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Study of Wear Behavior and Mechanical Mixed Layer on Artificial Aged Al6061 Composite Reinforced with B_4C Particles

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Abstract

Present study emphases on the enhancement in hardness and wear resistance of Al6061 composite reinforced with boron carbide particles of various weight percentage (2, 4 and 6) in peak aged condition during artificial aging. The effect of artificial aging treatment with different aging temperatures of 100, 150 and 200^{O}C was also investigated. Presence of B_4C particles in Al6061 alloy accelerating the aging process and thus attain higher strength. These particles provide more sites for the nucleation of fine precipitates. These fine precipitates anchor lattice strain to deform the matrix to increase hardness and wear resistance of materials. The combined effect of B_4C and artificial aging at lower temperature shows improvement in hardness by 150–175% and wear resistance by 100% due to the precipitation of secondary solute rich phase of alloying elements and dislocation mobility hindrance. Tribolayer or mechanically mixed layer was observed due to the transfer of material from rotating disc surface to the wear surface of composite, which is believed to be effect of friction and oxidation on iron particles. The results were correlated with the unreinforced Al6061 alloy. The analysis of the unreinforced alloy worn sample surface doesn't show presence of iron in the mechanically mixed layer.

Keywords: Al6061 Alloy, Age Hardening, Boron Carbide (B_4C), Mechanically Mixed Layer (MML),

1. Introduction

The mechanical properties of Al6061 alloys may be augmented by the formation of very small uniformly distributed particles of a secondary solute rich phase within the original phase matrix; by selecting proper heat treatment[1]. In the metal matrix composites, the presence of reinforcement particles in Al alloys accelerating the aging process and thus attains higher strength. Which inturn results in more nucleation sites for the fine precipitates[2,3]. They are presently considered in a wide range of components for use in several parts of aerospace, automobile, defence, marine, electronic industry and internal combustion engine etc[4].

According to the literature related to the aging sequence, the improvement in the hardness with respect to aging duration and temperature can be interrelated to the phase transformation kinetics during precipitation hardening treatment. The property of the material enhanced during aging is due to the vacancy assisted diffusion mechanism in under aged and peak aged conditions[5-8]. The formation of GP zones depends upon the aging temperature, which distorts the lattice planes[9]. This modification of the lattice planes hinders the dislocation movement as long as the coherency exists in the lattice[10].

The low density (2.52gm/cm^3) boron carbide (B_4C) particles considered to be hardest material, which retains high degree of thermal, chemical, electrical and mechanical properties, which results in attractive reinforced material to improve the properties of aluminium-based composites. The less dense, higher modulus of elasticity, refractoriness and hardness of B_4C than SiC and Al_2O_3 make it most suitable reinforcing particles for high performance MMCs[11-14]. Lot of study has been carried out by using SiC and Al_2O_3 as reinforcing materials[15]. Very limited research has been observed on aluminium alloy composites reinforced with boron carbide particles because

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of more expensive, poor wettability and complication of manufacturing of composites. Thus the main focus of the current work is to study the wear performance and formation of mechanical mixed layer on artificially aged Al6061 composite reinforced with B_4C particles.

2. Materials and Methods

2.1 Matrix and Reinforcement Materials

Table1 shows the nominal composition of matrix materials (Al6061) and Table 2 shows properties of the matrix alloy and reinforced material. The reinforced boron carbide particles used for preparation of composite in the current work is brought from Boron Carbide India limited, Mumbai. The size of the B_4C reinforcement is in the range of 35–40 μm (400 Mesh). The Scanning Electron Microscope (SEM) micrographs and X-Ray Diffraction (XRD) of the reinforcement materials shown in Figure 1 (a and b). A peak corresponding to carbon is also observed which is due to the inevitable impurity of carbon on the surface of B_4C formed during commercial synthesis of boron carbide particles.

2.2 Brinell Hardness and Wear Test

Brinell hardness tests was conducted according to ASTM E10-00 standards in a Brinell hardness tester with steel ball indenter of diameter 5mm and a load of 250 kgf (SAROJ Brinell Hardness Testing Machine, Model:-B/3000/00, Sl# 13/06/08-India).

