Experimental Investigations towards Optimization of the Parameters for Wear Loss Quantities in A356/Al$_2$O$_3$ Nanocomposites

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Abstract   Metal matrix composites (MMCs) reinforced with nano-particles which called Nanocomposites (MMNCs), are ex-tensively studied in the recent years. Nanocomposites present high strength, wear resistance, hardness and exception- al microstructure stability. The nano-particles can improve the base material in terms of wear resistance, damping properties and mechanical strength. In this paper the tribological behavior of A356/Al$_2$O$_3$ nanocomposites were in- vestigated at room temperatures under dry sliding conditions. The results showed that the wear rate of the A356 alloy was significantly improved by the addition of the Al$_2$O$_3$ nano-particles. The wear rate of the nanocomposites was re- duced to about 25% (for nanocomposites containing 5 vol.-% of nano-particles) of the wear rate of the A356 mono- lithic alloy.

Keywords: MMCs, MMNCs, A356/Al2O3, nanocomposites, Wear

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1. Introduction

In the recent years, metal matrix nanocomposites MMNCs have encountered a massive development. MMNCs consists of a metal matrix reinforced with nano-particles; Different species of nano-sized oxides (Al$_2$O$_3$, Y$_2$O$_3$), nitrides (Si3N4, AlN) carbides (TiC,SiC), hydrates (TiH2) and borides (TiB2) have been employed as reinforcement agents. Especially, carborundum and alumina are the most common ceramic reinforcements for MMNCs. The attractive physical and mechanical properties that can be obtained with MMNCs include high strength, wear resistance, hardness and excep-tional microstructure stability at high temperatures. They are suitable for high-performance applications where cast alloys or precipitation strengthened material cannot be employed due to their limited properties. Moreover, nanocomposite materials ensure performances far superior than alloys strengthened by micro-size particles, Normally, micro-sized ceramic particles are used to improve the yield and ultimate strength of the metal [1-8].

Superior wear resistance is one of the attractive properties in MMNCs. It has been found that particulate-reinforced MMNCs show wear resistance on the order of 10 times higher than the un-reinforced materials in some load ranges. Many studies have been performed in order to understand the effects of various factors on the wear resistance of conventional MMNCs such as the particle size, the fraction of the reinforcing particles, the load, and the sliding speed, on the wear resistance of the particulate-reinforced MMNCs with Al matrices. The reinforcing particles used in these studies are mostly SiC or Al$_2$O$_3$ [5,6,7].

Few investigations were reported on the wear behavior of MMNCs [9,10,11] however they are expected that the wear resistance of MMNCs will be higher than the conventional MMCs.

In the present investigation the tribological behavior of A356/Al$_2$O$_3$ MMNCs were investigated at room temperatures under dry sliding conditions.

2. Experimental Procedures

2.1. Materials

2.1.1. Matrix

The A356 Al-Si-Mg cast alloy was used as a matrix. The chemical composition of the A356 Al alloy is listed in Table 1.

Table 1. The chemical composition of A356 alloy

Alloy	Chemical Composition (wt.-%)						
	Si	Fe	Cu	Mn	Mg	Zn	Al
A356	6.6	0.25	0.11	0.002	0.14	0.026	Bal

2.1.2. Nano-Additives

Nano- Al_2O_3 particulates were used as reinforcing agents. The Al_2O_3 nano-particulates have two different average sizes, typically, 200 and 60 nm. Several metal matrix nanocom-posites (MMNCs) were fabricated with different volume factions of Al_2O_3 nano-particulates such as 1 vol.-%, 3 vol.-% and 5 vol.-%.

