of reinforcement; matrix material and manufacturing process; and test conditions.

ARTICLE HISTORY
Received 15 August 2016
Accepted 3 September 2016
Available online 30 September 2016

KEYWORDS
Aluminium, nanocomposites, manufacturing process, tribological properties.

1. INTRODUCTION

Intensifying demands in terms of increasing life service and reducing weight, and thus the prices of products, initiate the development and application of new materials. The increased use of composite materials is primarily due to their physical-mechanical and tribological properties that are better than the properties of the matrix material [1,2].

Due to its good characteristics, such as low density, good thermal conductivity and corrosion resistance, relatively low cost of production and good possibility of recycling, aluminium and its alloys are most often used as composite matrix [3,4]. Composite materials with aluminium alloys base are increasingly used in the aviation, aerospace, automotive and military industry. They are used for production of engine blocks, cylinder liners, connecting rods crankshafts, camshafts, cardan shafts, propellers of helicopters, as well as for production of brake discs and drums of cars and trains [5-15].

The improvement in mechanical and tribological properties of the aluminium composites is made by adding the appropriate reinforcements and improvers. Commonly used reinforcements are carbides, borides, nitrates, and oxides, i.e. Al_2O_3, SiC, TiC, TiO_2, B_4C, TiB_2, WC and others [16-18]. The choice of size and amount of reinforcement depends on the manufacturing process as well as on the practical application of composite material. By adding two or more reinforcements to the matrix material, a hybrid composite is obtained. However, in recent years, there is a trend of using the nanoscale reinforcements and production of nanocomposites [19-21].

This paper gives the overview of tribological properties of modern nanocomposites with aluminium matrix, with certain trends concerning test condition parameters influences. Classification of tribological properties was carried out on the basis of matrix material, amount, type and size of reinforcements, and manufacturing process as well as on the basis of counter-body material and equipment on which the test is conducted, together with the test conditions (sliding speed, load, and sliding distance). Our review is limited to studies with unlubricated sliding conditions conducted in the air, at room temperature.

2. MANUFACTURING PROCESS

The process for preparing nanocomposite materials based on aluminium base can be divided into three groups [22,23]:

- solid state processes include different powder metallurgy techniques with modifications in the processing steps such as high-energy ball milling, hot pressing, hot

CONTACT: Sandra Veličković, sandrav@kg.ac.rs

isostatic pressing, cold pressing followed by sintering treatment and extrusion;

- liquid state processes include different casting processes such as stir casting and squeeze casting;
- semi-solid processes include rheocasting technique with its variants such as compocasting or in combination with squeeze casting.

Mechanical milling is a process of milling the powder mixture by different methods. All these methods are based on the same principle of insertion of particulate material to the mill where they are subjected to high-energy collision with other particles and with the added steel balls that accelerate the procedure. The example of mechanical milling is presented through the research conducted by Sharifi and Karimzadeh [19]. They produced aluminium matrix nanocomposites by mechanical milling, followed by hot pressing. Aluminium powder with average particle size of 60 µm was milled with various amounts (5, 10 and 15 wt. %) of Al_2O_3–AlB_{12} nanopowders (average particle size ranging from 50 to 120 nm). Ball milling was carried out at rotation speed of 600 rpm and the ball-powder mass ratio was 10:1, for 5 h without interruption. The used steel balls were made of chrome-plated steel with a diameter of 20 mm. To prevent oxidation, the process was carried out under an argon atmosphere.

Stir casting represents a process very similar to the conventional casting method. The difference is that in stir casting there is a light stirring of the melt in order to obtain the equal distribution of the reinforcement in the matrix. Infiltration of the nanoparticles is performed into the overheated melt, with stirring in order to attain their favourable distribution. Compocasting method is similar to the stir casting method and the main difference is that the matrix is in semi-solid, not in liquid state. Basically, it is a variant of rheocasting or thixocasting method applied for composite production [6].

