Serbian Tribology Society

SERBIATRIB '17

15th International Conference on Tribology

Faculty of Engineering University of Kragujevac

Kragujevac, Serbia, 17 – 19 May 2017

A REVIEW ON TRIBOLOGICAL PROPERTIES OF MICROCOMPOSITES WITH ZA-27 ALLOY MATRIX

Filip VUČETIĆ[1,]*, Sandra VELIČKOVIĆ[2], Aleksandar MILIVOJEVIĆ[3], Aleksandar VENCL[3]

[1]University of Belgrade, Innovation Center of the Faculty of Mechanical Engineering in Belgrade, Belgrade, Serbia

[2]University of Kragujevac, Faculty of Engineering, Kragujevac, Serbia

[3]University of Belgrade, Faculty of Mechanical Engineering, Belgrade, Serbia

*Corresponding author: fvucetic@mas.bg.ac.rs

Abstract: *Manufacturing and testing of novel composite materials are one of the topics that had caught attention of many researchers. There are a vast number of possibilities for improving many characteristics of the base (matrix) material significantly with addition of relatively small amounts of different material to the matrix. This paper should give an overview on tribological properties of microcomposites with ZA-27 alloy as a matrix material. Following characteristics were taken into consideration in the process of making this overview: type, amount and size of reinforcement; manufacturing process; apparatus used for testing; and test parameters and conditions.*

Keywords: *ZA-27, microcomposites, manufacturing process, friction, wear.*

1. INTRODUCTION

Zinc-aluminium (ZA) alloys are materials well known for their good physical and mechanical properties, high corrosion resistance in atmospheric conditions, excellent casting properties, easy machining, and good tribological properties [1-7]. They have become a good, cost effective substitute for conventional materials such as bronzes, aluminium alloys and cast irons [1,5-11].

One of the most frequently used member of ZA alloy family is ZA-27 casting alloy with 25 – 28 wt. % Al, 2 – 2.5 wt. % Cu, and 0.01 – 0.02 wt. % Mg. It has been often used in applications intended for high load and low to moderate speed applications, especially for sliding bearings [4-8,10,11]. Due to its overall good properties, ZA-27 alloy has been interesting in past decades by many researchers. In order to obtain better mechanical and tribological properties, ZA-27 alloy was used for development of metal matrix composites (MMC). Improvement of these properties of ZA-27 composites was made by adding suitable amounts of improvers and reinforcements. In the case when two or more reinforcements are added to the matrix material a hybrid composite is produced.

This paper gives the overview of tribological properties of ZA-27 microcomposites with respect to the equipment used for testing, amount, type and size of reinforcements, manufacturing process, and test parameters (load, sliding speed and sliding distance) and conditions (dry or lubricated). Erosion test investigations, in situ manufactured ZA-27 microcomposites, and high temperature tribological investigations were not taken in consideration in this overview.

2. MANUFACTURING PROCESS

Production of metal matrix composites with casting techniques presents quite a challenge from the aspect of reinforcement material distribution in the matrix and thus obtaining desired properties. Difficulties emerge from the fact that reinforcement distribution in the melt is hard to control due to many factors, such as: properties of the reinforcement, viscosity of the slurry, wettability, effectiveness of agglomerates breaking with mixing, entrapped gas, etc. [12].

Most common production processes of ZA-27 microcomposites can be broadly divided in two groups:

- liquid state processes, which include different casting processes such as stir casting, centrifugal casting and ultrasound enhanced casting;
- semisolid process, i.e. compocasting.

Within these two groups, stir casting and compocasting processes are the most often used, i.e. in approximately 90 % of the reviewed papers [13-31]. Stir casting represents a process very similar to the conventional casting. The difference is that the stirring of the melt is introduced in order to obtain better distribution of the reinforcement in the matrix. Reinforcement in this process is infiltrated into the overheated melt of the matrix. Compocasting method is similar to the stir casting and the main difference is that the matrix is not in liquid state, but in semisolid [32].

On the other hand, there are much less publications for other mentioned processes. Centrifugal casting [21] was done on the machine consisting of a rotation system and a mould fixed on the centrifugal casting equipment; unidirectional solidification is enforced by the unidirectional heat transfer through the mould. Exposing melt to the ultrasound [24], and the cavitation effect that it induces is used to refine the grain size of the matrix during solidification. High intensity of ultrasound also introduces agitation of the melt which can, in combination with cavitation effect, give a better distribution of reinforcement.

