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INFLUENCE OF ARTIFICIAL AGING ON THE STIR CAST Al6061-SiC METAL MATRIX COMPOSITES UNDER DIFFERENT AGING CONDITIONS

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ABSTRACT

The present work aims to improve the microstructure and hardness related properties of age hardened Al6061-SiC reinforced composites produced by a two stage stir casting method. Three composites with 2, 4, and 6wt. % (35-40μm) of SiC reinforcement are subjected to microstructural examination and hardness test at different locations to analyse the uniform distribution of the reinforcements in the matrix. As-cast composites are solution-treated at 558°C, followed by an aging treatment conducted at 100, 150, and 200°C, during which peak hardness values are noted. The peak aged samples are subjected to hardness and wear tests. In line with the objectives, ranges from 80-100% and 120-145% additional increase in hardness values are observed over as-cast alloy during the aging treatment conducted at 100, 150 and 200°C, respectively. Lower temperature aging shows substantial improvement in hardness and wear resistance over high temperature aging in each respective group. Also higher weight percentages of reinforced composites show excellent wear resistance, due to the presence of eroded iron particles from the counter surface which is regarded as a beneficial effect during the wear test. The presence of SiC particles provides more sites for the nucleation of fine precipitates. These fine precipitates hinder the movement of dislocation and thus increases hardness as well as wear resistance after the precipitation hardening treatment.

Keywords: Aging temperature; Aging time; Al 6061 alloy; Precipitation hardening

1. INTRODUCTION

The demand for aluminium grows rapidly, due to the unique combination of properties which means aluminium is one of the most versatile in the range of engineering and construction materials (Wan Nik et al., 2010; Rizkia et al., 2015). The strength and hardness of Al6061 alloys may be enhanced by the formation of extremely small uniformly dispersed particles at a second phase within the original phase matrix; this must be accomplished by appropriate heat treatment (Askeland et al., 2010). In recent years aluminium matrix composites, have received more attention because of their high strength, high modulus and low density. In order to improve the mechanical properties, it was necessary to understand the strengthening mechanism, including the study of interfacial structure, dislocation generation and precipitation during the aging process. Consequently, it has been assumed that the high dislocation density in the SiC-reinforced aluminium alloy matrix composite was also caused by the difference between the thermal expansion coefficients. In metal matrix composites, the presence of reinforcement particles in Al alloys are shown to be capable of accelerating the aging process

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and thus attaining higher strength, which in turn results in more nucleation sites for the fine precipitates. Two step stir casting, as a means of improving cast metallic matrix, gives the best uniform distribution of the SiC particulates (Kenneth & Ayotunde, 2012). In the present work Al6061-SiC composites are produced by a two stage stir casting method of various weight percentages (2, 4, and 6wt. %) of SiC particles. From the reviewed literature, it was evident that the aging at higher temperature leads to a faster rate of diffusion of secondary solute precipitates, but limited or less work was observed for low temperature aging. Therefore, the objective of the current work was to characterize the peak aging behaviour at both higher and lower temperatures. Microstructure, hardness and wear properties of Al6061-based composite materials reinforced with silicon carbide particles were analysed and presented.

2. MATERIALS AND METHODS

2.1. Matrix and Reinforcement Materials

Table 1 shows the nominal composition of matrix materials (Al6061). The Silicon Carbide reinforcement particles were brought from Indian Fine Chemicals, Mumbai. The size of the SiC reinforcement was in the range of 35-40μm (400 Mesh). The reinforcement materials have irregular shapes and SEM (Scanning Electron Microscope) micrographs of the same are shown in Figure 1. X-Ray Diffraction (XRD) plots of the same are shown in Figure 2, which confirms the presence of SiC particles.