Muley et al. [21] studied aluminium based hybrid nanocomposites obtained by stir casting process, where the reinforcements were SiC and Al_2O_3 nanoparticles added in equal ratios (0.5, 1, 1.5 and 2 wt. %). The average size of nanoparticles was 25 – 50 nm (SiC) and 40 nm (Al_2O_3). The nanoparticles were preheated, in order to be free from moisture and to improve wettability with matrix alloy, and feed into crucible containing matrix alloy at the temperature of about 10 – 20 °C above its melting point. The stirring, with low carbon steel stirrer, was carried out at constant speed of 400 rpm for 4 – 5 min. To avoid oxidation, they carried out the whole process under an argon environment.

Friction stir processing is a solid state processing technique which has been used for the fabrication of a surface composite on aluminium substrates, and the homogenization of powder metallurgy aluminium alloys, metal matrix composites, and cast aluminium alloys. This technique is based on friction stir welding, with the aim to obtain a surface layer without porosity, with homogeneous distribution of reinforcement particles in matrix and strong bonding between reinforcements and matrix. It produces localized microstructural modification for specific property enhancement [24]. For example, Anvari et al. [25] applied friction stir processing on aluminium alloy plate coated with Cr_2O_3 powder by the atmosphere plasma spray process. Due to thermomechanical condition, Cr_2O_3 was reduced with aluminium so that pure Cr and Al_2O_3 were produced and, as a result of reaction between Al and Cr, some intermetallic compounds were obtained. As a final result, an Al–Cr–O nanocomposite was produced on the surface of Cr_2O_3 coating.

3. TRIBOLOGICAL PROPERTIES OF ALUMINIUM MATRIX NANOCOMPOSITES

There are many factors influencing tribological properties of nanocomposites. In this paper, an overview of literature data on nanocomposites with aluminium matrix is presented. Only the studies conducted in unlubricated sliding conditions, in the air, at room temperature, were analysed. Even those studies where the surrounding conditions (surrounding medium and its temperature) were not stated were analysed, assuming that they were conducted in the air, at room temperature.

The overview is given through the presentation of the main influencing factors such as: matrix material, type, amount and size of reinforcement, and the production process. In addition, testing conditions and obtained values of coefficient of friction and wear are also presented, together with the method used for materials characterisation (Table 1).

To compare the obtained tribological results is not an easy task. Aside from the influence of different aluminium alloy matrix materials and nanocomposite production process, the type, amount and size of reinforcements differ a lot and make the comparison difficult. In addition, testing conditions (type of contact and sliding direction, counter-body, sliding speed, load and sliding distance) in the analysed studies varied.

Table 1. Tribological properties in dry sliding of aluminium based nanocomposites and the performed analyses

