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Sand Abrasive Wear Behavior of Hot Forged Al 6061-TiO_2 Composites

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Nickel-coated TiO_2 particulate reinforced Al6061 matrix composites developed using the vortex technique were hot forged at a temperature of 500 °C. A constant deformation ratio of 6:1 was adopted. Hot forged Al6061 alloy and Al6061-TiO_2 composites were then subjected to heat treatment by solutionizing at a temperature of 530 °C for duration of 2 h followed by ice quenching. Both natural and artificial aging at 175 °C were performed on the quenched samples from 2 to 8 h duration in steps of 2. Microstructure, microhardness, and dry sand abrasive wear behavior of both matrix alloy and developed composites in both as-forged and heat-treated conditions have been evaluated. Worn surface studies have been carried out using scanning electron microscope. Results have revealed that nickel-coated TiO_2 particles are uniformly distributed through out the matrix alloy. Microhardness of Al6061-TiO_2 composites increases with increase in percentage of reinforcement. Heat-treated forged alloy and its composites possesses higher hardness when compared with the forged composites. Forged Al6061-TiO_2 composites exhibited lower abrasive wear loss when compared with the forged matrix alloy. Heat treatment has a profound effect on the abrasive wear resistance of both as-forged Al6061 alloy and Al6061-TiO_2 composites.

Keywords abrasion, forging, metal matrix composites

1. Introduction

Particulate reinforced aluminum alloy matrix composites have received wide spread attention over many years due to their superior performance over conventional alloys (Ref 1). Their several tailor-made properties such as low density, high stiffness, high strength, coupled with good wear resistance have made them suitable for many engineering applications.

Among several techniques available to develop aluminum-based metal matrix composites, liquid metallurgy route is one of the most effective method, in view of its simplicity, mass production, easy adaptability, and applicability to large quantity production (Ref 2, 3). However, composites prepared by this method do exhibit certain limitations such as nonuniform distribution and poor wettability of ceramic particles with the molten metal leading to the absence of sound interface between matrix and reinforcement. Formation of interfacial products and incomplete adhesion leads to generation of inherent casting defects (Ref 4, 5). It has been reported that the above-mentioned problems can be effectively addressed by providing a thin metallic coating on the ceramic particles before addition in to the molten metal (Ref 6, 7).

On the other hand, another important reason for recognizing aluminum-based composites as candidate materials for engineering applications especially for aerospace and automotive is that they can be readily shaped with conventional secondary metal working processes such as extrusion, forging, rolling, etc. (Ref 8). Since, these processes can alter the microstructural parameters of the composites, they do influence the mechanical and wear properties of the composite materials (Ref 9). Further, it has been reported that hot deformed aluminum-based composites do exhibit excellent strength coupled with high ductility when compared with primarily processed techniques such as casting, spray deposition, etc. (Ref 10). Among all the available secondary processing routes, forging is the most sought after in automotive applications, as it can offer large plastic deformation without the failure of formed parts (Ref 11). Added to this, it is possible to achieve rapid production of near-net-shaped components without incurring any damage (Ref 12). Further, improvements in the mechanical properties and wear resistance of aluminum matrix composites can be achieved by adopting suitable heat treatment. Das et al. (Ref 13) have reported the abrasive wear behavior of as-cast and heat-treated SiC reinforced Al-Si composites. They have reported that unreinforced alloy suffers from higher wear rates than that of composites in both as-cast and heat-treated conditions. Further, heat-treated composites exhibit better performance under all the studied conditions. Modi et al. (Ref 14) have studied the three body abrasive wear behavior of Al_2O_3 reinforced aluminum-zinc alloy and have reported excellent wear resistance of composites under all the test conditions employed. Sanjeev et al. (Ref 15) have carried out a comparative study on abrasive wear resistance of zircon sand and alumina reinforced aluminum matrix composites. Their results have revealed that abrasive wear resistance of both the composites improved with the decrease in particle size. However, alumina particle reinforced composite after forging shows relatively poor wear resistance property compared to zircon-reinforced composite. Ramesh et al. (Ref 16) have studied the adhesive wear behavior of cast Al6061-TiO_2 composites. Their results revealed

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that compared to matrix alloy, the wear resistance of the Al6061-TiO_2 composites is superior and it increases with increase in content of TiO_2 particles.

In the light of the above, the present investigation focuses on the sand abrasive wear behavior of hot forged Al6061-TiO_2 composites. Effects of heat treatment on wear resistance of Al6061-TiO_2 composites have also been studied.

2. Experimental Details

2.1 Material Selection

Al6061 alloy were chosen as matrix material owing to its several advantages such as excellent casting properties, reasonable strength, formability, and heat treatment capability. Table 1 shows the chemical composition of Al6061 alloy used in this study.

Titanium dioxide (TiO_2) of particle size 2-40 µm was used as the reinforcement material in Al6061 matrix. TiO_2 possess very high hardness and modulus coupled with superior corrosion resistance (Ref 16).

TiO_2 particles were nickel coated to improve its wettability in molten aluminum alloy and to avoid any possible reaction between the matrix and reinforcement. Electroless coating technique was used to nickel coat TiO_2 particles as described elsewhere (Ref 7, 8).

