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Investigation of friction and wear behaviors of 2024 Al and 2024 Al/SiCp composite at elevated temperatures

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ABSTRACT

Friction and wear behaviors of artificially aged 2024 Al and 2024 Al/20 vol.% SiC composite – prepared by powder metallurgy method – were investigated in the temperature range 20–250 °C. Dry sliding wear tests were conducted at a constant sliding velocity of 0.5 m/s, an applied load of 20 N, and a sliding distance of 2500 m using a pin-on-disc apparatus. Worn surfaces and wear debris were also examined by using SEM and EDS techniques. All specimens showed a transition from mild-to-severe wear above a critical temperature. In the mild wear regime, the wear rate and the friction coefficient of the composite specimen were higher than those of the unreinforced alloy. The SiC particles led to an increase in the critical transition temperature and in the severe wear regime, they caused a considerable improvement in the wear resistance. Analysis of worn surfaces and wear debris indicated that dominant wear mechanisms of the unreinforced alloy were microploughing and slight adhesion in the mild wear regime, whereas the composite specimen showed microcutting and oxidation mechanisms in the same regime. The dominant wear mechanisms shifted to severe adhesion for all specimens in the severe wear regime.

1. Introduction

Aluminum matrix composites (AMCs) are one of the advanced engineering materials that have been utilized in high-tech structural and functional applications like aerospace, automotive, defense, electronic industries, as well as in sports and recreation [1–4]. As compared to monolithic materials, AMCs show lower wear rates due to protection of contact surfaces by hard reinforcements [5]. Various kinds of materials, e.g., SiC, Al_2O_3, MgO and B_4C, are extensively used to reinforce aluminum alloys. Superior properties of these materials such as refractoriness, high hardness, high compressive strength, wear resistance, etc. make them suitable for use as reinforcement in matrix of composites [6–8]. Since 1980 many researches have been carried out on the wear behavior of AMCs [9]. However, there have been discrepancies among the reported results. These discrepancies may come from the large number of variables which can affect wear behavior. These variables include applied load, test geometry, test duration, materials properties, and environmental factors, such as temperature, humidity, etc. [10]. Temperature is one of the important factors. In industry field, the tribological components are inevitably to work under high temperature due to the heat generated or other factors. So the high temperature wear behavior becomes important. Dry sliding wear behaviors of AMCs at ambient temperature are available in the literature, but the wear properties at elevated temperatures are very limited, whereas wear at elevated temperatures is a serious problem in a large number of industrial applications such as pistons, cylinder heads and blocks for car engines, in where these components are often required to operate at temperatures around 200 °C [10]. A transition from mild-to-severe wear of AMCs can be induced by temperature changes [11]. Tribological components are supposed to work in the mild wear region and try to avoid the severe wear region, so identification of the transition temperature of the AMCs is important. Among little researches that have been carried out on the wear behavior of AMCs at elevated temperatures, different conclusions have been drawn. Singh and Alpas [12] showed that in the mild wear regime, the wear rate and the friction coefficient of 6061 Al alloy decreased slightly with temperature, but the temperature had not obvious effect on the wear rate and the friction coefficient of 6061 Al alloy/20 vol.% Al_2O_3 composite in the same regime. They also reported, in this regime, the wear rate of the unreinforced alloy was less than that of its composite. The presence of Al_2O_3 reinforcing particles leads to an increase in the transition temperature from 180 °C for the unreinforced alloy to around 250 °C for its composite. Yao-hui et al. [11] reported that the wear rate of both Al–12%Si alloy and its composite reinforced with 4% C and 12% Al_2O_3 decreased with temperature in the mild wear regime. In this regime, the wear rate of the composite was less than that of the unreinforced alloy. They showed that transition temperature increased about 200 °C with addition of the

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Table 1
Chemical composition of 2024 Al alloy (wt.%).

Element	Cu	Mg	Mn	Si	Fe	Al
Chemical composition (wt.%)	4.30	1.40	0.55	0.01	0.01	Balance

reinforcements. Muratoglu and Aksoy [10] showed that the wear rate of 2124 Al alloy/25 vol.% SiCp composite increased significantly with temperature till 50 °C, but for the test temperatures above 50 °C, the temperature had almost no effect on the wear rate. As a result, a general statement cannot be made concerning the high temperature wear behavior of a composite in relation to the matrix. Thus, there exists a continuing need for further investigations. The aim of this research was to study the changes in the wear resistance of the aged 2024 Al/20 vol.% SiC composite and the matrix alloy 2024 Al in the temperature range 25–250 °C.

2. Experimental procedure

2.1. Materials

The materials used for wear test specimens were 2024 Al/20 vol.% SiC(α) composite and its unreinforced alloy. The specimens were manufactured by powder metallurgy techniques. The chemical composition of the matrix alloy is shown in Table 1. The average particle size of the SiC was 20 μm. The matrix powders and the SiC particulates were mechanically blended and subsequently cold compacted at 250 MPa, followed by hot extrusion with the extrusion ratio of 16:1 at 495 °C. Fig. 1 shows a SEM micrograph of 2024 Al/20 vol% SiC composite in the as-extruded condition. One can see the uniform distribution of SiCp arranged in the direction of extrusion (ED) at the matrix structure. All specimens were aged artificially. The heat treatment consisted of solution treatment at 495 °C for 2 h followed by aging at 191 °C. The composite and the unreinforced alloy were aged at this temperature for 4 and 6 h, respectively. The mean hardness values of the composite and the unreinforced alloy were 185 and 136 HV, respectively. Further details of the synthesis and process parameters are mentioned elsewhere [13].

