Journal of the Balkan Tribological Association *Vol. 18, No 4, 548–558* (*2012*)

INFLUENCE OF Al_2O_3 PARTICLE CONTENT ON THE SLIDING WEAR BEHAVIOUR OF ZA-27 ALLOY COMPOSITES

S. MITROVIC[a]*, M. BABIC[a], F. ZIVIC[a], I. BOBIC[b], D. DZUNIC[a], M. PANTIC[a]

[a] *Faculty of Mechanical Engineering, Tribology Center, University of Kragujevac, Kragujevac, Serbia*
E-mail: *boban@kg.ac.rs*, *babic@kg.ac.rs*, *zivic@kg.ac.rs*, *dzuna@kg.ac.rs, pantic@kg.ac.rs*
[b] *Institute of Nuclear Sciences 'Vinca', University of Belgrade, Serbia*
E-mail: *ilijab@vinca.rs*

ABSTRACT

The lubricated and dry sliding wear behaviour of ZA-27 alloy composites reinforced with Al_2O_3 particles of size 250 μm was evaluated. The content of Al_2O_3 particles in the alloy was 3, 5 and 10 wt.%. Composites were produced by the compocasting process using mechanical mixing of the matrix, i.e. Al_2O_3 particles as reinforcement were added into the semi-solid ZA-27 alloy by infiltration and admixing. A block-on-disc wear test device was used to evaluate the wear rate, whereat 30CrNiMo8 steel disc was used as the counterface, under dry and lubricated sliding conditions at different specific loads and sliding speeds. Results indicated that the wear rates of the composites were lower than those of the matrix alloy and further decreased with the increase in Al_2O_3 particles content in all combinations of applied loads and sliding speeds in both dry and lubricated tests.

Keywords: composites, ZA-27 alloy, Al_2O_3 particles, sliding wear, wear rate.

AIMS AND BACKGROUND

Zinc-aluminium alloys (ZA) have broad industrial application. These alloys show very good wear resistance under high loads, slow to medium speed and poor lubrication conditions, good tribo-mechanical properties, low weight, excellent foundry cast ability and fluidity, good machining properties, low initial cost and environmental-friendly technology. ZA alloys are capable of replacing aluminum

* For correspondence.

cast alloys and bearing bronzes, as well as cast iron, plastics, or even steels for manufacturing the triboelements for operation under conditions of moderate exploitation temperatures[1–8].

Besides many good characteristics that this alloy shows at room temperature, its main disadvantage is degradation of tensile strength and creep resistance at temperatures above 100°C, that significantly lowers its area of its application. In order to improve its characteristics for high-temperature zones, researchers began to use ceramic materials to reinforce the alloys since the mid-1980s (Refs 9 and 10).

Investigation results showed that it is favourable to reinforce it with different dispersed reinforcement materials (short fibres, whiskers or particles) in order to obtain much more enhanced mechanical and tribological properties. As a result, in the recent years, metal matrix composites (MMCs) based on ZA matrix are being increasingly applied as light-weight and wear-resistant materials[11–13].

To understand the wear behaviour of different MMCs, wear tests are often carried out with suitable wear-testing techniques, with variation of contact conditions (sliding speed, applied load, particle wt.% and duration of sliding). There are different types of wear mechanisms involved: adhesive wear, abrasive wear, oxidation wear or others. However, adhesive wear is by far the most dominant form of material loss among sliding components in machinery[14]. The block-on-disc sliding wear-testing machine is a standard method commonly used for adhesive wear experiments. Both surfaces of the contact pair exhibit wear during sliding between block and disc. Disc is usually selected to have higher hardness, in order to monitor wear easier. Wear is most often measured by volume or wear rate of the block, calculated based on width of the wear track. Composite wear behaviour is influenced by normal load, sliding speed, duration of friction and mass content of the reinforcement materials.

In the present work, the compocasting method was used to produce Al_2O_3 particle reinforced ZA-27 composites. An attempt has been made to evaluate the dry and lubricated wear behaviour of ZA-27/Al_2O_3 composite over a range of applied loads and sliding speeds. The unreinforced ZA-27 alloy was tested as a reference material.

EXPERIMENTAL

Materials and preparation. The matrix material was ZA-27 alloy with a chemical composition shown in Table 1.

