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Effects of Carbon Black Nanoparticles on Wear Resistance of AA6063/CB Metal Matrix Composites

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Abstract

Tribology is the study of surfaces in relative motion, and lubrication is one of the most life-threatening and underestimated aspects of mechanical design. In the current study, the effect of additions of different volume fractions of carbon black nanoparticles into AA6063 alloy prepared by stir casting on the fracture and wear behavior under different loads was investigated. The design of experiments was carried out as per Taguchi technique. The different parameters like volume fraction of carbon black nanoparticles, applied load, sliding speed and sliding distance were taken for this study. The wear tests were conducted on the pin-on-disc machine. The wear rates of AA6063 reinforced with carbon black nanoparticles are decreased with increasing the nanoparticles content. The results, also, show that the wear rate is found decreasing by increase in sliding distance.

Keywords: AA6063, carbon black, wear rate, fracture.

1. INTRODUCTION

Metal matrix composites (MMC), reinforced by nano-particulates, are being extremely examined for structural, thermal-management, and wear applications. Most of the studies on metal matrix composites have focused on aluminum (Al) as the matrix metal [1-9]. The combination of lightweight, corrosion resistance and adequate mechanical properties has made Al and its alloys composites very widespread. The retention and distribution of the nano-particulates are very important in production of composites materials. Most of the experimental and numerical studies have been carried out to understand the effect of the morphological variables, such as the particle volume fraction, particle size, shape and orientation on the deformation and damage behavior of the alloy [10-18].

These composites suffer a great loss in ductility and toughness due to the incorporation of non-deformable ceramic reinforcements. The wear properties dictate the life span of components in several applications [19, 20]. A combination of high wear resistance and high toughness of the interior bulk material is required to prolong the life span. The effects of reinforcement volume fraction, reinforcement size, sliding distance, applied load, sliding speed, hardness of the counter face and properties of the reinforcement phase which influence the dry sliding wear behavior of metal matrix composites are studied in greater aspects [21, 22].

In the current study, the fracture and wear behaviors of AA6063/carbon black metal matrix composites have been investigated.

2. MATERIALS AND METHODS

The matrix material was AA6063 aluminum alloy. The reinforcement material was carbon black nanoparticles of average size 100nm. The matrix alloys and composites were prepared by the stir casting and low-pressure die casting process. The major advantage of stir casting process is its applicability to mass production [23]. 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 AA6063/CB composites against hardened ground steel (En32) disc. 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 AA6063/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

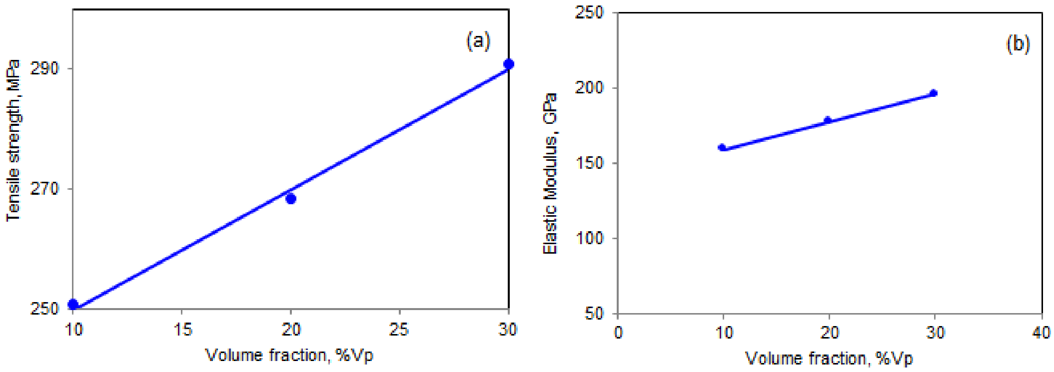

Figure 1: Effect of volume fraction on (a) tensile strength and (b) Elastic modulus.

