Tribological Behavior of Aluminum Micro-and Nano-Composites

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Abstract
Aluminum metal matrix composites are a class of advanced materials which have been developed for weight-critical applications in the aerospace and automotive industries. In the present investigation, tribological performance of aluminum micro- (100 to 200 μm particle size) and nano- (47 nm particle size) composites was studied using a three pin-on-disk apparatus under dry sliding conditions. As a basis for comparison, the tribological performance of aluminum alloys was also studied. The pins made of these materials were then slid against a steel disk under ambient conditions. Tests were conducted at a sliding velocity of 1.58 m/s for a normal load of 30 N. The worn surfaces of the pins and wear debris were analyzed using a scanning electron microscope. Based on the experiments, it was observed that the nano-composites significantly outperformed all of the other materials with respect to friction levels. It was also discovered that the nano-composites exhibited the best wear performance among the composites investigated. The size of the reinforcement particle trapped at the interface and the hardness of the mating material were specifically found to play an important role in determining the friction and wear behaviors of the materials investigated.

Keywords: Aluminum, Metal Matrix Composites, Friction, Wear, Nano-Composites.

1. INTRODUCTION
Metal matrix composites (MMCs) are a class of advanced materials in which the metallic base material (matrix) is reinforced with a ceramic phase (in the form of continuous or short fibers or particulates). This is done in order to achieve a combination of attributes not attainable by either constituent individually [1, 2]. The structure of composite materials is determined by the type and form of the reinforcement components. MMCs are being applied in many new areas such as automotive, aerospace, thermal management, recreational and infrastructure industries. They are being more readily utilized due to their improved properties which included higher specific strength and stiffness, excellent tribological performance, improved high temperature properties, and lower thermal expansion coefficients in comparison to their base alloys [3–5].

Aluminum has been exploited as a matrix material for various MMCs due to its low density and ease of fabrication [6]. Properties of Aluminum matrix composites (AMCs) can be tailored to many of the requirements of different industrial applications by suitable combination of matrix, reinforcement and processing route. The most commonly used base materials in AMCs are Al-Si or Al-Cu alloys [7–10]. Most recently, Al–Mg and Al–Zn based alloys have also been investigated as potential matrix materials for AMCs [11–13]. The reinforcement particles typically used in Aluminum Metal Matrix Composites (AMMCs) are SiC and Al_2O_3 [10–16].

Efforts have been made to study the tribological behavior of particle reinforced aluminum-based composites. It has been reported that these composites showed significant improvements in modulus, strength and related properties, as well as improved tribological performance compared to base alloys [17–25]. Most of these research results showed that the addition of ceramic particles up to certain volume

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fraction levels resulted in substantial improvements in the friction and wear properties relative to that of the alloys into which they were incorporated. The composition, size, shape and the volume fraction of the reinforcement additions control the degree to which the friction and wear rates are vary. Other variables such as the composition of the matrix, particle distribution, and interface between the particles and the matrix also affect the tribological behavior of particle-reinforced composites. In addition, the operational conditions affect the friction and wear behavior of metal matrix composites. These conditions include the type of counterpart material, roughness, contact pressure, velocity, contact geometry and environment. The friction and wear properties are therefore a system dependent variable and can be interpreted relative to the testing conditions employed.

It is well know that metal matrix composites (MMC's) containing micro-size reinforcements are ideal materials for application in high performance and wear resistant components due to their attractive mechanical, physical and tribological properties. Hence, in the present study, the tribological performance of AMMCs was investigated. In the experiments, Aluminum A206 alloy was chosen as the matrix material and the reinforcement was made of micro sized SiO_2 particles. Magnesium was used as a wetting agent to help with the incorporation of the SiO_2 into the aluminum alloy. It is recognized that some of the SiO_2 added to A206 alloy will get converted to spinel and later Al_2O_3 due to the presence of magnesium. Hence, the tribological performance of composites containing Al_2O_3 reinforcement was also studied separately. Nano- Al_2O_3 particles were specifically chosen in this study as the nano-composites because they have emerged as an important class of materials that show the potential for improvement in properties far greater than that afforded by incorporation of micro-size reinforcements [26–36].