Alloy was cast into a cold graphite mould, and ingot with 12 mm in diameter and 100 mm in height was produced[15]. No grain refinement treatment was performed during the process of casting. Composites were produced by the compocasting process using mechanical mixing of the matrix, i.e. Al_2O_3 particles as reinforcement were added into the semi-solid ZA-27 alloy by infiltration and ad-

Table 1. Chemical composition (wt.%) of ZA-27 alloy

Element	Al	Cu	Mg	Fe	Zn
Percentage	28.47	2.51	0.011	0.145	balance

mixing. The average size of Al_2O_3 particles was 250 μm, whereas the amount of particles was 3, 5 and 10 wt. %.

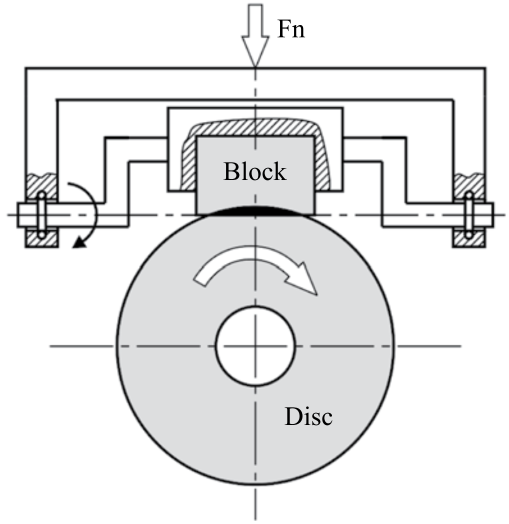
Preparation of the charge consisted of measuring and chemical cleaning of the prepared bars of the ZA-27 alloy. The bars were melted in the previously heated pot (to about 600°C) of the electric-resistance furnace. The melt was then heated up to 550°C (57°C above the alloy melting point) for additional cleaning of the slag, then it was cooled down to the mixing temperature of 485°C (18 mass. % of the solid phase). After the mixer was brought in, the mixing started (from 0 to 500 rpm) with simultaneous cooling of the melt down to do 462°C (32 mass. % of the solid phase), i.e., to the compocasting procedure working temperature. After the working temperature and operating number of rpm were reached, for the following 5 min the isothermal isotropic processing of the semi-solidified melt was performed by mixing, to destroy the dendritic structure, namely to prepare the melt for infiltration.

No chemical pretreatment of Al_2O_3 was performed except that the powder was preheated at 460°C to avoid the disturbance of isothermal condition in the melt during the compocasting process. Al_2O_3 was poured in continuously for 3 min, immediately next to the mixer's shaft, at 200 rpm (at the mentioned temperature of 462°C). After the reinforcement was finished, for the next 2 min the number of rpm was gradually increased up to the working number of 500 rpm. The isothermal 'mixing in' of the Al_2O_3 particles into the semi-solidified melt of ZA-27 was then realised, for next 30 min at working conditions: 500 rpm and temperature of 462°C, for the purpose of homogenisation, i.e. to achieve better distribution of particles. After the mixing of composite was finished, the mass was cooled down to 430°C and poured into the steel mold, which was previously heated up to 300°C. Cylindrical bars were obtained with 36-mm diameter and length of 100–130 mm.

It was necessary to perform the hot pressing to reduce porosity, after manufacturing of the composite materials samples. Finally, the samples aimed for wear testing were made from the ZA-27 as-cast alloy and pressed pieces.

Methods of characterisation. Characterisation of matrix material and composites included metallographic examinations with optical microscope and hardness measurements. Metallographic samples were prepared in a standard way applying grinding and polishing, whereas etching in the Keller solution was used to reveal the microstructure. Hardness of the samples was measured using a Vickers hardness tester. Density of the samples was measured by the Archimedes method.

Fig. 1. Scheme of contact pair geometry



The samples were tested using a computer-aided block-on-disc sliding wear-testing machine with the contact pair geometry in accordance with ASTM G 77–83. A schematic configuration of the test machine is shown in Fig. 1. More detailed description of the tribometer is available elsewhere[15,16].

