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RESEARCH

Development of an Extrusion Process to Ameliorate the Tribological Properties of Heat Treated Al Mg Si (Cu) System Alloys Matrix Composites in Consolidated State

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A B S T R A C T

The developments of AA6061 aluminum matrix composites are of great interest in industrial applications for lighter materials with high specific strength, stiffness and wear resistance. In this article, the dry wear behavior of AA6061 matrix composites was investigated under different sliding speeds and applied loads. It is observed that the composites exhibit higher friction coefficients and greater wear resistances than the Al alloy against the steel disc surface. Low-speed wear rates are associated with abrasive wear, indicating the dominant wear mechanism, though minor, delamination wear may be produced. Abrasive wear associates with the formation of deep scratches on the worn surface in the sliding direction. For a given load and sliding velocity the extent of iron transfer is highest in case of 15 % SiC reinforced Al6061 composite among all the material studied.

1. INTRODUCTION

The use of different types of metal matrix composites (MMCs) is constantly growing because they possess better physical, mechanical and tribological properties compared to the matrix materials [1-7]. Composite materials based on light metals like aluminium, magnesium and zinc find application in many industries due to their low density [8-11]. Different reinforcing materials like SiC, TiB_2, Al_2O_3, B_4C, zircon sand, SiCrFe and CrFeC, and cerium oxide have been used to reinforce the metal-based matrices in an attempt to improve their mechanical and wear properties [7-14]. The idea that a relatively small amount of reinforcement can improve characteristics of matrix material is attractive, and constant improvements of MMCs technological processing and possibilities for their new applications are not a surprise. These popular composites are currently manufactured by powder metallurgy, liquid metallurgy, spray forming and diffusion bonding techniques [9-14].

Numerous authors investigated friction and wear properties of aluminium matrix composites studying the influence of different parameters, including the type of the matrix and counter body material and their hardness, the type of the reinforcements, their shape, size and volume fraction and testing conditions (load, speed, temperature, type of relative motion, lubrication and environment) [15]. Most of these investigations were conducted on model type pin-on-disc tribometers. The results obtained from the applied load and reinforcement content effects on friction and wear properties of various aluminium alloys and their composites, under dry sliding conditions, indicate existence of critical transition behaviour from mild to severe wear. Improvements of the wear resistance of aluminium MMCs were more than one order of the magnitude compared with matrix materials at low contact pressures [15].

In the light of the above, the present investigation focuses on the effect of the SiC particles reinforcement with average sizes of 1μm and volume fraction of 5, 10, 15 % on the microstructure and tribological properties of AA6061. Composites were produced by applying powder metallurgy process. Tribological properties of unreinforced alloy and composites were studied, using pin-on-disc, under dry sliding conditions at different specific loads. Hardness measurements and scanning electron microscope were used for microstructural characterization and investigation of worn surfaces and wear debris.

2. EXPERIMENTAL PROCEDURE

Composites used in this study were AA6061– SiC particles composites. The tribological properties of these grades of composites were evaluated using hardness and wear values obtained from extruded samples. The AA6061– SiC composite material is fabricated by a powder metallurgy process. The nominal chemical composition of Al6061 alloy is shown in Table 1. First, the 6061 powder was dehydrated in a vacuum chamber at 450 °C for 3 hours. Different volume percentages of SiC powder (5, 10, 15 vol .%) was added to 6061 Aluminum powder (60 μm) by means of a mechanical alloying under argon atmosphere.

Table 1. The nominal chemical composition of Al6061 alloy.

Material	Si	Fe	Cu	Zn	Ti	Mg	Cr
(wt. pct)	0.6	0.7	0.3	0.25	0.15	1	0.1

Silicon carbide is a material of particular interest due its low density, high melting point and hardness. These properties make silicon carbide an attractive candidate for reinforcement of aluminium alloys when mechanical properties and wear resistance are demanded. Table 2 shows the properties of the SiC reinforcement (1 μm).

Table 2. The properties of the SiC reinforcement.