2.2. Wear tests

Dry sliding wear tests were conducted in the air using a pin-on-disc apparatus, according to the ASTM G99-04 Standard, with a high temperature system. The schematic illustration of the apparatus is shown in Fig. 2. The test pins were loaded against a SAE 52100 bearing steel disc, 100 mm in diameter and 20 mm in thickness, with an average hardness of HRC 63. The size of pins was 6 mm in diameter and 25 mm in height. The contact surfaces of the pins and disc were polished on 1000 grit SiC paper before each wear test. The tests were carried out at a constant sliding speed of 0.5 m/s and the applied loads of 20 and 50 N. The sliding distance was 2500 m. Before and after each test, the pins were cleaned in acetone, dried in hot air, and then weighted using an electronic balance with the sensitivity of 0.1 mg. The wear rate was calculated from the weight-loss measurements [14]. The frictional force was measured during the test by a force transducer attached to the wear apparatus. The friction coefficient was determined as the ratio of the friction force to the applied load [12].

The sliding wear tests were carried out at a temperature range of 25–250 °C. During wear test the temperature of contact surfaces was estimated with a thermocouple placed inside the specimen close to the contact surface.

A VEGA2 TESCAN scanning electron microscope (SEM) and a RONTOC energy dispersive spectroscope (EDS) were used to observe and analyze the worn surfaces and wear debris.

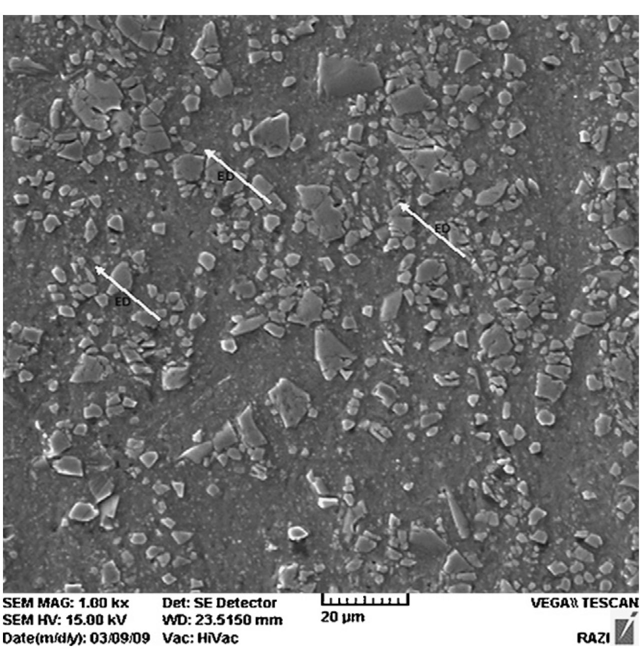

Fig. 1. SEM micrograph of 2024 Al alloy–20 vol.% SiC composite in the as-extruded, showing a uniform distribution of SiC particles in the extrusion direction (ED).

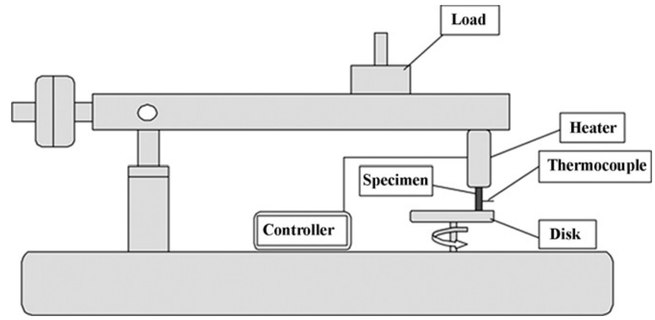

Fig. 2. The schematic diagram of the high temperature sliding wear apparatus.

3. Results and discussion

3.1. Influence of temperature on wear rate and friction coefficient

The variations of friction coefficient and wear rate as a function of test temperature are shown in Fig. 3(a) and (b), respectively (at the applied load of 20 N). It can be seen that the variation of wear rate is almost proportional to that of the friction coefficient for both the unreinforced alloy and the composite specimens. There is a critical transition temperature from mild-to-severe wear for the specimens during sliding wear, which is characterized by a marked increment in the wear rate and in the friction coefficient. In fact, at the test temperatures beyond this temperature, amount of material removal increases significantly. According to Fig. 3(a) and (b), the critical transition temperatures of the unreinforced alloy and the composite were about 125 and 200 °C, respectively. It is clear that the SiC particles increase the transition temperature about 75 °C. The presence of hard and thermally stable SiC particles strengthens the matrix alloy and improves load-bearing capacity and thermal stability of the matrix and also prevents its plastic deformation. These help to reduce material removal. So the critical transition temperature of the composite specimen improved compared with that of the unreinforced alloy due to the joint effect of SiC particles.

One can observe from Fig. 3(a) and (b) that in the mild wear regime, at the test temperatures below 125 °C, the friction coefficient and the wear rate of the unreinforced alloy were lower than those of the composite specimen. Fig. 4(a) and (b) shows the worn surfaces of the unreinforced alloy and the composite, respectively, at 100 °C. It can be seen that the plastic deformation of the edges of grooves in the unreinforced alloy (indicated by the arrows) is more than that in the composite specimen. Since the formability of the unreinforced alloy is more than that of the composite specimen, so it can be said that material removal from the formed grooves on the worn surfaces of the unreinforced alloy is less than that of the composite specimen. This leads to lower wear rate in the unreinforced alloy compared with the composite specimen.

