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Effect of Mg on the Wear Behaviour of as-cast Al-4.5Cu-3.4Fe in-situ Composite

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Abstract Wear behaviour of Al-4.5 mass% Cu-3.4 mass% Fe in-situ composite with different Mg additions was investigated. The composite was produced by solidification processing whereby Al_3Fe intermetallic formed in-situ in Al-Cu matrix. The percentages of iron, copper and aluminium were kept constant while varying the mass% of Mg. The microstructure of the original composite revealed needle shaped Al_3Fe intermetallic phase/precipitates. These needle shaped precipitates changed to fine irregular shaped precipitates which were widely dispersed throughout the matrix as Mg additions were increased from 1.5 mass% to 4.0 mass%. The hardness of the composite also increased as Mg additions were increased. The wear behaviour of the composites was studied by performing dry sliding wear test using a pin-on-disc wear tester by varying the applied load from 5-15 N for 600 seconds and also by varying the time from 300 to 1200 seconds at an applied load of 5 N. The morphology of the worn out surface was determined by scanning electron microscopy (SEM). It is observed that as the applied load and time increases, the wear rate increases but decreases with increasing Mg addition to the composite. The wear resistance increased as hardness of the composite increased. Hence, incorporation of Mg in the Al-4.5 mass% Cu-3.4 mass% Fe in-situ composite increases the hardness and wear resistance of the material due to change in the morphology of the intermetallic phase/precipitate.

Keywords: *Al-Cu-Fe in-situ composite, intermetallic phase/precipitates, dry sliding wear*

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1. Introduction

Metal-matrix composites (MMC) have, in recent years, steadily replaced the use of conventional alloys in various sectors due to better combination of properties. Increasing demand on lightweight materials in industrial sectors, specifically the aerospace and automotive sectors, Al-based metal-matrix composites (AMCs) have excellent stiffness to density and strength to density ratios and have become popular for critical structural applications. AMCs find wide applications in various automotive industries for manufacturing parts such as brake discs and rotors, gear shafts, pistons, connecting rods and integrally cast engine blocks. The tribological properties, specifically dry sliding wear behavior, of AMCs have garnered much attention. Most of the Al-based MMCs are produced by ex-situ techniques; the reinforcing particles like short fibers, whiskers, particulates are synthesized separately and then inserted into the matrix during a secondary process such as infiltration or powder processing [1,2].

On the other hand, the in-situ technique, in which the reinforcing particles are precipitated from within the alloy during solidification processing, can offer certain advantages, viz., ease of processing, low cost and uniformity in the distribution of reinforcing phase [2]. In-situ processes can create a variety of reinforcement morphologies, ranging from discontinuous to continuous [3].

In the Al-Fe binary system, the intermetallic phase Al_3Fe exists under equilibrium [4,5]. An earlier study has shown that Al-Fe binary alloys [6] offers a possibility of producing in-situ composite by casting route. The addition of Cu to the Al-Fe system offers the probability of creating an age hardenable matrix that further enhances the properties of the material [7].

In the present work, Al-4.5mass% Cu-3.4 mass% Fe x-mass% Mg [x=1.5–4.0] in-situ composites was produced by solidification processing. Wear behaviour of the composite was studied under dry sliding conditions, microstructure was observed and the microhardness of each sample was determined.

2. Experimental

2.1. Specimen Preparation

Commercially pure aluminium was melted in a graphite crucible and superheated to 850^0C. Electrolytic copper (from discarded electric cables) in the form of wire was added to the superheated melt and stirred manually to homogenize the solution. The required amount of low carbon steel chips (source of iron) was then added to the superheated melt. The melt was again homogenized by manual stirring and a degasser was added. It was then cast into a pre-heated metal mould. The melt was allowed to solidify under slow cooling conditions.