Table 1. Composition (wt.%) of Al6061 alloy

Material	Si	Fe	Cu	Mg	Cr	Al
Wt % (Actual)	0.52	0.55	0.24	0.95	0.25	Balance
Wt % (Standard)	0.40–0.80	0.70 max	0.15–0.40	0.80–1.20	0.04–0.35	Balance

Table 2. Properties of Al6061alloy and B_4C reinforcements

Properties	Al6061	B_4C
Elastic Modulus (GPa)	70–80	480
Density (g/cc)	2.7	2.52
Poisson's Ratio	0.33	0.207
Hardness (HB 500)	30	3000 kg/mm^2 (30GPa)
Size Range	-	Average (35-40μm- 400 Mesh#)

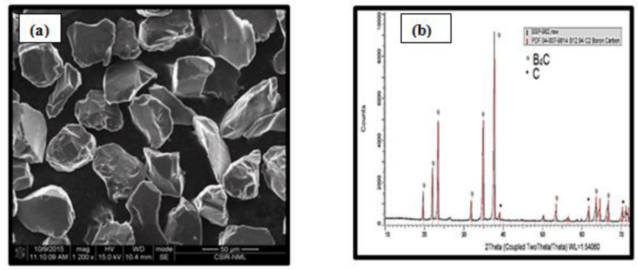

Figure 1. **(a)** SEM micrographs of boron carbide particles and **(b)** XRD plots of B_4C particles.

Wear study was done by using ASTM G-99 standards. The surfaces of test sample and disc were polished with 600 grit silicon carbide emery paper to allow smooth contact interface before the beginning of each test trial. The test samples were cleaned with ethanol solution prior to and later of every test trial. The track diameter is kept fixed at 60mm, load and speed is varied and one run is carried out for duration of one hour (1h). Different loads (15, 30 and 45 N) are applied through dead weight loading system and three different speeds are used (150, 300 and 450 rpm). After each 15 minutes run throughout the test, the sample mass was measured to determine the loss in mass. A high accuracy electronic balancing machine (Model: IN2011) with a resolution of 0.001 mg. is employed for weighing. After one hour (1h) run, machine is allowed to cool and disc is cleaned using emery paper of# 600 fine grit size, to remove the abrasive particles. The test sample dimensions used for wear test are 8 mm diameter and 30 mm height. After each test span of 1hour, the micrograph of wear sample surface is taken with the help of an Inverted metallurgical microscope (IM 7000 series).

2.3 Aging Treatment

The specimens are subjected to age hardening heat treatment. Specimens are soaked at 558°C for duration of 2h, then immediately quenched in water at room temperature. The quenched specimens were artificially aged in the furnace at 100, 150 and 200°C for various durations of time to find and retain peak hardness values at the given aging temperature. The presence of Mg_2Si is a strengthening phase and dissolves completely at 558°C during solutionizing and precipitates during age hardening to maximize the strengthening effect. These secondary precipitated phases result in particle strengthening and coherency of the crystal structure of the particle and the matrix. The samples of Al6061 composites solution treated at 558°C results in better improvement in mechanical properties such as hardness, tensile strength and lesser wear rate[16].

3. Results and Discussions

3.1 Hardness Measurement

Both as cast and aged samples are tested to determine the Brinell Hardness Number (BHN). Table 3 shows the peak hardness values obtained in as cast and different aging temperatures at 100, 150 and 200°C. In as cast condition it is clear that the hardness values increase with the presence of reinforcements when compared to the unreinforced alloy. The increase in percentage weight of B_4C increases the hardness of the composite. The expected increase in hardness is mainly due to presence of reinforcement particles being a hard dispersoid positively contribute to the hardness of the composite[17]. Increased weight percentage of B_4C particles in the Al6061 matrix alloy results in higher dislocation density during cooling due to the mismatch in CTEs of the B_4C reinforcement particles and base alloy matrix. This induces larger thermal internal residual stress and misfit strain to alter matrix microstructure and enhancement of composite properties. The plastic deformation of the alloy matrix to accommodate the smaller volume expansion of the reinforcement particles results in increasing dislocation density. This increased dislocation density is responsible for additional increase in hardness of composites[18].

Similar to base alloy, the Al6061 matrix composite is very sensitive to age hardening irrespective of lower or higher aging temperature. It is evident that composites exhibit accelerated rate of aging kinetics as compared to unreinforced matrix alloy. Aging kinetics gets accelerated in the composites with increase in wt. % of reinforcements. Aging is accelerated due to the presence of areas with a high concentration of dislocation close to Al6061 matrix and B_4C reinforcements interface. These high density locations provide heterogeneous nucleation sites for the precipitation and high diffusivity path for the diffusion of alloying elements[19]. Compared to base alloy, composites show drastic increase in the hardness in as cast and treated conditions. At the same time increase in weight percentage of B_4C in the composites gives positive effect on hardness value. Lower aging temperature shows increase in hardness of base alloy as well as composites as compared to higher aging temperature. Lower temperature aging contributes to the increased hardness by increasing the number of intermediate zones during precipitation, increase in the number of finer inter-metallic and decreased interparticle distances. Higher the aging temperature, lower is the time required to attain peak hardness[16].

