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Research Article

Temperature Effects on the Friction and Wear Behaviors of SiCp/A356 Composite against Semimetallic Materials

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Due to the low density and high temperature resistance, the SiCp/A356 composites have great potential for weight reduction and braking performance using the brake disc used in trains and automobiles. But the friction coefficient and braking performance are not stable in the braking process because of temperature rising. In this paper, friction and wear behaviors of SiCp/A356 composite against semimetallic materials were investigated in a ring-on-disc configuration in the temperature range of 30°C to 300°C. Experiments were conducted at a constant sliding speed of 1.4 m/s and an applied load of 200 N. Worn surface, subsurface, and wear debris were also examined by using SEM and EDS techniques. The third body films (TBFs) lubricated wear transferred to the third body abrasive wear above 200°C, which was a transition temperature. The friction coefficient decreased and weight of semimetallic materials increased with the increase of temperature and the temperature had almost no effect on the weight loss of composites. The dominant wear mechanism of the composites was microploughing and slight adhesion below 200°C, while being controlled by cutting grooves, severe adhesion, and delamination above the 200°C.

1. Introduction

Particle reinforced aluminum alloy composites (PRACs) exhibit high specific strength and stiffness, high thermal conductivity, and good thermal resistance and have been used in a variety of structural applications ranging from civil transportation to aerospace [1, 2]. PRACs have great potential to be used in the automobile and trains for the weight reducing and energy saving [3, 4]. High and stable friction coefficient and low wear rates are requested in the braking process.

Some researchers have studied the friction properties under different load and sliding speed for the PRACs which were used in automobile. Natarajan et al. investigated the friction behavior of 25 wt.% SiCp/A356 composites against semimetallic material under different load and sliding velocity, and PRACs were found more suitable to be used as a candidate material for brake rotor application than cast iron [5]. Uyyuru et al. used the Al-Si-SiCp composite to study the wear rate and friction coefficient varied with the applied normal load and the sliding speed against the brake pad material. The applied normal load was found to be the most important parameter affecting wear performance [6]. A comparative experiment on wear resistance of brake materials against two different Al-MMCs brake drums was conducted on a Chase Machine by Zhang and Wang [7]. It was found that the friction coefficient continuously decreased with the increase of load and speed and converged gradually at temperatures of 177°C and 316°C, and the friction fading took place at higher temperature. The changes of friction coefficient and wear rate at different load and speed range of the 20 vol.% SiCp/A359 composites and cast iron were studied by Daoud and Abou El-khair, against a commercial automotive brake material on a pin-on-disc type apparatus. The result shows that the friction coefficient of the composite was higher than cast iron at all test conditions [8].

The tests above were undertaken at ambient temperature without considering the effect of temperature on friction performance. However, heat generation must be considered during braking which causes the surface temperature to

increase with braking time and load increasing and affects the friction behavior during the sliding process. The mechanical properties and performance of the PRACs and the brake pad material decreased with the temperature rise [9–13]. So it is important to study the temperature effects on the friction behavior. Some researchers have studied the dry friction behavior under different environment temperature using a pin-on-disc type apparatus and investigated the effects of temperature on the friction behavior of the PRACs against the steel counterface.

Research on the influence of environment temperature on the wear behavior of Al-based composites has been made since 1993. Martinez et al. [14], Wilson and Alpas [15], Martín et al. [16], and Singh and Alpas [17] found that the presence of reinforcing particle extended the temperature range compared with aluminum alloys which were used in wear limited applications, such as piston liners and cylinder heads for car engines or brake drums and rotors [18]. Muratoğlu and Aksoy studied abrasive wear of the 25 vol.% SiCp/2124Al composites on a pin-on-disc type machine against abrasive paper. Result showed that the wear rate of 25 vol.% SiCp/2124Al composites increased significantly with temperature till 50°C. For the tests at temperatures above 50°C, the temperature had almost no effect on the wear rate [19]. Yao-hui et al. reported that the wear rate of both Al-12% Si alloy and its composite reinforced with 4 vol.% C_f and 12% Al_2O_3f decreased with temperature in the mild wear regime [20]. They showed that transition temperature increased about 200°C with addition of the reinforcements. A comparative investigation on dry sliding wear behaviors of 20 vol.% Al_2O_3p/6061Al composite and unreinforced 6061Al against a SAE 52100 bearing steel counterface was conducted on the ring-on-flat configuration in the temperature range of 25°C to 500°C by Singh and Alpas. It was found that the Al_2O_3 reinforcing particles lead to an increase in the transition temperature from 180°C for the unreinforced alloy to around 250°C for its composite [21]. Rodríguez et al. [22] carried out tests at different pressures and temperatures on 15 vol.% SiCp/8090Al composite sliding against carbon steel (SAE 1045) on a pin-on-disc configuration. It was concluded that wear rate increased about two orders of magnitude when temperature was above a critical one. Mousavi Abarghouie and Seyed Reihani investigated the friction and wear behaviors of 20 vol.% SiCp/2024Al composite and 2024Al at elevated temperature range 20–250°C using a pin-on-disc apparatus and found that transition from mild-to-severe wear above a critical temperature [23]. Labib et al. reported the tribological behavior of the 5–15 vol.% SiCp/Mg composite and pure Mg sliding against AISI/SAE 52100 steel disk on pin-on-disk wear tests at temperature of 25–200°C [24]. It was found that the transition from a mild wear to a severe wear extended to a higher load at higher temperatures. However, in these tests MMCs were tested against steel counterface under different environment temperature and without considering the friction heat produced during the dry sliding process.

With friction time increased, temperature rises during the dry sliding process and results in performance degradation and unstable friction properties, which is different with the result of environment temperature. The dry sliding process of the PRACs is a complex process involving not only mechanical but also thermal and chemical interactions between the surfaces in contact. The temperature, produced by the friction heat, is one of the important factors, which influence the performance and surface topography of two rubbing materials. Researchers studied the friction behavior for the PRACs against steel materials at high temperature, or the friction properties for the PRACs against brake pad materials under room temperature using pin-on-disc type apparatus. However, the friction properties are not yet understood well for the PRACs against semimetallic materials with friction heat, and the friction characteristics are also changing with the varied counterface materials against PRACs.

Table 1: Nominal chemical composition of A356/Wt.%.