The cast master composite alloy was then cut into several pieces. Each of the pieces were melted again and to each of them required amounts of Mg in the form of ribbons was added to make alloys containing 1.5, 2.5, 3.5 and 4 mass% Mg. During addition Mg was wrapped in aluminium foil to minimize loss of Mg in the form of magnesium oxide. Since the magnesium ribbons are very reactive, the temperature of the melt was lowered to 750^0C before Mg addition to reduce Mg loss. The melt was then stirred manually and then cast into preheated metal molds. The melt was then allowed to solidify under slow cooling conditions.

2.2. Microstructural Analysis

The specimens for microstructural analysis were machined to cylindrical shapes. Standard techniques were followed for the preparation for metallographic observation. Grinding was done on silicon carbide abrasive papers, final polishing being done on a velvet cloth using a suspension of fine alumina (Al_2O_3) powder. The microstructures were studied using a metallurgical microscope and an scanning electron microscope (SEM) equipped with an energy dispersive spectroscopy (EDS) system. Surface morphology of the worn samples was studied by SEM.

2.3. Hardness Test

A Vickers hardness testing machine was used and ASTM-E384 was followed to determine the hardness values of the samples. A load of 5 N (510 gm) was applied for a duration of 6 seconds by a diamond indenter having opposing indenter faces set at 136 degree angle from one another.

2.4. Wear Test

A pin-on-disc test apparatus was used to study the wear behaviour of the in-situ composites as per ASTM G99-95a standard. Medium carbon steel discs, 8 mm thick and 120 mm track diameter, and a hardness of RC 52 were used as the counter body. During the test, the pin was pressed against the rotating disc. The wear test was conducted (i) by varying applied load from 5 to 15 N (510-1530 gm) keeping time fixed at 600 seconds and rpm at 1000 and (ii) by varying time from 300 to 1200 seconds with a constant applied load of 5 N (510 gm) and a constant rpm of 1000.

