Research Paper

STUDIES ON DRY SLIDING WEAR BEHAVIOR OF ALUMINIUM METAL MATRIX COMPOSITE PREPARED FROM DISCARDED WASTE PARTICLES

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ABSTRACT

In this investigation, Aluminium Metal Matrix Composite was prepared by reinforcing discarded waste particles like wet grinder stone dust particles and waste tonner. Dry sliding wear test was conducted using Pin-on-Disc wear testing apparatus for the different combinations of wear parameters like loads, sliding speed and sliding distance using Taguchi and ANOVA techniques. Regression analysis was also employed to establish the correlations between the wear parameters and the wear rate. Finally, a confirmation test was conducted to validate the taguchi method. From the experimental results, the composite prepared by reinforcing 5wt % of Wet grinder stone dust particles and 5 wt % of Al_2O_3 has shown good resistance to the wear rate compared to Al6063 alloy and the composite prepared by reinforcing 5wt % of waste tonner + 5 wt % of Al_2O_3. The sliding distance was the most significant parameter influencing the wear rate followed by applied load, sliding speed and percentage of reinforcement material respectively.

KEYWORDS: Waste tonner, wet grinder stone dust particles, aluminum metal matrix composites, dry sliding wear test, taguchi optimization method, ANOVA, regression equation, wear test.

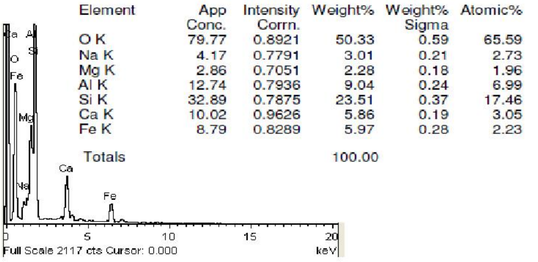
1. INTRODUCTION

Aluminum metal matrix composites (AMMC) has gained more attention as engineering materials because of their higher specific strength, stiffness and in addition to their better wear resistance compared to unreinforced aluminium alloys [1]. Preparation of MMCs chiefly dependents upon the type of reinforcement and matrix materials. AMMCs are mainly used in defense, aerospace, sports and in industries because of many desirable properties like higher stiffness, strength, thermal conductivity and combined properties like wear resistance, fracture toughness and corrosion resistance [2-5]. On the other hand, Al alloys are soft and have poor wear resistance[6] and the application of AMMC is restricted because of poor wear resistance under dry lubrication conditions [7]. Wear is one of the most commonly encountered industrial problems where the material is affected mainly by working load, speed and environmental conditions [8]. Wear is a slow and progressive loss of material from a solid surface which occurs on moving parts which are subjected to repetitive rubbing action. Wear causes a huge amount of expenses either by repairing or replacing the equipment or worn out parts [9]. The wear resistance of metal matrix composite depends mainly on a mixture of micro structural characteristics like particle shape, distribution of reinforcement material and size volume fraction [10-12]. At present preparation of AMMC at low cost is gaining more attention among researchers [13, 14]. AMMC was prepared by reinforcing breadfruit seed hull ash [15]. Palm oil clinkers a biomass waste material was used as reinforcement in preparation of the composite [16]. Industrial by-products like Fly ash was used as low cost reinforcement material to prepare AMMC [17]. Rice husk ash (RHA) and alumina was used as reinforcing material to prepare AMMC [18]. In this research work AMMC was prepared by using discarded waste materials like waste tonner and wet grinder stone dust particles. Figure 1 shows the EDAX test report of wet grinder stone dust particles, revealing the presence of Si, ca, Fe, Al, Mg, Na as the major elements in the wet grinder stone dust particles. Figure 2 shows the EDAX test report of waste tonner revealing the presence of Si, C, O, and Fe as its major constituents.