Powder metallurgy				
Reference	Sharifi and Karimzadeh [19]	Ravindran et al. [26]	Nemati et al. [27]	Abbass and Fouad [28]
Apparatus	Pin-on-disc	Pin-on-disc	Pin-on-disc	Pin-on-disc
Matrix material	Aluminium (Al99.7)	2024 (AlCu4Mg1)	Aluminium + 4.5 wt. % copper	Aluminium + 12 wt. % silicon
Reinforcement	Particles: Al_2O_3–AlB_{12}	Particles: SiC + Gr	Particles: TiC	Particles: Al_2O_3; TiO_2; Al_2O_3 + TiO_2
Reinforcement amount	5, 10 and 15 wt. %	5 wt. % SiC + 0, 5 and 10 wt. % Gr	0.5 – 7 wt. %	4 wt. % Al_2O_3; 4 wt. % TiO_2; 4 wt. % Al_2O_3 + TiO_2
Reinforcement size	50 – 120 nm	SiC (100 nm); Gr (40 – 50 nm)	30 nm	Al_2O_3 (50 nm); TiO_2 (30 nm)
Production process	Powder metallurgy	Powder metallurgy	Powder metallurgy	Powder metallurgy
Counter-body	Pin: AISI 52100 steel (780 HV)	Disc: EN31 steel	Disc: AISI 52100 steel (62 HRC)	Disc: Steel (63 HRC)
Sliding speed	0.08 m/s	1 m/s	200 rpm	0.078 mm/s
Load	5 – 20 N	10, 15, 20 and 25 N	10 and 20 N (0.13 and 0.25 MPa)	5, 7.5, 10 and 12.5 N
Sliding distance	500 m	2500 m	1500 m	70 mm
Coefficient of friction	0.30 – 0.55	/	approx. 0.3	/
Total wear	0.02 – 0.14 mg/m	4.6 – 13.6 × 10^{-3} mg/m	2 – 25 × 10^{-3} mg/m	0.8 – 5.8 × 10^{-6} mg/m
Analyses	SEM, EDS, XRD	SEM, XRD	SEM, XRD	OM, SEM, AFM
Powder metallurgy / Friction stir processing				
Reference	Alizadeh et al. [29]	Jeyasimman et al. [30]	Yazdani et al. [31]	Mostafapour Asl and Khandani [32]
Apparatus	Pin-on-disc	Pin-on-disc	Ball-on-disc (reciprocating motion)	Pin-on-disc
Matrix material	5083 (AlMg4.5Mn0.7)	6061 (AlMg1SiCu)	Al_2O_3 nanopowder	5083 (AlMg4.5Mn0.7)
Reinforcement	Particles: B_4C + CNT	Particles: Al_2O_3 + TiC	Fibres: GNP + CNT	Particles: Al_2O_3 + Gr
Reinforcement amount	5 and 10 vol. % B_4C + 5 vol. % CNT	2 wt. %	0.3 – 5 wt. % GNP + 0 and 1 wt. % CNT	/
Reinforcement size	B_4C (5 μm); CNT (10 – 20 nm x 10 – 30 μm)	TiC (200 nm); Al_2O_3 (40 – 50 nm)	GNP (6 – 8 nm × 5 μm); CNT (40 nm)	Al_2O_3 (80 nm); Gr (10 – 50 μm)
Production process	Powder metallurgy	Powder metallurgy	Powder metallurgy	Friction stir processing
Counter-body	/	Disc: Oil hardened steel (62 HRC)	Ball: Si_3N_4	Disc: AISI 52100 steel (58 – 60 HRC)
Sliding speed	0.3 m/s	0.6, 0.9 and 1.2 m/s	10 mm/s (amplitude 10 mm)	0.24 m/s
Load	10, 15 and 20 N	5, 7 and 10 N (0.6, 0.9 and 1.3 MPa)	5, 15, 25 and 35 N	24.8 N (1.7 MPa)
Sliding distance	500 m	1600 m	72 m	950 m
Coefficient of friction	0.5 – 0.9	0.26 – 0.33	0.40 – 0.65	0.18 – 0.37
Total wear	0.024 – 1.1 mg/m	6 – 16 × 10^{-3} mm^3/m	0.5 – 7.2 × 10^{-5} mm^3/Nm	4.8 – 8.5 × 10^{-2} mg/m
Analyses	SEM, EDS	SEM, EDS	SEM, XRD	SEM

Gr – graphite; GNP – graphene nanoplatelets; CNT – carbon nanotubes; OM – optical microscopy; SEM – scanning electron microscopy; EDS – energy dispersive spectroscopy; XRD – X-ray diffraction; AFM – atomic force microscopy