Element	Si	Mg	Ti	Fe	Cu	Mn	Ni
Wt.%	7.23	0.332	0.128	0.112	0.001	0.001	0.001

Table 2: Nominal chemical composition of SiC/Wt.%.

Element	SiC	C	Si	SiO_2	Fe_2O_3
Wt.%	97.2	0.28	0.23	1.73	0.56

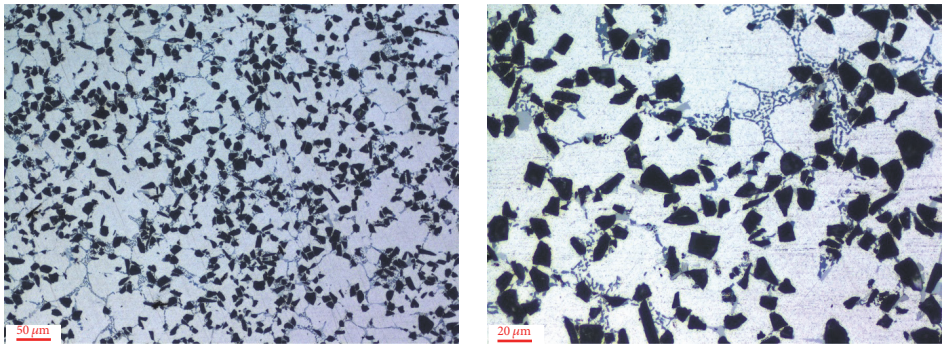
This paper was concerned with the friction and wear behaviors of SiCp/A356 composites against semimetallic brake materials. The transition from the mild-to-severe wear during sliding was studied at various temperatures on a ring-on-disc configuration. The effect of friction heat on wear behavior of the composites was studied at a constant sliding speed of 1.4 m/s and load of 200 N. Moreover, the worn surfaces and subsurface regions of the composites at different test temperatures were analyzed to investigate the wear mechanisms.

2. Experimental Procedure

2.1. Materials. The materials used for the wear test samples were SiCp/A356 composites containing 20 vol.% SiC particle which is produced by Beijing Jiaotong University. The studied composites were subjected to solution and precipitation heat treatment (T6). The material was produced using stirring casting and the average size of the SiC particle was 20 μm. The nominal chemical compositions of the A356 and SiC are shown in Tables 1 and 2, respectively. The microstructure of SiCp/A356 composites is presented in Figure 1.

A commercial semimetallic phenolic brake pad material was used as the counterbody material, which contained binder materials (phenolic resin and rubber), reinforced fiber materials (steel fibers and so on), filler materials ($BaSO_4$, $CaCO_3$, and so on), and others as friction modifier materials.

2.2. Experimental Techniques. Dry sliding wear tests were performed in the air using a ring-on-disc apparatus, which is shown in Figure 2. The ring specimens were made of SiCp/A356 composites and it was loaded against a semimetallic material disc, which was 34 mm in diameter and 6 mm in thickness. The size of ring was 32 mm in outer diameter



(a) (b)

Figure 1: Microstructure of SiCp/A356 composites: (a) 200x and (b) 500x.

Figure 2: The ring-on-disc testing equipment.

and 7 mm in height. The size of the specimens is shown in Figure 3.

The counterface surfaces of specimens were polished on 1000-grit SiC paper before the wear test. The tests were carried out at a constant sliding speed of 1.4 m/s and the applied load of 200 N. The test stopped until the temperature of the ring specimen reached the required temperature.

Before and after each dry sliding wear test, the specimens of disc and ring were cleaned in alcohol, dried by air, and then weighed by using an electronic balance which was accurate to within 0.1 mg. The wear rates were calculated from the rate of weight loss to the friction work, which can be calculated by formula, $A = (W_0 - W_1)/Q$, where A is the wear rates (g/MJ), W_0 and W_1 (g) are weight before and after wear test, respectively, and Q (MJ) is the friction work recorded by the equipment. The initial weight of disc and ring is 16.1729 g and 8.8986 g, respectively.

The friction coefficient was measured as the ratio of the friction torque to the applied load and arm of load. The frictional torque was recorded by a torque transducer attached to the wear apparatus. And the friction coefficient was calculated and recorded during the dry sliding test.

The sliding wear tests were carried out in a temperature range from 30°C to 300°C. The temperature range was divided into five temperature levels of 30°C~100°C, 30°C~200°C, 30°C~300°C, 100°C~200°C, and 200°C~300°C. The temperature of contact surfaces was measured by using a thermocouple fixed on the SiCp/A356 composites specimen close to the contact surface. The samples tested at 100°C~200°C and 200°C~300°C were heated to the lower level by a resistance heating furnace. And the temperature would reach the higher level of the temperature range during friction process because of the generation of friction heat. The worn surface and wear debris were observed and analyzed by scanning electron microscope (SEM) and energy dispersive spectroscope (EDS). For subsurface observations, tested specimens of SiCp/A356 composites were cut along the sliding direction and metallographically polished.

3. Results and Discussion

3.1. Friction and Wear Behavior. The friction coefficient and temperature changing with sliding time during the wear test are shown in Figure 4. It can be seen that the temperature rises with the sliding time during the dry sliding process because of the generation friction heat. The friction coefficient decreases slowly with an increase in sliding time. Due to the external preheating with the resistance heating furnace, the temperature rises fast during the temperature range of 100°C~200°C and 200°C~300°C. The friction coefficient has great fluctuation for test under the temperature of 200°C~300°C.

