Influence of microstructural changes caused by ageing on wear behaviour of Al6061/SiC composites

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Abstract : Al-based metal matrix composites are being used to manufacture various parts of automobiles. The automobile components undergo sliding as well as abrasive type of wear against the counter surface during operation. In order to understand this phenomenon, wear tests of the as-cast and aged-composites were carried out at different loads. The removal of the particles from the matrix will play a major role in enhancing wear. With the increase in hardness of the composite due to aging as well as the formation of the hard precipitates, the aged composite is expected to provide resistance against microcutting. The reason for formation of precipitates near the interface can be attributed to the high density of dislocations near the interface.

Keywords : Metal matrix composites, Al-based particulate composites, Automobile component, Microstructure, Wear behaviour.

INTRODUCTION

The automobile industry has successfully applied Al-based particulate composites, largely Al/SiC and Al/Al$_2$O$_3$ to manufacture pistons, engine blocks, disc rotor brakes, drums, connecting rods, internal combustion engine cylinder liners, and drive shafts. Ebisawa *et. al.*[1] reported that Al-based particulate composite engine block was manufactured by Honda in the early 1990s. The Al-based particulate composite engine block is added compact with significant weight reductions compared with cast iron engine blocks and those made of aluminum alloy with cast iron liners. Aluminum composites have superior thermal conductivity and lower density than cast iron, and this has been cost-effective in disc brake manufacturing. Aluminum composite brake rotors provide up to 60% weight reduction when compared to cast iron as per the conclusion drawn by Weiss[2]. The automobile components undergo sliding as well as abrasive type of wear against the counter surface during operation. Several studies have been carried out to evaluate the sliding and abrasive wear behavior of aluminum matrix composites under varying tribological conditions[3]. Most of these studies have been focused on the influence of the type, volume fraction, size and the geometry of the reinforcing elements on wear behavior. Very little attention has been directed towards the effect of ageing on the wear resistance.

Prabhu et al have revealed that a uniform dispersion of the reinforcement into the liquid matrix is difficult due to poor wetting of the ceramic particles by molten alloy, obtaining[4]. It was also found that the presence of brittle and nearly non-deformable reinforcements in metal matrix composites can result in undesirable phenomena, such as fracture of reinforcement, debonding of interface, or surface cracking in the extruded product[5].

In the present investigation, an effort has been made to transmit the changes in the microstructure

caused by ageing to the changes in the wear behavior of composite. In order to understand this phenomenon, wear tests of the as-cast and aged-composites were carried out at different loads.

EXPERIMENTAL PROCEDURE

The matrix alloy is Al 6061 having the chemical composition given in Table 1. Al 6061 was melted in a resistance furnace. The crucibles were made of graphite. The melting losses of alloy constituents were taken into account while preparing the charge. The charge was fluxed with coverall to prevent dressing. The molten alloy was degasified by tetrachlorethane (in solid form). The crucible was taken out of the furnace and modified with sodium. Then the liquid melt was allowed to cool down just below the liquidus temperature to bring the melt semi solid state. At this stage, the preheated (1000^{0}C for 1 hour) silicon carbide (SiC) particles were added to the liquid melt. The volume fraction SiC is 20%. The average SiC particle size is 10μm. The molten Al 6061 alloy and SiC particles are thoroughly stirred manually. After sufficient manual stirring, the semi-solid liquid melt was reheated to a fully liquid state in the resistance furnace followed by automatic mechanical stirring using a mixer to make the melt homogenous for about 15 minutes at 200 rpm. The temperature of the melt was measured using a dip type thermocouple. The dross removed melt was finally gravity poured into the preheated cast iron mould.

