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Tribological potential of particulate composites with ZA-27 alloy matrix

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Abstract: *The tribological effects of particle reinforcement on the wear behavior of ZA-27 alloy composites were investigated. The ZA-27/Al_2O_3, ZA-27/SiC, ZA-27/Gr, ZA-27/SiC/Gr composites with different particle content were produced by the compocasting procedure. Tribological properties of unreinforced alloy and composites were studied, using block-on-disk tribometer under dry friction conditions at different specific loads and sliding speeds. The worn surfaces of samples were examined by the scanning electron microscopy (SEM). The obtained results clearly indicate that reinforcement with Al_2O_3, SiC or/and graphite particles could significantly improve tribological properties of ZA-27 alloy. The effects of reinforcement on wear behavior depend on type of particles, their content and combination (hybrid composites), as well as sliding speed and applied load. The wear mechanisms of composites in tested conditions are explained by micro cracking tendency and the formation and destruction of mechanical mixed layers (MMLs).*

Keywords: *ZA-27 alloy, Tribology, Composites.*

1. Introduction

Zinc–aluminum (ZA) alloys have emerged as important material for tribological applications, especially suitable for high-load and low-speed applications [1 - 8]. However, the relatively inferior high-temperature wear and mechanical properties of these alloys are major limitations of wider industrial application.

The development of particulate reinforced metal matrix composites (MMCs) has been recognized as way to overcome these deficiencies of ZA alloys. This approach is based on positive experiences about the influence of the ceramic particle reinforcement on properties of aluminum-based alloys.

Investigators, who have worked on particulate reinforced ZA alloys [9-11, 16–28] have reported that the incorporation of reinforcing particles significantly improves their abrasive and sliding wear resistance. Investigators of MMCs based on ZA alloys generaly reported that reinforcement by hard ceramic particles, like SiC and Al_2O_3 contributes to an improvement of resistance to abrasion (two-body [9, 16] and three-body [17]) and erosion/corrosion [18, 19] of MMC based on ZA alloys matrix. However, the effectiveness of particles influence depends on the dominance of set factors[20].

The resutlts of tribological investigetions obtained by Sharma et al. [21] confirm that the SiC particle reinforced ZA-27 alloy composites exhibited reduced wear rate with respect to that of the unreinforced ZA-27 alloy specimens in conditions of dry sliding. Also, with the increase in SiC content, within range of 1.0–5.0 wt%, the wear resistance and the hardness of the composites increased monotonically. Improvement of wear response of ZA-27/SiC composite in lubricated sliding conditions was reported by Tjong and Chen [22]. The volume loss decreases almost steadily with increasing in SiC particles content. Auras and Schvezov [23] analyzed the wear behavior of five different ZA-27 alloys reinforced by SiC, under dry and lubricated conditions. The results indicate that the wear rate of ZA alloys is strongly dependent on the test load nonlinearly, and that the addition of SiC particles improved the wear properties of the matrix alloys.

Tribological effects of ZA reinforcement by Al_2O_3 particles have not been so widely investigated. Sharma at al. reported that in conditions of dry sliding wear behavior of Al_2O_3 particle reinforced ZA alloy is influenced by the sliding speed and pressure [11]. The composites exhibited higher wear rate than the matrix alloy, at lower sliding speeds. This was attributed to the predominant effect of micro cracking tendency of composite, caused by Al_2O_3 reinforcing particles. Reduced wear rate and higher seizure pressure of the composite, than those of the matrix alloy at high sliding speed, was attributed to the enhanced compatibility of the matrix with hard Al_2O_3dispersed phase. The positive tribological effects of ZA-27 alloy reinforcement with Al_2O_3 particles also are presented in [29].

In recent decades, considerable research efforts have been done on graphite reinforced MMCs. However, the properties of Zn–Al alloy/graphite particulate composites have not been studied so extensively. Previous studies [26, 27]. showed that addition of graphite particles to the ZA-27 alloy matrix improved the wear resistance of the composite, in spite of the significant decrease in hardness. Risent investigations [1] suggest that composite specimens exhibited significantly lower wear rate and coefficient of friction than the matrix alloy specimens in all combinations of applied loads and sliding speeds in lubricated and dry sliding conditions. The difference in the wear resistance of composite with respect to the matrix alloy, increased with the increase of the applied load in the dry sliding conditions. This increase was moderate, while in the case of the lubricated sliding it was very prominent. Also, the wear resistance difference between the composite and the matrix alloy very gradually increased with the sliding speed increase. The advantage of composite, with respect to the matrix alloy, when the antifriction properties are concerned, is more prominent in the area of higher applied loads and sliding speeds. This tribological improvement has been explained by self-lubricating role of graphite in sliding contact.

The objective of the present investigation was to assess the influence of particle reinforcement on tribological behavior of ZA-27 alloy. The graphite, Al_2O_3 and SiC particles were used as the reinforcement. Combining ceramic and graphite particles were produced hybrid composites. The composites were produced by the compocasting procedure. Tribological properties of unreinforced alloy and composites were studied, using block-on-disc tribometer, under dry sliding conditions at different specific loads and sliding speeds. The worn surfaces of the samples were examined by scanning electron microscopy (SEM). The obtained results approved that MMCs based on ZA-27 alloys could significantly improve trbological potential of ZA alloys in area of higher sliding speeds and loads.

2. Experimental procedure

2.1 Preparation of the Composites

The matrix material ZA-27 alloy (28.1% Al, 2.51% Cu, 0.011% Mg, 0.145% Fe, and balance Zn) was used as the base matrix alloy. Alloy was melted in a graphite crucible in an electric resistance furnace. The melt was overheated to 680^{o}C and cast into a steel mold to obtain samples as 100 mm long bars with rectangular cross-section with dimensions of 30 X 20 mm^2. No grain refinement treatment was performed during the process of casting.

As reinforcement were used of graphite (Gr) particles of mean size 30 µm, Al_2O_3 particles particles of mean size 220 µm and SiC particles of mean size 60 µm. Also, the ZA-27/SiC/Gr hydride composites were produced. The contents of reinforcements are shown in Table 1.

