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Effect of Heat Treatment on the Wear Behavior of AlSi5Mg Alloy Matrix Composites Reinforced with SiC_p Particles

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Abstract
Aluminum alloy (AlSi5Mg) matrix composite materials reinforced with different volume fraction of silicon carbide particles (SiC_p) were heat treated to T6 temper, and the effects of SiC_p content and heat treatment on the mechanical and frictional properties were investigated. The aging time was optimized and dry sliding ball- on-disc type wear tests were carried out. Besides, the microstructural analyses were carried out by using optical microscopy to observe the distribution of SiC particles in the matrix alloy. Also, worn surfaces of the composite samples were investigated by SEM to observe the interface characteristics between aluminum matrix and SiC_p reinforcements. The distribution of SiC_p in the AlSi5Mg matrix was homogenous and the optimum aging time was 6 hours for all fractions. The mechanical and tribological properties of the samples are improved with increasing volume fraction of SiC_p and the matrix hardness.

Keywords: Aluminum matrix composites, Aging time, Wear, AlSi5Mg, Heat treatment.

1. Introduction

Aluminum alloys have been the primary material of choice for mainly structural components of aircraft and automotive industry until now. Nowadays, the need for lightweight and high strength materials has increased in many areas including automotive, aerospace and defense. These needs have significantly accelerated the use of metal matrix composite materials (MMCs). The reason of the use of aluminum and its alloys as matrix material in the production of MMCs is due to high specific strength, high ductility, good formability, high fatigue strength, high corrosion resistance, high thermal conductivity and recyclability (Starke and Staley, 2011; Benedyk, 2010; Koli et al., 2015). Aluminum matrix composites (AMCs) are preferred in many areas due to their combination of advanced mechanical properties and better wear resistance compared to matrix alloy (Ramnath et al., 2014; Sijo and Jayadevan, 2016; Rahman and Rashed, 2014; Ravikumar et al., 2017; Rana et. al., 2015). Aluminum matrix composites are used in various fields like aerospace, aircrafts, underwater, automobile industry (as pistons, cylinders, engine blocks, brakes), substrate in electronics, turbine blades, etc. (Koli et al., 2015; Ramnath et al., 2014; Sijo and Jayadevan, 2016).

A considerable amount of work has been carried out on the mechanical and tribological properties of aluminum matrix composites containing different types of ceramic reinforcements such as SiC, Al2O3, WC, and graphene with any shape such as fibers, whiskers or particles (Suryanarayanan et al., 2013; Singh and Chauhan, 2016; Han et. al., 1995). Among all discontinuous reinforcements, silicon carbide particles (SiC_p) are the most commonly used reinforcements for AMCs (Rana et. al., 2015; Suryanarayanan et al., 2013; Singh and Chauhan, 2016; Han et. al., 1995; Deuis et. al., 1996). According to the earlier studies (Du et. al., 2017; Kaushik and Rao, 2016; Walczak et. al., 2015), SiC_p reinforcements generally improve the mechanical and wear properties of aluminum matrix when used in optimum amounts. There are numerous studies in which SiC_p reinforced aluminum alloy matrix composites were produced by different processes and with various heat-treated conditions. Research carried out by Walczak et.al. (2015) worked with the alloy which is commonly used for automotive industry for manufacturing of pistons and brake discs. The research showed that the friction coefficient and wear of the SiC_p reinforced cast AlSi9Mg matrix composites were notably lower than the matrix alloy and T6 heat treatment also resulted in an improvement of wear behavior. In another study, Ma et al. (2003) examined the dry sliding wear behavior of squeeze cast A390 aluminum alloy matrix composites with 20 and 50% discontinuous SiC_p addition. They found that both 20% and 50% SiC reinforced composites show better sliding wear resistance than A390 matrix alloy. Also, the transition temperature for wear behavior (when wear rate transmits from mild to severe) increases with increasing SiC content. Rahman and Rashed (2014) investigated the effects of SiC reinforcement (5, 10 and 20 wt. %) on the microstructural, wear and mechanical properties of AMCs produced by using stir casting technique. The results showed that hardness and tensile strength were maximum for 20 wt. % SiC_p addition. Also, wear resistance increased with the increasing amount of SiC particles. Bauri and Surappa (2008) investigated the effects of SiC_p addition and age hardening on dry sliding wear behavior of stir casted and extruded Al 8090 matrix. They reported that the unreinforced 8090 alloy and 8090/ SiC_p composites show mild wear behavior at 10 and 20N; however, they exhibit severe wear characteristics when the load is 50N. Also, composites show better wear resistance in severe wear conditions and the wear rates decrease with increasing SiC_p content. The aging treatment improves the wear resistance up to 20N loading, the wear resistance of composites is lower in peak-aged condition at 50N load and this was attributed to higher surface and subsurface deformation in peak-aged condition at higher load. Maleque and Karim (2009) worked on the wear behavior of stir casted and T6 tempered SiC_p reinforced (20 wt. %) AA6061 matrix composites. They found that the heat-treated composite samples exhibit better wear resistance than the as-cast ones and heat treatment could be and effective method of optimizing the wear resistance of these MMCs. Vieira et.al. (2003) studied the influence of centrifugal casting processing parameters on the distribution of SiC particles and the dry sliding wear behavior of Al alloy/SiC_p functionally graded composites. They found that as the volume fraction of SiCp increases the wear resistance of the composite increases. In addition, the dominant wear mechanisms were two-body abrasion, oxidative wear, adhesion and delamination for functionally graded aluminum matrix composites. Wiechec et al. (2016) focused on the electrical properties and hardness of permanent mold casted AlSi5Mg alloys having different Mg content. They observed that both properties are strongly susceptible to heat treatment conditions and T6 temper treatment gives better hardness than T4 and T7 tempers. The study carried out by Daoud and Abou El-Khair (2010) on the friction and wear behavior of sand cast A359/20vol.% SiC_p composite brake rotor sliding against automobile friction material has shown that the wear rate of the composite decreases with increasing load from 30 to 50N and increases with increasing load from 50 to 100N. They also found that the wear rate of composite samples decreases with increasing speed. Pradhan et al. (2017) studied the tribological properties of Al/SiC composite materials under three different wear test conditions such as dry, aqueous and alkaline medium. They observed that the wear loss increases with the increasing test load and sliding speed for all mediums and also the wear rate is maximum under the alkaline medium followed by aqueous medium and dry sliding conditions. In other work, Hassan et al. (2009) studied the wear behavior of stir casted Al-Mg-Cu/ SiC_p composites. They added Cu and SiC particles to Al-4wt. %Mg alloy matrix and observed the change on wear properties of the composites. They found that the addition of SiC_p reinforcement improves the wear resistance of the matrix alloy. On the other hand, the addition of Cu up to 5wt. % increases the hardness of the matrix, and resultantly improves the wear resistance of the composites.

