Wear behavior of as-cast and heat treated triple particle size SiC reinforced aluminum metal matrix composites

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Abstract

Purpose – The purpose of this paper is to study the wear behavior of as-cast (AC) and heat treated (HT) triple particle size (TPS) silicon carbide (SiC) reinforced aluminum alloy-based metal matrix composites (SiC_p/Al-MMC).

Design/methodology/approach – Al-MMCs were prepared using 20 vol.% SiC reinforcement into aluminum metal matrix and developed using a stir casting process. Stir casting is a primary process of composite production whereby the reinforcement ingredient material is incorporated into the molten metal by stirring. The TPS composite consist of SiC of three different sizes viz., coarse, intermediate, and fine. The solution heat treatment was done on AC composite at 540°C for 4 h followed by precipitation treatment. The wear test was carried out using a pin-on-disc type tribo-test machine under dry sliding condition. A mathematical analysis was also done for power factor values based on wear and friction results. The wear morphology of the damaged surface was also studied using optical microscope and scanning electron microscope (SEM) in this investigation.

Findings – The test results showed that HT composite exhibited better wear resistance properties compared to AC composite. It is anticipated that heat treatment could be an effective method of optimizing the wear resistance properties of the developed Al-MMC material.

Practical implications – This paper provides a way to enhance the wear behavior of automotive tribo-components such as brake rotor (disc and drum), brake pad, piston cylinder, etc.

Originality/value – This paper compares the wear behavior of AC and HT TPS reinforced Al-MMC material under dry sliding condition.

Keywords Heat treatment, Alloys, Composite materials, Wear, Wear resistance

Paper type Research paper

1. Introduction

Silicon carbide (SiC) reinforced aluminum metal matrix composite (Al-MMC) is a promising addition to the MMC family. The important characteristics of SiC_p Al-MMC are low specific gravity, high thermal conductance, and low corrosiveness. Moreover, these advanced materials have the potential performance to perform better under severe service conditions such as, higher speed and load which are increasingly being encountered in modern tribo-components. These features provide SiC_p Al-MMC for tribological application and replace cast iron material. Researchers are working to increase the wear resistance properties of Al-MMC (Kennedy *et al.*, 1997; Kwok and Lim, 1999).

Heat treatment plays an important role in controlling the wear and friction properties of a SiC reinforced composite material. The silicon combines chemically with impurity like Mg and form magnesium-silicide (Mg_2Si) and this compound, when finely dispersed by precipitation during heat treatment, is responsible for strengthening of the material with improved microstructure. This improved microstructure is responsible for improved wear resistance properties. Improvement in the properties upon heat treatment is mainly due to the size, shape, and distribution of Mg_2Si precipitate particles during ageing (Prasad and Ramesh, 2006). The presence of Mg, Cu, and Ni are also responsible for the formation of inter metallic compound which can modify eutectic structure. It has been reported that Mg is one of the most important element that confers strength, but its strengthening effect is fully observed only after heat treatment. Zongyi *et al.* (1991) found that in the case of wear of discontinuous SiC reinforced aluminum composites, as hardness is increased (by ageing at a given temperature) the abrasive wear rate is decreased.

Skolianos and Kiourtsidis (2002) studied the abrasive wear behavior of heat treated (HT) AA2024 SiC_p composites using a pin-on-disc technique. The composites were developed using compocasting and squeeze casting techniques for different volume fractions of the SiC particles. The composites were also tested in the peak-aged (PA) and over-aged (OA) aging conditions. They found that the wear resistant was improved with the increasing of SiC_p volume fraction in both the PA and OA aging condition. Straffelini *et al.* (1997) investigated the wear behavior of the 6061 Al-alloy reinforced with 20 vol.% Al_2O_3 particles under dry sliding against a tool steel counter face as a function of load and with reference to different values of the matrix hardness obtained by submitting the extruded composite to thermal and forging treatments. The results showed that extruded composite which was characterized by lower matrix hardness with the formation of mixed scale (iron oxide) protect the composite and hence reduced the wear rate. Lim *et al.* (1999) reported the tribological (friction and wear) properties of a

