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# SLIDING WEAR OF AA6061/CARBON BLACK METAL MATRIX COMPOSITES

**T. Prasad and A. Chennakesava Reddy**
Department of Mechanical Engineering, JNTUH College of Engineering,
Hyderabad, Telangana, India

**ABSTRACT**

*In this study, the effects of carbon black amount on fracture and wear behaviors of AA6061-carbon black metal matrix composites produced by stir casting route were investigated. Wear tests were performed in a pin on type wear apparatus under different loads of 10, 20, 30 N with different sliding speeds of 2, 3 and 4 m/s, at three different sliding distances of 500, 750 and 1000 m. The design of experiments was carried out as per Taguchi technique. Wear rate function was determined in terms of volume fraction, normal load, sliding speed and sliding distance. It was found that there was a good agreement between the theoretical and the experimental value of wear rate. Maximum sliding wear of 68.72% was attributed sliding distance. Sliding wear resistance increases by 42.56% for AA6061/30%CB metal matrix composites as compared to the matrix alloy AA6061.*

**Key words:** AA6061, Carbon black, wear rate, fracture.

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## 1. INTRODUCTION

Metal matrix composites are being used for industrial applications because of their high modulus of elasticity, hardness and strength [1-9]. Especially due to their excellent wear and corrosion resistance, they are widely used in automotive and aerospace industry. Al alloys are widely used in metal matrix composite production as matrix material due to their low density and high corrosion resistance [10-18]. It is well known that hard ceramic particles improve wear resistance as compared to unreinforced matrix material.

Extensive studies have been conducted on dry sliding wear of metal matrix composites wherein the wear mechanisms can be well demarcated into mild and severe wear. [19-20]. The wear rate is related to sliding velocity, particle size, hardness, and normal load, chemical composition of the matrix material, particle volume fraction and particle homogeneity. An experimental investigation was conducted on 6061 Al at the load range of 1-450 N and sliding velocity 0.1-5.0 m s-1. Mild to severe wear transition was found to depend on a combination of load and velocity [21]. The wear behavior of Al alloys also depends on the alloy hardness, along with weight percent, size, and aspect ratio of second phase particles [22]. The objective the present paper is to investigate the dry wear characteristics of AA6061/carbon black nanocomposites.

## 2. EXPERIMENTAL SETUP

The matrix material was AA6061 aluminum alloy. The reinforcement material was carbon black (CB) nanoparticles of average size 100nm. The matrix alloys and composites were prepared by the stir casting and low-pressure die casting process. The volume fractions of carbon black reinforcement were 10%, 20%, and 30%. Prior to the machining of composite samples, T6 heat treatment was given.

The heat-treated samples were machined to get flat-rectangular specimens for the tensile tests. The tensile specimens were placed in the grips of a Universal Test Machine (UTM) at a specified grip separation and pulled until failure. The test speed was 2 mm/min (as for ASTM D3039). A strain gauge was used to determine elongation. Fracture surfaces of the test samples were analyzed with a scanning electron microscope (SEM) using S-3000N Toshiba SEM to define the macroscopic fracture mode and to establish the microscopic mechanisms governing fracture.

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 AA6061/CB composites against hardened ground steel (En32) disc as shown in figure 1. 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 AA6061/CB composite specimens.

**Table 1** Control parameters and levels

| Factor | Symbol | Level–1 | Level–2 | Level–3 |
|---|---|---|---|---|
| Reinforcement, vf | A | 0.1 | 0.2 | 0.3 |
| Load, N | B | 10 | 20 | 30 |
| Speed, m/s | C | 1 | 2 | 3 |
| Sliding distance, m | D | 500 | 750 | 1000 |

**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 |


**Figure 1** shows the photograph of the experimental setup

## 3. RESULTS AND DISCUSSIONS

The tensile strength and elastic modulus of AA6061/CB metal matrix composites increase with increasing volume fraction of carbon black content as shown in figure 2. In AA6061/10%CB composites, the fracture was occurred in the matrix only. While, the fracture was noticed in the regions of particle-matrix interface and in the matrix for the composites of AA6061/20%CB and AA6061/30%CB. The fracture of carbon black nanoparticles was not revealed in all the composites.