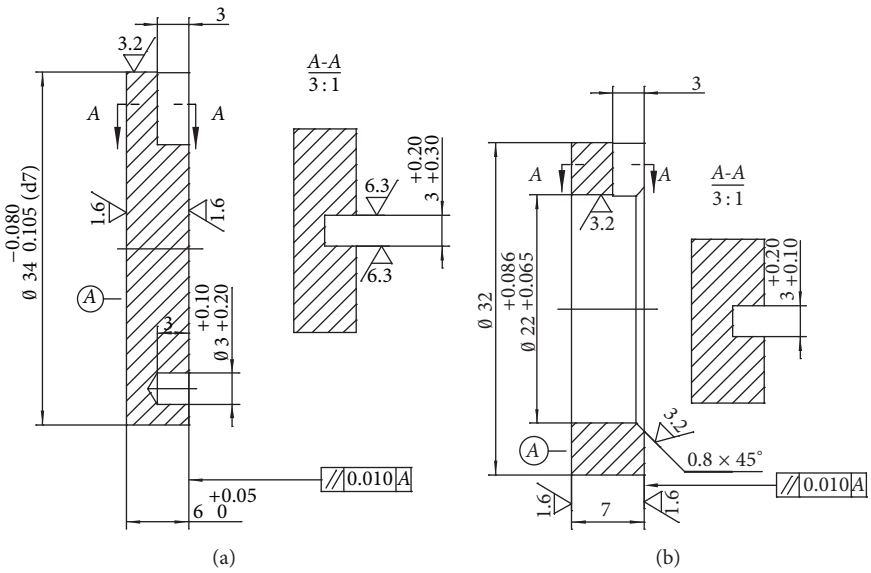


Figure 3: Dimensions of wear tests specimen: (a) disc and (b) ring.

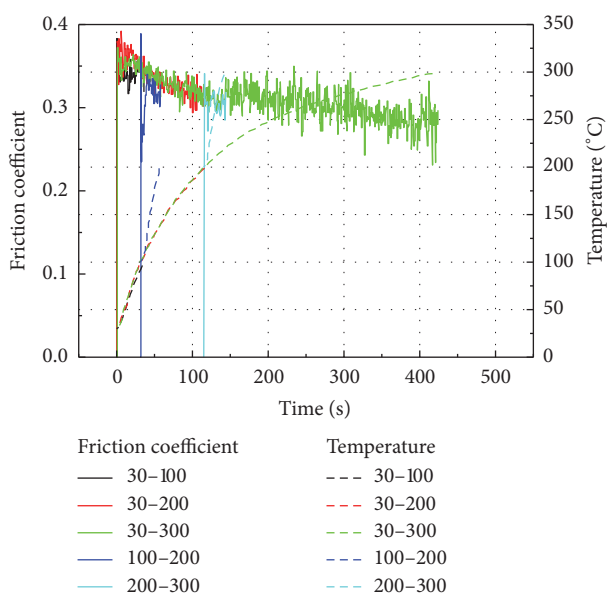


Figure 4: The friction coefficient and temperature change with the sliding time.

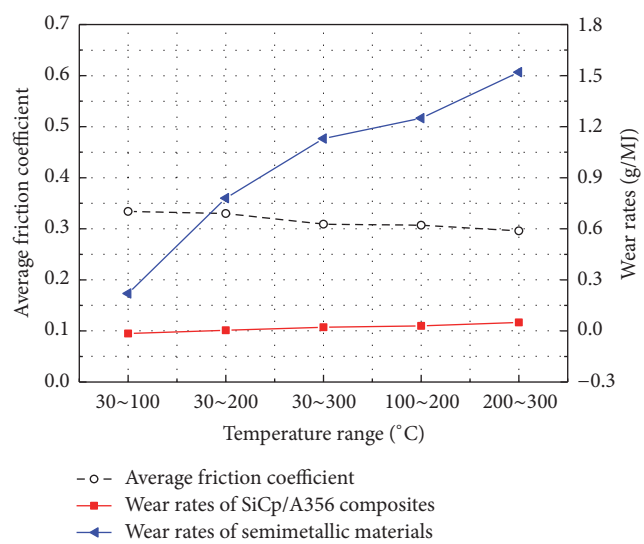
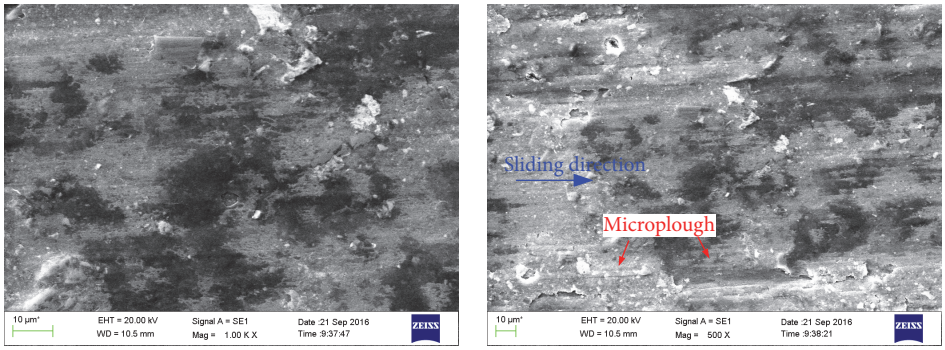


Figure 5: The average friction coefficient and wear rates for different temperature ranges.

Figure 5 shows the average friction coefficient and wear rates for five temperature levels. The average friction coefficient decreased slowly with the increase of temperature during the tests under temperature level of 30°C~100°C, 30°C~200°C, and 30°C~300°C. And the friction coefficient was higher in the test of 100°C~200°C, while the lowest friction coefficient appeared in the test of 200°C~300°C. However, the average friction coefficient was about 0.3 and showed little difference on the average value of the friction coefficient for five temperature levels. The largest difference was found to be 16.7%. It indicates that the SiCp/A356 composites have stable friction coefficient in the friction tests when coupling against a semimetallic material.

The wear rates of semimetallic materials increased obviously with the increase of temperature in the test of 30°C~100°C, 30°C~200°C, and 30°C~300°C. The highest value of wear rates was observed in the test of 200°C~300°C, which was 1.52 g/MJ. Wear rate in the test of 100°C~200°C was also higher. The wear rate in the test of 200°C~300°C was nearly seven times of 30°C~100°C, which was 0.22 g/MJ. The wear rates of SiCp/A356 composites increased with rising of temperature, but the fluctuation amplitude was very small. The highest value of the wear rate was 0.05 g/MJ, which occurred in the test of 200°C~300°C. It reveals that



(a) (b)

Figure 6: The worn surface topography of composites specimen for the test of 30°C~100°C: (a) 1000x and (b) 500x.

the temperature has almost no effect on the weight loss of SiCp/A356 composite.

The result shows that the temperature has important effect on the friction properties. The friction coefficient decreased slowly and became not smooth with the temperature rising. The wear rates have great increase with the temperature rising for the cumulative friction heat. There are lower friction coefficient and higher wear rates for the higher temperature.