2.2 Composite Preparation and Hot Forging

Al6061-TiO_2 composites were prepared using vortex technique (Ref 8). Al6061 alloy was melted using a 6 kW electrical resistance furnace. Nickel-coated TiO_2 particles were slowly added in to the molten alloy and mixed thoroughly by means of mechanical stirrer. After thorough mixing the composite melt maintained at a temperature of 720 °C was poured in to the preheated metallic molds. The proportion of nickel-coated TiO_2 was varied from 4 to 8 wt.% in steps of 2 wt.%. However, 8 wt.% of uncoated TiO_2 particles were also dispersed in the matrix alloy for comparison.

Cast Al6061 alloy and Al6061-TiO_2 composites were machined to cylindrical billets of diameter 80 mm and 80 mm length. The machined cast samples were then subjected to hot forging using a one tonne drop forge hammer. Billet temperature of 500 °C and a constant deformation ratio of 6:1 was adopted for all the forging operations.

2.3 Heat Treatment

Hot forged Al6061 alloy and Al6061-TiO_2 (Ni-P coated) were subjected to heat treatment by solutionizing at a temperature of 530 °C followed by quenching in ice media. Both artificial and natural aging (0 h) were adopted on the quenched samples. Artificial aging was performed at a temperature of 175 °C for duration of 2 to 8 h in steps of 2 h.

2.4 Microstructure

Forged Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites were subjected to scanning electron microstructural studies. For microstructural characterization, the samples were cut from both forged Al6061 alloy and its composites and polished using standard metallographic techniques. The polished samples were etched with Keller's reagent.

2.5 Microhardness

Microhardness tests were carried out on polished samples of forged Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites, using Vickers hardness tester. A load of 100 g for a period of 10 s was adopted. The test was carried out at five different locations to controvert the possible effect of indenter resting on the harder particles. The average of all the five readings was taken as hardness of sample.

2.6 Sand Abrasion Test

The three body (also termed as low-stress) abrasion test was performed at room temperature on forged Al6061 alloy and Al6061-TiO_2 composites in both unheat-treated and heat-treated conditions. The tests were carried out using standard rubber wheel abrasion test apparatus as per ASTMG65-81 standards. Figure 1 shows the photograph, while Table 2 reports the details of the sand abrasion tester used in this study. Metallographically polished samples (3.0 µm CLA) of size $75 \times 25 \times 8$ mm served as test samples. Loads varied from 2 to 10 N in steps of 2N while maintaining a constant wheel speed of 200 rpm. Silica sand of size 50 µm was used as abrasive media. Test duration of 1 h was adopted for all the samples. The detailed test procedure is described elsewhere (Ref 17). Wear loss was measured in terms of mass loss using a digital weighing balance of accuracy 0.1 mg. After the test, the worn surfaces were subjected to SEM studies to analyze the wear mechanisms involved. JEOL 8000 was used for this purpose.

3. Results and Discussions

3.1 Nickel-Coated TiO_2 Particle Analysis

Figure 2 shows the SEM of as procured TiO_2 powder and nickel-coated TiO_2 powder. The procured TiO_2 powder has an irregular morphology with their size varying between 2 and 20 µm. Coated TiO_2 have a spherical morphology (Fig. 2b). Figure 3 shows the EDAX pattern of nickel-coated TiO_2 powder confirming the presence of nickel. Tin is also observed as TiO_2 powders were subjected to sensitization using stannous chloride.

Table 1 Chemical composition of Al6061 alloy

Si	Fe	Cu	Mn	Ni	Pb	Zn	Ti	Sn	Mg	Cr	Al
0.43	0.43	0.24	0.139	<0.05	0.024	0.006	0.22	0.001	0.802	0.184	Balance

Fig. 1 Photograph of sand abrasion tester

Table 2 Details of sand abrasion tester

Sl. no.	Description	Capacity
1	Abrasive	AFS 50-70 test sand
2	Wheel speed	200 rpm through a helical geared motor of 1.5 kW (3 phase)
3	Test load	1 to 45 N
4	Wheel diameter	228 mm
5	Power input	430 V AC (3 Phase)
6	Dimension of the specimen	75 × 24 × 8 mm
7	Erodent	AFS3080
8	Mass flow rate	0.25 kg/min or 2.45 N/min
9	Hardness(Rubber)	60-62 shore A
10	Duration	30 min (6000 rev)
11	Pressure	5.88 N/mm^2
12	Load	12.75 N

3.2 Microstructural Studies

Figure 4 shows the SEM of forged Al6061 alloy, while Fig. 5 shows the optical micrographs of forged composites after image analysis confirming the uniformity in the distribution of TiO_2 particles throughout the matrix alloy.

Figure 6 shows the SEM micrograph of intermetallic precipitates (Mg_2Si) formed after heat treatment. Most of the precipitates are located along the grain boundaries. Figure 7 shows the EDAX pattern of Mg_2Si precipitates clearly indicating the presence of Mg and Si peaks.

