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RESEARCH

Tribological Potential of Hybrid Composites Based on Zinc and Aluminium Alloys Reinforced with SiC and Graphite Particles

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A B S T R A C T

The paper reviews contemporary research in the area of hybrid composites based on zinc and aluminium alloys reinforced with SiC and graphite particles. Metal matrix composites (MMCs) based on ZA matrix are being increasingly applied as light-weight and wear resistant materials. Aluminium matrix composites with multiple reinforcements (hybrid AMCs) are finding increased applications because of improved mechanical and tribological properties and hence are better substitutes for single reinforced composites. The results of research show that the hybrid composites possess higher hardness, higher tensile strength, better wear resistance and lower coefficient of friction when compared to pure alloys.

1. INTRODUCTION

Metal matrix composites (MMCs) have attracted considerable attention recently because of their potential advantages over monolithic alloys. The MMCs are commonly reinforced with high strength, high modulus, and brittle ceramic phases, which may be in the form of fibre, whiskers, or particulates. The addition of ceramic reinforcement to a metal matrix improves strength and stiffness, but at the expense of ductility. Compared to the continuous fibre-reinforced composites, particulate-reinforced MMCs offer several advantages such as improved anisotropy, ease of fabrication, and lower cost.

Zinc–aluminium (ZA) alloys are important bearing materials, especially suitable for high-load and low-speed applications. Their main advantages are good tribo-mechanical properties, low weight, excellent foundry castability and fluidity, good machining properties, low initial cost, and environmental-friendly technology.

Good characteristics of ZA alloys have inspired researchers to reinforce them with different dispersed reinforcement materials (SiC, Al_2O_3, glass fibres, graphite and garnet) in order to obtain much more enhanced mechanical and tribological properties [1-18].

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. MMCs have attracted considerable attention recently because of their potential advantages over monolithic alloys.

Aluminium matrix composites with multiple reinforcements (hybrid AMCs) are finding increased applications because of improved mechanical and tribological properties and hence are better substitutes for single reinforced composites.

Composites with combined reinforcement of SiC and Gr particulates are referred as Al–SiC–Gr hybrid composites. Thus, use of multiple reinforcements yields aluminium matrix hybrid composites to posses better tribological properties over composites with single reinforcement. However, reported studies [19-34] have indicated that efforts are scarce on parametric studies on the tribological behaviour of aluminium matrix hybrid composites. Consequently, an attempt is made here to study the influence of % reinforcement (SiC and Gr particulates), sliding speed, load and sliding distance on the tribological behavior of Al–SiC–Gr hybrid composites.

2. COMPOSITES BASED ON ZA ALLOYS

This chapter focuses on MMCs prepared with ZA27 (zinc–aluminium 27) alloy as the matrix and SiC and graphite particles as the reinforcement.

However, their broader application is limited. One of the major limitations of conventional ZA alloys, containing 8–28 % Al, 1–3 % Cu, and 0.05 % Mg (ZA8, ZA12 and ZA27), is the deterioration of their mechanical and wear resistance properties at elevated temperatures (above 100 °C) and their dimensional instability [1-4]. Thus, recent investigations have focused attention to development of modified version of the ZA27 alloy.

In addition, heat treatment of ZA alloys is one of the possible measures for their improvement. The effects of heat treatment on the microstructure, hardness, tensile properties, and tribological behaviour of ZA27 alloy were examined in [1,3]. Tests included the heating up to 370 °C for 3 or 5 h, quenching in water, and natural aging. The friction and wear behaviour of alloys were tested in contact with steel discs using combinations of three levels of load (10, 30, and 50 N) and three levels of linear sliding speeds (0.26, 0.50, and 1.00 m/s).

2.1 ZA27/graphite composite

In recent decades, many authors have reported that graphite in zinc aluminium alloys MMCs imparts improved tribological properties of the composites. However, the properties of Zn–Al alloy/graphite particulate composites have not been studied so extensively. It was found that the mechanical properties of the ZA27 zinc–aluminium alloy/graphite particulate composites are significantly changed by varying the amount of graphite.

Tribological tests showed that addition of graphite particles to the ZA27 alloy matrix improved the wear resistance of the composite, in spite of the significant decrease in hardness [5,6].