Table1 Reinforcing particles and their content

Renforcement	Content, wt%	Composites
Graphite (Gr)	2	ZA-27/2%Gr
Al2O3	3, 5, 10	ZA-27/3% Al_2O_3, ZA-27/5% Al_2O_3 ZA-27/10% Al_2O_3
SiC	5, 10	ZA-27/5%SiC, ZA-27/10%SiC
SiC + Gr	5+1, 5+3, 5+5, 10+1, 10+3, 10+5	ZA-27/5%SiC/1%Gr, ZA-27/5%SiC/3%Gr, ZA-27/5%SiC/5%Gr, ZA-27/10%SiC/1%Gr, ZA-27/10%SiC/3%Gr, ZA-27/10%SiC/5%Gr,

The composite specimens were obtained by dispersing reinforcement particles in the ZA-27 alloy matrix using compocasting isothermal technique, detailed elsewhere [8, 28]. After obtaining the composite materials samples, it was necessary to perform the hot pressing to reduce porosity. The samples for the tribological investigations were then made from the ZA-27 as-cast alloy and pressed pieces.

2.2. Wear tests

The specimens were tested using a computer aided block-on-disk sliding wear testing machine with the contact pair geometry in accordance with ASTM G 77-98. More detailed description of the tribometer is available elsewhere [29].

The test blocks (6.35 9 15.75 9 10.16 mm) were prepared from the comosites and as-cast ZA-27 alloy. Their contact surfaces were polished to a roughness level of Ra = 0.2 lm. The counter face (disk with 35 mm diameter and 6.35 mm thickness) was fabricated using the casehardened 30CrNiMo8 steel with hardness of 55 HRC. The roughness of the ground contact surfaces was Ra = 0.3 lm. The tests were performed under dry sliding condition at different sliding speeds (0.26, 0.5 and 1.00 m/s) and normal loads (10, 30 and 80 N), with a sliding distance of 600 m. Each experiment was repeated five times. The tests were performed at room temperature.

2. Results

3.1 Wear rates

The wear behavior of the blocks made of tested materials was monitored in terms of the wear scar width. Using the wear scar width and geometry of the contact pair, the wear volume (in accordance with ASTM G77-83) and wear rate (expressed in mm^3/m) were calculated [29].

Figures 1 - 5 shows the wear rate of the tested materials as a function of sliding speed at different normal load. The graphs indicate that the wear rate of the matrix alloy, as well as that of the composites, increases with sliding speed at all tested normal loads.

The influence of sliding speed on wear rate is very significant, and almost linear in the case of ZA-27 as cast alloy and in a case of ZA-27/2% Gr composite. The sensibility of the all other tested composites on sliding speed change is very moderate, especially at higher normal loads. Experimental data suggest that adding of graphite and forming hydride ZA-27/SiCGr composites contributes to very moderate slope of wear rate vs. sliding speed curves.

The effect of normal load on the wear rate of the tested materials at different sliding speeds is presented in Figs. 6 - 10. The plots indicate that the wear rate of the matrix alloy, as well as that of the composites, increases with applied load at tested sliding speeds (0.26, 0.5, and 1.0 m/s), Nature of that increase is not equal for all materials. Namely, ZA-27 as cast alloy and ZA-27/ Al_2O_3 composites are characterized by almost linear changing of wear rate with normal load. Wear rate of ZA-27/2%Gr increase with higher intensity in area of higher normal load. On contrary, in a case of composites containing SiC the increasing trend of the wear rate is much more distinctive at lover level of applied loads.

In Figs 11-14 are presented comparative column graphs for all tested composites, as well as matrix ZA-27 alloy. It could be seen that composite specimens exhibited significantly better wear properties than the ZA-27 matrix alloy specimens in almost all combinations of applied loads and sliding speeds.

The wear rate decrease with increase of the Al_2O_3 content in all tested combination of sliding speeds and normal loads. In a cases of ZA/3% Al_2O_3 and ZA/5% Al_2O_3composites, the highest wear rate reduction is obtained in conditions the lowest sliding speed (0,25 m/s) at varied normal loads. However, in a case of ZA/10% Al_2O_3 tribological improvement with respect to the matrix alloy is decrease with sliding speed increase. Generally, it is obvious that wear rate improvement decreases with normal load increase, for all tested ZA-27/Al_2O_3 composites.

The nature of SiC content in ZA-27 on wear rate is same, but not in all conditions of testing. Namely, adding of SiC particles contributes to worsening wear behavior of ZA-27 matrix alloy in conditions of the lowest sliding speed (0,25 m/s).

The difference in the wear rate of composites reinforcing by SiC partices with respect to the matrix alloy, increased with the increase of the applied load and sliding speed, as well as particle content. Superior wear behaviour of ceramic particulate reinforced MMCs based on ZA-27 and ZA/ Al_2O_3 alloys, especially at higher sliding speeds and pressures, have also reported by various investigators [10, 11, 21, 25, 26].

