Wear Characteristics of ZA-27/Al_2O_3 Composites Processed by Centrifugal Casting

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Abstract: An investigation on ZA-27/Al2O3 Composites processed by centrifugal casting technique was carried out to study wear characteristics of reinforced particles on the base alloy. Operating parameters such as size of reinforced alumina particle (20-100 μm), location of specimen from the center of pin-on disc apparatus (0- 40 mm), melting temperature of the melt (450-650° C), wt. % of alumina added (5- 25), sliding speed (100 - 500 rpm) and normal wear load (10 - 50 N) were concentrated. Taguchi technique with notation L25 was chosen for the analysis. It was noticed that, normal wear load is one of the most influencing factors on wear rate and has the highest influence on the dry sliding wear of composites followed by sliding speed, wt. % of Al2O3, specimen location, particle size and melting temperature.

Key words: alumina particles, centrifugal casting, Taguchi Technique, Wear behaviour, ZA-27 alloy.

1. Introduction

In the modern world, applications of Metal matrix composites (MMC) have increased considerably due to its better mechanical and Tribological properties compared to monolithic alloys. MMC are reinforced with high strength, high Modulus and brittle ceramic phases, which may be in the form of fibers, whiskers or particulates. This reinforcement increases the strength and stiffness of MMC at the expense of ductility. Use of particulates as reinforcements provides several advantages like improved anisotropy, ease of fabrication and reduced cost [1]. In automobile industry for low friction and smoother operation of automobile components, bearings are the most important components used. Widely used bearing materials in automobile industries are Copper, Brass, Bronze, Aluminium alloys, Babbitt, etc. [2]. ZA alloys are much suitable for applications having higher load concentration at lower speeds. Due to the improved characteristics like good tribo-mechanical properties, excellent wear characteristics, low weight, excellent castability, fluidity, low initial cost and environment friendliness, ZA alloys have become one of the most popular bearing materials and thus it effectively finds a distinctive place amongst all other bearing materials. But the properties of ZA alloys deteriorate at higher temperature and cannot be used at elevated temperatures. To overcome this, ZA alloys are reinforced with ceramic fibers or particles. Amongst all ZA alloys, ZA-27 alloy has the highest strength, lowest density, excellent bearing characteristics and wear resistance. Much work has been carried out on ZA-27 alloy based MMC by reinforcing it with SiC, Al2O3, glass fiber, garnet particles, graphite particles, Zircon particles etc., these MMC may be fabricated by any of the processes such as gravity casting, squeeze casting, compo casting, stir casting, etc. Several researches have been carried out on sliding wear mechanism of MMC reinforced with ceramic particulates and have indicated significant improvements in wear and abrasion resistance [3] – [5]. S. Mitrovic *et.al* in their paper stated that mechanical properties of ZA-27/ graphite particulate composites processed by compo casting are significantly varied by varying the amount of graphite particulates in the base alloy. Wear resistance of the composite shows an improvement due to addition of graphite particles but results in decreased hardness. The SiC-reinforced composites exhibit reduced wear rate when compared to unreinforced ZA-27 alloy. The wear rate decreases with increasing SiC content [4]. The garnet particle when reinforced with ZA-27 alloy, exhibited reduced dry sliding wear loss than the unreinforced alloy and the wear loss decreased with increased garnet content [6]. Wear rate of MMCs is improved when reinforced with Al2O3 processed through Stir casting [7].

In the present study, ZA-27/alumina MMCs were processed by centrifugal casting process and the effects of Al2O3 content on wear resistance of ZA-27 alloy was taken into consideration. Alumina of different particle sizes (20, 40, 60, 80, 100 μm) was used as reinforcement in to the base alloy. The locations of the specimen were taken from 0, 10, 20, 30 and 40 mm from the center. The melting temperature of the MMCs is taken as 450, 500, 550, 600 and 650 ° C, the wt. % of the Alumina as 5, 10, 15, 20 and 25 %, different sliding velocity of the wear as 100, 200, 300, 400 and 500 rpm and normal load of 10, 20, 30, 40 and 50 N were considered for our experiment. A standard Taguchi experimental plan with notation L25 was chosen for analysis. Conventional experimental design would require 65 = 7776 runs to study six parameters each at five levels, whereas Taguchi's experimental approach reduces it to only 25 runs, offering a great advantage in terms of experimental time and cost. The experimental observations were further transformed into signal-to-noise (S/N) ratio. The S/N ratio for minimum erosion rate can be expressed as "lower is better" characteristic, which is calculated as logarithmic transformation of loss function as per equation.

$$S/N=-10\log\frac{1}{n}\sum(y2) \tag{1}$$

where 'n' is the number of observations, and y is the observed data. With "lower is better (LB)" characteristic, the above S/N ratio transformation, were suitable for minimization of wear rate.