Table 1 : Chemical composition of Al6061 alloy

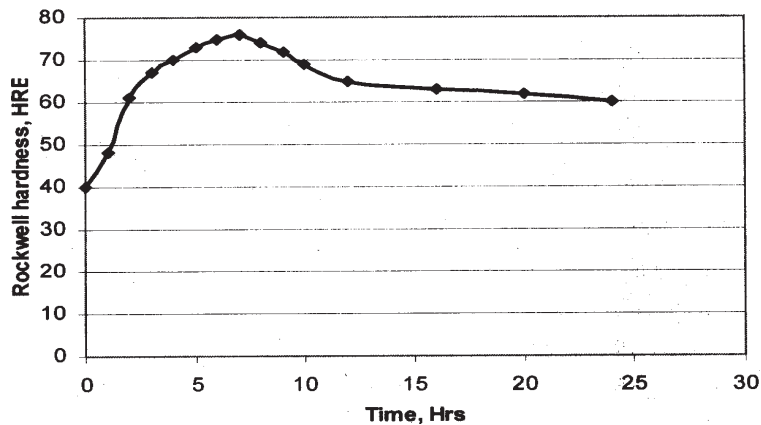| Alloy	Composition determined spectrographically, %								
	Al	Si	Fe	Cu	Ti	Mg	Mn	Zn	Cr
6061	97.6	0.62	0.61	0.021	0.053	0.98	0.044	0.072	0.0051

Fig. 1 : Pin-on-disc testing device for the determination of wear properties.

Wear test

The wear test was carried out with a pin-on-disk tester as shown in Fig. 1. The tests were carried out at room temperature. Each specimen was ground up to grade 600 abrasive paper to ensure that the wear surface was in complete contact with the abrasive counterface. Round specimens having 5 mm diameter were loaded against a disk, which rotated at 200 rpm. A 60 grit size was bonded on the circular disc with the help of a double- sided scotch tape so that the emery paper was rigidly fixed on the disc surface to act as an abrasive medium. The specimens

were kept stationary, while the disc was rotated. The applied normal loads used were 2.0, 3.0, 4.0, 6.0, and 10.0 N. Thus the applied pressure varied from 0.102, 0.153, 0.204, 0.306, and 0.509 MPa. Each test was carried out on a new emery paper. The sliding distance and velocity were kept constant at 60 meters and 1.5m/sec respectively for each specimen. The samples were cleaned prior to and after each interval of wear test with acetone. The wear rates of the composite were calculated by measuring the difference in weight of the specimens measured before and after the tests using an analytical balance with 0.1mg precision per unit density and sliding distance. The unit of the wear rate came out to be mm^3/m. For each test condition, three tests were performed and the average wear rate was used for analysis.

Heat treatment

The heat treatments used in this study to increase the hardness and wear resistance of the composite were three step processes :

– Solution treatment of the composite which resulted in the dissolution of the soluble phases was carried out at 565°C for 2 hours.
– Quenching which resulted in the development of a supersaturated state was done by rapidly cooling the specimen in cold distilled water.
– Artificial aging which involved the precipitation of solute atoms was carried out immediately after quenching at 175°C.

Hardness testing

The hardness of the composite was measured using Rockwell B hardness tests using 1/16" diameter steel ball with a 100-kilogram load. Three specimens were used and an average of five measurements was reported.

Microscopic examination

AL6061/SiC and worn samples were prepared for evaluation by optical and scanning electron microscopy. These samples were rough polished using silicon carbide emery paper and then fine polished using alumina paste down to 0.05µm finish. Mounting and polishing of the worn samples was not done in order to identify actual wear mechanism. Samples were not etched so that the volume percent of the reinforcement was properly represented. The worn samples were sputter coated with gold and palladium in order to minimize charging because of the presence of SiC which is a non conductor for scanning electron microscopic examination.
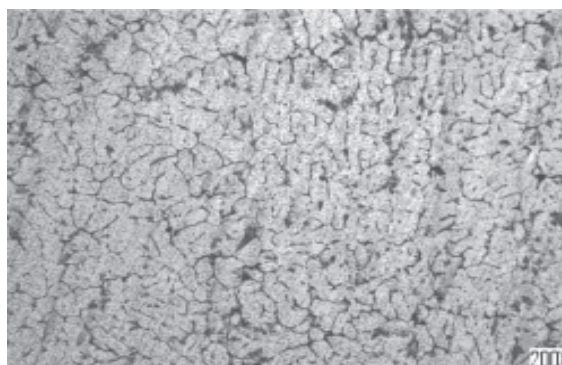

Fig. 2 : Microstructure of the composite showing uniform distribution of SiC particles in the matrix

RESULTS AND DISCUSSION

The microstructure of the as received composite shown in Fig. 2 shows a reasonably uniform distribution of the SiC particles dispersed in the aluminum matrix. The matrix seems to be well bonded with no visible voids. The densities of the as cast Al/SiC composite and Al-Si(10wt%) alloy were measured using Archimedes principle of water displacement were found to be 2.7543gm/cc and 2.6136gm/cc respectively.