3.2. Wear Mechanism. A layer of surface film was formed on the surface of the PRACs composite material in the dry sliding process due to the accumulation and compaction of transfer debris. The formation of this film could stable the friction coefficient and reduce the wear rate [25, 26]. Figures 6 and 7 show the worn surface and subsurface topography after dry sliding test under the temperature level of 30°C~100°C. It can be seen that there is a continuous layer of third body films (TBFs) which are 3~5 μm in thickness and continuously distributed. The TBFs are a composite of elements of Al, Si, Ca, Fe, C, O, Mg, and S. The elements of Al, Si, and Mg were mainly from the SiCp/A356 composites, while the elements of Ca, Fe, and S represented the transferring of the material from the semimetallic specimen. The elements C and O were transferred products of both SiCp/A356 composites and semimetallic materials.

The TBFs, also called tribolayers or mechanical mixed layers, are third body materials which are different from the two-body grinding materials. The TBFs could isolate the friction heat and bear the load [27]. The TBFs are composite of the materials of both SiCp/A356 composites and semimetallic materials, and the content of each material is determined by the hardness of each grinding material [28]. There was mild abrasive wear on the surface of TBFs for the test under the temperature level of 30°C~100°C. Figure 6 exhibits the traces of slight abrasive wear and microplough on the TBFs. Due to the existence of the TBFs on the surface of SiCp/A356 composites, the direct contact of two-body materials of SiCp/A356 composites and semimetallic materials can be avoided during dry sliding. Therefore, the TBFs can protect the surface of SiCp/A356 composites from wear and reduce the wear rates.

With the increase of temperature during the dry sliding process due to the friction heat, some damage appeared on the surface of TBFs. The integrity of the surface films was gradually destroyed and the TBFs became loose. With plenty of voids, adhesive pits appeared on the TBFs in the temperature range of 30°C~200°C. Microplough and delamination can also be seen in Figure 8.

The TBFs are made up of the SiCp/A356 composites and the semimetallic materials, which are mixed with the material such as the debris and accompanied by a variety of chemical reactions in the process of friction [6]. Figure 9 presents the element distribution of TBFs in position P1 of Figure 8(b) for the test under temperature range of 30°C~200°C. The surface of SiCp/A356 composites was exposed due to the delamination of TBFs and was damaged without the protection of TBFs. The TBFs contain the elements of Al, Si, and Mg, which come from SiCp/A356 composites. And the elements of Fe, Ca, Ba, and S in the TBFs were transferred from semimetallic materials. The elements of C and O cover all surfaces of specimens all the time.

The thermal expansion coefficient and performance degradation were different for the TBFs with the increase of temperature. As is shown in Figure 8(b), it leads to the formation of voids, the emergence of a variety of mild delamination and adhesion, and the wear with microplough at the same time. There was microcrack found on surface of TBFs, which could cause further damage of the TBFs when the cracks were connected with voids and adhesive pits. The friction coefficient reduced gradually with the rising temperature for the test of 30°C~200°C. The growth of wear rates of semimetallic materials was more than three times for the test of 30°C~200°C than of 30°C~100°C. The result of wear rates was due to the damage of the TBFs.

As is shown in Figures 10(a) and 10(b), severe wear appeared in the temperature range of 30°C~300°C and many grooves and adhesive pit have appeared in the worn surface. It can be seen from Figure 10 that a large number of surfaces of SiCp/A356 composites were exposed without coverage of TBFs. The existence of Al elements in Figure 10(d) proved the exposure of surface of SiCp/A356 composites. The existence of Fe elements which can be observed in Figure 10(c) is the evidence of the existence of transferred debris.