Table 3. Hardness of Al6061- B_4C (0, 2, 4 and 6% wt.) as cast and peak aged condition

	As cast condition BHN	Peak aged condition at 100°C BHN	Peak aged condition at 150°C BHN	Peak aged condition at 200°C BHN
Al6061 alloy	50	85	74	65
Al6061- 2% B_4C	60	118	107	95
Al6061- 4% B_4C	65	126	115	100
Al6061- 6% B_4C	74	134	123	105

3.2 Wear Characteristics

The wear resistance of the alloy is improved significantly due to the incorporation of reinforcements as shown in Figure 2. Under all the testing conditions it is revealed that the wear rate of unreinforced Al6061 alloy is maximum irrespective of loads. Increase in weight percentage of B_4C particles results in decrease in direct metal to metal contact between surface of the composite and the counter disc surface and thus reduction in wear rate was observed.

The applied load has a substantial impact on the wear rate of composite specimens. Increase of the applied load, the wear rate of both the composites and unreinforced

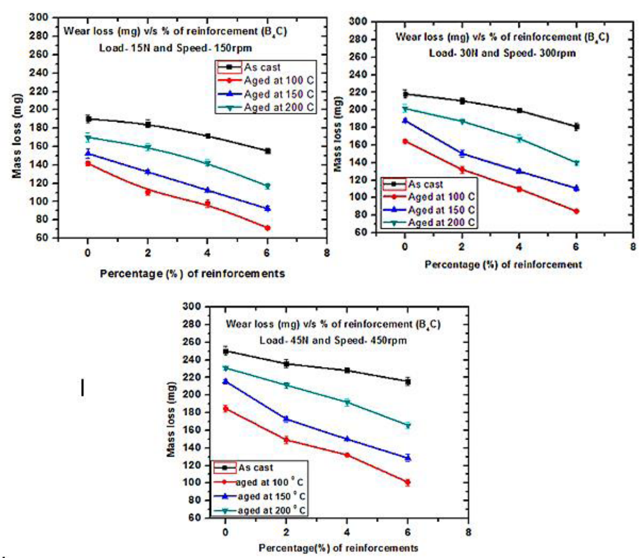

Figure 2. Wear loss of untreated and heat treated Al6061-B_4C composites under different speeds.

aluminium alloy also increases. This is mainly due to higher extent of plastic deformation inturn results in formation of wear debris at higher loads. More amount of material removal and cracking of subsurface takes place is due to greater extent of plastic deformation.

The unreinforced aluminium alloy shows increasing wear rate with increasing applied load, due to direct interaction of metal surface and counter surface as a result of more amount of plastic deformation during wear test. Whereas, in the case of Aluminium MMC's, the presence of reinforcement particles governs the harder asperities of hardened steel disc. Thus, B_4C particles carry the major portion of the applied load. The main function of the reinforcement particles is to control higher plastic deformation rate and abrasion between the pin and disc surfaces and hence reduce the amount of removal of metal[20,21]. Improvement in wear resistance of Al6061-6 wt.% B_4C composites even at higher loads is mainly due to the fact that B_4C itself being hard can contest itself to the abrasion, thereby reduction in wear rate and seizure resistance of materials.

The Al6061 alloy and Al6061-B_4C MMCs shows a decreasing trend in wear rate when subjected to precipitation hardening. In all the cases the specimens aged at lower temperature (100°C) showed better wear resistance. It is also revealed that, increase in aging temperature decreases the wear resistance of the alloy or the composites. Since wear resistance is directly proportional to hardness, the improved abrasion wear resistance after age hardening treatment can be attributed to further improvement in the hardness. Al6061-6 wt.% B_4C peak aged composites at 100°C shows maximum wear resistance as compared to 2 and 4% wt. B_4C composites under different aging conditions. This is mainly due to, increased weight percentage of B_4C particles in the Al6061 alloy results in increased dislocation density during cooling due to the thermal mismatch between Al6061 alloy and B_4C particles. Higher dislocation densities together with the reinforcement particles will result in strain hardening, thereby, hindering the dislocation movement to enhance the hardness during age hardening treatment. Specimens aged at lower temperature are more sensitive to reduce wear than higher temperature aged specimens. Lower aging temperature contributed to increase in coherency strain in the matrix with the precipitation of more number of finer intermetallics obtained by number of intermediate stages with smaller average interparticle distance. But higher the aging temperature higher is the wear rate. Higher aging temperature coarser the grain, lesser is the hardness and lesser number of intermediate zones in the formation of coherent precipitates leading to lesser strain on the matrix. This phenomenon is clearly observed in wear loss curves as shown in Figure 2 under different load conditions.