2. EXPERIMENTAL DETAILS

In this study, the base material was made of aluminum A206 alloy and the chemical composition of the alloy is shown in Table 1. The various materials prepared for the study are shown in Table 2.

To prepare the micro-composite samples, the aluminum alloy A206 was melted in an induction furnace under an argon atmosphere. After the temperature of the melt reached to 800°C, SiO_2 sand particles and 5 wt. % Mg (99.98% pure) were added into the molten metal under argon cover, over a period of 7 min, using a stir-mixing technique. Two different melts were prepared via this method into which 9 and 13 wt. % SiO_2 sand particles were added. The SiO_2 sand particles were irregular in shape with sizes ranged from 100 to 200 μm and had a composition (wt. %) of 99.70% SiO_2, 0.12% Al_2O_3, 0.12% K_2O, 0.04% CaO, 0.02% Fe_2O_3, 0.01% Na_2O, < 0.1% MgO, and < 0.1% TiO_2. As a basis for comparison, a melt without SiO_2 sand particles also prepared. Then the melt was poured into a preheated steel mold at a pouring temperature of 750°C for gravity casting. Sections of the castings were prepared for the as-cast properties evaluation and the remainder was heat treated to the T6-condition where the samples were solutionized at 510–516°C for 2 hours followed by 526–532°C for 14–20 hours. The samples were then water quenched and aged at 199°C for 8 hours. The optical photograph of the SiO_2 (13 wt. %) sand particles embedded in the A206 alloy matrix is shown in Fig. 1.

Table 1. Chemical composition of aluminum A206 alloy

Elements	Cu	Mn	Mg	Ti	Fe	Zn	Si
Wt.%	4.20–5.00	0.20–0.50	0.15–0.35	0.15–0.30	< 0.10	< 0.10	< 0.05

Table 2. Materials used for the study

Sl. no.	Materials	Type
1	A206	Alloy
2	A206 + 5 wt. % Mg	Alloy
3	A206 + 5 wt. % Mg + 9 wt. % SiO_2	Micro-composite
4	A206 + 5 wt. % Mg + 13 wt. % SiO_2	Micro-composite
5	A206 + 5 wt. % Mg + 2 wt. % Al_2O_3	Nano-composite

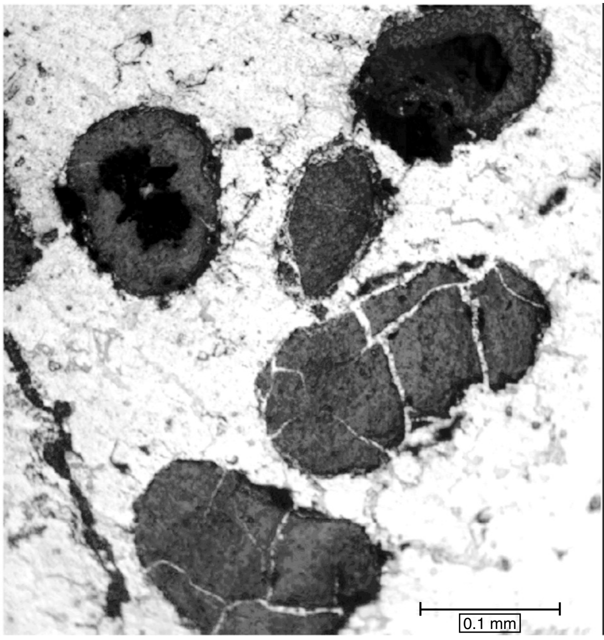

Figure 1. Optical photograph of the cast Al-A206/SiO_2 composite.

To prepare the nano-composite sample, aluminum alloy A206 was melted in an induction furnace under an argon atmosphere. After the temperature of the melt reached to 900°C, approximately, 5 wt. % Mg and 2 wt. % Al_2O_3 nano particles were added into the molten metal under argon cover, over a period of 20 min, using a stir-mixing technique. The Al_2O_3 particle had a spherical morphology and was 99.5 wt. % pure with an average particle size of 47 nm. The composite slurry was then squeeze cast in a steel permanent mold preheated to 500°C. The transmission electron micrograph of the Al_2O_3 particles embedded in the A206 alloy matrix is shown in Fig. 2.