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group of aluminium alloy-based SiC particulate reinforced MMCs (Al-4.5Cu/SiC_p) which was manufactured using rheocasting process and compared with the materials was manufactured using powder metallurgy route. The amount of SiC particulates was kept at 13 vol.%. In general, at a sliding speed of 1 m/s and normal loads ranging from 30 to 70 N, the rate of wear increased with increasing applied normal load. More specifically, the rheocast samples exhibited better wear resistance properties at higher loads when compared to MMCs having the same composition but fabricated using the powder metallurgy route incorporating mechanical alloying.

Dwivedi (1994) has conducted research work on SiC_p reinforced Al-MMC for the tribological behavior with different volume fraction and it has been reported that no significant improvement was observed on the tribological properties when added more than 20 percent reinforcements.

No information is available in the literature on the comparative wear behavior study of as-cast (AC) and HT SiC reinforced Al-MMC with triple particle size (TPS) reinforcement. In this paper, a comparative study on the wear behavior of AC and HT SiC reinforced Al-MMC has been performed using a tribo-test machine under dry sliding condition with 20 wt.% of SiC reinforcement. The main objective of this paper is to develop the SiC_p reinforced Al-MMC with and without heat treatment and performs a study on the wear behavior in order to find out the improvement of wear resistance properties in HT composite. The wear morphology of the damaged surface was also studied using optical microscope and scanning electron microscope (SEM) in this investigation.

2. Materials and wear-test details

2.1 Materials

The aluminum alloy AA6061 was used as a matrix material for the development of composite. The chemical composition of the alloy can be found elsewhere (Maleque and Karim, 2008). The composite was developed in this study contained a total of 20 wt.% (5 percent fine, 5 percent intermediate, and 10 percent coarse) TPS SiC particles. The reinforcement combinations are represented in Table I.

The stir casting technique was chosen as it is frequently used for commercial manufacture of Al-MMC. Industrial maturity and low potential cost of the melting process are reasons which have made it cost effective process. The stir casting rig was similar to the stir caster designed by Naher *et al.* (2004). The aluminum alloy was initially placed inside a graphite crucible and heated up to 700°C in a resistance-heated furnace. The molten metal was transferred to a graphite crucible and SiC particles were added. This was then stirred using a vane operated at 200 rpm speed. To optimize uniform particle distribution into the melt, the stirring parameters were selected as follows: stirring time, 6 s; number of blades in the stirrer, four; stirrer speed, 200 rpm; blade angle, 45°. After stirring, the mixture was reheated at a temperature of 750°C. Finally, the developed composite was poured into a metallic mold and exposed for solidification to make wear test samples.

Table I Reinforcement and Al-alloy combination in the composites

Composite material	TPS SiC (wt.%)	Aluminum alloy (wt.%)
AC	20	80
HT	20	80

Full heat treatment, i.e. solution heat treatment, ageing/precipitation treatments were carried out on AC specimens. The annealing was carried out in a resistance heating muffle furnace at 540°C for 4 h and then the specimens were quenched in hot water at 60°C. After 15 min, they were removed and then after drying, they were kept in a freezer at -10°C for over night. The ageing or precipitation treatment was carried out at 180°C for 8 h. The heat treatment thermal cycle is shown Figure 1.

During heat treatment the material was heated into the single phase region (540°C) and held until the material forms a homogenous solid solution. During this stage, any existing particles are dissolved into the aluminum and a single phase is formed. Then quenching seizes the solute element in unstable condition. After freezing the material was heated to a temperature in the two-phase region (180°C) and holding for a period of time. Figure 2 shows the optical micrographs of AC and HT composites. The increased temperature (during aging) allows the alloying elements to move more quickly and form the second phase within the grains.

2.2 Wear and friction test

The wear test was carried out using a pin-on-disc type tribo-test machine at ambient room temperature under dry sliding condition. Figure 3 showed the photograph of the wear and friction test apparatus.