3.3 Microhardness

Figure 8 shows the variations of microhardness of forged Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites in as forged and heat-treated conditions. It is observed that the microhardness increases with increase in percentage of TiO_2 particles in matrix alloy in both as-forged and heat-treated conditions. A maximum of 28.78 and 54.5% improvement is noticed in as-forged and heat-treated Al6061-8 wt.% TiO_2 composite, respectively, when compared with as forged matrix alloy.

Increased microhardness with increase in percentage of TiO_2 particles in the matrix alloy can be attributed to the following reasons.

1. Higher hardness of TiO_2 particles. Hard reinforcement in a soft and ductile matrix always enhances the hardness of the matrix alloy in general (Ref 17, 18).
2. Excellent bond between matrix alloy and reinforcement as a result of metallic coating of TiO_2 particles (Ref 16-18).
3. Increased content of reinforcement in the matrix alloy leads to increased dislocation densities during solidification due to thermal mismatch between Al6061 alloy and TiO_2 particles leading to retardation in plastic deformation. Higher dislocation densities together with the reinforcement particles will result in hindered dislocation movement resulting in higher hardness (Ref 8, 18).

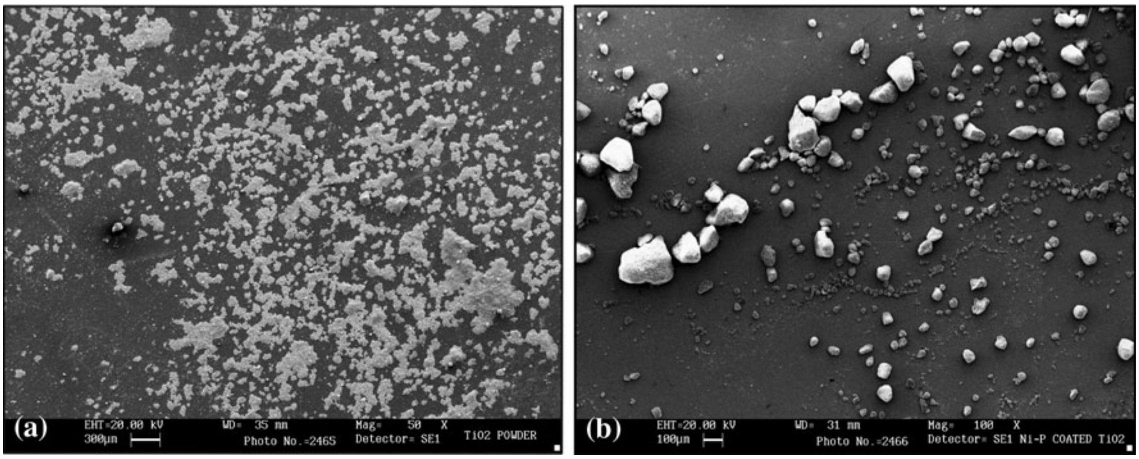

Fig. 2 Scanning electron micrographs of TiO_2 particles. (a) TiO_2 particles as procured and (b) nickel-coated TiO_2 particles

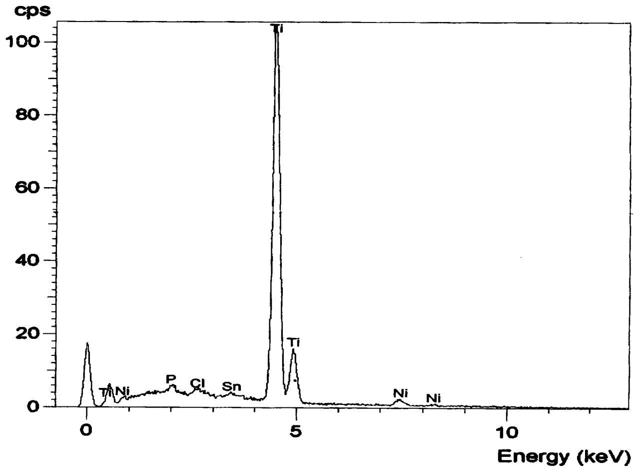

Fig. 3 EDAX pattern of nickel-coated TiO_2 particulate

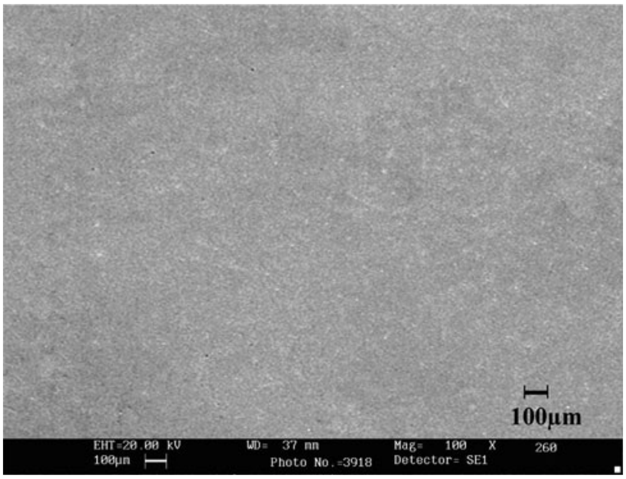

Fig. 4 Scanning electron micrograph of hot forged Al6061 alloy

It is also observed that the heat treatment has profound influence on microhardness of forged Al6061 alloy and Al6061-TiO_2 composites. All the heat-treated samples exhibit higher microhardness values when compared with as forged alloy and its composites. Improved hardness in heat-treated samples can be mainly attributed to the formation of intermetallic precipitates namely Mg_2Si from the super saturated solid solution as evidenced in Fig. 6.