The test blocks were prepared from the Al_2O_3-reinforced ZA-27 alloy composite and as-cast ZA-27 alloy. Their contact surfaces were polished to a roughness level of R_a = 0.2 μm. The counterface was fabricated using the case-hardened 30CrNiMo8 steel with hardness of 55 HRC. The roughness of the ground contact surfaces was R_a = 0.3 μm. The tests were performed under lubricated and dry sliding conditions at different sliding speeds (0.26–1.00 m/s) and applied loads (10–80 N) with fixed sliding distance (1000 m for lubricated and 500 m for unlubricated conditions).

The lubricant used for lubricated tests was ISO grade VG 46 hydraulic oil, a multipurpose lubricant recommended for industrial use in plain and antifriction bearings, electric motor bearings, machine tools, chains, and gear boxes, as well as in high-pressure hydraulic systems.

The wear behaviour of the block was monitored in terms of the wear scar width. Using the wear scar width and geometry of the contact pair the wear volume and wear rate (expressed in mm^3/m) were calculated.

RESULTS

Microstructure, hardness and density. The results of metallographic investigation of the matrix alloy and composites are illustrated in Fig. 2. The microstructure of the matrix alloy revealed primary α dendrites, eutectoid α + η, and metastable

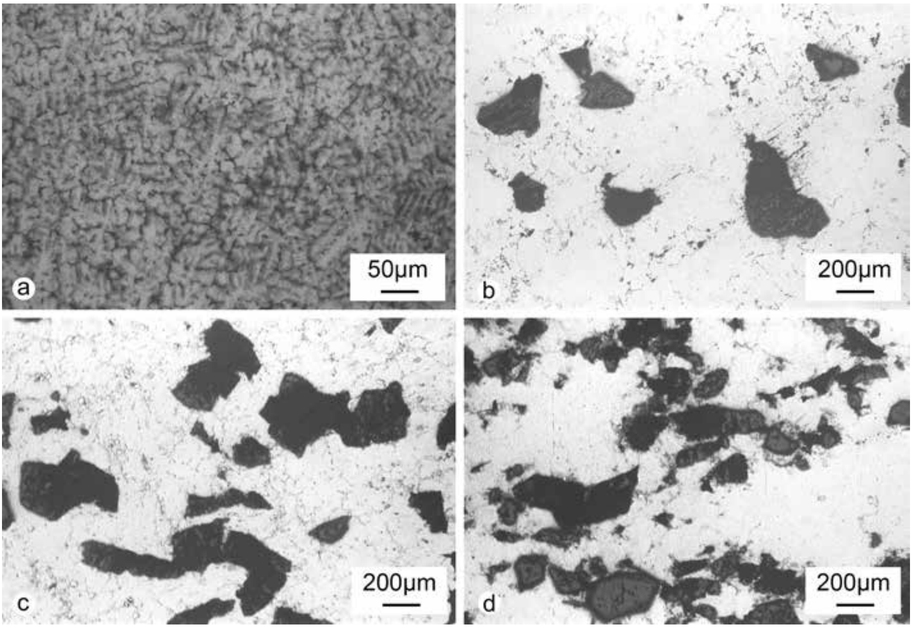


Fig. 2. Microstructure of the tested materials: ZA-27 alloy (*a*), composite 3% Al_2O_3 (*b*), composite 5% Al_2O_3 (*c*) and composite 10% Al_2O_3 (*d*)

ε phase (Fig. 2*a*). The structures of the composite samples are morphologically so similar (Fig. 2*b*, *c*, *d*) that there is no need to describe them individually, at least in regard to the shape of the primary particles. The fundamental reason for obtaining the morphologies presented in the photos is the change in the solidification process due to the parameters of the compocasting method. Namely, in the semi-solidified state at the temperature interval of compocasting, the Za-27 alloy melt is subjected to very slow cooling (average cooling rate of 5°C/min). If the melt was not subjected to the mixing procedure in the semi-solidified state, the structure at the room temperature consists of rough, very developed dendrites. However, due to the shear forces action during the compocasting procedure, the large, elliptic primary particles were formed as large grains. In other words, the transformation of the dendritic into the non-dendritic structure has occurred.

The distribution of the reinforcing agent points to a tendency that a lot of particles are placed in the interdendritic phase area. This is clear due to mixing of the semi-solidified melt of the alloy, which at the process temperature has a large portion of the liquid phase and low resistance to the infiltration of particles. Later, during the cooling, the particles become rounded. It is interesting that there are many particles that are placed within the primary dendrites that points to their relatively large energy acquired from the mixer. It looks like a 'knocking-in' of the particles into the dendrites.