Wear test results obtained in the mild wear regime showed that the friction coefficient and wear rate of the composite specimen

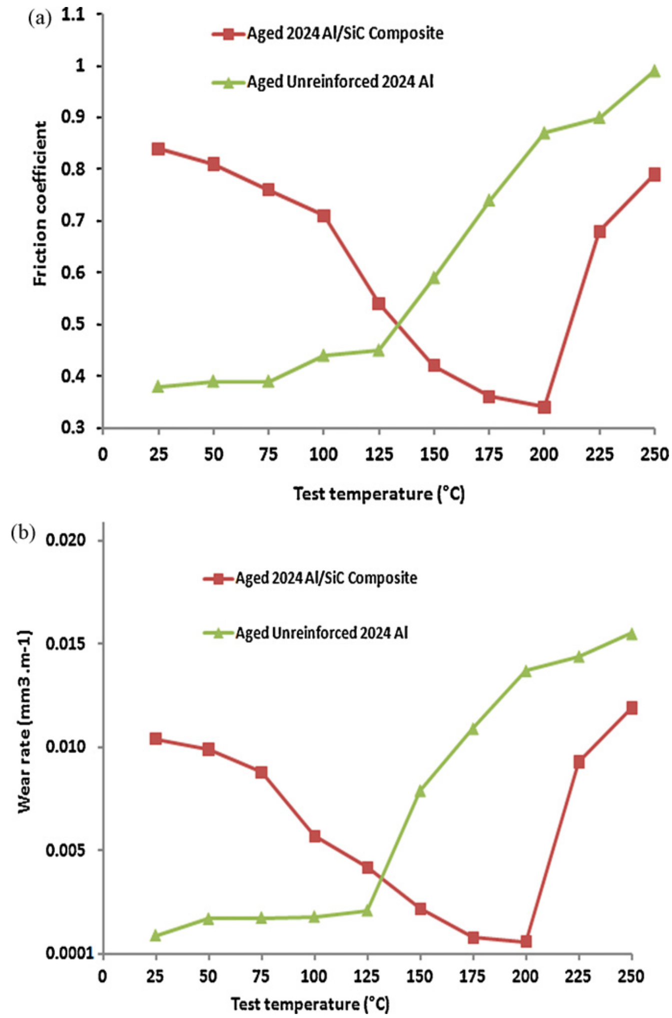

Fig. 3. Variations of (a) friction coefficient, and (b) wear rate with test temperatures for aged 2024 Al/20 vol.% SiC composite and aged unreinforced 2024 Al, at the applied load of 20 N.

decreased with temperature, as seen in Fig. 3(a) and (b). This behavior can be attributed to formation of a protective oxide layer on the contact surfaces during wear [12,15]. For sliding wear of materials when the temperature of operation is high, oxidation of the materials has a significant effect on the wear rate. The importance of oxidation during wear of metallic materials was first identified by Fink [16]. In particulate reinforced metal matrix composites (PMMCs), the hard ceramic particles erode the metal counterface. The formed debris could interact with oxygen of surrounding environment to produce an oxide layer. The oxide layer can provide an in situ lubrication effect and decrease the friction coefficient and wear rate. In this study, the elements of Fe and O_2 were observed on the worn surface of the composite specimen (Fig. 5(a)) by EDS analysis, with spectra resembling in Fig. 5(b). Similar EDS spectra were also observed for wear debris. However, amount of these elements was negligible on the surface of the composite specimen (Fig. 6(a)) before wear test. The EDS analyses with spectra resembling in Fig. 6(b) have proved it. The elements of Fe and O_2 can indicate the oxide layers. These oxides often are FeO or Fe_2O_3 [[12,17], and [18]]. The oxide layers can be seen by the bright color on the worn surfaces of the composite specimens, as shown in Fig. 5(a). With increasing temperature the oxide layers are thickened, so the friction coefficient and wear rate decreased with increasing temperature below 200 °C. But in the severe wear regime, at the test temperatures upper than 200 °C, the friction coefficient and wear rate increased significantly with temperature. This behavior can be attributed to the fact that at high temperatures, test temperatures upper than 200 °C, the matrix alloy becomes soft gradually. It leads to increase the adhesion and transfer of the matrix to the steel counterface and will subsequently cause to increase the friction coefficient and wear rate. So there exists a critical temperature for the composite specimen, about 200 °C in this research, so that in this temperature, the lowest friction coefficient and wear rate are achieved (see Fig. 3(a) and (b)).

A worn surface of the unreinforced alloy in the mild wear regime is shown in Fig. 7(a). The results of EDS analyses of the worn surface,