3. RESULTS AND DISCUSSION

Figure 1 expresses the functions of tensile strength and elastic modulus of AA6063/CB metal matrix composites with volume fraction of carbon black. The tensile strength and elastic modulus of AA6063/10%C composites increase with volume fraction of CB. In AA6063/10%CB composites the matrix rupture takes place through a mechanism, which involves the growth of the voids by plastic straining and subsequent coalescence by localized necking of the intervoid matrix (figure 2a). The fracture due to tensile loading is ductile in the 6063/CB composite having volume fraction of 10%CB. The fracture process in 20%CB volume fraction 6063/CB composites is very much localized and the failure path in these composites is through the matrix due to the matrix rupturing and the connection of these microcracks to the main crack (figure 2b). Brittle fracture of 6063/30%CB composite indicates the interaction of dislocations with other dislocations, precipitates, and CB nanoparticles causes the dislocation motion (figure 2b).

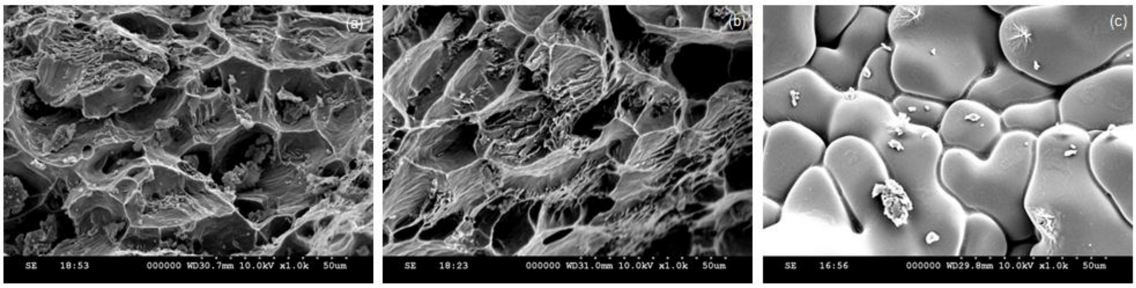

Figure 2: Fractographs of AA6063/ CB metal matrix composites: (a) 10%CB, (b) 20%CB and (c) 30% CB.

The percent contribution indicates that the volume fraction of CB, furnishes 28.34% to the variation in the wear rate as given in Table 3. The normal load offers 6.75% of variation in the wear rate. The sliding speed extends 5.64% of variation in the wear rate. The sliding distance enables 59.28% of the total variation in the wear rate. The R-squared values of %reinforcement, normal load, sliding speed and sliding distance are, respectively, 0.9723, 0.9344, 0.8952 and 0.9886. 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	2.45E-02	2.09E-02	1.89E-02	5.51E-06	2	2.76E-06	28.34
B	1.98E-02	2.23E-02	2.21E-02	1.31E-06	2	6.56E-07	6.75
C	2.09E-02	2.29E-02	2.04E-02	1.10E-06	2	5.49E-07	5.64
D	1.79E-02	1.39E-04	6.42E-02	1.15E-05	2	5.77E-06	59.28
e				-1.08E-19	0	0.00	0.00
T	8.31E-02	6.62E-02	1.26E-01	1.95E-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.

Owing to high hardness of CB nanoparticles, the wear rate was decreased with increase in volume fraction of CB nanoparticles in AA6063 alloy matrix (figure 3a). As the volume fraction of CB nanoparticles increases, the contact area between the nanoparticles and the steel disk increases, where the nanoparticles prevent the matrix becoming directly involved in the wear process. Therefore, at high volume fraction of nanoparticles, they cover nearly all the sample surface. As a result of that, increasing the volume fraction of CB nanoparticles in AA6063 based composite is accompanied by decreasing the wear rate. An increase in wear rate is with increase of normal load as shown in figure 3b. Under the application of load on the carbon black structure during the wear test of the composites, the bonding is easily broken resulting in enhancing the wear rate of the AA6063/CB composites. The wear rate was decreased by the increase of speed (figure 3c). A protective tribolayer was formed at nearly all sliding speeds. The formation of a thicker and more stable tribolayer, delaying the mild-severe wear transition as compared to the AA6063 aluminum alloy. The wear rate increased with the sliding distance as shown in figure 3d. the volume loss due to sliding wear increased linearly with the sliding distance, indicating that wear progressed under the steady state.