Wear behaviour of tested ZA27/graphite composite samples in lubricated and dry sliding conditions is illustrated in Fig. 1 (a and b) on the example of wear curves obtained in tests with 0.5 m/s of sliding speed for varying applied loads [2,4].

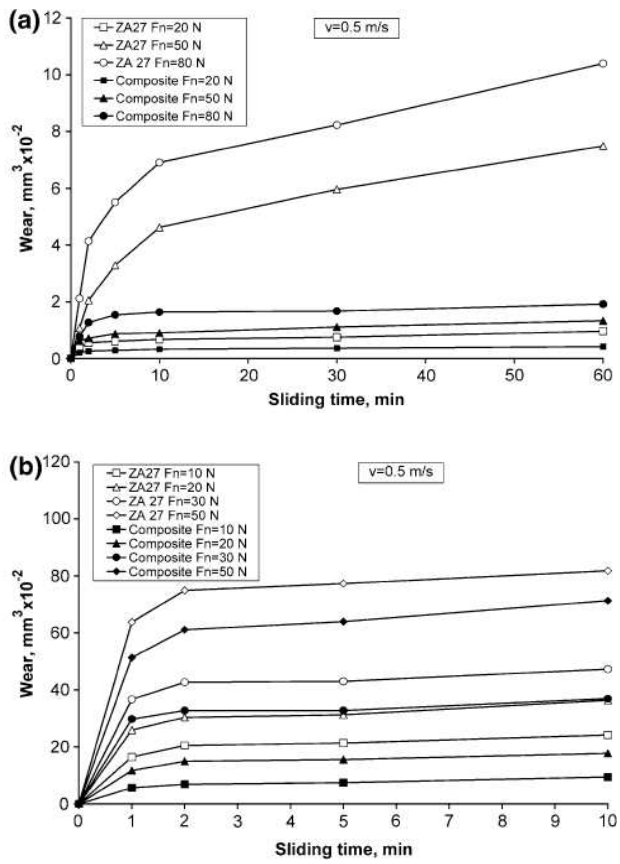

Fig. 1. Wear curves of tested materials; a) Lubricated sliding, b) Dry sliding [2,4].

It could be noticed that wear of the composites with addition of the graphite particles is always significantly lower compare to the matrix ZA27 alloy.

Figure 2 shows the wear rate of the tested materials as a function of applied load at different sliding speeds during lubricated sliding (a) and dry sliding (b) [2,4].

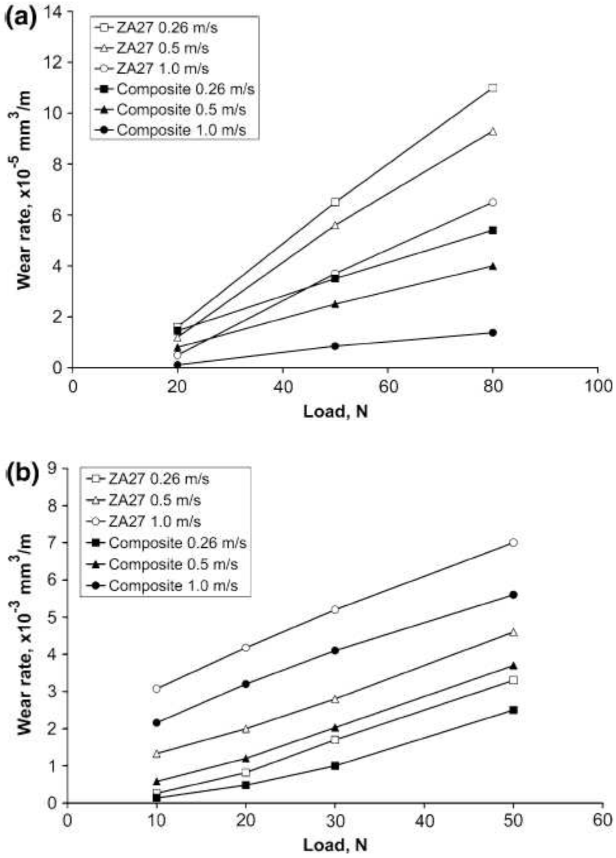

Fig. 2. Wear volume vs. applied load; a) Lubricated sliding, b) Dry sliding [2,4].

The effect of sliding speed on the wear rate of the composite, as well as the matrix alloy specimens at different applied loads is presented in Fig. 3 [2,4].