Hardness (VHN)	Density (g/cc)	Elastic Modulus (Gpa)	Properties
2600	3.2	410	SiC

Citric acid was added to the blend in order to minimize welding during the milling process. The homogenous powder mix is then compacted by using uni-axial pressing at 200 MPa. The samples were then degassed at 400 °C, prior to extrusion at 550 °C. Figure 1 shows the XRD pattern of the 10 % SiC reinforced Al6061 composites after primary processing prior to extrusion. It is observed that there is no evidence of interfacial reaction including Al_4C_3 which is mostly formed due to the direct reaction between the Al alloy and SiC particles. All of the compacted billets were extruded in an extrusion machine to reach a fully consolidated state. The composites were subjected to solutionizing at a temperature of 530 °C for a duration of 1 h and then quenched in water. Artificial ageing was carried out at 175 °C for a duration of 4–10 h in steps of 2 h.

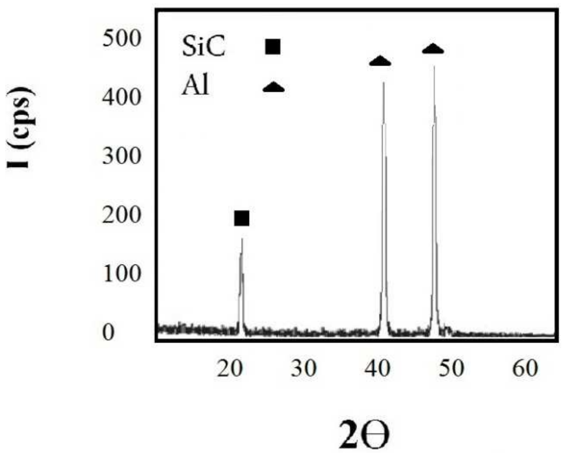


Fig. 1. Typical XRD pattern of the 10 % SiC reinforced Al6061 composites.

Metallographic, hardness and wear tests were carried out on the heat treated samples. Microscopic investigations of the composite specimens and matrix alloy were carried out using a scanning electron microscope (SEM) (CAMSCAN-MV2300 Model, Oxford). Mechanical and tribological tests were done on the specimens with T6 temper, i.e., in the peak-age condition. Hardness measurements were carried out using Shimadzu Microhardness tester using a load of 1 N for a period of 10 s. For each sample, five hardness tests on randomly selected regions were performed in order to eliminate the possible segregation effects and get a representative value of the matrix material hardness. During the hardness measurements, precaution was taken to make indentation at a distance of at least twice the diagonal length of the previous indention. The extruded composites were characterized by wear testing. Sliding wear tests were conducted in pin-on-disc wear testing apparatus under load of 10 and 20 N against case hardened steel disc of hardness 63 HRC. Test specimens were cut and shaped in the form of pins having 6 mm in diameter and 25 mm in height. Before the abrasion tests, each specimen was polished to 0.5 µm. Figure 2 shows schematic diagram of the abrasion wear test. The experiment was carried out at room temperature with water as the lubricant. The samples were cleaned with acetone and weighed prior to and after each test.

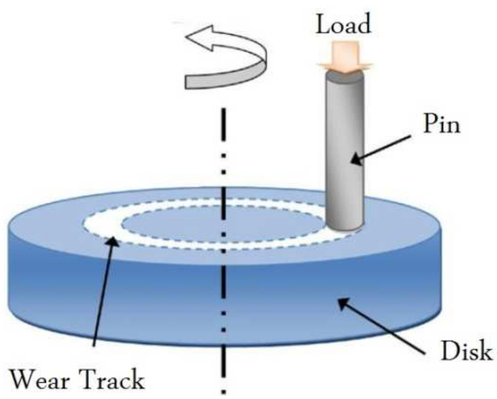


Fig. 2. Schematic diagram of the abrasion wear test.

3. RESULTS AND DISCUSSION

The homogenous distribution of the reinforcement phase is an essential condition for a composite material to achieve its superior performance. Particularly in the case of discontinuous MMCs, the homogeneous distribution of the reinforcing phase is an essential requirement. Microscopic investigations of the composite specimens indicate that the distribution of SiC in a matrix alloy is fairly uniform (Fig. 3).