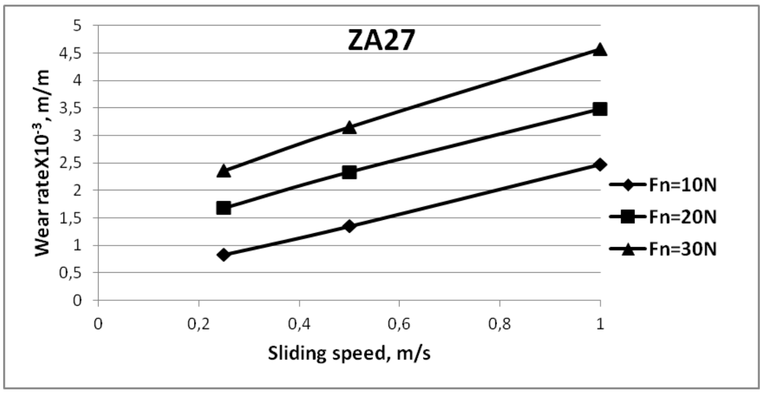

Fig.1. Wear rate vs. sliding speed of the ZA-27 alloy at different normal loads

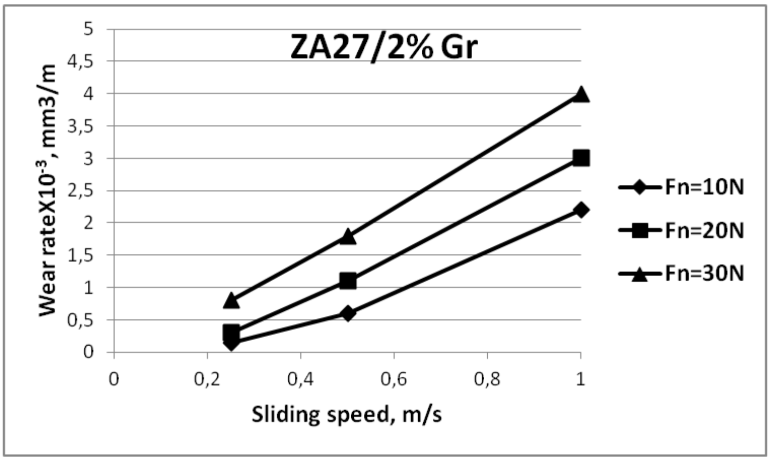

Fig. 2. Wear rate vs. sliding speed of the ZA-27/2%Gr composite at different normal loads

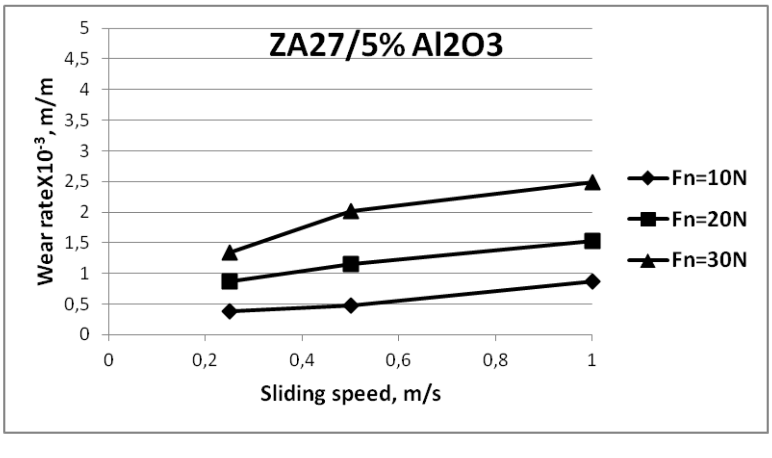

Fig. 3. Wear rate vs. sliding speed of the ZA-27/5%Al_2O_3 composite at different normal loads

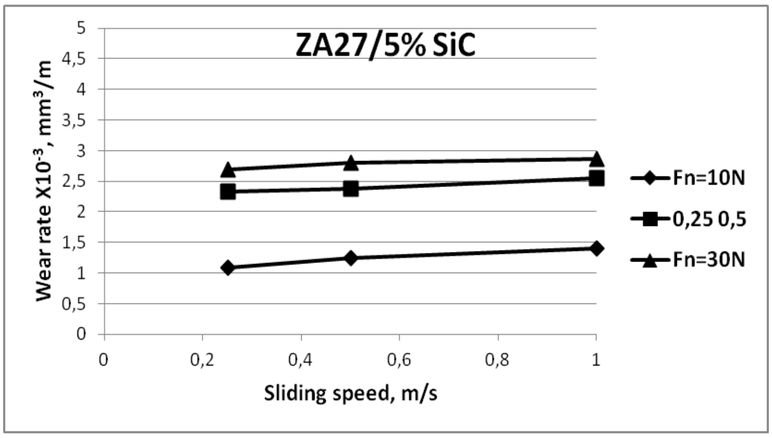

Fig. 4. Wear rate vs. sliding speed of the ZA-27/5%SiC composite at different normal loads

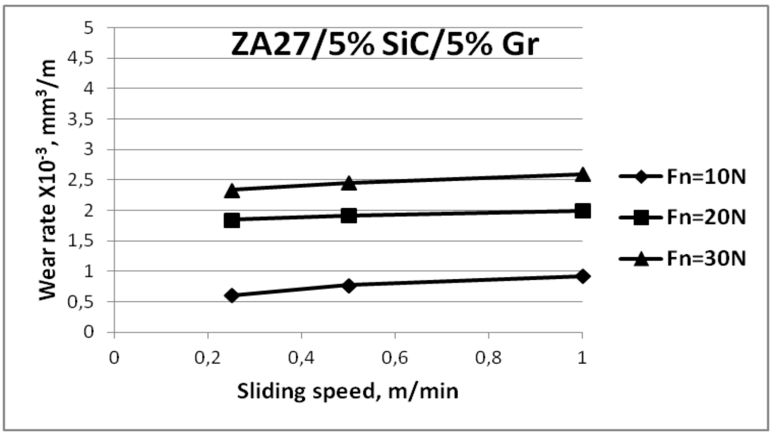

Fig. 5. Wear rate vs. sliding speed of the ZA-27/5%SiC5%Gr composite at different normal loads