Table 1. *Continued*

Friction stir processing				
Reference	Anvari et al. [25]	Maurya et al. [33]	Vatankhah Barenji et al. [34]	Eskandari et al. [35]
Apparatus	Cylinder-on-plate (reciprocating motion)	Ball-on-disc (reciprocating motion)	Pin-on-disk	Pin-on-disc
Matrix material	6061 (AlMg1SiCu)	6061 (AlMg1SiCu)	6061 (AlMg1SiCu)	8026
Reinforcement	Particles: Cr + Al_2O_3	Particles: Gr; CNT; G	Particles: Al_2O_3 + TiB_2 (35/65 wt. %)	Particles: TiB_2; Al_2O_3; TiB_2 + Al_2O_3 (40/60 wt. %)
Reinforcement amount	/	/	/	/
Reinforcement size	50 nm	Gr (16 μm); CNT (30 – 50 nm × 10 – 20 μm); G (15 nm × 15 μm)	approx. 500 nm	TiB_2 (5 μm); Al_2O_3 (70 nm)
Production process	Friction stir processing	Friction stir processing	Friction stir processing	Friction stir processing
Counter-body	Cylinder: AISI 52100 steel	Ball: Stainless steel	Disk: GCr15 steel (55 HRC)	Disk: Steel (60 HRC)
Sliding speed	0.14 m/s	0.5 mm/s (amplitude 100 μm)	0.5 m/s	0.5 m/s
Load	10 N	5 N	50 N (2.5 MPa)	15 N (0.37 MPa)
Sliding distance	1000 m	1 m	1000 m	1200 m
Coefficient of friction	0.17	0.30 – 0.53	0.28 – 0.54	/
Total wear	0.005 – 0.01 mg/m	3 – 8 × 10^{-5} mm^3/m	approx. 4 × 10^{-3} mg/m	2.0 – 6.8 × 10^{-3} mg/m
Analyses	SEM, EDS, XRD, TEM	SEM, EDS, XRD, TEM	OM, SEM, XRD	OM, SEM, TEM
Stir casting				
Reference	Lekatou et al. [36]	Dorri Moghadam et al. [37]	Karbalaei Akbari et al. [38]	Ekka et al. [39]
Apparatus	Ball-on-disk	Sphere-on-disc	Pin-on-disk	Pin-on-disk
Matrix material	1050 (Al99.5)	Aluminium	A356 (AlSi7Mg)	7075 (AlZn5.56MgCu)
Reinforcement	Particles: TiC; WC	Particles: TiB_2 + Al_2O_3	Particles: TiB_2; TiO_2	Particles: Al_2O_3; SiC
Reinforcement amount	0.7 and 1 vol. % TiC; 0.5 and 1 vol. % WC	1 wt. % TiB_2 + 1 wt. % Al_2O_3	0.5, 1.5, 3 and 5 vol. %	0.5, 1 and 1.5 wt. % Al_2O_3; 0.5, 1 and 1.5 wt. % SiC
Reinforcement size	TiC (400 – 700 nm); WC (200 – 400 nm)	TiB_2 (8 – 20 nm); Al_2O_3 (50 – 150 nm)	TiB_2 (20 nm); TiO_2 (20 nm)	Al_2O_3 (40 – 45 nm); SiC (40 – 45 nm)
Production process	Stir casting	Stir casting	Stir casting	Stir casting
Counter-body	Ball: AISI 5210 steel	Disc: SAE 440 stainless steel	Pin: 100Cr6 steel (62 HRC)	/
Sliding speed	0.1 m/s	25 mm/s	1.5 m/s	1.5, 2.25 and 3 m/s
Load	1 N	700 MPa	10 – 40 N (0.13 – 0.53 MPa)	35, 55 and 75 N (0.7, 1.1 and 1.5 MPa)
Sliding distance	1000 m	1500 m	500 m	1500, 2500 and 3500 m
Coefficient of friction	/	0.36 – 0.38	0.37 – 0.87	/
Total wear	8.4 – 23.9 × 10^{-3} mg/Nm	1.7 – 2.9 × 10^{-6} mm^3/Nm	2.7 – 5.3 × 10^{-3} mm^3/m	1.3 – 5.2 × 10^{-9} mm^3/m
Analyses	SEM, EDS	SEM, EDS, XRD, TEM	SEM, XRD	SEM, Taguchi, ANN

Gr – graphite; G – graphene; CNT – carbon nanotubes; OM – optical microscopy; SEM – scanning electron microscopy; EDS – energy dispersive spectroscopy; XRD – X-ray diffraction; TEM – transmission electron microscopy; ANN – artificial neural network

Table 1. *Continued*

Reactive casting / Squeeze casting		
Reference	Kalashnikov et al. [40]	Babu et al. [41]
Apparatus	Pin-on-disc	Pin-on-disc
Matrix material	Aluminium (Al99.3)	A356 (AlSi7Mg)
Reinforcement	Particles: Ti + Ni + W / TiCN / W–C	Fibres: Gr + Al_2O_3
Reinforcement amount	3 wt. % Ti + 3 wt. % Ni + 0.25 wt. % W / 0.25 wt. % TiCN / 0.25 wt. % W–C	10, 15 and 20 vol. %
Reinforcement size	Ti (100 μm); Ni (20 μm); W (50 nm); TiCN (30 nm); W–C (30 nm)	Gr (0.05 × 10 μm); Al_2O_3 (3 × 120 μm)
Production process	Reactive casting	Infiltration (squeeze casting)
Counter-body	Disc: EN C45 steel	Disc: SUS 304 stainless steel
Sliding speed	0.39 m/s	240, 360 and 480 rpm
Load	18 – 60 N	10, 30 and 50 N (0.2 – 1 MPa)
Sliding distance	350 m	1000, 3000 and 5000 m
Coefficient of friction	/	0.52 – 0.62
Total wear	$4 – 37 \times 10^{-3}$ mm^3/m	$8 – 50 \times 10^{-6}$ mg/m
Analyses	SEM, EMPA	SEM, EDS, Taguchi