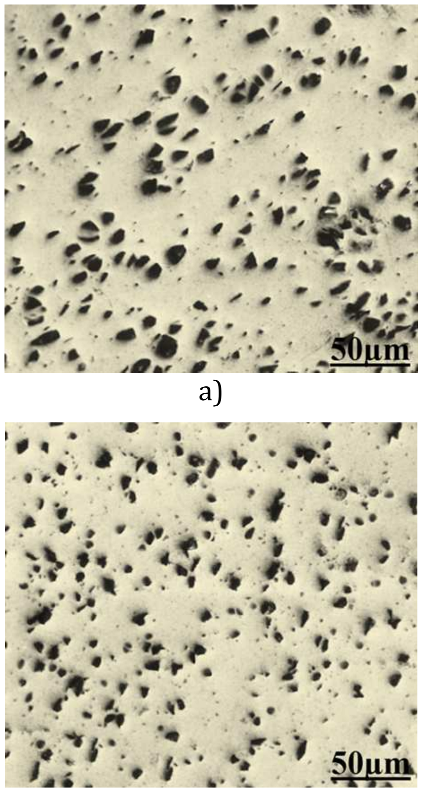


Fig. 3. The optical microstructures of the composites: a) Al6061-10 % SiC, b) Al6061-15 % SiC.

Tribological properties of AA6061 aluminum alloy matrix composites is of great interest. The plastic deformations are unwelcome and represent the limiting factor for tribological application of these materials. The influences of sliding speed and the SiC content on the wear resistance of AA6061 aluminum alloy matrix composites are illustrated in Fig. 4.

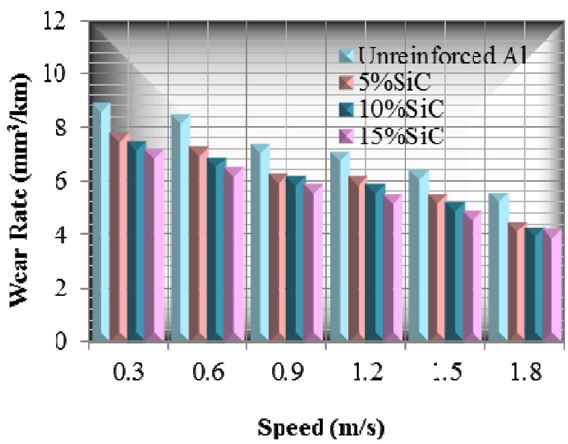


Fig. 4. Effect of sliding speed and the volume fraction of the SiC phase on the wear rates of the composites.

The wear rate of the unreinforced alloy is found to be higher than that of the composites. The lowest value of mass loss in wear test was distinct for Al–15 vol. % SiC and the highest mass loss in wear test was for bare Al alloy. It is noted that the wear rate decreases with increasing the SiC volume fraction for the composites. A number of studies have been engaged during the last twenty years on wear behaviour of Al based particulate reinforced composite [12-15]. Reinforcement of Al based alloy with SiC or Al_2O_3 are usually found to improve the wear resistance under both abrasion and lubricated sliding conditions. The addition of reinforcements improves the critical transition values of applied load and wear resistance compared with corresponding matrix alloy. However, increase of the volume fraction can also provoke clustering of the particles during fabrication of the composite. Strength of particles/matrix interface is very important parameter since that interfaces could be relatively weak due to interfacial reaction. If the reinforcement is well bonded to the matrix, the composite wear resistance increases continuously with increasing volume fraction of reinforcement. In contrast, if the reinforcement is not well bonded to the matrix, the wear resistance of the composite increases up to a critical amount of the reinforcement and thereafter starts to decrease [14, 15].

Figure 4 shows that the wear rate is to decrease with increasing sliding speed under the applied load of 10 N. Under low load, abrasion wear mechanism becomes dominant. The hard SiC particles support the normal pressure on the surface resulting in increased wear resistance. This effect diminishes at higher loads due to the fragmentation of particulates [15-17].