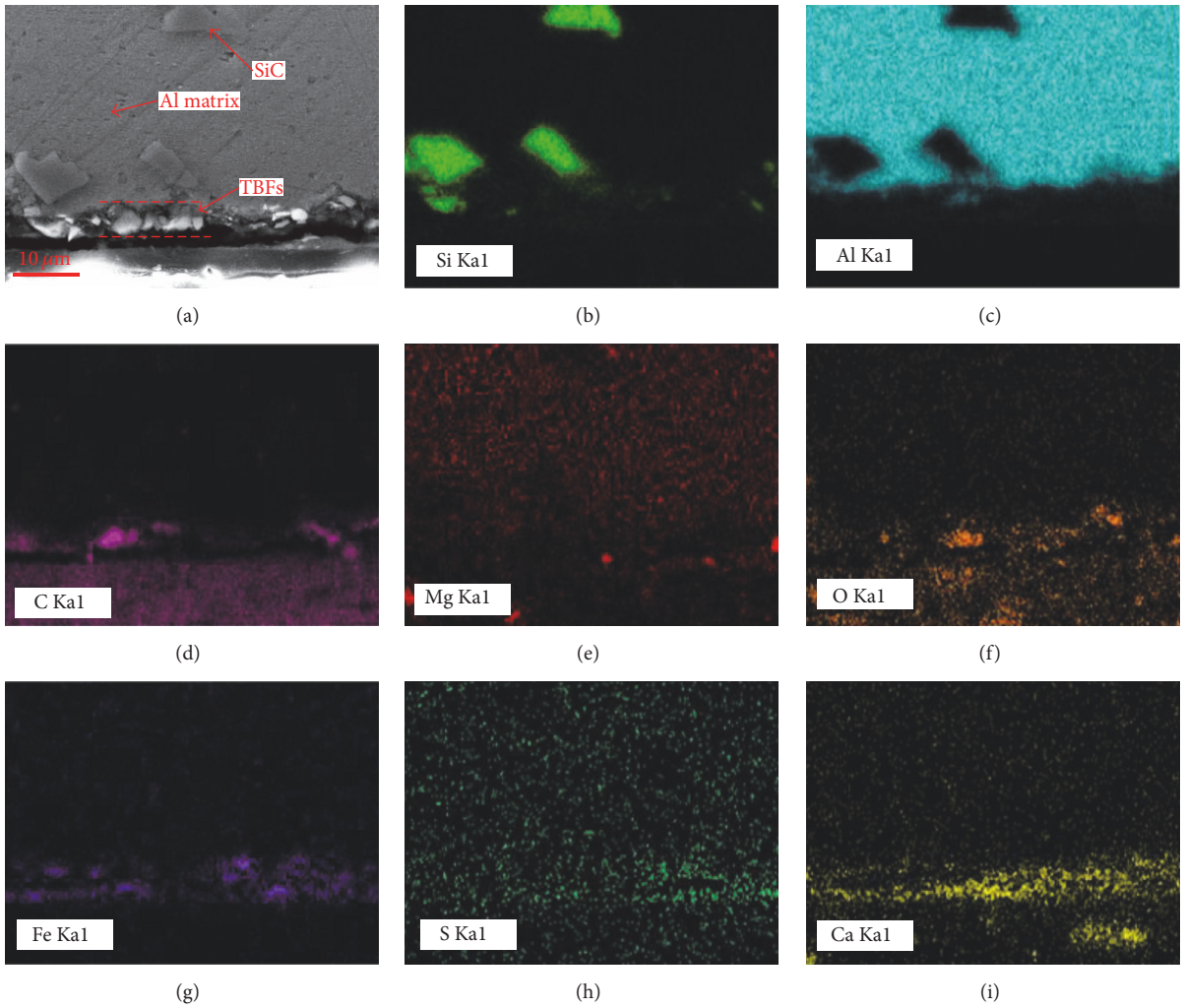


Figure 7: The subsurface topography and element distribution of composites specimen for the test of 30°C~100°C: (a) subsurface topography, (b) Si, (c) Al, (d) C, (e) Mg, (f) O, (g) Fe, (h) S, and (i) Ca.

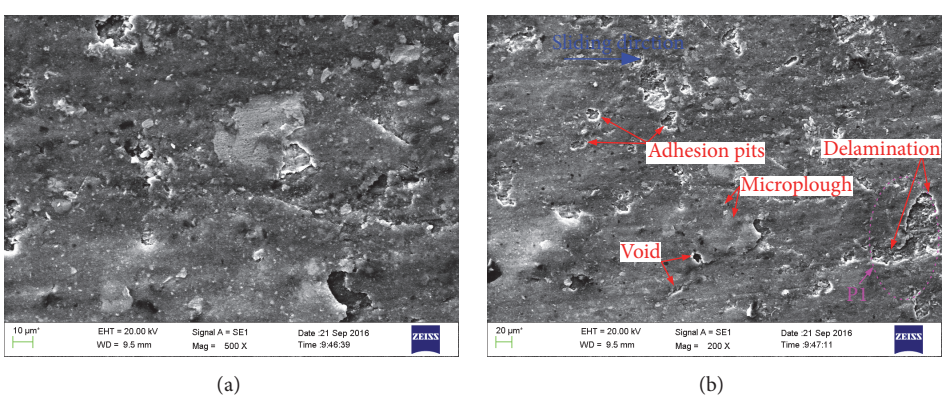


Figure 8: The worn surface topography of composites specimen for the test of 30°C~200°C: (a) 500x and (b) 200x.

When temperature reached 300°C, the continuous TBFs on the surface of SiCp/A356 composites were destroyed gradually. Then it was transformed into a status of discrete distribution, which reduced the load carrying capacity. Coupled with the effect of oxidation, delamination, and severe adhesion, the massive mechanically mixed particles (MMPs) which approximate spherical shape were produced under compressive force, which is as shown in Figure 11(a). The

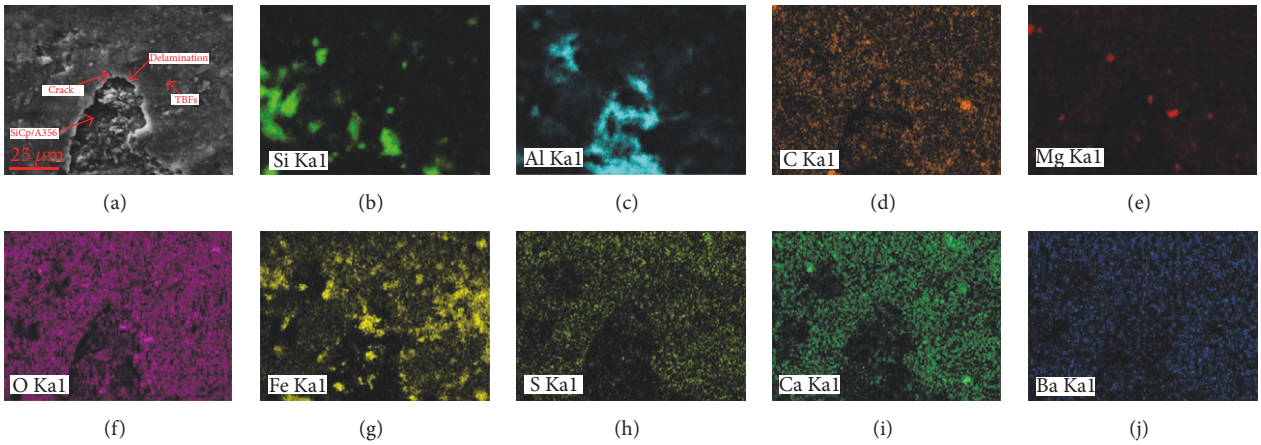


Figure 9: The surface topography and element distribution of position P1: (a) surface topography, (b) Si, (c) Al, (d) C, (e) Mg, (f) O, (g) Fe, (h) S, (i) Ca, and (j) Ba.