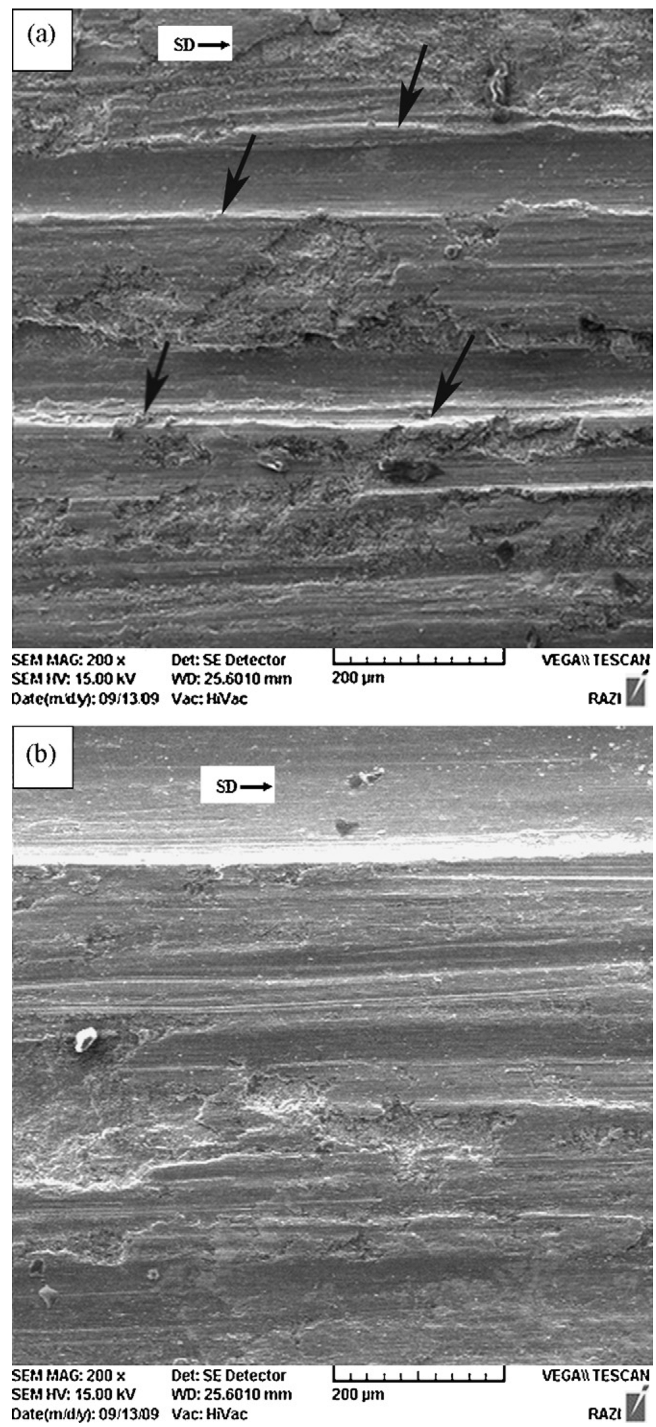

Fig. 4. SEM images of worn surfaces of (a) unreinforced 2024 Al, (b) 2024 Al/20 vol.% SiC composite at 100 °C (applied load = 20 N), (SD: sliding direction).

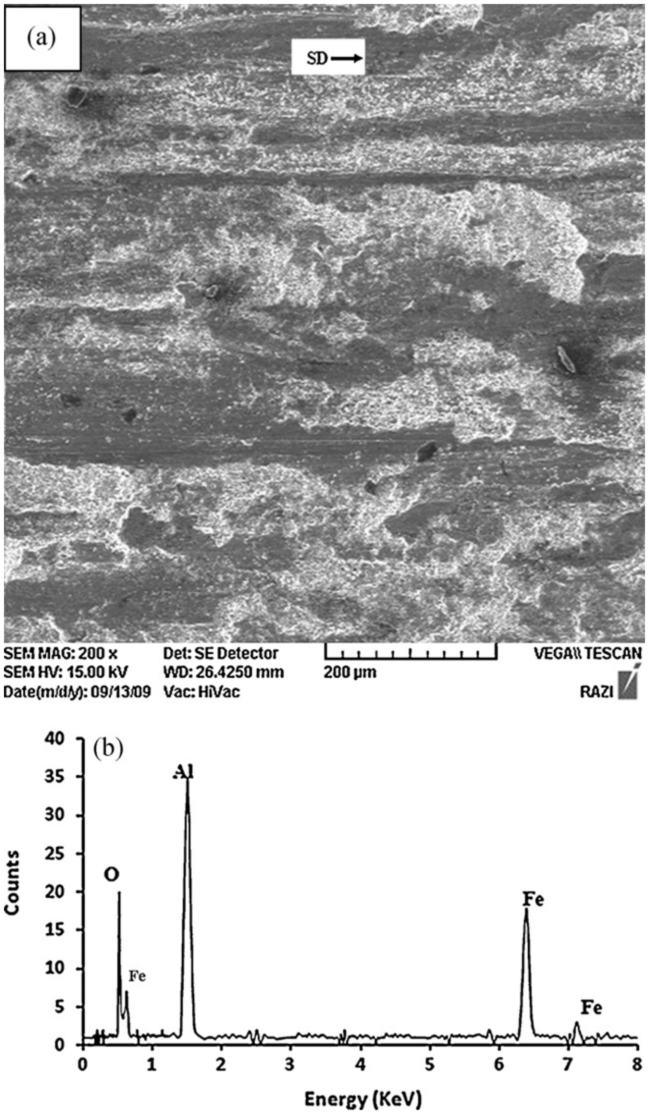

Fig. 5. (a) SEM image of worn surface of the 2024 Al alloy/20 vol.% SiC composite at 100 °C (applied load = 20 N), and (b) its EDS spectrum.

with spectra resembling in Fig. 7(b), showed that the Fe content of the worn surface of the unreinforced alloy is much less than that of the worn surface of the composite specimen (Fig. 5(b)). No considerable oxide layer (layers with bright color) on the worn surface of the unreinforced alloy (Fig. 7(a)) was also observed. So it can be said that the protective oxide layer is not considerable to decrease the friction coefficient and wear rate of the unreinforced alloy.

The friction coefficient and wear rate of the composite specimen were lower than those of the unreinforced alloy in the severe wear regime (according to Fig. 3(a) and (b)). This behavior is attributed to the fact that the reinforcing phases improve the hardness and strength of composites and act as hard barriers against the plastic deformation of the matrix [19–22], which contribute to the reduction of adhesion between metal matrix and steel counterface.

In order to investigate the effect of applied load on the wear behavior at the different test temperatures, the wear rate of the aged composite specimen was measured at two applied loads of 20 and 50 N. As seen in Fig. 8, with increasing the applied load, the wear rate of composite specimen increased at all test temperatures. Also with increasing the applied load, the critical transition temperature from the mild-to-severe wear regime decreased, the critical transition temperatures were 200 and 150 °C for the applied loads of 20 and 50 N, respectively. This behavior may be because at lower loads, the protective oxide layer is stable for more time and temperature rise, which leads to more adhesion of the matrix to the steel counterface, is also low, whereas at higher loads the protective oxide layer is destroyed at faster rate and the temperature rise is also high [23]. So the severe wear took place at lower temperature in the condition of the applied load of 50 N. Previously, Singh and Alpas [12] reported the same results about 6061 Al/20 vol.% Al_2O_3 composite at the two applied loads of 10 and 50 N.

