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TECHNICAL PAPER

# Investigation of wear behavior of aged and non-aged SiC-reinforced AlSi7Mg2 metal matrix composites in dry sliding conditions

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**Abstract**
Metal matrix composites (MMCs) with their splendid mechanical properties have been specifically designed for use in fields such as aerospace and aviation. The presence of hard ceramic particles in MMC increases the hardness of the matrix product and decreases its coefficient of friction. Therefore, the wear resistance is improved. Moreover, the mechanical properties of these composite materials can be improved by applying heat treatments. In this study, AlSi7Mg2 MMCs with 15 wt% SiC reinforcement were produced by squeeze casting technique. Some of the composites were aged by heat treatment. Hardness values of aged and non-aged composites were compared. In addition, abrasive wear behaviors of these composites were investigated on pin-on-disk device, depending on the load (7, 12 and 17 N), the sliding speed (0.2, 0.3 and 0.4 m/s) and the sliding distance (700, 1000 and 1300 m). Worn surfaces were also analyzed by scanning electron microscopy (SEM). As a result of the analyses, it was determined that both the hardness values and the wear resistance were higher in the composites subjected to aging treatment. Furthermore, it was observed that the increase in the applied load led up to the weight loss. The increase in the sliding distance increased both friction coefficient and weight loss. The increase in sliding speed also made way for the friction coefficient but ensured less weight loss. When SEM images were examined, it was ascertained that deformation and tribo-surface formation had a significant effect on weight losses.

**Keywords** Aging · Composite · SiC · Squeeze casting · Wear

## 1 Introduction

Aluminum and its alloys are commonly used in many different transport industries, from space to marine, due to their high strength, low specific gravity and ability to adapt to environmental factors. Although the use of these alloys is considered advantageous in many respects (lightness, strength/weight ratio, availability, low price, etc.), its utilization in machine elements is limited due to its low resistance to abrasion. Machine elements with low abrasion resistance wear off seriously over time due to friction and become unusable. This situation causes 1.6% loss of the gross national product of the developed countries; for example, in the USA, there is financial loss over 100 billion dollars annually, depending on friction and wear. The magnitude of financial losses as a consequence of friction and wear is due to the severe wear of few parts, which disrupts the entire mechanical system [1]. Thus, the demand for producing new materials having more abrasion resistance and better tribological properties has led to the development of aluminum MMCs [2]. Hard ceramic particles such as SiC,

