UDK 669.018.9:539.538:669.715 ISSN 1580-2949
Original scientific article/Izvirni znanstveni članek MTAEC9, 49(1)9(2015)

WEAR BEHAVIOUR OF B_4C REINFORCED HYBRID ALUMINUM-MATRIX COMPOSITES

VEDENJE HIBRIDNEGA KOMPOZITA NA OSNOVI ALUMINIJA, OJAČANEGA Z B_4C, PRI OBRABI

Thiyagarajan Thirumalai[1], Ramanathan Subramanian[2], Somasundaram Dharmalingam[3], Nachiappan Radika[4], Annadurai Gowrisankar[2]

[1]Department of Mechanical Engineering, Erode Sengunthar Engineering College, Perundurai, Erode, India
[2]Department of Metallurgical Engineering, PSG College of Technology, Coimbatore, India
[3]Department of Mechanical Engineering, RVS Faculty of Engineering, Coimbatore, India
[4]School of Mechanical Engineering, Amrita Vishwa Vidyapeetham University, Coimbatore, India
thirumalaimet@gmail.com

Prejem rokopisa – received: 2013-08-12; sprejem za objavo – accepted for publication: 2014-03-24

Harnessing the benefits of aluminum hybrid composites requires strengthening of materials with better reinforcing materials. Hence, this investigation was carried out to identify the optimum level of B_4C reinforcement to enhance the wear resistance of aluminum alloys. Four amounts of B_4C reinforcement (3, 6, 9 and 12) % and a constant amount of 3 % graphite were mixed with an aluminum alloy to produce aluminum hybrid composites. The hybrid composites thus produced were tested for wear resistance at various loads and sliding speeds. The change in the wear resistance of the newly produced hybrid material was studied with SEM micrographs to confirm the results. Al-B_4C-Gr composites produced with the stir-casting method including various amounts of B_4C reinforcement show that the B_4C reinforcement of up to 9 % was found beneficial as it increased the wear resistance of the aluminum alloy. The addition of a constant amount of graphite provides for the lubrication effect, while B_4C increases the strength of the parent material (Al). SEM micrographs confirmed that aluminum hybrid composites showed less debris and finer grooves with delamination at lower loads and sliding speeds. Hence, 9 % B_4C reinforcement with 3 % graphite is a better way of increasing the wear resistance of aluminum alloys.

Keywords: aluminum-matrix composites, boron carbide, graphite, wear, stir casting, sliding distance

Izkoriščanje prednosti hibridnih kompozitov na osnovi aluminija zahteva ojačanje materiala z boljšimi materiali za utrjevanje. Zato je bila izvršena ta preiskava, da bi se ugotovil optimalni dodatek B_4C za povečanje obrabne odpornosti aluminijevih zlitin. Štiri vsebnosti B_4C (3, 6, 9 in 12) % kot dodatka za utrjevanje in 3 % grafita so bile dodane aluminijevi zlitini, da bi dobili aluminijeve hibridne kompozite. Tako izdelani hibridni kompoziti so bili preizkušeni v odpornosti proti obrabi pri različnih obtežbah in hitrostih drsenja. Potrditev rezultatov in spremembe v odpornosti proti obrabi hibridnih materialov so bile ugotavljane s SEM-posnetkov. Kompoziti Al-B_4C-Gr, izdelani z metodo vmešavanja v talino, z različno vsebnostjo sredstva za utrditev B_4C so pokazali, da je dodatek do 9 % B_4C ugoden in poveča obrabno odpornost aluminijeve zlitine. Dodatek enake količine grafita zagotavlja učinek mazanja, medtem ko B_4C daje višjo trdnost osnovnemu materialu (Al). SEM-posnetki hibridnih kompozitov aluminija so pokazali manj zlomnin in drobnejše opilke z delaminacijo pri manjših obtežbah in hitrostih drsenja. Torej je dodatek 9 % B_4C za ojačanje in 3 % grafita boljša tehnologija za povečanje obrabne odpornosti aluminijevih zlitin.