Effect of ageing on the composite hardness

Fig. 3 shows the variation of composite hardness as a function of aging time at temperature of 175°C. The hardness increases initially with increasing time. It reached a maximum at around 5 hours. Further aging reduced the composite hardness. The SEM micrographs of the as-cast composite and the heat treated showing precipitates aged at 175°C for various times are revealed in Fig. 4. The peak aged condition as exposed in Fig. 4b is characterized by an optimum precipitate size and a large number of precipitates. As the aging time increases the precipitates become coarse and the distance between them becomes large.
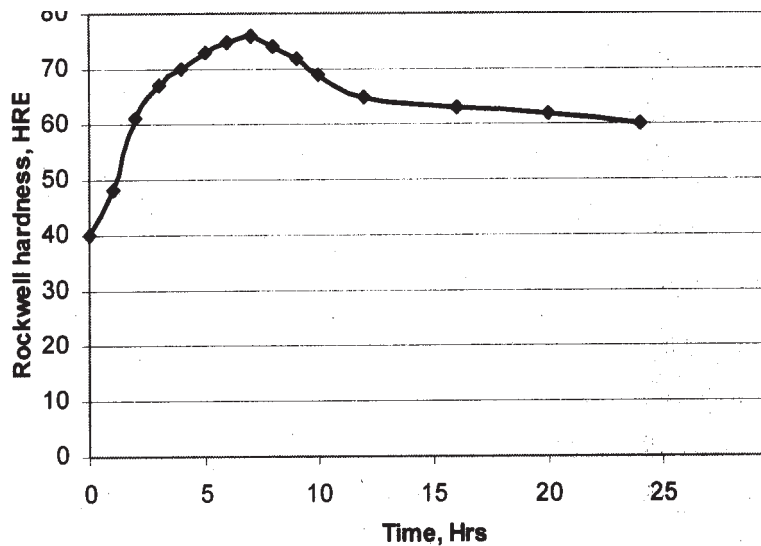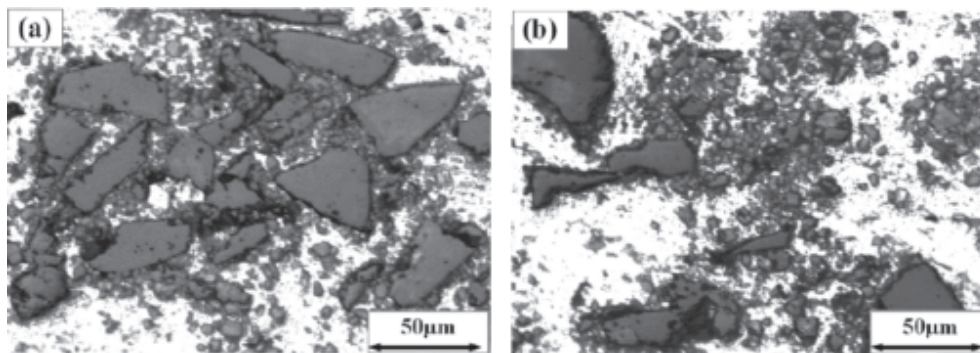

Fig. 3 : Variation of hardness with aging time

Fig. 4 : Micrographs of the Composite showing (a) as-cast composite (b) composite aged for 5 hours

The solid solubility of silicon in aluminum increases with increase in temperature. At around 565°C the solubility of silicon is around 1.6wt%. When the composite is kept at this temperature for two hours to allow sufficient diffusion, part of the silicon will be diffused into the solid solution. When the composite is quenched in water from 565°C, the solid solution becomes supersaturated with silicon and as a tendency to achieve thermodynamic equilibrium precipitation of silicon takes place on the subsequent ageing.