3.2. Worn surface analysis

Fig. 9(a) and (b) shows the worn surfaces of the unreinforced alloy and the composite, respectively, in the mild wear regime (at 125 °C for the unreinforced alloy and 200 °C for the composite) at the applied load of 20 N. It can be seen that there existed numerous grooves on the worn surfaces paralleling to the sliding direction (SD). The grooves on the worn surface of the unreinforced alloy were wide and depth (Fig. 9(a)). Also slight plastic deformation at the edge of grooves can be seen (indicated by the arrows). However, the worn surface of the composite specimen was relatively smooth. The grooves were fine and plastic deformation at the edge of grooves was not seen (Fig. 9(b)). Moreover, the worn

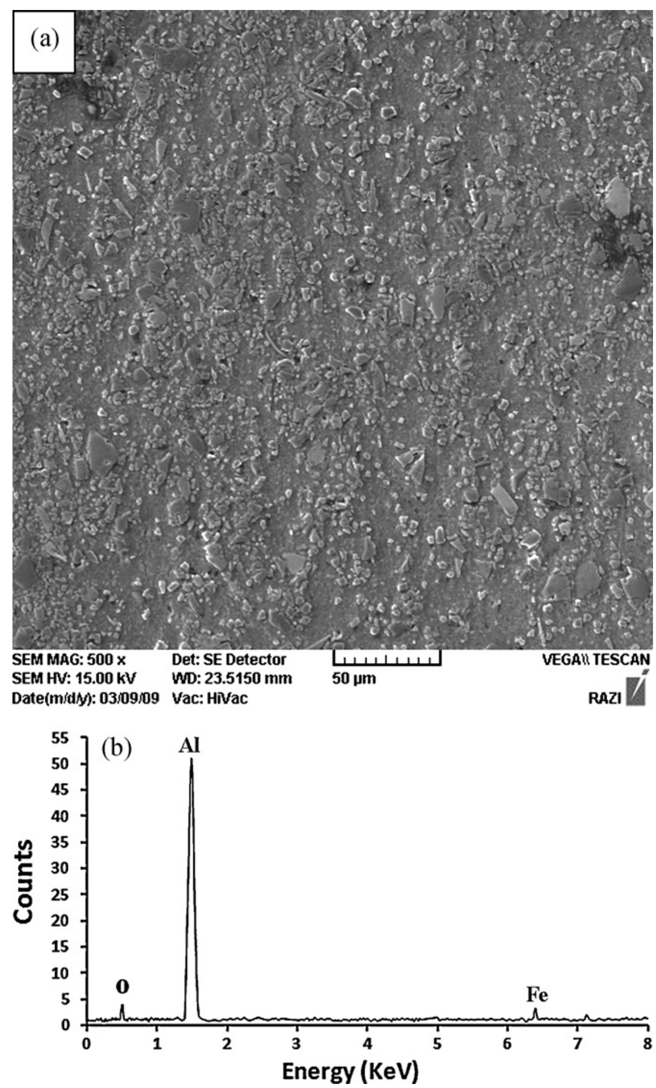

Fig. 6. (a) SEM image of the surface of the 2024 Al alloy/20 vol.% SiC composite before the wear test, and (b) its EDS spectrum.

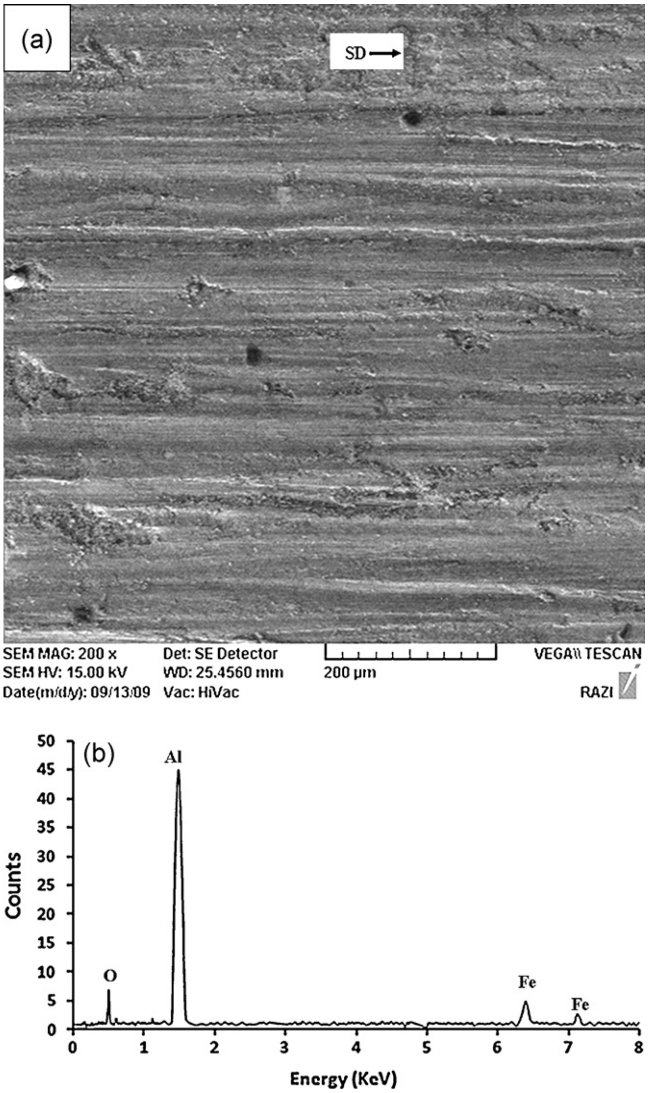

Fig. 7. (a) SEM image of worn surface of the unreinforced 2024 Al alloy at 100 °C (applied load = 20 N), and (b) its EDS spectrum.

surfaces of the composite specimen (Fig. 5(a) and Fig. 9(b)) show characteristics of oxidation occurring during the sliding wear process, as evidenced by the bright color of the worn surfaces and by the enrichment in the Fe content according to the EDS analysis (Fig. 5(b)). Debris particles generated during sliding wear at 125 °C