Gr – graphite; SEM – scanning electron microscopy; EDS – energy dispersive spectroscopy; EPMA – electron probe microanalysis

For example, sliding speeds were in the range from 1 mm/s to several m/s, and applied loads from 0.1 MPa to several hundreds MPa, and it is well-known that coefficient of friction and especially wear depend very much on these conditions. The important thing to note is that many authors did not present all the experimental details and that some of them even made mistakes in presenting the results. The obvious mistakes were corrected, while the presenting of testing conditions and results was uniform as much as it was possible.

The majority of studies were conducted by the authors from India and Iran, and powder metallurgy was the most popular process for nanocomposite production. Friction stir processing was also a commonly used technique for nanocomposite production, which was surprising since this is a relatively new technique. Particles' reinforcements were used far more often than other types of reinforcements, since they are cheaper to produce in most cases. Among them, ceramic particles such as Al_2O_3, SiC, TiC, TiO_2 and TiB_2 prevailed, but graphite and some new reinforcements like graphene and carbon nanotubes were also used. The amount of nanosized reinforcing ceramic particles was usually up to 5 %, but was is also noticed that it can be up to 10 %. Nevertheless, these amounts were lower than the amounts used for the micro-sized reinforcing particles, which can be up to 20 % [9].

The geometry of samples and type of contact in most of the studies were flat and conformal (surface) contact, which indicates the possible applications of these materials. Non-conformal (line and point) contacts are not recommendable since in these cases there is a possibility that the contact would be in the region without nanoparticles (or with reduced amount), especially if they are not well distributed over the surface. Concerning the performed analyses for materials characterisation, scanning electron microscopy (SEM) and energy dispersive spectroscopy (EDS) were set as "standard" methods, as it was the case with characterisation of microcomposites. On the other hand, the use of transmission electron microscopy (TEM) was more often the characterisation of nanocomposites. This was expected since structural phenomena in nanocomposites occur at nanolevel.

3.1 Coefficient of friction

The coefficient of friction values obtained in different studies were easier to compare than the wear values, because the coefficient of friction in unlubricated sliding conditions is less dependent on testing conditions such as normal load and sliding speed. Its value was mainly in range from 0.2 to 0.6. Thus, with the increase of load, the coefficient of friction in some cases increases [29] or decreases [38], but, in most cases, it remains more or less constant [27,30,31,41]. The same happens with the change of sliding speed, i.e. with its increase, the coefficient of friction is more or less constant [30,41]. This is in accordance with the classical theory for metals in unlubricated sliding, which states that the coefficient of friction is independent of normal load and sliding speed.

The increase in the amount of hard particles/fibre reinforcements did not influence the coefficient of friction in the significant manner, so that the coefficient remained more or less constant [19,41]. Only in some cases it increased [38] or slightly decreased [29]. This is not in correlation with the microcomposite behaviour, since the increase in hard reinforcement amount in microcomposite decreases the coefficient of friction [6]. In microcomposite, this decrease occurs with the amounts higher than 15 to 20 %, so this could be the explanation, since in analysed nanocomposites the amount of hard reinforcement was smaller. On the other hand, the influence of graphite/graphene addition was in correlation with the microcomposite behaviour [5], i.e. the addition of graphite/graphene decreased the coefficient of friction of the matrix alloy [31-33].

3.2 Wear

Unfortunately, different authors have led investigations under different conditions, and this makes comparison of their results very difficult. In addition, wear values were often presented in different way, i.e. through the mass wear rate, volume wear rate or wear factor. A possible solution to the comparison of results would be a construction of wear mechanism maps [42], as it is the case with aluminium matrix microcomposites [43,44]. The increase of normal load induced higher wear in all analysed studies [19,26-31,38-41], which was expected and in accordance with the theory. On the other hand, there is no general rule for the influence of sliding speed on the wear value, i.e. higher sliding speeds were associated with a slight increase [30] of the wear value, its decrease [39], or did not show a significant influence on the wear value [41].