2. PREPARATION OF THE COMPOSITES

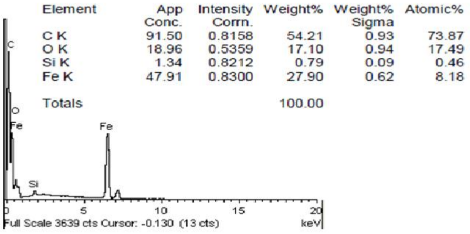
Al6063 alloy was selected as the base matrix material for preparing the composite. Al6063 alloy is used in architectural applications, window frames, aircraft applications, extrusions and irrigation tubing [19]. The Al6063 alloy has the following chemical composition (%) Si = 0.303, Fe = 0.071, Cu = 0.0050, Mn = 0.0759, Mg = 0.529, Cr = 0.0037, Ni = 0.014, Zn = 0.025, Ti = 0.0151, Ca = 0.0146, Al = 98.94.

In this work three samples were prepared by two-step stir casting process with the following combinations. Sample I= Al6063 alloy, Sample II = Al6063+ 5wt% of wet grinder stone dust particles + 5wt % of Al_2O_3, Sample III= Al6063 alloy + 5wt % of waste tonner + 5 wt % of Al_2O_3. The composites were prepared by initially preheating the reinforcement particles like wet grinder stone dust particles (WSD), waste tonner and Al_2O_3 particles up to 250°C in order to remove the moisture content and improve its wettability with the base matrix alloy. Then the base matrix alloy Al6063 was charged into the crucible which is heated up to 780° C. Then the further heating was stopped and the molten alloy was permitted to cool up until it attains semi-solid state around 600◦C. Then the preheated reinforcement particles were added into the melt which is in the semi solid state and stirred manually for 15 minutes. Then, the temperature was raised to 850° C and a second stirring was done for 15 minutes. Finally the prepared composite were poured into the sand moulds.



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
O K	79.77	0.8921	50.33	0.59	65.59
Na K	4.17	0.7791	3.01	0.21	2.73
Mg K	2.86	0.7051	2.28	0.18	1.96
Al K	12.74	0.7936	9.04	0.24	6.99
Si K	32.89	0.7875	23.51	0.37	17.46
Ca K	10.02	0.9626	5.86	0.19	3.05
Fe K	8.79	0.8289	5.97	0.28	2.23
Totals			100.00		

Figure 1: EDAX test report of WSD particles



Element	App Conc.	Intensity Corrn.	Weight%	Weight% Sigma	Atomic%
C K	91.50	0.8158	54.21	0.93	73.87
O K	18.96	0.5359	17.10	0.94	17.49
Si K	1.34	0.8212	0.79	0.09	0.46
Fe K	47.91	0.8300	27.90	0.62	8.18
Totals			100.00		

Figure 2: EDAX test report of Waste tonner particles

3. EXPERIMENTAL PROCEDURE

Dry sliding wear test was conducted on the prepared samples by pressing the prepared samples against the rotating EN32 steel disc with hardness 65HRC. Pin-on-disc test apparatus (Model TR 20-LE, Ducom) was used and the experiments were conducted as per the ASTM G99 Standards. The specimens were machined to pin size of 10 × 10 × 25 mm. The wear loss was calculated directly as the height loss of the specimen using LVDT. The test was conducted at normal room temperature with the load ranging from 9.81, 19.62 and 29.43 N at a sliding speed of 1.5, 3.0 and 4.5 m/s and with a sliding distance of 1000, 2000 and 3000 meter.

4. PLAN OF EXPERIMENTS USING TAGUCHI TECHNIQUE

In this work, Taguchi method was used to determine the optimal level of the parameters for minimal wear rate. Four control factors were chosen (1) sliding speed (m/s) (2) load (N), (3) sliding distance (m) and (4) Working Material(R). Table 1 shows the control factors and levels. The experiments were planned using Taguchi's based design of experiments (DOE). The DOE is an effective method to reduce the number of experiment, cost and time [20]. Taguchi method uses an effective design of orthogonal array which is very simple compared to other traditional experimental design methods [21, 22]. The level of influence or highest effect of a particular parameter on the response - wear rate was determined using analysis of variance (ANOVA) [23].The orthogonal array was chosen based on the concern that the number of degrees of freedom for the orthogonal array must be more than or equal to the number of degrees of freedom required for studying the main and interaction effect [24].