The pin material was prepared from a developed Al-MMC. The pin was 5 mm diameter and 14 mm height round specimen. High speed steel disc of Rockwell hardness R_C 60 was used as counterpart material. The disc was 160 mm diameter and 6 mm thickness. The sliding distance for each test was 0.6 km and total sliding distance for each pin sample was 3.6 km. The wear rate was calculated from the weight difference of the pin specimen before and after the wear test. The frictional force was measured using strain gauge and finally coefficient of friction was calculated using the equation: $\mu = R/F$. Here, μ is friction co efficient, R is reaction due to friction and F is applied load.

2.3 Wear morphology test

The optical microscope and SEM JEOL model-840A and SemaFore version 4.01 digital slow scan image recording software were used for image capturing and processing of the wear worn surface of both composites after wear test.

3. Results and discussion

3.1 Wear of AC and HT Al-MMC

Figure 4 represents wear comparison of AC and HT composite. It shows that wear of HT composites are fairly less than that of the AC composites tested under same test conditions (dry sliding condition; speed, 2 m/s; load, 29.4 N).

From Figure 4 it can be seen that wear improvement (in terms of less wear) from AC composite to HT composite was $\sim$35 percent. Due to heat treatment, the SiC elements showed some spheroidising, i.e. sharp corners have become rounded (Figure 2). The silicon combines chemically with Mg to form Mg_2Si and this compound, when finely dispersed by precipitation during heat treatment, is responsible for strengthening of the alloy. These strengthening increases wear protection capability.

Figure 1 Heat treatment thermal cycle

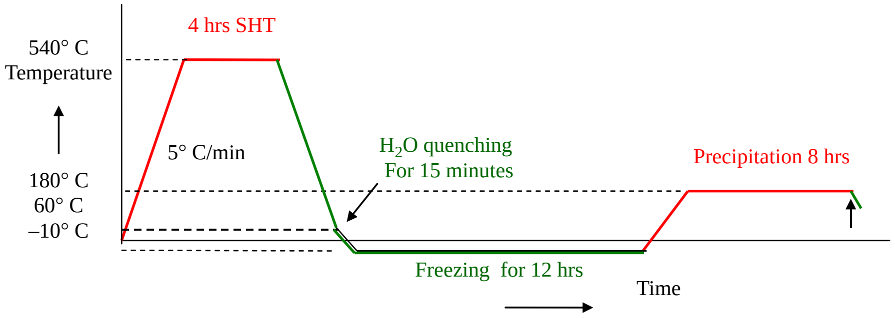


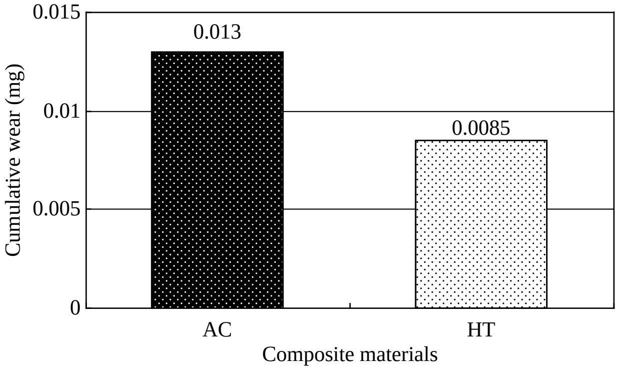
Figure 2 Microstructure of AC and HT Al-MMC using optical microscope at × 200


As cast specimen
Heat treated composite

Note: Reproduced from the only available original

Figure 3 Photograph of the wear and friction test apparatus

Figure 4 Cumulative wear (mg) of AC and HT composites tested under dry sliding condition; speed, 2 m/s; load, 3 kg