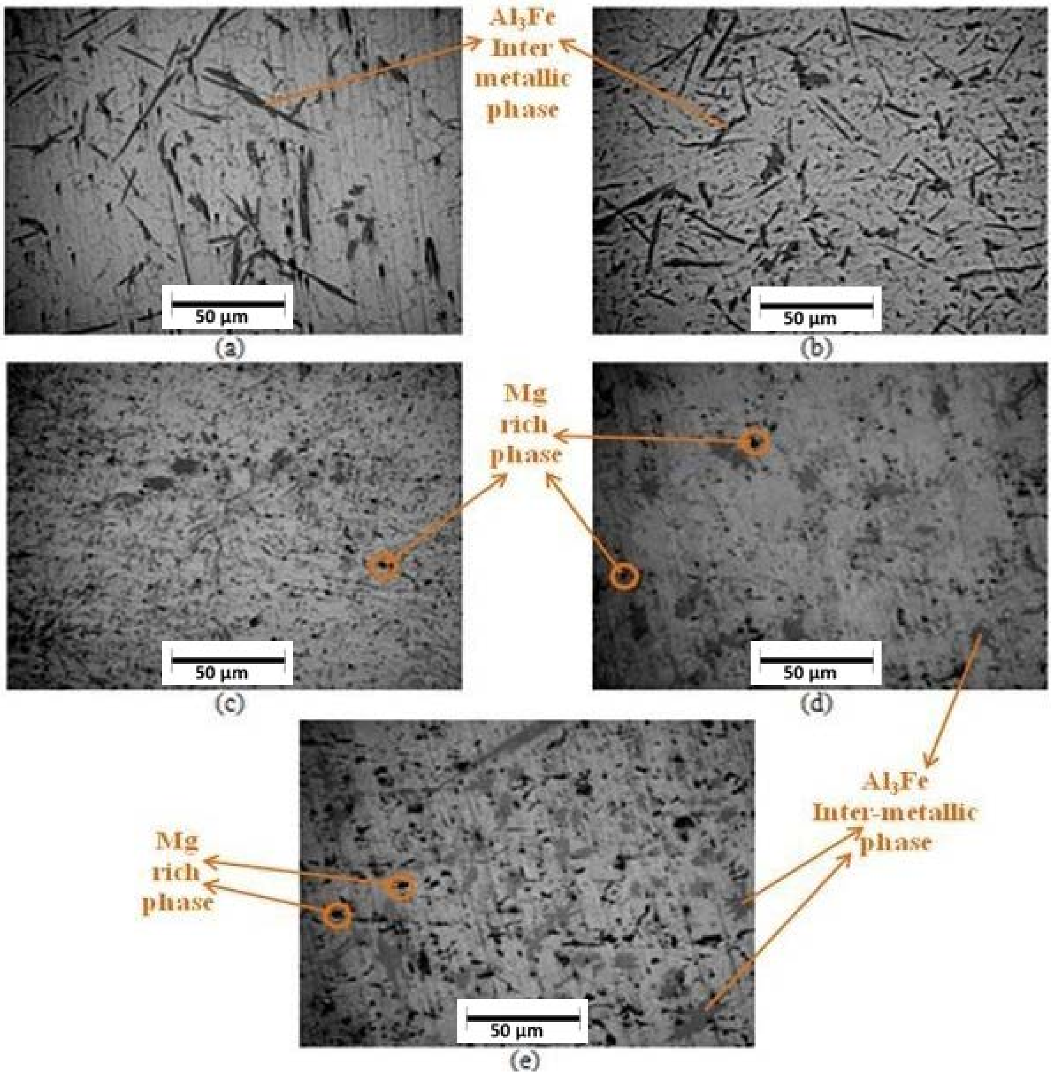

Figure 1. Microstructure [Magnification: 200X] of as-cast in-situ composite with (a) no Mg; (b)1.5 mass% Mg; (c) 2.5 mass% Mg; (d) 3.5 mass% Mg; (e) 4.0 mass% Mg

3. Results and Discussions

3.1. Microstructure Evaluation

The microstructure of as-cast Al-4.5Cu-3.4Fe revealed needle-shaped Al_3Fe intermetallic precipitates throughout the matrix [Figure 1(a)]. With increasing Mg additions the needle shaped inter-metallic phase steadily converted to irregular shaped precipitates [Figure 1(b) –(e)]. The precipitates became finer and more widely dispersed. This may be attributed to the fact that the addition of Mg caused a change in the interfacial energy and thus changed the geometry of the precipitate phase.

Scanning electron microscopic investigation revealed that the needle-shaped precipitates in the composite with 2.5 mass% Mg and the irregular shaped precipitates in 4.0 mass% Mg composite are in fact Al_3Fe intermetallic phase that acts as the reinforcing phase in the composite [Figure 2]