The increase in hardness due to ageing can be explained by dislocation theory. A precipitate particle acts as an obstruction to the motion of a dislocation. Such obstruction provides resistance to the motion of dislocation and consequently increases strength and hardness. For the dislocation to move it must either slice through the precipitate particles or move between them. In both the cases an increase in stress is required as compared to the matrix which does not contain precipitates. This additional stress calculated by Orowan is given by equation:

$$\tau = \frac{2Gb}{d} \qquad\qquad ... (1)$$

where τ is the shear stress, b is the Burgers vector, and d is the distance between two particles, and. If d is smaller between precipitates, the material will become harder. This elucidates the cause for the increase in hardness with the increase in the number of precipitate particles corresponding to the peak aged condition. Beyond the peak aged condition, the precipitates begin to grow and become less in number (Fig. 4). The smaller precipitates will dissolve and the larger ones will grow. For the smaller ones to dissolve and the larger ones to grow, there must be diffusion of the solute.

Effect of load and ageing on wear

Fig. 5 represents the effect of applied pressure and ageing on the wear rate. It is illustrated that wear rate of the composite increased with increasing applied load. The Al 6061/SiC composite has a minimum value of wear rate at peak-aging (5hrs aging) condition corresponding to the maximum value in hardness. Aging for 12 hours resulted in lowering the wear resistance of the composite.
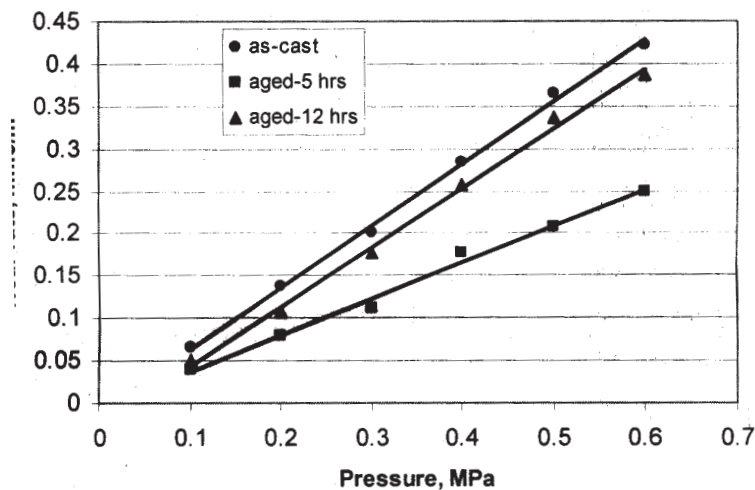

Fig. 5 : Variation of wear rate with pressure at sliding distance of 80 m

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The wear rate of each specimen increased on increasing the load following almost a linear relationship. The abrasive particles will act as microindentors and an increase in load will lead to an increase in the depth of penetration of these abrasives into the sample. This would in turn result in gouging off the matrix from deeper areas resulting in more wear loss. Moreover, an increase in load would also increase the depth of scratches made on the specimen surface.
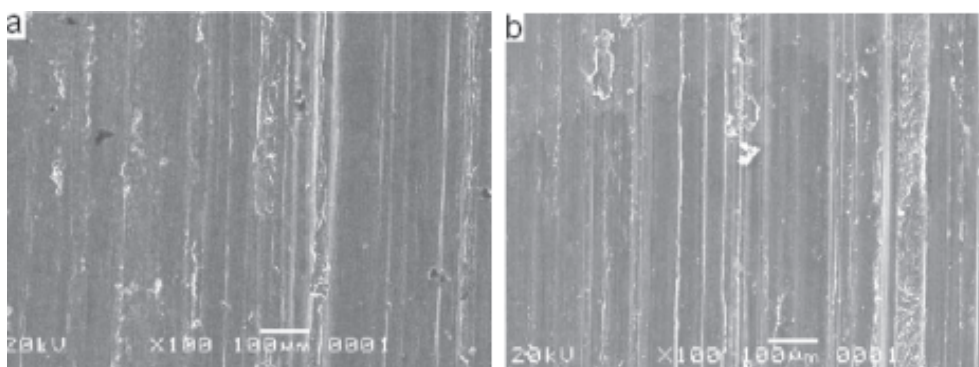