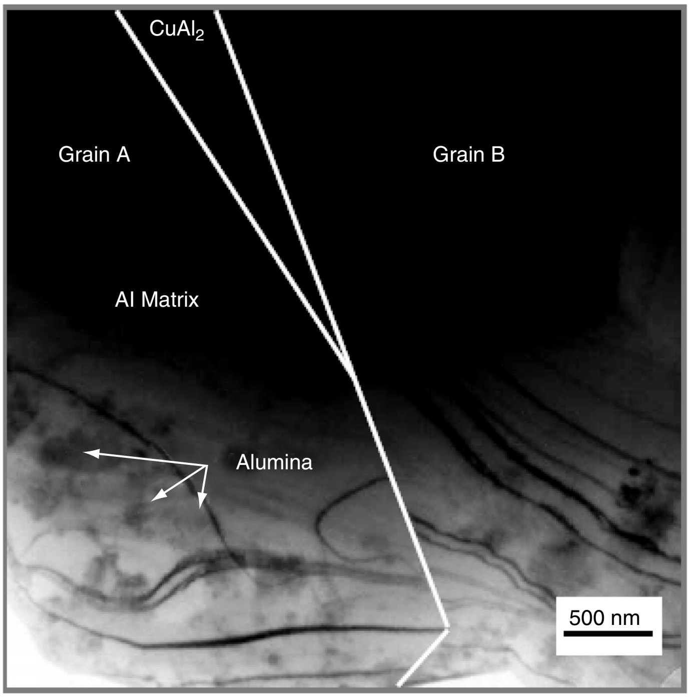

Figure 2. Transmission electron micrograph of the cast Al-A206/Al_2O_3 composite.

Friction and wear tests were carried out under dry sliding conditions using a three pin-on-disk Falex-6 wear testing machine, the schematic diagram of which is shown in Fig. 3. The cylindrical pins were machined with a diameter of 6 mm and length of 15 mm. Three pins were secured vertically in the holder at positions equidistant from the center of the holder and at angles of 120° in reference to each other. The Rockwell F-scale (1/16" steel ball, 60 kg) hardness of the investigated materials was measured prior to each test. The hardness values are presented in Table 3. The counterface, disk was made of SAE 1045 steel of diameter of 60 mm and had a hardness of 62 HRC. Prior to each test, the counterfaces were polished in order to ensure the consistency of the surface roughness, R_a for about 0.6 μm. During the test, the rotational speed was held constant at 1.58 m/s. Normal load of 30 N was used in the test and the duration of the testing was 60 min. The weight loss of the pins was measured using a Micro-balance with a precision of 0.0001 g. Density was measured using Archimedes method. The details of calculating friction coefficient, wear volume loss and density measurement are presented in Appendix A. The debris from the disk was collected after each test. The worn surfaces of the pins and wear debris were analyzed using a scanning electron microscope.

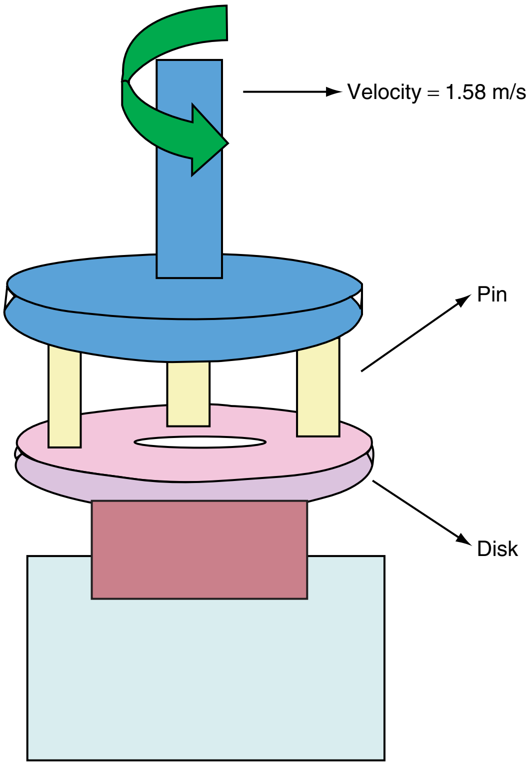

Figure 3. Schematic diagram of three pin-on-disk apparatus.