2.2. Nanocomposites Fabrication

The A356/Al_2O_3 nanocomposites were prepared using a combination of rheocasting and squeeze casting techniques. Preparation of the composite alloy was carried out according to the following procedures: About 1 kg of the A356 Al alloy was melted at 680+2°C in a graphite crucible in an electrical resistance furnace. After complete melting and degassing by argon gas of the alloy, the alloy was allowed to cool to the semisolid temperature of 602°C. At such temperature the liquid/solid fraction was about 0.7. The liquid/solid ratio was determined using primary differential scanning calorimeter (DSC) experiments performed on the A356 alloy. A simple mechanical stirrer with three blades made from stainless steel coated with bentonite clay (see Figure 1) was introduced into the melt and stirring was started at approximately 1000 rpm. Before stirring the nano-particles reinforcements after heating to 400°C for two hours were added inside the vortex formed due to stirring. After that, preheated Al_2O_3 nanopar-ticles were introduced into the matrix during the agitation. After completing the addition of Al_2O_3 nanoparticles, the agitation was stopped and the mixture was poured into pre-heated tool steel mould specially designed for this purpose and immediately squeezed during solidification. Figure 2 shows a photograph of the mould used for squeezing the nanocomposites and the ingot after squeezing. The produced ingot has 30 mm diameter and 130+10 mm length.
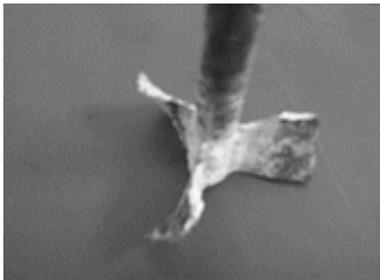

Figure 1. The three blades stainless steel stirrer
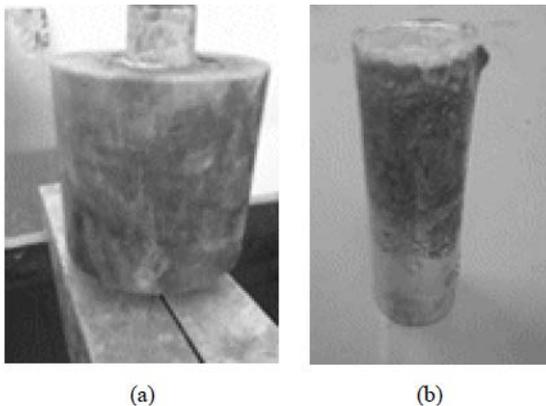

(a)   (b)

Figure 2. A tool steel mould used to squeeze the nanocompo- sites (a) and the ingot after squeezing (b)

2.2.1. Heat Treatment of Nanocomposites

The nanocomposites were heat treated at T6 before conducting the machining tests. The nanocomposites were solution treated at 540 + 1°C for three hours and then quenched in cold water. After cooling specimens were arti-ficially aged at 160 + 1°C for 12 hours. A schematic dia-gram of the heat treatment process is shown in Figure 3.

The A356/Al_2O_3 MMNCs fabricated in the current in-vestigation exhibited higher hardness values when compared to the unreinforced matrix alloy. The hardness of the MMNCs increases with increasing both the size and volume fraction (up to 3vol-%) of the Al_2O_3 nano-particles. The A356 monolithic alloy exhibited hardness between 38 and 47 VHN. While the MMNCs exhibited a hardness values be-tween 49 and 64 VHN.
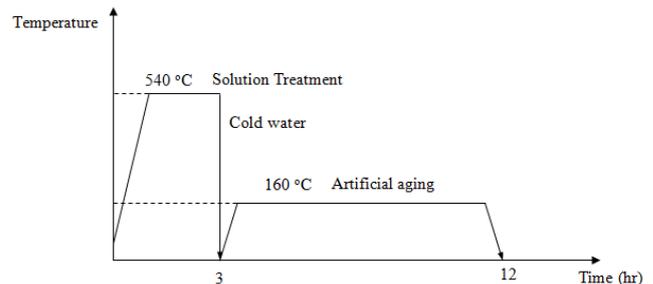

Figure 3. A schematic diagram of the solution treatment and artificial aging process

3. Wear Tests

Dry wear tests were carried out on the pin-on-disc wear testing machine shown in Figure 4. The wear tests were carried out at room temperature under several sliding speeds of 0.4, 0.8 and 1.2 m/s. The load was kept constant at 15 N. The chemical composition of the 314 stainless-steel disc was 0.13 wt% C, 1.8 wt% Si, 21.2 wt% Ni, 24.8 wt% Cr, 1.4 wt% Mn and balance Fe.