Fig. 6 : SEM Micrographs showing microcutting in (a) as cast composite
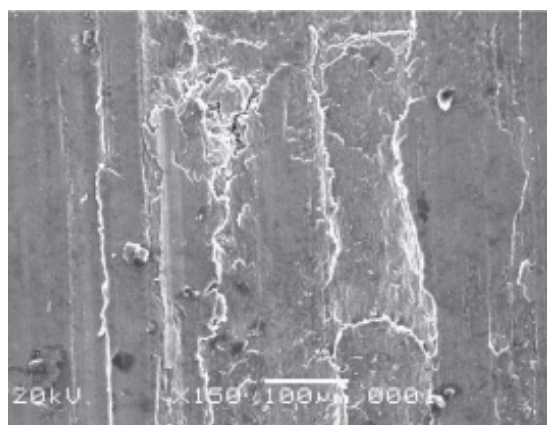*(b) composite aged for 5 hours*

Fig. 7 : SEM Micrographs showing microcracking in as-cast composite

Scanning electron micrographs of the wear surfaces showing microcutting and microcracking are shown in Fig. 6 and Fig. 7 respectively. The worn surfaces of the as cast and the aged composites showed microcutting (Fig. 6) and microcracking (Fig. 7) wear. Microcutting results in the formation of grooves. The depth and the width of the grooves controls the amount of material removed from the specimen surface. With the increase in hardness of the composite due to aging as well as the formation of the hard precipitates, the aged composite is expected to provide resistance against this action. When compared to the alloy, these reinforcements would carry most of the load and the penetration of the abrasive would be restricted by these hard reinforcements. Microcracking occurs when there is an increase in the stress concentration in selective areas of the wearing surface. Internal notches in the form of pores, microcracks, inclusions etc are the cause of increase in the stress concentration. In this case, large wear debris are detached from the wearing surface due to crack initiation and propagation.
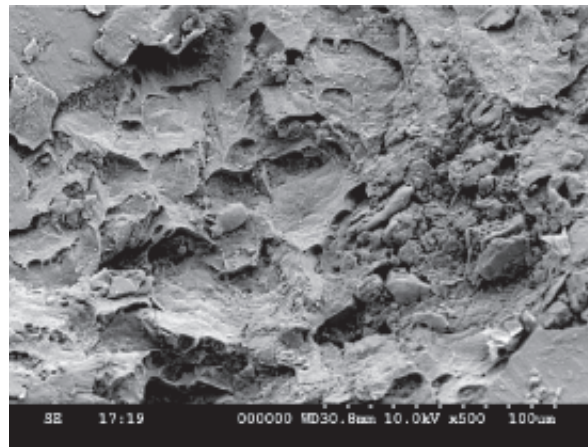
Fig. 8 : SEM Micrograph of the composite showing weakening of the interfacial bond between the matrix and the particle
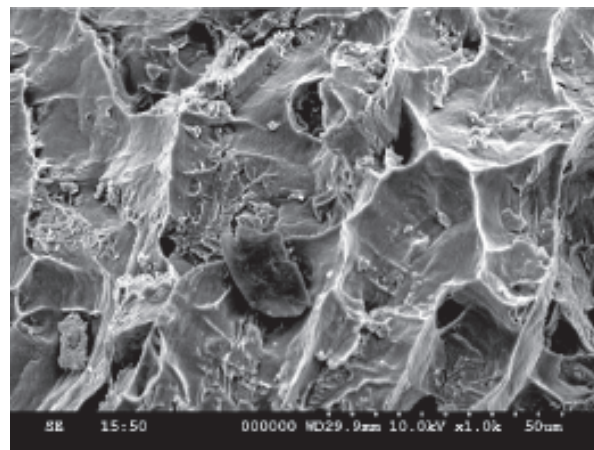