Previous studies have generally focused on the effect of reinforcement content and distribution, friction load and heat treatment on the dry sliding wear behavior of aluminum alloy matrix SiC_p reinforced composites. Increasing the amount of reinforcement is reported to be beneficial for most of Al alloy matrix, but increasing the hardness of the matrix has different effects in low load conditions and high load conditions. In our previous study, Tekmen et al. (2003) the mechanical properties of AlSi5Mg matrix alloy and SiC_p reinforced composites were compared according to different volume ratios of reinforcement. Also, using extrusion after stir casting was thought to be beneficial for mechanical properties. The present study evaluates the effects of the SiC_p reinforcement content, T6 conditions and matrix hardening by aging on the dry sliding behaviors of these composites and the aim is to optimize aging time according to proper SiC_p addition. Also, the wear behavior study of this composite system has not been issued in the literature to the best of our knowledge.

2. Materials and Methods

The matrix material used in the work is AlSi5Mg alloy and the reinforcement is SiC_p (5-10 µm) which is added in amounts of 23, 30 and 37 vol. %. The chemical composition of the matrix alloy is shown in Table 1. The composite samples are produced by melt stirring technique and cast into cylindrical ingots, which are further hot extruded into bars of 10 mm diameter. The production procedure of the composite samples is well explained in an earlier publication (Tekmen et. al., 2003).

Table 1. The composition of the matrix alloy (AlSi5Mg).

Element	*Si*	*Mg*	*Ti*	*Mn*	*Cu*	*Fe*	*Zn*	*Al*
Weight	*5.0*	*0.2*	*0.2*	*0.1*	*0.02*	*0.15*	*0.10*	*Rest*

The extruded samples were then undergone T6 heat treatments with different aging durations. AlSi5Mg/ SiC_p composite samples were firstly heated up to the solutionizing temperature of 540 °C, held for 1 hour and finally quenched. Following the quenching, the samples were aged at 180 °C for different durations (from 30 minutes to 9 hours) in order to compare the effects of T6 heat treatment on the tribological properties of the matrix material and composites.

Dry sliding wear tests were carried out for both non-heat treated and heat treated samples in order to analyze the effects of T6 heat treatment on wear behaviors of AlSi5Mg/ SiC_p composites. The cylindrical shaped samples with dimensions of 10 mm diameter and 15 mm height were prepared for wear tests. Ball-on-disc mode wear tests were carried out by using CSM Tribometer Instruments at room temperature. The counter material was 100Cr6 steel balls. The wear tests were carried out under two different wear conditions. In the first condition, the load was 1 N, the sliding distance was 500 m and the sliding speed was 6 $cm.s^{-1}$. In the second condition, which was the most aggressive condition for the test device, the load was 10 N, the sliding distance was 1000 m and the sliding speed was 10 $cm.s^{-1}$. The mass of the samples was measured by analytical balance with the accuracy of ±0.01 mg before and after all wear tests. The mass loss and the changes of friction coefficient values were obtained from wear tests.