2. Experimental Details

Fig. 1. Horizontal centrifugal casting machine.

A centrifugal casting machine was used (Fig. 1) for casting the components. The casting machine consists of a power rotation system and a mould fixed on the centrifugal casting equipment for forming cylinder samples. The mould is made of graphite, and unidirectional solidification is enforced directly by the unidirectional heat transfer of outer circumference of the mould. In this experiment, the mould was pre-heated to 500 °C and the pouring temperature of $Al2O_3$/ZA-27 composite slurry was 750°C. A centrifugal casting was performed at different speeds, which corresponded to the maximum centrifugal acceleration of 54g (the values of the centrifugal accelerations are given in terms of g, the acceleration due to gravity). The dimensions of the cylinder are 100 mm diameter and 200 mm length, weighing 2500 g each approximately.

Cylindrical wear test specimens of diameter 6 mm and length 15 mm were cut, ground and polished to the required size before testing. The wear tests were carried out pin-on-disc wear testing machine in accordance with ASTM G99 standards. Loss of weight method is used to estimate the wear of a specimen.

A standard Taguchi experimental plan with notation L25 was chosen and the operating parameters under which wear test were carried out are given in Table 1.

Table 1. Levels of Variables Used in the Experiment

Parameters	Levels					
	Unit	01	02	03	04	05
Particle size	μm	20	40	60	80	100
Location	mm	00	10	20	30	40
Melting temp	°C	450	500	550	600	650
Al2O3	Wt.%	5	10	15	20	25
Sliding speed	Rpm	100	200	300	400	500
Normal load	N	10	20	30	40	50

3. Results and Discussion

3.1. Design of Experiment Results

The wear rates at different test conditions and the wear rate (response) so obtained according to Taguchi experimental design are given in Table 2.

Table 2. Centrifugal Casting and Wear Parameters and Wear Rate of ZA-27/Al_2O_3 MMCs

Sl. No.	Particle size, μm	Location, mm	Melting temp. °C	Wt.% of Al_2O_3	Sliding Speed, rpm	Normal load, N	Wear rate, mm^3/km
01	20	0	450	5	100	10	0.4000
02	20	10	500	10	200	20	0.3539
03	20	20	550	15	300	30	0.3341
04	20	30	600	20	400	40	0.3775
05	20	40	650	25	500	50	0.5210
06	40	0	500	15	400	50	0.5212
07	40	10	550	20	500	10	0.3289
08	40	20	600	25	100	20	0.2309
09	40	30	650	5	200	30	0.3275
10	40	40	450	10	300	40	0.4278
11	60	0	550	25	200	40	0.4319
12	60	10	600	5	300	50	0.5522
13	60	20	650	10	400	10	0.3667
14	60	30	450	15	500	20	0.3322
15	60	40	500	20	100	30	0.2821
16	80	0	600	10	500	30	0.5474
17	80	10	650	15	100	40	0.4252
18	80	20	450	20	200	50	0.4263
19	80	30	500	25	300	10	0.3176
20	80	40	550	5	400	20	0.4665
21	100	0	650	20	300	20	0.4153
22	100	10	450	25	400	30	0.4893
23	100	20	500	5	500	40	0.5734
24	100	30	550	10	100	50	0.4812
25	100	40	600	15	200	10	0.3404

Using Regression Analysis the optimum equation for Wear rate is,

Wear Rate = 0.261781 + 0.000972735 particle size - 0.001739 Location - 1.59271e-005 Melting temperature - 0.0040195 Wt. % of Al_2O_3 + 0.000261633 Sliding speed + 0.00386712 Normal load