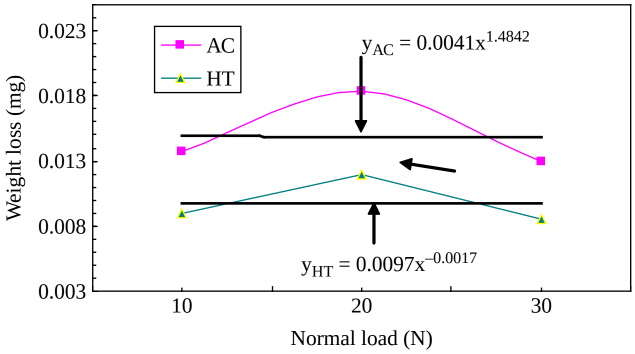
The Vickers hardness value (at 10 kgf) of AC material was 85 whereas for HT material was 103 which showed that HT composite exhibited almost 24 percent more hardness than that of AC composite. This increase in harness was also the reason for improving the wear resistance properties of HT composite.

3.2 Analysis of wear for AC and HT Al-MMC

Figure 5 represents wear at different normal loads of AC and HT composites tested under dry sliding condition; speed, 2 m/s and at different normal loads. Respective trend line has been shown as dark solid line. The trend lines are power based. Trend line equations also can be seen in the same figure.

It is observed that in general, wear (weight loss) of AC and HT composites increased with increasing load. Wear increment of HT TPS was less in compare to AC composite. At higher load HT TPS exhibited comparatively less wear.

Figure 5 Wear (mg) vs normal load (N) of AC and HT composites



In the trend line equation the co-factor value of x-variable indicates initial point of trend lines. According to geometric rule of parallel transfer of line both the trend lines on a plane can be transferred along Y-axis and geometrically their initial points can be coincided at one point. In such analysis the value of co-factor (C) indicates initial point of a wear trend line. Power factor (P) value indicates the increment or decrement order of a trend line. Mathematically, the composite with negative power factor value suppose to show maximum decreasing order of wear and the composite with positive power factor value suppose to show maximum increasing order of wear. The co-factor and power factor values of Figure 5 have been tabulated in Table II. The table represents a comparison of co-factor and power factor value of AC and HT composites material. From this table it is evident that HT TPS composite exhibited lower power factor value in compare to AC composite, hence at variable load the wear rate was lower.

Figure 6 represents wear with respect to sliding speed of AC and HT composites tested under dry sliding condition; normal load, 10 N; and at three different speeds. Respective trend lines have been shown as dark solid line. A general increase in wear with increase of sliding distance has been observed in Figure 6. At higher speed, HT TPS composite exhibited comparatively less wear. Wear increment for speed increment from 1 to 1.5 m/s was considerably higher for both composites whereas, wear increment for speed increment from 1.5 to 2 m/s was moderate.

The co-factor and power factor values of Figure 6 have been tabulated in Table III which represent the comparison of co-factor and power factor for two composites (AC and HT). From this table it is observed that HT composite exhibit higher power factor value in compare to AC composite.

Table IV shows the multiplication of the two power factors at variable load and speed for AC and HT composites. The respective values were extracted from Tables II and III. The multiplication values of $P1$ and $P2$ in Table IV shows the wear characteristics as a whole for a particular composite at different load and speed. HT composite exhibits lower multiplication value of $P1$ and $P2$. Hence, HT composite can be considered as better wear resistant material in compare to AC composite.

Table II Wear rate trend line equation, co-factor, and power factor values of AC and HT Al-MMC at different load

Composite material	Trend line equation	Co-factor value ($C1$)	Power factor value ($P1$)
AC	$y_{AC} = 0.0041x^{1.4842}$	0.0041	1.4842
HT	$y_{HT} = 0.0097x^{-0.0017}$	0.0097	− 0.0017