Table 3. Hardness values of the pin materials

Materials	Hardness (HRF)
A206	57.19
A206 + 5 wt. % Mg	60.20
A206 + 5 wt. % Mg + 9 wt. % SiO_2	94.90
A206 + 5 wt. % Mg + 13 wt. % SiO_2	100.70
A206 + 5 wt. % Mg + 2 wt. % Al_2O_3	65.70

3. RESULTS AND DISCUSSION

The variation of average coefficient of friction of aluminum alloys, micro-composites and nano-composite tested under dry sliding conditions are presented in Fig. 4. It is important to note that the experiments were conducted using a three pin-on-disk apparatus. The coefficient of friction values presented in the figure is the average of three pins tested against the steel counterface. It can be seen that the A206 alloy exhibited the highest coefficient of friction values. Addition of 5 wt. % Mg to the A206 alloy decreased the coefficient of friction to lower values. It can also be observed that the coefficient of friction values of the micro-composites are lower than that of aluminum alloys. Specifically examining the micro-composites, A206 + 5Mg + $9SiO_2$ and A206 + 5Mg + $13SiO_2$, the coefficient of friction of the composite containing 13 wt. % SiO_2 showed a lower coefficient of friction when compared to the composite having 9 wt. % SiO_2. It is important to note that the nano-composite showed the lowest coefficient of friction when compared to other materials.

Figure 5 shows the variation of wear rate tested under dry sliding conditions for aluminum alloys, micro-composites and nano-composite. As these experiments were conducted using a three pin-on-disk apparatus, the wear rates presented in the figure are the average of the three pins tested against the steel counterface. The error bars in the figure indicate the maximum and minimum values of the wear rates of three pins tested. It can be observed that the addition of 5 wt. % Mg to the A206 alloy decreased the wear rate to lower values. However, the wear rates of micro-composites were higher than that of the aluminum alloys. Examining the micro-composites, the A206 + 5Mg + $13SiO_2$ micro-composite showed better wear performance when compared to the A206 + 5Mg + $9SiO_2$ micro-composite. It is important to note that the wear performance of nano-composite is almost similar to A206 + 5Mg + $13SiO_2$ micro-composite and showed better wear performance than A206 + 5Mg + $9SiO_2$ micro-composite.

Figure 6 shows the scanning electron micrograph of the A206 + 5Mg + $13SiO_2$ micro-composite pin slid under dry conditions against the steel disk. Strong surface shearing and plowing marks were observed on the pin surfaces. Similar observations were found for the nano-composite pin slid on steel disk. However, the intensity of surface shearing was significantly reduced for the case of aluminum alloys when compared to that of micro- and nano-composites. Figure 7 shows the scanning electron micrograph of the debris collected at the end of the wear tests when A206 + 5Mg + $13SiO_2$ composite slid against steel disk. Wear debris revealed irregular lumps of materials broken from the pin material. It is also evident that the debris particles are of different shapes and sizes. Similar observations were

