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Adhesive and Abrasive Wear Behavior of AA4015 Alloy/Si_3N_4 Metal Matrix Composites

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ABSTRACT

In the present work, the AA4015 alloy/Si_3N_4 metal matrix composites were manufactured at 10% and 30% volume fractions of Si_3N_4. The pin-on-disc wear test was conducted with different combinations of reinforcement, sliding distance, normal load, sliding speed. Based on the experimental results empirical models were established. The wear resistance increases with increase in volume fraction of Si_3N_4 in AA4015 alloy matrix. Combined effect of adhesion and abrasions were predominant in the wear mechanisms of AA4015 alloy/Si_3N_4 metal matrix composites.

Keywords: AA4015 alloy, silicon nitride, wear, sliding distance, normal load, sliding speed.

Abbreviations:
W_{rp} is the wear rate due to vol.% of reinforcement (v_f), g/m
W_{rf} is the wear rate due to normal load (F), g/m
W_{rn} is the wear rate due to speed (N), g/m
W_{rd} is the wear rate sliding distance (S), g/m.
SS is the sum of square
v is the degrees of freedom
V is the variance
F is the Fisher's ratio
P is the percentage of contribution
T is the sum squares due to total variation.

1. INTRODUCTION

Metal matrix composite is synthesized by mixing a base metal or alloy with a ceramic reinforcement. The metal matrix composites obtain high values of specific strength, stiffness; wear resistance, fatigue resistance, creep and corrosion resistance depending on the reinforcement used and volume fraction of the reinforcement. In previous research works, aluminum based metal matrix composites such as AA6061/SiC (Reddy, 2011), 6063/Al_2O_3 (Reddy and Essa Zitoun, 2010), AA6063/SiC (Reddy, 2010), AA7072/SiC (Reddy, 2011), AA6061/Al_2O_3 (Reddy and Essa Zitoun, 2011), 7072Al/Al_2O_3 (Reddy, 2011) have been studied experimentally to describe the mechanical properties.

The subject of wear equations and modeling was debated on a regular but infrequent basis. Many research papers have been written but little tangible trend has taken place for developing good wear models. Barwell (1958) suggested that wear rate may be classified as one of three curves obtained by the expressions given below:

$$V = \frac{\beta}{\alpha}(1 - e^{-\alpha t}) \quad (1)$$

$$V = \alpha t \quad (2)$$

$$V = \beta e^{\alpha t} \quad (3)$$

where, V is the volume loss, α is a constant and t is time. β is identified as "some characteristic of the initial surfaces".

Rhee (1970) found that the total wear of a polymer-matrix is a function of the applied load F, speed V and sliding time t according to

$$\Delta W = KF^{a}V^{b}t^{c} \quad (4)$$

where ΔW is the weight loss of the friction material and K, a, b and c are empirical constants. Archard (1953) determined the material loss due to wear as follows:

$$W = Ks\frac{P}{P_m} \quad (5)$$

Where, W is the worn volume, s is the sliding distance, P is the applied load, P_m is the flow pressure which is equivalent to hardness of the softer material and K is a constant.

The tribological test are performed in different tribological testers such as pin-on-disk, block-on-ring, abrasive wear tester, etc. Mainly factors like applied load, sliding speed, sliding distance and temperature are varied during tribological testing to study the variation in wear rate and friction coefficient. The researchers have also carried out hardness and microstructure study of the materials to evaluate the hardness improvement and wear behavior of the materials. The wear characteristics of metal matrix composites depend upon the material morphology such as composition, size, shape and distribution of reinforcements and service conditions such as load, contact surface, contact time and sliding speed (Reddy and Kotiveerachari, 2011; Reddy and Madahava, 2010; Reddy and Vidya Sagar, 2010; Reddy, 2016).

In order to develop an empirical models for AA4015/silicon nitride composites, wear tests were performed on pin-on-disc equipment. The design of experiments was based on Taguchi techniques (Reddy and Shamraj, 1998; Reddy et al., 1999).

2. MATERIALS AND METHODS

The matrix material was AA4015 alloy. The reinforcement material was silicon nitride (Si_3N_4) nanoparticles of average size 100nm. AA4015 alloy/Si_3N_4 composites were fabricated by the stir casting process and low pressure casting technique with argon gas at 3.0 bar. The composite samples were given H18 heat treatment. The heat-treated samples were machined to get cylindrical specimens of 10 mm diameter and 30 mm length for the wear tests. The levels chosen for the controllable process parameters are summarized in Table 1. The orthogonal array, L9 was preferred to carry out wear experiments (Table 2). A pin on disc type friction and wear monitor (ASTM G99) was employed to evaluate the friction and wear behavior of AA4015 alloy/Si_3N_4 composites against hardened ground steel (En32) disc (Figure 1).