The graphite particle reinforcing influenced significant tribological improvement of ZA27 matrix material. This improvement in conditions of dry sliding could be explained by tribo-influenced graphite film formation and its effect on friction and friction reduction. In conditions of lubricated sliding the positive tribological effects of graphite can be attributed to its influence on tribological characteristics of lubricating oil.

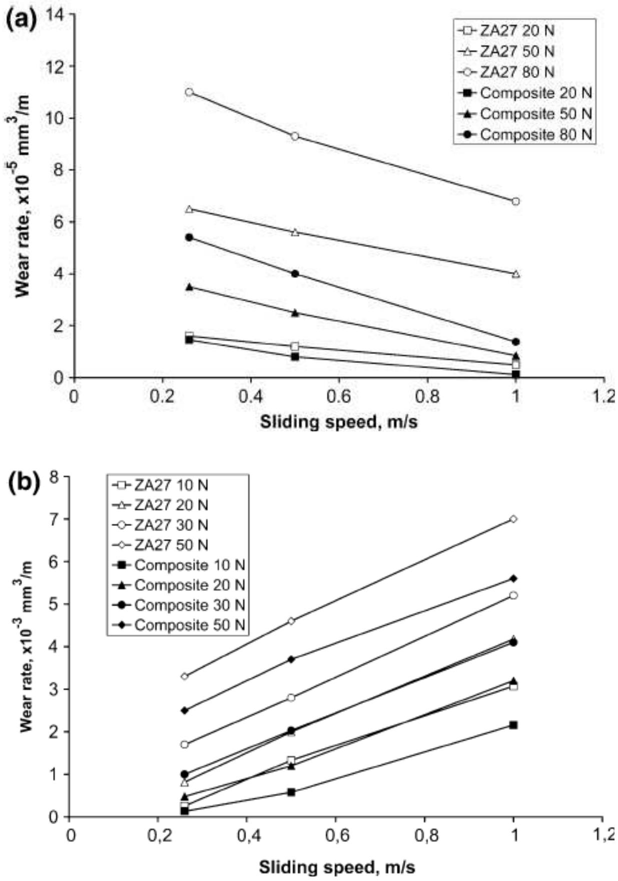

Fig. 3. Wear curves of tested materials; a) Lubricated sliding, b) Dry sliding [2, 4].

In [7,8], the effect of macroscopic graphite particles on damping behaviour of ZA27 alloy composites is investigated. ZA27 based MMCs have been prepared by the compo casting method with 0 %, 4 %, 6 % and 8 % of graphite particulate reinforcement. The damping behaviour, storage modulus and loss modulus of composite specimens are studied with varying percentages of graphite particulate, reinforced composites over a temperature range of 30–300 °C using a Dynamic Mechanical Analyzer.

2.2 ZA27/SiC composite

The SiC-reinforced composites exhibit reduced wear rate when compared to unreinforced ZA27 alloy specimens during dry lubricated [9] and lubricated sliding [10], Fig. 4. The wear rate decreased with increasing SiC content. The positive effect of silicon carbide toward improvement of the tribological behaviour of the ZA27 alloy was confirmed by Sharma et al. [9]. In mentioned research, the percentage of SiC was varied from 1-5 % in steps of 2 % by weight.

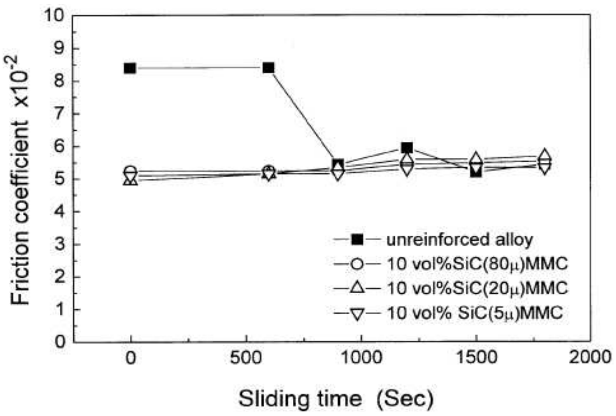

Fig. 4. Friction coefficient *vs* sliding time for unreinforced ZA27 alloy and MMCs containing SiC particles of various sizes [10].