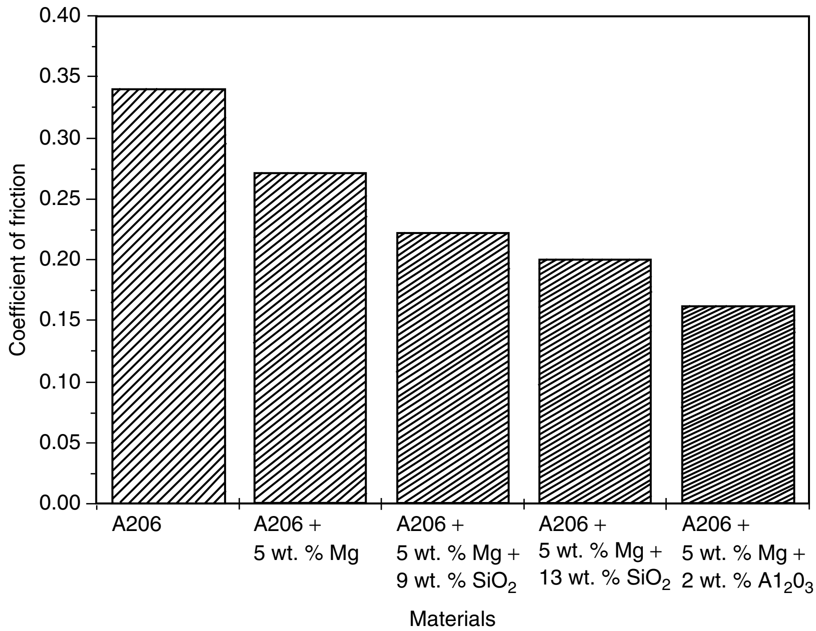

Figure 4. Variation of coefficient of friction for various materials.

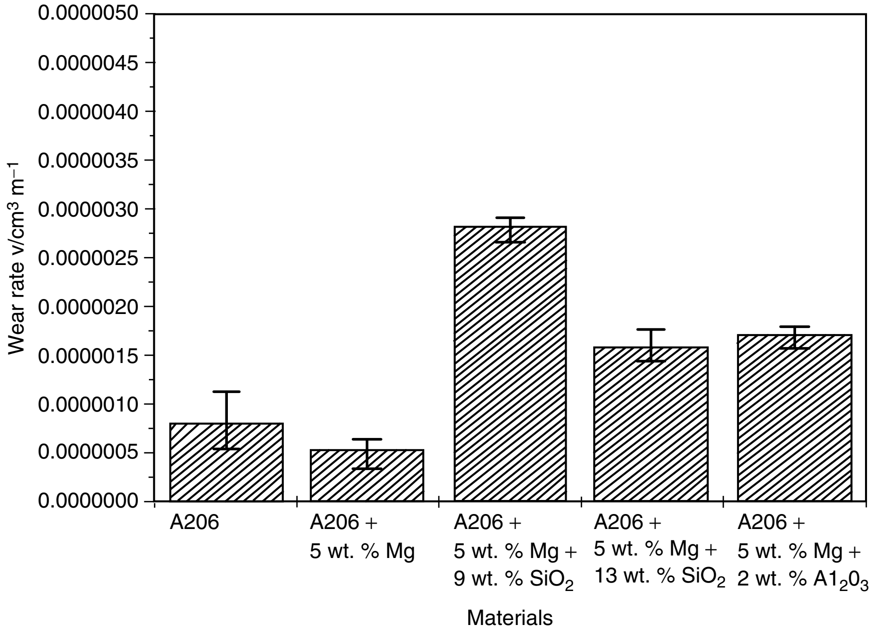

Figure 5. Variation of wear rate for various materials.

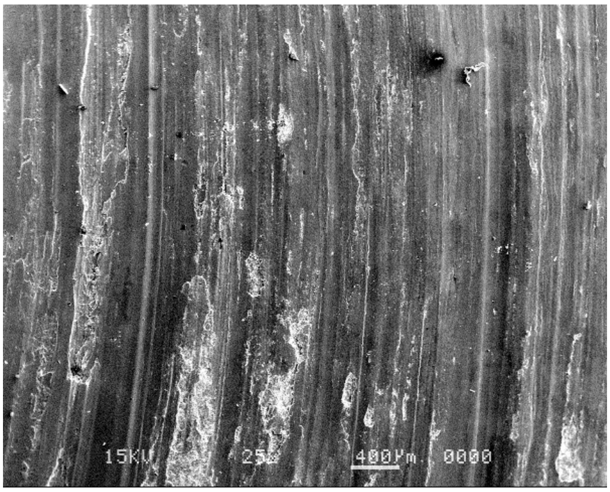

Figure 6. Scanning electron micrograph of A206 + 5Mg + 13 SiO_2 pin surface.

found in other composite materials. However, in the case of alloys, a transferred layer formation on the steel disk was observed.