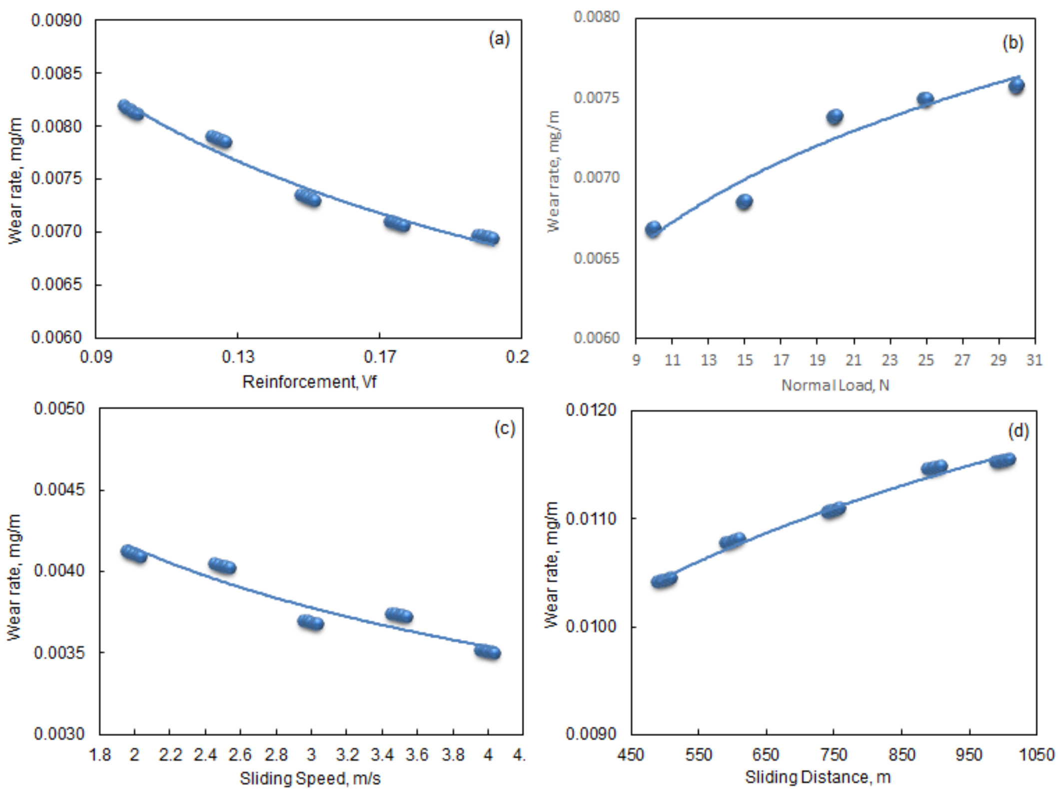

Figure 3: Variation of wear rate with (a) volume fraction of CB, (b) Normal load, (c) sliding speed and (d) sliding distance.

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

$$W_{rp} = 0.0046 v_f^{-0.2470} \quad (1)$$

$$W_{rf} = 0.005 F^{0.1258} \quad (2)$$

$$W_{rn} = 0.0048N^{-0.2270} \tag{3}$$

$$W_{rd} = 0.0042d^{0.1471} \tag{4}$$

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 [24] 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

$$\Delta W = KF^aV^bt^c \tag{5}$$

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

$$\Delta W = KF^aV^bt^cS^d \tag{6}$$

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, -0.2470, 0.1258, -0.2270 and 0.1471 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