Table 2. Hardness and density of matrix alloy and composites

Properties	ZA-27	Composites		
		3% Al_2O_3	5% Al_2O_3	10% Al_2O_3
Hardness ($HV_{0.3}$)	103	106	109	113
Density (g/cm^3)	4.85	4.36	4.14	3.73

The results of hardness and density measurements are shown in Table 2. It can be seen that the hardness of tested materials increases with addition of Al_2O_3 particles amount. Density decreased with addition of Al_2O_3 particles.

Wear behaviour. Wear behaviour of tested ZA-27/Al_2O_3 composite samples, as a function of the test duration in lubricated and dry sliding conditions, at sliding speed of 0.5 m/s, and applied load of 50 N, is illustrated in Fig. 3*a*, *b*. Generally, the wear behaviour of tested materials was characterised by initially very intensive wear (run-in) during the first minutes of sliding, after which the steady state period followed.

Wear curves shown in Fig. 3*a*, indicate that running-in period is relatively short for lubricated conditions contact. Also, it can be noticed that a period of initial wear decreased with increase of reinforcement mass content. Contact of the investigated sample (block) and counterbody (disc) over the whole length of the contact, is realised over reinforcement particles that act as load bearer, for composites with higher reinforcement mass content, what can be explanation of the previous result.

Wear curves for unlubricated conditions are given in Fig. 3*b*. It can be noticed that wear curves are almost identical for all tested samples and the advantage of samples with higher reinforcement mass content is obvious, if compared both to the matrix alloy material and samples with lower mass content. Running-in period is relatively short and it can be said that it is finished after 2 min, for all samples.

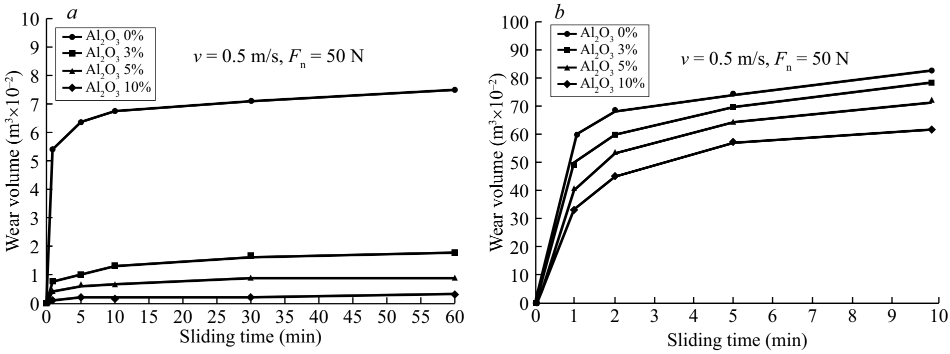


Fig. 3. Wear curves of tested materials: lubricated sliding (*a*), dry sliding (*b*)