Ključne besede: kompoziti na osnovi aluminija, borov karbid, grafit, obraba, vmešavanje v talino, razdalja drsenja

1 INTRODUCTION

Aluminum-matrix composites (AMCs) have recently gained momentum due to their structural applications in aircraft, automotive, construction, packaging, electronics and military industries. Next to iron and steel, aluminium alloys are the most widely used metallic materials. They are used particularly in the manufacturing of automotive components such as cylinder liners, pistons, drive shafts, brake rotors, cylinder heads, cylinder blocks, intake manifolds, rear axles and differential housings[1–3]. Their high strength-to-weight ratio, high thermal conductivity and specific stiffness enhanced the interest of the researchers to further improve the material characteristics so that they are appropriate for all the applications. Aluminium represents around 8 % of the vehicle curb weight in today's cars, trucks and minivans. However, an inadequate wear resistance and low seizure loads prevent a direct use of aluminium alloys in automotive parts due to the intensive friction, high thermal and mechanical loading[4].

Boron carbide (B_4C) is found to be a promising ceramic material due to its high strength, low density (2.52 g/cm^3), extremely high hardness and better chemical stability. Extreme hardness of this material makes it a better alternative to silicon carbide (SiC) and aluminum oxide (Al_2O_3) for reinforcement with aluminum alloys. A hybrid aluminum-matrix composite combines the high strength and hardness of reinforcing materials with the ductility and toughness of light metals[5,6]. A study conducted to test the wear behaviour of Al-B_4C and Al-SiC composites fabricated with the stir-casting method revealed that the wear rate and friction coefficient of Al-B_4C were lower than those of Al-SiC[7]. The aluminum-matrix composite reinforced with B_4C particles and SiC particles through the pressureless-infiltration method indicated that the strength of the Al-B_4C composite was greater than that of the Al-SiC composite.[8] Hence, a decrease in the reinforcement particle size to the nanometer range can improve the mechanical and tribological properties of AMCs. The tribological behaviour of stir-cast Al-Si/SiC composites (15 % and 20 % volume fraction) against the automobile-brake-pad material using a pin-on-disc tribotester showed an inverse proportionality between the sliding speed and the wear rate[9]. Dry-sliding wear performance of a hypereutectic A390 Al-Si alloy reinforced with graphite particulates (4 % and 8 %) showed that both the wear rate and COF of the composites decreased considerably with the addition of graphite[10].

The fabrication and characterization of bulk Al-B_4C nanocomposites containing different mass fractions of B_4C w = (5, 10 and 15) % showed an increase in the wear resistance with the increasing B_4C amount[11]. The fabrication of mass fractions 40 % SiC/% Gr/Al composites with the additions of various amounts of graphite using the squeeze-casting technology showed that the addition of graphite decreased the friction coefficient of the composites and increased the wear resistance by 170 to 340 times[12]. A study on the influence of the sliding speed on dry-sliding wear behaviour and the extent of subsurface deformation in an Al 2219/15 % SiCp composite and an Al 2219/15 % SiCp-graphite hybrid composite due to liquid metallurgy reported that the wear rates of the composites remained almost unchanged with the increasing sliding speed up to 4.6 m/s, after which an increasing trend in the wear rate was observed[13].

Extensive researches on individual reinforcements of boron carbide and graphite improving the wear resistance and the strength of hybrid aluminum composites were carried out. However, very limited research was conducted in order to explore the combined effect of boron-carbide and graphite-particulate reinforcements on hybrid aluminum composites. Hence, this study was carried out i) to develop new hybrid aluminum composites with boron carbide and graphite and ii) to test the improvement in the wear resistance of the material under varying sliding speed and load.

2 MATERIALS AND METHODS

Hybrid aluminum composites with boron carbide (B_4C) in various amounts and constant graphite reinforcement were cast using the stir-casting method. The hybrid Al composites were reinforced with (3, 6, 9 and 12) % of B_4C and a constant amount of 3 % graphite. The boron-carbide and graphite particles with the average particle size of 25 μm to 75 μm were preheated up to 300 °C. Degassing tablets were added during the melting to remove gaseous molecules. Magnesium (w = 2 %) was added to the molten metal to improve the wettability between the reinforcements and aluminium.