The Brinell hardness values of the cylindrical composite samples were measured according to the ASTM E10-14 standard. The diameter of the ball was 5 mm and the load was 2452 N with dwell time of 15 s. In addition, the hardness values of the AlSi5Mg matrix alloy were tested on the Vickers microhardness equipment using 4.90 N load.

The microstructural analysis were carried out by optical microscopy. The volume fractions and distributions of SiC particles in the microstructure and the porosity contents of the composite samples were determined by using Lucia image analyzer. The worn surfaces after wear tests were observed by scanning electron microscopy (SEM) (JSM–6060, JEOL, Japan). Also, elemental mapping technique was used for determining the wear behaviors of the samples and the counter material in wear tests.

3. Results and Discussion

3.1 Microstructures

Fig. 1 shows the typical microstructure of the composite sample with 37 vol. % reinforcement in the as-extruded condition. The pores were situated at the matrix-reinforcements interfaces. Besides, it can be observed that the size of SiC particles is approximately 5-10 µm.

The volume fractions of the SiC particle reinforcements in the matrix alloy were 23, 30 and 37%vol.

and the porosity contents were 4.13, 2.36 and 4.32%vol. The difference between these porosity content values was related to the production procedure (Cöcen and Önel, 2002). It is showed in the previous study that the porosity content of the composite samples was notably reduced after the hot extrusion process (Tekmen et. al., 2003). The distribution of SiC_p reinforcements in the microstructure was generally homogenous for all samples. However; some local small cluster of particles were observed in the microstructures.

Figure 1. The microstructure of the as-extruded sample with 37 vol. % reinforcement.

3.2 Hardness Results

The Brinell hardness values of the composite samples having different amounts of SiC_p addition with corresponding aging times are given in Fig. 2. As shown in Fig. 2, the hardness values in solution treated condition and in aged condition increase with increasing SiC_p content, the composite with the highest SiC_p addition having the highest hardness value (which is quite high for this composition). It is observed that the hardness values increased significantly after T6 heat treatment process for all the composite samples. The peak hardness values were obtained after aging for 6 hours for all composite samples, then the process was terminated. These results related to the effect of SiC_p content and heat treatment on the mechanical properties are in agreement with the findings of Rahman and Rashed, 2014; Liu et al., 2015; Veeravalli et al., 2016 and the earlier work of many others. Liu et al. (2015) investigated the effects of heat treatment on the mechanical properties of aluminum matrix SiC_p reinforced composites, and observed that the tensile strength and hardness values were improved significantly after T4 and T6 heat treatments; however, the effect of T6 was better than T4 at the same solid solution temperature (Liu et. al., 2015). In other work, Rao et.al. investigated the mechanical and tribological properties of AA7075 matrix TiC reinforced composites in T6 heat treated and cast conditions. According to their results, T6 heat treated samples shown improved hardness and mechanical properties for both matrix and composite system compared to cast ones.

It is known that T6 heat treatment increases the hardness of matrix and resultantly enhances the hardness of the composites (Tan and Said, 2009; Dossett and Totten, 2013). The observed Vickers microhardness values of the AlSi5Mg matrix of the composite samples were plotted against corresponding aging times and shown in Fig. 3. In parallel with the hardness values of the composites, the matrix hardness values of the composites increase with aging time and reach the peak value after aging for 6 hours, therefore the optimum aging period was determined to be six hours.

The results in Fig. 3 show that in the as solution treated condition the matrix hardness values of the composite samples are different in each other, which the sample with the lowest SiC_p addition has the lowest hardness value (60 HV) while other two additions have quite higher values (78 and 82 HV). This difference may be induced by reinforcement content which affects the matrix microstructure. However, the difference in matrix hardness values of the composite samples tends to decrease after two hours of aging treatment.