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$Al_2O_3$ and $B_4C$ are added to the ductile matrix material in order to increase abrasion resistance of the aluminum alloys [3]. This situation also provides significant improvements in the particle/matrix interface strength [4]. These improvements include physical properties such as thermal expansion, density and mechanical properties such as tensile and compressive strengths, creep and tribological behaviors. Particularly in wear behavior, various factors such as load, sliding speed, sliding distance, abrasive size, slope angle of abrasive particles, size and percentage of dispersoid phase are also very important in addition to the physical, chemical and mechanical properties of composites [5, 6]. This has led researchers to focus on MMCs with good physical, chemical and mechanical properties. Umanath et al. [7] investigated the wear behavior of SiC- and $Al_2O_3$-reinforced Al 6061 MMCs using both experimental and statistical regression and variance analyses (ANOVA). They determined that high reinforcement volume ratio, low load and rotational speed reduced the wear rate. They emphasized that the reinforcement volume ratio acts as a more important factor than other parameters. Jinfeng et al. [8] investigated the effect of graphite reinforcement and grain size on the friction and wear properties of Al matrix composites with 40% SiC and 5% graphite reinforcement developed by the squeeze casting process. It has been found that 10 wt% of SiC and 3 wt% of B4C hybrid composites have enhanced tribological properties. They determined that the graphite reinforcement reduced the friction coefficient of the composites and promoted the abrasion resistance between 170 and 340 times. Rao and Das [9] investigated the effect of SiC and sliding speed on wear behavior of aluminum alloy and its composites. Hekner et al. [10] studied the wear behaviors of SiC-, SiC/carbon nanotube (CN)- and SiC/glassy carbon-reinforced Al matrix composites produced by mechanical alloying and hot pressing at 25 °C and 450 °C separately. They observed that the presence of both carbon forms significantly reduced wear in comparison with composites which do not include carbon. Veeresh Kumar et al. [11] compared the mechanical and tribological properties of Al 6061 matrix composites reinforced with SiC (2, 4 and 6 wt%) and unreinforced alloys produced by liquid metallurgy techniques. They found out that the tensile strength and wear resistance of composites were higher than Al 6061 alloy. Shorowordi et al. [12] investigated the effect of different contact pressures (0.75–3.00 MPa) on aluminum composites with 13 wt% $B_4C$-reinforced Al and 13 wt% SiC-reinforced Al, which were abraded against commercial phenolic brake fluids, under dry sliding conditions. Padmavathia and Ramakrishnan [13] produced Al 6061 matrix composites reinforced with multilayer carbon nanotubes (SiCNTs) and SiC by stir casting method. They conducted friction and wear experiments of composites on a pin-on-disk device. Uvaraja [14] investigated the wear behavior of Al 6061 matrix composites reinforced with $B_4C$ and SiC on the pin-on-disk device under dry sliding conditions, depending on the parameters such as applied load, sliding speed, reinforcement ratio and sliding distance. Al 6061 matrix composites, which have a homogeneously dispersed hard-phase SiC and $B_4C$ particles, had higher hardness than unreinforced alloys. It was detected that 10 wt% SiC and 3 wt% $B_4C$ hybrid composites show better tribological properties. Uthayakumar et al. [15] compared the friction and wear behavior of the Al hybrid composites reinforced with 5% SiC and 5% B4C with the unreinforced alloys developed by the stir casting process. Erturun and Karamış [16] examined friction and wear behavior of reciprocatingly extruded 5% SiC-reinforced Al 6061 matrix composites in lubricated and dry conditions and compared with the unreinforced alloy. They detected that there was a constant relationship between wear resistance, weight loss and hardness. They also observed that weight loss in lubricated conditions was less than that of dry conditions. The mass loss was found to be promoted with increasing the number of passes and load. In the all applied loads, they determined that the abrasion resistance initially increased and decreased, respectively. Karamış et al. [17] investigated the friction and wear behavior of SiC-reinforced Al matrix composites that are produced by reciprocating extrusion method, depending on the sliding distance, load and number of passes. They determined that the experimental density of the composites was lower than that of theoretical density. The maximum weight loss in both lubricated and dry sliding conditions was obtained from 50 N load and one pass.

The uses of reinforcement elements are truly crucial to improve the properties of aluminum-based materials. In addition, properties of these materials can be also improved by heat treatment such as aging. In this way, these materials are heavily demanded both scientifically and technologically. When a certain reinforcement substance is added to a heat-treatable aluminum alloy matrix, both the composite and the alloy reflect superior aging characteristics [18]. Das et al. [19] applied T6 heat treatment to the 15% SiC-reinforced Al 7075 matrix composites which were produced by stir casting method. They studied the porosity, density, stiffness and wear behavior of the composites. By using Taguchi method, they determined that the parameters of 30 N load and 400 revolutions per minute were suitable values for wear rate. By using (ANOVA) analysis of variance, they also figured out that the load was effective on the wear rate, and the sliding speed was an insignificant parameter. Lin and Liu [20] investigated the effect of aging on wear behaviors by aging Al alloys and SiC-reinforced aluminum composites at different temperatures. They observed that the aging temperature and duration of SiC-reinforced aluminum composites were essential factors for the wear rate. They also determined that high temperature or long aging time provided better wear resistance. Meyveci et al. [21] examined the wear behaviors of aged aluminum Al 2024 and Al 6063 alloys. Al 2024 alloys had higher hardness values than Al 6063 alloys. It was determined that aged composite had higher hardness values than the untreated composite. They also found that the wear resistance of the Al 6063 alloy was higher than that of Al 2024 alloy and consequently leads to a lesser mass loss.

It has been revealed that many studies related to Al matrix composite materials have been carried out so far. However, both composites produced by using different matrix materials and the aging process have not led to a decrease of interest in this topic. In this study, hardness and wear behaviors of aged and non-aged SiC/AlSi7Mg2 MMCs produced by squeeze casting method were investigated.