The mixture of the molten alloy was mechanically stirred using a steel stirrer for 10 min to obtain a homogenous mixture. A speed of 400 r/min was maintained and a pouring temperature of 710 °C was maintained. After removing them from the metal dye, the specimens were collected and subjected to the wear tests performed with a pin-on-disc machine. The test specimens were in the form of pins having a diameter of 10 mm and a height of 40 mm. The ends of the specimens were polished with abrasive paper of grade 600 followed by grade 1000. The disc was made of EN-31 steel having a hardness of 63 HRc under dry conditions. The wear loss of the pin in microns was recorded during the wear test. The pin surface wore out during the rubbing with the counter disc, continuously moving down to have a contact with the surface of the disc. The tests were conducted as per ASTM G99-95a test standards with a constant sliding distance of 2500 m and a normal load of 10 N to 30 N. The sliding speed of 1 m/s to 3 m/s was tested under dry conditions and the wear resistance was recorded.

3 RESULTS AND DISCUSSIONS

Dry-sliding wear tests were conducted for the hybrid composites and an unreinforced aluminium alloy (the parent material) using a pin-on-disc apparatus at different normal loads (10 N to 30 N) and sliding speeds (1 m/s and 2 m/s) with a constant sliding distance of 2500 m. The wear rate was calculated by weighing the specimens before and after the test. The variation in the wear rate with varied levels of the normal load and reinforcement percentage at different sliding speeds is shown in the graphs (**Figures 1** to **4**). It can be observed that the wear loss increases with the increasing load and the highest wear is noted at the load of 30 N at both sliding speeds. Comparing various materials tested for the wear loss, it was evident that the maximum wear loss occurred on the parent material (Al) and the minimum wear loss occurred on 3 % Gr + 9 % B_4C + Al compo-

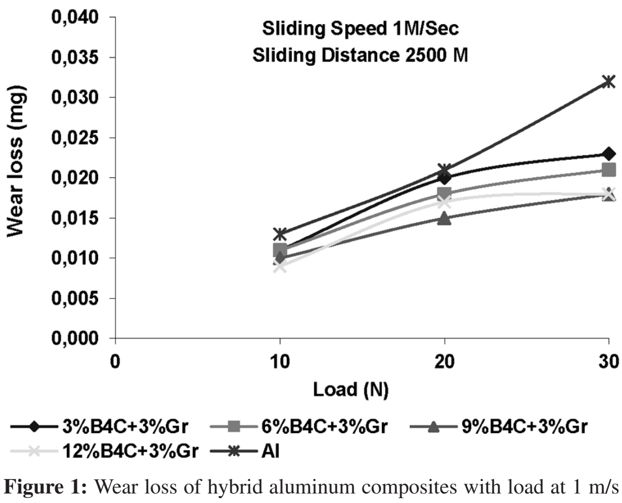

Figure 1: Wear loss of hybrid aluminum composites with load at 1 m/s sliding speed

Slika 1: Izguba zaradi obrabe hibridnega kompozita aluminija z obtežbo pri hitrosti drsenja 1 m/s sites (C3) which might have happened due to its better wear resistance.

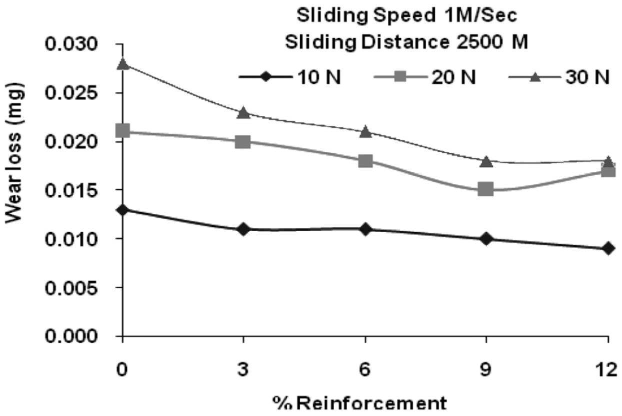

Figure 2: Wear loss of hybrid aluminum composites with reinforcement fraction at 1 m/s sliding speed