Table 1 Control factors for wear rate and their levels

Symbol	Control factors	Level		
		I	II	III
S	Sliding Speed, (m/s)	1.5	3	4.5
L	Applied Load (N)	9.81	19.62	29.43
D	Sliding Distance (m)	1000	2000	3000
R	Working material (R)	Al6063	Al6063+5 wt% of WSD+ 5Wt of Al$_2$O$_3$	Al6063 + 5 wt% of Waste Tonner + 5Wt of Al$_2$

In this present investigation, four factors at three levels and the interactions between sliding speed × applied load, sliding speed × working material and applied load × working material are to be studied. The required degree of freedom is 26. As the degrees of freedom for orthogonal array is greater than the number of degrees of freedom required for studying the main and interaction effect, L27 orthogonal array was selected, which has 27 rows and 13 columns as shown in table 2.The response to be studied was the wear rate with an objective as smaller the better. The experiments were conducted as per the orthogonal array. The first column in table 2 was assigned to sliding speed; second was assigned to load; fifth column was assigned to sliding distance and the ninth column was assigned to working material and the left over columns was assigned to their interactions [25]. The levels and the values used of the control factors were determined by conducting preliminary experiments.

TABLE 2: ORTHOGONAL ARRAY L27 (3^{13}) OF TAGUCHI METHOD.

L27(3^{13})	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	2	1	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

5. EXPERIMENTAL RESULTS AND DISCUSSION

The experiments were conducted with an intention to relate the influence of sliding speed (S), Applied load (L), sliding distance (D) and working material (R) on the wear rate. Table 3 shows the experimental results using L27 orthogonal array. The wear rate with an objective smaller the better was the response to be studied. The experiments were conducted based on the plan of experiment and then the results were analyzed with the help of MINITAB 15 commercial software.

5.1Analysis of variance (ANOVA)

The optimum combination of control factors for smaller wear rate was found out by using ANOVA method. Table 4 presents the results of ANOVA for wear rate. The experimental plan was evaluated at a confidence level of 95% [26, 27]. In this work, the R^2 value for wear rate was 99.0 which is desirable [28]. From table 4 it is clear that the p-value for sliding speed, applied load, sliding distance is less than or equal to 0.05 which indicates that the factors are statistically significant and have significant influence on the wear rate[29].The Working material and the interaction among sliding speed × load, Sliding speed × working material and applied load × working material has p-value greater than 0.05 which indicates that they do not have any significant influence on the wear rate. It is clear from table 4 that, sliding distance is the most significant parameter increasing the wear rate and contributes (p=46.88%) on the wear rate followed by applied load (p=32.28%), sliding speed (p=9.84%),interaction among applied load × Working material contributes (p=5.43%), sliding speed × load contributes (p=2.249%). The Working material and the interaction between Sliding speed × Working material contributes only (p=0.206%) and (p=0.931%) respectively. The error associated with ANOVA table was approximately about 2.176%.

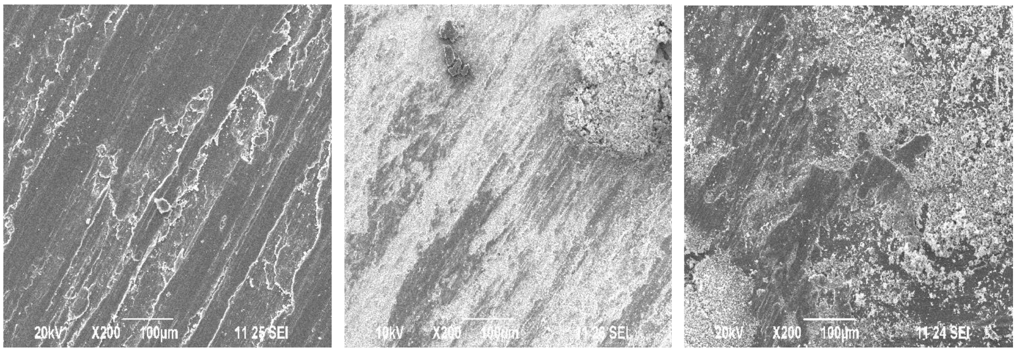
Table 3 Experimental results using L27Orthogonal array

