Vol. 36, No. 2 (2014) 220-227

Tribology in Industry

www.tribology.fink.rs

RESEARCH

The Enhancement of Wear Properties of Compo-Cast A356 Composites Reinforced with Al_2O_3 Nano Particulates

M.R. Rahimipour[a], A.A. Tofigh[a], M.O. Shabani[a], P. Davami[b]

[a] Materials and Energy Research Center (MERC), Tehran, Iran,
[b] Department of Materials Engineering, Sharif University of Technology, Tehran, Iran.

Keywords:

Nano
Compocast
Wear
EMS
DAS

Corresponding author:

Ali Asghar Tofigh
Materials and Energy Research Center (MERC), Tehran,
Iran
E-mail: aliasghartofigh60@gmail.com

ABSTRACT

Aluminum matrix nano composites have become of great interest in the lightweight fields because of their high specific stiffness and high specific strength. Many processing techniques have been developed to manufacture metal matrix nano composites on the commercial scale. Compocasting is a relatively new technology for composite forming, different from the conventional composite shaping technologies that use either solid or liquid metals as the starting material. An investigation is carried out on the influence of applied load, sliding speed, wearing surface hardness, reinforcement fracture toughness and morphology as the critical parameters in relation to the wear regime. In general, EMS composites offer superior wear as compared to the SC irrespective of applied load and sliding speed.

1. INTRODUCTION

Aluminum matrix composites (AMCs) account for 69 % of the annual metal matrix composites (MMCs) production by mass. Metal matrix nano-composites (MMNCs) are a new class of nano-structured materials, consisting of nano-scale particles used as reinforcements (1 _ 100 nm) [1-8]. It is expected that the strength of aluminum reinforced by ceramic nano-particles, would be enhanced considerably, while the ductility of the aluminum matrix is retained [3]. Currently, there are several fabrication methods of MMNCs, including in situ technique, disintegrated melt deposition powder metallurgy, vortex process, and ultrasonic method. Al_2O_3 nano-particles have been added to the Al 356 alloy using a compo cast method [5]. Experimental results showed a relatively uniform distribution of nano particles and more than 50 % improvement in yield strength of A356 alloy only with 2.0 wt. % of nano-sized Al_2O_3 particles. One of the major driving forces for the technological development of aluminum-matrix composites reinforced with ceramic whiskers/fibers/particles is a result of the fact that these composites possess superior wear resistance and are hence potential candidate materials for a number of tribological applications [9-14]. The wear resistance of aluminum alloys is improved as a consequence of the incorporation of ceramic fibers or particles which act as the load bearing and abrasive member [7]. There are excellent reviews on the tribology of aluminum-matrix composites which has been generally found to be a function of the applied load as well as the reinforcement volume fraction, particle size, and the shape and nature of the reinforcing phase [15-21]. Researchers reported that the addition of hard ceramic particles as a reinforcement to aluminum alloys supported and protected the aluminum matrix from wear and minimized sever surface shear strain that was associated with the unreinforced alloys [22-28]. The matrix structure also influences the wear and friction behaviors of MMCs, so that the processing route and/or heat treatment conditions can enhance the wear resistance of these materials via their effects on the matrix microstructure, distribution of particles, porosity content, particle matrix bonding and mechanical properties [29-37]. No attempt is reported in the literature using an electromagnetic stirrer (EMS) device to obtain a uniform distribution of the particles. It is of a interest to obtain a high wear resistant nano composite by optimization of materials possessing which requires a stable tribolayer on the wearing surface and the formation of fine equiaxed wear debris. It is attempted to examine the wear behavior of aluminum alloy based composites reinforced with nano Al_2O_3 particulates.