Slika 2: Izguba zaradi obrabe hibridnega kompozita aluminija z deležem ojačitvene faze pri hitrosti drsenja 1 m/s

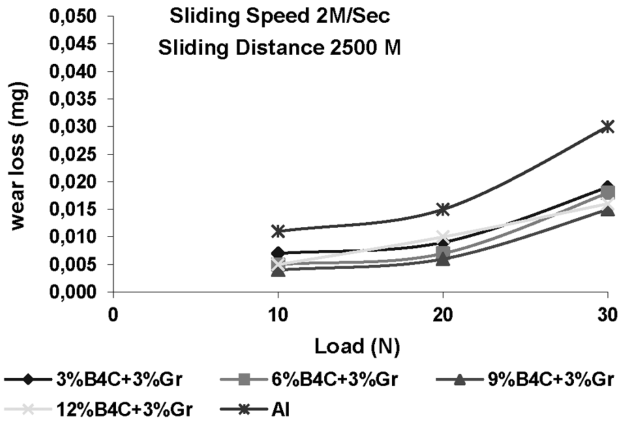

Figure 3: Wear loss of hybrid aluminum composites with load at 2 m/s sliding speed

Slika 3: Izguba zaradi obrabe hibridnega kompozita aluminija z deležem ojačitvene faze pri hitrosti drsenja 2 m/s

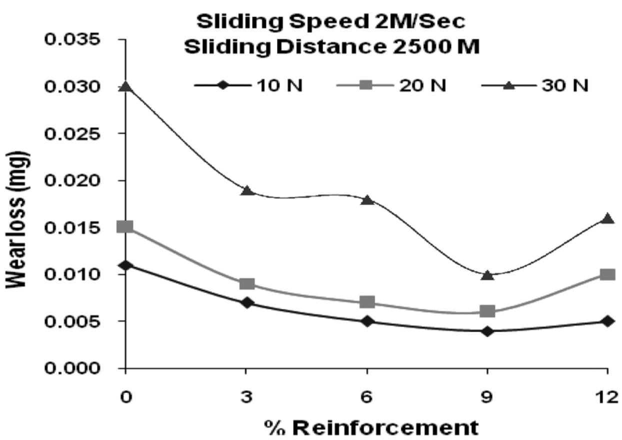

Figure 4: Wear loss of hybrid aluminum composites with reinforcement fraction at 2 m/s sliding speed

Slika 4: Izguba zaradi obrabe hibridnega kompozita aluminija z deležem ojačitvene faze pri hitrosti drsenja 2 m/s

The wear resistance increases with the increasing B_4C amount up to 9 % in the composites, but a mixture containing more than 9 % B_4C decreases the wear resistance. The beneficial effect noticed up to 9 % B_4C reinforcement could be due to its higher hardness, causing a better wear resistance of the composites[11]. Like the parent material, the other compositions, 3 % Gr + 3 % B_4C + Al (C1), 3 % Gr + 6 % B_4C + Al (C2) and 3 % Gr + 12 % B_4C + Al (C4), also showed higher wear losses which can be ascribed to larger quantities of the particles. Many investigators reported that the low density (2.52 g/cm^3), high hardness (HV = 30 GPa) and thermal stability of boron carbide might be possible reasons for the increased wear resistance[14–17]. A decreased wear resistance at a higher level of B_4C reinforcement (w = 12 %) could be due to a reduction in the interfacial strength. This reduction in the interfacial strength is attributed to the formation of a boron-rich Al-B phase at the grain boundaries[18,19]. The sliding speed is an important factor that needs to be tested to understand the wear loss of any new composite. Hence, two sliding speeds were tested under various loads and B_4C reinforcement percentages and the results revealed that the wear loss decreased with the increasing sliding speed irrespective of the reinforcement percentage and the load. The wear loss of the parent material was the highest at the higher load (30 N) and it decreased with the sliding speed which must have been due to the reduced particle retention time for abrasion[11,20]. The formation of the surface