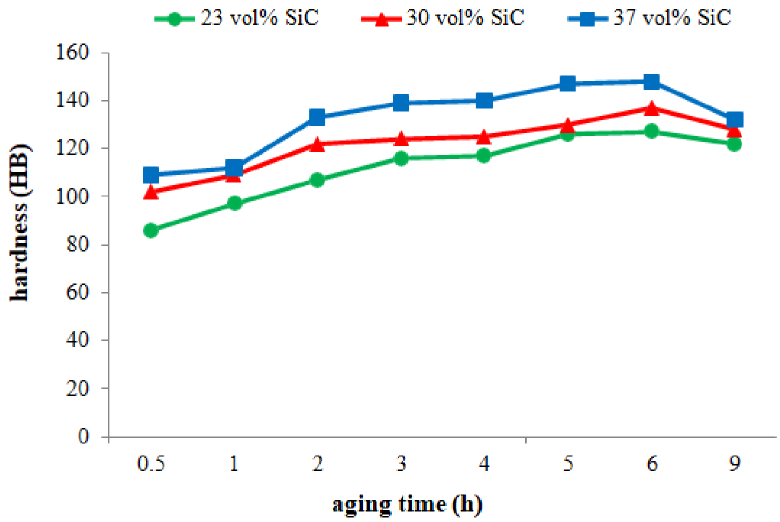


Figure 2. Brinell hardness values of composite samples with corresponding aging times.

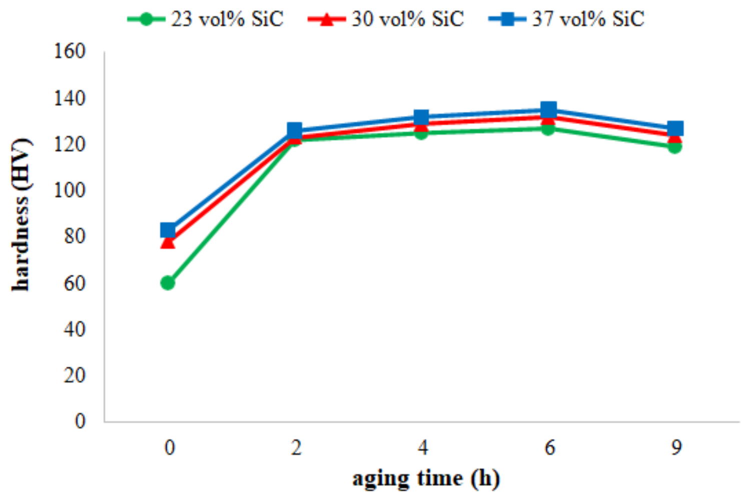


Figure 3. Vickers microhardness values of AlSi5Mg matrices with corresponding aging times.

3.3 Wear Tests

The change of friction coefficient values versus sliding distance were obtained from wear tests for heat treated and non-heat treated composite samples in aggressive and relatively soft wear conditions. The results for non- heat treated samples which were tested in aggressive conditions are shown in Fig. 4, where the friction coefficient values exhibit dynamic character. According to the literature, dynamic behavior of the friction coefficient is unfavorable for the service life of materials, the friction coefficient values have to exhibit stable behavior during the wear tests (Guezmil et. al, 2014). Here, 37 vol. % reinforced composite sample shows the most stable friction coefficient and also lowest value among others.

The changes of friction coefficient with sliding distance under the loads of 1 and 10N for the heat treated composite samples are shown in Figures 5 and 6, where the increasing volume fractions of SiC particles in the composite provides more stable wear behavior for both soft and aggressive wear conditions. The sample with the lowest SiC_p addition has the highest friction coefficient and, this value is not stabilized. This indicates that SiC_p addition improves frictional properties and this behavior is not affected by loading level.

Figures 4 and 6 show the change of frictional coefficient for non-heat treated and heat treated composites under high load conditions. For the samples with 23 vol. % SiC_p addition, the friction coefficient changed irregularly during the whole wear test. On the other hand, 30 vol. % SiC_p containing sample shows irregular behavior at the beginning of the test up to a sliding distance of 100 meters, then the friction coefficient is stabilized. The composite with 37 vol. % SiC_p exhibited the most stable wear behavior, there was no significant changes in friction coefficient during the whole test. It must be noted that for all test conditions the friction coefficient values are lowest for the specimen containing 30 vol. % SiC_p.

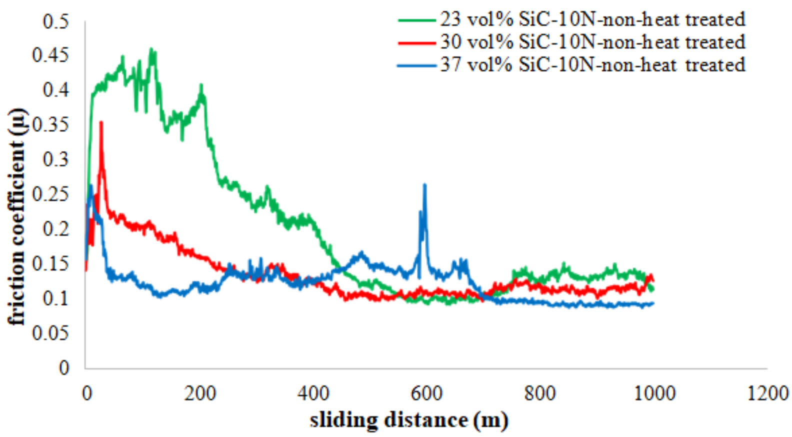


Figure 4. The changes of friction coefficient with sliding distance under the load of 10N for non-heat treated samples.