## 2 Material and method

### 2.1 Composites production

Al alloy was used as matrix material because of its suitability for the squeeze casting. As a reinforcement material, silicon carbide (SiC) particles having 10–40 µm size were selected to obtain good interfacing with the matrix alloy. The reason for using different particle sizes is directly related to the fact that large particles enable to obtain a homogeneous mixture and small particles increase the strength of bonding [22]. The density of SiC to be used as reinforcement material is 2.80 g/cm$^3$. This provides significant advantages for the specific strength values of the composites.

In the preparation of matrix material, initially aluminum with 99.9% purity was added to the ETIAL-140 alloy in order to reduce Si ratio to 7%. It was necessary to have sufficient time to extend the solidification range of the matrix material and to sufficiently wet the reinforcement by the matrix alloy. When the particles cannot be well wetted by the matrix in particle-reinforced composites, the mechanical properties of Al MMCs are adversely affected. To increase the wettability of these composites and to provide excellent bonding between the ceramic and the metal matrix, reactive alloy elements such as Mg, Ca, Ti or Zr were also added into the matrix [23, 24]. Melting process was carried out in the induction furnace having a capacity of 2 kW power and 1000 °C. AlSi7Mg2 alloy was obtained by making the slag removal process at approximately 550 °C to prevent the formation of unwanted structures in the interior after the melting of the matrix alloy was carried out. The chemical compositions of the matrix material are given in Table 1.

In addition to reinforcement element, the SiC reinforcement having a particle size of 10–40 µm was added in the molten matrix material at a speed of about 15 g/min until it was 15% by weight. At this stage, the material was in the liquid–solid range and the mixing was carried out with a graphite rod. In the mixing process, the mixer was moved up and down in the induction furnace to ensure the homogenous particle distribution. After the addition of the particle, the furnace was turned off to get liquid/solid mixture; by this means, reinforcement/matrix interface formation was provided. The mixing process continued until the melt became dough by mechanical force. And the temperature of the composite material was increased up to 750 °C. At this temperature, the molten metal was poured into the mold, a pressure of 100 MPa was applied and the material was kept under pressure until it gets solidified. Schematic view of vertical squeeze casting is given in Fig. 1. The composite material produced by the squeeze casting method was removed from the mold. The diameter and length of this AlSi7Mg2 MMC were 90 mm and 150 mm, respectively.

To improve the mechanical properties of 15% SiC-reinforced composites, MMC composites were subjected to homogenization and aging. In homogenization heat treatment, composites were dissolved at 550 °C for 5 h and then quenched. Later, the oversaturated composites was stabilized by heating at low temperature (8 h at 185 °C).

The heat treatment conditions and hardness values of 15% SiC-reinforced AlSi7Mg2 MMCs having 228 MPa tensile

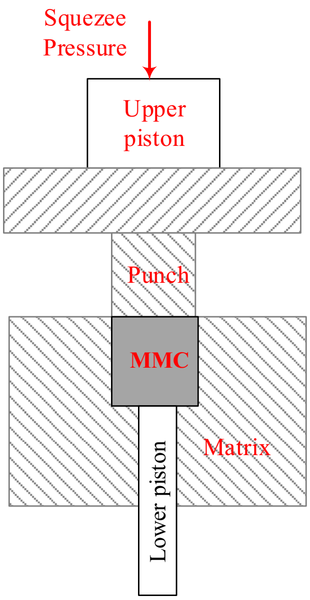


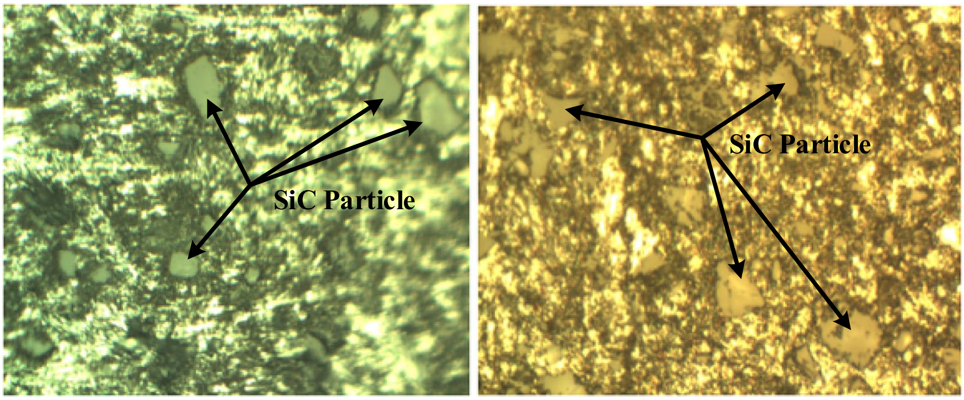
**Fig. 1** Schematic view of vertical squeeze casting