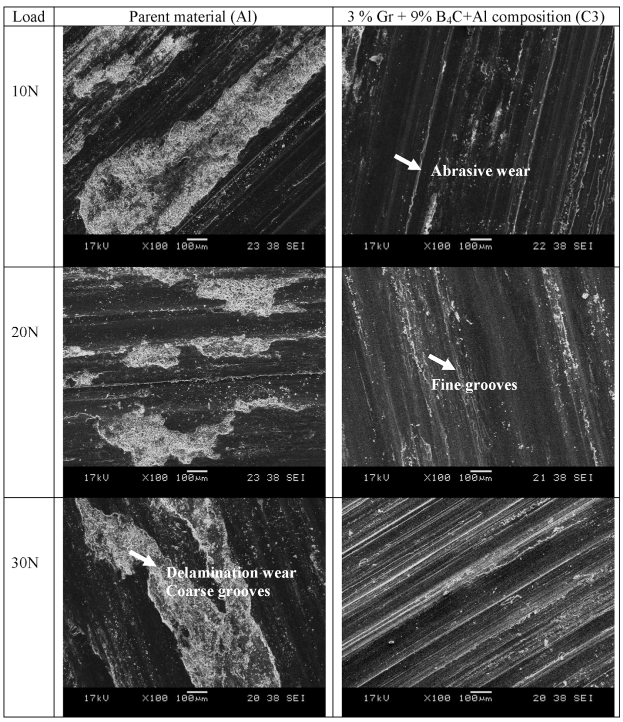

Figure 5: SEM micrographs of the worn surfaces of hybrid Al-B_4C composites and aluminum (sliding speed 1 m/s, sliding distance 2500 m)

Slika 5: SEM-posnetki obrabljene površine hibridnega kompozita Al-B_4C in aluminija (hitrost drsenja 1 m/s, razdalja drsenja 2500 m)

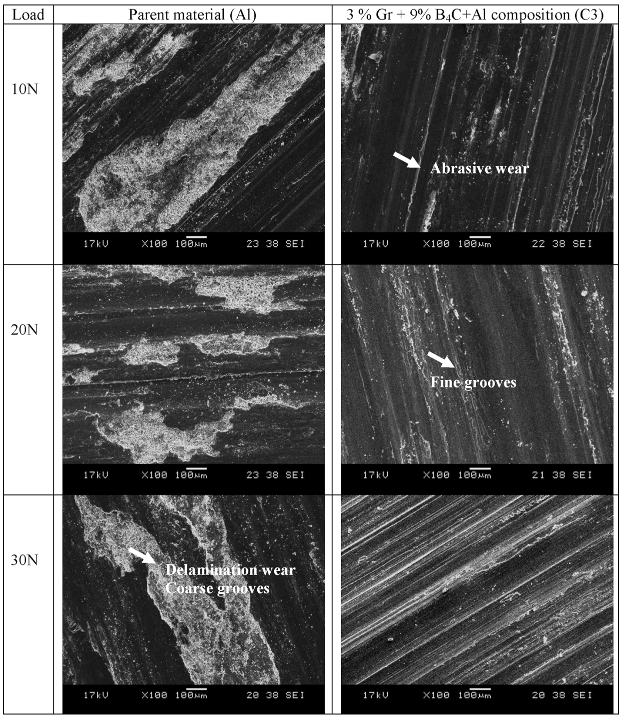

Figure 6: SEM micrographs of the worn surfaces of hybrid Al-B_4C composites and aluminum (sliding speed 2 m/s, sliding distance 2500 m)

Slika 6: SEM-posnetki obrabljene površine hibridnega kompozita Al-B_4C in aluminija (hitrost drsenja 2 m/s, razdalja drsenja 2500 m)

coatings of oxidized debris at the higher sliding speed might have reduced both the wear rate and the coefficient of friction.

Wear-track patterns of hybrid composites and the parent material at three different loads and two sliding speeds were studied by taking SEM micrographs. **Figures 5** and **6** show the typical wear-track patterns developed on the surfaces of the composites and the parent material. On the parent material, the increasing load increases the formation of coarse grooves, debris particles and surface delamination. At the lower load (10 N), more debris particles and abrasive wear of the surfaces were noticed. With the increased load (20 N) wider grooves and more debris were formed. Delamination, wider grooves with more debris and mixed adhesive wear were noticed when the parent material was subjected to the 30 N load[21,22].