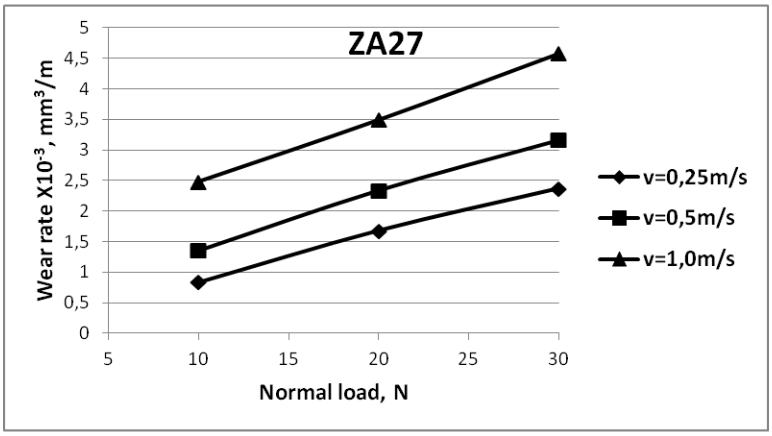

Fig. 6. Wear rate vs. normal load fot the ZA-27 aloy at different sliding speeds

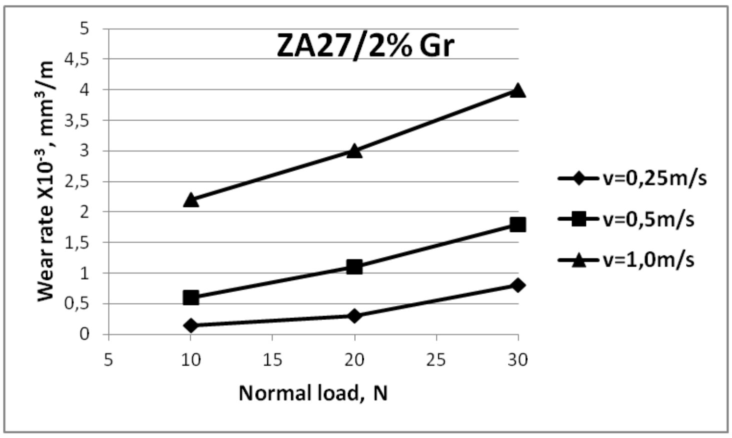

Fig. 7. Wear rate vs. normal load fot the ZA-27/2%Gr composite at different sliding speeds

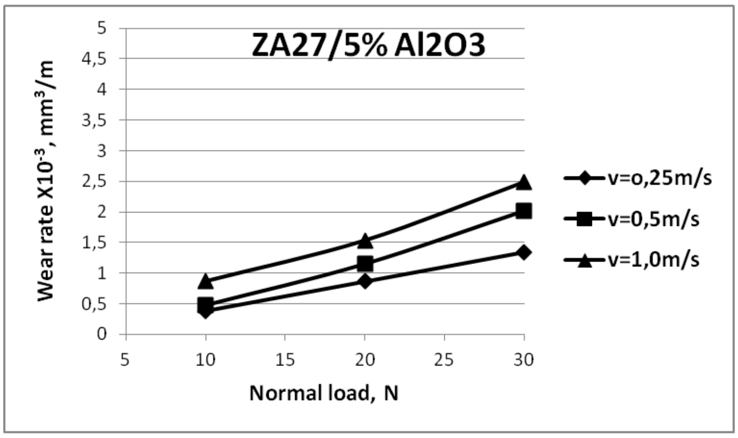

Fig. 8. Wear rate vs. normal load fot the ZA-27/5% Al_2O_3 composite at different sliding speeds

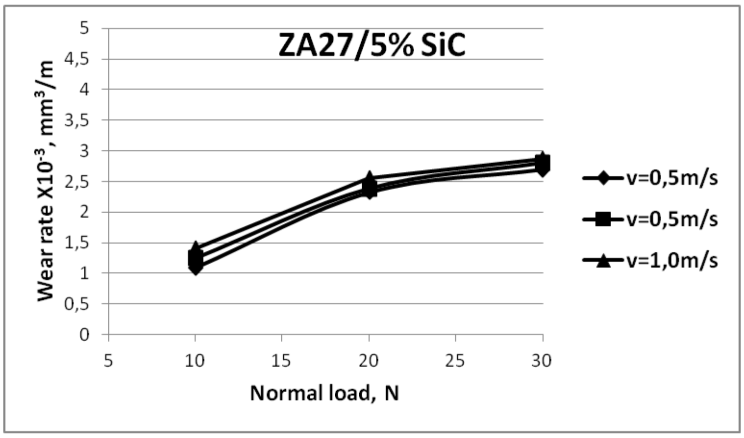

Fig. 9. Wear rate vs. normal load fot the ZA-27/5% SiC composite at different sliding speeds

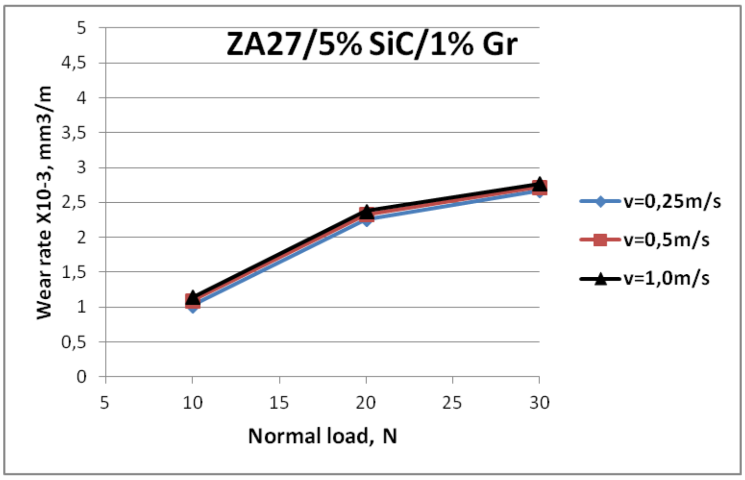

Fig. 10. Wear rate vs. normal load fot the ZA-27/5%SiC/1%Gr composite at different sliding speeds