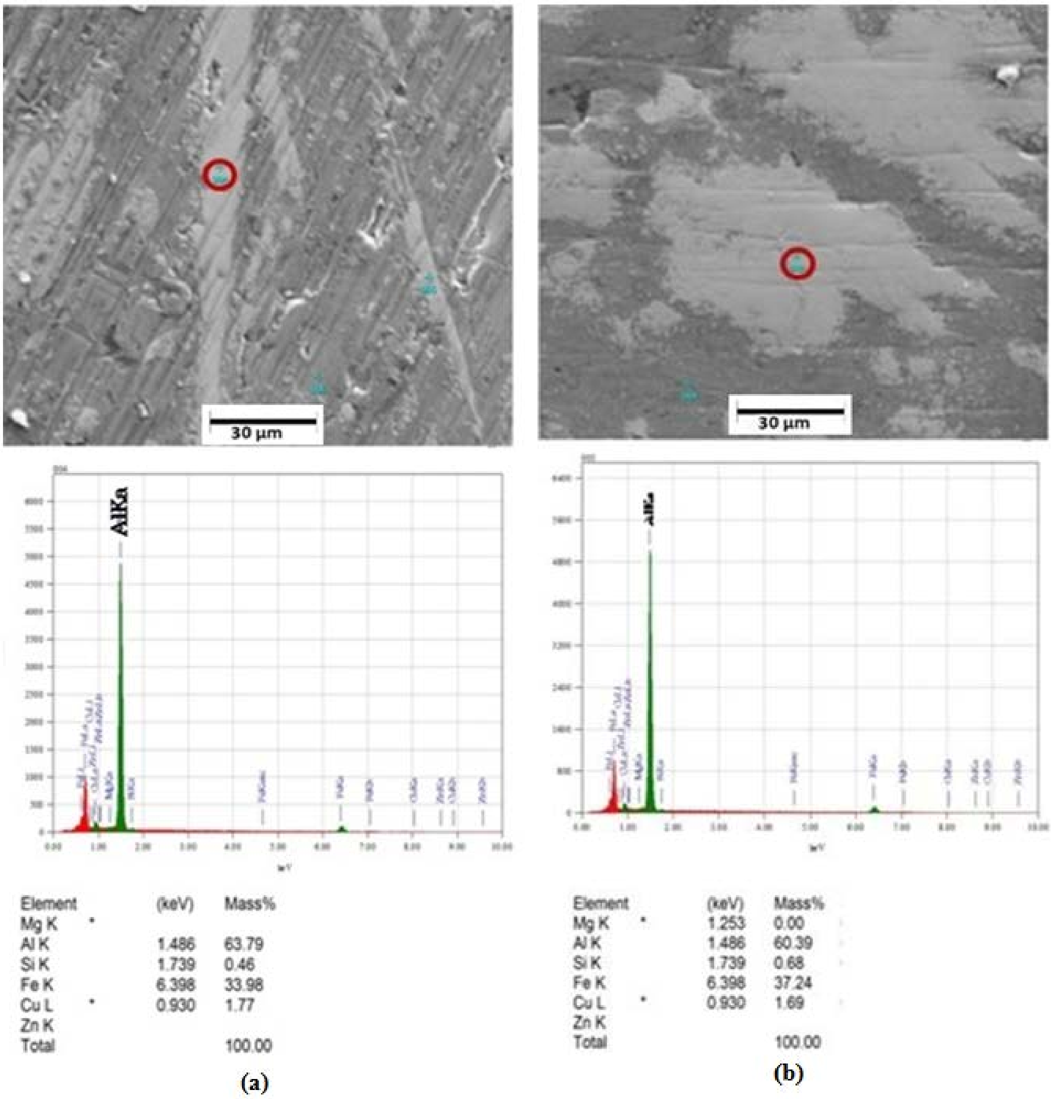

Figure 2. Microstructure [Magnification : 300X] and SEM/EDS spectrum of (a) 2.5 mass% Mg; (b) 4.0 mass% Mg composite

3.2. Hardness evaluation

The hardness values increase significantly with increasing Mg additions (Table 1). It can be seen that the hardness value of the composite increased from 104 HV in case of the composite with no Mg to 172 HV for composite containing 4 mass% Mg; an increase of about 1.7 times. This increase in hardness may be attributed to the presence of irregular shaped Al_3Fe intermetallic precipitates that replaced the needle shaped precipitates upon Mg additions.

Table 1. Vickers microhardness values

Composite	Al-4.5Cu-3.4Fe	+1.5 mass% Mg	+2.5 mass% Mg	+3.5 mass% Mg	+4.0 mass% Mg
Vickers microhardness (HV)	104	130	144	160	172

It is to be noted that it was difficult to locate the indentation exactly on the precipitates. That is why microhardness values reported in this presentation are averages of eight to ten measurements. While the accuracy of the measurements may not be very high, it nevertheless suggests that upon Mg additions the irregular shaped precipitates have higher hardness than the original needle-shaped precipitates.

