Tribological behavior of dual and triple particle size SiC reinforced Al-MMCs: a comparative study

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Abstract

Purpose – The aim is to study the tribological behavior of dual particle size (DPS) and triple particle size (TPS) SiC reinforced aluminum alloy-based metal matrix composites – MMCs (Al/SiC$_p$ MMC).

Design/methodology/approach – Al-MMCs with DPS and TPS of SiC were prepared using 20 wt% SiC and developed using stir-casting process. The TPS composite consist of three different sizes of SiC and DPS composite consist of two different sizes of SiC. The tribological test was carried out using a pin-on-disc type tribo-test machine under dry sliding condition.

Findings – The TPS composite exhibited better wear resistance properties compared to DPS composite. It is anticipated that when a composite is integrated with small, intermediate and large SiC particle sizes (which is known as TPS) within the same composite could be an effective method of optimizing the wear resistance properties of the developed material.

Practical implications – This study provides a way to enhance the tribological behavior of automotive tribo-components such as brake rotor, piston, cylinder, etc.

Originality/value – This investigation compares the tribological behavior of DPS and TPS SiC reinforced aluminum MMCs.

Keywords Wear, Friction, Composite materials, Alloys

Paper type Research paper

1. Introduction

The use of light-weight materials for tribo-components in automotive engine or any other tribological applications can contribute significantly towards achieving reduced weight and energy consumption. Cast iron is a conventional material for tribo-component which is significantly massive due to its high-specific gravity. Kennedy *et al.* (1997) and Kwok and Lim (1999) worked to substitute cast iron with the aluminum composites for the application of tribological-components of automotive engine. The classic examples of these components include brake rotor, cylinder blocks, cylinder heads and pistons.

Skolianos and Kiourtsidis (2002) and Lim *et al.* (1999) have shown that aluminum alloy-based metal matrix composites (MMCs) with ceramic particulate reinforcement exhibited great promise for the substitution of cast iron. Al-MMC having lower density and higher thermal conductivity compared to conventionally used gray cast iron is expected to exhibit significant weight reduction. 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. Manufacturing process plays a big role in developing the light-weight material with effective cost and environmental factors. Many researchers found that among the various MMC manufacturing processes, stir-casting process is the most cost effective and widely used commercial manufacturing process (Torralba *et al.*, 2003; Seo and Kang, 1999; Yilmaz and Altintas, 1994).

Hunt and Herling (2003) reported that Al-MMC can be cost and performance competitive if the results of more recent development are considered for better tribo-characteristics. According to Unal and Mimaroglu (2003) in general, the specific wear rate is not influenced by the change in load. Hutchings (1994) observed the wear resistance behaviour study of Al-MMC with the particle volume fraction and particle size. He concluded that the wear resistance of MMCs containing fine SiC particles was significantly higher than that of MMCs with coarse SiC particles. The reason ascribed for this behavior was that for fine reinforcement, the response of the composite to deformation is comparatively more homogenous. Prabhakar *et al.* (2001) conducted research work on dual particle size (DPS) reinforced composite and compared with single particle size (SPS) reinforced composite. They found that the DPS composite exhibited better wear resistance compared to same volume fraction of SPS composite. This is because coarse particles play important role to shield fine particles during gauge action and they also bear the additional load. Yang (2003) and Shorowordi *et al.* (2004) examined the friction and wear behavior of SPS SiC-reinforced Al-MMCs. Purohit and Sagar (2001) have done research work on SPS reinforcement Al-MMC for the tribological behavior with 20 wt% reinforcement's material and found no significant improvement on the properties when added more than 20 wt% reinforcements.

No information is available in the literature on the tribological behavior of triple particle size (TPS) composite.

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In this paper, a comparative study on the tribological behavior of DPS and TPS SiC reinforced Al-MMC has been performed using a tribo-test machine under dry sliding condition and at constant speed and normal load with 20 wt% of SiC particle. The main objective of this paper is to develop the SiC_p reinforced Al-MMC and perform a comparative study on the tribological behaviour (wear and friction) of DPS and TPS composites in order to find out the better wear resistant material with appropriate combination of reinforcement particles in the matrix. The wear morphology of the damaged surface was also studied using scanning electron microscope (SEM) in this investigation.

2. Composite material and tribo-test details

2.1 Composite materials

The aluminum alloy AA6061 was used as a matrix material for the development of composite. The chemical composition of this alloy is shown in Table I.

The composite developed in this study contained a total of 20 wt% SiCp with two different combinations, viz. DPS and TPS. In the DPS composite, the average size of the SiC particles was 20 and 80 μm. In the first combination of DPS (designated by DPS1) there was 13 per cent coarse and 7 per cent fine SiC, whereas, in the second combination (designated by DPS2) there was 7 per cent fine and 13 per cent coarse SiC.