Upon sliding, the higher speed caused abrasive wear which pulled some of the material from the surface and formed loose abrasive debris. As the sliding process proceeded with the increasing speed, the material attached to alumina was delaminated and defoliated to form more small debris and deep widened grooves. As the load increased, greater amounts of the material from the surfaces were defoliated, forming deep grooves with wider widths due to ploughing in the aluminum alloy[23]. In the case of major wear mechanisms, the abrasion wear was predominant at the lower load (10 N) while at the higher load (30 N) the adhesive wear was higher. In contrast, the reinforcement with B_4C and graphite showed a beneficial effect on the wear resistance of the composites.

The reinforced hybrid composites exhibited fine grooves and less debris at the 10 N load. Like in the case of the parent material, the increasing load increased the delamination and the adhesive wear of the composites to a lesser extent. The B_4C reinforcement decreased the groove width and debris formation due to an improvement in the load-carrying capacity of the composites, enhancing the abrasion resistance of the composites and, thus, decreasing the wear loss[24,25]. At the lower load and sliding speed (L = 10 N and S = 1 m/s) the worn pin surface predominantly revealed fine and shallow grooves in the sliding direction. Such features are characteristic of the abrasive wear, where hard asperities of the counter face plough into the hybrid composite pin, causing wear by removing small fragments of the material.

4 CONCLUSIONS

Al-B_4C-Gr composites were produced with the stir-casting method using various levels of B_4C reinforcement and a constant amount of 3 % graphite addition. An evaluation of the morphological properties and the wear showed that the B_4C reinforcement of up to 9 % was beneficial in increasing the wear resistance of aluminum hybrid composites. In the presence of graphite, B_4C made the parent material (Al) even stronger, resisting both the abrasive and the adhesive wear. Subjecting the composites and the unreinforced aluminum parent material to various levels of the load showed that the increased load increased the wear of the composites. At the lower load and sliding speed, less debris and fine grooves with delamination were formed which was confirmed with SEM micrographs. The improved wear resistance of the composites is due to the hardness of B_4C and the lubricating effect of graphite. Hence, 9 % B_4C reinforcement with 3 % graphite can be a better way of increasing the wear resistance of aluminum alloys.

5 REFERENCES

[1] W. S. Miller, L. Zhuang, J. Bottema, A. J. Wittebrood, P. D. Smet, A. Haszler, A. Vieregge, Recent development in aluminium alloys for the automotive industry, Materials Science & Engineering A, 280 (**2000**), 37–49

[2] I. Sinclair, P. J. Gregson, Structural performance of discontinuous metal matrix composites, Materials Science and Technology, 13 (**1997**), 709–726

[3] I. A. Ibrahim, F. A. Mohamed, E. J. Lavernia, Particulate Reinforced Metal Matrix Composites – A Review, Journal of Materials Science, 24 (**1991**), 1137–1156

[4] V. Kevorkijan, Engineering wear-resistant surfaces in automotive aluminium, JOM, 55 (**2003**), 32–34

[5] B. R. Henriksen, T. E. Johnsen, Influence of microstructure of fiber/matrix interface on mechanical properties of Al/SiC composites, Materials Science and Technology, 6 (**1990**), 857–863

[6] Y. H. Kim, C. S. Lee, K. S. Han, Fabrication and Mechanical Properties of Aluminum Matrix Composite Materials, Journal of Composite Materials, 26 (**1992**), 1062–1086

[7] K. M. Shorowordi, A. S. M. A. Haseeb, J. P. Celis, Tribo-surface characteristics of Al–B_4C and Al–SiC composites worn under different contact pressures, Wear, 261 (**2006**), 634–641

[8] K. B. Lee, H. S. Sim, S. Y. Cho, H. Kwon, Tensile properties of 5052 Al matrix composites reinforced with B_4C, Metall. Mater. Trans. A, 32 (**2001**), 2142–2147