Also, reinforcement with SiC particles improved the abrasive wear response of matrix zinc-based alloys [11-13], Fig. 5. It has been noticed that the presence of SiC particles in ZA alloys leads to a substantial improvement in elastic modulus and hardness. Also, the wear resistance of ZA27 alloy is improved significantly by the alumina fibre reinforcement.

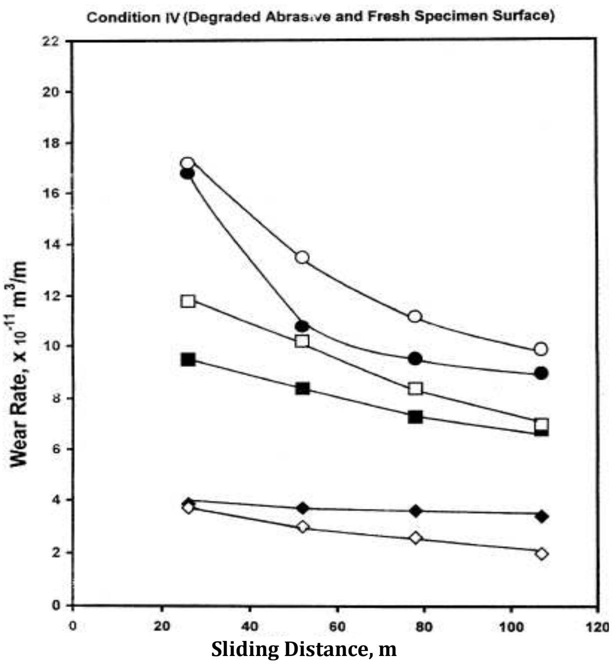

Fig. 5. Wear rate of the specimens as a function of sliding distance at various applied loads in experimental condition (open symbols: composite; closed symbols: matrix alloy, ♦: 1 N, ■: 3 N, ▲: 5 N, ●: 7 N [13].

According to Ranganath et al. [14], wear rate increases monotonically with load and decreases with an increase in wear speed.

Generally, the speed of forming of the protective tribolayers is directly dependent on the sliding speed, contact loads, and on the graphite content in the composite.

Prasad [13] conducted lubricated pin-on-disk wear test of zinc-based alloy reinforced with SiC particles and examined the effect of different amounts of graphite on tribological characteristics of lubricating oil in conditions of boundary lubrication. He prepared the series of SAE 40/graphite mixtures by mixing the graphite particles of 50 – 100 lm size in varying concentrations, ranging from 0 to 10 wt%. He found that positive effects of graphite additions to the lubricating oil, in decreasing the friction coefficient of tested composite in boundary lubrication, could be realized with the lower concentration of graphite (up to 4 wt%). The higher concentration of graphite in the lubricant mixture caused the reversed trend.

3. HYBRID COMPOSITES BASED ON ALUMINIUM ALLOYS

Hybrid composites represent the merging of two philosophies in tribological material design: hard particle reinforcement, for example by carbide particles; and soft particle reinforcement (and consequent lubrication), for example by graphite powder [33].

The tribological behaviour of self-lubricated aluminium/SiC/graphite hybrid composites with various amount of graphite addition synthesized by the semi-solid powder densification method has been studied by Ted Guo and Tsao [19]. Mixtures of 6061 aluminium powder (average powder size: 30 mm), SiC powder (average powder size: 45 mm) of 10 vol.%, and graphite powder (average powder size: 8 mm) of 2, 5 and 8 vol.% were investigated. Mechanical characteristics (hardness, coefficient of thermal expansion and fracture toughness) of tested materials decreased with the increase of graphite content.

The tribological tests lasts for 5 min under dry sliding condition, constant of 0.094 MPa and sliding speed of 1.09 m/s. The authors found that the seizure phenomenon which occurred with a monolithic aluminium alloy did not occur with the hybrid composites. The amount of graphite released on the wear surface increases as the graphite content increases, which reduces the friction coefficient, Fig. 6.