Figure 6 Wear (mg) vs sliding speed (m/s) of AC and HT composites

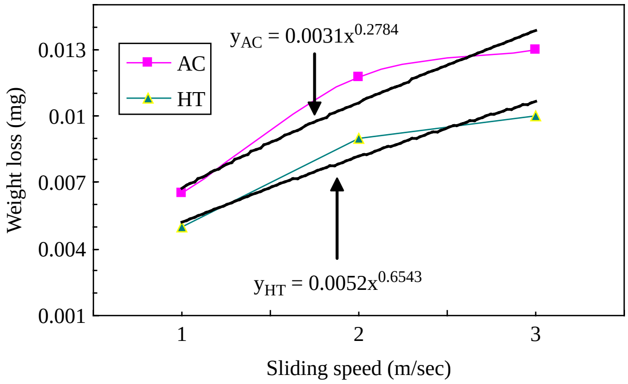


Table III Wear rate trend line equation, co-factor, and power factor values of AC and HT Al-MMC at different speed

Composite material	Trend line equation	Co-factor value ($C2$)	Power factor value ($P2$)
AC	$y_{AC} = 0.0031x^{0.2784}$	0.0031	0.2784
HT	$y_{HT} = 0.0052x^{0.6543}$	0.0052	0.6543

Table IV Multiplication of power factors at variable load and speed for AC and HT composites

Composite material	Power factor from Table III ($P1$)	Power factor from Table IV ($P2$)	Multiplication of $P1$ and $P2$
AC	1.4842	0.2784	0.413
HT	− 0.0017	0.6543	− 0.00111

3.3 Average co-efficient of friction of AC and HT Al-MMC

The average co-efficient of friction of both AC and HT composites tested under dry sliding condition at speed 2 m/s, total sliding distance 3.6 km (on six interval) and load 30 N represented in Figure 7. The average co-efficient of friction was measured from six tribo tests, each involved with 0.6 km sliding. The value of co-efficient of friction for AC and HT composites was 0.44 and 0.38, respectively. Between AC and HT composites, HT composite exhibited lower co-efficient of friction value in this investigation. This trend coincides with previous investigation (Chen *et al.*, 2000). It can be seen that heat treatment on SiC reinforced Al-MMC leads to a moderate rate of reduction in friction coefficient (~ 14 percent).

3.4 Analysis of co-efficient of friction for AC and HT Al-MMC

Co-efficient of friction vs sliding distance of AC and HT composites tested under dry sliding condition at a speed 2 m/s and normal load 30 N have been shown in Figure 8. Respective trend lines have been shown as dotted line.

Figure 7 Average co-efficient of friction of AC and HT composites after 3.6 km sliding at 2 m/s speed and 30 N normal load

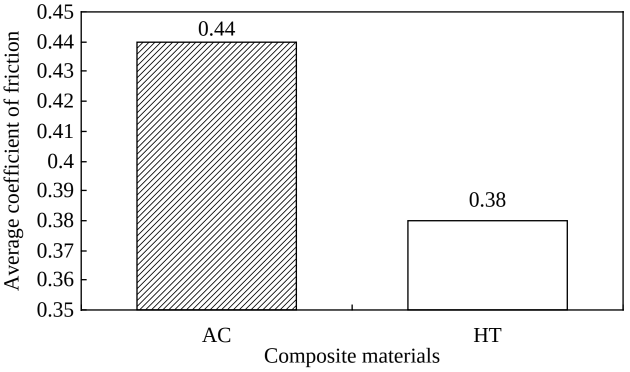
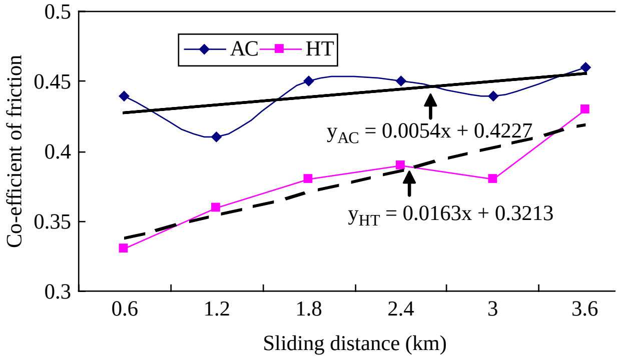


Figure 8 Co-efficient of friction vs sliding distance (km) of AC and HT composite



The trend lines are linear and shown in the same figure. It is observed that HT composite exhibited stable co-efficient of friction as compared to AC composite. Co-efficient of friction of AC composite initially decreases with increasing sliding distance followed by increasing trend, whereas in HT composite the trend was almost straight with slight increase in coefficient of friction. Slope and constant of trend line equations from Figure 8 have been tabulated in Table V.