Figure 9 shows the variation of microhardness of hot forged Al6061 and Al6061-TiO_2 composites with increase in aging duration. It can be observed that increase in aging duration resulted in increased microhardness for both the matrix alloy and its composites. Further, all the composites and matrix alloy do exhibit maximum hardness at 6 h of aging duration. A maximum of 51% improvement in hardness is noticed in forged Al6061-8 wt.% of TiO_2 composite aged for 6 h duration. The increased microhardness with increased aging duration can mainly be attributed to the formation of larger extent of intermetallic precipitates in a fine state of dispersion. Finer the precipitates, greater will be the obstruction to the motion of dislocations there by leading to increased microhardness. However, slight decrease in microhardness was noticed for both the matrix alloy and composites on aging for 8 h. This may be due to the fact that the long aging duration does result in coarsening of intermetallic precipitates. Presence of coarser intermetallic precipitates does results in reduced hardness (Ref 19, 20).

3.4 Sand Abrasion Test Results

3.4.1 Effect of Ni-P Coating. Figure 10 shows variation of abrasive weight loss of as-forged Al6061 alloy and Al6061-8 wt.%TiO_2 composites (both coated and uncoated). It is observed that Ni-P coating on TiO_2 particles has resulted in significant improvement of the abrasive wear resistance of the composites at all the loads studied.

3.4.2 Effect of Reinforcement. Figure 11 shows variation of abrasive weight loss of as-forged and heat-treated Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites. It is observed that weight loss decreases with increase in reinforcement in matrix alloy in both as-forged and heat-treated conditions. In all the samples studied, heat-treated samples do exhibit better performance than as-forged alloy and its composites. A maximum of 61 and 69% reduction is noticed in as-

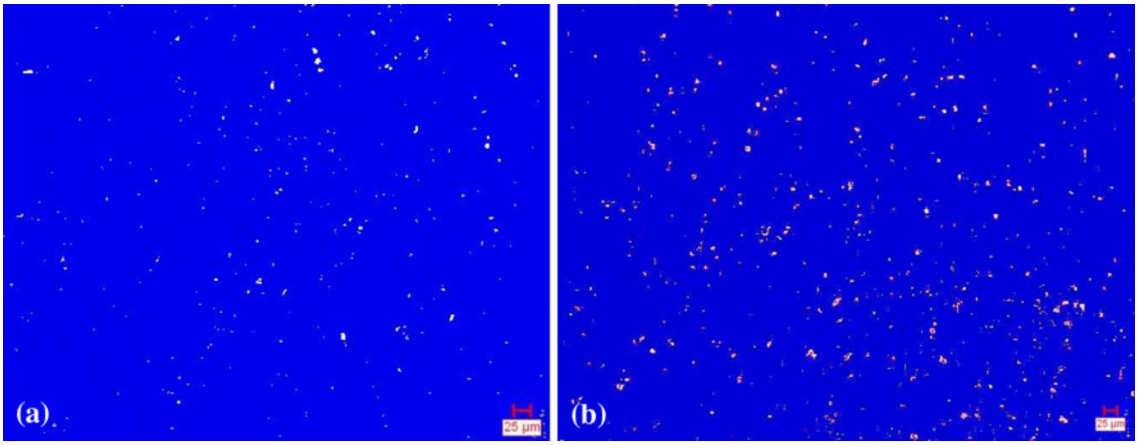

Fig. 5 Optical micrographs of hot forged Al6061-TiO_2 composites. (a) Al6061-6 wt.% TiO_2 composite and (b) Al6061-8 wt.% TiO_2 composite