3.3. Wear Behaviour

Figure 3(a) shows the wear rate of as-cast Al-4.5Cu-3.4Fe composite with different Mg additions as a function of time where sliding speed and load (5 N) were kept constant. The wear rate increases rapidly from 0 to 300 seconds followed by a gradual increase in the wear rate. The rate of wear was found to be the highest in the case of as-cast composite with 1.5wt% Mg addition and lowest in the case of as-cast composite with 4wt% Mg addition. For composite with 3.5wt% Mg there was a sharp increase in the wear rate after 9×10^2 seconds.

The wear rate of all samples increased gradually from 0 to 5 N followed by a dramatic increase in the wear rate [Figure 3(b)]. The rate of wear was found to be the highest in the case of the composite with 1.5wt% Mg addition and lowest in the case of as-cast composite with 4wt% Mg addition. The composite with 1.5wt% Mg showed the highest rate of wear at a load of 15 N.

The wear rate of all the samples at a load of 15 N is given in Table 2. It can said from the table that the wear rate of as-cast composite with 4wt% Mg is almost four times lower than that of as-cast composite with 1.5wt% Mg.

Table 2. Wear Rate of the samples [applied load: 15 N, duration: 10 min]

Composite	Wear Rate ($\times 10^{-8}$ kg.s^{-1})
1.5%Mg	30.58
2.5%Mg	24.68
3.5%Mg	13.23
4.0%Mg	8.35

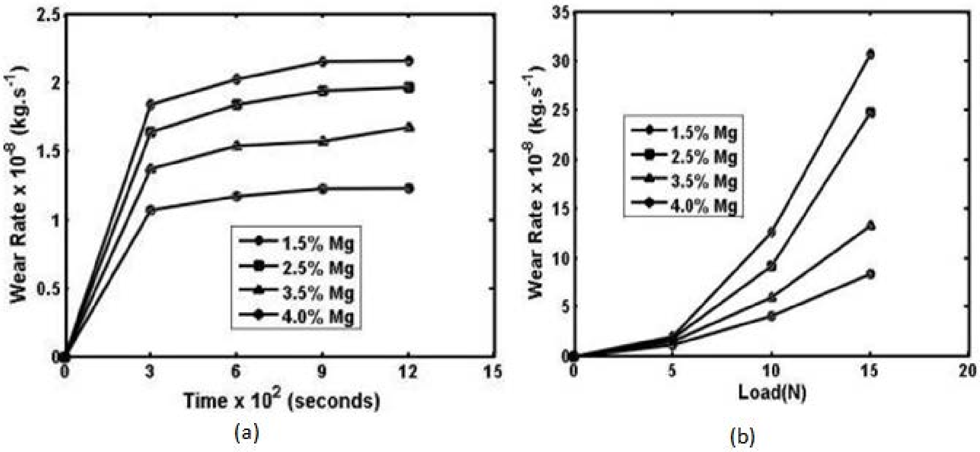

Figure 3. Wear rate of as-cast composites with different Mg additions as (a) function of time; (b) function of load