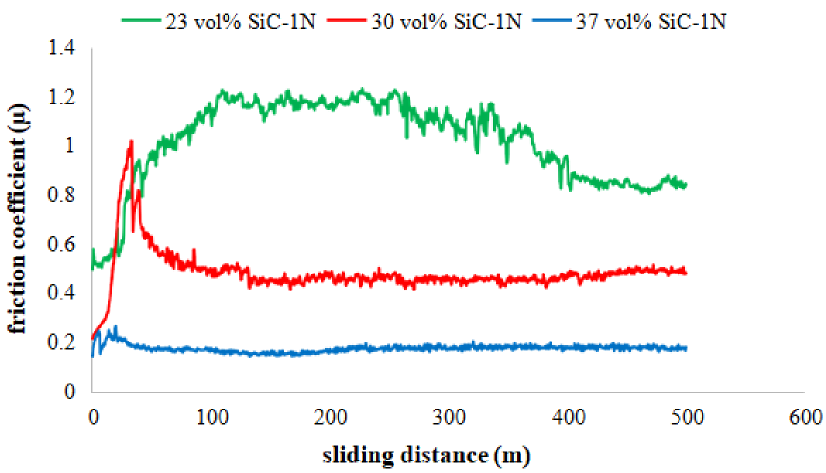


Figure 5. The changes of friction coefficient with sliding distance under the load of 1N for heat treated samples.

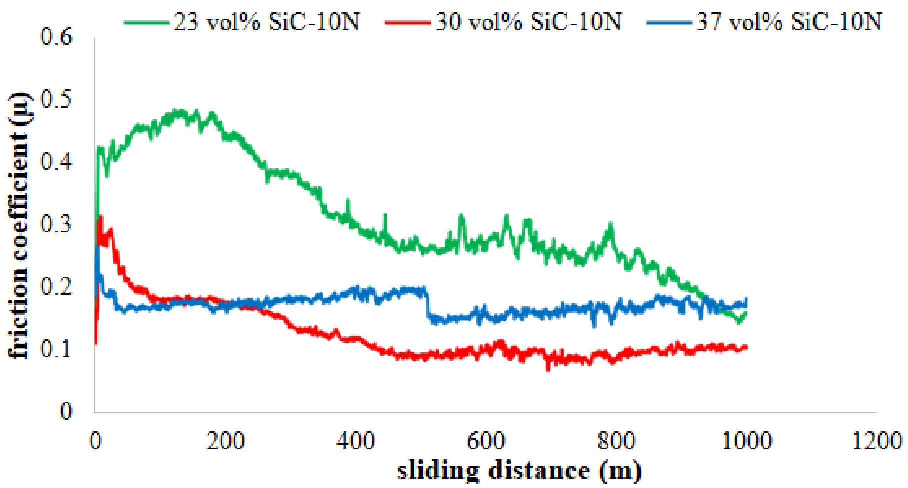


Figure 6. The changes of friction coefficient with sliding distance under the load of 10N for heat treated samples.

The results of the wear loss measurements are given in Fig. 7. In non-heat treated composite samples, weight loss values are greater than the heat treated composites both in aggressive and relatively soft wear conditions. The mass loss of non-heat treated composite samples is affected by reinforcement volume fraction as it decreases with increasing volume fractions of SiC_p reinforcement. In aggressive wear conditions the weight loss observed in the heat treated samples is lower than that observed in the non-heat treated samples. In addition, the more aggressive wear conditions brought about higher wear losses. For example, the percentage of weight loss of the sample with 37 vol. % SiC_p was 0.18% for aggressive wear conditions, on the other hand no mass loss was observed in relatively soft wear conditions.