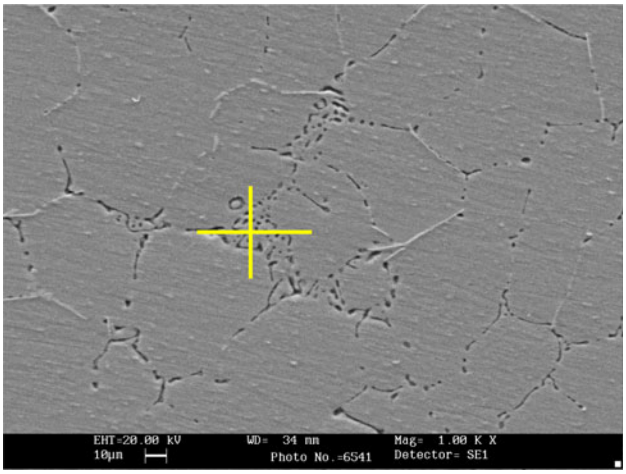

Fig. 6 SEM photograph showing Mg_2Si Precipitate

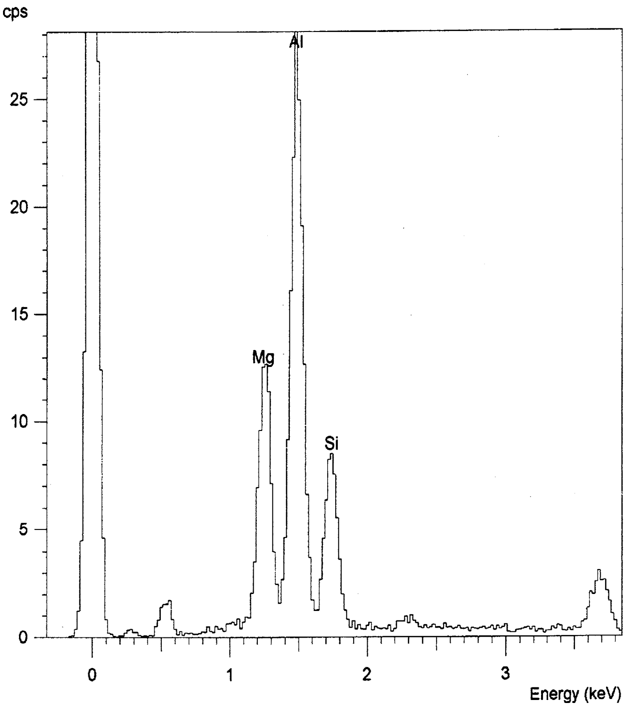

Fig. 7 EDAX pattern of Mg_2Si precipitate

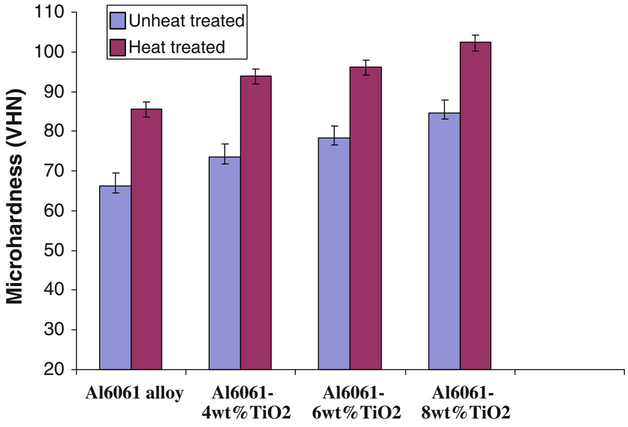

Fig. 8 Variation of microhardness of hot forged and heat-treated Al6061-TiO_2 (Ni-P coated) composites with percentage of reinforcement

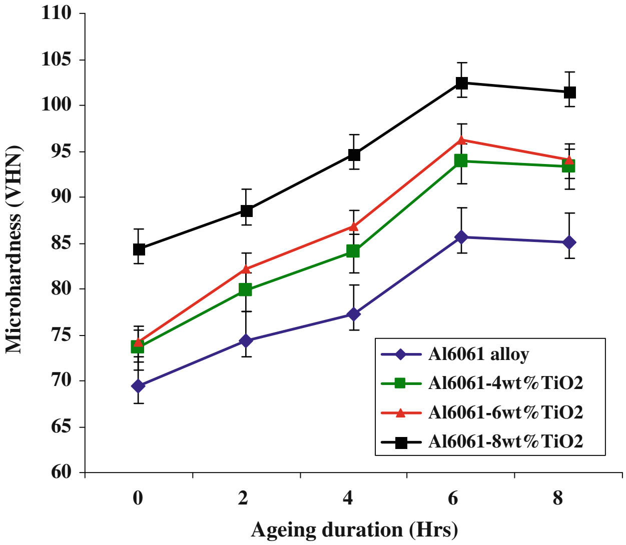

Fig. 9 Effect of aging duration on microhardness of Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites

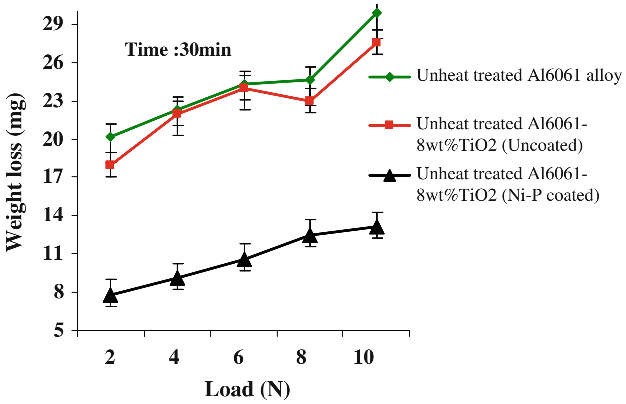

Fig. 10 Variation of abrasive wear loss of uncoated and Ni-P coated TiO_2 reinforced composites with load