The wear tests were conducted under dry sliding and oil lubricating conditions. The Mobile 1 Fully Synthetic SEA 15W-50engine oil was used as a lubricant. The synthetic oil should be provided high enough level for lubrication during the test running.

The wear tests were carried out after heat treating the in-vestigated alloys to T6 condition. The specimens used were of a cylindrical shape having a diameter of 8 mm and a length of 12 mm. The specimen's ends were polished with 1200 grit SiC emery paper and cleaned with acetone. The specimens were then weighted before each experiment on a sensitive balance having sensitivity of 10^{-4}g. The specimen was fixed on a three jaws clutch. The load was applied to the specimen through a vertical pin fixed with the specimen holder. A fixed track diameter of 100 mm was used in all tests, and a variable sliding time with an interval of 5 min up to 30 min were applied to conduct the wear tests. The duration of the experiment was controlled by a stopwatch. After each ex- periment the specimen is weighed again and the weight loss was calculated.

For each test condition, at least three runs were per-formed. The wear rates (the slopes of the sliding time versus cumulative weight loss curves) of the investigated alloys were calculated by using the data after the run-in stage.
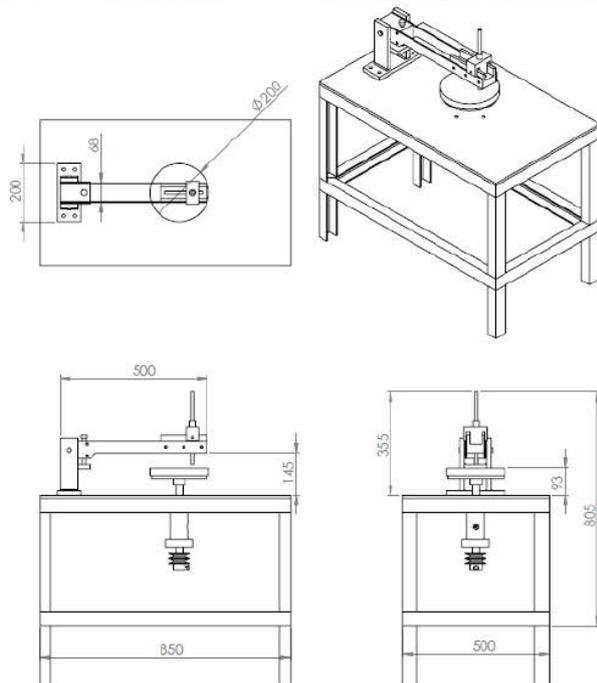
Figure 4. The pin-on-disc wear tester

Figure 6. Variation of the weight loss of the A356/Al$_2$O$_3$ (60 nm) nanocom- posites with sliding time (a) 1 Vol.-%, (b) 3 Vol.-% and (c) 5 Vol.-%