Reinforcements in the form of particles have been used in almost all the cases with ZA-27 microcomposites. This can be explained by cost effectiveness of particles when compared to other types of reinforcements. The most frequently used reinforcements were hard particles, such as Al_2O_3, SiC and minerals, followed by graphite (Gr), fly ash, etc. There are also cases when two reinforcements were used to obtain hybrid microcomposites; besides SiC and Gr, there are also hybrid microcomposites with various of different weight percents combinations of Al_2O_3 and fly ash on one side and Al_2O_3 and Gr on the other.

Amount of reinforcement varied and it was usually up to 10 wt. %. Differences in particle sizes are also significant. Minimum and maximum particle size along with minimum and maximum weight percent of each reinforcement is given in Table 1.

Table 1. Reinforcement amount and size ranges in ZA-27 microcomposites

Reinforcement	Amount [wt. %], min – max	Size [µm], min – max
SiC	1 – 15	5 – 80
Al_2O_3	3 – 25	10 – 250
Graphite	1 – 5	25 – 150
Other	1 – 20	4 – 70

3. TRIBOLOGICAL PROPERTIES OF ZA-27 MICROCOMPOSITES

Great number of factors influencing the tribological properties of microcomposites makes the comparison between different studies and examinations difficult, and in some cases even impossible. Only the studies with ZA-27 alloy matrix are reviewed and presented in Table 2, through the influencing factors such as: manufacturing processes, type, amount and size of reinforcement, test apparatus (type of contact) and testing parameters (load, sliding speed and sliding distance), and test conditions (unlubricated or lubricated).

Table 2. Tribological properties of ZA-27 microcomposites with influencing factors

Manufacturing processes	Compocasting			
Reference	Ranganath et al. [15]	Babic et al. [16]	Babic et al. [18]	Sharma et al. [19]
Apparatus	Pin-on-disc	Block-on-disc	Block-on-disc	Pin-on-disc
Reinforcement	Garnet	Al_2O_3	Graphite (Gr)	Zircon ($ZrSiO_4$)
Amount of reinforcement	2, 4 and 6 wt. %	3, 5 and 10 wt. %	2 wt. %	1, 3 and 5 wt. %
Size of reinforcement	30 – 50 µm	220 µm	30 µm	30 – 50 µm
Counter-body material	Steel EN24	Steel 30CrNiMo8 (55 HRC)	Steel 30CrNiMo8 (55 HRC)	Steel EN24 (57 HRC)
Sliding speed	7.35 – 31.5 m/s	0.26, 0.5 and 1 m/s	0.26, 0.5 and 1 m/s	1.86 m/s
Load	20, 30, 40 and 50 N	20, 50 and 80 N	10 – 50 N (dry); 20 – 80 N (lubricated)	20, 40, 60, 80, 100 and 120 N
Sliding distance	2 km	1 km	0.5 km (dry); 1 km (lubricated)	0.5 – 2.5 km
Test conditions	Dry sliding	Lubricated sliding (ISO VG 46)	Dry and lubricated sliding (ISO VG 46)	Dry sliding
Coefficient of friction	/	0.04 – 0.13	0.2 – 0.48 (dry); 0.018 – 0.05 (lubricated)	/
Wear	1 – 47 × 10^{-3} mm^3/m	0.01 – 0.74 × 10^{-3} mm^3/m	0.2 – 6.8 × 10^{-3} mm^3/m (dry); 0.2 – 11 × 10^{-5} mm^3/m (lubricated)	1.8 – 16.2 × 10^{-3} mm^3/m