3.2. Effect of Individual Factor on Wear Properties

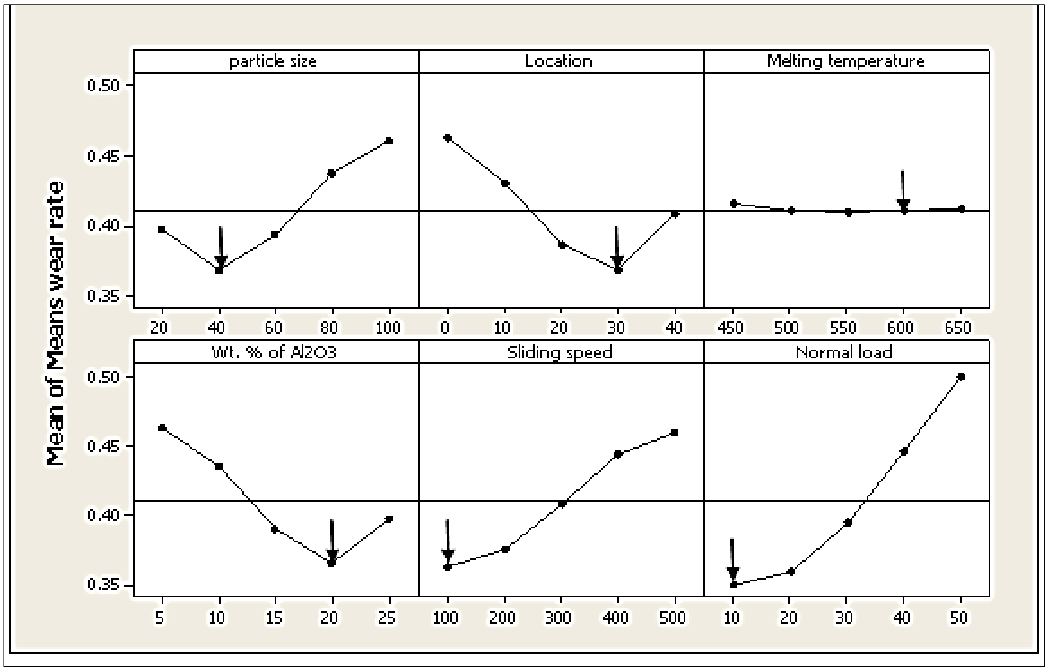

Fig. 2. Relative effect of main factors on wear rate of the ZA-27/Al_2O_3 composites at sliding distance of 1 km