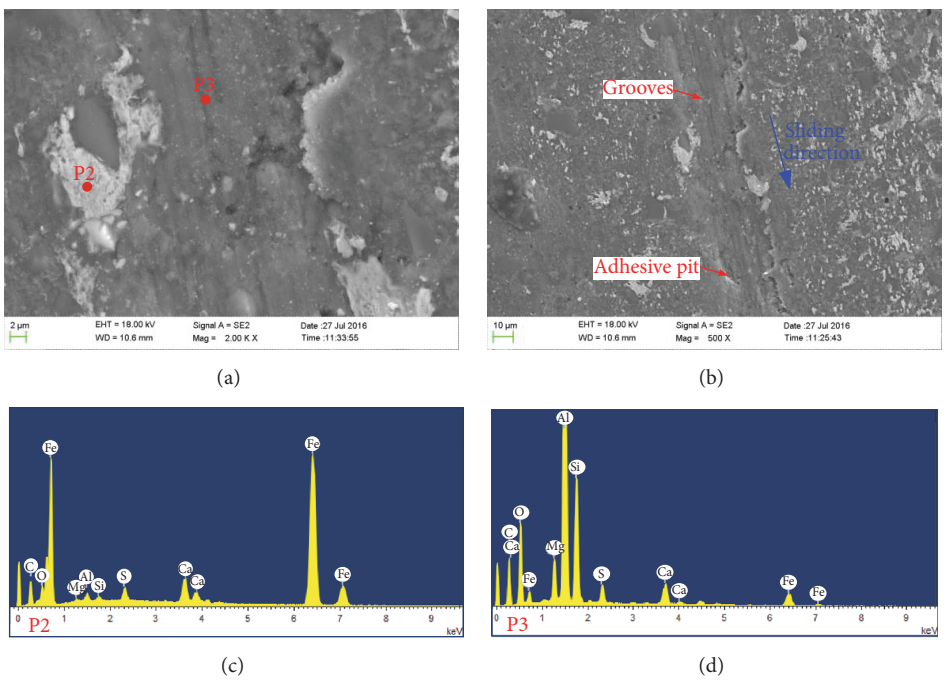


Figure 10: The surface topography and EDS of composites specimen for the test of 30°C~300°C: (a) 200x, (b) 500x, (c) EDS of position P2, and (d) EDS of position P3.

severe grooves on the friction surface proved that the spherical particles have higher hardness than grinding materials. It can be seen from Figures 11(b) and 11(c) that the hard MMPs contain the debris coming from both SiCp/A356 composites and semimetallic materials. The morphology of MMPs proved that the compacted materials consist of broken SiC particles and mixed materials transferred from the semimetallic materials and aluminum matrix and experienced complex mechanical and chemical effects and oxidation.

Hard MMPs formed at high temperature and scratched the friction surface constantly. The MMPs began to scratch the surface of SiCp/A356 composites after the TBFs had been destroyed, and then serious grooves formed on the SiCp/A356 composites surface. In addition, the performance degradation of SiCp/A356 composites and semimetallic materials at high temperatures exacerbate the formation of grooves [11, 12]. It leads to decrease in the friction coefficient and increase in wear rate under high temperature.

In the dry sliding process, the constant TBFs were produced and covered on the surface of SiCp/A356 composites. The TBFs protected SiCp/A356 composites from direct contact with the coupling friction materials. With the existence of TBFs, the friction coefficient was stable and the wear rate

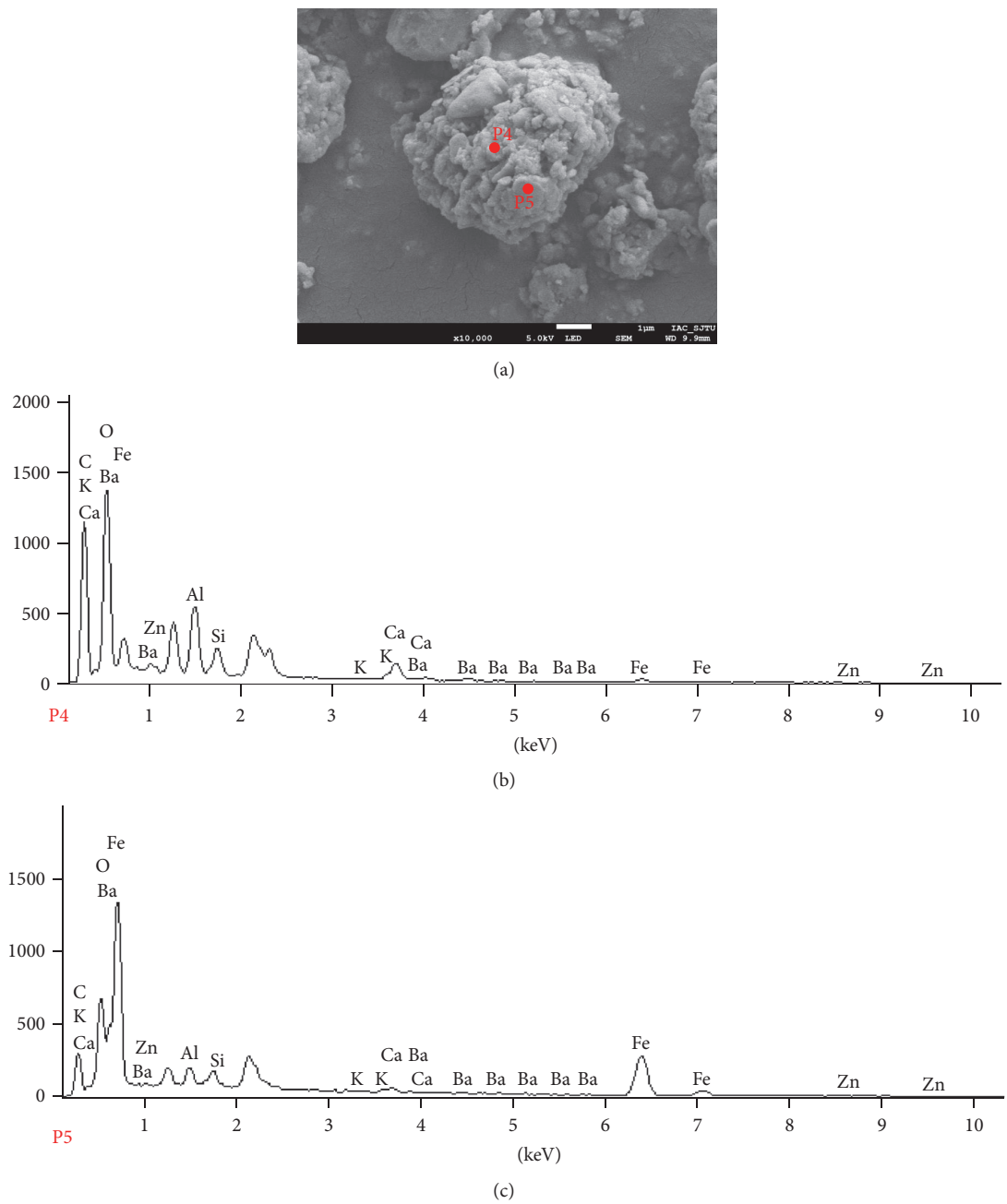
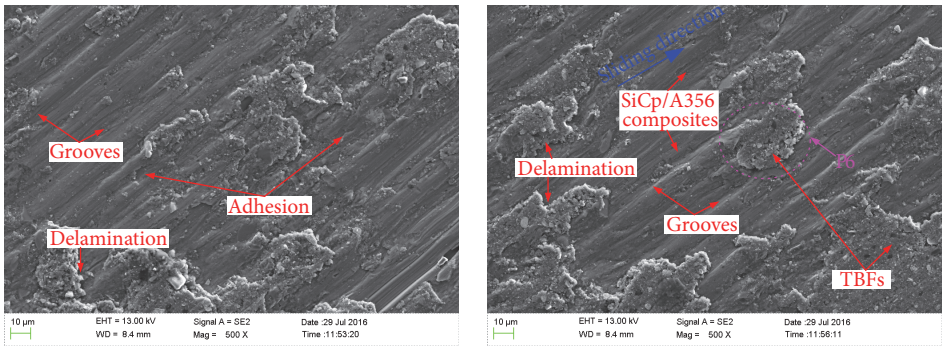