2. EXPERIMENTAL PROCEDURE

In this study, a commercial casting-grade aluminum alloy (A356) {(wt. %): 7 Si, 0.3 Mg, 0.02 Zn, 0.001 Cu, 0.3 Fe, and Al (balance)} was employed as the matrix material while the Al_2O_3 nano particles with average particle sizes of 100 nm were used as the reinforcements. For manufacturing of the MMCs, 1.8 vol. % Al_2O_3 nano particles were used. Nano particles were injected into the melt in the form of a mixture of Al_2O_3 nano particles (25 %), Mg powder (25 %) and Al powder (50 %). The powders were mixed and then pressed into the disk shape. The diameter and height of each disk were 10 mm and 3 mm, respectively. The alloy was melted in a resistance furnace at 720 °C, and then degassed for 10 min with argon gas through a graphite lance. The disks were then added using an electromagnetic stirrer (EMS) device to obtain a uniform distribution of the particles. The current was varied from 30 and 70 A while voltage was kept constant and equal to 220 V. Mg was added to the melt in order to increase the wettability between the matrix and the reinforcements. The temperature was lowered to convert the liquid into semisolid slurry. The slurry was immediately poured into the die cavity and squeezed during the solidification. For comparison, conventional liquid squeeze cast (SC) samples were poured at 720 °C without electromagnetic stirrer device treatment.

The compocast samples were heat-treated based on T6 heat treatment specifications: solution treatment at 545 °C for 4 h; ageing at 155 °C for 6 h. The metallographic samples were cut off from the castings, ground, finely polished and etched by an aqueous solution of 0.5 % HF. The microstructures were observed and analyzed with an optical microscope and SEM. Hardness values of the samples were measured on the polished samples at a load of 100 gr. For each sample, five hardness tests on randomly selected regions were performed in order to eliminate the possible segregation effects and get a representative value of the matrix material hardness. During the hardness measurements, precaution was taken to make indentation at a distance of at least twice the diagonal length of the previous indention.

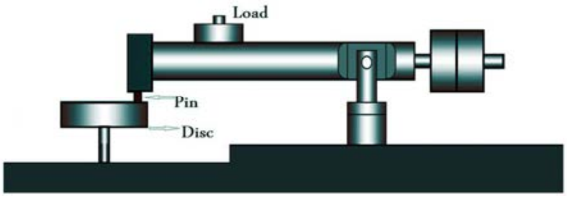


Fig. 1. Schematic diagram of the abrasion wear test.

Sliding wear tests were conducted in pin-on-disc wear testing apparatus under varying applied loads against case hardened steel disc of hardness 63 HRC. Test specimens were cut and shaped in the form of pins having 6 mm in diameter and 35 mm in height. Before the abrasion tests, each specimen was polished to 1 μm. Fig. 1 shows schematic diagram of the abrasion wear test. A set of three samples was tested in every experimental condition, and the average along with standard deviation for each set of three tests is measured. The wear tests were conducted up to the total sliding distance of 1600 m.

3. RESULTS AND DISCUSSION

Figure 2 shows the effect of various electromagnetic currents on the microstructure of the compocast A356 reinforced with 1.8 % nano Al_20_3. Microstructure of this alloy contains coarse dendritic α-Al and continuous eutectic network (Si particles and α-Al).