4. Results & Discussion

Figure 5 shows the variation of the weight loss with slid-ing time for different sliding velocity for the A356 mono-lithic alloy. Figure 6 and Figure 7 show the variation of the weight loss with sliding time for nanocomposites containing 60 nm and 200 nm Al$_2$O$_3$ nano-particles for different sliding veloc-ities, respectively.
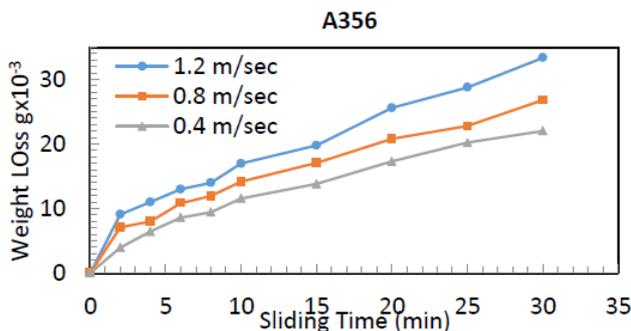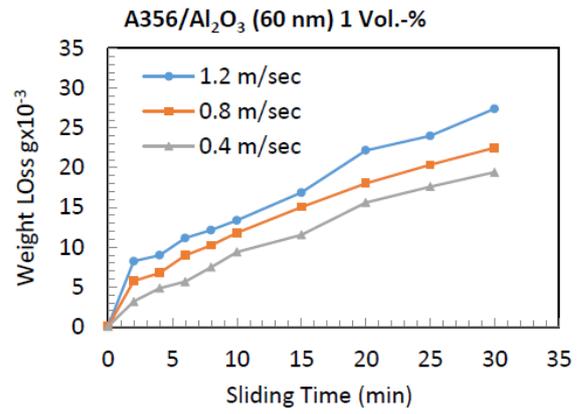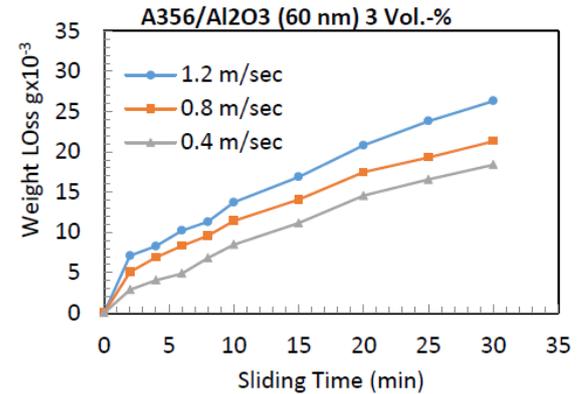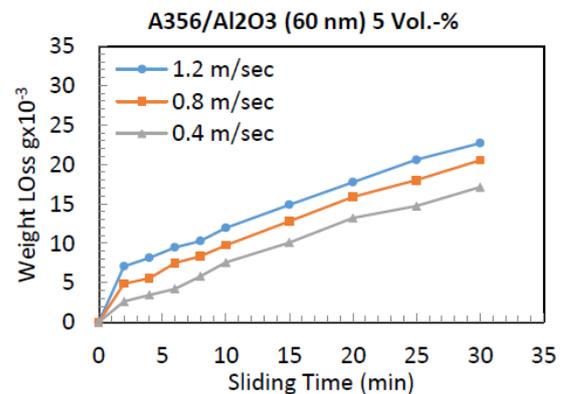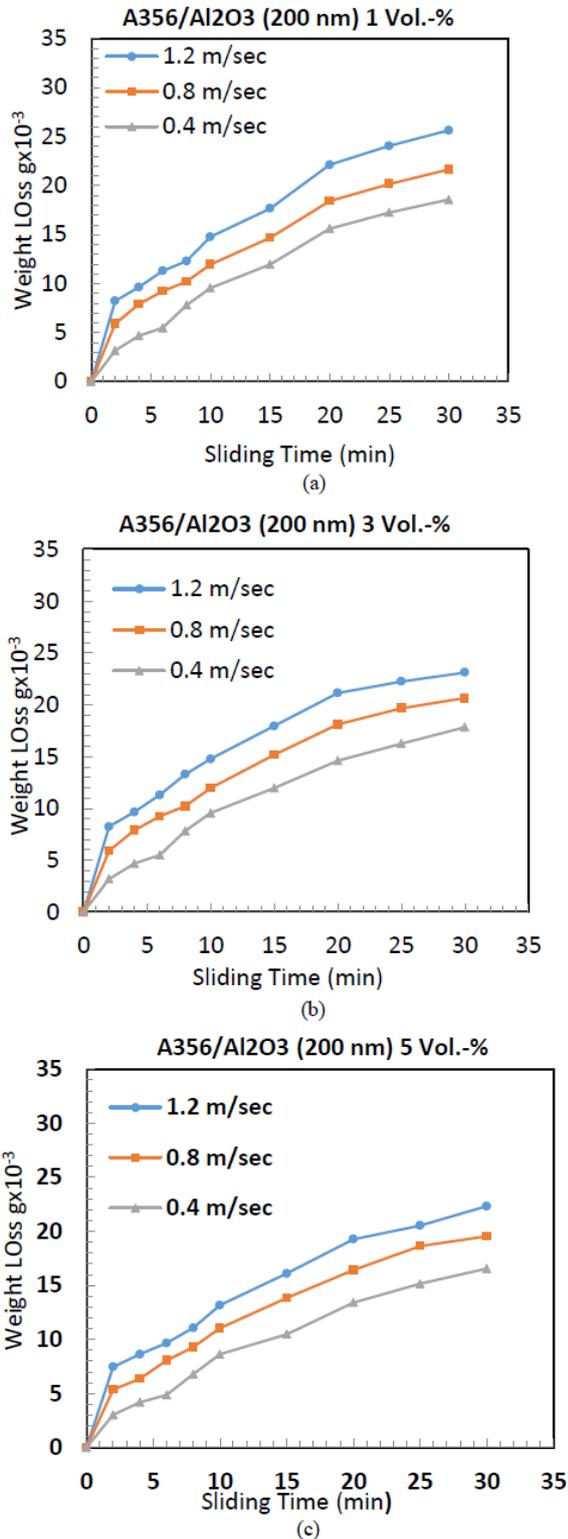