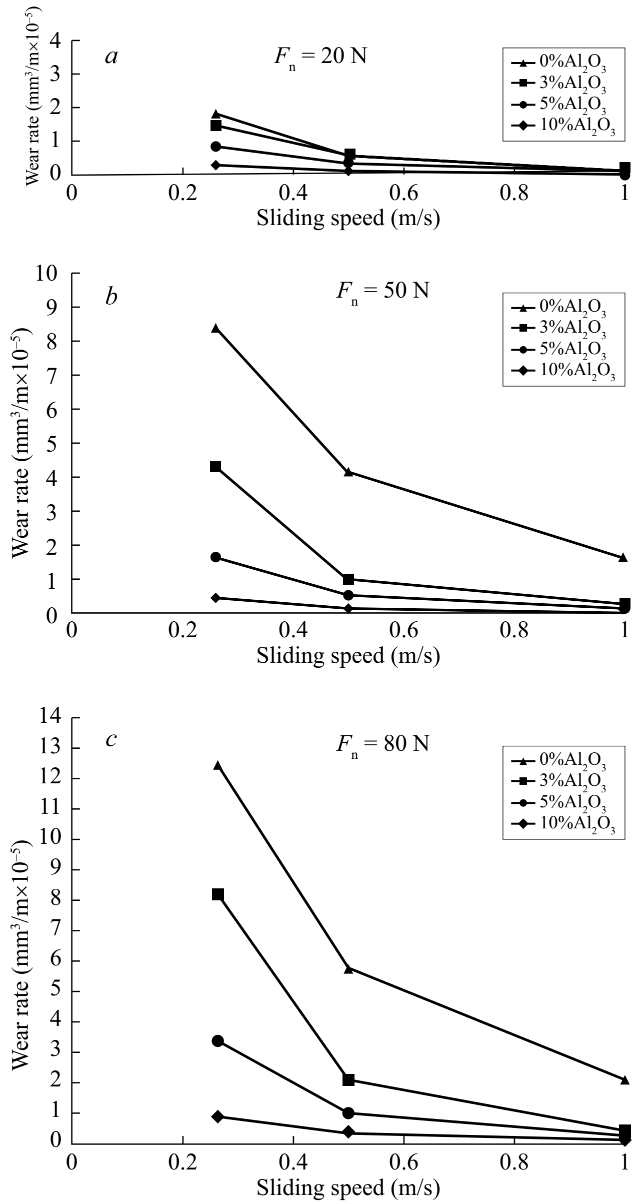


Fig. 4. Wear rate versus sliding speed, during lubricated sliding of the ZA-27 alloy composites at applied load of: 20 (*a*); 50 (*b*) and 80 N (*c*)

The incorporation of Al_2O_3 particles to the ZA-27 alloy improves the sliding wear resistance in comparison with the unreinforced alloy. The effects of both applied speed and load, during lubricated and dry sliding were investigated as a function of Al_2O_3 wt. %.

Figure 4 (*a–c*) shows the graphs representing the wear rates of the composites as well as the base alloy samples as a function of the sliding speed during

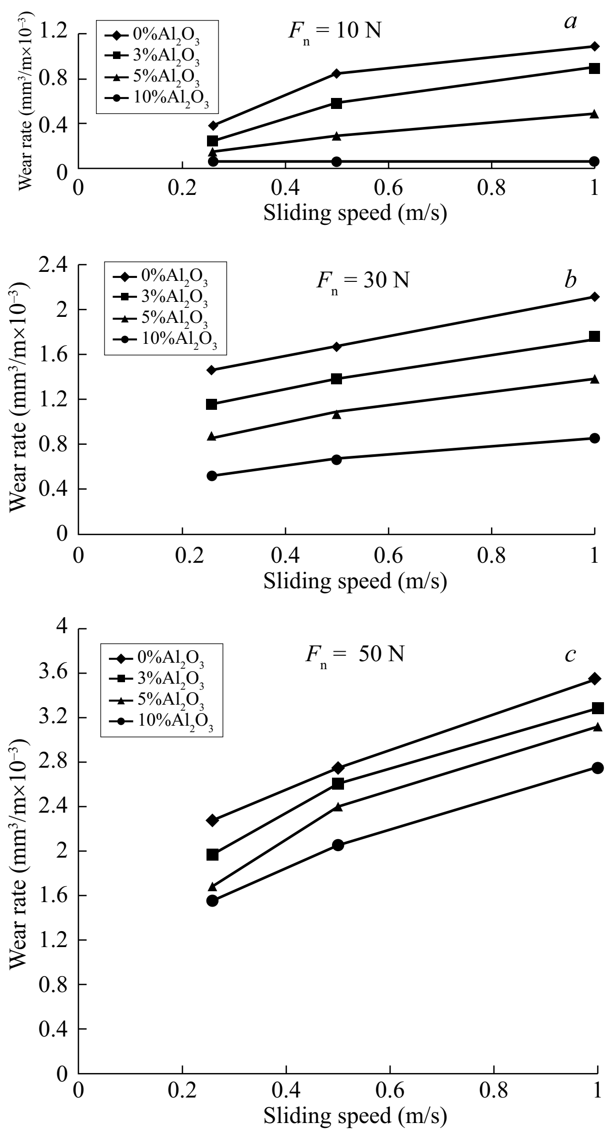


Fig. 5. Wear rate versus sliding speed, during dry sliding of the ZA-27 alloy composites at applied load of: 10 (*a*); 30 (*b*); and 50 N (*c*)

lubricated sliding, at applied load of 20, 50 and 80 N, respectively. The wear rate of the unreinforced alloy as well as of the composite samples decreases with the increase of sliding speed. Note that the composite samples exhibited significantly lower wear rates than the base alloy samples. This is especially pronounced at higher loads and lower sliding speeds.