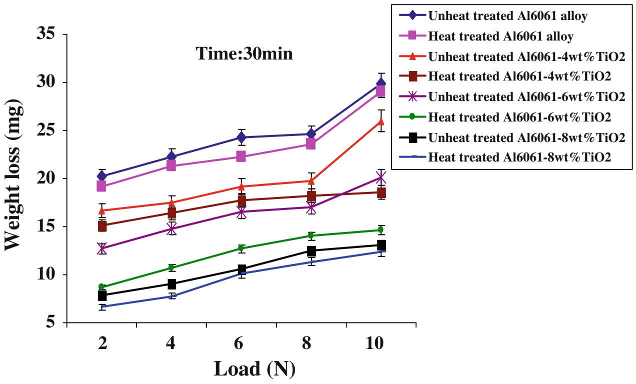

Fig. 12 Variation of weight loss of Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites with load

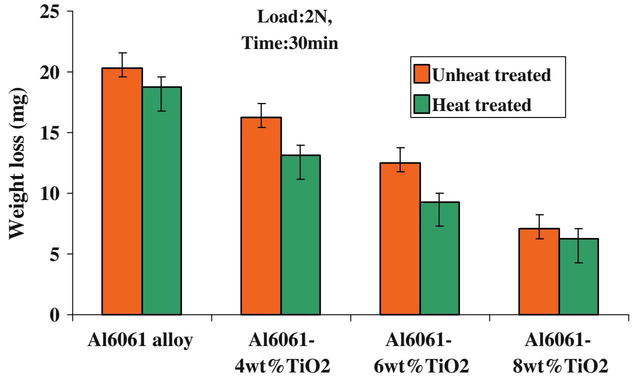

Fig. 11 Variation of weight loss of Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites with reinforcement

forged Al6061-8 wt.%TiO_2 composites and heat-treated Al6061-8wt.%TiO_2 composites, respectively, when compared with their alloys. Decreased weight loss with increase in percentage of reinforcement can be attributed to higher hardness of composites. Higher the hardness better is the abrasive wear resistance of the materials. The presence of hard TiO_2 particles protects the soft ductile matrix by reducing the extent of penetration of the abrasive particles on the surface (Ref 21).

On the other hand, there exist excellent bond between matrix and reinforcement as a result of metallic coating of TiO_2 particles. The presence of good bond between the matrix and the reinforcement is a major factor that influences the wear behavior of forged composites. In absence of a good bond, three body abrasive wear situation does arise resulting in large wear rates (Ref 3, 22).

Further, there is no indication of plucking of TiO_2 particles from the matrix as a result of abrasion. This fact suggests that a strong bond exist between TiO_2 particles and the matrix. It is also reported that the wear behavior of hard particle-reinforced composites depends primarily on the type of interfacial bonding between the Al matrix and the reinforcement (Ref 23).

3.4.3 Effect of Load. The dependence of weight loss of Al6061 matrix alloy and Al6061-TiO_2 composite with load in as-forged and heat-treated condition is shown in Fig 12. There is a steady increase in wear up to a load of 6 N and a steep increase in wear is observed at 8 N for all the materials studied. The increase in wear loss with increased load can be attributed to the larger extent of plastic deformation at higher loads and an increased effective contact area between rubber wheel and specimen.

In a multiphase material like metal matrix composites containing hard phases like ceramic reinforcement and softer metallic matrix, the harder one carries the major portion of applied stress and protects the relatively soft alloy matrix. The hard dispersoid particles also remain present on the specimen surface as protuberance and protect the abrasives to come in effective contact with the matrix surface. Thus, the ceramic particles can protect the matrix more effectively at lower loads (Ref 24).

In the regime where composites exhibit less wear as compared to the alloy, the improvement in wear resistance of the composite over the base alloy increases with increase in load. This shows that at higher load, the composite shows significantly higher wear resistance than that of the base alloy. This may be due to increased protection offered by dispersoid particles to matrix from the abrasive action of the abrasive particles (Ref 25, 26).

The increase in weight loss with increased load of all the materials studied can be attributed to the larger extent of plastic deformation at higher loads. It is reported that the wear loss of MMCs increased with applied load since the extent of fracture of the reinforcement also increases as the load rises (Ref 27).

3.4.4 Effect of Aging Duration. Figure 13 shows the variation of weight loss Al6061 alloy and Al6061-TiO_2 composites with increase in aging duration. The abrasive wear resistance of Al-based composites may be controllably altered by thermal aging. When the composites were under-aged, the aluminum alloy matrices contain significantly less number of coherent and semi-coherent precipitates which had little resistance to plastic deformation and therefore provided the aluminum low wear resistances (Ref 28).

It is observed that an increase in aging duration has resulted in reduced abrasive wear loss up to 6 h of aging for both the forged 6061 alloy and Al6061-TiO_2 composites. The abrasive weight loss has almost becomes stable beyond 6 h of aging. A maximum decrease of 72.2% in the abrasive wear loss has been noticed in the Al6061-8 wt.%TiO_2 composites in ice quenched and artificial aged for 6 h duration, when compared with as-forged Al6061 alloy. The decreased abrasive wear loss of the composites with increase in aging duration can be attributed to improved hardness with increased aging duration. The increased aging duration will accelerate the kinetics of precipitation hardening in the composites. This phenomenon will result in larger extent of formation of intermetallic precipitates in fine state of dispersion, leading to higher hardness. However, further increase in aging duration results in coarser intermetallic precipitates, reducing the hardness as discussed earlier leading to increased weight loss. On the other hand, formation of such precipitates (Mg_2Si) provides resistance to plastic deformation as the abrasive particles pass across the composite surface and lowers the material loss from the surface (Ref 28).