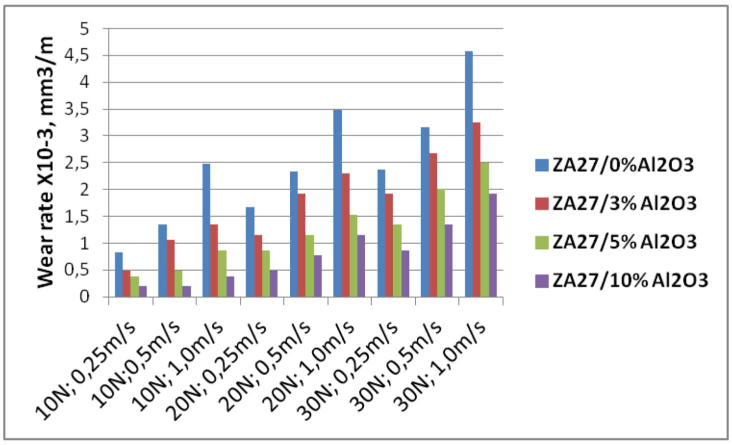

Fig. 11. Wear rates variations of ZA-27/Al_2O_3 composites with content of Al_2O_3 particles at different sliding conditions

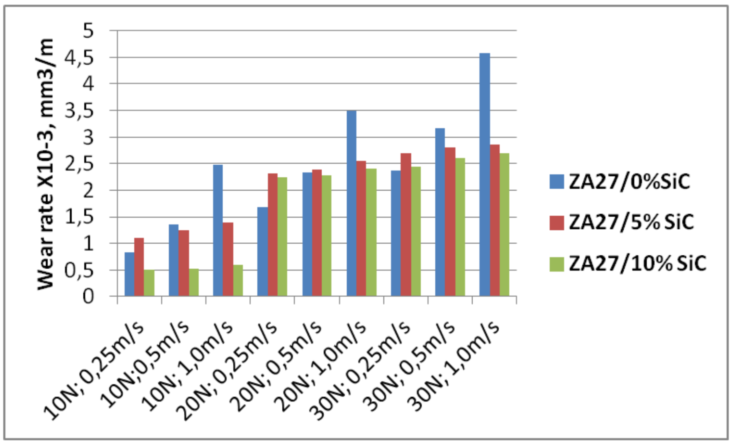

Fig.12. Wear rates variations of ZA-27/SiC composites with content of SiC particles at different sliding conditions

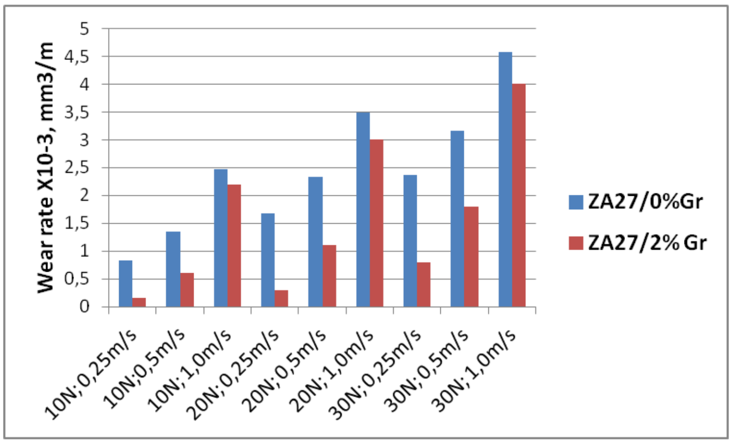

Fig. 13. Wear rates variations of ZA-27/Gr composites with content of graphite particles at different sliding conditions

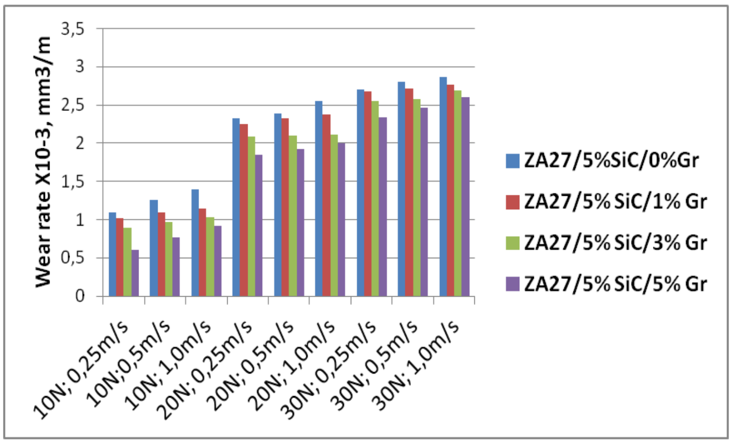

Fig. 14. Wear rates variations of hybride ZA-27/5%SiC/Gr composites with content of graphite particles at different sliding conditions

3.2 Morphology of the Worn Surfaces

The SEM micrographs of typical worn surfaces of the composites are presented in Figs. 15 and 16. Worn surface of the 5% Al_2O_3 reinforced composite at applied load of 30 N (Fig. 15a) indicates formation of relatively smoother mechanically mixed layer (marked by A) with shallow wear grooves (marked by B) and some damaged regions (marked by C). In the region of the continually mechanically mixed layer one can clearly notice appearance of an initial crack (marked by D). Besides that, clearly visible are evenly distributed Al_2O_3 particles sheared and then adhered to the surface (marked by E).

The more detailed morphology of this worn surface is shown in Fig. 15,b. Damage of surface appeared in forms of patches, which are relatively evenly distributed over the worn surface, but also in the form of deep grooves (marked by G). Besides that, on the worn surface one can notice presence of the reduced Al_2O_3 particles as well as stuck debris (marked by F). Micrograph clearly shows appearance of cracks in mechanically mixed layer (MML), which in the wear process led to its destruction. Disintegration of mechanically mixed transfer layers (micro composite) results in direct contact of mating surfaces and enhanced severity of wear. On the worn surface one can also notice appearance of the brittle fractures (Fig. 15c). Namely, during sliding, the nucleation and propagation of cracks within Al_2O_3 particles and matrix alloy occurred causing the brittle fracture.

The SEM micrographs presented in Fig. 16 show the typical surface morphologies of the ZA-27/2%Gr composite samples worn in the dry friction conditions at the sliding speed of 1.0 m/s and applied load of 30 N. One can clearly notice that on the worn surface the black graphite film is smeared and it covers the large portion of the contact surface and reduces the metal-to-metal contact between the sliding pairs.