An exploration has been carried out to study the effects of sliding speed, contact time, normal pressure, and volume fraction of Si_3N_4 on the wear characteristics. Knoop microhardness was conducted before and after wear tests. Optical and scanning electron microscopy analyses were also carried out to find consequence of wear test AA4015/ Si_3N_4 composite specimens.

Table 1

Wear parameters and levels

Factor	Symbol	Level–1	Level–2	Level–3
Reinforcement, Vol.%	A	10	20	30
Load, N	B	20	30	40
Speed, m/s	C	2	3	4
Sliding distance, m	D	500	1000	1500

Table 2

Orthogonal array (L9) and control parameters

Treat No.	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Table 3

ANOVA summary of the effective stress

Source	Sum 1	Sum 2	Sum 3	SS	v	V	F	P
A	21.91	20.84	19.64	0.85	1	0.85	1.51E+13	49.19
B	19.97	20.80	21.62	0.45	1	0.45	7.98E+12	25.96

C	20.98	21.15	20.26	0.14	1	0.14	2.62E+12	8.52
D	20.71	135.87	62.39	0.28	1	0.28	5.02E+12	16.33
e				0.00	4	0.00	1.00E+00	0
T	83.57	198.66	123.91	1.74776	8			100

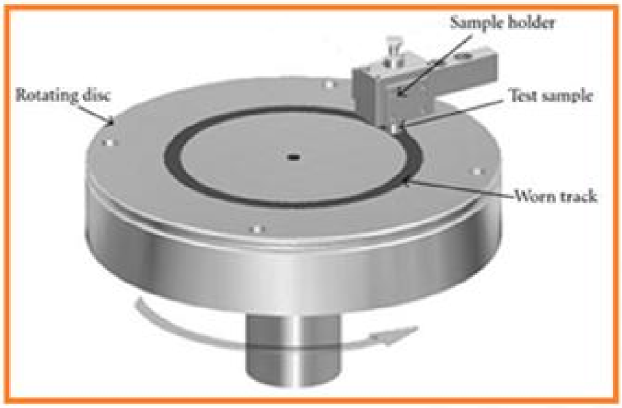

Figure 1

Tests carried out in the present work: (a) Pin-on-disc wear test.

3. RESULTS

Rhee [8] developed wear models for wear rate as a function of the applied load *F*, speed *V* and sliding time *t*. In the present work, wear models are developed for wear rate in terms of the volume fraction of reinforcement V_f, applied load *F*, sliding speed *N* and sliding distance *d*. The Knoop microhardness was conducted to know the effect of reinforcement on the hardness of the composites. The microhardness of AA4015 alloy/Si_3N_4 composites was increased with increased in Si_3N_4 content as shown in Figure 2.

All process parameters are acceptable as they satisfy Fisher's test at 90% confidence level. The analysis of variance (ANOVA) is presented in Table 3. The percent contribution indicates that the volume fraction of Si_3N_4 (A), contributes 49.19%. The normal load (B) shares 25.96% of variation in the wear rate. The speed (C) dispenses 8.52% of variation in the wear rate. The sliding distance (D) affords 16.33% of the total variation in the wear rate. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.953, 0.938, 0.501 and 0.636. The trend of mean values obtained by Taguchi techniques is same as that of R-squared values. The percent contribution of a particular variable indicates whether the performance of that variable is sensitive to change in variation in the wear rate. The top sensitive variable is volume fraction of Si_3N_4; the lease sensitive variable is sliding speed in the variation of wear rate of AA4015 alloy/Si_3N_4 composites.

Analysis of means (AOM) is used to estimate variation in the wear rate as the independent variables change from level 1 to 3. The same results are presented in the form of mean plots as shown in Figures 3 to 6. The strength of % reinforcement, normal load, sliding speed ad sliding distance is directly proportional to the slope of their graphs. The influence of %Si_3N_4 on wear rate is shown in Figure 3. It can be seen that the wear rate was decreased with increase in hardness of composites with volume fraction of Si_3N_4 in AA4015 alloy matrix. Composites produced by low volume fraction of Si_3N_4, wear out faster than those produced by high volume fraction of Si_3N_4. Si_3N_4 particles minimize the plastic deformation on the wearing surface resulting reduced wear rate. As seen from Figure 4, an increase in wear rate is with increase of normal load applied on the test specimen. The increase in the load causes rise in friction and contact between pin and disc. This promotes the formation of an AA4015 alloy-rich layer on the disc's surface. This effect results in adhesion and increases the matrix deformation at the surface layers, leading to loss of the metal.