Attained friction coefficient values of the matrix alloy and composite materials were in expected range for light metals in dry sliding conditions. Figure 5 shows that the friction coefficient decreases slightly with increasing the sliding speed. Relatively low friction coefficient values of the matrix alloy are due to the fact that at applied specific load, pin surface starts to deform plastically and to flow. Increase of the coefficient of friction with the amount of reinforcement particles is ascribed to the fact that the amount of protruded particles increases during wear occupying larger area of pin surface. In the same time, one part of protruded particles are torn away from the matrix and fractured into fragmented pieces. In this situation, the contact between hard particles and the counter body material was established, resulting in higher values of the coefficient of friction. Compared with the matrix alloy, higher coefficient of friction values of composite correspond to lower values of the wear rate. On the other hand, the higher coefficients of friction in the case of composites containing hard SiC particles can be to the formation of tribofilm at the interface between pin and disk. If the effective load on the individual particle increased above its flexural strength, the particles get fractured. Parts of the removed SiC particles are entrapped between two partners, i.e. asperities of softer material of pin and asperities of harder material (hardened steel disk), possibly leading to three-body abrasion; then it will result in surface roughness between contacting surfaces and increased coefficient of friction [14, 15].

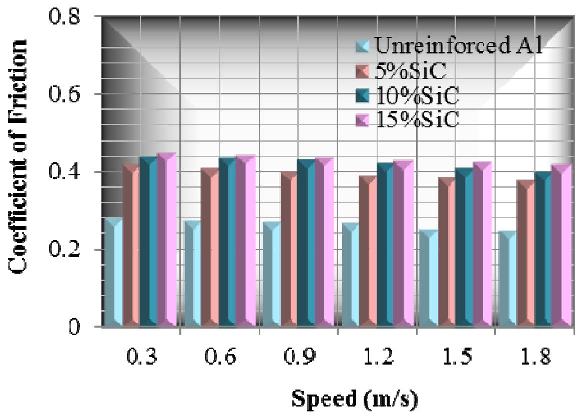
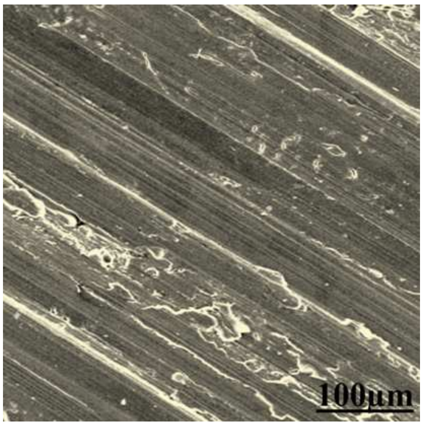


Fig. 5. Friction coefficient behavior of the composites under the applied of 20 N.

Microstructural characterization of the worn surfaces was carried out using an electron microscope. A combination of three wear mechanisms, namely abrasion, delamination, and adhesion coexists under the majority of test conditions. Cavities or craters of rough regions indicate that locally adhesive wear and fine grooves or ploughing of smooth regions suggests that locally abrasive wear were dominant mechanisms [15]. Figure 6 shows the worn surfaces of the unreinforced Al alloy and the composite at the sliding speed of 0.3 m/s and applied load of 20 N. The unreinforced matrix alloy is much softer than the counter body material and during sliding counter body penetrates into the matrix alloy producing deep grooves and causing extensive plastic deformation of the surface, which results in great material loss and significant wear rate. The worn surfaces also contain the evidence of adhesive wear in the form of adhesive pits. On the other side, the large scale of the matrix alloy is transferred to the counter body. Beside the formation of parallel lips along the continuous groove marking, delamination and adhesion of the worn surfaces seem to be the primary wear mechanisms [11].