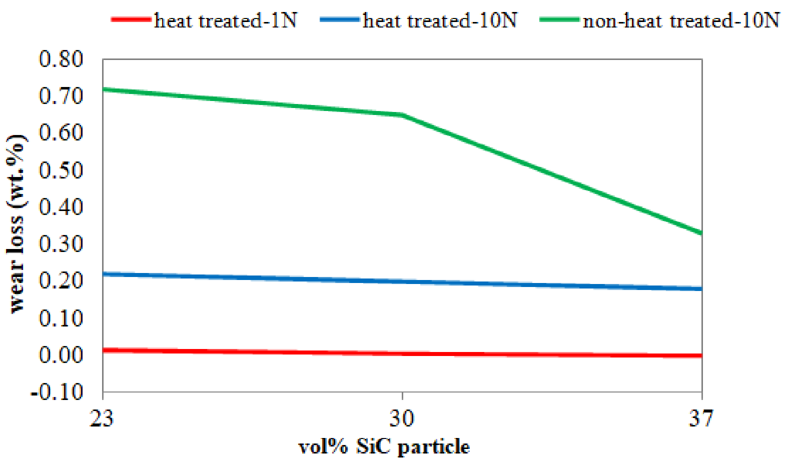
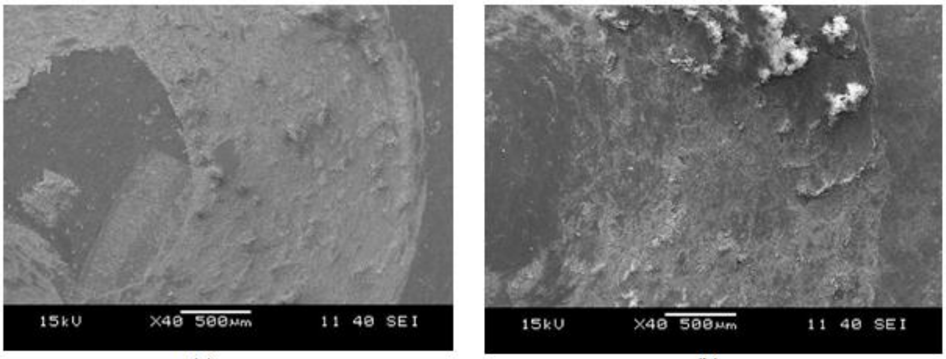


Figure 7. The curves illustrating changes of wear loss (wt. %) vs. volume fractions of SiC particles.

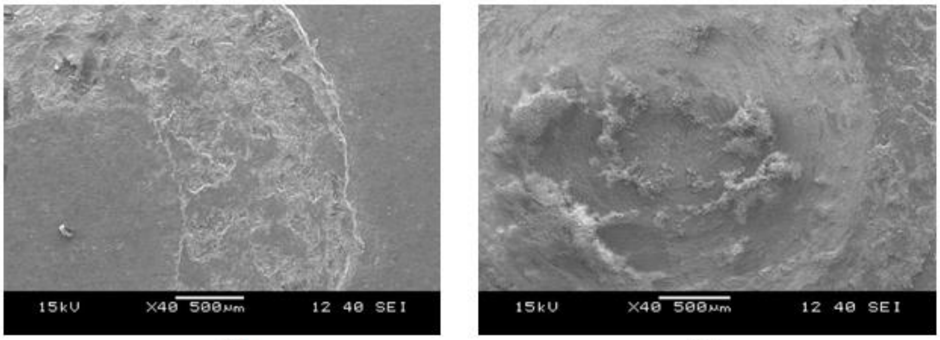
The SEM images of the worn surfaces (under two different loads) belong to heat-treated 23, 30 and 37 vol.% reinforced composite samples are given in Figures 8, 9 and 10 respectively. As seen in Fig.8 the image taken from worn surface of the 23 vol.% reinforced sample tested under low load shows relatively smooth friction trace indicating little destruction, whereas the destruction of the abrasion is more apparent on the surface of the specimen tested under high load condition. When the friction surfaces of the tested samples are examined visually, the abrasion marks on the surfaces of all the samples tested under high load are found to be much more noticeable than those of the specimens tested under low load. These observations are also in agreement with the wear loss results given in Fig. 7.

In addition to the images of worn surface, EDX analyses were carried out on the samples and on the counter material. In this work, it is also aimed to determine the wear in counter material, 100Cr6 steel ball. Therefore; the distributions of the elements Al, Si, Fe and C were also investigated in the microstructures. Figures 11, 12 and 13 show the elemental mapping images of different composite samples after the wear tests under 1N load. The examination of microstructures has shown that there is no silicon carbide particle agglomeration, and also there is no separation in the matrix-reinforcement interfaces.



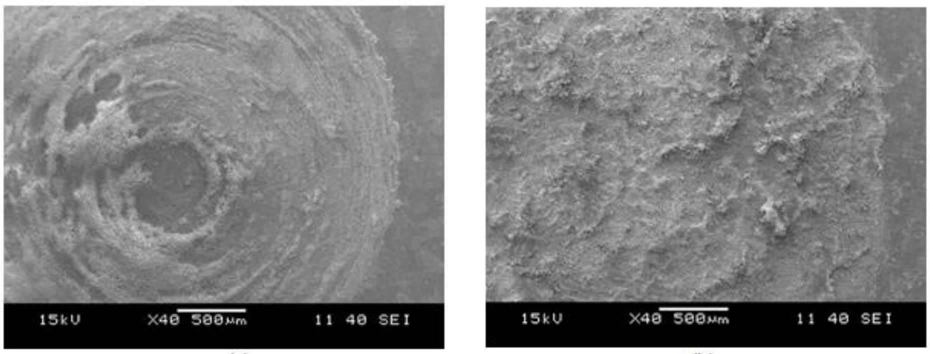
(a) (b)

Figure 8. SEM image of wear trace belongs to the heat treated AlSi5Mg/SiC/23 vol. % sample: (a) 1N and (b) 10N load.