Wear rate is clearly influenced by the presence of the reinforcing Al_2O_3 particles, for lubricating conditions. Wear rate of the composite is significantly lower in comparison with unreinforced alloy, except in the lowest load case (20 N), when wear rate values were very close to each other at higher speeds. Differences in wear rate values between matrix alloy and composite become more pronounced with increase of applied load and decrease of sliding speed.

Figure 5 (*a–c*) shows the wear rate of the composites and the base alloy samples as a function of the sliding speed during dry sliding, at applied load of 10, 30 and 50 N, respectively. The wear rate of the alloy as well as of the composite samples increased with increase of the sliding speed. Also, increase of the reinforcement mass content resulted in decrease of the wear rate. Trend of the wear rate increase with sliding speed increase is almost identical for all tested samples, irrespective of normal load applied. It is obvious that the trend of wear rate increase is more inclined at higher loads and it can be concluded that the sliding speed variation has much higher influence on the wear rate for higher contact loads.

Figure 6 shows the wear rate as a function of reinforcement mass content, wt.% at different sliding speed and applied load, for lubricated (Fig. 6*a*) and non-lubricated (Fig. 6*b*) conditions. The wear rate decreased with increase of the mass

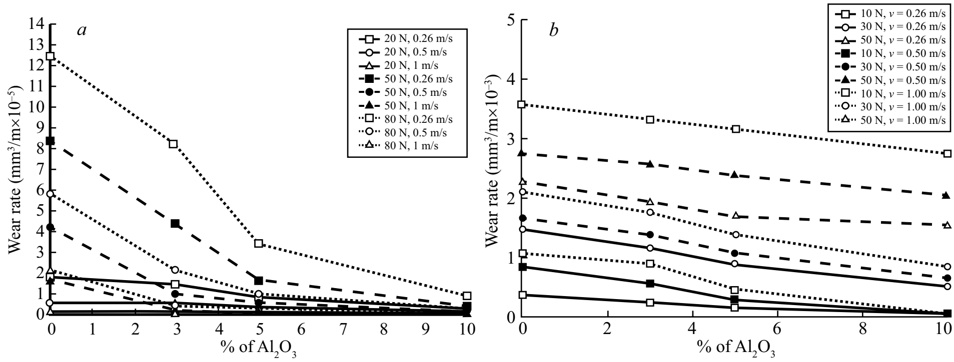


Fig. 6. Wear rate versus wt.% of Al_2O_3: lubricated sliding (*a*), dry sliding (*b*)

content of Al_2O_3 and sliding speed increase resulted in even more pronounced effect, what can be clearly noticed in these diagrams and what exactly was the goal of this paper. More pronounced influence of reinforcement mass content increase was noticed under lubricating conditions (Fig. 6*a*). Also, load and speed variation showed lower influence on wear rate with increase of Al_2O_3 mass content, under lubricating conditions. Influence of load and speed on wear rate is approximately the same for basic alloy and investigated composites, for non-lubricated conditions (Fig. 6*b*). Generally speaking, increase of Al_2O_3 particles mass content resulted in wear resistance increase. Based on realised investigations, it can be concluded that the highest wear resistance was noticed at composite reinforced with amount of Al_2O_3 particles of 10 wt.%.

CONCLUSIONS

Experimental results showed that it is possible to influence the wear behaviour of tested composites based on ZA-27 alloy, by changing the reinforcing Al_2O_3 particles mass share. According to investigation of wear characteristics of tested composites based on ZA-27 alloy, reinforced by Al_2O_3 particles, the following conclusions can be drawn:

- The ZA-27 alloy composites reinforced with Al_2O_3 particles of 250 μm size exhibited reduced wear rate than the unreinforced ZA-27 alloy samples in all the combinations of applied loads and sliding speeds in dry and lubricated tests.
- The reinforcement Al_2O_3 particles led to reduce the wear rate of the alloy. In lubricated conditions, wear rate of the composites as well as the matrix alloy increased with the increase in load applied, but decreased with the increase in sliding speed. In dry conditions, wear rate of the composites as well as the matrix alloy increased with the increase in load applied and sliding speed.
- In lubricated conditions, positive effect of Al_2O_3 particles was higher for higher contact loads and lower sliding speeds, while in dry conditions, positive effect of Al_2O_3 particles was almost identical for all combinations of applied load and sliding speed.