Table 1 Composition (wt. %) of Al6061 alloy

Material	Si	Fe	Cu	Mn	Mg	Cr	Al
Wt % (Actual)	0.59	0.52	0.21	0.159	0.99	0.22	Balance
Wt % (Standard)	0.40–0.80	0.70 max	0.15–0.40	0.150	0.80–1.20	0.04 –0.35	Balance

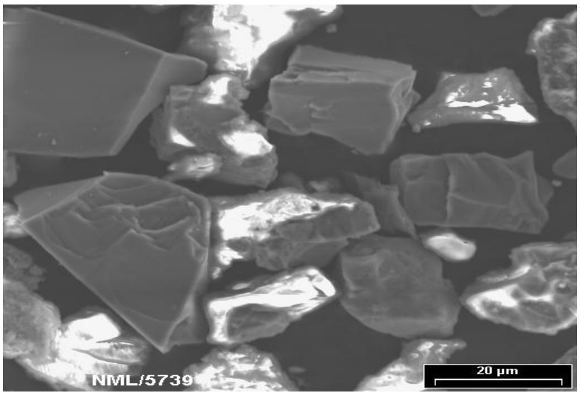


Figure 1 SEM micrographs of silicon carbide particles (SiC) used for the experiments

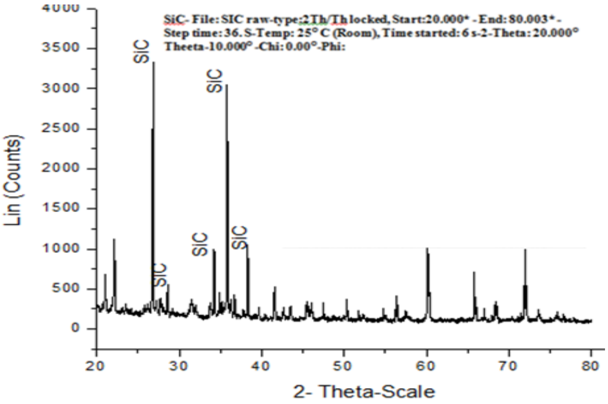


Figure 2 XRD plot of the SiC particles

2.2. Double Stir Casting Technique

The Al6061 billets were melted in a graphite crucible by an electric resistance furnace with a 5 kW rating and melting was allowed to progress until a uniform temperature of 750^{o} C was reached. A small amount of scum powder was introduced into the mixture to remove slag or flux. The entire melt was then degassed by adding a dry hexa chloroethane tablet weighing 10 grams (C_2Cl_6, 0.3wt. % (Gruzleski, 1990). The SiC particles were preheated to a temperature range between 600–800^{o}C for 2 h in order to remove the volatile substances and to maintain a particle temperature closer to the melt temperature of 750^{o}C. Also, in the SiC particles, preheating leads to artificial oxidation, which occurs by altering the surface composition. This step leads to the formation of a SiO_2 layer on the surface. This SiO_2 layer reacts with the molten aluminium to form a continuous reaction layer constituted mainly by an Al–Si–O compound. This chemical reaction was thermodynamically favored, having a negative value of its Gibbs free energy and increasing the adhesion work, which resulted in improving the wettability of the particle (Pech-Canul, 2011; Veeresh Kumar et al., 2010). The melt was then allowed to cool down to 600°C (slightly below the liquidus temperature, T_L or T_{liq}) to a semi-solid state. At this stage, preheated silicon carbide mixture, in varying wt. % (2, 4, and 6%) was poured in the vortex, which resulted due to stirring. A mild steel stirrer with its axis in the vertical position was utilised. The speed of stirring was kept in the range 150-200 rpm and mixing was done for 10 min. to permit better dispersion of the silicon carbide in the molten alloy. After mixing the reinforcements in a semisolid state, the composite slurry was reheated and maintained at a temperature of 750°C ± 10°C (above the liquidus temperature) and once again the stirring operation was performed for 10 minutes at an average stirring rate of 400 rpm. The melt was poured in the cast iron moulds, which were preheated to 500°C. Al 6061-SiC composites were fabricated by altering the amount of silicon carbide particles in the range between 2-6wt. % and the melt was allowed to solidify in air for 2 hrs. The cast composites are shown in Figure 3.