Manufacturing processes	Compocasting			
Reference	Almomani et al. [20]	Mitrović et al. [25]	Sharma et al. [26]	Mitrović et al. [29]
Apparatus	Pin-on-disc	Block-on-disc	Pin-on-disc	Ball-on-block
Reinforcement	Fly ash; Al_2O_3; fly ash + Al_2O_3	SiC + graphite (Gr)	Short glass fibres	Al_2O_3
Amount of reinforcement	2, 4 and 6 wt. %; 2, 4 and 6 wt. %; every combination of previous wt. %	5 wt. % SiC + 1 wt. % Gr	1, 3 and 5 wt. %	3, 5 and 10 wt. %
Size of reinforcement	44 µm (fly ash); 10 µm (Al_2O_3)	/	4 – 6 × 400 – 600 µm	250 µm
Counter-body material	Stainless steel (644 HV)	Steel 90MnV8 (62 HRC)	Steel EN24 (57 HRC)	Steel ball
Sliding speed	0.314 m/s	0.25, 0.5 and 1 m/s	1.86 m/s	10, 20 and 30 mm/s
Load	70 N	10, 20 and 30 N	20, 40, 60, 80, 100, 120 and 140 N	10, 50 and 100 mN
Sliding distance	95 – 565 m	30, 60, 90, 150 and 300 m	0.5, 1, 1.5, 2 and 2.5 km	Reciprocating motion
Test conditions	Dry sliding	Dry sliding	Dry sliding	Dry sliding
Coefficient of friction	/	/	/	0.075 – 0.48
Wear	0.2 – 6.8 × 10^{-3} mm^3/m	0.59 – 4.34 × 10^{-3} mm^3/m	1.6 – 15.6 × 10^{-3} mm^3/m	/

Table 2. *Continued*

Manufacturing processes	Compocasting		Ultrasound enhanced casting	Centrifugal casting
Reference	Mitrović et al. [30]	Mitrović et al. [31]	Tjong and Chen [21]	Jyothi et al. [24]
Apparatus	Block-on-disc	Pin-on-disc	Block-on-disc	Pin-on-disc
Reinforcement	Al_2O_3	Fly ash	SiC	Al_2O_3
Amount of reinforcement	3.5 and 10 wt. %	1, 2 and 3 wt. %	5, 10 and 15 wt. %	5, 10, 15, 20 and 25 wt. %
Size of reinforcement	12 and 250 µm	3 – 5 µm	5, 20 and 80 µm	20, 40, 60, 80 and 100 µm
Counter-body material	Steel 30CrNiMo8 (55 HRC)	Steel	Steel GR15 (60 HRC)	Steel
Sliding speed	0.26, 0.5 and 1 m/s	1.56 m/s	0.47 m/s	100 – 500 rpm
Load	20, 50 and 80 N	20, 40, 60, 80, 100 and 120 N	294, 588 and 882 N	10, 20, 30, 40 and 50 N
Sliding distance	156, 300 and 600 m (dry); 936, 1800 and 3600 m (lubricated)	0.5, 1, 1.5, 2 and 2.5 km	846 m	1 km
Test conditions	Dry and lubricated sliding	Dry sliding	Lubricated sliding (SAE 20)	Dry sliding
Coefficient of friction	/	/	0.05 – 0.085	/
Wear	0.36 – 3.62 mm (wear scar width)	$3 – 18 \times 10^{-3}$ mm^3/m	$1.18 – 56.7\ mm^3/m$	$0.23 – 0.57 \times 10^{-3}$ mm^3/m

Manufacturing processes	Stir casting			
Reference	Auras and Schvezov [23]	Joshi et al. [13]	Prasanna Kumar et al. [14]	Sharma et al. [17]
Apparatus	Pin-on-disc	Pin-on-disc	Pin-on-disc	Real bearings
Reinforcement	SiC	Al_2O_3 + graphite (Gr)	Garnet	Graphite (Gr)
Amount of reinforcement	8 and 16 wt. %	3, 6 and 9 wt. % Al_2O_3 each with 3 wt. % Gr	5, 10, 15 and 20 wt. %	1, 3 and 5 wt. %
Size of reinforcement	4.2 – 6.3 µm	/	50 – 70 µm	80 – 120 µm
Counter-body material	Steel (27 HRC)	Steel	Steel EN24 (57 HRC)	Steel EN24 (58 – 60 HRC)
Sliding speed	2 m/s	1, 2, 3, 4 and 5 m/s	1.25 – 3.65 m/s	0.019 m/s
Load	30, 50 and 80 N	10, 20, 30, 40 and 50 N	50, 100, 150 and 200 N	98, 196, 294, 392 and 490 N
Sliding distance	7.2 km	200, 400, 800 and 1000 m	1.19 – 2.8 km	7.2 km
Test conditions	Dry and lubricated sliding	Dry sliding	Dry sliding	Dry, semidry and lubricated sliding (SAE 10)
Coefficient of friction	/	/	0.25 – 0.7	0.13 – 0.45 (dry); 0.035 – 0.175 (semidry); 0.022 – 0.085 (lubrica.)
Wear	$2 – 82 \times 10^{-3}\ mm^3/m$ (dry); $0.15 – 3.6 \times 10^{-5}$ mm^3/m (lubricated)	10 – 340 mg	0.3 – 26 mg	/