Figure 5. Variation of the weight loss of the A356 monolithic alloy with sliding time

The results revealed that the wear loss of the unreinforced alloy and nanocomposites appears to increase with increas-ing the sliding time. It is noticeable that, at constant applied load, the nanocomposites exhibit lower wear loss compared with the unreinforced alloy. Moreover, it can be seen that the weight loss of the unreinforced alloy and nanocomposites specimens increases with the increase of the sliding velocity. It is clear that mild wear was taken place for both the unre-inforced alloy and nanocomposites. Sever wear region was not observed for both the unreinforced alloy and nanocom-posites.

Figure 8 shows the variation of the wear rate with sliding velocity for the A356/Al$_2$O$_3$ nanocomposites containing 60 nm and 200 nm Al$_2$O$_3$ nanoparticles. The results showed that, for the unreinforced A356 alloy, increasing the sliding ve-locity increases significantly the wear rate. While for the A356/Al$_2$O$_3$ nanocomposites, increasing the sliding velocity increases slightly the wear

rates. Such observation was no-ticed for nanocomposites containing 60 nm and 200 nm Al_2O_3 nano-particles. Ithas been found that, at constant sliding velocity and volume fraction, the nanocomposites containing 60 nm of Al_2O_3 nano-particles exhibited slightly lower wear rates than the nanocomposites containing 200 nm of Al_2O_3 nano-particles. At constant nanoparticles size, in-creasing the volume fraction of the nano-particles reduces the wear rates of the nanocomposites (see Figure 9).

Figure 7. Variation of the weight loss of the A356/Al_2O_3 (200 nm) nanocom- posites with sliding time (a) 1 Vol.-%, (b) 3 Vol.-% and (c) 5 Vol.-%
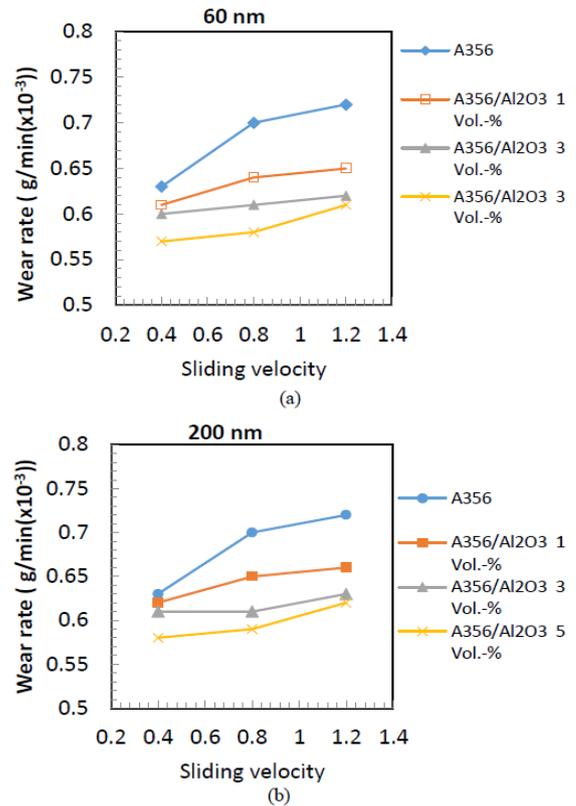
Figure 8. Variation of the wear rate with sliding velocity for the A356/Al_2O_3 nanocomposites containing (a) 60 nm and (b) 200 nm Al_2O_3 nanoparticles