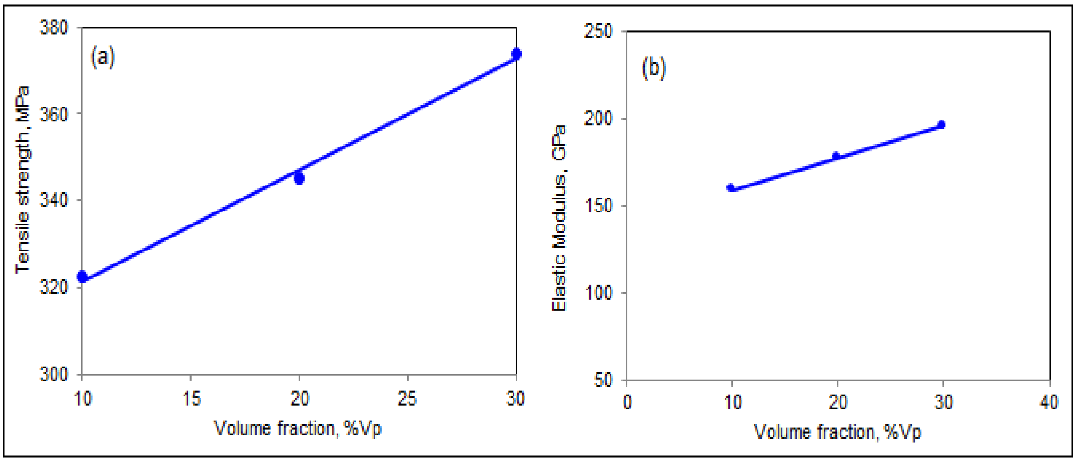


**Figure 2** Effect of volume fraction on (a) tensile strength and (b) Elastic modulus.

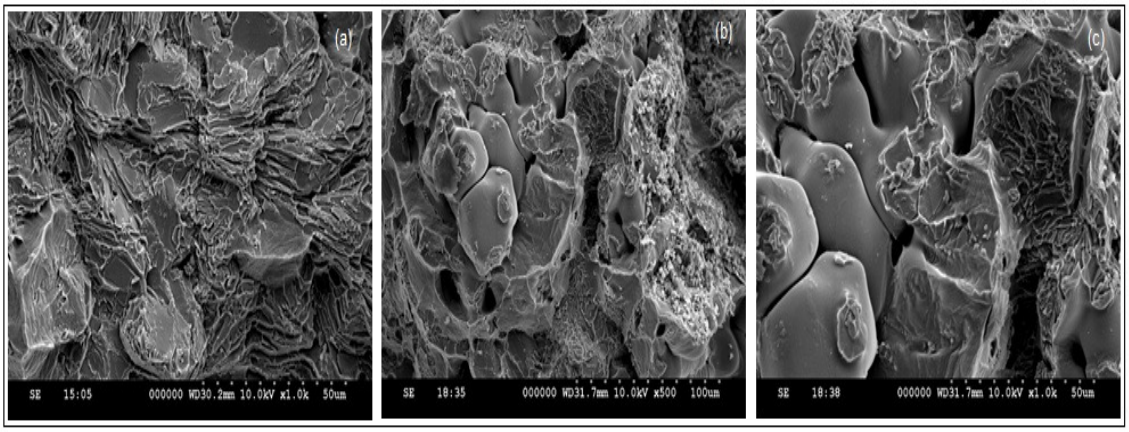


**Figure 3** Fractographs of AA6061/CB metal matrix composites: (a) 10%CB, (b) 20%CB and (c) 30% CB.

The percent contribution indicates that the volume fraction of CB, contributes 21.95% to the variation in the wear rate as given in Table 3. The normal load gives 2.96% of variation in the wear rate. The sliding speed affords 6.36% of variation in the wear rate. The sliding distance tenders 68.72% of the total variation in the wear rate. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.9640, 0.7338, 0.28872 and 0.9651. The trend of mean values obtained by Taguchi techniques is same as that of R-squared values.

**Table 3** ANOVA summary of the wear rate

| Source | Sum 1 | Sum 2 | Sum 3 | SS | v | V | P |
|---|---|---|---|---|---|---|---|
| A | 2.36E-02 | 2.07E-02 | 1.85E-02 | 4.25E-06 | 2 | 2.13E-06 | 21.95 |
| B | 2.01E-02 | 2.19E-02 | 2.09E-02 | 5.74E-07 | 2 | 2.87E-07 | 2.96 |
| C | 2.02E-02 | 2.25E-02 | 2.01E-02 | 1.23E-06 | 2 | 6.16E-07 | 6.36 |
| D | 1.71E-02 | 1.31E-04 | 6.28E-02 | 1.33E-05 | 2 | 6.66E-06 | 68.72 |
| e | | | | 5.42E-20 | 0 | 0.00 | 0.00 |
| T | 8.09E-02 | 6.53E-02 | 1.22E-01 | 1.94E-05 | 8 | | 100.00 |

**Note:** SS is the sum of square, v is the degrees of freedom, V is the variance, P is the percentage of contribution and T is the sum squares due to total variation.