With the increase in the hard particles/fibre reinforcements' amount, wear value mainly decreased [19,27,29,31,36], which was expected and in correlation with microcomposites behaviour [6], although there were cases when wear increased [32,38] or was more or less constant [39]. The increase of the wear value was attributed to the higher porosity [38], or absence of the lubrication effect of graphite particles which were also added to the nanocomposite [32]. Generally, the initial addition of graphite/graphene decreases wear value of the matrix alloy [26,31-33], and with further increase of the graphite/graphene this effect is less obvious. This is also in correlation with the microcomposite behaviour [6].

4. CONCLUSIONS

Comparing the tribological properties of aluminium matrix nanocomposites, obtained in different studies, certain conclusions can be drawn:

- First of all, composites with added nanosized reinforcement generally have lower coefficient of friction and higher wear resistance than unreinforced matrix alloys.
- Powder metallurgy is the most popular process for nanocomposite production and particles reinforcements are used far more often than other types of reinforcement.
- Ceramic particles such as Al_2O_3, SiC, TiC, TiO_2 and TiB_2 prevail as reinforcements, but graphite, graphene and carbon nanotubes are also used. The amount of reinforcement is usually up to 5 %.
- The coefficient of friction values were mainly in the range from 0.2 to 0.6, and were not significantly affected by the applied normal load, sliding speed or amount of hard particles/fibre reinforcements. On the other hand, addition of graphite/graphene decreased coefficient of friction of the matrix alloy.
- Wear values were higher for higher loads in all analysed studies, while there was no general rule for the influence of sliding speed on wear value. With the increase in hard particles/fibre reinforcements' amount and with the addition of graphite/graphene wear value mainly decrease.
- The application of aluminium matrix nanocomposites is mainly for tribological pairs with conformal contact, since most of the studies simulated this type of contact. Characterisation of the worn surfaces was mainly performed with SEM and EDS analysis.

ACKNOWLEDGEMENT

This review has been conducted as a part of activities within the project TR 35021, supported by the Republic of Serbia, Ministry of Education, Science and Technological Development, which financial help is gratefully acknowledged.

REFERENCES

[1] B.Ž. Stojanović, Tribological Behaviour of Hybrid Composites with A356 Matrix (Ph.D. Thesis), Faculty of Engineering, University of Kragujevac, Kragujevac, 2013, (in Serbian).

[2] A.A. Vencl, The Research of the Al-Si Alloys Tribological Properties Improvement Possibilities in Sliding Conditions (Ph.D. Thesis), Faculty of Mechanical Engineering, University of Belgrade, Belgrade, 2007, (in Serbian).

[3] M.K. Surappa, Aluminium matrix composites: Challenges and opportunities, Sādhanā 28 (1-2), 2003: 319–334.

[4] D.B. Miracle, Metal matrix composites – From science to technological significance, Compos. Sci. Technol., 65 (15-16), 2005: 2526–2540.

[5] S.V. Prasad, R. Asthana, Aluminium metal-matrix composites for automotive applications: Tribological considerations, Tribol. Lett., 17 (3), 2004: 445–453.

[6] A. Vencl, Tribology of the Al-Si Alloy Based MMCs and Their Application in Automotive Industry, in: L. Magagnin (Ed.), Engineered Metal Matrix Composites: Forming Methods, Material Properties and Industrial Applications, Nova Science Publishers, New York, 2012, pp.127–166.

[7] B. Stojanović, L. Ivanović, Application of aluminium hybrid composites in automotive industry, Teh. Vjesn., 22 (1), 2015: 247–251.

[8] B. Stojanovic, J. Glisovic, Automotive Engine Materials, in: S. Hashmi (Ed.), Reference Module in Materials Science and Materials Engineering, Elsevier, Oxford, 2016, pp.1–9.

[9] A. Vencl, A. Rac, I. Bobić, Tribological behaviour of Al-based MMCs and their application in automotive industry, Tribol. Ind., 26 (3-4), 2004: 31–38.