Pin-on-disc tribometer was used more than all other testing apparatus, so the type of contact in most of the studies was conformal (surface) contact, which indicates the possible applications of these microcomposites (Fig. 1). It is followed by block-on-disc with non-conformal (line) contact. Since the contact area in line contact is much smaller than in the case of pin-on-disc, there is always a potential danger of conducting tests on a region without reinforcement (depending on the distribution of reinforcement on the surface).

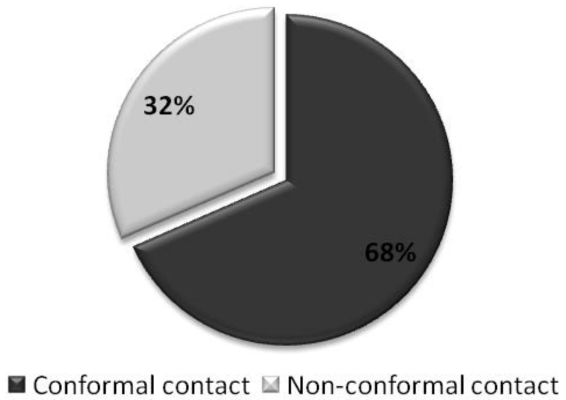

Figure 1. Share of contact types in tribological tests of ZA-27 microcomposites

As for test conditions, unlubricated (dry) sliding conditions are present in 70 % of the studies; the rest was in lubricated sliding conditions. Some of the authors conducted tests in both dry and lubricated conditions in order to obtain better insight in tribological behaviour of their microcomposites. Since the environment (temperature, humidity, surrounding medium) was usually not stated, it is taken under the assumption that tests were conducted at room temperature in air, with standard humidity.

3.1 Coefficient of friction

The coefficient of friction was not studied in all of the reviewed papers. There are only several papers with investigations of coefficient of friction, which is insufficient to understand the tribological behaviour of ZA-27 microcomposites properly. Nevertheless, some regularities could be observed.

Results of dry sliding friction were easier to compare since the influence of normal load and sliding speed is less pronounced. Coefficient of friction varies from 0.13 to 0.7, with an exception of 0.075 which was the lowest coefficient of friction value recorded in the paper of Mitrović et al. [29] on nanotribometer. With the increase of normal load the coefficient of friction increased in all cases [14,17,18,29]. Influence of sliding speed on coefficient of friction can be seen only in one paper [18], where the increase of speed lowered the coefficient of friction. Generally, lower friction was observed in microcomposites when compared to the coefficient of friction of the matrix itself, which indicates the positive effect of reinforcement addition on friction in dry sliding conditions. In case when the graphite was added to the microcomposites [17,18], it smeared on the surface and enabled the decreased probability of direct metal-to-metal contact and thus reducing the coefficient of friction. Effect of coefficient of friction decrease with addition of hard particles such as garnet [14] and alumina [29] was not elaborated by the authors.

There are also several results of friction investigations in lubricated sliding condition. Variation of coefficient of friction values is between 0.018 and 0.13. Here, the normal load and siding speed variations have significant influence on the coefficient of friction value. The increase of normal load also increases the coefficient of friction [16-18]. Tjong and Chen [21] had varied three different loads but only presented the results of coefficient of friction under the highest load. Higher speeds gave lower friction in all cases. Reinforcement addition had favourable effect on friction [17,18], as well as the adverse effect [16]. This can be explained with difference in reinforcement type, i.e. graphite particles provided solid lubrication by forming the graphite-rich film on the surface [17,18] which lowered the coefficient of friction. Increased level of coefficient of friction of microcomposites over that of the matrix alloy in study conducted by Babic et al. [16] was attributed to two-body and three-body abrasive action caused by Al_2O_3 particles of reinforcement.