[9] R. K. Uyyuru, M. K. Surappa, S. Brusethaug, Tribological behavior of Al-Si-SiCp composites/automobile brake pad system under dry sliding conditions, Tribology International, 40 (**2007**), 365–373

[10] T. S. Mahmoud, Tribological behaviour of A390/Gr_P metal-matrix composites fabricated using a combination of rheocasting and squeeze casting techniques, Journal of Mechanical Engineering Science, 222 (**2008**), 257–265

[11] E. Mohammad Sharifi, F. Karimzadeh, M. H. Enayati, Fabrication and evaluation of mechanical and tribological properties of boron carbide reinforced aluminum matrix nanocomposites, Materials and Design, 32 (**2011**), 3263–3271

[12] L. Jinfeng, J. Longtao, W. Gaohui, T. Shoufu, C. Guoqin, Effect of Graphite Particle Reinforcement on Dry Sliding Wear of SiC/Gr/Al Composites, Rare Metal Materials and Engineering, 38 (**2009**), 1894–1898

[13] S. Basavarajappa, G. Chandramohan, A. Mahadevan, M. Thangavelu, R. Subramanian, P. Gopalakrishnan, Influence of sliding speed on the dry sliding wear behaviour and the subsurface deformation on hybrid metal matrix composite, Wear, 262 (**2007**), 1007–1012

[14] S. Basavarajappa, G. Chandramohan, K. Mukund, M. Ashwin, M. Prabu, Dry Sliding Wear Behavior of Al 2219/SiC_p-Gr Hybrid Metal Matrix Composites, Journal of Materials Engineering and Performance, 15 (**2006**) 6, 668–674

[15] M. Gui, S. B. Kang, J. M. Lee, Dry sliding wear behavior of spray deposited AlCuMn alloy and AlCuMn/SiCp composite, Journal of Materials Science, 35 (**2000**), 4749–4762

[16] R. M. Mohanty, K. Balasubramanian, S. K. Seshadri, Boron carbide-reinforced alumnium 1100 matrix composites: fabrication and properties, Materials Science and Engineering A, 498 (**2008**), 42–52

[17] J. Oñoro, M. D. Salvador, L. E. G. Cambronero, High-temperature mechanical properties of aluminium alloys reinforced with boron carbide particles, Materials Science and Engineering A, 499 (**2009**), 421–426

[18] I. Kerti, F. Toptan, Micro structural variations in cast B4C-reinforced aluminium matrix composites (AMCs), Materials Letters, 62 (**2008**), 1215–1218

[19] U. B. Gopala Krishna, K. V. Sreenivas Rao, B. Vasudeva, Effect of boron carbide reinforcement on aluminium matrix composites, International Journal of Metallurgical & Materials Science and Engineering, 3 (**2013**), 41–48

[20] Y. Sahin, S. Murphy, The effect of sliding speed and microstructure on the dry wear properties of metal-matrix composites, Wear, 214 (**1998**), 98–106

[21] D. Poirier, R. A. L. Drew, M. L. Trudeau, R. Gauvin, Fabrication and properties of mechanically milled alumina/aluminum nanocomposites, Materials Science and Engineering A, 527 (**2010**), 7605–7614

[22] N. Hosseini, F. Karimzadeh, M. H. Abbasi, M. H. Enayati, Tribological properties of Al6061-Al_2O_3 nanocomposite prepared by milling and hot pressing, Mater. Des., 31 (**2010**), 4777–4785

[23] D. Cree, M. Pugh, Dry wear and friction properties of an A356/SiC foam interpenetrating phase composite, Wear, 272 (**2011**), 88–96

[24] M. Ramachandra, K. Radhakrishna, Effect of reinforcement of flyash on sliding wear, slurry erosive wear and corrosive behavior of aluminium matrix composite, Wear, 262 (**2007**), 1450–1462

[25] M. Jafari, M. H. Enayati, M. H. Abbasi, F. Karimzadeh, Compressive and wear behaviors of bulk nanostructured Al2024 alloy, Mater. Des., 31 (**2010**), 663–669