**Table 1** Chemical composition of AlSi7Mg2 matrix alloy (%)

| Mg | Zn | Cu | Fe | Si | Ni | Co | Ti | Al |
|---|---|---|---|---|---|---|---|---|
| 2 | 0.11 | 0.13 | 0.54 | 7 | 0.074 | 0.116 | 0.086 | 89.944 |

**Table 2** Heat treatment conditions and hardness of 15% SiC/AlSi7Mg2 MMC

| Heat treatment | Solution treatment | Quench condition | Aging treatment | Hardness (BH) |
|---|---|---|---|---|
| As-received | – | – | – | 95 |
| Solution treated | 5 h at 550 °C | Water quenched | – | 97 |
| Aged | 5 h at 550 °C | Water quenched | 8 h at 185 °C | 116 |



**(a)** *Non-aged SiC/AlSi7Mg2 composites* **(b)** *Aged SiC/AlSi7Mg2 composites*

**Fig. 2** Optical views of composites through a microscope

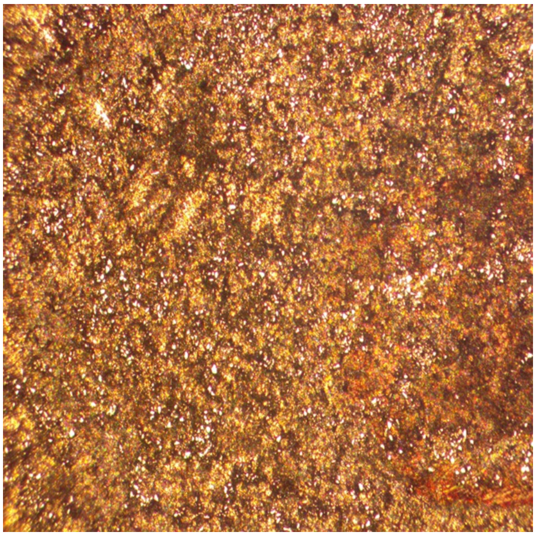


**Fig. 3** Homogenous distribution of SiC particles in matrix

strength are given in Table 2. The SiC particle distributions of aged and non-aged composites are also given in Fig. 2. The homogeneous distribution is also given in Fig. 3.

### 2.2 Wear test

The centers of the composites were drilled with a 5-mm-diameter drill to perform the wear tests of aged and non-aged composites. The drilled composites were fixed to the pin-on-disk wear device (Turkyus brand) by screwing and were ready for the experiment. Under the application arm of the wear device, the abrasive pink grinding stone was attached and the determined weight was placed on application arm. Then, the wear time was entered on the device screen, and the test was launched. The experiments were conducted with regard to the combinations of different loads (7 N, 12 N and 17 N), sliding speeds (0.2, 0.3 and 0.4 m/s) and sliding distances (700, 1000 and 1300 m) in dry sliding conditions. At the end of each experiment, the composites were weighed on the precision scale (RADWAG brand with a sensitivity of 0.001 mg); and the final weights were calculated. The wear test device image and test setup are given in Fig. 4.

## 3 Results and discussion

In the wear behavior; the sliding distance, applied load, lubrication status, sliding time and properties of material pair are very pivotal to take into consideration. In the wear device, these parameters can be kept under control. However, the friction coefficient varies depending on the parameters such as the formation of the tribo-surface, the mass loss, the deformation and the heat released from the metal/abrasive part contact during friction. Friction coefficients and forces of SiC-reinforced AlSi7Mg2 MMCs were measured by the wear device during wear tests. The friction coefficients of the aged and non-aged composites measured by the device are given in Fig. 5.