[10] A. Vencl, A. Rac, New wear resistant Al based materials and their application in automotive industry, Mobility & Vehicles Mechanics (MVM), 30 (Special Edition), 2004: 115–139.

[11] A. Elmarakbi (Ed.), Advanced Composite Materials for Automotive Applications, John Wiley & Sons, Chichester, 2014.

[12] European Aluminium Association, Aluminium in Cars – Unlocking the Light-Weighting Potential, European Aluminium Association, Brussels, 2013.

[13] J. Hirsch, Recent development in aluminium for automotive applications, Trans. Nonferrous Met. Soc. China, 24 (7), 2014: 1995−2002.

[14] K.U. Kainer (Ed.), Metal Matrix Composites: Custom-made Materials for Automotive and Aerospace Engineering, Wiley, Weinheim, 2006.

[15] M. Al Mehedi, Aluminium matrix composites in automotive application, Aluminium, 87 (7-8), 2011: 55–57.

[16] A. Vencl, I. Bobić, S. Arostegui, B. Bobic, A. Marinković, M. Babić, Structural, mechanical and tribological properties of A356 aluminium alloy reinforced with Al_2O_3, SiC and SiC + graphite particles, J. Alloys Compd., 506 (2), 2010: 631–639.

[17] B. Stojanovic, M. Babic, S. Mitrovic, A. Vencl, N. Miloradovic, M. Pantic, Tribological characteristics of aluminium hybrid composites reinforced with silicon carbide and graphite. A review, J. Balk. Tribol. Assoc., 19 (1), 2013: 83–96.

[18] M. Babić, B. Stojanović, S. Mitrović, I. Bobić, N. Miloradović, M. Pantić, D. Džunić, Wear properties of A356/10SiC/1Gr hybrid composites in lubricated sliding conditions, Tribol. Ind., 35 (2), 2013: 148–154.

[19] E.M. Sharifi, F. Karimzadeh, Wear behaviour of aluminium matrix hybrid nanocomposites fabricated by powder metallurgy, Wear, 271 (7-8), 2011: 1072–1079.

[20] M.T. Khorshid, E. Omrani, P.L. Menezes, P.K. Rohatgi, Tribological performance of self-lubricating aluminium matrix nanocomposites: Role of graphene nanoplatelets, Eng. Sci. Technol., Int. J., 19 (1), 2016: 463–469.

[21] A.V. Muley, S. Aravindan, I.P. Singh, Mechanical and tribological studies on nano particles reinforced hybrid aluminium based composite, Manuf. Rev., 2, 2015: 1–9.

[22] R. Casati, M. Vedani, Metal matrix composites reinforced by nano-particles – A review, Metals, 4 (1), 2014: 65–83.

[23] C.D. Marini, N. Fatchurrohman, A review on the fabrication techniques of aluminium matrix nanocomposites, J. Teknologi, 74 (10), 2015: 103–109.

[24] Z.Y. Ma, Friction stir processing technology: A review, Metall. Mater. Trans., A 39 (3), 2008: 642–658.

[25] S.R. Anvari, F. Karimzadeh, M.H. Enayati, Wear characteristics of Al-Cr-O surface nano-composite layer fabricated on Al6061 plate by friction stir processing, Wear, 304 (1-2), 2013: 144–151.

[26] P. Ravindran, K. Manisekar, S. Vinoth Kumar, P. Rathika, Investigation of microstructure and mechanical properties of aluminum hybrid nano-composites with the additions of solid lubricant, Mater. Design, 51, 2013: 448–456.

[27] N. Nemati, R. Khosroshahi, M. Emamy, A. Zolriasatein, Investigation of microstructure, hardness and wear properties of Al-4.5 wt.% Cu–TiC nanocomposites produced by mechanical milling, Mater. Design, 32 (7), 2011: 3718–3729.

[28] M.K. Abbass, M.J. Fouad, Study of wear behavior of aluminum alloy matrix nanocomposites fabricated by powder technology, Eng. Technol. J., 32 (7), 2014: 1720–1732.