The more detailed morphology of the composite's worn surface is shown in Fig. 16b,c. Besides the very prominent results of graphite smearing, the brittle fracture appeared on the contact surface (marked by Bf). It probably occurred in the clustered region of graphite particles. Namely, during sliding, the nucleation and propagation of cracks within the graphite particles occurred causing the brittle fracture of the surface.

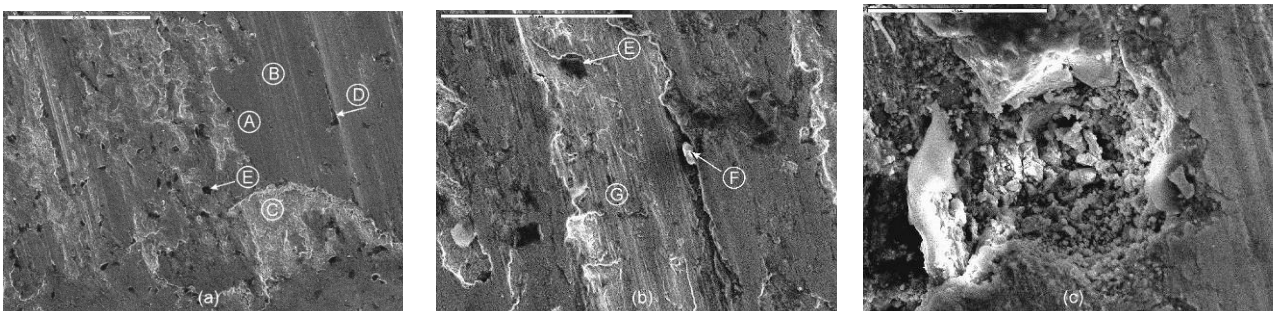

Fig. 15. SEM micrographs of worn surfaces of the 5% Al2O3 reinforced composite sample at sliding speed of 1.0 m/s and applied load of 30 N

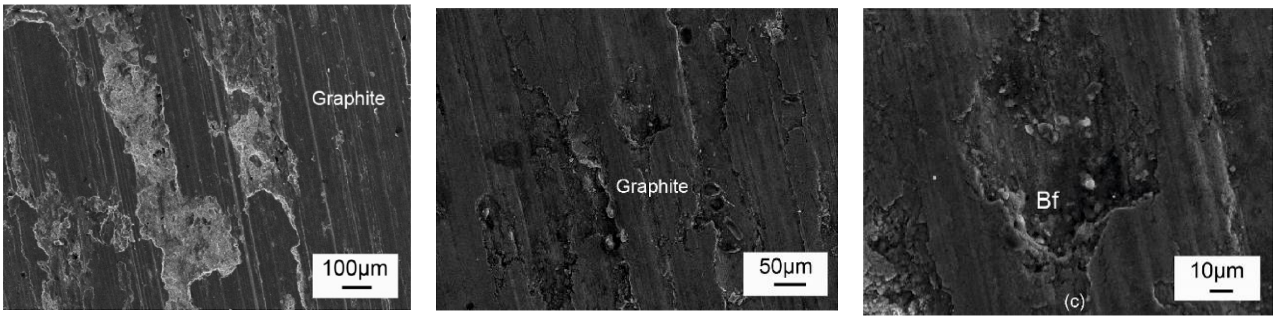

Fig.16. SEM micrographs of worn surfaces of the 2% Gr reinforced composite sample at sliding speed of 1.0 m/s and applied load of 30 N

Range of wear rate obtained in dry sliding of ZA-27/ Al_2O_3 and ZA-27/Gr composites, as well as the worn surfaces morphology, indicate mild wear regime. In that regime, wear behavior of composite was primarily controlled by the formation of tribo-layers on contact surfaces..

3. Discussion

Tribological behavior of the ZA-27 was well investigated. Zn-Al based alloys basically comprise a mixture of the two solid solutions of α and η phases, which impart load bearing and solid lubricating properties [7, 21, 25, 29]. However, the α and η phases possess poor thermal stability [26, 27] due to low melting characteristics. Accordingly, the benefits become effective under the condition of low frictional heating.

Generaly, hard ceramic particles provide increase of the elevated temperature hardness/strength of the alloy and resist the plastic flow of matrix [33]. Additionally, during the process of sliding wear, hard particles protrude on the composite contact surface causing roughness to be higher. These protruded particles bear contact loads and protect the alloy material from direct contact with the steel counter surface. Furthermore, ceramic particles act as pinning points to hold the debris particles on the wear surface resulting in their accumulation [32]. Generally, the hard phase provides protection of the alloy matrix and offers increased load bearing capacity that can lead to less wear in composite as compared to the matrix alloy.

However, tribological behavior of composites with hard second phase like Al_2O_3 and SiC represents the result of very complex mechanisms involved in wear caused by micro cracking tendency, as well as by generation and destruction of MMLs on the mating surfaces. Namely, in composite materials the dispersoid/matrix interfacial regions act as potential sites for the nucleation and propagation of micro cracks [8, 10, 11, 18, 27, 29,30]. Predominant micro cracking tendency appears at lower operating temperatures, i.e., in conditions of lower sliding speeds and pressures. This is a consequence of poor compatibility between the hard dispersoid phase and the matrix alloy [12, 17, 29, 30,31]. Wear properties deterioration of the composite at lower sliding speeds/pressures have been reported by many researchers [11, 24].

Thermal stability of composites predominates at relatively higher operating temperatures [10, 11, 24]. The higher frictional temperatures at higher level of sliding speed and load provides softer and ductile matrix to be more accommodative, supporting the dispersoid particles in position. Accordingly, suppressing micro cracking tendency, the dispersoid phase allows a more effective transfer of load between matrix and dispersoid phase and effective carrying of load. Due to that, effects of reinforcing hard particles are manifested through the reduced wear rate and higher seizure pressure of the composite over that of the matrix alloy at high sliding speeds and loads.