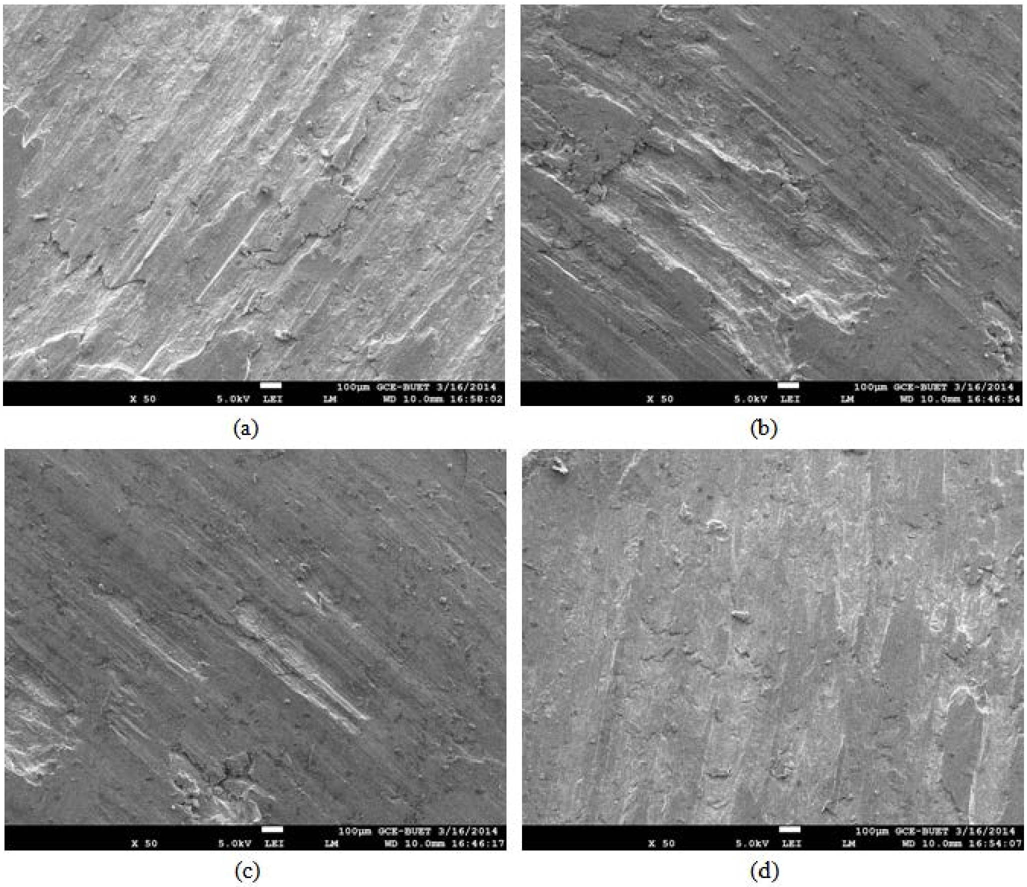

Figure 4. Scanning electron micrographs of the worn surfaces of the composite with (a) 1.5 mass% Mg; (b) 2.5 mass% Mg; (c) 3.5 mass% Mg; (d) 4.0 mass% Mg [load 5 N; time: 1200 seconds]

Figure 3 clearly shows that the composite with 1.5 wt% Mg has the highest wear rate while the composite with 4 wt% Mg has the lowest wear rate. The beneficial effect of the reinforcement on the wear resistance of the composites is observed to be the best at low load and reduces drastically with increase in applied load. With higher load, contact temperatures become high and plastic deformation occurs with consequence of very high wear. Also when applied load are increased, there was a sudden increase in wear rate of all the specimens.

The scanning electron micrographs (Figure 4) of the worn samples subjected to wear test with a load of 5 N for 1200 seconds show (Figure 4) the presence of grooves and valleys on the worn surface of all samples, suggesting that abrasive wear mechanism is the most probable wear mechanism. The extent of abrasive wear is found to be the highest for the composite with 1.5 mass% Mg addition, as is evidenced by deep and wide grooves on the worn surfaces and as well as by the highest wear rate. The abrasive wear is found to be lowest for as-cast composite with 4 mass% Mg additions, as is evidenced by shallow grooves as well as by the lowest wear rate. This can be attributed to the change in microstructure from needle shaped precipitates in case of composite with 1.5 mass% Mg to more globular shaped precipitates in case of composite with 4.0 mass% Mg. It is known that globular precipitates act as better reinforcing phase than needle shaped precipitates, as needle shaped precipitates act as stress points which yields poor properties. Since, the hardness of composite with 4 mass% Mg additions is greatest, this also contributes to its low abrasive wear. Samples with 1.5 and 2.5 mass% Mg show evidence of surface delamination [Figure 4 (a) and (b)]. This can be due to voiding/cracking between the reinforcement and the matrix, both of which lead to fragmentation and delamination of the surface.