The results showed that the wear rate of the A356 alloy was significantly improved by the addition of the Al_2O_3 nanoparticles. The wear rate of the nanocomposites was reduced to about 25% (for nanocomposites containing 5 vol.-% of nanoparticles) of the wear rate of the A356 monolithic alloy. The wear rate of the nanocomposites was slightly influenced by increasing the sliding velocity. In contrast, wear rate of the unreinforced A356 alloy was significantly influenced by the sliding velocity. The wear rate of the nanocomposites was reduced by increasing the volume fraction and/or reducing the Al_2O_3 nanoparticles size.
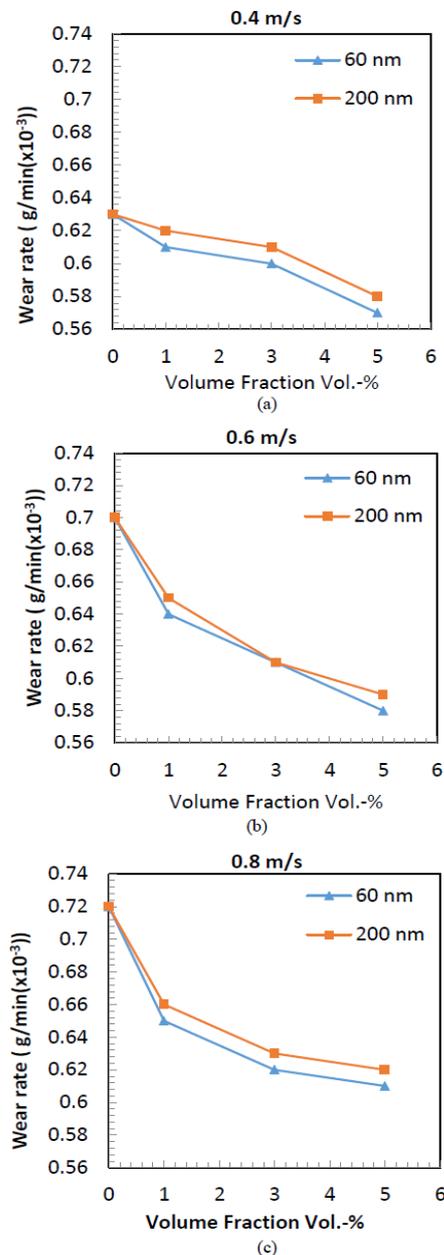
For any given nanoparticles content, 1 vol.-%, the mean distance between neighboring nanoparticles for the nano-composite with smaller filler particles (as in 60 nm nano-sized particles) was smaller than that with the bigger particles (200 nm nano-sized particles). For, example, the number of the nanoparticles per unit volume for the nano-composite with 60 nm Al_2O_3 nanoparticles would be greater than that of the composite with the 200 nm Al_2O_3 nanopar-ticles.

As the nanoparticles were uniform sized spherical parti-cles, the greater the number of the particles on the worn surface, the larger the contact area between the particles and the contact disc, and hence the better the wear resistance offered by the Al2O3 nanoparticles. That might be a reason for explaining the better improvement of the wear resistance by using nanoparticles.
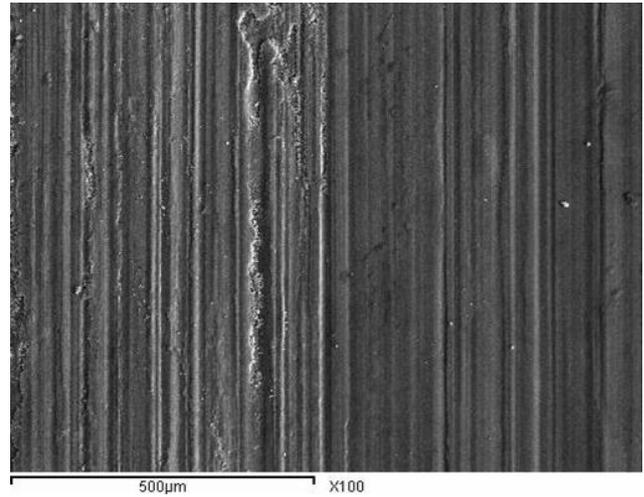
For the Al unreinforced matrix and the nanocomposites, wear tests performed at temperatures below the transition temperature produced relatively smooth worn surfaces (see Figure 10). SEM examinations of the worn surface of the nanocomposites showed that the worn surfaces were par-tially covered with layers of iron oxide (see Figure 11).