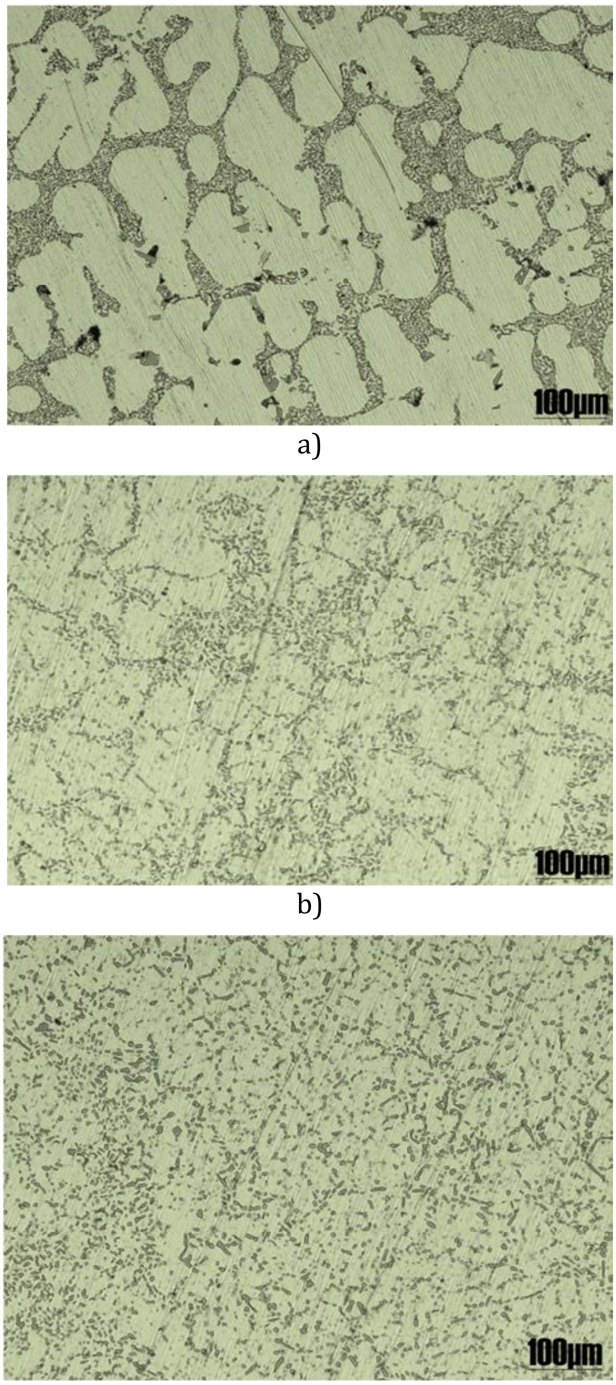


Fig. 2. Effect of various electromagnetic currents on the microstructure of the compocast A356 reinforced with 1.8 % nano Al_20_3 a: SC, b: 30A and c: 70A.

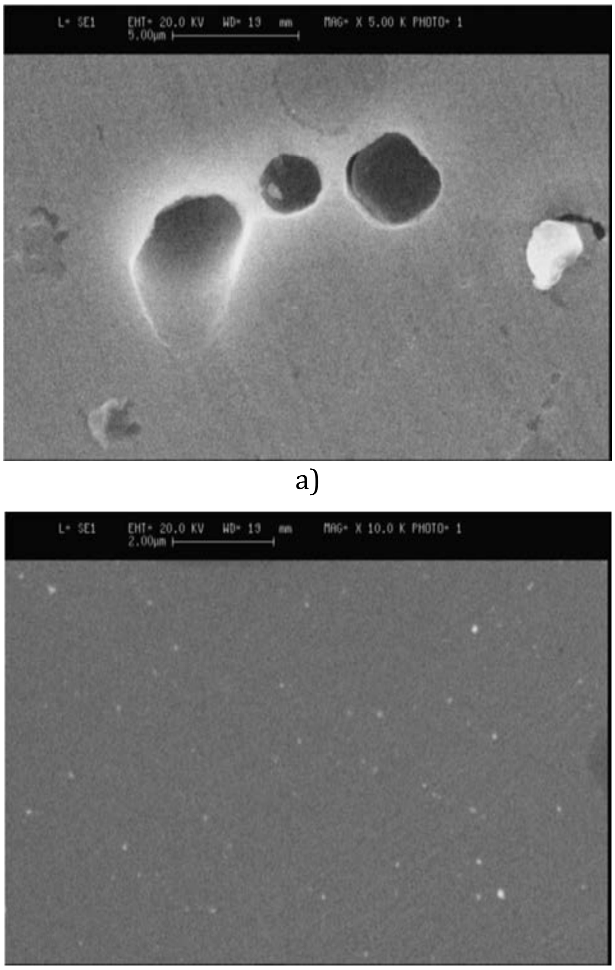
Figure 2a shows the cast sample with dendritic primary α-Al and coarse arms in which the electromagnetic current is not imposed. Figures 2 b and c shows the microstructures of A356 Al alloy obtained at the different electromagnetic field. The maximum sphericity and medium mean diameter of the globules are obtained by I=70 (Fig. 2c).

When the EMS current is 30 A, the morphology of primary α-Al particles turned out to be coarse, while the microstructure of A356 Al alloy processed at 70 A consists of primary α-Al particles with globular-like with fine grain size. Shabani and Mazahery [16] reported that fragmentation mechanism, intense stirring and localized rapid cooling cause severe temperature disturbances in the melt which leads to the melting of dendritic arms.