(a) (b)

Figure 9. SEM image of wear trace belongs to the heat treated AlSi5Mg/SiC/30 vol. % sample: (a) 1N and (b) 10N load.



(a) (b)

Figure 10. SEM image of wear trace belongs to the heat treated AlSi5Mg/SiC/37 vol. % sample: (a) 1N and (b) 10N load.

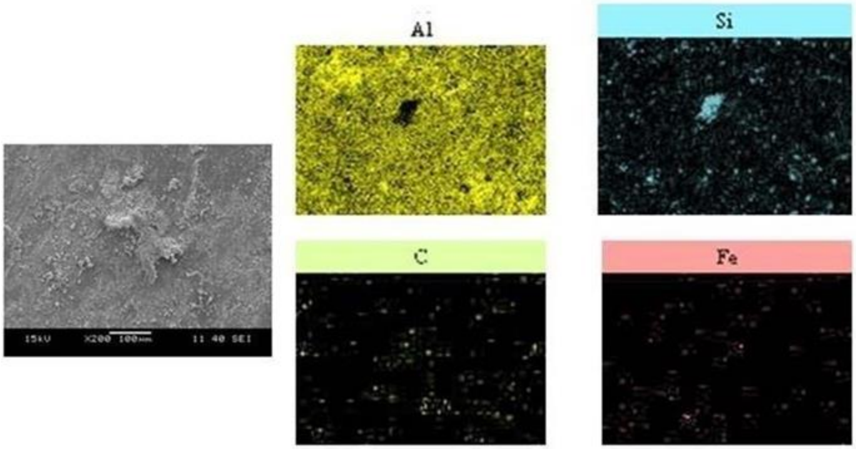


Figure 11. Elemental mapping image of AlSi5Mg/SiC/23 %vol.

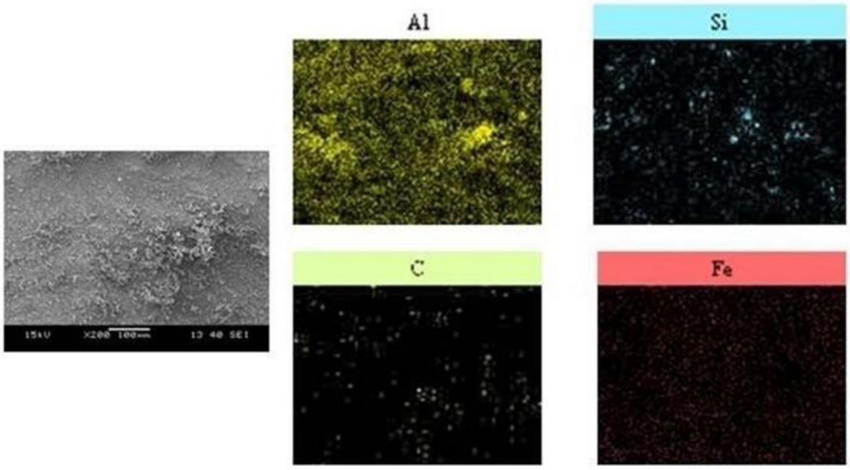


Figure 12. Elemental mapping image of AlSi5Mg/SiC/30 %vol.

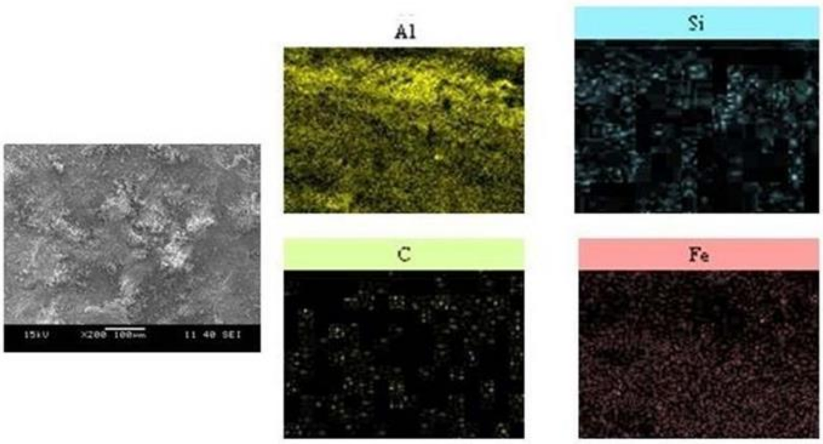


Figure 13. Elemental mapping image of AlSi5Mg/SiC/37%vol.