Test	Sliding speed, S	Applied Load, L (N)	Sliding distance, D (m)	Working material (R) (%)	Wear Rate (mm)
1.	1.5	9.81	1000	1	0.02501
2.	1.5	9.81	2000	2	0.02492
3.	1.5	9.81	3000	3	0.03100
4.	1.5	19.62	1000	2	0.02768
5.	1.5	19.62	2000	3	0.02899
6.	1.5	19.62	3000	1	0.03132
7.	1.5	29.43	1000	2	0.03124
8.	1.5	29.43	2000	1	0.03265
9.	1.5	29.43	3000	2	0.03465
10.	3.0	9.81	1000	2	0.02368
11.	3.0	9.81	2000	3	0.02452
12.	3.0	9.81	3000	1	0.03098
13.	3.0	19.62	1000	3	0.02681
14.	3.0	19.62	2000	1	0.02869
15.	3.0	19.62	3000	2	0.03122
16.	3.0	29.43	1000	1	0.02873
17.	3.0	29.43	2000	2	0.02771
18.	3.0	29.43	3000	3	0.03366
19.	4.5	9.81	1000	3	0.02357
20.	4.5	9.81	2000	1	0.02372
21.	4.5	9.81	3000	2	0.02852
22.	4.5	19.62	1000	1	0.02435
23.	4.5	19.62	2000	2	0.02856
24.	4.5	19.62	3000	3	0.03054
25.	4.5	29.43	1000	2	0.02736
26.	4.5	29.43	2000	3	0.02698
27.	4.5	29.43	3000	1	0.03174

TABLE 4: ANALYSIS OF VARIANCE OF SN RATIOS FOR WEAR RATE

Source	DOF	Seq SS	Adj SS	Adj MS	F	P	Percentage of contribution
Sliding speed	2	2.4949	2.4949	1.24744	13.56	0.006	9.84
Applied Load	2	8.1846	8.1846	4.09232	44.50	0.000	32.28
Sliding distance	2	11.8869	11.8869	5.94347	64.63	0.000	46.88
Working material	2	0.0524	0.0524	0.02621	0.29	0.762	0.206
Sliding speed × Applied Load	4	0.5703	0.5703	0.14258	1.55	0.300	2.249
Sliding speed × Working material	4	0.2362	0.2362	0.05904	0.64	0.652	0.931
Applied Load × Working material	4	1.3770	1.3770	0.34425	3.74	0.074	5.43
Residual Error	6	0.5518	0.5518	0.09196			2.176
Total	26	25.3541					100

DOF: degrees of freedom; Seq SS: sequential sum of squares; Adj SS: adjusted sum of squares



(a) (b) (c)

Figure 3: SEM image of wear surface at sliding speed of 4.5m/sec and 29.43N applied load: (a) Sample-I after running 1000m (b) sample-II after running 2000m (c) sample-III after running 3000m

In the literature [30, 31] it is pointed out that, the wear resistance of the composite is found to increase with the increase in the volume fraction of the reinforcement. In this work, the sample II and Sample-III has shown improved resistance to wear rate compared to the sample-I. It is clear from the Figures 3 (b) and (c) that the worn surface of Sample-II and Sample-III are covered with near continuous oxide films compared to the Sample-I. The Fe present in the rotating disc reacts with the aluminium to form Fe_2O_3 [32]. It is also pointed out in the literature that, the COF decrease due to the formation of the oxide layer on the sample surface [33]. Further the reinforced particles in sample-II and sample-III gets crushed into very fine particles and forms the mechanically mixed layer (MML). The SEM image of sample-II and sample-III as shown in figures 3 (b) and (c) confirms the MML formation on the surface of the composites. The MML acts as a protective layer between the sample and rotating disc and prevents the wear rate. In case of sample-II, the wear rate is comparatively less compared to other two samples taken for investigation. This may be due to the uniform distribution of the reinforcement particles. The decrease in the wear rate with increase in the sliding speed may be due to the increased extent of oxidation of Al alloy due to higher interfacial temperature caused by the rubbing action at the interface of the contact surfaces. The oxide layer formed on the sample surface has low coefficient of friction and thus the wear rate decreases with the increase in the sliding speed and distance [34].