Globulization of structure during stirring can be made by breaking of dendrite arms results from shear force or melting of them and subsequently growth of these broken dendrites. With increasing shear intensity, globalization of structure occurs by changing the geometry of diffusion in the melt around the growing solid phase [2].

Compared with conventional solidification, the actual nucleation rate may not be increased but all nuclei will survive, resulting in an increased effective nucleation rate. In addition, the intensive mixing action is likely to disperse the clusters of potential nucleation agent, giving rise to an increased number of potential nucleation sites.

The most important factor in the fabrication of MMCs is the uniform dispersion of the reinforcements. Figure 3 represents typical SEM images of this composite in SC and EMS with I=70A. Figure 3b show the uniform distribution of Al_2O_3 particles through the matrix alloy. It is assumed that electromagnetic field improves the wetting kinetics in the liquid aluminium which results in uniform distribution of Al_2O_3 particles. It is believed that strong mechanical bonding made between Al and Al_2O_3 particles combined with EMS process help to disperse them more uniformly in the liquid.



a)

b)

Fig. 3. SEM images of composite a: SC and b: EMS.

Figure 4 shows the hardness of the EMS A356 matrix composite reinforced with 1.8 % nano Al_20_3 produced by a variety of electromagnetic fields. The highest value of hardness is obtained by addition of 1.8 % Al_20_3 nano-particles and using electromagnetic current of I=70A which is attributed to finer dendritic microstructure and uniform distribution of Al_20_3 nano-particles. Hardness of this alloy is enhanced by precipitation of Mg_2Si in the supersaturated Al solid solution.

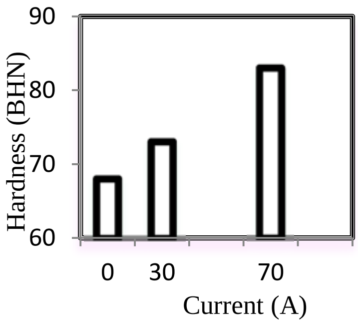


Fig. 4. The hardness of the EMS A356 matrix composite reinforced with 1.8 % nano Al_20_3 produced by a variety of electromagnetic fields.

The weight loss of the samples as a function of applied load is depicted in Fig. 5. It is noted that the wear rate in all the samples increases marginally with applied load. The increase in the applied load leads to increase in the penetration of hard asperities of the counter surface to the softer pin surface, increase in micro cracking tendency of the subsurface and also increase in the deformation and fracture of asperities of the softer surface.

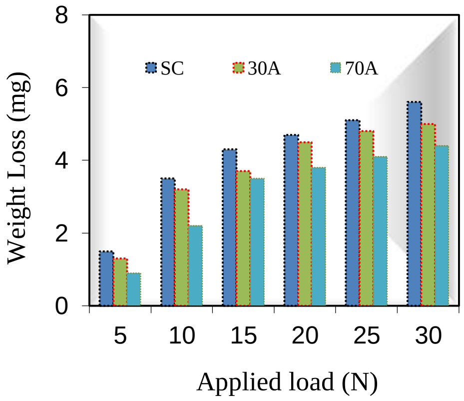


Fig. 5. The weight loss of the composites as a function of applied load.

Figure 6 shows the weight loss as a function of sliding distance at an applied load of 10 N. It is noted that the weight loss of the EMS composite is less than that of SC composite.