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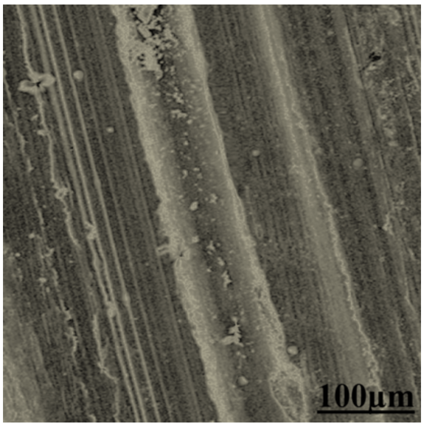

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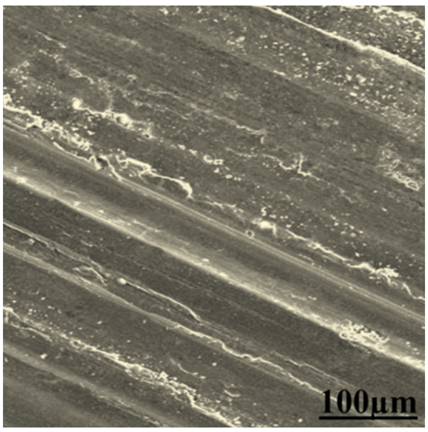


c)

Fig. 6. Worn surfaces of the unreinforced Al alloy and the composites at the sliding speed of 0.3 m/s and applied load of 20 N: a) Unreinforced Al 6061 alloy, b) Al 6061-5 % SiC, c) Al 6061-10 % SiC.

The wear surface of the Al matrix composite reinforced with 5 % SiC at the sliding speed of 1.8 m/s and applied load of 20 N is depicted in Fig. 7. The flow of materials along the sliding direction, generation of cavities due to delamination of surface materials and tearing of surface material is also noted in this Figure. It is noted that the slider could penetrate and cut deeply into the surface and cause an extensive plastic deformation on the surface, resulting in a great amount of material loss.

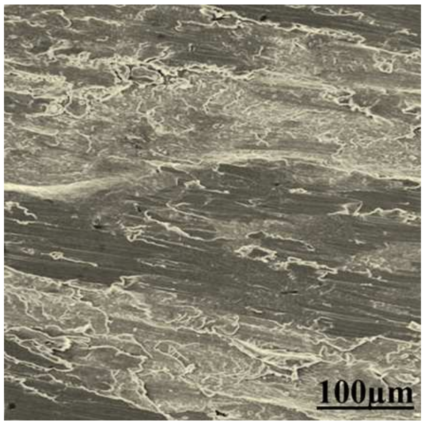
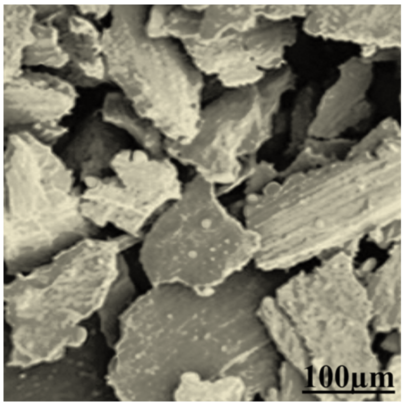


Fig. 7. Worn surface of the Al 6061-5 % SiC composites at the sliding speed of 1.8 m/s and applied load of 20 N.



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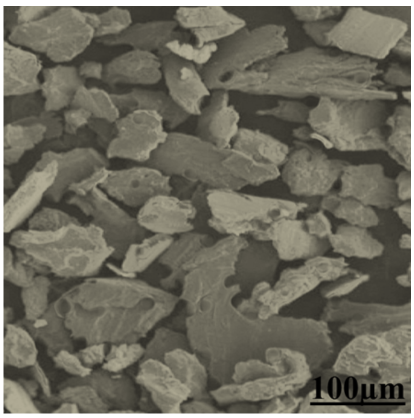
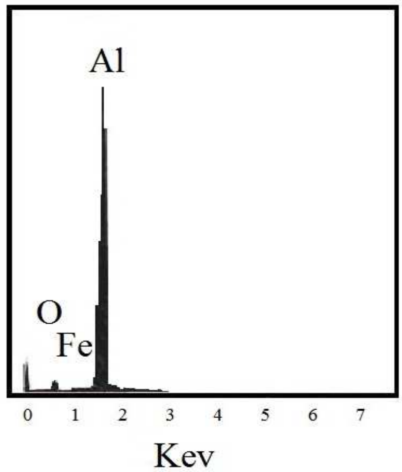


b)

Fig. 8. The SEM micrographs of wear debris in: a) Al6061 alloy, b) Al6061–15% SiC composites.