Figure 3 As cast Al 6061-SiC composites in different mould shapes

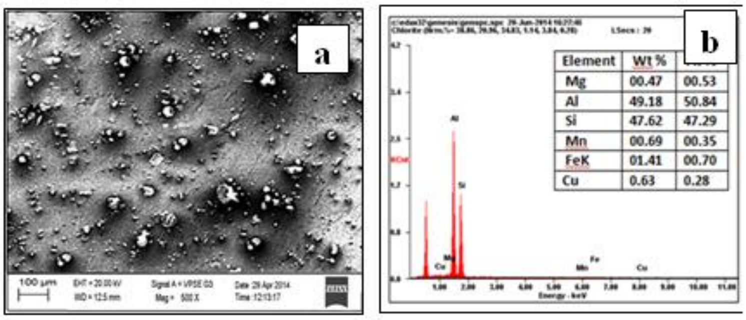
2.3. Age Hardening/ Precipitation Hardening Treatment

The specimens prepared for above test were subjected to age hardening heat treatment. Specimens are soaked at 550°C for duration of 2 hrs, then immediately quenched in water at room temperature. The quenched specimens were artificially aged in the furnace at temperatures of 100, 150, and 200°C for various durations of time. It was reported that the samples of 6061 Al/SiC composite, with the solution heat-treated at 558°C, exhibited better strength compared to the samples solution treated at 530°C after aging treatment (Rajasekaran et al., 2012).

3. RESULTS AND DISCUSSION

3.1. Microstructure Studies

The uniform dispersion of the reinforcement was one of the most important factors in the fabrication of metal matrix composites. So the appearance of the microstructure could give an insight into the quality of the composite. For ensuring the homogeneous dispersion of silicon carbide particles, the cast samples were analysed by an inverted metallurgical optical microscope (IM 7000). Figure 4a shows a Scanning Electron Microscope (SEM) image and Energy Dispersive X-ray (EDX) spectra at compositional results performed on the matrix and reinforcement to ensure that the spots are dispersed SiC. It was observed from Figure 4a that SiC are distributed uniformly in the Al alloy matrix. In Figure 4b, it was confirmed that the particles are SiC through the EDX spectra. Figure 5 shows optical microscope images at 100X and confirms the uniform distribution of SiC particles in the Al6061 alloy matrix. The micrographs clearly indicate the evidence of minimal porosity in both the Al6061 alloy and Al6061-SiCp composites. The microstructure does not reveal the existence of the blow holes or air pockets and agglomeration of reinforcements in the matrix.



Element	Wt %	
Mg	00.47	00.53
Al	49.18	50.84
Si	47.62	47.29
Mn	00.69	00.35
FeK	01.41	00.70
Cu	0.63	0.28

Figure 4 Scanning Electron Microscope (SEM) image of Al6061-6% SiC composite and corresponding Energy Dispersive X-ray (EDX) spectra of SiC

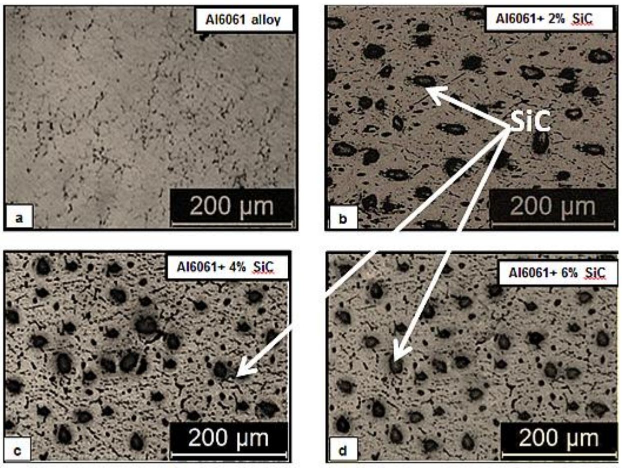


Figure 5 Optical microphotograph of Al6061 alloy and Al6061-SiC composites: (a) Al6061 alloy; (b) Al6061-2%SiC; (c) Al6061-4% SiC; and (d) Al6061-6% SiC composites

3.2. Aging Curve and Hardness

Both cast and aged samples are tested to determine the Brinell Hardness Number (BHN). Graphs of hardness values for all the three aging temperatures against the time for Al6061 alloy and Al6061-SiC$_p$ composites are plotted as shown in Figure 6.