Figure 11: The wear debris and EDS of dry friction for the test of 30°C~300°C: (a) debris morphology, (b) EDS of position P4, and (c) EDS of position P5.

was lower. But the TBFs could be destroyed gradually with the rising temperature which is caused by cumulated friction heat. The surface of SiCp/A356 composites was exposed gradually and scratched by MMPs with higher hardness. The wear mechanism transferred from the third body films lubricated wear to the third body abrasive wear. It also turned out that the continuous TBFs have important effect on stabilizing the friction performance and extending wear life.

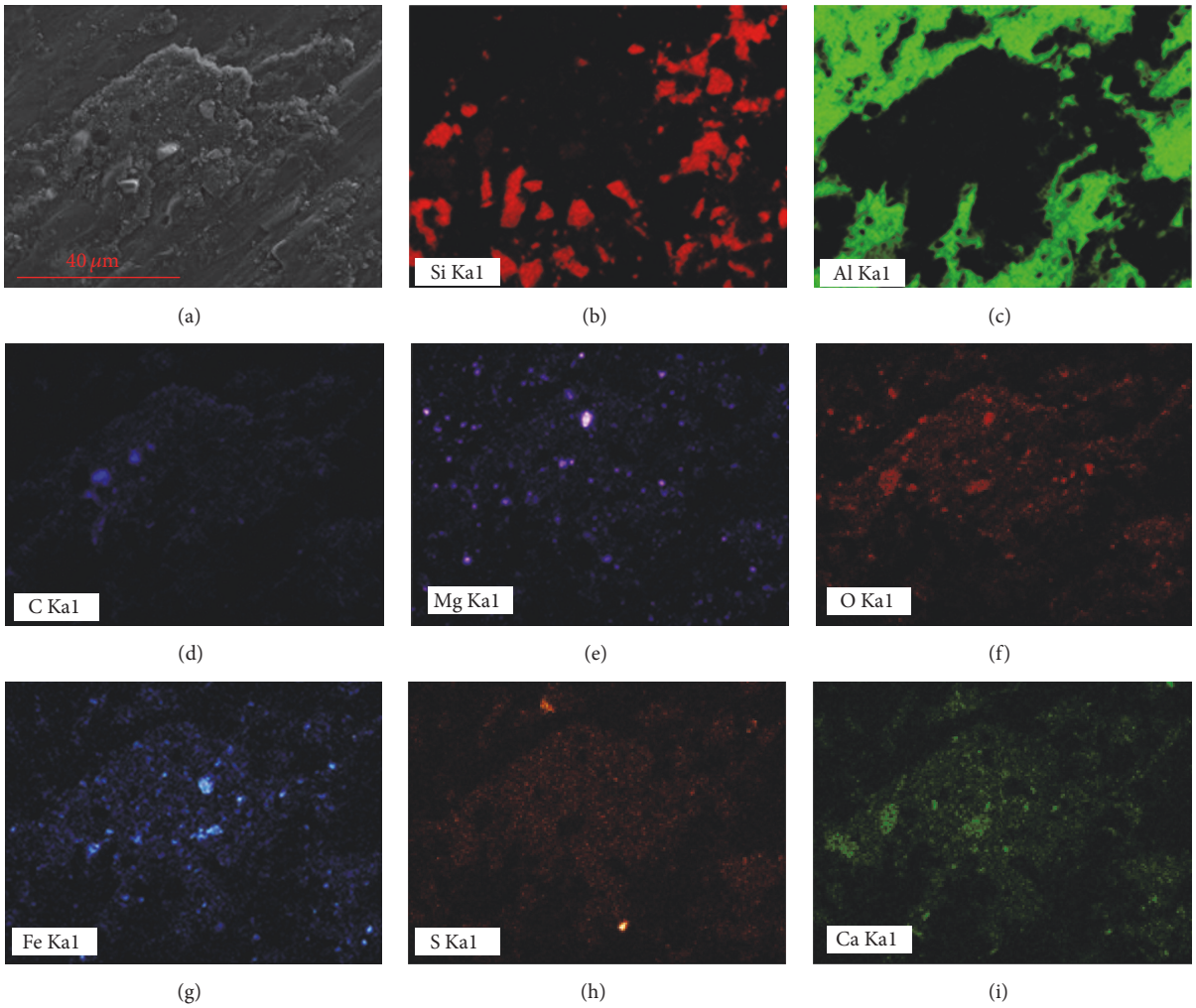
Figures 12 and 13 show the topography and element distribution at position P6 on the surface for the test at the temperature range of 100°C~200°C. Comparing with the test of 30°C~200°C shown in Figure 8, the TBFs at the temperature range of 100°C~200°C was discrete distributed, which have lower load capacity than continuous TBFs. The exposed surface worn against semimetallic materials directly and the hard MMPs scratched the surface of SiCp/A356 composites. Therefore, it led to serious grooves, delamination, and adhesion. The friction coefficient became fluctuated and wear rates of semimetallic materials were five times of 30°C~100°C.

The SiC particles were exposed and broken under the dry sliding test under the temperature level of 200°C~300°C.