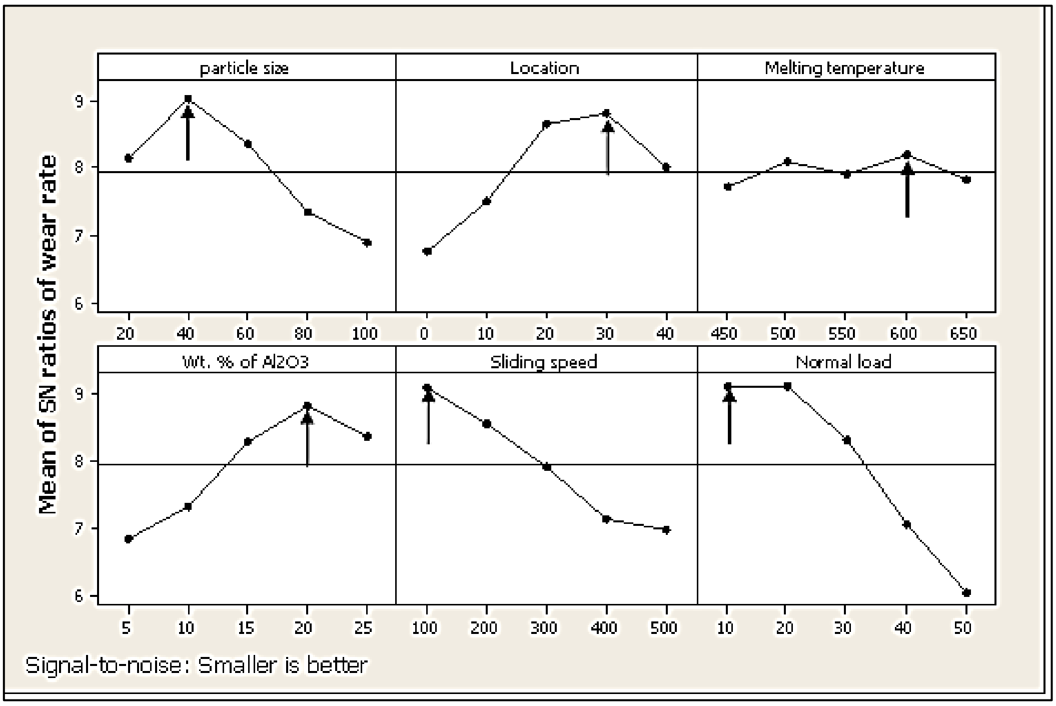

Fig. 3. Relative effect of S/N ratio on wear rate of the ZA-27/Al_2O_3 composites at sliding distance of 1 km

The wear rate of the factors such as particle size, location, melting temperare, wt. of Al_2O_3 particles, sliding speed and normal load selected as the control factor, and their effects on the wear rate and S/N ratios are shown in Fig. 2 and Fig. 3 respectively. The levels that have the lowest value of wear rate and highest value of the S/N ratio in these figures are the best factor levels. The optimum A2-B4-C4-D4-D1-F1 equation obtained by the S/N raio is explained. The second level of particle size (40 μm), forth level of location (30 mm from centre), forth level of temperature (600 °C), forth level of wt.% of particles (20 wt.%), first level of sliding speed (100 rpm) and first level of normal load(10 N) gives best results. The higher the difference, the more influential is the control factor. Figs. 2 and 3 shows the change in wear rate with particle size reinforced ZA-27 alloy composites measured at different sliding speeds, normal wear load and location of the specimen. It is observed that the overall variation of wear rate with particle may be categorized into three stages. At initial stage the wear rate decrease with particle size, during intermediate stage the values are constant with increase in the particle size and during final stage the wear rate increase with the particle size. The 40 μm particle size reinforced specimen shows minimum wear rate compare to 30 and 100 μm particles. The weight percentage of particle increases continuously at the outer periphery with the progress of relative time in case of the large particle. The tendency is different in case of small particle. Initially, the weight percentage of the small particle increases toward the outer periphery with the relative time, however the weight percentage have a small peak. The large particles migrate towards outer periphery faster than the small particle. Therefore, weight percentage of the large particles at the ring outer periphery is larger than that of the small particles, and the wt. % of the large particles at the interior periphery is smaller than that of the small particles. If these two kinds of particles have different physical property each other, physical property of the MMCs with a unique density gradient should show a unique variation as a function of normalized thickness. Therefore, we can expect the fabrication of MMCs, which have the highest strength at outer ring periphery, by a combination of particles with different size. This is an important advantage of the FGM fabricated by two kinds of particles compared with usual MMCs fabricated by one kind of particle. The S/N response for wear rate is presented in Fig. 3.

The wear rate results for the MMCs investigated in this study was found to decrease as a function of distance from the base of the ingot as seen in case of 20 mm, it decrease as a function of distance. The increase in micro hardness along the deposition direction in the case of all MMCs can be attributed to the increase in the weight percentage of Al_2O_3 and grain refinement. The presence of stiffer and stronger alumina reinforcement, lead to an increase in the constraint to plastic deformation of the matrix during wear test. Moreover, with grain refinement, more grain boundaries are present. Grain boundaries being microstructural defects, will provide resistance to the dislocation motion, thus affecting the indentation during wear testing. But it increases towards the end of the ingot because the larger particle moves toward end. The larger particle indicates that significantly different tribological and mechanical response can be expected from the two ends of the MMCs. This was confirmed, in part, by an earlier study [8] which revealed that a wear rate difference of about few times can be realized by establishing a gradient equivalent to a difference in wt.% particulates on the extreme ends of the MMCs ingot, synthesized using the same technique.