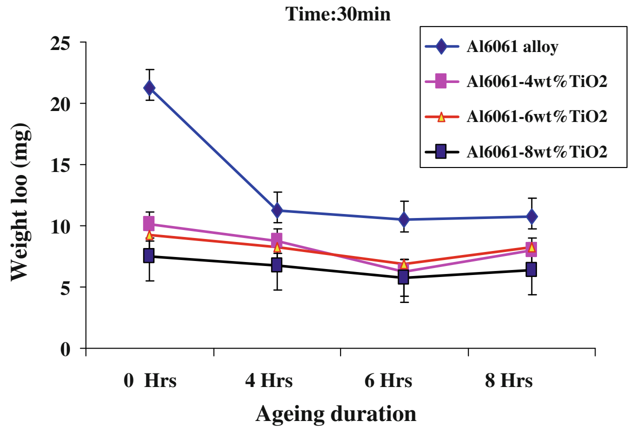

Fig. 13 Variation of weight loss of Al6061 alloy and Al6061-TiO_2 composites with aging duration

3.4.5 Worn Surface Analysis. SEM photographs of the worn surfaces of the matrix alloy and its composites in both heat-treated and unheat-treated conditions are shown in Fig. 14. Extensive plastic grooving and plowing have been observed on unheat-treated Al6061 alloy when compared with heat-treated Al6061 alloy. This may be due to the increased hardness of the matrix due to aging. It is observed from Fig. 14(b) and (d) that the extent of grooving in composite is minimal when compared with matrix alloy under identical test conditions. Further, the grooves are fine and minimal plastic deformation has been noticed in case of composite as shown in Fig. 14(c) and (d). It is also observed that among all the systems studied, heat-treated Al6061-8 wt.% TiO_2 composites exhibited the least extent of grooving as shown in Fig. 14(d). Owing to the lower surface hardness of the matrix alloy, the abrasive particles are capable to dig in and plow out the material. As far as composites materials are concerned, the abrasive particles have resulted in surface scratching rather than plowing out leading to lower material removal.

The above discussion is supported by the average roughness values of the worn surfaces as shown in Fig. 15(a) to (d). The average peak-to-valley height (R_a) values are 3.22 and 3.07 µm for unheat-treated and heat-treated matrix alloy, respectively, while 8 wt.% TiO_2 composite under unheat-treated and heat-treated exhibited R_a values of 1.52 and 1.44 µm, respectively.