$$\Delta W = 1.55\,x10^{-3}F^{-0.2470}V^{0.1258}t^{-0.2270}S^{0.1471} \tag{7}$$

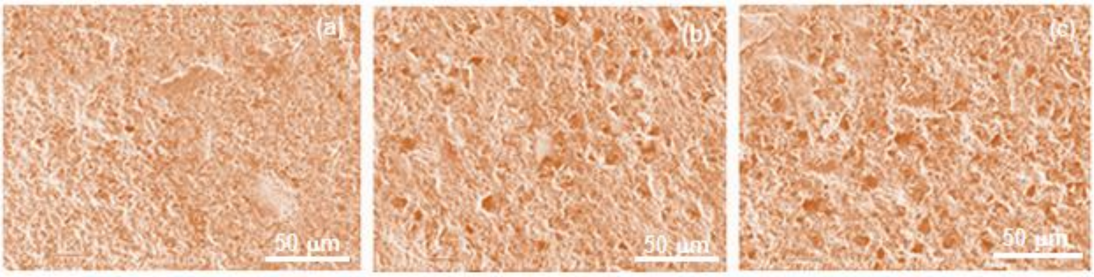

Figure 4: Worn surfaces of AA6063/CB composites: (a) 10%CB, (b) 20%CB and (c) 30%CB.

During wear process, cracks are propagated and later joined together to form flake-shaped wear debris. This infers that plastic deformation is localized in the subsurface region of the material adjacent to the contact surfaces. Large plastic strains boost the nucleation and growth of the voids at the nanoparticles located in the subsurface region. These voids then grow and coalesce to form crack, alloying the wear debris to delaminate. The dislodged CB nanoparticles, which mixed in the loose debris, may have acted as third body abrasive on both composite and steel surface (figure 4). If the interfacial cohesion between the CB nanoparticles and AA6063 matrix is weak, decohesion between the CB nanoparticles and AA6063 matrix will happen to nucleate microcracks before the CB nanoparticles are dislodged.

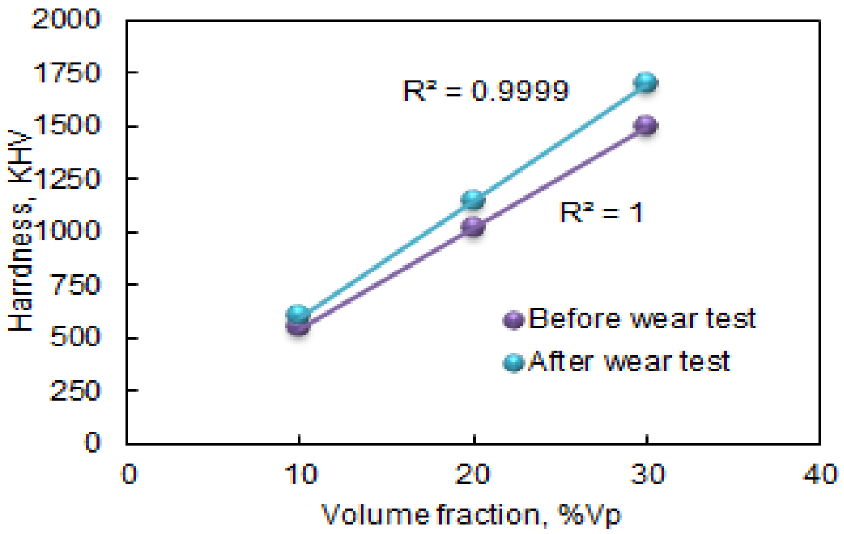

Figure 5: Function of Knoop hardness with volume fraction of CB nanoparticles.

The experimentally determined hardness data are included in the figure 5. It can be seen that the knop hardness of the composites increases with the volume fraction of the CB nanoparticles. The increase in the

Knop hardness of the composites is caused by the decrease in the dislocation slip distance with the increase in the volume fraction of the CB nanoparticles.

4. CONCLUSION

In the current work experiments were conducted on AA6063/CB metal matrix composites to assess the fracture behavior and sliding wear. The significant parameters were volume fraction of CB 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 59.28% was ascribed to sliding distance. Compared with sliding wear of matrix alloy AA6063, sliding wear of AA6063/CB metal matrix composites is very low. Sliding wear resistance increases by 39.94% for AA6063/30%CB metal matrix composites as compared to the matrix alloy AA6063.

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