Wear debris can be generated by microcutting, plastic deformation as well as material transfer from one surface to another. Morphology and size of wear debris collected during the wear tests of Al6061 alloy and Al6061–15 % SiC composites at an applied load of 10 N are shown in Fig. 8. Debris generated by the wear of the materials in contact originates mostly from the pin material. SEM microphotographs of composite indicate that the wear debris is finer than those from the matrix alloy. Among the wear debris of Al matrix alloy and composites with low volume fraction of SiC, at higher specific loads prevail mainly sharp edge, plate-like particles. On the surface of these plate-like particles, presence of material plastic flow could be noticed. Thus, at higher specific load, the wear debris are mainly plate-like, with sharp edges, which are typical for adhesive wear. Presence of the rodlike particles, longer indicates existence of severe wear. Analyses of pin and counter body worn surfaces condition and generated wear debris show that the predominant mechanism of wear was adhesion followed with plastic deformation. Sporadic deep caverns formed by the pull outs of SiC particles from the matrix indicate relatively weak interfacial bonding between aluminium matrix and SiC particles in these areas. These SiC particles, fractured into fragmented pieces, have been entrapped between the pin and counter body and together with protruded SiC particles from the matrix act as abrasives. Presence of brown layer on the pins worn surface as well as brown-coloured wear debris indicate formation of the iron oxides and existence of the oxidation wear. The EDAX patterns of the wear debris for the unreinforced Al alloy and the composites are shown in Fig. 9. The superior wear resistance of the developed composites can mainly be attributed to the formation of mechanically mixed layer (MML) contributed by the back transfer of iron from the counter disk on to the sliding pins. Fig. 9a revealed the presence of small amount of iron in the wear debris of unreinforced Al. X-ray analysis shows that Iron, aluminium, oxygen are the major elements observed in the debris of the composites indicating the formation of MML which acts as a lubricating film lowering the wear rates of the composites (Fig. 9b). During sliding wear, iron, and possibly other alloying elements, from the steel counterface were transferred to the surface of the composites. The iron rich transfer layers help the SiC particles to remain unbroken during wear and act as load-bearing elements. Since there is little evidence for any large-scale plastic deformation and damage in the matrix adjacent to the wear surfaces, the removal of material from the surface of the steel slider should be due to the abrasive action of hard SiC particles on these surfaces. It is reported that iron was oxidized during this process and oxide layers, in particular Fe_2O_3 layers generated during wear, act as solid lubricants and help to reduce the wear rates.



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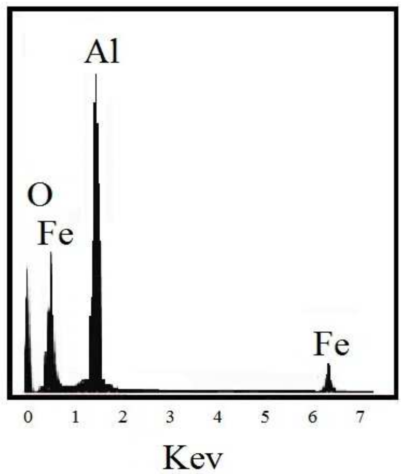

b)

Fig. 9. The EDAX pattern of the wear debris: a) Al6061 alloy; b) Al6061–15 % SiC composites.