The peak hardness values obtained in the as cast condition and in the different aging temperatures at 100, 150, and 200°C, respectively are shown in Figure 7. In the as cast condition it was clearly observed that the hardness values increase with the addition of reinforcements when compared to the unreinforced alloy. The increase in hardness was expected, since SiC particles are identified as being a hard dispersoid positively contribute to the hardness of the composite (Veeresh Kumar et al., 2010). Presence of hard reinforcement particles positively contribute to increase in hardness. Increased content of reinforcement in the matrix alloy leads to higher dislocation densities during solidification due to the thermal mismatch of the matrix alloy and the reinforcement. This results in large internal stresses and mismatch strain that affects the microstructure and mechanical properties of the composites. The matrix deforms plastically to accommodate the smaller volume expansion of the reinforcement particles leading to increased dislocation density. Enhancement in dislocation densities results in higher resistance to plastic deformation and is responsible for additional increase in hardness of composites (Ramesh & Safiulla, 2007; Zulfia et al., 2016). Composites exhibit an accelerated rate of aging kinetics as compared to unreinforced matrix alloy. Aging was accelerated due to the presence of areas with a high concentration of dislocation close to the Al6061 matrix and SiC reinforcements interface. These high density locations provide heterogeneous nucleation sites for the precipitation & high diffusivity path for the diffusion of alloying elements (Kulkarni et al., 2004).

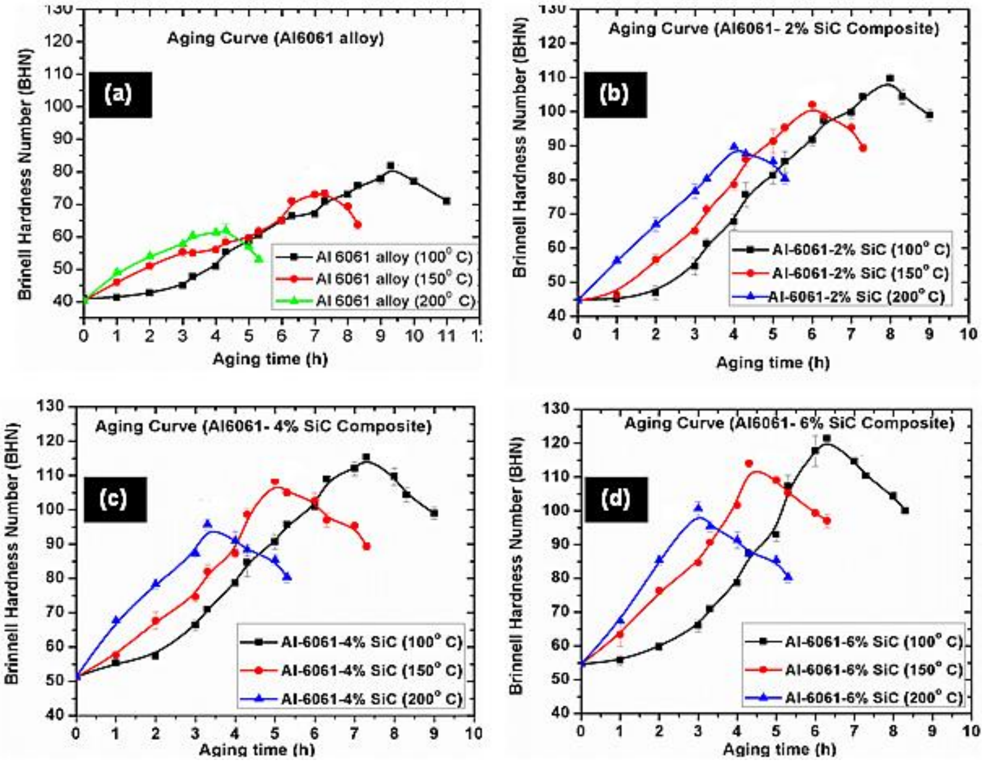
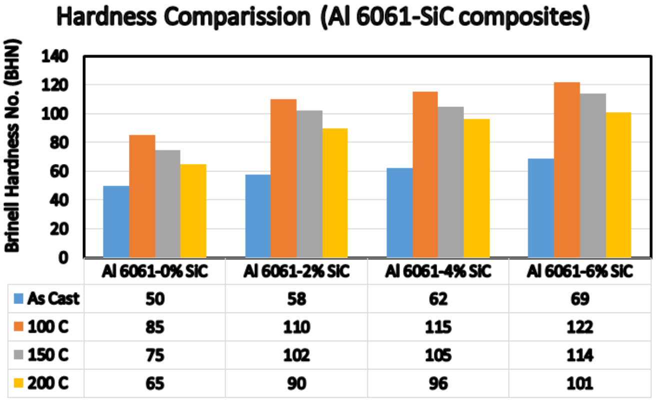