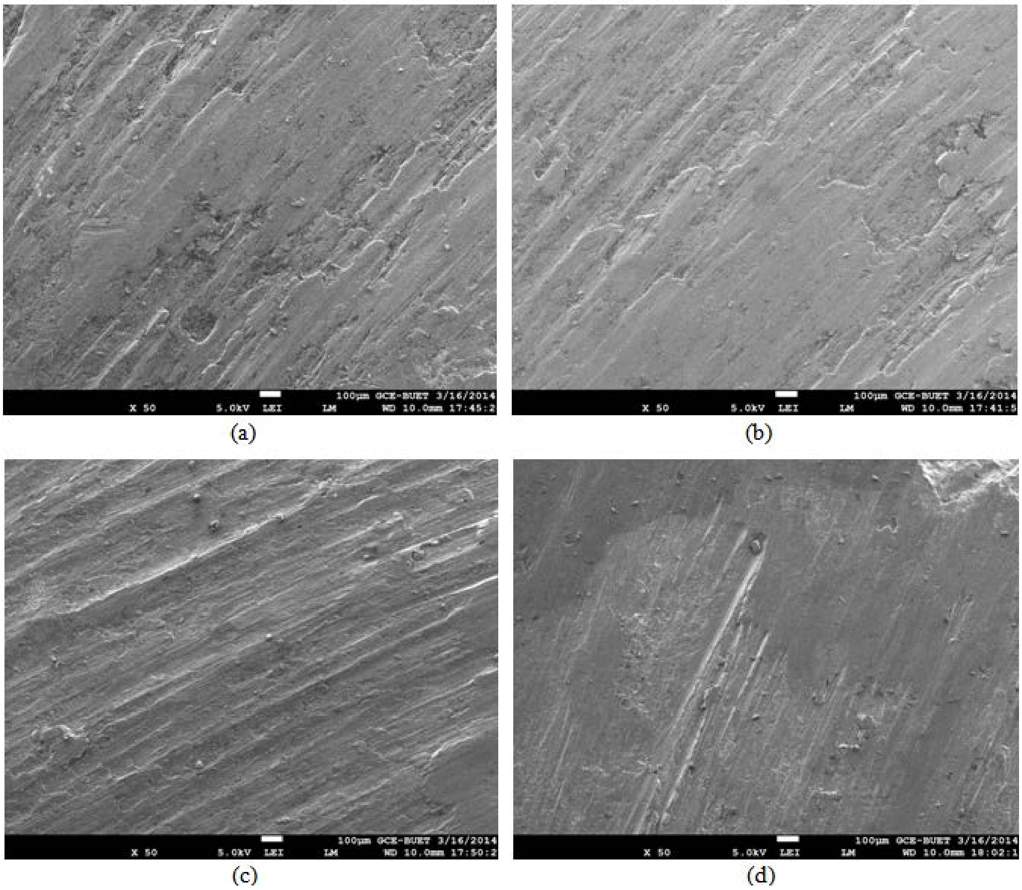

Figure 5. Scanning electron micrographs [Magnification : 50X] of the worn surfaces of the composite with (a) 1.5 mass% Mg; (b) 2.5 mass% Mg; (c) 3.5 mass% Mg; (d) 4.0 mass% Mg, subjected to wear test [load: 15 N; time: 600 seconds