Fig. 10 is based on semi-quantitative EDAX results to show a physical transfer of iron from the rotating disk to the worn surface of the composite pin. It is noted that the amount (wt.%) of iron transferred from the tool steel mating disk to the composite decreases with increasing speed for all the composites under the load of 20 N. The relatively large transfer of iron debris at low speed can be attributed to the dominating abrasion wear mechanism on the composite. At high sliding speeds, delamination dominates as the primary wear mechanism on the composite surface thus minimizing the transfer of the iron to the composite.

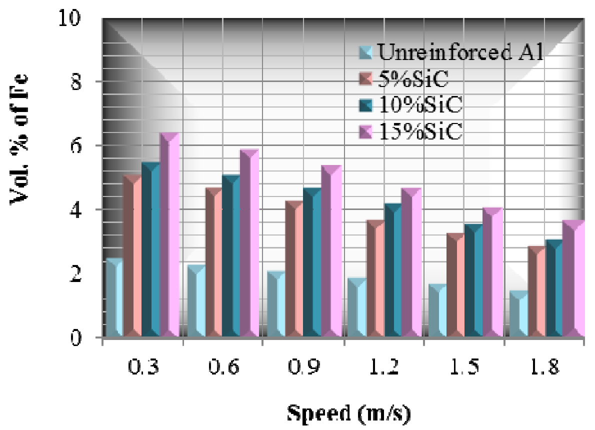

Fig. 10. The amount of iron transferred from the disk to the pins.

The hardness of the composites with different volume fractions are shown in Fig. 11. It can be seen that the hardness of all composites are higher than that of the 6061 alloy and increases with increasing SiC content. The higher hardness of the composites could be attributed to the fact that SiC particles act as obstacles to the motion of dislocation. The application of the extrusion is assumed to enhance the mechanical properties of the matrix alloy. It is known that the incorporation of particulate reinforcements brings an increment in the material tensile strength and promote the load transfer from the matrix to the reinforcement phase. Higher dislocation densities together with the reinforcement particles will result in hindered dislocation movement resulting in higher hardness.

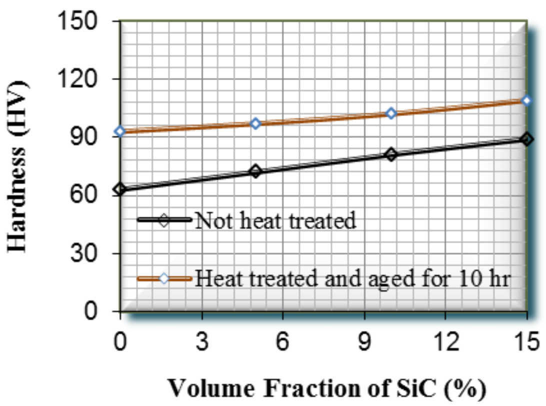

Fig. 11. The hardness results of the Al6061 alloy matrix composites reinforced with SiC particulates.

4. CONCLUSION

It is concluded that unreinforced Al alloy show very intensive wear rate from the beginning of the test. Wear behaviour was determined by extensive material plastic flow on pin surface indicating severe wear regime as dominant. However, composite did not show plastic deformation on the worn surface. Values of the friction coefficient of the matrix alloy and composite materials were in expected range for light metals in dry sliding conditions. Increase of the friction coefficient with the amount of SiC reinforcement was ascribed to the higher amount of protruded SiC particles occupying larger area of pin surface during wear. The higher coefficient of friction was the consequence of established contact between hard SiC particles and the counter body material. The rough and smooth regions are distinguished on the worn surface of the composites similar to the unreinforced Al alloy. Plastic deformation occurred when the applied specific load was higher than the critical value. The high shear stresses on the sliding surface cause initiation and propagation of the cracks in the subsurface, leading to the loss of material from the worn surface in the form of flakes. The debris of the composites with low wear rate comprise of a mixture of the fine particles and small shiny metallic plate-like flakes and are associated with the formation of more iron-rich layers on the contact surfaces. Iron, aluminium, oxygen are the major elements observed in the debris indicating the formation of MML which acts as a lubricating film lowering the wear rates of the composites.

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