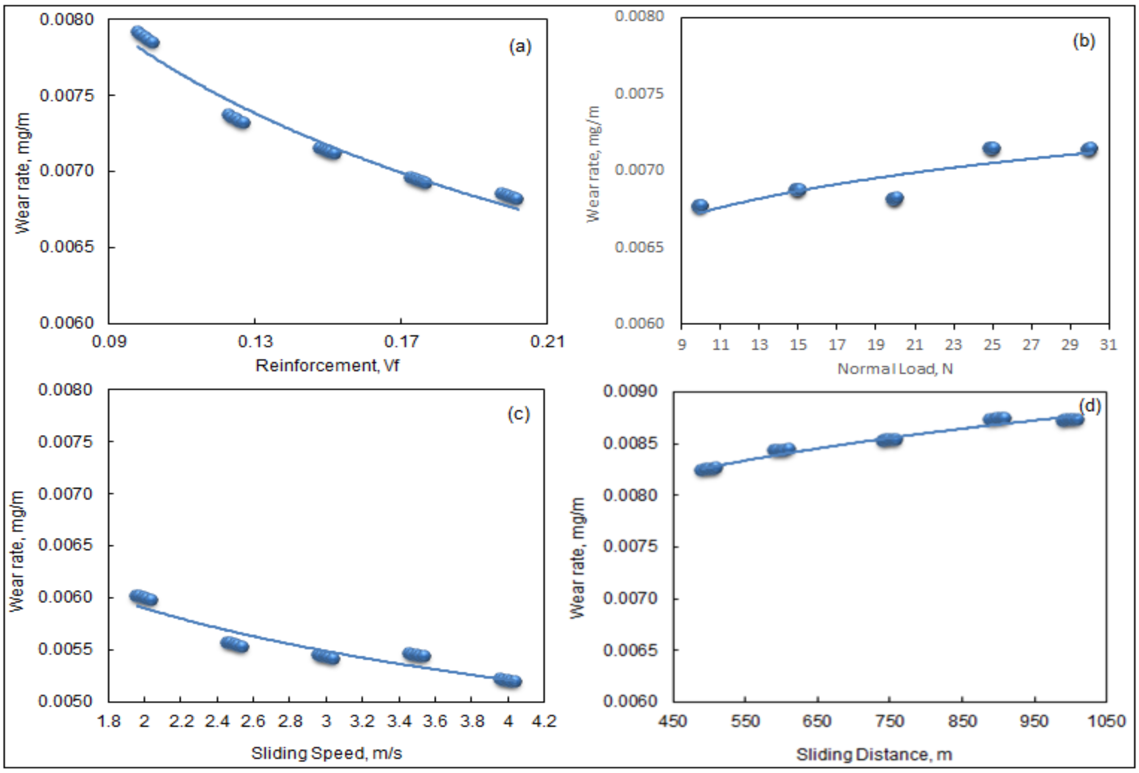


**Figure 4** Variation of wear rate with (a) volume fraction of CB, (b) Normal load, (c) sliding speed and (d) sliding distance.

The wear rate was decreased with increase in volume fraction of CB nanoparticles in AA6061 alloy matrix (figure 4a). This is due to high hardness of CB nanoparticles as compared to soft matrix. An increase in wear rate is with increase of normal load applied on the test specimen (figure 4b). This effect was due to adhesion and increase in plastic deformation at the surface layers. The wear rate was decreased by the increase of speed (figure 4c). The wear rate increased with the sliding distance as shown in figure 4d.

The mathematical relations between wear and volume fraction of CB content, normal load, sliding speed and sliding distance are given by

$$W_{rp} = 0.0049{v_f}^{-0.2025} \quad (1)$$

$$W_{rf} = 0.006F^{0.0512} \quad (2)$$

$$W_{rn} = 0.0067N^{-0.1792} \quad (3)$$

$$W_{rd} = 0.0049d^{0.0832} \quad (4)$$

where,

$W_{rp}$ is the wear rate due to vol.% of reinforcement (vf), mg/m
$W_{rf}$ is the wear rate due to normal load (F), mg/m
$W_{rn}$ is the wear rate due to speed (N), mg/m
$W_{rd}$ is the wear rate sliding distance (d), mg/m.

Rhee [23] 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

$$\Delta W = KF^aV^bt^c \quad (5)$$

where ΔW is the weight loss of the friction material and K, a, b and c are empirical constants. F is the applied load; v is the sliding speed; and t is the sliding time. In earlier work [20], the total wear of a metal matrix composite was defined as a function of reinforcement volume fraction, applied load, sliding speed and

sliding distance according to

$$\Delta W = KF^aV^bt^cS^d \quad (6)$$

where a, b, c and d are power law coefficients of reinforcement volume fraction (vf), applied load (F), sliding speed (V) and sliding distance (S), respectively. K is the empirical constant.