The wear rate increased with increase in sliding speed. During sliding, the ZA-27 alloy specimen is exposed to air, which might lead to the formation of Al_2O_3. This layer is brittle and acts as a thermal insulator, whose temperature increases with further sliding. This raise in temperature causes transition wear. Consequently, the severe wear is delayed with increasing wt. % of reinforcement in composites. Research's [9] reported that critical speed was dependent on applied load, thermal diffusibility and hardness of the surfaces. For Al_2O_3 reinforced MMCs there was increase in strain rate with increase in speed, which leads to an increase in hardness of the wear surface and rise in temperature of the contact surface. They compensate each other and as a result of which the wear rate has been observed to marginally increase. However, above the critical speed there was an increase in temperature due to friction between the sliding surfaces which softens the specimen surface, and any decrease in surface hardness increases the true area of contact, resulting in a higher wear rate. Composites of Al_2O_3 reinforced composites hinder the transition to severe wear regime. Many researchers [10]-[11] have reported a delay in transition to severe wear regime with addition of Al_2O_3 particles in cast ZA alloy.

Superior steady state wear resistance was observed by the pins of the reinforced composites, as well as unreinforced matrix alloy at lower loads. The mild wear occurs at lower loads, where the contact resistance is high, the wear debris is fine and it consists mainly of aluminium and iron oxides on the rubbed surfaces which seems to be polished. At lower loads, the particles act as load-bearing and abrasive elements, between the composite and steel disc. At lower loads, the worn surface of ZA-27- Al_2O_3 composite exhibited formation of iron-rich layers. At medium loads (20-30 N), the specimen wears at a uniform rate exhibiting smaller plastic deformation and damages, due to cavitation taking place along the sliding direction of the surface. Formation of the iron oxide is less at low loads, but aluminium oxide is present at the morphological surface. No exposed Al_2O_3 particulates are observed, because they were pushed within the matrix, as the surface became softer at higher temperatures. At higher load (30N), the oxide film does not prevent metal/metal contacts. The hard brittle oxide formed on aluminium provides protection against wear. It is clearly evident from the graph, that there exists a transitional load at which there is sudden increase in wear rate of both reinforced as well as the unreinforced material. With a 30 N load, in Al_2O_3 reinforced MMCs, the particulates serve to suppress the transition to a severe wear rate. In the severe wear region at higher loads, the contact resistance is low. Wear debris includes coarse metallic particles of the surfaces and ceramic particles, which act as abrasive particles between the specimen and the disc. At higher loads, it was observed that there was more severe damage in unreinforced ZA-27 alloy than in reinforced composites.

3.3. Analysis of Variance

ANOVA is a statistical analysis tool which identifies the factors that are influencing the response i.e., wear resistance from the given set of data. ANOVA test results can then be used in an F-test on the significance of the regression formula overall. A full factorial experiment is an experiment whose design consists of two or more factors, each with discrete possible values or "levels" and whose experimental units take on all possible combinations of these levels across all such factors. Such an experiment allows studying the effect of each factor on the response variable, as well as the effects of interactions between factors on the response variable. For the vast majority of factorial experiments, each factor has only four levels.

Table 3. ANOVA Calculations for Wear Rate

Factor	DOF (f)	Sum of Squares(S)	Variance (V)	f calculated	Significance %	Ranking
A:Particle size, μm	4	0.0270	0.108	205.93	13.56	05
B: Specimen location, mm	4	0.0280	0.112	211.45	14.07	04
C:Melting temperature, °C	4	0.0001	0.0004	000	0.050	06
D: Wt. % of Al2O3	4	0.030	0.12	225.77	15.07	03
E:Sliding speed, rpm	4	0.035	0.14	263.82	17.58	02
F: Normal load		0.0789	0.3156	593.73	39.64	01
Total			0.7960			

ANOVA test is conducted for 81 runs to most influence factor, Table 3 shows the ANOVA result followed by ANOVA calculation for DOE sum of square, F-ratio and the significance. From the ANOVA analysis it is clear that the factor F has more significance around 39.64% on wear rate followed by factor E of 17.58 % significance on wear rate. Other factor like particle size, normal wear load and speed with interaction factor does not have much significant effect which can be neglected. The results of quantitative assessment of Al_2O_3 revealed that the MMCs synthesized in the present study exhibited a continuous gradient of Al_2O_3 along the deposition direction. It was also found that for all the MMCs, the overall amount of Al_2O_3 incorporated in each FGM was typically less than the starting. This could be due to

- The removal of the shrinkage cavity found at the top of all the MMCs
- The lower-than-critical stirrer velocity for maximum possible incorporation of particulates.