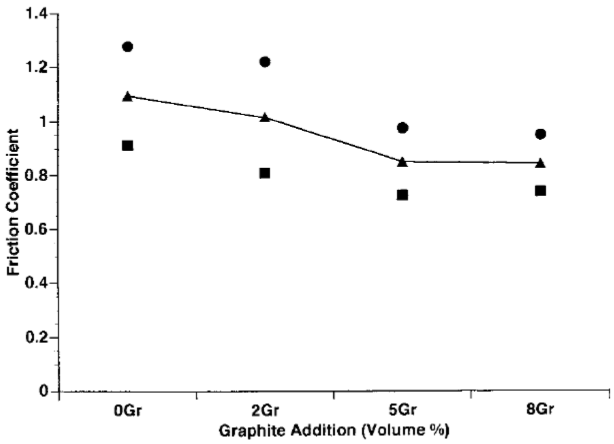

Fig. 6. Variations of friction coefficient with the percentage of graphite addition [19].

Authors also concluded that wear becomes more stable, and wear debris particles become smaller as the graphite content increases, Fig. 7.

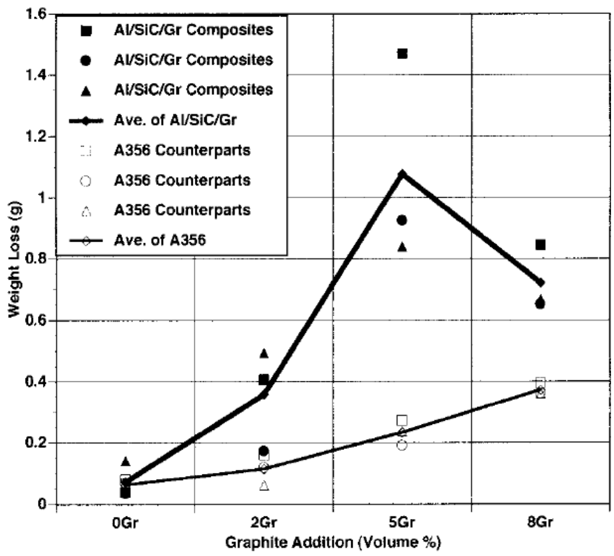

Fig. 7. Weight loss of the composites and the counterparts for various graphite additions [19].

Basavarajappa et al. [20-22] investigated dry sliding wear behaviour of as cast aluminium alloy 2219, composite with SiC particles and composite with SiC particles and graphite. The composites were produced using the liquid metallurgy technique. SiC reinforcement content was 10 wt.% and average particle size of 25 μm for both composites, while the graphite content in the second composite was 3 wt.% and the average particle size of 45 μm.

The tribological tests were conducted with the load ranging from 10 to 40 N at a sliding speed of 1.53, 3, 4.6 and 6.1 m/s with a constant sliding distance of 5000 m.

It was found that the addition of SiC particles increases the wear resistance of the composites comparing to the matrix alloy. The wear resistance increase further with the composite containing SiC particles and graphite. The wear rate of the tested materials increased with increase of the sliding speed but for the both composite that increase was not as drastic as for matrix alloy, and yet the composite containing SiC and graphite showed the lowest increase, Fig. 8.

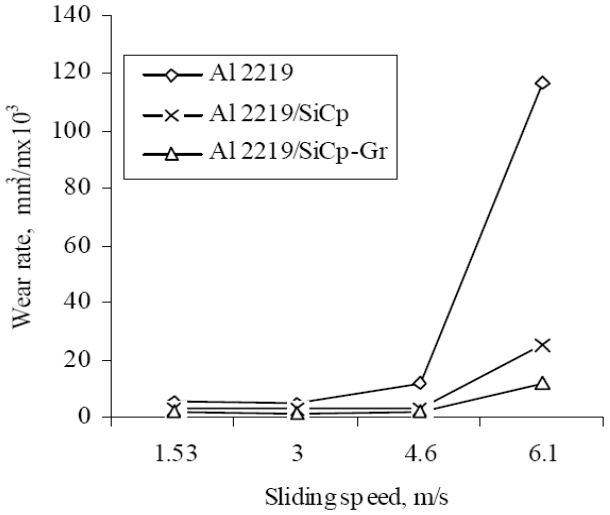

Fig. 8. The wear rate variation with sliding speed for both composites and its matrix alloy [20-22].

Variation of wear rate with applied load for different composites and sliding speed of 3 m/s and sliding distance of 5000 m is presented in Fig. 9.