6. REGRESSION ANALYSIS

Regression analysis can be effectively used to categorize the relationship between the variables taken for the investigation [35, 36]. The standard commercial statistical software package MINITAB 15 was used to derive the regression equation (1) of the form:

$$\text{Wear rate} = 0.0216 - 0.000819\,S + 0.000220\,L + 0.000003\,D + 0.000007\,R \quad \text{---------------- Eq. (1)}$$

Where;

S = Sliding Speed (m/s), L = Load (N), D = Sliding distance (m), R = Percentage of reinforcement material (%).

In regression analysis, R^2 value of the regression coefficient must be between 0.8 and 1 [37].In this work, the regression coefficient of the model is 0.83 which indicates that the model as fitted and explains 83.0% of the variability for wear rate.

From the Eq.(1), the negative value of the coefficient indicates that the wear rate decreases with an increase in the related parameters and the positive value of the coefficients gives a suggestion that the wear rate increases with an increase in the related parameters [32]. By substituting the recorded values of the parameters in Eq. (1), the wear rate of the samples can be premeditated .The importance of each parameter on wear rate is indicated by their magnitude. It is clear from Eq.(1) that the applied load is the most significant parameter which has more influence on the wear rate followed by sliding speed, sliding distance and prm. The coefficient linked with sliding speed is negative, which indicates that the wear rate decreases with increase in the sliding speed. The coefficient associated with Load, sliding distance and prm is positive, which indicates that the wear rate increases with the increase in the Load, sliding distance and prm.

7. CONFIRMATION TEST

The confirmation test is the essential step to verify the experimental [20]. In this study, the confirmation test was performed by selecting the set of parameters as shown in the table 5. The experiments were conducted and the results were compared with the regression equation (1).Table 6 shows the comparison between the experimental and the predicted value using the regression equation.

TABLE 5 VALUES USED IN THE CONFIRMATION TEST FOR WEAR RATE

Test	Sliding speed (m/s)	Load (N)	Sliding distance (m)	Prm (%)
1	2.45	12.5	600	1
2	3.12	23.5	1300	2
3	4.20	29.5	2550	3

TABLE 6 RESULT OF THE CONFIRMATION TEST FOR WEAR RATE (MM)

Test	Experimental value	Value predicted using the regression equation(1)	% of Error
1	0.02658	0.02415	9.14
2	0.02998	0.02812	6.20
3	0.03354	0.03232	3.64

From the confirmation test, the errors associated with wear rate ranges stuck between 3.64% and 9.14% which indicates that the developed regression equation for wear rate correlates with the experimental values with a reasonable degree of approximation

CONCLUSION

In this work, AMMC was prepared by reinforcing discarded waste particles like wet grinder stone dust particles and waste tonner. Dry sliding wear test was conducted on the prepared samples for the different combinations of wear parameters like loads, sliding speed and sliding distance using Taguchi and ANOVA techniques. The following conclusions can be drawn from this work.

- The composites, both sample - II and sample - III prepared by reinforcing Al6063+ 5wt% of wet grinder stone dust particles + 5wt % of Al_2O_3 and Al6063 alloy + 5wt % of waste tonner + 5 wt % of Al_2O_3 has shown good resistance to wear rate compared to the unreinforced alloy.
- A good approximation was achieved between the experimental and the predicted value and thus Taguchi and ANOVA techniques were effectively utilized to identify the optimal level of the wear parameters.
- Among the four wear parameters, the sliding distance was the most significant parameter influencing the wear rate followed by applied load, sliding speed and percentage of reinforcement material respectively.
- The wear rate increases with increase in the applied load for both the AL6063alloy and the prepared composites decreases with increase in the sliding speed.

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