It can be seen that the graphs in Fig. 5 are quite similar. The only difference between the graphs is that the coefficient of friction and the fluctuations change during friction. Initially, friction coefficients increased. This increase

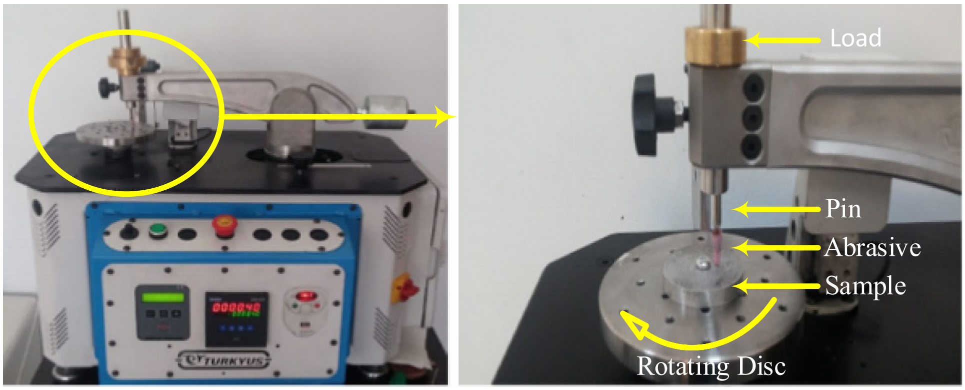
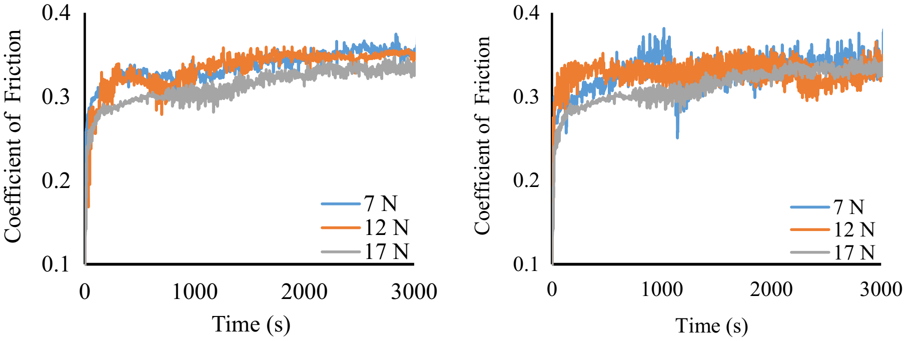
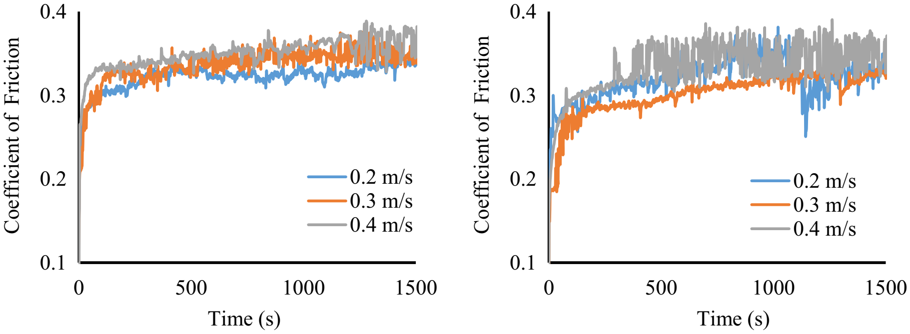