Peak aged samples show improved wear resistance and it is associated with load bearing capacity of the reinforcement in the matrix and the precipitation of intermetallics at the B_4C interface. These precipitates improves the interfacial bonding between reinforcements and the matrix, serve as refractory material and increases hot hardness, which in turn results improvement in high temperature wear resistance [22-24].

At 15N load conditions, where the load on the pin is very small the wear rate is small under all the aging conditions. At lower loads the intensity of strain hardening is small, accordingly the wear rate is not so sensitive with sliding distance and aging conditions. But appreciable changes are observed at higher loads. At the given sliding velocity for all the speeds, the wear rate increases as the normal load is raised. This trend is due to the fact that as the load increases, force of friction increases which in turn causes an enhanced de-bonding and fracture. During beginning, the initial rubbing breaks the layers of surface, which cleans and smoothens the surface and enhances the strength and contact between the surfaces.

The force of friction because of tillage effect between the surfaces leads to rise in the temperature between the mating surfaces. This effect results in adhesion and raises the intensity of deformation at the surface layers, resulting in further loss of the material. For sliding speed of 150 rpm wear rate is minimal, but increase in load and sliding speed has increased wear rate drastically. At high speed there will be more heat generation which induces softness in material. Lower aging temperature (100°C) with higher reinforcement contents (Al6061-6% wt. B_4C) on the disc is favorable condition for the improvement in wear resistance. On an average there is nearly 50 to 80% improvement in wear resistance in Al6061- B_4C composites as compared to Al6061 alloy.

3.3 Microstructure of Worn Surface

Al6061-6 wt.% B_4C aged at 100°C exhibits superior mechanical properties in comparison with Al6061 alloy, Al6061-2 wt.% B_4C and Al6061-4 wt.% B_4C composites. Figure 3 shows the surface morphology of the worn out surfaces of Al6061 alloy and Al6061-6 wt.% B_4C

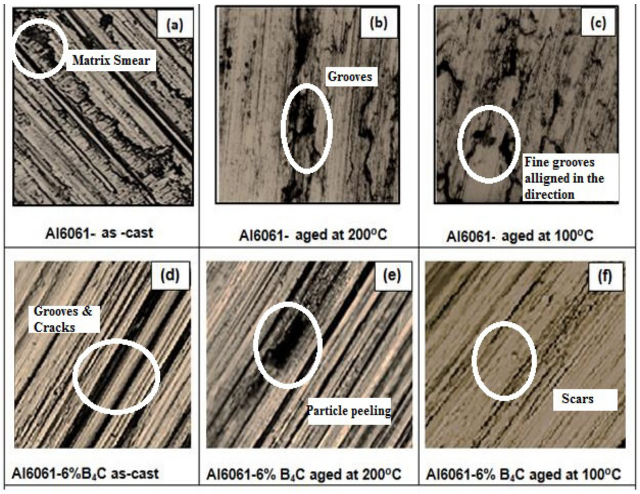

Figure 3. Worn out surface micrographs of Al6061 alloy and Al6061-6 wt.% B_4C composites in both as cast and aged at 100 and 200°C (Speed = 450 rpm, Load = 45 N and Track diameter = 60mm) at 200X.

composites in both as cast and age hardened conditions. The microstructures of the worn surfaces are highly reliant on sliding speed and load conditions[25]. Extensive plastic grooving and ploughing is observed in Al6061 alloy matrix. The grooves on the worn surface of cast matrix are coarse and the plastic deformation at the edge of the grooves is heavy when compared to the age hardened sample. However, the worn surface of higher percentage reinforced composite (Al6061-6% wt. B_4C) are relatively smooth in both as cast and age hardened conditions when compared with the matrix alloy. Heavy damage of surface with the matrix material smeared at more spots is observed under as-cast condition due to lower hardness [Figure 3(a)]. The extent of damage in the surface is minimized and deep grooves are formed to some extent when the samples are aged at 200°C [Figure 3(b)]. The development of fine grooves aligned to the direction of sliding with lesser number of surface cracks is observed when the samples are aged at 100°C [Figure 3(c)]. Wear resistance of aluminium alloy is enhanced due to addition of reinforcing particles. The chopped off B_4C particles have distributed over the entire area filling the gaps in narrow grooves. Cavitation appears to be low but cracks and grooves are also noticed in as cast Al6061-6 wt.% B_4C composite [Figure 3(d)]. Some particles have chopped off during sliding and in some area smaller particulate have come out from the composite matrix [Figure 3(e)]. The grooves are fine and seem to be subjected to slight plastic deformation at the edge in composites aged at 100°C. Some areas indicate the existence of scars resulting in an accumulation of hard particles in the damaged regions of grooves [Figure 3(f)].