Figure 6 BHN of: (a) Al6061 alloy; (b) Al6061-2% SiC; (c) Al6061-4% SiC; and (d) Al6061-6% SiC composites aged at 100, 150, and 200°C with aging time



	Al 6061-0% SiC	Al 6061-2% SiC	Al 6061-4% SiC	Al 6061-6% SiC
As Cast	50	58	62	69
100 C	85	110	115	122
150 C	75	102	105	114
200 C	65	90	96	101

Figure 7 Peak Hardness values of Al6061 alloy and Al6061-SiC composites in as cast and different aging conditions

Lower aging temperature shows an increase in the hardness of base alloy as well as composites as compared to higher temperature aging. Lower temperature aging contributes to the increased hardness by increasing the number of intermediate zones during precipitation, an increase in the number of finer inter-metallics and decreased interparticle distances. The hardness value decreases after peak aging conditions, due to coarsening of precipitates which form during aging and the condition is known as over aging. Over aging induces softness in the alloy, since the hardness value decreases drastically. The rise of temperature causes the ageing rate to increase, due the enhanced rate of diffusion of solid atoms throughout the matrix. From the above results it can be concluded that heat treatment has a profound influence on the hardness of matrix alloy as well as composites.

3.3. Tribological Characteristics

The wear resistance of the alloy improved significantly, due to the incorporation of reinforcements as shown in Figure 8. The Al6061 alloy and Al6061-SiC composites showed a decreasing trend in wear rate when subjected to precipitation hardening. In all cases the specimens aged at 100°C showed better wear resistance. Al6061-6 wt. % SiC peak aged composites at 100^{O}C show maximum wear resistance as compared to 2wt. % and 4wt. %, respectively, due to the presence of SiC composites under different aging conditions. This was mainly due to the increased content of reinforcement in the matrix alloy, leading to increased dislocation densities during solidification, attributed to the thermal mismatch between Al6061 alloy and SiC 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. Lower aging temperature contributed to an increase in coherency strain in the matrix with the precipitation of a greater number of finer intermetallics obtained by the frequency of intermediate stages with smaller average interparticle distances.

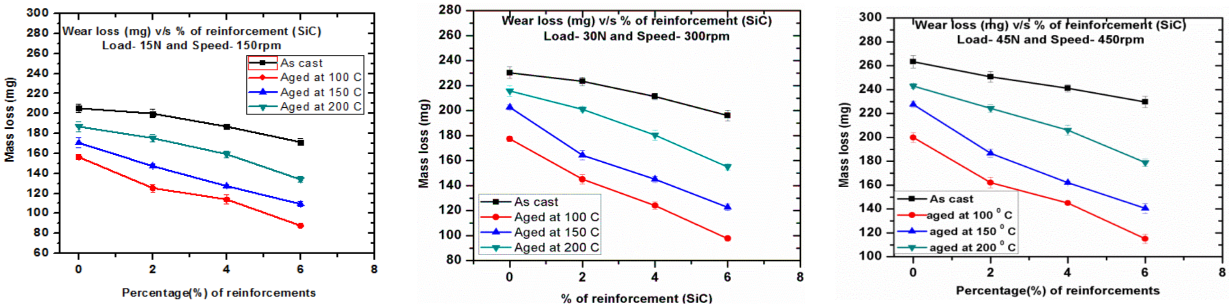


Figure 8 Wear loss with increase in percentage of reinforcement of untreated and heat treated Al6061-SiC composites under different speeds

At higher aging temperatures, the coarser the grain, the lower the hardness and the fewer number of intermediate zones occurred in the formation of coherent precipitates, leading to lesser strain on the matrix. Peak aged samples show improved wear resistance and it was associated with load bearing capacity of the reinforcement in the matrix and the precipitation of intermetallics at the SiC interface. These precipitates are believed to improve the interfacial bonding between reinforcements and the matrix, to serve as refractory material and to increase hot hardness, which in turn results in improvement in high temperature wear resistance. These observations are in accordance with Prabhu Swamy et al. (2010) and Amanov et al. (2013).