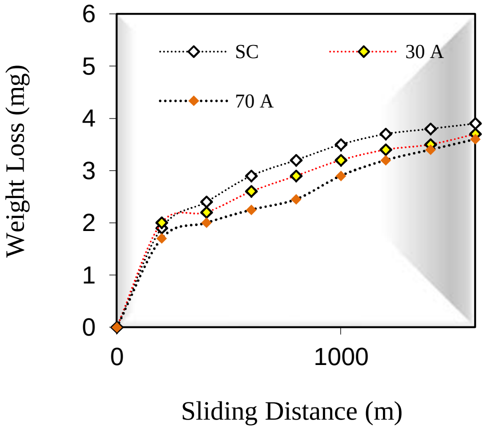
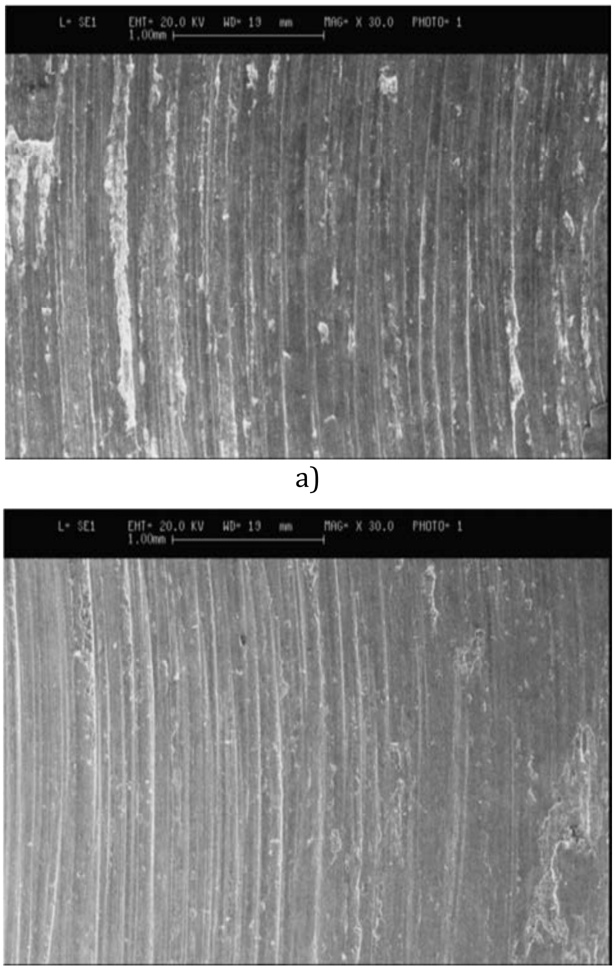


Fig. 6. The weight loss as a function of sliding distance at an applied load of 10 N.

The weight loss increases with increase in sliding distance, and has a declining trend with increasing the electromagnetic field. This result is consistent with the rule that in general, materials with higher hardness have better wear and abrasive resistance [5]. It is known that the wear loss is inversely proportional to the hardness of alloys. In case of SC composite, the depth of penetration is governed by the hardness of the specimen surface and applied load. But, in case of EMS composite, the depth of penetration of the harder asperities of hardened steel disk is primarily governed by the protruded hard and fine ceramic reinforcement that disperse in overall matrix and also fine dendrites. Thus, the major portion of the applied load is carried by particles. The role of the reinforcement particles is to support the contact stresses preventing high plastic deformations and abrasion between contact surfaces and hence reduce the amount of worn material.



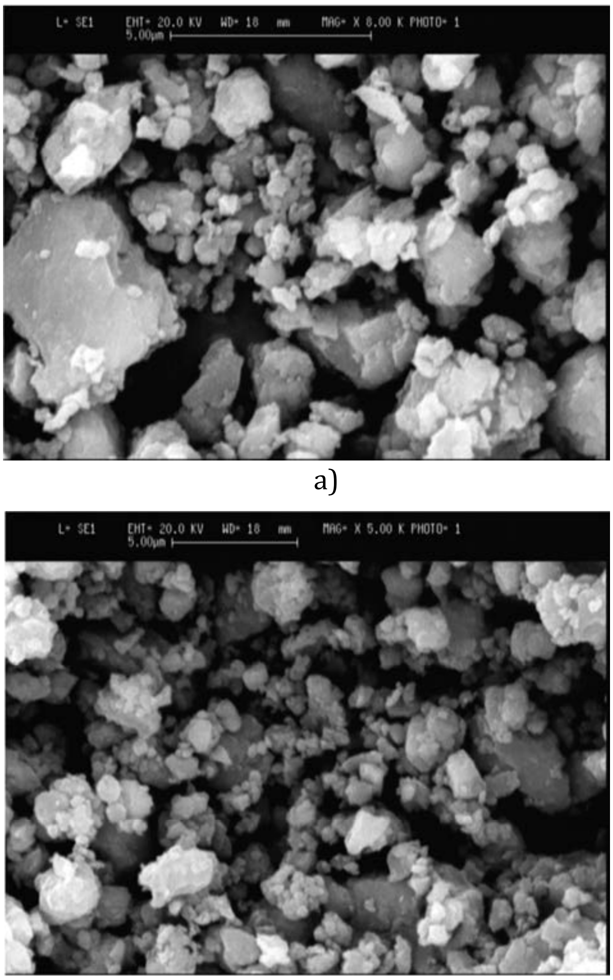
a)

b)

Fig. 7. The wear surface of a: SC and b: EMS composites (10 N).