Earlier studies conducted by other researchers have convincingly shown that Al_2O_3 will tend to settle most quickly in the Al matrix as also supported by the results obtained using the Stokes equation[11]. The relatively highest Viscosity lead to shorter settling time of the Al_2O_3, leading to the reverse gradient observed along the deposition direction for Al FGM. Secondly, addition of alloying element such as Mg had been reported to decrease the viscosity of aluminium [12]. Hence, this would lead to an increase in sedimentation of Al_2O_3 with increasing fluidity of the molten metal.

Clustering of Al_2O_3 was also found to increase from the low Al_2O_3 end to the high Al_2O_3 end, for ZA-27/30μm Al_2O_3 and ZA-27/50μm Al_2O_3 ingots. This could be essentially due to the slow stirring condition (400 rpm) adopted in this present study. This can be attributed to the ability of Mg to wet Al_2O_3, thus assisting in the improvement of their distribution [13]. In addition, for FGM, Cu-rich phases were observed in the Al matrix and this can be attributed to the near-equilibrium nature of solidification conditions realized in the present study. The formation of Cu-rich phase can be attributed to the sequential events involving:

- A sluggish solidification front velocity achieved during primary processing of materials,
- Rejection of Cu ahead of the moving liquid–solid interface
- Subsequent solidification when the temperature of the remaining liquid reached eutectic temperature [11].

Due to the formation of the reverse gradient of Al_2O_3 along the deposition direction wear decreasing with distance from the center of the ingots. The extreme ends of the FGM ingots synthesized in the present study exhibited significantly different wear rate values, which could be primarily attributed to the significant variation in the weight percentages of Al_2O_3. These results obtained were consistent with those reported by other researchers and with the principles established for the strengthening of the metallic matrices associated with ceramic particulates [14]-[15]. The presence of stronger and stiffer Al_2O_3 led to an increase in the constraint to the localized plastic deformation of the matrix during the wear test. Moreover, the significant difference in coefficient of thermal expansion between the matrix material and the Al_2O_3 led to an increase in the dislocation density in the matrix. Both of these effects led to the hardening of the metallic matrix and this hardening increases with the increasing presence of ceramic particulates [16].

The significant difference in hardness values obtained on the extreme ends of all the MMCs also indicated different tribological responses. This was partly confirmed by the wear rate results, which revealed that different wear rates were realized from specimens taken from the extreme ends of the three MMCs. The wear mechanisms observed could be generally described as:

- Abrasive wear,
- Delamination wear
- Adhesive wear.

It was found that either a combination of the above-mentioned mechanisms or a single wear mechanism was dominant on each end of the ingots. This increase in wear resistance could be attributed to: The increased resistance to plastic shear deformation imparted by the presence of more Al_2O_3; as a large number of cracks must be nucleated before loose debris could form [17].

The increase in hardness of the specimen at the high Al_2O_3 end (presence of more Al_2O_3) resulted in a decrease in the rate of plastic deformation and thus leading to crack propagation at shallow depth and lower crack propagation rate [18]. The presence of more alumina in the ZA-27 matrix did not show any positive influence on wear resistance, unlike for the case of the other two MMCs. This can primarily be attributed to FGM having the highest level of reinforcement among the two MMCs at their respective high Al_2O_3 ends.

4. Conclusions

- Normal load applied is the one of the most influencing factor on wear rate that has the highest physical properties as well as statistical influence on the dry sliding wear of the composites around 39.64 %, followed by sliding speed (17.58%), wt.% of Al_2O_3 (15.07 wt.%), specimen location (14.07 %), particle size (13.56 %) and melting temperature .
- The pooled error associated with the ANOVA is 5.17% for the factors and the coefficient of regression obtained with the multiple regression value of 0.76 shows that the satisfactory correlation.
- The optimum centrifugal casting parameters and wear parameters for minimizing the wear rate. The second level of particle size (40 µm), forth level of location (30 mm from centre), forth level of temperature (600 °C), forth level of wt.% of particles (20 wt.%), first level of sliding speed (100 rpm) and first level of normal load(10 N) gives best results.

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