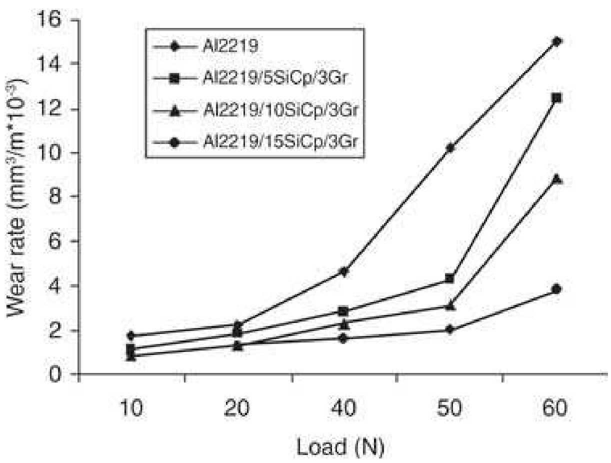

Fig. 9. Variation of wear rate with applied load at a sliding speed of 3 m/s for a sliding distance of 5000 m [20-22].

Few investigations S. Suresha, BK. Sridhara [23-25] have been reported on the tribological behaviour of these composites with reinforcement percent above 10 %. This study focuses on the influence of addition of graphite (Gr) particulates as a second reinforcement on the tribological behaviour of aluminium matrix composites reinforced with silicon carbide (SiC) particulates (Fig. 10). Dry sliding wear tests have been performed to study the influence of Gr particulates, load, sliding speed and sliding distance on the wear of hybrid composite specimens with combined % reinforcement of 2.5 %, 5 %, 7.5 % and 10 % with equal weight % of SiC and Gr particulates. Experiments are also conducted on composites with reinforcement percent of SiC similar to hybrid composites for the sake of comparison. Load and sliding distance show a positive influence on wear implying increase of wear with increase of either load or sliding distance or both.

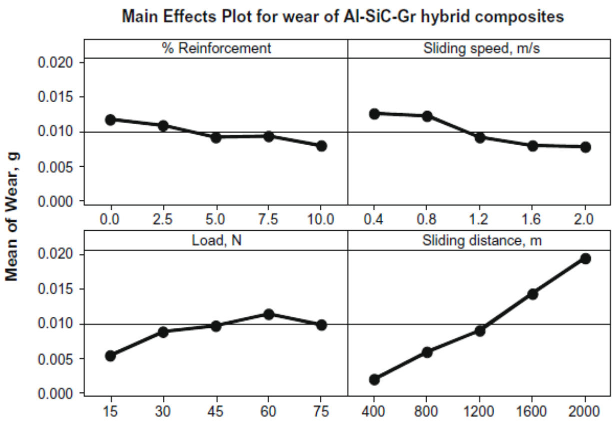

Fig. 10. Main effect plot of effect of factors on wear of Al-SiC-Gr hybrid composites [23-25].

Sliding speed shows a negative influence on wear indicating decrease of wear with increase of speed. Interactions among load, sliding speed and sliding distance are noticed in hybrid composites and this may be attributed to the addition of Gr particulates. Such interactions are not present in composite reinforced with SiC alone.

Authors A.R Riahi, A.T Alpas [26], provide a systematic investigation of the role played by the tribo-layers that form on the contact surfaces during the sliding wear of graphitic cast aluminium matrix composites. The graphitic composites include A356 Al–10 % SiC–4 % Gr that are being developed for cylinder liner applications in cast aluminium engine blocks. It was shown that because of the thicker and more stable tribo-layers on the contact surfaces of graphitic composites, than that of non-graphitic composites and the A356 Al alloy, the graphitic composites displayed a transition from mild-to-severe wear at load and sliding speed combinations, which were considerably higher than those of the A356 aluminium alloy and the non-graphitic A356 Al–20 % SiC composite (Fig. 11). A negative effect of the hard constituents in the tribo-layers was the scuffing damage that they inflicted on the counterface.

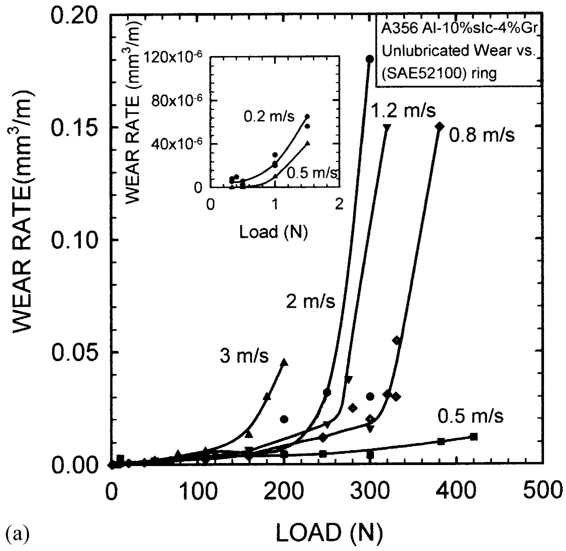

Fig. 11. Wear volume vs. applied load [26].