The iron oxides can act as solid lubricants and expected to reduce the wear rates with temperature.

The oxide layers (tribolayer) at the contact surfaces were formed as a result of the iron transferred from the counter-face due to the high compressive stresses developed at the interfaces. The compacted tribolayer is harder than the bulk material. During sliding metal–metal wear tests of the nanocomposites, the iron oxide layer formed on the contact surfaces acted as a solid lubricant and improved wear re-sistant. The formation of the tribolayers increased the surface hardness significantly and played an important role in de-laying the mild-to-severe wear transition in aluminum matrix nanocomposites. The presence of Al_2O_3 nano-particles served as a safeguard by generating a hard compacted tri-bolayer with smooth surface and sufficient thickness to protect the material underneath from excessive subsurface damage by forming a physical barrier of about 10 to 50 μm thick with the counterface.

Figure 10. SEM of the worn surface of A356/5 vol.-% 60 Al_2O_3 nanocompo-sites after 0.5 km at 0.4 m/s
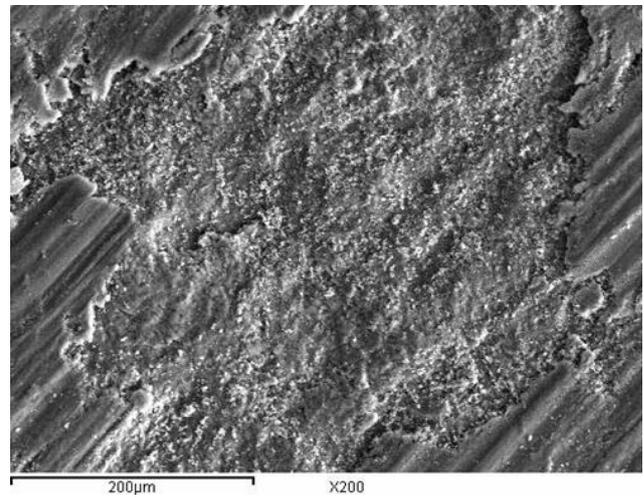
Figure 11. SEM micrograph shows the formation of the iron oxide layer on the worn surface of A356/5 vol.-% 60 nm Al_2O_3 nanocomposites

The reduction of the wear rate of the A356 alloy due to the addition of Al2O3 n nanoparticles may attribute also to the increase of the hardness of the nanocomposites compared with the A356 unreinforced matrix. Increasing the volume fraction of the nanoparticles increases the hardness of the nanocomposites and hence reduces the wear rate of the nanocomposites.

5. Conclusion

According to the results obtained the following conclu-sions can be pointed out:

1. The A356/Al_2O_3 nanocomposites exhibited higher wear resistance at room temperatures when compared with the A356 monolithic alloy. Increasing the volume fraction and/or reducing the Al_2O_3 nanoparticles size improves the wear resistance of the A356/Al_2O_3 nanocomposites.

2. The composites exhibited transition temperature be-tween 150 and 200°C, while the unreinforced alloy exhib-ited a transition temperature between 100 and 150°C.

3. SEM examinations of the worn surface of the nano-composites showed that the worn surfaces were partially covered with layers of iron oxide. The iron oxides can act as solid lubricants and expected to reduce the wear rates with temperature.

Figure 9. Variation of the wear rate with volume fraction for the A356/Al2O3 nanocomposites at sliding velocity of (a) 0.4 m/s, (b) 0.8 m/s and (c) 1.2 m/s

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