The coefficient of friction is controlled by two different friction components (a) adhesion and (b) plowing. The adhesion component depends on the material pair, lubrication and the real area of contact; the plowing component depends on the degree of plastic deformation taking place at the asperity level [37]. It can be seen from Figs. 4 and 5 that the addition of Mg to A206 alloy decreases the coefficient of friction and wear rates to lower values. As shown in Table 3, the hardness value of A206 + 5 wt. % Mg is more than that of A206 alloy. Mokhtar [38] experimentally proved that the atomic bonds in harder metals are strong and hence the resistance to adhesion is increased, providing low frictional characteristics. Moore and King [39] showed experimentally that low friction coefficients are obtained with metals of high hardness, high elastic modulus and high resistance to plastic flow. The effect of hardness on friction is attributed to the fact that lack of plastic deformability of hard metals, with subsequent decrease in the ability of metals to adhere, results in low friction. Thus, addition of Mg to A206 alloy decreases the adhesion due to increase in hardness of the material. Thus, both friction and wear rates are decreased for A206 + 5 wt. % Mg alloy.

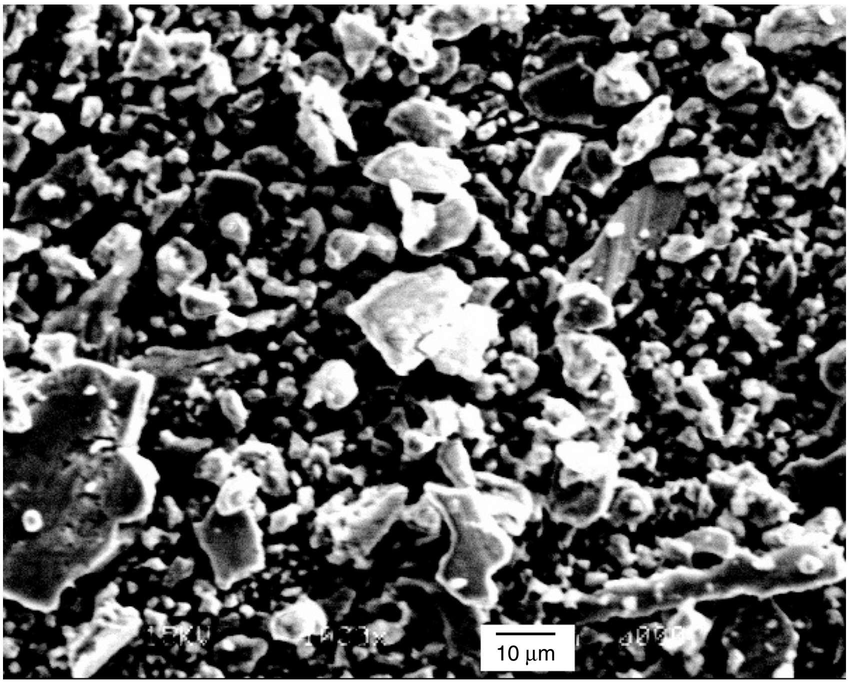

Figure 7. Scanning electron micrograph of wear debris when A206 + 5Mg + 13 SiO_2 pin slid against steel disk.

It was observed in the Figs. 4 and 5 that the micro-composites showed lower coefficient of friction and higher wear rates than the aluminum alloys. As explained earlier, the higher hardness of the micro-composites decreased the coefficient of friction to lower values. It is important to note from Table 3 that the hardness values of micro-composites are almost two times higher than that of aluminum alloys. However, the coefficient of friction is not significantly reduced in the case of micro-composites. This can be explained by the fact that the wear particles that are trapped at the interface during sliding would act as third body abrasive. This in turn reduces the substantial decrease in friction coefficient due to increase in hardness of the composite material. Thus, the abrasive nature of the third body particles which had irregular shaped morphology increases the wear rate of the composites and hence, the wear rates are much higher for the micro-composites than the aluminum alloys. Specifically examining the micro-composites, the A206 + 5 wt. % Mg + 9 wt. % SiO_2 micro-composite showed higher coefficient friction and wear rates than A206 + 5 wt. % Mg + 13 wt. % SiO_2 micro-composite. This can be explained by the fact that the hardness values of A206 + 5 wt. % Mg + 9 wt. % SiO_2 micro-composite is lower than that of A206 + 5 wt. % Mg + 13 wt. % SiO_2 micro-composite. Further, the abrasion action of the third body abrasive particles would be less effective in the case of A206 + 5 wt. % Mg + 13 wt. % SiO_2 micro-composite owing to higher hardness and thus lower coefficient of friction and wear rate. The work done by Hosking et al. [40] demonstrated that the coefficients of friction of composites were lower than that of the unreinforced alloys. Further, Rana and Stefanescu [41], Venkataraman and Sundararajan [42] found a substantial decrease in coefficient of friction with increasing volume fraction of the particulates.