The 40%SiC/5%Gr/Al composites with various-sizes graphite addition fabricated by squeeze casting technology and their friction and wear properties were investigated by Leng et al. in [27-29]. Results showed that, after the addition of graphite, the friction coefficient of composites decreased and the wear resistance increased by 170 to 340 times (Fig. 12). In addition, wear resistance was improved with in-creasing of graphite particle size, which is attributed to the enhancement of integrity of lubrication tribo-layer composed of a complex mixture of iron oxides, graphite as well as fractured SiC particles and some fine particles containing aluminium.

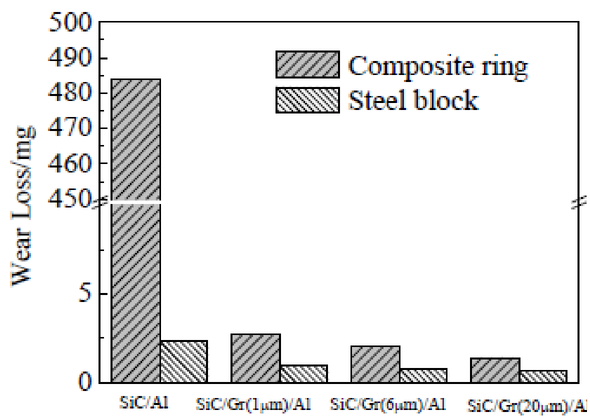

Fig. 12. Wear loss of the composites and counterfaces of wear process for SiC/Al and SiC/Gr/Al [27-29].

The wear behaviour of A356 aluminium alloy matrix composites reinforced with 20 % SiC particles and 3 or 10 % graphite was investigated by Ames, Alpas [30]. The wear tests were performed using a block-on-ring (SAE 52100 steel) wear machine under dry sliding conditions within a load range of 1 to 441 N. The wear resistance of 3 % graphite-20 % SiC-A356 hybrid composite was comparable to 20 % SiC-A356 without graphite at low and medium loads. At loads below 20 N, both hybrid and 20 % SiC-A356 composites without graphite demonstrated wear rates up to 10 times lower than the unreinforced A356 alloy due to the load-carrying capacity of SiC particles. The wear resistance of 3 % graphite 20 % SiC-A356 was 1 to 2 times higher than 10 % graphite-containing hybrid composites at high loads. However, graphite addition reduced the counterface wear. The unreinforced A356 and 20 % SiC-A356 showed a transition from mild to severe wear at 95 N and 225 N, respectively. Hybrid composites with 3 % and 10 % graphite did not show such a transition over the entire load range, indicating that graphite improved the seizure resistance of the composites.

In study [31], Mahdavi applied a new method, namely In situ Powder Metallurgy (IPM) for the preparation of Al6061/SiC/Gr hybrid composites. By this method, the stir casting and the powder metallurgy synthesizing processes are combined into an integrated net shape forming process. 0–40 vol.% of SiC particles with an average size of 19 lm, along with 9 vol.% of uncoated Gr particles, were introduced to the molten 6061 aluminium alloy. The best wear resistance is achieved in the hybrid composite containing 20 vol.% SiC particles.

Effect of the SiC content on the volume loss and the wear rate of 9 vol.% Gr contained composites and unreinforced aluminium alloy is shown in Figure 13. It is seen that the dry sliding volume loss of all hybrid composites is lower than that of the base alloy. However, the volume loss and the wear rate of Al–9 vol.% Gr composite in higher than that of the base alloy and the hybrid composites.

Figure 13 eveals that the volume loss and the wear rate of hybrid composites are decreased by increasing the SiC content to 20 vol.%, and after that any increase in SiC content leads to their increases. The wear rate of the hybrid composite containing 20 vol.% SiC particles is about eight times lower than that of the base alloy sample.