3.2 Wear

Different authors have led investigations under different test parameters which makes comparison of their results very difficult. In addition, wear values were not always presented in the same way. Increase of load raised the wear value in almost all of the analyzed studies (in dry and lubricated sliding conditions) [13-16,18,19,21,22,25-28,30,31], with exception in the work of Auras et al. [23], who reported ambivalent behaviour of microcomposites with increasing of the load under lubricated sliding condition. There was no clear rule for the influence of the sliding speed on wear of microcomposites. Higher sliding speed in dry sliding conditions in some cases raised wear [14,15,18,25,28,30,31], but also in some other cases lowered it [22,27]. As for lubricated sliding, higher sliding speed sometimes increases wear [16], but also sometimes decreases it [18,30].

Increase of the reinforcement amount was beneficial to wear resistance of the ZA-27 microcomposites in all studies [13-16,18-28,30]. Table 3 shows the increase of wear resistance for each study and type of reinforcement. Highest amount of reinforcement in each investigation was the one with the best contribution to wear resistance of the matrix, so the wear resistance increase values in Table 3 were calculated for maximum amount of reinforcement with consideration of variations of test parameters in each investigation (that is if variations exist). For instance, if the investigation was done under two different sliding speeds and two different loads, maximum and minimum increase of wear resistance was picked out of four that were calculated for maximum amount of reinforcement under:

- lowest sliding speed with minimum and maximum load (two percentages); and
- highest sliding speed with minimum and maximum load (two percentages).

Addition of hard particles such as oxides, carbides and minerals improve wear resistance significantly. Hard phases provide protection of the ZA-27 alloy matrix of direct contact which leads to less wear in composite as compared to the matrix alloy, but can cause higher wear of counterpart [16]. Graphite reinforcement, as a solid lubricant, can get smeared onto the sliding surfaces in both dry and lubricated conditions, thereby preventing a metal-to-metal contact and decreasing the wear [22].

Table 3. Influence of reinforcement type and amount on wear resistance

Reinforcement	Ref.	Maximum reinforcement amount [wt. %]	Increase of wear resistance [times], min / max
Al_2O_3	[16]	10	3 / 16
	[20]	6	4.6
	[30]	10	1.12 / 2.54 (dry); 1.6 / 2.6 (lubricated)
SiC	[21]	15	8 / 24
	[23]	16	1.76 / 3 (dry); * (lubricated)
	[27]	5	1.24 / 1.36
Gr	[22]	5	1.38 / 1.56
	[18]	2	1.26 / 3 (dry); 1.14 / 5 (lubricated)
SiC + Gr	[28]	9 SiC + 3 Gr	2.18 / 2.78
	[25]	5 SiC + 1 Gr	1.17 / 1.33
Al_2O_3 + Gr	[13]	9 Al_2O_3 + 3 Gr	3.0 / 16.5
Fly ash + Al_2O_3	[20]	6 fly ash + 6 Al_2O_3	11.5
Garnet	[14]	20	2.00 / 2.33
	[15]	6	1.78 / 7.67
Zircon	[19]	5	1.67 / 5.37
Short GF	[26]	5	1.70 / 6.28
Fly ash	[20]	6	2.3
	[31]	3	1.75 / 5.70

*up to no wear; Gr – graphite; GF – glass fibre

4. CONCLUSIONS

Through the comparison of tribological properties of ZA-27 microcomposites, obtained in different investigations and manufacturing and testing conditions, some conclusions can be made, such as:

- Stir casting and compocasting are the most popular processes for production of these microcomposites.

- Ceramic particles such as Al_2O_3 and SiC are the most frequently used reinforcements, followed by graphite and other reinforcements like garnet, zircon, fly ash and short glass fibres. Reinforcement amount was usually up to 10 wt. %.
- Coefficient of friction values are in the range of 0.018 – 0.13 for lubricated conditions, and 0.13 – 0.7 in case of unlubricated (dry) sliding conditions. Increase of sliding speed and normal load increases the coefficient of friction in both dry and lubricated conditions.
- Microcomposites exhibited lower wear than ZA-27 alloy and with increase of reinforcement amount wear value decreases in all cases. Increase of load raised the wear value in almost all analyzed studies (in dry and lubricated sliding conditions), while there was no general rule for the influence of sliding speed on wear value.
- Intended application for ZA-27 microcomposites is mainly for tribological pairs with conformal contact, since most of the studies simulated this type of contact.

ACKNOWLEDGEMENT

This review has been conducted as a part of activities within the projects TR 35021, TR 35040 and TR 33001, supported by the Republic of Serbia, Ministry of Education, Science and Technological Development, whose financial help is gratefully acknowledged.

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