Figure 5 shows the scanning electron micrographs of the worn samples subjected to wear test with a load of 15 N for 600 seconds. The micrographs show the presence of grooves and valleys on the surface of all samples, suggesting that abrasive wear mechanism is the predominant wear mechanism in this case too. Ploughing was seen as the main form of abrasive wear in all samples except for composites with 1.5 and 2.5 mass% Mg. In these samples cutting and fragmentation type abrasive wear has also been noticed [Figure 5 (a) and (b)]. Table 1 shows that the hardness values of composites with 1.5 and 2.5 mass% Mg are the lowest as a result of which the wear rates as seen in Figure 3(b) are the highest for these two compositions. This may be attributed to the needle shaped precipitates occupying large volume fraction of the matrix. On the contrary, composites with 3.5 and 4.0 mass% Mg have lower wear rates then the former and do not show evidence of cutting or fragmentation type abrasive wear. This can be attributed to the matrix containing irregular shaped precipitates instead of needle shaped precipitates. Since, these samples were subjected to wear at a higher load; the wearing process may have been aggravated by surface delamination and removal of material due to fragmentation.

Ploughing occurs when material is displaced to the side, away from the wear particles, resulting in the formation of grooves that do not involve direct material removal [8]. The displaced material forms ridges adjacent to grooves, which may be removed by subsequent passage of abrasive particles. Cutting occurs when material is separated from the surface in the form of primary debris, or microchips, with little or no material displaced to the sides of the grooves [8]. Fragmentation occurs when material is separated from a surface by a cutting process and the indenting abrasive causes localized fracture of the wear material [8]. These cracks then freely propagate locally around the wear groove, resulting in additional material removal by spalling [8]. The dependence of wear rate on the size of the reinforcing particles in AMCs has been studied in the past. Both an increase [9,10] and a decrease [11,12] in wear resistance with an increase in particle size have been observed depending upon particle size range, load etc. In the present case, the needle shaped precipitates/particles in the as-cast composite are rather large. Upon Mg additions these needle shaped particles change to globular shaped particles due to increase in the interfacial energy between the particles and the matrix. From Figure 6 it is clearly evident that as reinforcement of the as-cast composite increases the hardness and wear resistance increases.

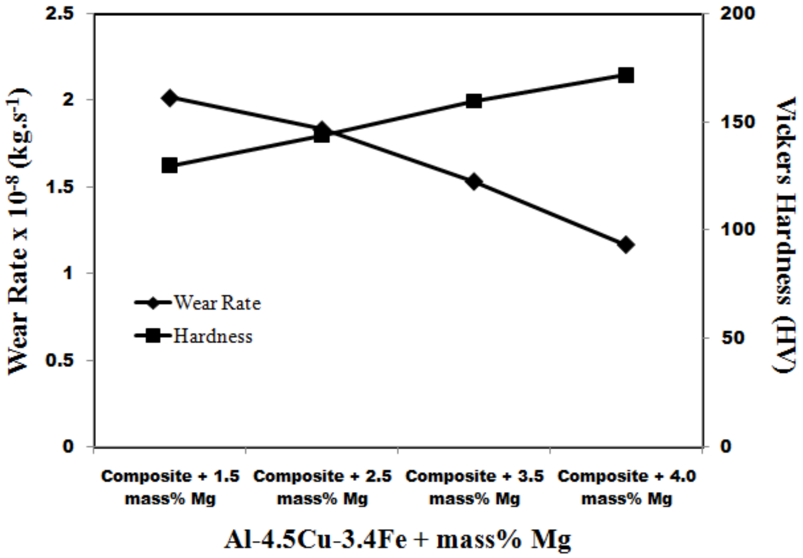

Figure 6. Dependence of Wear Rate and Hardness on Reinforcement

4. Conclusions

With increasing Mg additions, the needle shaped Al_3Fe precipitates changed to a more globular shaped particle spread throughout the matrix. As a result the hardness of the composites increased almost twice that of the original/monolithic composite. Abrasive wear has been identified as the predominant wear mechanism in all samples tested. Increasing mass% Mg addition increases the wear resistance of the composite by about four times at higher loads and by almost two times at longer duration. The transformation of the reinforcing Al_3Fe intermetallic phase as globular precipitates due to increasing mass% Mg addition are suggested to contribute to its better wear resistance.

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