The wear surface of the SC composite under the applied load of 10 N is depicted in Fig. 7 a. The SC matrix alloy is much softer than the counter body material and during sliding counter body penetrates into the matrix alloy producing deep grooves and causing extensive plastic deformation of the surface, which results in great material loss and significant wear rate. The worn surfaces also contain the evidence of adhesive wear in the form of adhesive pits. On the other side, the large scale of the matrix alloy is transferred to the counter body [16]. The flow of materials along the sliding direction, generation of cavities due to delamination of surface materials and tearing of surface material is also noted in this figure.

Worn surface EMS composite at an applied load of 10 N is shown in Fig. 8b. It indicates formation of continuous wear grooves, relatively smooth MML and some damaged regions. However, the degree of cracks formation on the wear surface is not much. The wear surface is characterized by the formation of parallel lips along the continuous groove marking.



a)

b)

Fig. 8. Morphology of wear debris a: SC and b: EMS composites (10 N).

Morphology of wear debris collected during the tests is also shown in Fig. 8a. Debris generated by the wear of the materials in contact originate mostly from the pin material. Among the wear debris of the composite, at higher specific loads prevail mainly sharp edge, plate-like particles. On the surface of these plate-like particles, presence of material plastic flow could be noticed. Thus, at higher specific load, the wear debris is mainly plate-like, with sharp edges, which are typical for adhesive wear. Presence of the rodlike particles also indicates existence of severe wear.

4. CONCLUSION

EMS plays an important role in the formation of non-dendritic primary α-Al particles in A356 Al alloy slurry. It can be seen that the increase in EMS current causes smaller and rounder primary α-Al particles. The maximum sphericity and medium mean diameter of the globules are obtained by I=70. A comparative study on abrasive wear behavior of nano Al_2O_3 reinforced aluminum metal matrix composite has been carried out in the present investigation. The mass loss of the pin was used to study the effect of Al_2O_3 addition on the wear resistance of the composite materials. The Al_2O_3 particulates increase the bulk hardness of the base Al alloy. The wear properties of EMS compo cast samples benefit from the refinement of the primary α-Al phase and uniform distribution of eutectic Si particles. The reason for lower wear rate in EMS composites can be attributed to their high hardness as compared to the conventional SC, resulting in lower real area of contact and therefore lower wear rate.

One of the common features observed on the worn surfaces of both base SC and EMS composite, is the formation of grooves and ridges running parallel to the sliding direction. A transfer layer of compacted wear debris along with the wear tracks can be observed over the sliding surface. This layer reaches a critical thickness before being detached resulting eventually in generation of wear debris. The extent of this transfer layer is determined by the load, sliding speed and it increases with increasing load because of the increased frictional heating and hence better compaction. For adhesive wear, the influence of applied load, sliding speed, wearing surface hardness, reinforcement fracture toughness and morphology are critical parameters in relation to the wear regime encountered by the material.

REFERENCES

[1] V.S. Aigbodion, S.B. Hassan, E.T. Dauda, R.A. Mohammed: *Experimental Study of Ageing Behaviour of Al-Cu-Mg/Bagasse Ash Particulate Composites,* Tribology in industry, Vol. 33, No. 1, pp. 28-35, 2011.

[2] A. Mazahery, M.O. Shabani: *Modification Mechanism and Microstructural Characteristics of Eutectic Si in Casting Al-Si Alloys: A Review on Experimental and Numerical Studies,* JOM, Vol. 66, No. 5, pp. 726-738, 2014.

[3] M. Kandeva, L. Vassileva, R. Rangelov, S. Simeonova: *Wear-resistance of Aluminum Matrix Microcomposite Materials,* Tribology in Industry, Vol. 33, No. 2, pp. 57-62, 2011.