Fig. 9 : SEM Micrograph of the composite showing a pull-out of a SiC particle from the matrix

The ease of particle removal is very vital since they protect the matrix from the cutting action of the abrasive. The examination of the surface after wear suggests a weakening in the interfacial bonding as seen in Fig. 8. This concludes that SiC particles have been pulled out of the wear surface in large number and are not offering much resistance to wear. In the present study, since the size of the SiC abrasive is quite large (262μm) as compared to the reinforcement size (10μm) the depth of penetration is expected to be quite high which will reduce the efficiency of the reinforcement particles in protecting the matrix. In addition, the continuous cutting action of the abrasive would remove the matrix from the adjacent areas of the reinforcement leading to the weakening of the interfacial bond and eventually resulting in the pull-out of the SiC particle as shown in Fig. 9.

Wear mechanism

The removal of the particles from the matrix will play a major role in enhancing wear. In this study, precipitates were observed to be attached to the SiC particles in the aged composites as

shown in Fig. 10. The reason for formation of precipitates near the interface can be attributed to the high density of dislocations near the interface. The difference in the thermal expansion coefficient between aluminum and SiC is of the order of 4.7. When the composite is cooled from elevated temperature (during solidification or solution treatment), misfit strains occur due to differential thermal contraction at the matrix/reinforcement interface that are sufficient to generate dislocations. These dislocations can serve as heterogeneous sites for the nucleation of precipitates and can provide short-circuit diffusion paths for solute atoms[3]. In addition, the interface between the SiC particle and aluminum matrix would itself act as a good heterogeneous nucleation site for the formation of precipitates.

Fig. 10 : SEM Micrograph of the aged composites showing the adhesion of the precipitate to the particle

The adhesion between the interface and precipitates is expected to provide resistance to the SiC particles from scooping off from the composite during wear and hence providing an increase in the wear resistance. The precipitates which are attached to the particle will have a certain degree of bonding with the matrix. These attached precipitates will increase the interfacial area in contact with the matrix. Higher the interfacial area more will be the energy required in extracting the particles. The adhering of the precipitates to the matrix will increase the surface area of the particles which would in turn cause a decrease in the pressure acting on the particles and thereby helping in reducing the rate of crack initiation and propagation to a certain extent. The adhering precipitates will increase the particle dimensions.

The ratio of the depth of cuts to the reinforcement size would have an effect on wear behavior. When the depth of the cuts is greater than the vertical dimension of the silicon carbide reinforcement, then the reinforcement will not offer any resistance and would be removed along with the matrix. This mechanism is expected to be a major contributor to wear since the abrasive size is quite large (262 μm) as compared to the reinforcement size (10 μm). After the wear tests not much SiC reinforcements were seen on the surface implying that the depth of penetration of the abrasive was greater than the reinforcement size in most cases. As the abrasive approaches the particles, the matrix being softer would not offer much resistance and would be removed by the cutting action of the abrasive. Since the depth of penetration is greater than the

particle size, the matrix underneath the particle would be removed and in the process take away the particle along with it. But with the adherence of the precipitates, the size of the particle increases, considering the attached precipitate and the particle as one system. Now as the abrasive moves towards this particle, the precipitates being harder than the matrix would resist the cutting action to a greater extent and the particle would remain intact in the matrix.

CONCLUSIONS

The automobile components undergo sliding as well as abrasive type of wear against the counter surface during operation. The removal of the particles from the matrix will play a major role in enhancing wear. With the increase in hardness of the composite due to aging as well as the formation of the hard precipitates, the aged composite is expected to provide resistance against microcutting. The reason for formation of precipitates near the interface can be attributed to the high density of dislocations near the interface. As the aging time increases the precipitates become coarse and the distance between them becomes large. Microcracking occurs when there is an increase in the stress concentration in selective areas of the wearing surface. The solid solubility of silicon in aluminum increases with increase in temperature. The wear rate of each specimen increased on increasing the load following almost a linear relationship. The continuous cutting action of the abrasive would remove the matrix from the adjacent areas of the reinforcement leading to the weakening of the interfacial bond and eventually resulting in the pull-out of the SiC particle.

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