For a certain composite, constant (*c*) indicates variation of friction force. Table V shows that the constant (*c*) is lower for HT composite material. Therefore, the average co-efficient of friction value of HT TPS composite showed lower than that of AC composite which was shown earlier in Figure 7.

3.5 Wear morphology

Figure 9 shows the worn surfaces of AC and HT composites after 3.6 km sliding. Worn surface of AC and HT composites showed dissimilar surface morphologies as shown in Figure 9. Sliding marks are observed on both composites. The AC composite sustains more damage due to wear (Figure 9(a) and (c)). The scar on the AC composite also shows areas with a compact transfer layer. It is not continuous rather randomly on the scar. The wear scar on the HT composite did not contain such a transfer layer (Figure 9(b) and (d)).

For the HT composite, abrasive wear has been found to be the main mechanism. Fine debris particles created in the wear process showed the evidence of micro cutting and ploughing on the surface. The wear mechanism depends upon the value of hardness of the materials (Czichos, 1989). Therefore, on the other hand, different wear mechanisms are observed in the AC composite. The presence of the transfer layer represents the occurrence of adhesive wear in the AC composite. Delamination and/or surface fatigue also occurs on the AC worn surface.

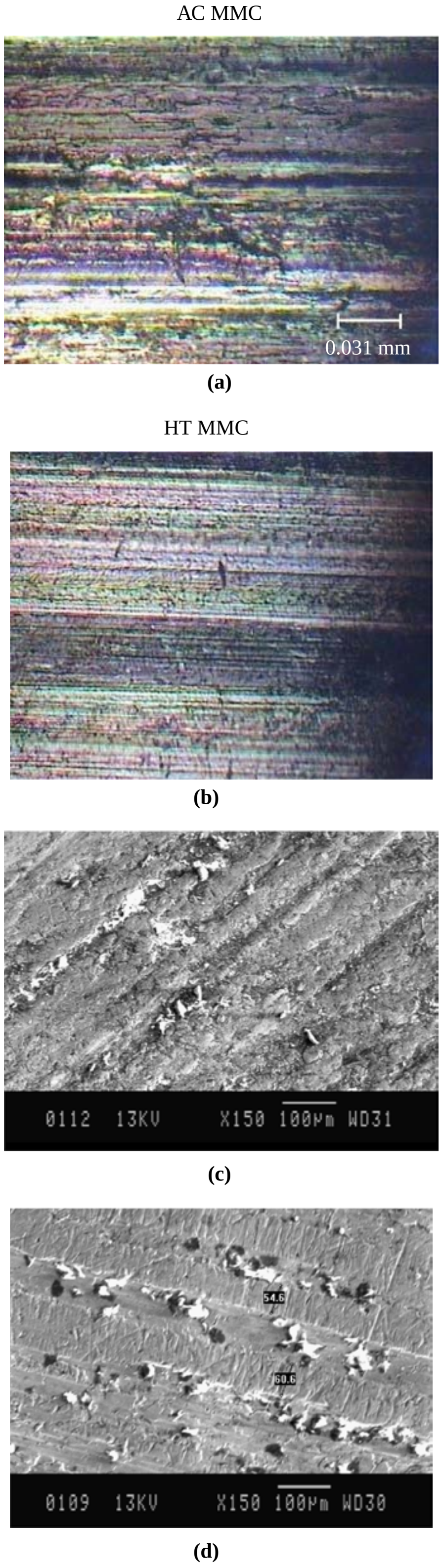
4. Conclusions

The wear behavior of AC and HT TPS SiC reinforced Al-MMC composite is studied for better understanding of the

