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Dry Sliding Wear Behavior of Metal Matrix Composites: A Statistical Approach

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The dry sliding wear behavior of SiCp and SiCp-graphite–reinforced aluminum alloy composites produced by liquid metallurgy is studied by means of a pin-on-disc type of wear-test rig. This study evaluates the influence of independent parameters such as sliding speed (S), applied load (L), and sliding distance (D) on dry sliding wear behavior of composites. A Taguchi design for the experiments is used to collect the data in a controlled way, and a linear regression model is developed. This article tries to model dry sliding wear with wear parameters using a statistical approach. The results obtained in this work enable the influence and significance of various parameters and their interactions to be better understood. It was found that SiCp-Gr (graphite)-reinforced composites exhibit less volume loss when compared with SiCp-reinforced composites. Sliding speed is the most significant factor affecting wear behavior followed by L and D. The effect of interactions between the S and the L is more pronounced in SiCp-Gr composites.

Keywords metal matrix composites, statistical analysis, Taguchi technique, wear

1. Introduction

Discontinuous reinforced metal matrix composite materials are one of the recent developments in the field of materials engineering (Ref 1, 2). These materials have superior properties compared with the monolithic alloys and can be tailored to suit specific applications (Ref 3-8). The presence of hard reinforcement phases, particulates, fibers, or whiskers has endowed these composites with good tribological (friction and wear) characteristics. Wear resistance along with good specific strength and modulus make them good candidate materials for many engineering applications where sliding contact is expected. Sannino and Rack (Ref 9) undertook an extensive review of dry sliding wear characteristics of aluminum alloy-based composites, while abrasive wear behavior was examined by Deuis et al. (Ref 10). In this study, the effect of reinforcement volume fraction, reinforcement size, sliding distance (D), applied load (L), sliding speed (S), hardness of the counter face, and properties of the reinforcement phase, which influence the wear behavior of this group of composites, were examined in great detail. The sliding wear rate and wear behavior are reported to be influenced by various wear parameters (Ref 11-15). The wear resistance of the graphitic composite was better than that of SiCp- or Al_2O_3-reinforced composites due to the natural lubrication from the graphite (Ref 16, 17). SiCp-graphite–reinforced hybrid composites demonstrate that without losing much of the material properties of Al-SiCp composite, its wear resistance can be substantially increased (Ref 18-20). Prasad et al. (Ref 21, 22) studied the contributions of various parameters governing the abrasive wear response by varying the L and D. In the authors' work, they used the design of experiments and statistical analysis, and concluded that the abrasives play a significant role in abrasive wear behavior.

Sahin (Ref 23) conducted abrasive wear tests on Al 2011 with 5 and 10% SiCp reinforcement with average particle sizes of 32 and 64 μm, respectively. A factorial "design of experiments" was used to assess the contribution of L, D, and particle size. It was reported that the wear rate increased with the increase in abrasive size and L, and decreased with the increase in D when Al_2O_3 emery paper was selected as the abrasive. Mondal et al. (Ref 24) studied the two-body abrasive wear behavior of cast aluminum with 10 wt.% Al_2O_3 particles at different loads (1-7 N) and abrasive sizes (30-80 μm). The wear behavior was predicted through statistical analysis of the measured wear rate at the different operating conditions. The equations developed qualitatively hold for alloys and composites. In addition to reinforcement size and the load, the interaction factors are also quite significant and must be taken into consideration when determining the wear rate of these materials.

In view of the above, an attempt is made in this investigation to study the effect of S, L, and D, and their interactions, on the dry sliding wear of Al/SiCp and Al/SiCp-Gr (graphite) composites. Such a study can provide vital information on the significant wear variables and their interactions. A Taguchi design for the experiments has been used to assess data in a controlled way, and the individual effect of these parameters and their interactions on wear behavior have been established.

2. Experimental Procedures

2.1 Materials

Aluminum AA2219 is used as the matrix material in the present investigation and has the following chemical composition: Si = 0.2 max; Fe = 0.3 max; Cu = 5.8 to 6.8; Mn = 0.2 to 0.4; Mg = 0.02 max; Zn = 0.1 max; V = 0.05 to 0.15; Ti = 0.02 to 0.1; Zr = 0.1 to 0.25; Al = balance. This matrix was chosen because it provides an excellent combination of

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Table 1 Orthogonal array $L_{27}(3^{13})$ of Taguchi design

$L_{27}(3^{13})$ test	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

Source: Ref 24

strength and damage tolerance at elevated and cryogenic temperatures (Ref 25). Two types of composites were produced: one with 15 wt.% of 23 μm SiCp; and the other a hybrid composite with 3 wt.% of 45 μm graphite added to a composite containing 15 wt.% SiCp reinforcement. A liquid metallurgy method was used to fabricate the composites (Ref 26-28).