ACKNOWLEDGEMENT

The results of this paper were realised through the national project TR–35021 financially supported by the Ministry of Science of the Republic of Serbia.

REFERENCES

1. V. V. VASILIEV, E. V. MOROZOV: Mechanics and Analysis of Composite Materials. Elsevier Science Ltd., The Boulevard, Langford Lane, Kidlington, Oxford OX5 lGB, UK, 2001.
2. R. D. PRUTHVIRAJ, P. V. KRUPAKARA: Influence of SiC additions on Mechanical Properties of the Zn-Al alloy (ZA-27). International J. of Material Science, **2** (1), 53 (2007).
3. B. K. PRASAD: Influence of Heat Treatment on the Physical, Mechanical and Tribological Properties of a Zinc-based Alloy. Zeitschrift Fur Metallkunde, **87**, 226 (1996).
4. M. D. HANNA, J. T. CARTER, M. S. RASHID: Sliding Wear and Friction Characteristics of Six Zn-based Die-casting Alloys. Wear, **203–204**, 11 (1997).
5. P. P. LEE, T. SAVASKAN, E. LAUFER: Wear Resistance and Microstructure of Zn-Al-Si and Zn-Al-Cu alloys. Wear, **117**, 79 (1987).
6. B. K. PRASAD, A. K. PATWARDHAN, A. H. YEKNESWARAN: Dry Sliding Wear Characteristics of Some Zinc-aluminium Alloys: A Comparative Study with a Conventional Bearing Bronze at a Slow Speed. Wear, **199**, 142 (1996).

7. R. W. CAHN, P. HAASEN: Physical Metalurgy, Vol. 3, North-Holland, Amsterdam–Lausanne–New York–Oxford–Shannon–Tokyo, 1996.
8. M. BABIC, A. VENCL, S. MITROVIC, I. BOBIC: Influence of T4 Heat Treatment on Tribological Behaviour of ZA27 Alloy Under Lubricated Sliding Condition. Tribology Letters, **36** (2), 125 (2009).
9. S. C. SHARMA, B. M. GIRISH, R. KAMATH, B. M. SATISH: Sliding Wear Behaviour of Zircon Particles Reinforced ZA-27 Alloy Composite Materials. Wear, **224**, 89 (1999).
10. S. C. SHARMA, B. M. GIRISH, B. M. SATISH, R. KAMATH: Aging Characteristics of Short Glass Fiber Reinforced ZA-27 Alloy Composite Material. Journal of Materials Engineering and Performance, **7**, 747 (1998).
11. S. C. SHARMA, B. M. SATISH, B. M. GIRISH, R. KRAMATH, H. ASANUMAT: Dry Sliding Wear of Short Glass Fibre Reinforced Zinc-aluminium Composites. Tribology International, **31** (4), 183 (1998).
12. B. K. PRASAD, O. P. MODI, H. K. KHAIRA1: High-stress Abrasive Wear Behaviour of a Zinc-based Alloy and Its Composite Compared with a Cast Iron Under Varying Track Radius and Load Conditions. Materials Science and Engineering A, **381**, 343 (2004).
13. B. K. PRASAD: Abrasive Wear Characteristics of a Zinc-based Alloy and Zinc-alloy/SiC composite. Wear, **252** (3–4), 250 (2002).
14. L. J. YANG: Wear Coefficient Equation for Aluminium-based Matrix Composites Against Steel Disc. Wear, **255** (1–6), 579 (2003).
15. M. BABIC, S. MITROVIC, B. JEREMIC: The Influence of Heat Treatment on the Sliding Wear Behaviour of a ZA-27 Alloy. Tribology International, **43** (1–2), 16 (2010).
16. M. BABIC, S. MITROVIC, D. DZUNIC, B. JEREMIC, I. BOBIC: Tribological Behaviour of Composites Based on Za-27 Alloy Reinforced With Graphite Particles. Tribology Letters, **37** (2), 401 (2009).

Received 6 November 2011
Revised 9 January 2012