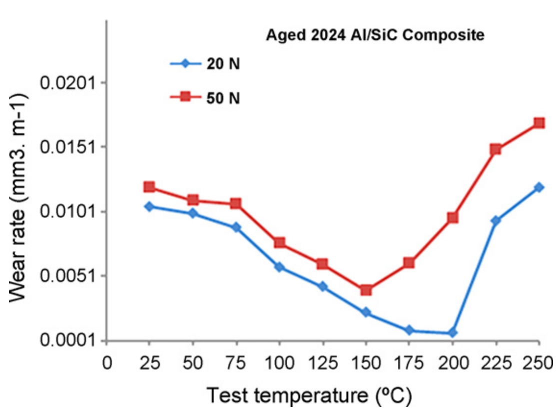

Fig. 8. Variations of wear rate with test temperature for the aged 2024 Al/20 vol.% SiC composite at the two applied loads of 20 and 50 N.

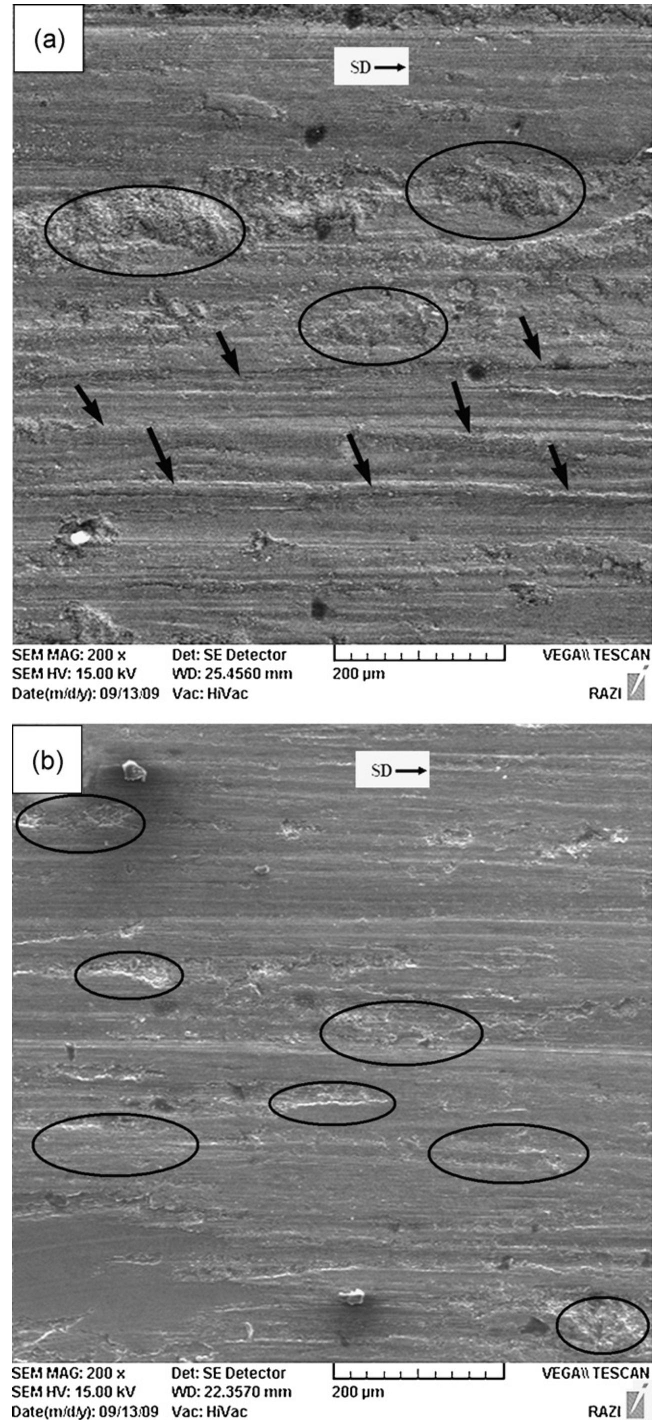

Fig. 9. SEM image of worn surfaces of (a) unreinforced alloy, and (b) composite specimen at 125 200 °C, respectively (applied load = 20 N).

for the unreinforced alloy and composite specimens are shown in Fig. 10(a) and (b), respectively. It has been noted that the volume fraction of debris of the unreinforced alloy was less than that of the composite specimen in this condition. Similar debris and worn surfaces were seen at the other test temperatures in the mild wear regime. It seems that the dominant wear mechanisms of the unreinforced alloy were microploughing and slight adhesion in the mild wear regime, whereas the composite specimen showed microcutting and oxidation mechanisms in the same regime.

Fig. 11(a) and (b) shows the worn surfaces of the unreinforced alloy and the composite, respectively, in the severe wear regime (at