Table 2 Process parameters with their values at three levels

Level	S, m/s	L, N	D, m
1	1.53	9.81	500
2	3.06	19.6	1000
3	4.59	39.2	1500

2.2 Design of Experiments

The experiments are conducted per the standard orthogonal array. The selection of the orthogonal array is based on the condition that the degrees of freedom for the orthogonal array should be greater than, or equal to, the sum of the wear parameters. In the present investigation, an L_{27} orthogonal array was chosen that has 27 rows and 13 columns, as shown in the Table 1. The wear parameters chosen for the experiments and their levels are shown in the Table 2. The experiment consists of 27 tests (each row in the L_{27} orthogonal array), and the columns are assigned to specific parameters. The first column is assigned to S, the second column is assigned to L, and the fifth column is assigned to D, with the remaining columns assigned to their interactions (Ref 29-32).

Linear regression technique was used to study the dry wear volume loss of the composites. The wear volume loss for both the materials is the response (dependent) variable. The factors that are independent and influence the response variables are (1) S, (2) L, and (3) D. The generalized linear regression equation for these experiments can be written as:

$$Y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_4x_1x_2 + a_5x_1x_3 + a_6x_2x_3 + a_7x_1x_2x_3 \quad \text{(Eq 1)}$$

where Y is wear volume loss. The variables x_1, x_2, and x_3 are the S, L, and D, respectively (Ref 21-23, 29). The a_1, a_2, and a_3 are coefficients of the independent variables, x_1, x_2, and x_3, respectively. The a_4, a_5, a_6, and a_7 are interaction coefficients between x_1:x_2, x_1:x_3, x_2:x_3, and x_1:x_2:x_3, respectively, within the selected levels of each of the variables. The true values of a_0 to a_7 are unknown and must be estimated from least-squares analysis (Ref 23, 24, 33-35).

2.3 Experimental Set Up and Procedure

The pin-on-disc test apparatus shown in Fig. 1 is used to investigate the dry sliding wear characteristics of the composite as per the ASTM G99-95 standard. A wear specimen 10 mm in diameter and 30 mm in height is cut from as-cast samples, machined to size, and then polished metallographically. The initial weight of the specimen is measured to 0.0001g. During the test, the pin is pressed against the counterface EN32 steel disc with a hardness of 65 HRC. After traversing a fixed D, the specimen is removed, cleaned with acetone, dried, and weighed to determine the mass loss due to wear. The difference in the mass before and after testing gives the dry sliding wear volume loss of the composite specimen.

3. Results and Discussion

3.1 Statistical Analysis

Based on the experimental results (Table 3), a linear regression model was developed using MINITAB-R14. The regres-

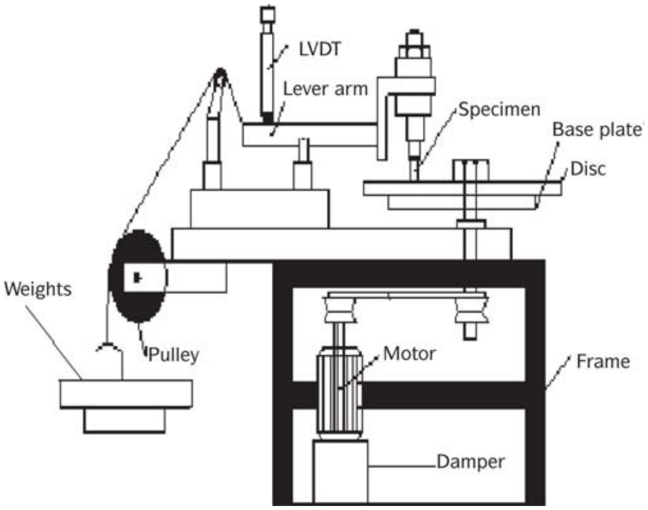

Fig. 1 Schematic view of the pin-on-disc apparatus used in this study

Table 3 Experimental results of wear volume loss for SiCp- and SiCp-Gr-reinforced composites