[4] M.O. Shabani, A. Mazahery: *Optimization of process conditions in casting aluminum matrix composites via interconnection of artificial neurons and progressive solutions*, Ceramics International, Vol. 38, pp. 4541–4547, 2012.

[5] A. Mazahery, M.O. Shabani: *Study on microstructure and abrasive wear behavior of sintered Al matrix composites,* Ceramics International, Vol. 38, pp. 4263–4269, 2012.

[6] A. Mazahery, M.O. Shabani: *Characterization of cast A356 alloy reinforced with nano SiC composites,* Transactions of Nonferrous Metals Society of China, Vol. 22, pp. 275280, 2012.

[7] B. Bobic, S. Mitrovic, M. Babic, I. Bobic: *Corrosion of Aluminium and Zinc-Aluminium Alloys Based Metal-Matrix Composites*, Tribology in Industry, Vol. 31, No. 3&4, pp. 44-52, 2009.

[8] A. Mazahery, M.O. Shabani: *Computational modeling of cast aluminum 2024 alloy matrix composites: Adapting the classical algorithms for optimal results in finding multiple optima,* Powder Technology, Vol. 249, pp. 77–81, 2013.

[9] S.F. Moustafa, S.A.L. Badry, A.M. Sanad, B. Kieback: *Friction and wear behavior of graphite–copper composites,* Wear, Vol. 253, pp. 699–710, 2002.

[10] M.O. Shabani, A. Mazahery: *Application of FEM and ANN in characterization of Al Matrix nano composites using various training algorithms, Metallurgical and Materials Transactions* A, Vol. 43, No. 6, pp. 2158-2165, 2012.

[11] A. Mazahery, M.O. Shabani: *Assistance of Novel Artificial Intelligence in Optimization of Aluminum Matrix Nanocomposite by Genetic Algorithm, Metallurgical and Materials Transactions* A, Vol. 43, No. 13, pp. 5279-5285, 2012.

[12] M.O. Shabani, A. Mazahery: *The performance of various artificial neurons interconnections in the*

modelling and experimental manufacturing of the composits, Materiali in tehnologije, Vol. 46, No. 2, pp. 109–113, 2012.

[13] S. Srivastava, S. Mohan: *Study of Wear and Friction of Al-Fe Metal Matrix Composite Produced by Liquid Metallurgical Method,* Tribology in Industry, Vol. 33, No. 3, pp. 128-134, 2011.

[14] M.O. Shabani, A. Mazahery: *Optimization of Al Matrix Reinforced with B4C Particles*, JOM, Vol. 65, No. 2, pp. 272-277, 2013.

[15] A. Mazahery, M.O. Shabani: *Application of the Extrusion to Increase the Binding between the Ceramic Particles and the Metal Matrix: Enhancement of Mechanical and Tribological Properties,* Journal of Materials Science & Technology, Vol. 29, No. 5, pp. 423-428, 2013.

[16] M. O. Shabani, A. Mazahery: *Development of an Extrusion Process to Ameliorate the Tribological Properties of Heat Treated Al Mg Si (Cu) System Alloys Matrix Composites in Consolidated State*, Tribology in Industry, Vol. 34, No. 3, pp. 166-173, 2012.

[17] P. Cavaliere, E. Evangelista: *Isothermal Forging of Metal Matrix Composites: Recrystallization Behaviour by Means of Deformation Efficiency,* Composite science and technoogy, Vol. 66, pp. 357–362, 2006.

[18] A. Mazahery, M. O. Shabani: *Ascending Order of Enhancement in Sliding Wear Behavior and Tensile Strength of the Compocast Aluminum Matrix Composites,* Transactions of the Indian Institute of Metals, Vol. 66, No. 2, pp. 171–176, 2013.

[19] P. Poddar, S. Mukherjee, K.L. Sahoo: *The Microstructure and Mechanical Properties of SiC Reinforced Magnesium Based Composites by Rheocasting Process,* Journal of materials engineering and performance, Vol. 18, pp. 849–855, 2009.

[20] A. Mazahery, M.O. Shabani: *Microstructural and abrasive wear properties of SiC reinforced aluminum-based composite produced by compocasting,* Transactions of Nonferrous Metals Society of China, Vol. 23, pp. 1905–1914, 2013.