Figures 4 and 5 show scanning electron microscope of worn surface of Al6061 alloy and Al6061B_4C (6 wt.%) composite. Severe erosion wear observed on the surface of Al6061 alloy wear samples. This is mainly due to metal to metal contact between matrix and counterface. Also combination of high stress and sliding speed engenders high friction energy, which results in softening of the matrix metal and leads to high metal removal rate.

The wear surface of composite shows MML which is formed due to the material transfer from counterface of the steel disc. During wear test of composites, the presence of hard reinforcements can with stands the applied load and scratch heavily on the counter surface. When the pin material is in contact with the counterface, disc material undergoes sever churning process and plough out the Iron (Fe) material from the counterface, which leads to formation of MML on the pin material.

Also the harder contacting reinforcement surface produces more friction, leads to increase interface temperature. The harder reinforcement removes counterpart material and iron present in it oxidises at such high temperature to form MML.

No traces of MML and concentration of iron are observed on the worn surface of Al6061 alloy shown in

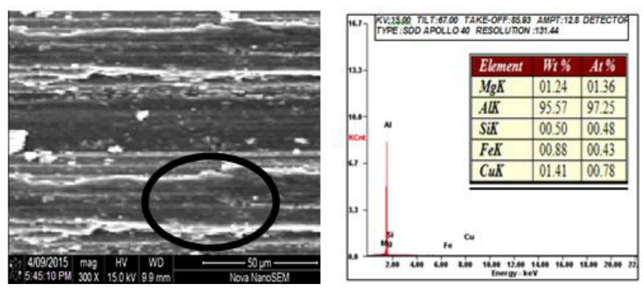

Figure 4. SEM and EDAX results of worn surface for the Al6061 alloy aged at 100°

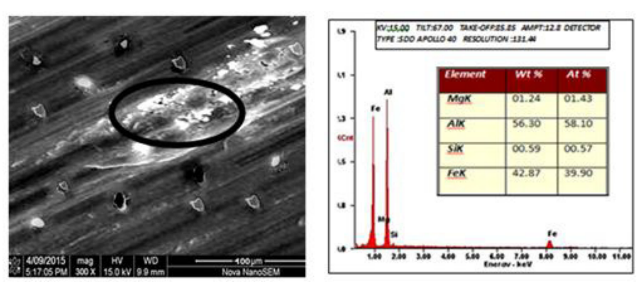

Figure 5. SEM and EDAX results of worn surface for the Al6061-6% wt. B_4C composite aged at 100°C.

Figure 4. The Energy Dispersive X-ray (EDAX) analysis of worn surface of Al6061- B_4C composite shows higher concentration of iron, which must come from the counterface as shown in Figure 5.

Hardness of MML is found to be 3 to 5 times than Al6061 alloy[26]. Therefore Al6061-B_4C composite shows better wear resistance as compared to Al6061 alloy. It is also clearly observed that presence of reinforcements plays an important role for the formation of MML on the worn surface.

4. Conclusions

Based on the present investigation study, the following results are obtained:

- Al6061 alloy and Al6061-B_4C composites positively responds to age hardening treatment with considerable improvement in mechanical properties.
- Slower precipitation kinetics and higher peak hardness is noticed at lower aging temperature for both unreinforced aluminium alloy and its composites.
- An improvement in peak hardness of 90-110% aged at 200°C and 140–175% (2–6 wt.% B_4C) aged at 100°C is observed in significant duration for the composites in comparison with untreated Al6061 alloy.
- Significant improvement in wear resistance of the Al6061 alloy with the presence of reinforcements. Peak aged samples show substantial improvement in wear resistance and it is related with type and size of the precipitation of intermetallics at the B_4C interface.
- Peak aged composites Al6061-6wt.% B_4C reinforcement displays excellent wear resistance.
- Formation of mechanically mixed layer on the composite pin surface plays an important role for controlling the wear mechanism of the composites.
- Al6061-6 wt.% B_4C shows better improvement in mechanical properties in comparison with Al6061 alloy, Al6061-2 wt.% B_4C and Al6061-4 wt.% B_4C composites.

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