The presented results obtained in present tribological investigation of ZA-27/SiC and ZA-27/Al_2O_3 composites and matrix alloy, at tested sliding speeds and applied loads are consistent with the described effects of hard ceramic particle dispersion on dry sliding wear behavior of ZA-27 alloy. Namely, wear rates of ZA-27/5%SiC and ZA-27/10%SiC composites are significantly lower than that of ZA-27 matrix alloy at higher sliding speeds (0,5 and 1,0 m/s). However, at the lowest sliding speed of 0.25 m/s and at applied load results are opposite. The matrix alloy is characterized by lower level of wear rate at all applied load. This effect is a consequence of influence of the micro cracking tendency of composite. However, suppressing micro cracking tendency at higher sliding speeds and applied loads results in increase of the tribological superiority of ZA-27/SiC composites with respect to the matrix alloy.

In a case of tested ZA-27/3%Al2O3 and ZA-27/5%Al2O3 composites positive effects of reinforcement increase with sliding speed. That is result of the described better compatibility between the hard phase and the matrix alloy at higher frictional temperatures. On the contrary, for ZA-27/10%Al2O3 composite is obtained worsening of wear properties at sliding speed of 0,25 m/s, what is result of what is of influence of the micro cracking tendency. It is probably contributed by high level of Al_2O_3 particles.

In analysis of the tribological response of the ZA-27/SiC and ZA-27/Al_2O_3 composites at higher sliding speeds, besides effects of the suppressed micro cracking tendency, one needs to include the crucial role of the MMLs on the contact surfaces during the wear process. Generally, sliding wear of alloys and metals is characterized by forming a MML over the mating surface, which strongly dictates wear mechanism, i.e., the wear behavior of the materials [29–35]. Namely, formation of wear debris, fragmentation of oxide layer, transfer of materials between the contact surfaces and mixing and compaction of these constituents mechanically on the surfaces under applied load and higher frictional heating, lead to formation of MML (micro composite) during sliding wear of metals and alloys. The formation of stable transfer layer protects the mating surfaces from further direct contact. This results in the formation of mild wear situation [9, 24]. On the other hand, disintegration of the unstable transfer layer results in intimate contact between the mating surfaces with renewed adhesion, thereby leading to enhanced severity of wear. The overall stability and thickness of MML depends on the magnitude of rate of formation and rate of destruction of MML on the worn surface [33]. More severe wear conditions produce higher frictional heating, thereby facilitating a larger extent of material transfer, as well as mass fusion of the material onto the sliding surface, causing material seizure [11].

Phenomenon of the MML creation is especially prominent in contact of ceramic particle reinforced alloys and steel. Hard ceramic particles, like SiC and Al_2O_3, are significantly harder than the counter steel surface and scratch the counter surface materials. That causes generation of more counter surface debris (steel particles) that gets compacted on the specimen surfaces during sliding wear process. Additionally, the possibility of accumulation of wear debris at the valleys between protruded ceramic particles is greater in composite as compared to the alloy. As a result, larger amounts of counter surface materials get transferred and finally accommodated as MML on the composite surface as compared to that on the matrix alloy surface [33]. The extent of occurrence of the above facts increases with increase in hard particle content. The formation of mechanically mixed layers was also observed in present investigation. The SEM micrographs in Fig. 15 clearly point to the final effects of creating and destruction of those tribo-induced layers on the contact surfaces of the samples made of the ZA-27/ Al_2O_3 composites after tests performed at sliding speed of 1.0 m/s and the highest applied load. Wear rate of tested ZA-27/ Al_2O_3 and ZA-27/SiC composites in range of (0,5 – 4,5)X10^{-3} mm^3/m, as well as earlier described morphology of worn surfaces, point to the processes of mild wear, which were primarily controlled by the formation and destruction of MML. It can be seen that increasing of applied load resulted in the increased destruction of the MML, what had contributed to decreased proportion of the contact surface, which was protected with MML and increased extent of surface damage.

Graphite particles reinforcement has very positive effect on improvement anti wear properties of ZA-27 alloy (Fig. 15). The difference in the wear rate of composite with respect to the matrix alloy is very prominent at combination of the lowest level of sliding speed and normal load. This difference decreases with increase of sliding speed and normal load. Also, the positive effect of Gr particles on decreasing of wear rate is established in cases of hybrid ZA-27/SiC/Gr composites. This effect is more prominent with sliding speed reducing. Except that, wear rate decrease with increase of Gr content from 1% wt. to 5 wt. %.

Many authors have reported that during dry sliding, the metal/graphite composites tribo-influenced the graphite film forming on the tribosurface [20–22, 26, 29,30], which acts as solid lubricant that reduces metal-to-metal contact between the sliding surfaces. The formation of graphiterich lubricant film between the sliding surfaces has been explained as a result of the soft second phase (graphite) squeezing-out from the subsurface toward the mating surface due to extensive plastic deformation [20, 27].

In a view of the above, it is possible to explain the tribological behavior of tested ZA-27/graphite composite in dry sliding conditions. Namely, our tests were conducted with Al27/Gr composite containing 1 to 5wt.% of graphite at the modest sliding speeds (0.26–1.0 m/s) and applied load (10–30 N). In such conditions, the complete separation of the contact surfaces was not ensured by the self-lubricating layers leading to the increase of wear rate with increase of the sliding speed.