It is interesting to note that the nano-composite recorded the lowest coefficient of friction when compared to other materials. The hardness value of the nano-composite is much lower than that of micro-composite and is higher than that of aluminum alloys. The higher hardness of the nano-composite when compared to the aluminum alloys decreases the coefficient of friction to lower values. The micron sized SiO_2 particles trapped at the interface during sliding increased the friction coefficient to high values, however the nano sized Al_2O_3 particles did not contribute highly to the friction coefficient. It is important to note that the Al_2O_3 particle had a spherical morphology and therefore were less effective as an abrasive when compared to SiO_2 particles which had irregular shapes. Also, the nano particles would fill in the asperities of the steel plate as the roughness of the steel disk is in the micron range. Thus, the coefficient of friction is lowest and wear rate is almost similar to that of micro-composite.

Previously, efforts were made to study the tribological performance of Al–micro- and nano- Al_2O_3 composites [43–45]. Qu et al. [45] studied tribological behavior of both Al-micro and nano Al_2O_3 composites with three nominal particle sizes, 50 nm, 200 nm, and 2–3 µm, and particle volume fraction 5, 10 and 15 %. In their experiment, the matrix was made of Al 319 alloy and the counterpart was 52100 steel. The authors [45] concluded that the nano-composites with 15% particle volume and 50 nm particle size had the superior wear performance. The present results were also compared with data existing in the literature on Al-micro and nano- Al_2O_3 composites. It was observed that A206 + 5 wt. % Mg + 2 wt. % Al_2O_3 nano composites showed the best tribological performance in terms of both friction and wear when compared to Al–micro- and nano- Al_2O_3 composites.

4. CONCLUSIONS

In the present investigation, tribological performance of aluminum micro- and nano- composites was studied using a three pin-on-disk apparatus under dry sliding conditions. As a basis for comparison, tribological performance of aluminum alloys was also studied. Based on the results for the experimental conditions studied, the following conclusions can be drawn:

1. Addition of alloying elements decreases the coefficient of friction to lower values. Further, the coefficient of friction was found to be low for the micro-composite materials when compared to the aluminum alloys. The nano-composites significantly outperformed all of the other materials with respect to frictional performance.
2. Although, the composites showed higher wear rates than the aluminum alloys, nano-composite exhibited optimum wear performance among the composites investigated.
3. The size of the wear particle trapped at the interface and the hardness of the mating material play an important role in determining the friction and wear behaviors of the materials investigated.

APPENDIX A

The friction coefficient (μ) was calculated as shown in Eq. (1)

$$\mu = \frac{T}{(P.R)} \tag{1}$$

where T is the torque (frictional force), P is the applied load and R is the wear track radius.

The Archimedes principle was applied to calculate the density of the specimens (ρ) using Eq. (2):

$$\rho = \frac{(\rho_{H20}.W_W)}{(W_W - W_A)} \tag{2}$$

where ρ_{H2O} is the density of the water at 25°C (g/ml), W_W is the weight of the pin in air (g) and W_A is the weight of the pin in water (g).

The wear volume loss was measured by recording the weight of the pins before and after the test. The wear volume loss (v), was calculated using the Eq. (3)

$$v = \frac{\Delta W_L}{(\rho.x)} \tag{3}$$

where ρ is the density of the sample studied, ΔW_L is the weight loss and x is the sliding distance.

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