Table V AC and HT Al-MMC's friction characteristic parameters

Composite material	Trend line equation	Slope (m)	Constant (*c*)
AC	$y_{AC} = 0.0054x + 0.4227$	0.0054	0.4227
HT	$y_{HT} = 0.0163x + 0.3213$	0.0163	0.3213

Figure 9 Wear worn surface micrographs of AC and HT composites after wear test: normal load, 30 N; sliding speed, 2 m/s; sliding distance, 3.6 km. First top two micrographs were taken using optical microscope at magnification of 100 × and bottom two were taken using SEM



effect of heat treatment on the AC composite. The wear of HT composite was found to be lower than AC composite. A general increase in wear with an increasing in sliding distance was observed for both AC and HT composites. It is anticipated that heat treatment could be an effective method of optimizing the wear resistance properties of the developed Al-MMC material. HT Al-MMC exhibited less friction coefficient in compare to AC composite. Experimental test results on wear and friction were supported by mathematical analysis on the wear and friction test results. For AC composite an adhesive type of wear with delamination was observed; on the other hand, for HT specimen abrasive type of wear mechanism was observed on the wear worn surface.

References

Chen, R., Iwabuchi, A. and Shimizu, T. (2000), "The effect of a T6 heat treatment on the fretting wear of a SiC particle-reinforced A356 aluminum alloy matrix composite", *Wear*, Vol. 238, pp. 110-9.

Czichos, H. (1989) in Loonis, N.R. (Ed.), *New Direction of Lubrication, Materials, Wear and Surface Interaction in Tribology in the 80's*, Noyes, Park Ridge, NJ.

Dwivedi, R. (1994), "Metal matrix composites", Society of Automotive Engineers, SAE/SP-94/1010, 400 Commonwealth Drive, Warrendale, PA, February, pp. 65-71.

Kennedy, F.E., Balbahadur, A.C. and Lashmore, D.S. (1997), "The friction and wear of Cu-based silicon carbide particulate metal matrix composites for brake applications", *Wear*, Vol. 203-204, pp. 715-21.

Kwok, J.K.M. and Lim, S.C. (1999), "High Speed tribological properties of some Al/SiC_p composites: II wear mechanisms", *Composites Science and Technology*, Vol. 59, pp. 65-75.

Lim, S.C., Gupta, M., Ren, L. and Kwok, J.K.M. (1999), "The tribological properties of Al-Cu/SiC_p metal-matrix composites fabricated using the rheocasting technique", *Journal of Materials Processing Technology*, Vol. 89-90, pp. 591-6.

Maleque, M.A. and Karim, M.R. (2008), "Tribological behavior of dual and triple particle size SiC_p reinforcement aluminum metal matrix composites – a comparative study", *International Journal of Industrial Lubrication and Tribology*, Vol. 60 No. 4, pp. 189-94.

Naher, S., Brabazon, D. and Looney, L. (2004), "Development and assessment of a quick quench stir caster design for the production of metal matrix composites", *Material Processing Technology*, Vol. 166, pp. 430-40.

Prasad, T.B. and Ramesh, C.S. (2006), "Effect of heat treatment on tribological characteristics of Al-Si alloy (as cast from scrap piston)", *Proceedings of International Conference on Manufacturing Science and Technology (ICOMAST), August 28-30, Melaka*, pp. 341-4.

Skolianos, S.M. and Kiourtsidis, G.E. (2002), "Wear behavior of artificially aged AA2024/40 μm SiC_p composites in comparison with conventionally wear resistant ferrous materials", *Wear*, Vol. 252, pp. 946-56.

Straffelini, G., Bonollo, F., Molinari, A. and Tiziani, A. (1997), "Influence of matrix hardness on the dry sliding behavior of 20 vol.% $Al_2O_3^-$ particulate-reinforced 6061 Al metal matrix composite", *Wear*, Vol. 211, pp. 192-7.

Zongyi, M., Jing, B., Yuxiong, L., Hongwei, S. and Yinuxuan, G. (1991), "Abrasive wear of discontinuous SiC reinforced aluminum alloy composites", *Wear*, Vol. 148, pp. 287-93.

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