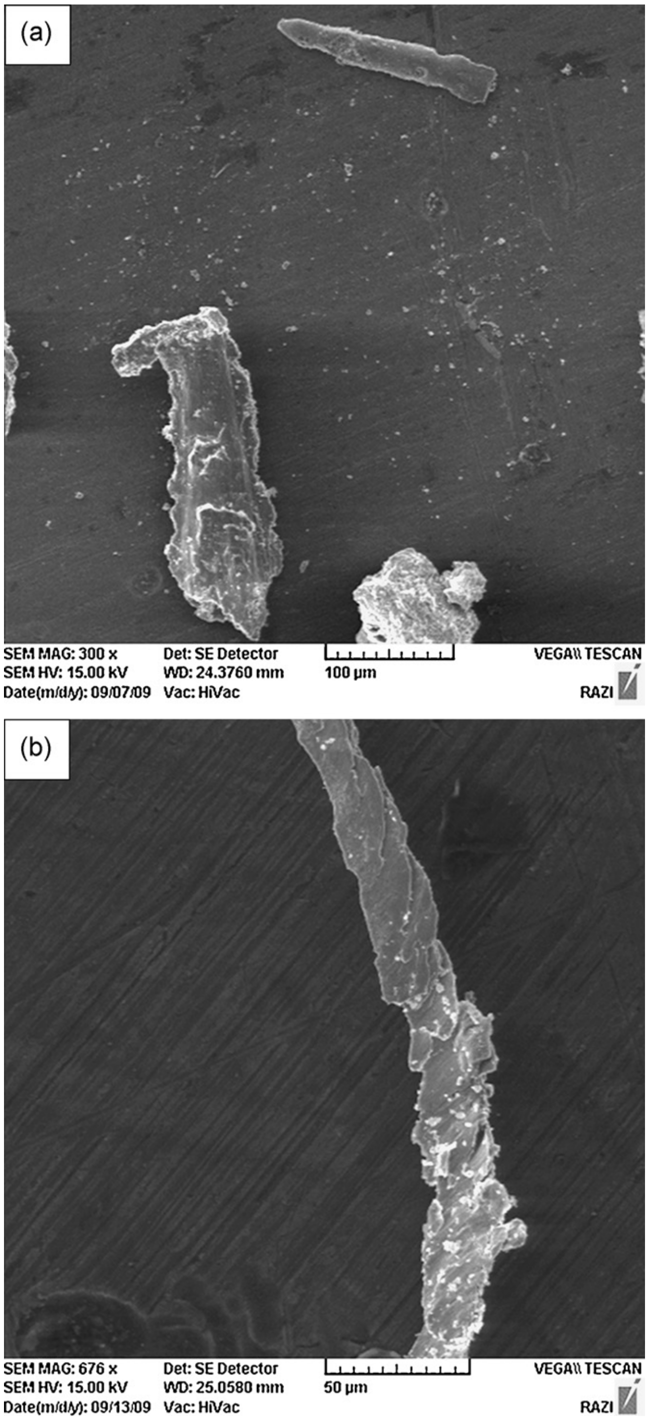

Fig. 10. SEM image of debris particles generated during sliding wear at 125 °C for (a) the unreinforced alloy, and (b) the composite specimen.

200 °C for the unreinforced alloy and 250 °C for the composite) at the applied load of 20 N. As it can be seen from Fig. 11(a), the massive deformation took place at 200 °C for the unreinforced alloy specimen. It suggests that the dominant wear mechanism to be severe adhesion. However, in this temperature (200 °C), the composite specimen was still in the mild wear regime and the worn surface was relatively smooth (Fig. 9(b)). This is attributed to the fact that for the unreinforced alloy, strength and resistance to deformation decrease with increasing temperature, so the heavy plastic deformation at the edge of grooves can be observed (Fig. 11(a)). However, for the composite specimen, the presence of hard and thermally stable SiC particles improves the strength and thermal stability of the matrix and prevents its plastic deformation [11]. These help to reduce material adhesion to the counterface. But at higher temperatures as it can be seen from Fig. 11(b), the traces of severe adhesion can be observed on the worn surface of the composite specimen. This is because with increasing temperature the bond strength between the SiC particles and the matrix alloy decreases. This leads to decrease the effect of SiC particles at improving strength and preventing plastic deformation of the matrix alloy, so the adhesion increases.

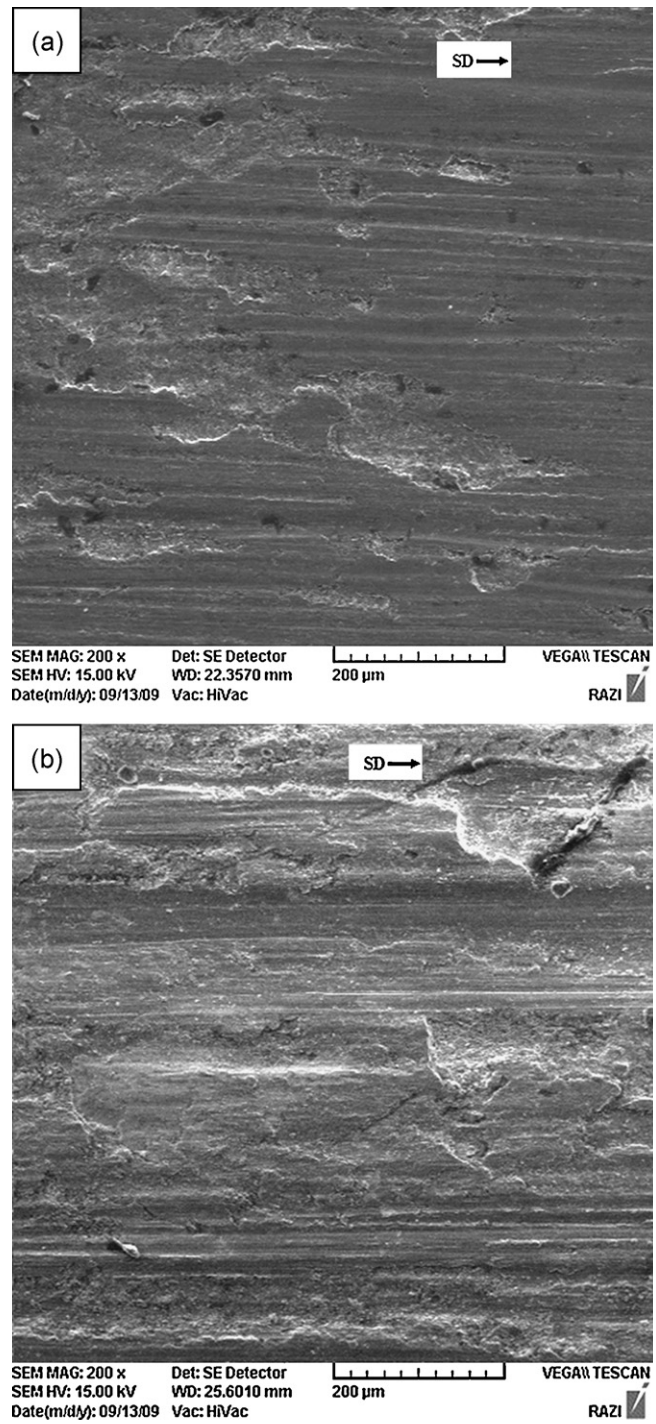

Fig. 11. SEM image of worn surfaces of (a) unreinforced alloy (b) composite specimen at 200 and 250 °C, respectively (applied load = 20 N).