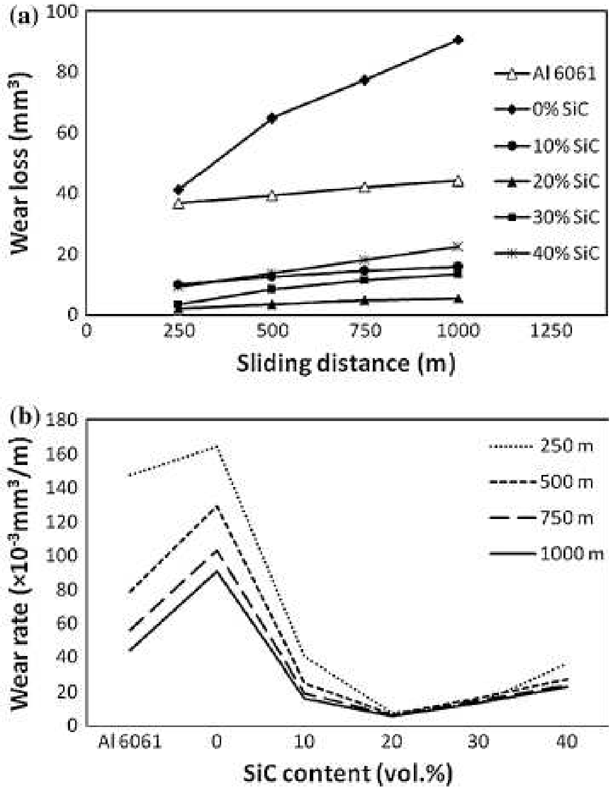

Fig. 13. The variation of a wear loss with a)sliding distance and b) wear rate with SiC content for the hybrid composites containing 9 vol.% Gr particles [31].

Tribological investigation of these materials was just an initial one, with preliminary results and some more experiments to be done to completely understand their tribological behaviour. In order to achieve a higher confidence level in evaluating test results, three to four replicate tests were run for all the tested materials, Vencl et al. [32,33]. Obtained average values of the wear testing are presented in Fig. 14. The highest value showed A356 aluminium alloy, then composite C1 (with Al2O3 particles), composite C2 (with SiC particles), and composite C3 showed the lowest wear (with SiC and graphite particles). These results are in correlation with the hardness values of the tested materials, except for the composite C3. The A356 aluminium alloys showed lower wear than it could be expected since it was not reinforced. Wear resistance of as cast A356 aluminium alloy is affected by silicon particles in the form of sticks that were created as a result of eutectic reaction during the alloy solidification.

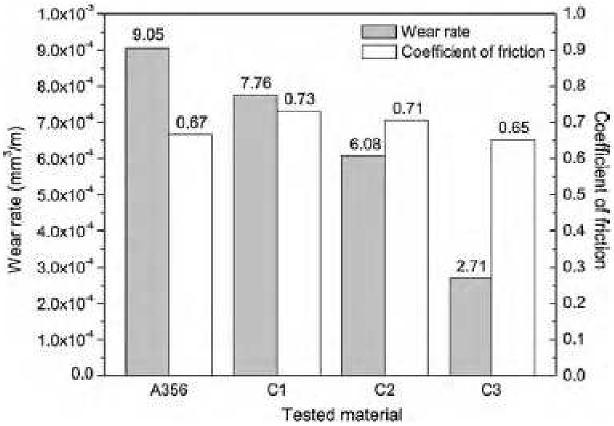

Fig. 14. Wear rate and coefficient of friction values of heat treated (T6) A356 aluminium alloy, composite C1(with 10 wt% Al_2O_3 particles), composite C2 (with 10 wt% SiC particles), and composite C3 (with 10 wt% SiC and 1 wt% graphite particles) [32,33].

4. CONCLUSION

Among the zinc-based foundry alloys, the zinc-aluminium (ZA) family of alloys has been used increasingly in past decades.

Interest for extending the practical application of zinc aluminium alloys is based on tribological, economical, and ecological reasons. These alloys are relatively cheap and can be processed efficiently with low energy consumption, without endangering the environment.

According to reviewed research, application of hybrid composites based on zinc and aluminium alloys reinforced with SiC and graphite particles will provide better tribological behaviour.

A combination of good properties, low cost and high workability has made them attractive for many applications.

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