(a) (b)

Figure 12: The surface topography of composites specimen for the test of 100°C~200°C: (a) 500x and (b) 500x.

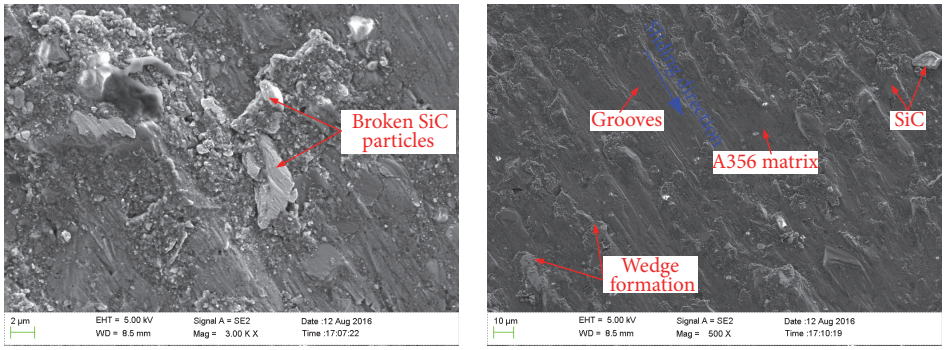


(a) (b) (c)

(d) (e) (f)

(g) (h) (i)

Figure 13: The surface element distribution of position P6 of composites specimen for the test of 100°C~200°C: (a) surface topography, (b) Si, (c) Al, (d) C, (e) Mg, (f) O, (g) Fe, (h) S, and (i) Ca.



(a) (b)

Figure 14: The surface topography of composites specimen for the test of 200°C~300°C: (a) 3000x and (b) 500x.

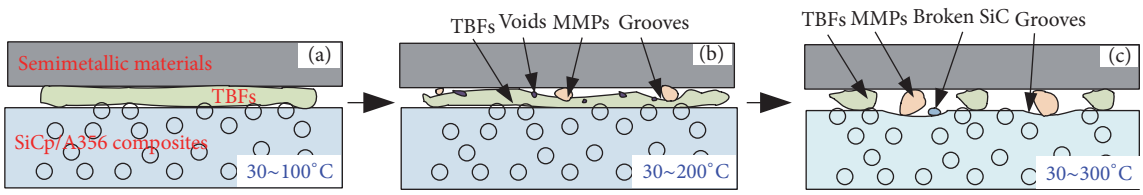


Figure 15: The transformation process of temperature effect on the surface third body films (TBFs) of dry friction: (a) 30°C~100°C, (b) 30°C~200°C, and (c) 30°C~300°C.

Thus, many severe wedge and grooves can be observed in Figure 14. The hard MMPs scratched the surface of SiCp/A356 composites without the protection of TBFs. The reinforced SiC particles burst out of the surface to prevent the MMPs from cutting the surface of composites. The reinforced SiC particles were broken under the constant load pressure and high temperature. It resulted in the unstable friction coefficient. And wear rates of semimetallic materials were nearly seven times higher than that of 30°C~100°C.

The analysis above revealed that the 200°C was a transition temperature. The continuous TBFs were destroyed and discrete distributed above 200°C. The hard MMPs scratched the SiCp/A356 composites above the transition temperature and the protecting effect of TBFs for the SiCp/A356 composites was weakened.

Figure 15 exhibits the effect of elevated temperature produced by friction heat on the wear mechanism and transformation process of TBFs during dry friction. A layer of continuous TBFs emerged after dry friction, which is shown in Figures 15(a) and 7. The TBFs could protect the SiCp/A356 composites from being worn directly and play an important role in the third body lubricated wear. With the temperature rising, the material properties of the TBFs were reduced. With plenty of voids, adhesive pits and slight grooves appeared, as is shown in Figures 15(b) and 8. A lot of mechanically mixed particles (MMPs) appeared and rubbed on the surface. The MMPs experienced slight adhesive, delamination, and abrasive wear in the temperature range of 30°C~200°C. With the continuous rising in friction temperature, the surface films were gradually destroyed and the abrasive was intensified. The protective effect of the TBFs was further reduced and resulted in scratch on the surface of SiCp/A356 composites. Then severe adhesive wear and abrasive wear can be seen in Figures 15(c) and 10.

The TBFs have important protection effect on the SiCp/A356 composites which can prevent or delay the severe abrasive wear. Although the friction heat could damage the TBFs, the surface morphology of SiCp/A356 composites has big difference whether there are TBFs before dry friction under high temperature or not, which can be displayed by comparing the surface morphology in Figures 8 and 12. The thickness and morphology of the surface films also affect the transition temperature.

4. Conclusions

The friction and wear behaviors of SiCp/A356 composites, which can be used for brake disc material for the train and automobile, were studied to analyze temperature effects on the wear mechanism, friction coefficient, and wear rates. It is necessary to have a better understanding in the influence of rising temperature on braking performance. The following conclusions can be drawn according to the discussion above.

(1) A beneficial layer of continuous third body films (TBFs) with thickness of 3–5 μm was generated on the surface of SiCp/A356 composite surface. TBFs can help to stabilize the friction coefficient below 200°C. TBFs are also useful to reduce the wear loss by protecting the friction surface of composites and isolating the high temperature.

(2) The massive hard mechanically mixed particles (MMPs) were produced above 100°C. MMPs consist of compacted materials containing broken SiC particles and

mixed materials which are transferred from the semimetallic materials and aluminum matrix. The MMPs could lead to deep grooves and severe adhesive pit on the surface of composite above 200°C. It is accompanied by decrease in friction coefficient and increase in wear rate.

(3) The transition temperature was found to be 200°C. The third body films lubricated wear transfers to the third body abrasive wear above 200°C. The supporting effect of particle changes to scratching the surface of composites because of broken and oxidation during the dry sliding process.

(4) The surface films could be gradually destroyed and discrete distributed and became thinner with the rising temperature. The wear mechanisms observed during friction test went through the third body lubricated wear in the test of 30°C~100°C and mild adhesive wear and slight abrasive wear at 100°C~200°C. The wear mechanisms transferred to the severe adhesive and abrasive wear in the temperature range of 200°C~300°C.

Conflicts of Interest

The authors declare that there are no conflicts of interests regarding the publication of this paper.

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