The wear rate was decreased with increase of speed (Figure 5). At higher speeds an oxide-like transferred layer formed at the sliding interface and reduced direct metallic contacts. This resulted in a lower wear rate. It is also observed from Figure 6 that the wear rate was proportional to the sliding distance. For long sliding distances, the shear stress exceed the shear strength of the particle/matrix interface resulting particle debonding contributing to an increase in the rate of wear. This might be due to the delamination and chipping out of the Si_3N_4 particles from the matrix. At the same time due to the inclusion of trapped wear particles and roughening the substrate, the friction force increases due to the increase of ploughing effect.

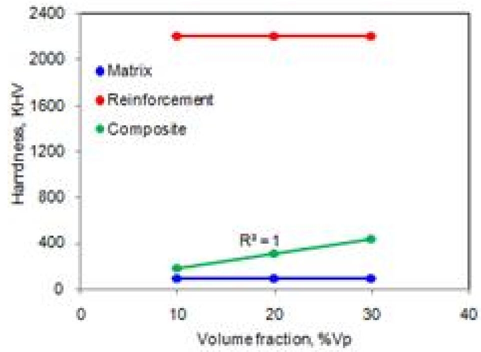

Figure 2
Effect of reinforcement on the hardness of composite

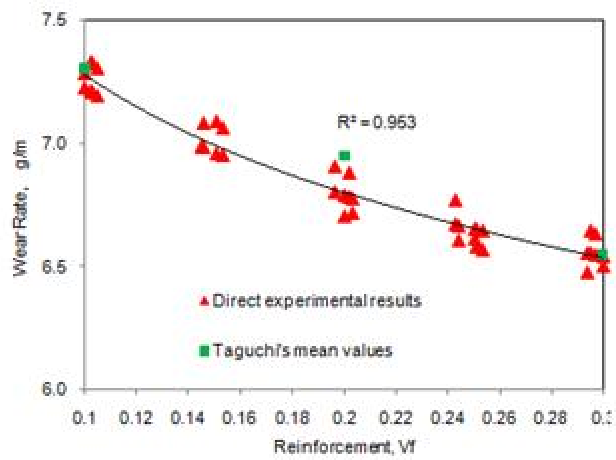

Figure 3
Effect of reinforcement on the wear rate

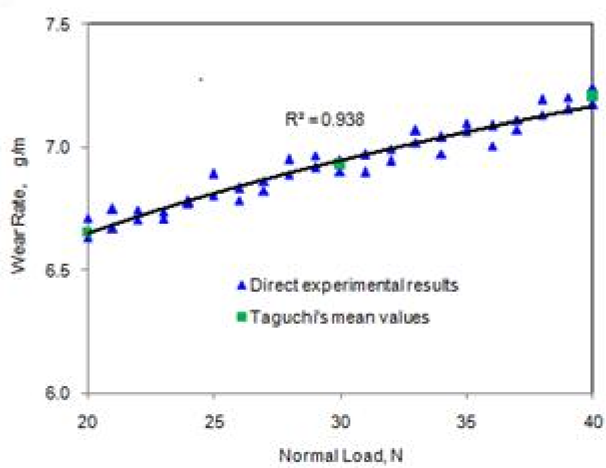

Figure 4
Effect of normal load on the wear rate

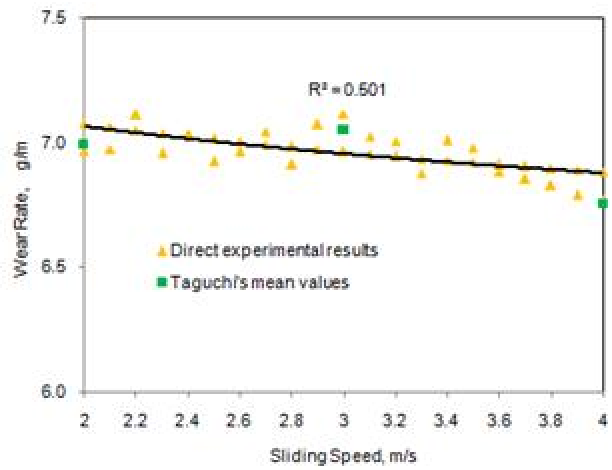

Figure 5
Effect of sliding speed on the wear rate

4. DISCUSSION

The mathematical relation between wear and volume fraction of reinforcement, applied load, sliding speed and sliding distance are obtained by curve fitting in terms of power laws as follows:

$$W_{rp} = 5.805 v_f^{-0.09} \quad (6)$$

$$W_{rf} = 4.807 F^{0.108} \quad (7)$$

$$W_{rn} = 7.259 N^{-0.03} \quad (8)$$

$$W_{rd} = 5.844 D^{0.025} \quad (9)$$

These individual relations are combined to get over-all equation as follows:

$$W = K v_f^{a} F^{b} N^{c} S^{d} \quad (10)$$

The values of power law coefficients a, b, c and d are, respectively, -0.09, 0.108, -0.03 and 0.025 from Equations (6) to (9). By substituting the representative values of V_f, *F*, *N* and *S* and their corresponding power law coefficients on the right side of Equation (10) and substituting the experimentally obtained wear rates on the left side of Equation (10), the value of *K* is determined. The over-all wear rate (g/m) equation for AA4015 alloy/Si_3N_4 composites is given by

$$W = 3.6 v_f^{-0.09} F^{0.108} N^{-0.03} S^{0.025} \quad (11)$$

It is necessary to understand the corollary of wear in AA4015/ Si_3N_4 composites. The worn specimens were tested for Knoop hardness. The hardness values increase after wear test as shown in Figure 7. The increase in hardness may be endorsed to the work hardening and frictional temperature.

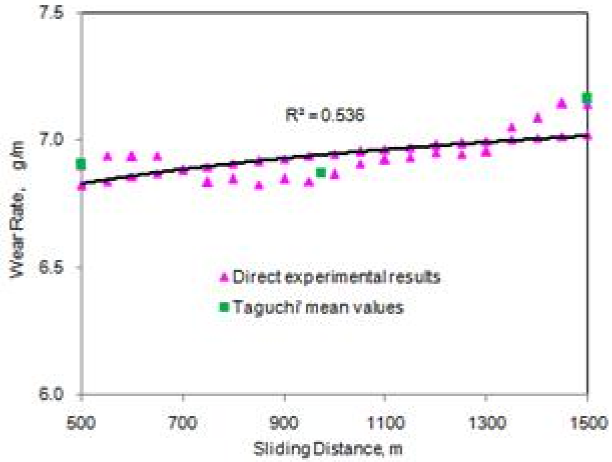

Figure 6

Effect of sliding distance on the wear rate

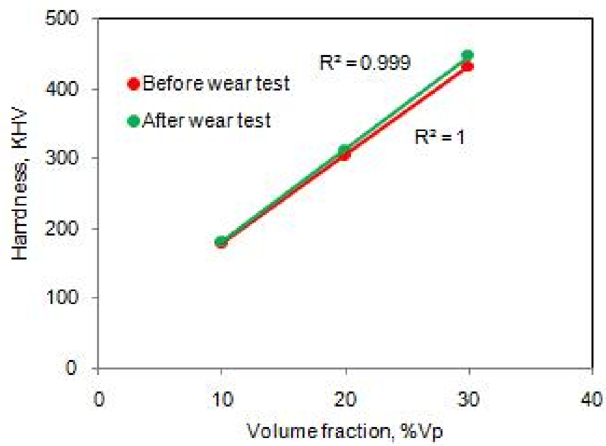

Figure 7

Hardness of AA4015/ Si3N4 composites after wear test

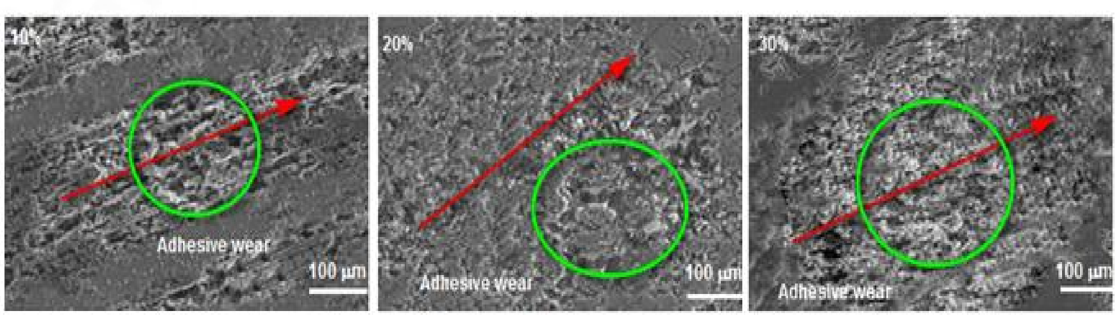

Figure 8

Adhesive wear

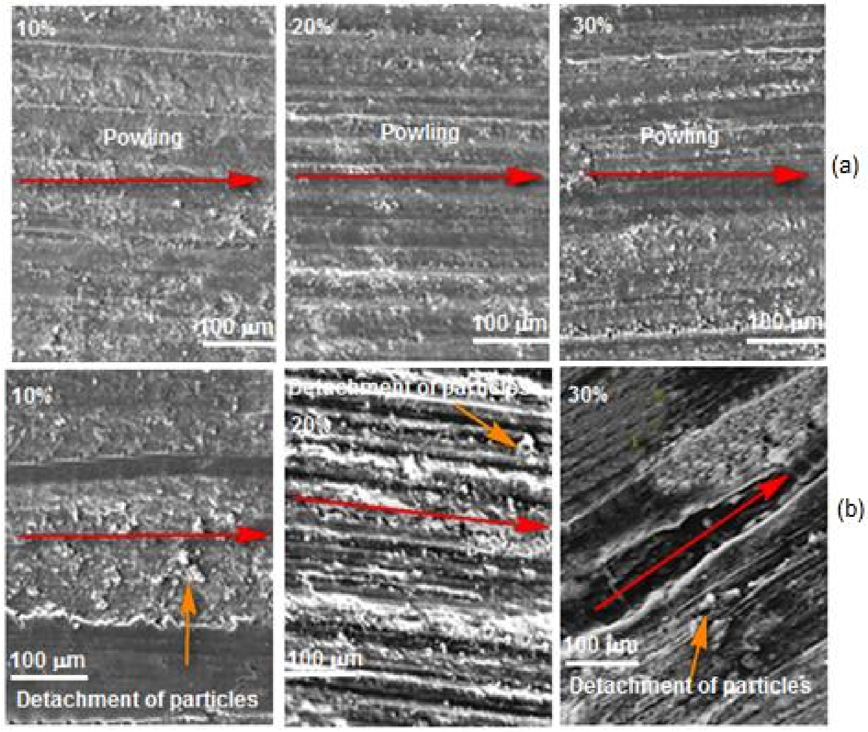

Figure 9
Abrasive wear: (a) stage-I and (b) stage-II

Adhesion wear is owing to the plastic deformation of the pin contact surface and adhered to the outer surface of the steel disc. When the applied increased the plastic deformation would take place in the AA4015 alloy matrix which could adhere to the steel disc and consequently, resulting the conditions illustrated in Figure 8. A decrease in wear rate was detected on account of increasing Si3N4 nanoparticles from 10% to 30% in AA4015 alloy matrix (Figure 3). This might be resulting from the increase of composite hardness with increase of Si3N4 content in AA4015 alloy matrix.