[21] L. Ceschini, G. Minak, A. Morri: *Forging of the AA2618/20 vol.% Al2O3 Composite: Effects on Microstructure and Tensile Properties,* Composite science and technology, Vol. 69, pp. 1783–1789, 2009.

[22] B. Nedic, G. Lakic: *Friction Coefficient for Al Alloys and Tool Materials Contact Pairs,* Tribology in Industry, Vol. 27, No. 3&4, pp. 53-56, 2005.

[23] A. Mazahery, M.O. Shabani: *Existence of Good Bonding between Coated B4C Reinforcement and Al Matrix via Semisolid Techniques: Enhancement of Wear Resistance and Mechanical Properties,* Tribology Transactions, Vol. 56 pp. 342-348, 2013.

[24] A. Hamid, P. Ghosh, S. Jain, S. Ray: *The influence of porosity and particles content on dry sliding wear of cast in situ Al (Ti)–Al2O3(TiO2) composite,* Wear, Vol. 265, No. 1&2, pp. 14-26, 2008.

[25] A. Mazahery, M.O. Shabani: *Process conditions optimization in Al-Cu alloys matrix composites,* Powder Technology, Vol. 225 pp. 101–106, 2012.

[26] M. O. Shabani, A. Mazahery: *The GA optimization performance in the microstructure and mechanical properties of MMNCs* , Transactions of the Indian Institute of Metals, Vol. 65, No. 1, pp. 77–83, 2012.

[27] R. Bauri, M.K. Surappa: *Processing and compressive strength of Al–Li–SiCp composites fabricated by compound billet technique,* Journal of Material Processing Technology, Vol. 209, pp. 2077–2084, 2009.

[28] A. Mazahery, M.O. Shabani: *Elaboration of an operative and efficacious optimization route to ameliorate the mechanical and tribological properties of implants,* Powder Technology, Vol. 249, pp. 530–535, 2013.

[29] B.M. Viswanatha, M.P. Kumar, S. Basavarajappa, T.S. Kiran: *Effect of Ageing on Dry Sliding Wear Behaviour of Al-MMC for Disc Brake,* Tribology in Industry, Vol. 36, No. 1, pp. 40-48, 2014.

[30] A. A. Tofigh, M.O. Shabani: *Efficient optimum solution for high strength Al alloys matrix composites,* Ceramics International, Vol. 39, pp. 7483–7490, 2013.

[31] 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,* Tribology in Industry, Vol. 35, No. 2, pp. 148-154, 2013.

[32] A. Mazahery, M.O. Shabani: *The performance of TV-MOPSO in optimization of sintered steels,* Kovove Mater, Vol. 51, pp. 333–341, 2013.

[33] K.K. Alaneme, B.O. Ademilua, M.O. Bodunrin: *Mechanical Properties and Corrosion Behaviour of Aluminium Hybrid Composites Reinforced with Silicon Carbide and Bamboo Leaf Ash,* Tribology in Industry, Vol. 35, No. 1, pp. 25-35, 2013.

[34] M.O. Shabani, A. Mazahery: *A Novel Computational Strategy to Enhance the Ability of Elaborate Search by Entire Swarm to Find the Best Solution in Optimization of AMCs* , Defect and Diffusion Forum, Vol. 332, pp. 27-33, 2012.

[35] S. Mitrović, M. Babić, B. Stojanović, N. Miloradović, M. Pantić, D. Džunić: *Tribological Potential of Hybrid Composites Based on Zinc and Aluminium Alloys Reinforced with SiC and Graphite Particles,* Tribology in Industry, Vol. 34, No. 4, pp. 177-185, 2012.

[36] A. Mazahery, M.O. Shabani: *Investigating the effect of reinforcing particulates on the weight loss and worn surface of compocast AMCs,* Kovove Mater, Vol. 51, pp. 11–18, 2013.

[37] S. Mitrović, M. Babić, B. Stojanović, N. Miloradović, M. Pantić, D. Džunić: *Tribological Potential of Hybrid Composites Based on Zinc and Aluminium Alloys Reinforced with SiC and Graphite Particles,* Tribology in Industry, Vol. 34, No. 4, pp. 177-185, 2012.