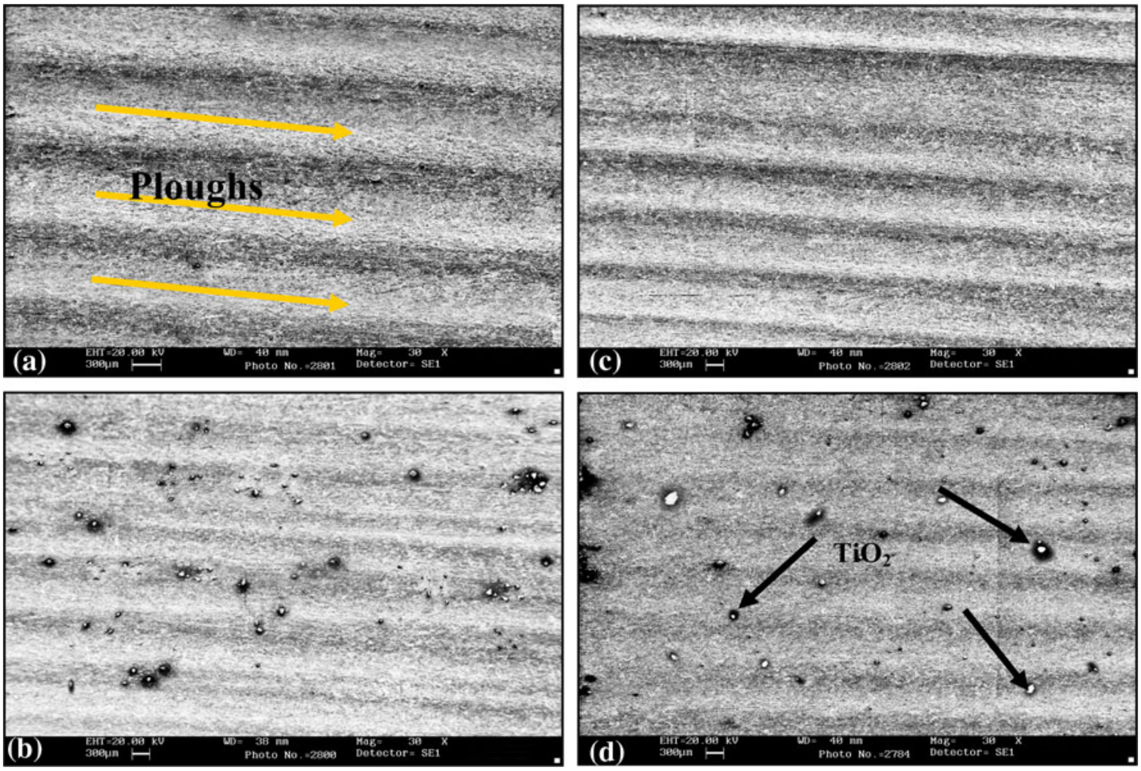

Fig. 14 SEM Photographs of hot forged worn surfaces (a, b) unheat-treated Al6061 alloy and Al6061-8 wt.%TiO_2, respectively; (c, d) heat-treated Al6061 and Al6061-8 wt.%TiO_2, respectively

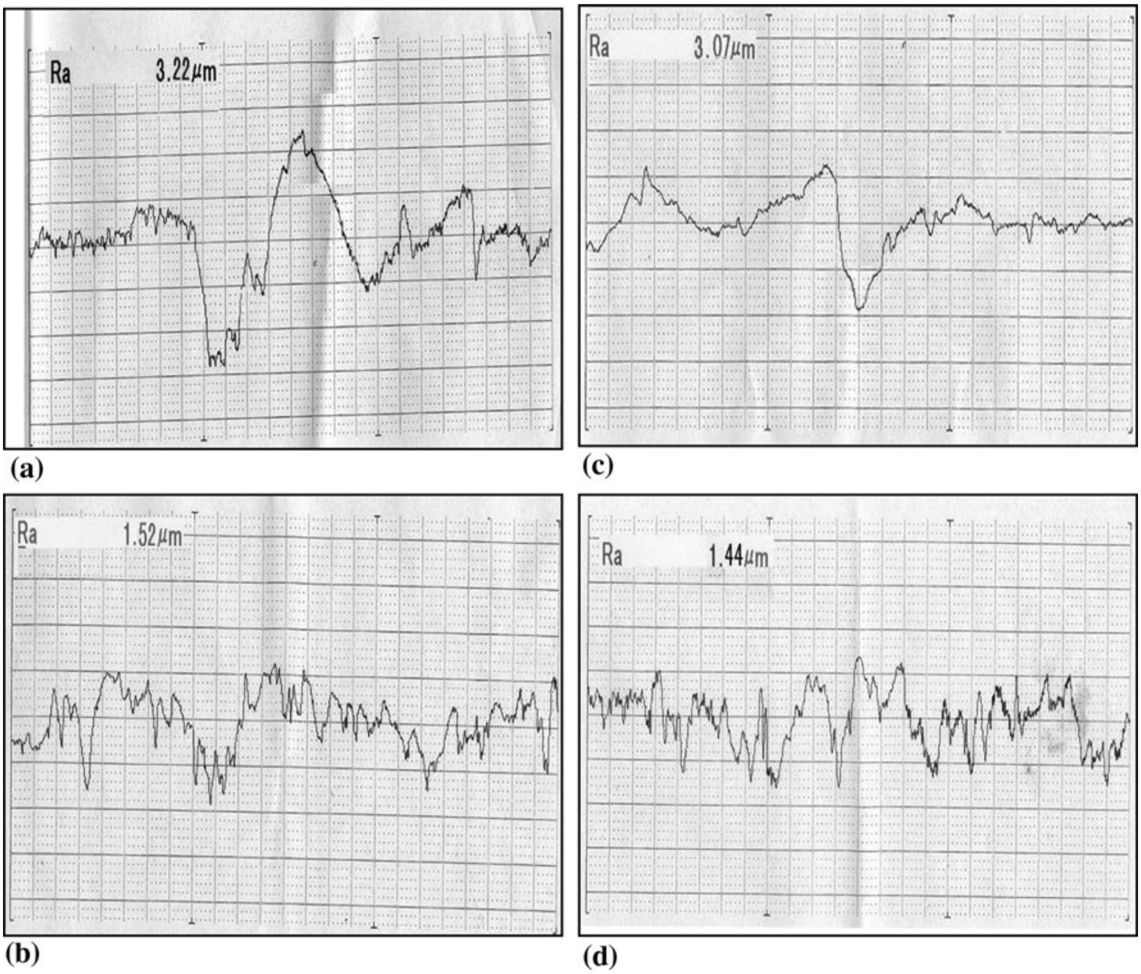

Fig. 15 Surface roughness of hot forged worn out surfaces (a, b) unheat-treated Al6061 alloy and Al6061-8 wt.%TiO_2, respectively; (c, d) heat-treated Al6061 and Al6061-8 wt.%TiO_2, respectively (Ni-P coated)

4. Conclusions

Al6061-TiO_2 composites exhibit superior microhardness and abrasive wear resistance than Al6061 alloy in as-forged and heat-treated conditions. Microhardness and abrasive wear resistance increases with aging duration, reaches a peak value at 6 h with further increase in aging duration there is a decrease in both hardness and abrasive wear resistance of Al6061 alloy and Al6061-TiO_2 (Ni-P coated) composites.

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