Abrasive wear is due to detachment of reinforced particles and moving along the counter surface of the steel disc. If the wear is caused by reinforced nanoparticles (Si_3N_4) trapped between the pin and the steel disc is called three body wear. The AA4015 alloy matrix is shifted to the sides of the wear groove due to ploughing action as shown in Figure 9a. This is the first stage of abrasive wear. In this stage, the material is removed (lost) from the surface in the volume equal to the volume of the wear track or groove. In the second stage of abrasive wear, AA4014 alloy matrix tears in its subsurface regions surrounding the wear groove as shown in Figure 9b. In this stage, the volume of the lost material is higher than the volume of the wear track.

5. CONCLUSION

The study on the wear behavior of AA4015/Si_3N_4 composites could conclude power law relations between the wear rate with volume fraction of Si_3N_4, normal load, sliding speed and sliding distance. The results obtained from the predicted mathematical model could match with those results obtain from the wear tests. The following are drawn from the present work as follows:

1. The wear resistance increases with increase in volume fraction of Si_3N_4 nanoparticles in AA4015 alloy matrix.
2. The wear resistance decreases with increase in normal load and sliding distance.
3. The dominant mechanisms of wear were combination of adhesion and abrasion.

SUMMARY OF RESEARCH

1. Wear equations and modeling was deliberated but the influence of reinforcement content in the composites was not considered for developing good wear models.
2. The wear tests were conducted on pin-on-disc test rig as per the design of experiments. The wear rate of AA4015/ Si_3N_4 metal matrix composites are characterized by different combinations of reinforcement, sliding distance, normal load, sliding speed.
3. The wear rate of AA4015/ Si_3N_4 metal matrix composites was modeled mathematically based on power laws.
4. Adhesion wear is owing to the plastic deformation of the pin contact surface and adhered to the outer surface of the steel disc. Abrasive wear is due to detachment of reinforced particles and moving along the counter surface of the steel disc.
5. The wear rate was decreased with increase in volume fraction of Si_3N_4 in AA4015 alloy matrix. an increase in wear rate is with increase of normal load applied on the test specimen. The wear rate was decreased with increase of speed. The wear rate was proportional to the sliding distance.

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