The values of power law coefficients a, b, c and d are, respectively, -0.2025, 0.0512, -0.1792 and 0.0832 from Equations (1) to (6). By substituting the representative values of Vf, F, N and S and their corresponding power law coefficients on the right side of Equation (6) and substituting the experimentally obtained wear rates on the left side of Equation (6), the value of K is determined. The over-all wear rate (mg/m) equation for AA6061/CB composites is given by

$$\Delta W = 2.96\,x10^{-3}F^{-0.2025}V^{0.0512}t^{-0.1792}S^{0.0832} \quad (7)$$

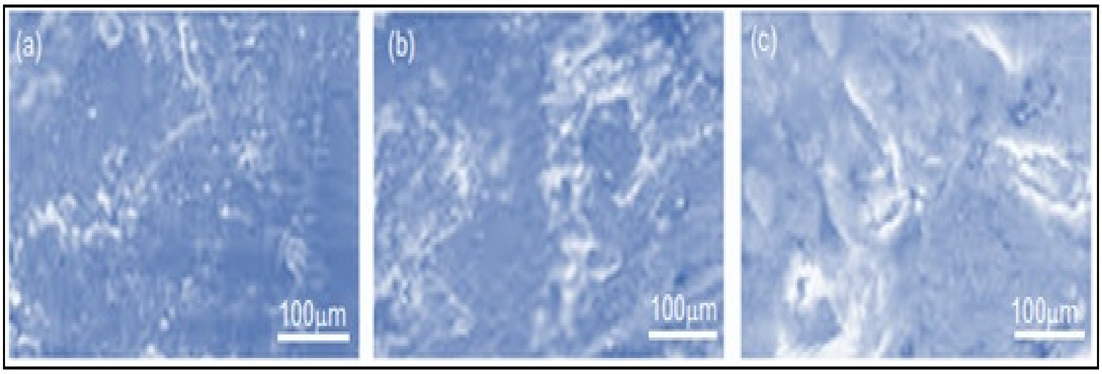


**Figure 5** Worn surfaces of AA6061/CB composites: (a) 10%CB, (b) 20%CB and (c) 30%CB.

The abrasive and adhesive wear mechanisms were recognized based on the worn surfaces as seen in figure 5. An increase in the reinforcement reduced the wear. The worn surfaces of AA6061/CB composites revealed cavities and large grooved regions on the wear surfaces and also enclosed carbon nanoparticles in the cavities, some of them having been pulled out. There was a change from a mild to a severe wear resulted by an increase in the sliding distance due to a greater plastic flow on the pin surface of the specimen. The particle pull-out was due to the poor particle/matrix bonding. This was on account of the abrasive mechanism of the composite material while resisting the delamination process. The wear resistance was greater in the case of composites having high volume fraction of carbon nanoparticles. The surface hardness of the composites was increased after wear test due to work hardening as shown in figure 6.

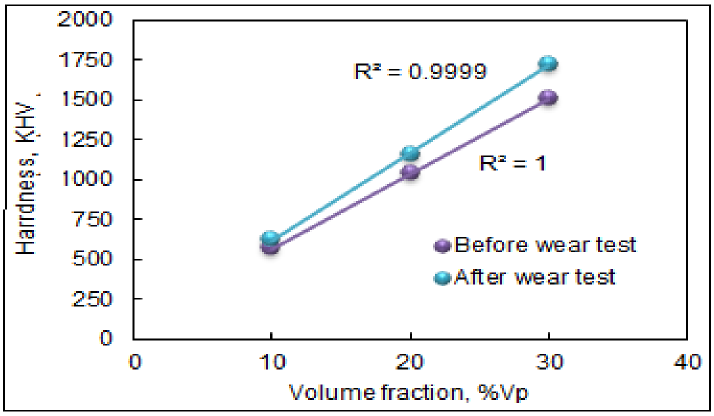


**Figure 6** Variation of knop hardness with volume fraction of CB.

## 4. CONCLUSION

In the present work experiments were conducted on AA6061/CB metal matrix composites to find the fracture behavior and sliding wear. The influential parameters were volume fraction of CB, normal load, sliding speed and sliding distance. The sliding wear is increased with increasing sliding distance and is decreased with increasing volume fraction of CB. Maximum sliding wear of 68.72% was attributed sliding distance. Compared with sliding wear of matrix alloy AA6061, sliding wear of AA6061/CB metal matrix composites is very low. Sliding wear resistance increases by 42.56% for AA6061/30%CB metal matrix composites as compared to the matrix alloy AA6061.

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