Test	S, m/s	L, N	D, m	Wear, mm^3 SiCp	Wear, mm^3 Graphitic
1	1.53	9.81	500	1.08	0.8
2	1.53	9.81	1000	1.6	1.34
3	1.53	9.81	1500	2.01	1.8
4	1.53	19.6	500	1.6	1.44
5	1.53	19.6	1000	2.19	2.1
6	1.53	19.6	1500	3.0	2.8
7	1.53	39.2	500	1.55	1.4
8	1.53	39.2	1000	2.8	2.5
9	1.53	39.2	1500	3.8	3.41
10	3.06	9.81	500	0.82	0.6
11	3.06	9.81	1000	1.39	1.01
12	3.06	9.81	1500	1.98	1.6
13	3.06	19.6	500	1.06	0.91
14	3.06	19.6	1000	1.7	1.48
15	3.06	19.6	1500	2.1	1.8
16	3.06	39.2	500	1.4	1.00
17	3.06	39.2	1000	2.22	1.8
18	3.06	39.2	1500	2.62	2.2
19	4.59	9.81	500	0.77	0.6
20	4.59	9.81	1000	1.32	1.0
21	4.59	9.81	1500	2.21	2.06
22	4.59	19.6	500	1.52	1.00
23	4.59	19.6	1000	2.51	2.15
24	4.59	19.6	1500	3.46	3.2
25	4.59	39.2	500	1.33	1.10
26	4.59	39.2	1000	2.33	2.0
27	4.59	39.2	1500	3.96	3.3

Table 4 Parameters used in the confirmation wear test

Test	S, m/s	L, N	D, m
1	2.29	14.71	750
2	3.44	24.5	1150
3	4.20	29.43	1350

sion equations are given in Eq 2 and 3 for SiCp-reinforced and SiCp-Gr-reinforced composites, respectively.

$$Y1 = 0.93 - 0.168\,x_1 + 0.0012\,x_2 + 0.0003\,x_3 + 0.0002\,x_1x_2 + 0.000193\,x_1x_3 + 0.000034\,x_2x_3 - 0.000002\,x_1x_2x_3 \qquad \text{(Eq 2)}$$

$$Y2 = 0.83 - 0.237\,x_1 + 0.0015\,x_2 + 0.00021\,x_3 + 0.0014\,x_1x_2 + 0.000257\,x_1x_3 + 0.000034\,x_2x_3 - 0.000004\,x_1x_2x_3 \qquad \text{(Eq 3)}$$

In these equations, $Y1$ and $Y2$ are the dry sliding wear volume loss for SiCp- and SiCp-graphite-reinforced composites, respectively.

The coefficient of determination (R^2) for the SiCp-reinforced composite is 82.3%, and for the SiCp-Gr-reinforced composite it is 79.4%. This is an expected result because the metal matrix composite has a multiphase microstructure, and the wear data are usually scattered. From the individual linear regression results, it appears that the wear behavior of SiCp-reinforced composite can be described more accurately than the graphitic composite. The low value of the R^2 (79.4%) for the graphitic composites is due to the variation in the formation of graphite layer during the initial stage of wear of the composite. The maximum deviation of the experimental values from the calculated values for SiCp-reinforced composite is 25%, and that for SiCp-Gr-reinforced composite is 34%.

The values of a_0 for SiCp- and SiCp-Gr-reinforced composites are 0.93 and 0.83, respectively. The value of a_0 is the intercept of the plane and is a mean response value for all the experiments conducted (Ref 33). The value of a_0 depends not only on the major parameters S, L, and D, which are considered in this study, but also with experimental irregularities like machine vibrations, environmental conditions, and the surface finish of both the pin and the disc. The experiments are repeated twice to minimize the possible experimental errors, and the averages of the readings are shown in Table 3. It is very clear from the experimental results and the coefficient a_0 of the equations that the wear resistance of SiCp-graphite-reinforced composite is more than that of SiCp-reinforced composite.

The dry sliding wear volume loss of the composite can be calculated from Eq 2 and 3. The positive values of the coefficients suggest that the dry sliding wear volume loss of the composites increases with the increase in the associated variables, whereas the negative values of the coefficients indicates an opposite effect. The magnitude of the variables indicates the relative weight of each of these factors. It is observed from Eq 2 and 3 that S has a greater effect on the dry sliding wear volume loss of the composite, followed by L and D. The interactions among the factors are not significant in the SiCp-reinforced composites, but the interaction between S and L is pronounced in the SiCp-Gr-reinforced composites.