**Fig. 4** Wear test device image and test setup



Non-aged; Sliding speed: 0.2 m/s

Aged: Sliding speed: 0.2 m/s



Non-aged; Load: 7 N

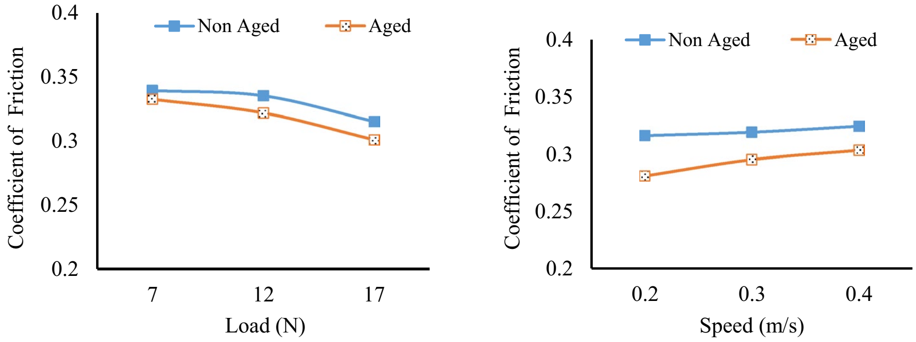
Aged; Load: 7 N

**Fig. 5** Variation in the friction coefficient of aged and non-aged composites depending on load and sliding speed for a sliding distance of 700 m

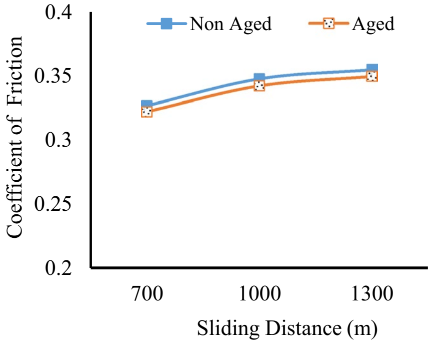
in the friction coefficient was very low as the sliding time increased. This situation was related to the change in initial surface roughness of the composite during friction. On the other hand, it was related to the compatibility of abrasive and composite material. In addition, in some experiments, fluctuations were small, but in some, they were high, and in some experiments, there was an increase after a certain sliding time. The increase in these fluctuations was brought about by the decrease in the force, submerging of abrasive in composite material and contact of abrasive with SiC reinforcement in the composite. Considering the fluctuations, the analysis of the average friction coefficients for the determination of friction coefficient values is gaining importance. The average friction coefficient changes of aged and non-aged composites depending on load, sliding speed and sliding distance are shown in Fig. 6.

In all the wear parameters, it was determined that the friction coefficients of the aged composite were lower than those of non-aged composite. With the increase in the applied load in abrasive wear tests, it was observed that the friction coefficient decreased in both aged and non-aged composites. In some studies, it was observed that the friction coefficient increased due to the increase in the load [25–27], whereas in others, it was observed that it decreased as in our study [28, 29]. This is due to the formation of the tribo-surface. The tribo-surface

**Fig. 6** Variation in friction coefficient of aged and non-aged composites depending on applied load, sliding distance and time



**(a)** Speed: 0.2 m/s; Sliding Distance: 700 m **(b)** Load: 17 N; Sliding Distance: 1000 m



**(c)** Sliding Speed: 0.3 m/s; Load: 12 N

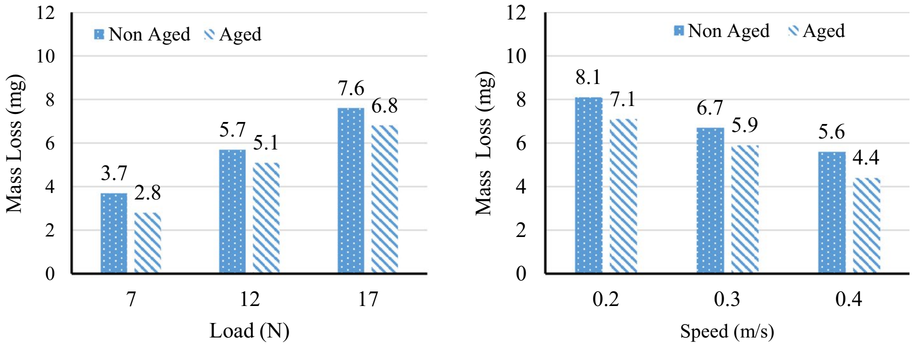
formed between the abrasive piece and the sliding surface reduces the friction coefficient. In other words, when the load increases, the nominal contact area between the pin and the opposite surface increases, so an increase in the contact temperature results in a softening of the surface; therefore, sliding movement between the contact surfaces causes reduction in the friction coefficient [29]. It was observed that the decrease in the friction coefficient with increasing the applied load from 7 to 12 N was less than raising the load from 12 to 17 N. Considering the sliding speed, the friction coefficient of both aged and non-aged composites increased with increasing the sliding speed. The friction coefficient of the aged composite was higher than that of the non-aged composite. It was understood that the effect of increasing sliding speed on the aged composite was higher. The main factor in the increase in friction coefficient depending on sliding speed was that the SiC reinforcements in the composites were squeezed out onto the mating surfaces forming mechanically mixed layer [25]. For the sliding distance, it was observed that the friction coefficient increased linearly for both aged and non-aged composites with increasing sliding distance. This was thought to be a function of the heat during friction or of pulling out of SiC particles from mechanically abraded parts between the contact surfaces [25]. It was seen that the increase in friction coefficient decreased with increasing sliding distance.