[29] A. Alizadeh, A. Abdollahi, H. Biukani, Creep behavior and wear resistance of Al 5083 based hybrid composites reinforced with carbon nanotubes (CNTs) and boron carbide (B_4C), J. Alloys Compd., 650, 2015: 783–793.

[30] D. Jeyasimman, R. Narayanasamy, R. Ponalagusamy, V. Anandakrishnan, M. Kamaraj, The effects of various reinforcements on dry sliding wear behaviour of AA 6061 nanocomposites, Mater. Design, 64, 2014: 783–793.

[31] B. Yazdani, F. Xu, I. Ahmad, X. Hou, Y. Xia, Y. Zhu, Tribological performance of graphene/carbon nanotube hybrid reinforced Al_2O_3 composites, Sci. Rep., 5, 2015: 11579.

[32] A. Mostafapour Asl, S.T. Khandani, Role of hybrid ratio in microstructural, mechanical and sliding wear properties of the Al5083/Graphite$_p$/Al_2O_{3p} a surface hybrid nanocomposite fabricated via friction stir processing method, Mater. Sci. Eng., A 559, 2013: 549–557.

[33] R. Maurya, B. Kumar, S. Ariharan, J. Ramkumar, K. Balani, Effect of carbonaceous reinforcements on the mechanical and tribological properties of friction stir processed Al6061 alloy, Mater. Design, 98, 2016: 155–166.

[34] R. Vatankhah Barenji, V.M. Khojastehnezhad, H.H. Pourasl, A. Rabiezadeh, Wear properties of Al-Al_2O_3/TiB_2 surface hybrid composite layer prepared by friction stir process, J. Compos. Mater., 50 (11), 2016: 1457–1466.

[35] H. Eskandari, R. Taheri, F. Khodabakhshi, Friction-stir processing of an AA8026-TiB_2-Al_2O_3 hybrid nanocomposite: Microstructural developments and mechanical properties, Mater. Sci. Eng., A 660, 2016: 84–96.

[36] A. Lekatou, A.E. Karantzalis, A. Evangelou, V. Gousia, G. Kaptay, Z. Gácsi, P. Baumli, A. Simon, Aluminium reinforced by WC and TiC nanoparticles (ex-situ) and aluminide particles (in-situ): Microstructure, wear and corrosion behaviour, Mater. Design, 65, 2015: 1121–1135.

[37] A. Dorri Moghadam, E. Omrani, P.L. Menezes, P.K. Rohatgi, Effect of in-situ processing parameters on the mechanical and tribological properties of self-lubricating hybrid aluminum nanocomposites, Tribol. Lett., 62 (2), 2016: 2-10.

[38] M. Karbalaei Akbari, S. Rajabi, K. Shirvanimoghaddam, H.R. Baharvandi, Wear and friction behavior of nanosized TiB_2 and TiO_2 particle-reinforced casting A356 aluminum nanocomposites: A comparative study focusing on particle capture in matrix, J. Compos. Mater., 49 (29), 2015: 3665–3681.

[39] K.K. Ekka, S.R. Chauhan, Varun, Dry sliding wear characteristics of SiC and Al_2O_3 nanoparticulate aluminium matrix composite using Taguchi technique, Arab. J. Sci. Eng., 40 (2), 2015: 571–581.

[40] I.E. Kalashnikov, L.K. Bolotova, L.I. Kobeleva, P.A. Bykov, A.G. Kolmakov, Wear products that form during tribological tests of aluminum-matrix composite materials, Russ. Metall., 2015 (4), 2015: 285–289.

[41] J.S.S. Babu, C.G. Kang, H.H. Kim, Dry sliding wear behaviour of aluminium based hybrid composites with graphite nanofiber-alumina fiber, Mater. Design, 32 (7), 2011: 3920–3925.

[42] S.C. Lim, Recent developments in wear mechanism maps, Tribol. Int., 31 (1-3), 1998: 87–97.

[43] D.Z. Wang, H.X. Peng, J. Liu, C.K. Yao, Wear behaviour and microstructural changes of SiCw-Al composite under unlubricated sliding friction, Wear, 184 (2), 1995: 187–192.

[44] S. Wilson, A.T. Alpas, Wear mechanism maps for metal matrix composites, Wear, 212 (1), 1997: 41–49.