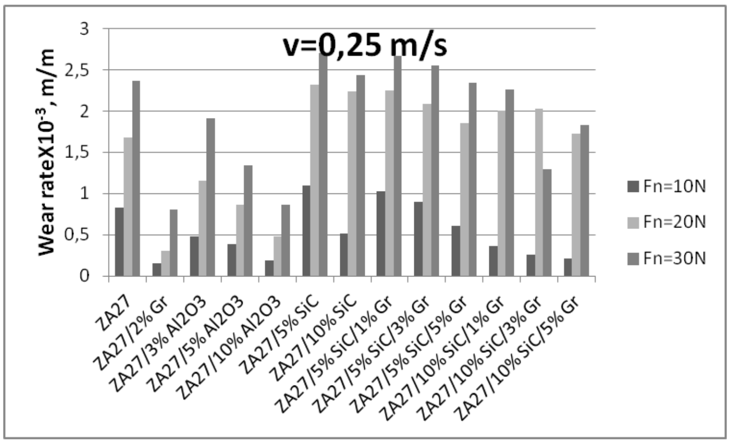

Fig. 17. Wear rate comparison of tested composites at sliding speed of 0,25 m/s for different applied loads

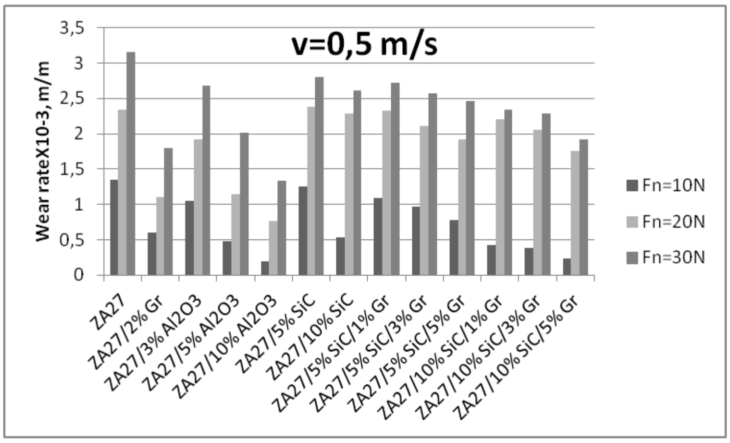

Fig 18. Wear rate comparison of tested composites at sliding speed of 0,5 m/s for different applied loads

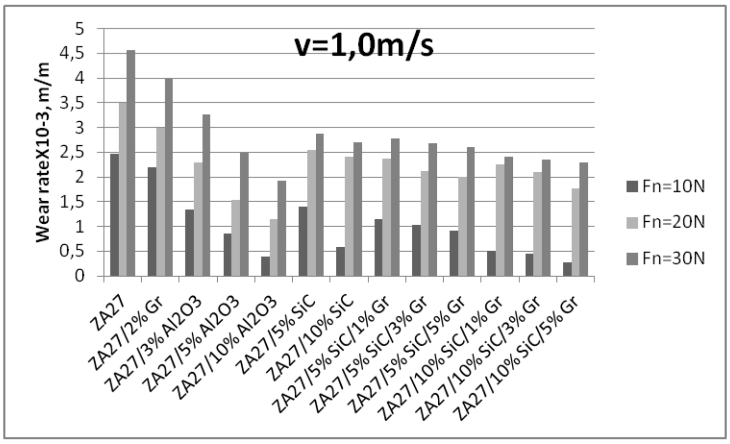

Fig. 19. Wear rate comparison of tested composites at sliding speed of 1,0 m/s for different applied loads

At the end of discussion it is important to make comparison on tribological properties between tested materials, what is expressed in Figs. 17 – 19. It is obvious that differences of wear rates for tested materials are influenced by contact conditions – sliding speed and normal load.

The results indicate that in conditions of the lowest sliding speed and normal load the superior wear behaviour correspond to the composites containing graphite particle reinforcement (ZA-27/Gr, and ZA-27/SiC/Gr composites). Also, wear rate composites (binary and hybrid) with graphite particles is the lowest at normal load of 10N for all sliding speeds, unless wear rate of ZA-27/10%Al_2O_3 composite is lowest at sliding speeds of 0,5 and 1,0 m/s. Generally, for the ZA-27/Al_2O_3 composites, the wear rate was much lowers than that of the ZA-27 matrix alloy and other tested composites at all other combinations of sliding speed and normal load. It is specially reported in a case of reinforcement with 10% of Al_2O_3 particles. The results show that SiC particle reinforcement was responsible for the good tribological properties of the binary and hybrid composites at high normal loads and sliding speeds.

4. Conclusions

The obtained results clearly indicate that reinforcement with Al_2O_3, SiC, and graphite particles could significantly improve tribological properties of ZA-27 alloy. The influence of reinforcement on wear behavior depends on type of particles and their combination (hybrid composites), content of particles and contact conditions defined by sliding speed and applied load.

Reinforcement with 2%Gr was responsible for very prominent wear rate decrease of ZA-27 alloy, but only in friction conditions of the lowest normal load, and lower sliding speeds. On the other hand, ZA-27/ Al_2O_3composites exhibit very good tribological properties in all combinations of sliding speeds and applied loads. The rate of tribological improvement increases with content of Al_2O_3particles, from 3 to 10%. The improvement of ZA-27 alloy tribological properties by adding of SiC particles corresponds to the friction conditions of higher sliding speeds and applied loads. In conditions of the lowest sliding speed ZA7/SiC composite has higher wear rates than ZA-27 alloy. The increase of SiC content contributes to decrease of ZA-27/SiC composite wear rate in all combinations of sliding speeds and applied loads. Hybrid ZA-27/SiC/Gr composites are tribologicaly superior to ZA-27/SiC composite in all tested conditions. The superiority increases with Gr content (from 1 to 5%).

The improvement in wear resistance of composites with $Al_2O_3$and SiC particles can be attributed to the changes in the wear mechanism induced by presence of hard particles. Rate of improvement was moderate at the lowest sliding speed of 0.26 m/s and applied load of 10 N, which was affected by micro cracking tendency of composite in conditions of lower friction temperatures. Suppressing micro cracking tendency at higher sliding speeds/loads has resulted in increase of the tribological superiority of composites with respect to the matrix alloy.

The positive effects of graphite reinforcement in dry sliding could be explained by formation of the graphite-rich film on the tribo-surface, which provides solid lubrication. The tribo-induced graphite films were nonuniform, because of small graphite content and modest sliding speeds and applied loads. In such conditions, the complete separation of the contact surfaces was not ensured, leading to the increase of wear rate with increase of the sliding speed and applied load.

Level of wear rate of tested composites, as well as morphology of worn surfaces, pointed to the process of mild wear, which was primarily controlled by the formation and destruction of MML.

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