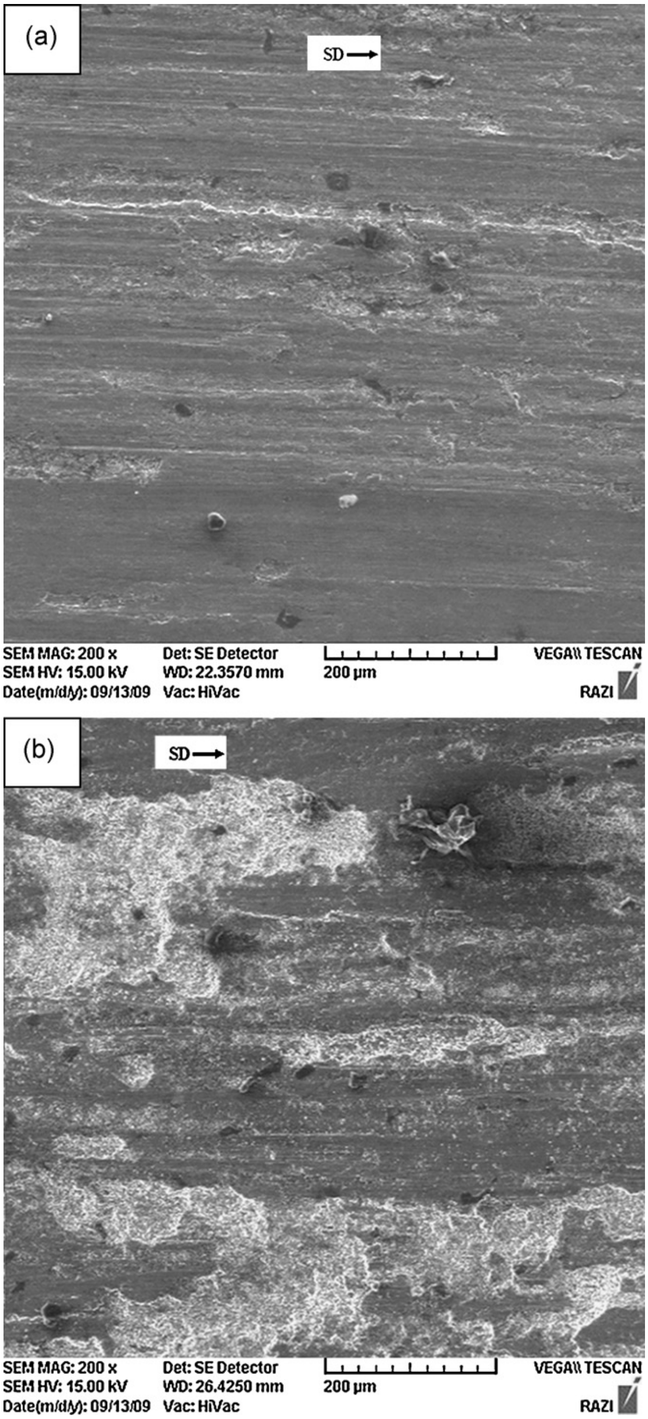

Fig. 12. SEM image of worn surfaces of the aged 2024 Al/20 vol.% SiC composite at (a) 100 °C, and (b) 200 °C (applied load = 50 N).

Finally, Fig. 12(a) and (b) shows the worn surfaces of the composite specimen in the mild and severe wear regimes, respectively, at the applied load of 50 N. As compared to the worn surfaces of the composite specimen at the applied load of 20 N (see Fig. 9(b) and Fig. 11(b)), there was little difference between the worn surfaces of the composite specimen at the applied loads of 20 and 50 N, which suggested that the dominant wear mechanisms remained unchanged at the applied load of 50 N. Therefore, it can be concluded that the effect of applied load was primarily on the critical transition temperature and the wear rate, but it has no significant effect on the wear mechanisms.

4. Conclusions

The friction and wear behaviors of the artificially aged 2024 Al alloy and 2024 Al alloy/20 vol.% SiCp composite were investigated in the temperature range 25–250 °C. The conclusions derived from this study can be given as follows:

1. The wear rate of the aged 2024 Al alloy and its composite reinforced with 20 vol.% SiCp, achieved the lowest values at 25 and 200 °C, respectively, and then it increased with increasing temperature.
2. All specimens showed a mild-to-severe wear transition. The unreinforced alloy underwent a transition to severe wear at 125 °C, while the transition occurred at 200 °C for the composite specimen.
3. In the mild wear regime, the wear rate and the friction coefficient of the composite specimen were higher than those of the unreinforced alloy. The SiC particles led to a considerable improvement in the wear resistance in the severe wear regime.
4. The dominant wear mechanisms of the unreinforced alloy were microploughing and slight adhesion in the mild wear regime, whereas the composite specimen showed microcutting and oxidation mechanisms in the same regime. The dominant wear mechanisms of both the unreinforced alloy and the composite specimens shifted to severe adhesion in the severe wear regime.
5. At the high temperature wear tests conducted on the composite specimen at the applied loads of 20 and 50 N, it was concluded that with increasing the applied load, the critical transition temperature and the wear rate decreased and increased, respectively, but no change occurred on the wear mechanisms.

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