3.3.1. Microstructure of worn surface

Figure 9 shows the surface morphology of the worn out surfaces of Al6061-0% SiC and Al6061-6 wt. % SiC composites in both as cast and heat treated conditions. The structures of the worn surfaces are highly dependent on sliding speed and applied load conditions (Prasad, 2006). Extensive plastic grooving and ploughing was 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 was heavy when compared to the age hardened sample. However, the worn surface of higher percentage reinforcement composite (Al6061-6 wt. % SiC) are relatively smooth in both as cast and age hardened composites when compared with the matrix alloy. Heavy damage of the surface with the matrix material smeared at more spots was observed under as-cast conditions, due to lower hardness (See Figure 9a). The extent of damage to the surface was minimized and deep grooves were formed to some extent when the samples were aged at 200^{O}C (Figure 9b). The development of fine grooves aligned to the direction of sliding with a lower number of surface cracks were observed when the samples were aged at 100°C (Figure 9c). Wear rate of the aluminium matrix alloy was enhanced, due to the addition of reinforcing particles.

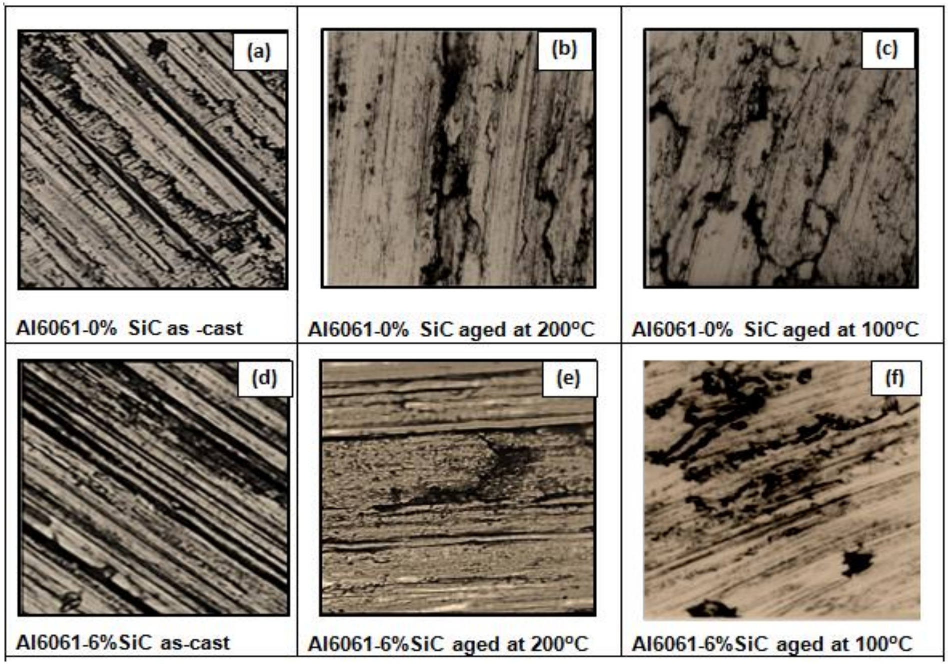
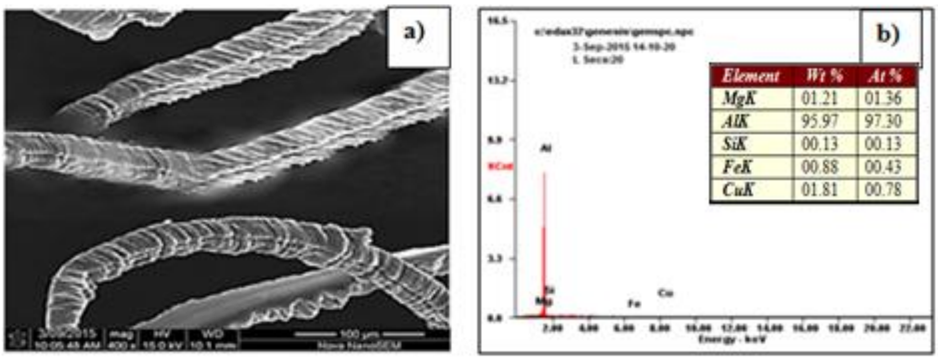