The mass losses due to the applied load, sliding speed and sliding distance of the aged and non-aged composites are given in Fig. 7.

Figure 7a shows that mass losses increased for both aged and non-aged composites due to the increase in applied load. Although the decrease in mass loss is expected due to the reduction in friction coefficient, it is thought that mass loss increases because SiC pieces on the tribo-surface are ruptured from the softening material with increasing surface temperature. Similar studies by some researchers [30, 31] seemed to be consistent with these results. In Fig. 7b, it was observed that mass losses decreased due to increasing sliding speed contrary to applied load. Unlike our study, Chowdhury and Rahaman determined that increasing sliding speed resulted in decreased friction coefficient and increased weight loss [32]. With increasing sliding speed, it could be said that the mass loss was reduced due to shorter contact time of abrasive or formation of tribo-layer at the contact surfaces [25, 33]. In Fig. 7c, it was determined that the mass loss increased with increasing sliding distance [34, 35]. Compared to other sliding distances, a significant mass loss occurred at a sliding distance of 1300 m. In all three conditions, the mass losses of the aged composites were determined to be less.

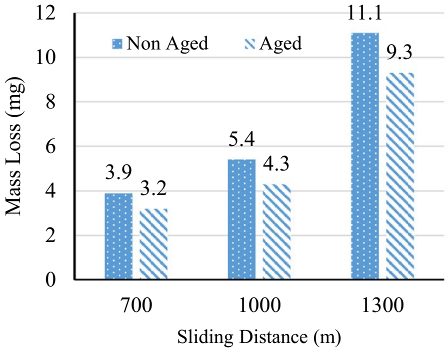
It was observed that the wear loss in aged composites was less in all experimental conditions. To interpret this in detail, it is necessary to analyze the SEM images of

**Fig. 7** Mass loss of aged and non-aged composites



**(a)** Speed: 0.2 m/s, Sliding distance: 700 m

**(b)** Load: 17 N, Sliding distance: 1000 m



**(c)** Speed: 0.3 m/s, Load: 12 N

the worn surface. The SEM images of the aged and non-aged composites on worn surfaces for an applied load of 12 N, a sliding speed of 0.3 m/s and a sliding distance of 1000 m are given in Fig. 8. In Fig. 8, it can be seen that the wear cavity in the aged composite was less than that of non-aged composite. The wear surface of the aged composite was subjected to less plastic deformation due to the fact that the wear surface was not easily worn (high wear resistance) because, depending on the aging process, precipitation formation increased the strength of the matrix and supported the reinforcement better [20, 36]. However, because the strength value of the non-aged composite was worse than that of aged, more wear cavity width was obtained in the same wear parameter. As the wear width increased, the contact area on the friction surfaces increased. The increase in contact area increased the penetration of the hard particles of the opposite surface into the soft pin surface, while, at the same time, it increased the plastic deformation and deformation of the soft surface. On the other hand, deformation and plastic deformation increased the stresses on the material surface. Due to high stress concentration, plastic deformation occured in roughness and moved away from the surface of the material [37].