The important factor affecting dry sliding wear is S, with the associated coefficient being negative. This suggests that the dry sliding wear volume loss decreases with increasing speed for the range of parameters tested. This can be attributed to the increased extent of oxidation of the aluminum alloy as a result of higher interfacial temperatures, resulting in a thicker oxide film, which protects the sliding interfaces, thereby lowering the wear rate (Ref 36-39). This may be the reason for the decrease in wear rate with increased S in the present case. As the speed increases for the L, the projecting SiCp particles plough the surface of the counterface. In the process, the projected SiC particles are crushed, leading to third-body abrasion between the pin and the counterface. When the speed increases further, the ploughed surface of the counterface (Fe) will react and

Table 5 Confirmation dry sliding wear test results and their comparison with regression model

	SiCp-reinforced composite			SiCp-Gr-reinforced composite		
Test	Experimental	Model (Eq 2)	Error, %	Experimental	Model (Eq 2)	Error, %
1	1.6	1.45	9.33	1.5	1.23	18.04
2	2.02	2.27	11.05	2.3	2.00	13.13
3	2.4	2.8	14.33	2.35	2.48	5.08

form Fe_3O_4 (Ref 11, 18, 21). The Fe_3O_4, Fe, minute fractured particles of SiCp, and the oxide film form a layer between the work-hardened pin and the counterface. This layer, called the mechanical mixed layer (MML) (Ref 38), reduces the wear volume loss for this range of test parameters. The coefficient associated with the SiCp-Gr composite indicates that as the speed increases, wear volume loss decreases more than it does in the SiCp-reinforced composite. This is attributed to the smearing of graphite within the protecting layer (MML) formed in the SiCp-Gr composite.

The positive value of the L coefficient in both SiCp and SiCp-Gr composites indicates that as the load increases, volume loss also increases. This can be attributed to an increase in the penetration ability of the fractured particles with an increase in load (Ref 21). The fractured small particles of SiCp between the pin and the counterface form a third body. As the load increases further, more SiCp particles are fractured. The brittle fracture of SiCp particles in an irregular fashion leads to the formation of new edges. These new edges plough the pin. In the case of the SiCp-Gr composite, the smeared graphite between the pin and the counterface along with SiCp particles reduces volume loss. As D increases, the volume loss increases for both SiCp and SiCp-Gr composites. This may be attributed to the ploughing ability of the fractured SiCp particles between the pin and the counterface, which does not decrease with the increase in D (Ref 38-40).

The interaction between the speed and load indicates an increase in volume loss with the increase in the associated variables. The influence of L on volume loss is greater compared with S in both the cases. Under the influence of L, along with S, the ploughing efficiency of the fractured SiCp particles increases, causing the formation of wider and deeper wear grooves (Ref 40). The influence of interaction between S and L is predominant in SiCp-Gr-reinforced composite. It influences more than D on wear volume loss. This may be attributed to the ploughing ability of the particles in SiCp-Gr composites, which increases with the increase in L and S. The protecting MML layer will partially break down under the influence of L as the newly fractured SiCp particles penetrate into the matrix and plough the surface of the pin. The interaction coefficient between S and D indicates that the influence of the D is greater compared with that of the S. Thus, the ploughing ability of the particles will not decrease as the D increases under the combined influence of S and D for both of the composites tested. The other interaction effects indicated in Eq 1 and 2 are marginal.

3.2 Confirmation Tests

Confirmation tests were conducted to validate the statistical analysis by conducting the dry sliding wear tests selecting experimental conditions that are different from those used for analysis. Table 4 shows the experimental conditions selected for the confirmation tests. Table 5 shows the results obtained from the tests, and a comparison is made between the computed values from the regression model developed in the present work (Eq 2, 3) and the values obtained experimentally.

From analyzing the data in the tables, the error associated with the relationship between the experimental values and the calculated values from the regression model for SiCp-reinforced composites is between 9 and 14%, while for SiCp-Gr-reinforced composites it is between 5 and 18%. Hence, the model demonstrates a feasible and effective way to evaluate dry sliding wear for the composites.

4. Conclusions

The Taguchi design of the experiments can be successfully used to describe the dry sliding wear behavior of Al-SiCp and Al-SiCp-Gr hybrid composites. Empirical linear regression equations were developed for predicting the wear volume loss within selected experimental conditions. The equations illustrate that the SiCp-Gr composite exhibits higher wear resistance when compared with SiCp-reinforced composites. Wear volume loss decreases with an increase in the S for both of the composites, but increases with an increase in L and D. The interaction effect between L and S is predominant in SiCp-Gr-reinforced composites when compared with D. The results of the confirmation test demonstrate that the models can be effectively used within the experimental domain described herein.

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