Figure 9 Worn out surface micrographs of Al6061-0% SiC and Al6061-6 wt.% SiC composites in both as cast and aged at 100° and 200°C (Speed=450 rpm, Load=45 N and Track diameter= 60mm) at 200×

The chopped off SiC particles have been distributed over the entire area, filling the gaps in narrow grooves. Cavitation appears to be hollow, but cracks and grooves are also noticed in as cast Al6061-6 wt. % SiC composite conditions (Figure 9d). Some particles have been chopped off during sliding and in some areas smaller particulates have come out from the composite matrix (Figure 9e). The grooves are fine and slight plastic deformation at the edge is noticed in composites aged at 100°C. Some areas indicate the existence of scars, resulting in an accumulation of hard particles in the damaged grooved regions (Figure 9f).

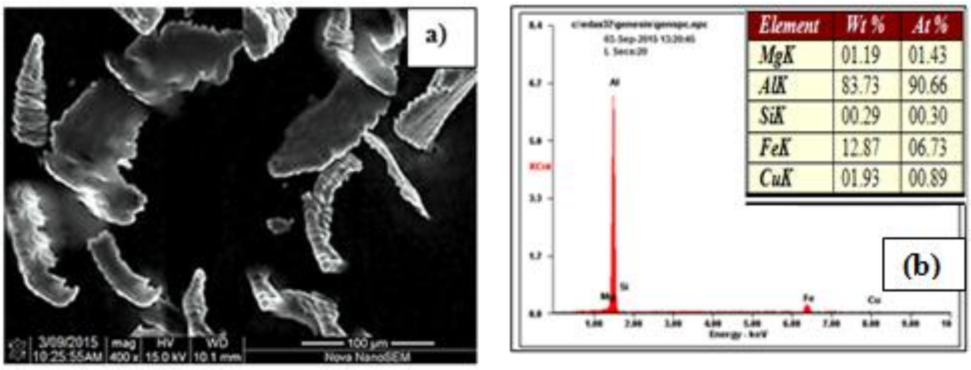
A SEM image of wear debris and a corresponding EDAX spectra of an Al 6061 alloy and Al 6061-6 wt. % SiC composites aged at 100°C is shown in Figures 10 and 11. The length of debris decreased with the increase of the reinforcement content. The debris of the monolithic alloy contains only long curved chips, while the 6% SiC/Al composites inidcated shorter and wider chips (debris consisting brittle fragments which could be produced by delamination or cracking).

The wear surface of age hardened Al6061-6 wt. % SiC composite shows smoother conditions as compared to the Al 6061 alloy. Since reinforcements present in the matrix are in contact with the counter surface, there may be removal of counter surface material. This counter surface material was having a lubricating effect on Al 6061 composites. Therefore, the presence of iron (Fe) was clearly observed in the wear debris of composites (Figure11b).



Element	Wt %	At %
MgK	01.21	01.36
AlK	95.97	97.30
SiK	00.13	00.13
FeK	00.88	00.43
CuK	01.81	00.78

Figure 10 Wear debris of Al 6061 alloy aged at 100^{O}C and corresponding EDAX



Element	Wt %	At %
MgK	01.19	01.43
AlK	83.73	90.66
SiK	00.29	00.30
FeK	12.87	06.73
CuK	01.93	00.89

Figure 11 Wear debris of Al 6061-6% SiC composites alloy aged at 100^{O}C and corresponding EDAX

4. CONCLUSION

In conclusion, the composites fabricated by a two step stir casting method are positively responding to the age hardening treatment with an almost 145% and 50% additional improvement in hardness and wear resistance, respectively. However the mechanical characterization and microstructural investigation justifies the effort of choosing lower aging temperature with optimum weight percentage of reinforcements for the improvement in hardness and wear resistance of the composites. Beneficial effects are also observed, due to the diffusion of iron from the disc to the pin surface at a higher weight percentage of reinforced composites to improve wear resistance. Finally, it can be concluded that Al6061-6 wt.% SiC exhibits superior mechanical properties in comparison with the Al6061 alloy, Al6061-2, 4wt. % of SiC composites.

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