## 4 Conclusion

The effects of aging, applied load, sliding speed and sliding distance on the tribological behaviors in MMCs were analyzed, and the following results were obtained;

- It was determined that the hardness of the composites increased with the heat treatment to the composite materials. The hardness of aged composites increased by about 22% compared to the non-aged composites.
- It was detected that the friction coefficient decreased due to the increase in applied load. It was also observed that the friction coefficient increased with increasing the sliding distance and speed. The effect of load and sliding speed on the friction coefficient was found to be greater than the sliding distance. The friction coefficients of aged composites at minimum and maximum loads were obtained as 0.332 μ and 0.301 μ, and those of non-aged composites were obtained as 0.339 μ and 0.315 μ, respectively, for 0.2 m/s speed and 700 m sliding distance. The friction coefficients of aged composites at minimum and maximum sliding speeds were found to be 0.281 μ and 0.303 μ, and those of non-

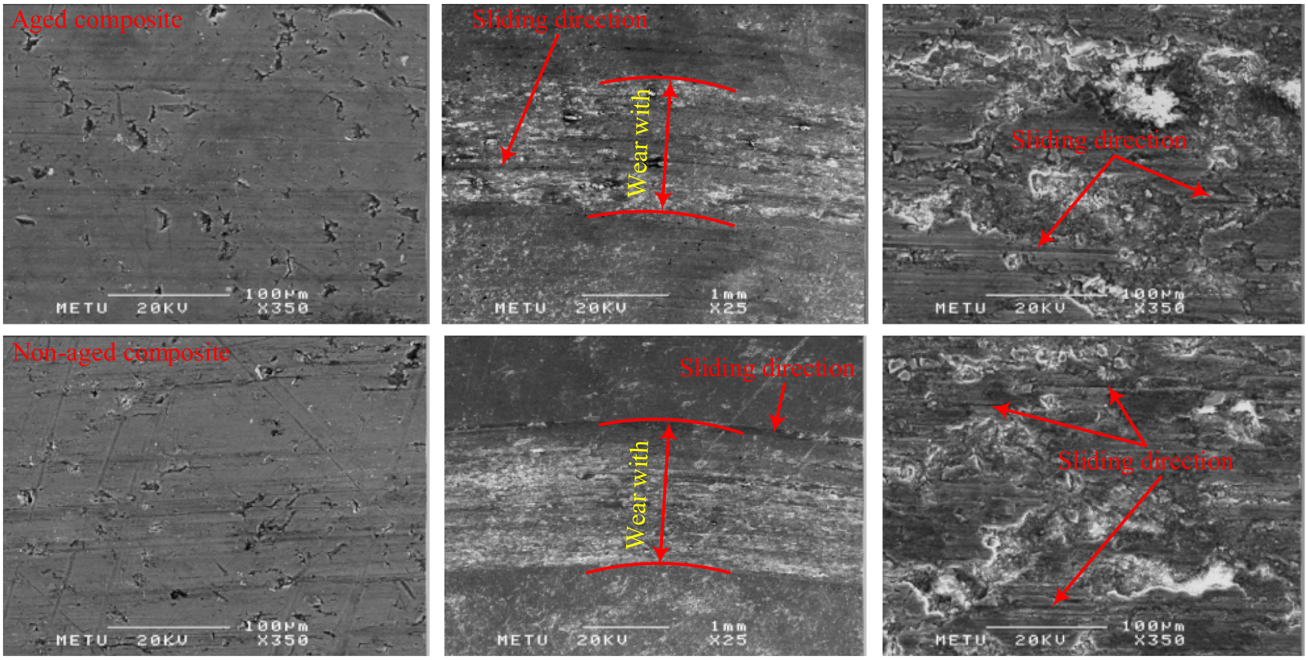


**Fig. 8** SEM images of aged and non-aged composites

aged composites were found to be 0.316 μ and 0.324 μ, respectively, for 17 N load and 1000 m sliding distance.

- It was concluded that the abrasion resistance of aged composites was higher than that of non-aged composites.
- It was seen that the mass losses increased by increasing load and sliding distances, but decreased by increasing sliding speed. The mass loss of aged composites at minimum and maximum loads was obtained as 2.8 and 6.8 mg, and that of non-aged composites was obtained as 3.7 and 7.6, respectively, for 0.2 m/s speed and 700 m sliding distance. The mass losses of aged composites at minimum and maximum sliding distances were found to be 3.2 and 9.3 mg, and those of non-aged composites were found to be 3.9 and 11.1 mg, respectively, for 0.3 m/s sliding speed and 12 N load.

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