The elemental mapping images given in Figures 12 and 13 show Fe distribution on the worn surfaces of the composite samples, indicating that material transfer occurred from counter material to composite samples. The mapping results also show that the amount of Fe transferred from the counter material increases with increasing volume fraction of SiC particles as seen in Fig. 11. The results of wear tests of the present work show that the increase of reinforcement content improves frictional behavior of the AlSi5Mg/SiC_p composites. Rao et al. (2010) investigated the effect of heat treatment on the sliding wear behavior of stir casted Al-Zn-Mg (7009) alloy reinforced with SiC particle (10, 15 and 25 wt. %) composite systems. They reported that heat treatment improved the hardness values of the composite samples regardless of the content of SiC particles. Also, the peak hardness values of the composites were obtained from 6 hours aging period. In other words, minimum wear rate could be achieved at peak-aged condition. Moreover, the minimum wear rate was found in the sample with 25 wt. % SiC particle reinforcements, since the wear rate significantly related to the amount of SiC particles in the matrix alloy. Besides, investigations of the deformed surface of the samples after wear tests showed that the deformation region was thinner but stable at lower loads while the thickness, amount of Fe and stability increased at medium loads, whereas the deformation zone at high loads is fully destroyed. Rahman and Rashed, 2014; Bauri and Surappa, 2008; Vieira et. al., 2009 and Hassan et al., 2009 have reported that the addition of SiC_p into Al alloy matrix improves wear resistance. In these investigations up to 20 vol. % reinforcement was used. The results of Bauri and Surappa (2008) showed that the addition over 20 vol. % SiC_p lowers the wear resistance. In the present work the friction coefficient values are lowest for 30 vol. % SiC_p composite, and the addition over this volume fraction increases the friction coefficient. The results of the present work indicate that this trend of behavior does not seem to be affected by the applied load and heat treatment. The ageing treatment is reported to improve the wear resistance up to 20N loading in the work (Bauri and Surappa, 2008). Maleque and Karim (2009) also reported that the ageing treatment improves wear resistance of SiC_p reinforced aluminum matrix composites. The wear loss results given in Fig.7 indicates that increasing volume fraction of SiC_p reinforcement decreases the wear loss in all test conditions, and increased friction load increases the wear loss. In addition, and increased matrix hardness by application of heat treatment improves wear resistance of the composite samples. Zhu et al. (2012) worked on the effects of T6 tempering on the microstructure, tensile and fracture characteristics of the A356 alloys modified by mischmetal containing La and Ca elements. The results of the study has shown that the tensile properties especially ductility of the modified A356 alloys could be improved compared with unmodified ones due to the precipitation hardening and decreasing of secondary arm spacing. In addition, T6 temper was considerably affect the spherodization of the fine eutectic silicon and it brought about the enhancement of the mechanical characteristics of mischmetal modified A356 alloys.

4. Conclusions

In this work AlSi5Mg alloy matrix-particulate SiC reinforced composite samples were heat treated to peak hardness and, mechanical and tribological properties of heat treated and non- heat treated samples were studied. It was observed that the addition of reinforcing SiC particles to AlSi5Mg alloy matrix and an age hardening treatment enhanced the mechanical and tribological properties. From the results obtained in this study the following conclusions can be reached:

1. The distribution of SiC particles in the microstructure has been found homogeneous in the whole volume of the samples. The microstructural characterization of the wear trace surface of aluminum matrix composites has shown that there is no separation in the matrix-reinforcements interfaces.
2. The hardness of the composite samples increases with the increased volume fraction of SiC_p addition.
3. The application of T6 heat treatment increases the matrix hardness and resultantly increases the composite hardness.
4. A comparative analysis of the friction coefficient for soft wear conditions demonstrated that the friction coefficient value decreases with increasing volume fraction of SiC particles. The composite sample with the highest volume fraction of SiC particles showed the most stable friction coefficient.
5. For the soft wear conditions, the mass losses were low; however, increasing the friction load increased the percentage of mass loss.

6. Increasing the volume fraction of SiC_p reinforcement decreases the wear loss in all test conditions.
7. Increased matrix hardness by application of heat treatment improves wear resistance of the composite samples.
8. Material (iron) transfer has occurred from counter material to composite samples. The mass of iron transferred from the counter material increases with increasing volume fraction of SiC particles.

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