There is a size variation in coarse and fine particles. Therefore, it is necessary to create a correlation between fine and coarse particle to reduce the size variation and bear the average load. Incorporating an intermediate size particle, a new type of combination is formed which inclusion is termed as TPS. The average size of the SiC particle was 20, 40 and 80 μm. In this composite there were three combinations. In the first combination of TPS (designated by TPS1) consist of 5 per cent fine, 5 per cent coarse and 10 per cent intermediate SiC particles whereas, in the second combination (designated by TPS2) there were 10 per cent fine, 5 per cent coarse and 5 per cent intermediate SiC particles. In the third combination (designated by TPS3), there were 5 per cent fine, 10 per cent coarse and 5 per cent intermediate SiC particle. The reinforcement combinations are represented in Table II.

Table I Chemical composition of Al alloy AA6061

Element	Si	Fe	Cu	Mn	Mg	Zn	Cr	V	Ti	Al
wt%	0.65	0.25	0.25	0.03	0.89	0.01	0.07	0.01	0.02	Balance

Table II Reinforcement and Al alloy combination of DPS and TPS composites

Composite material	Fine (wt%)	Intermediate (wt%)	Coarse (wt%)	Aluminum alloy (wt%)
DPS1	7	0	13	80
DPS2	13	0	7	80
TPS1	5	10	5	80
TPS2	10	5	5	80
TPS3	5	5	10	80

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 some other 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, 4; 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 tribo-test pin samples.

2.2 Wear and friction test

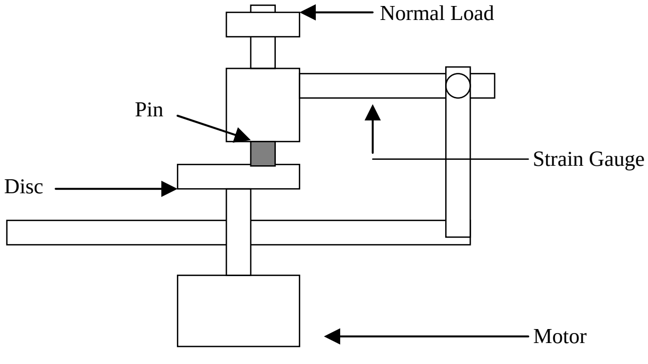
The tribological test was carried out using a pin-on-disc type tribo-test machine at ambient room temperature under dry sliding condition. Figure 1 shows schematic diagram of the test rig.

The pin material was prepared from a developed Al-MMC of DPS and TPS reinforcement. 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. All the tests were carried out at 29.4 N normal load and at a fixed sliding speed of 2 m/s. 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 coefficient, R is reaction due to friction and F is applied load.

2.3 Wear morphology test

The SEM was used to study the wear morphology of the damaged surface after wear and friction test. The JEOL model-840 A SEM and SemaFore version 4.01 digital slow scan image recording software were used for image capturing and processing of wear worn surface.

Figure 1 Schematic diagram of the wear and friction test rig



3. Results and discussion

3.1 Wear behavior of DPS and TPS Al-MMC

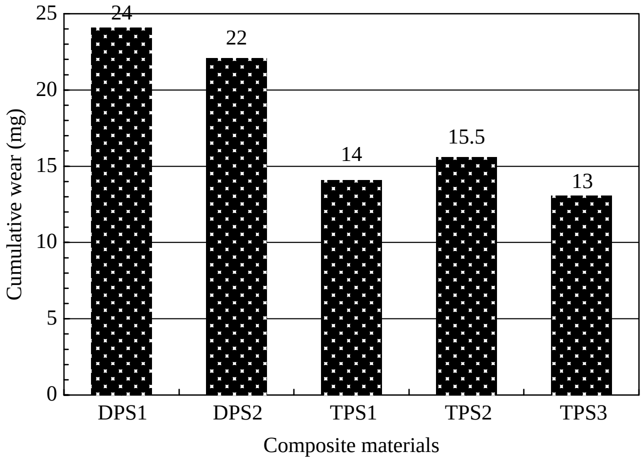
Figure 2 shows cumulative wear (in terms of weight loss) of DPS and TPS SiC_p reinforcement composite materials tested under dry sliding condition. It can be seen that the TPS composite, in generally, showed a fairly lower wear compared to DPS composite. The DPS2 which contains more fine particles exhibited lower wear (weight loss) compared to DPS1 which contains less fine particles. Among the three different types of TPS composites, the TPS3 showed least wear compared to other two combinations. It can be seen that inclusion of intermediate SiC particle in the TPS composite leads to a remarkable reduction in wear weight loss.

However, this inclusion into TPS forms a correlation between larger and smaller particles to reduce the impact of particle size variation between two reinforcements. Additionally, it plays an important role to fill up the gap of inter particle space which leads to reduce the porosity of the TPS composite (the porosity of TPS1 is 1.44 per cent) compared to DPS composite (the porosity of DPS1 is 5.44 per cent). At the same time, this inclusion could disseminate the load from coarser particles to intermediate to the smaller particles while shielding the finer particles. It can be explained using a hypothesis as shown in Figure 3.

Prabhakar *et al.* (2001) studied and found that the optimum wear rate significantly depends on proper shielding of base metal and fine particles. As shown in Figure 3, in the DPS composites, the larger SiC particles help to shield only the fine SiC particles and base metal. In TPS, base material and fine particles are shielded not only by coarse particles but by intermediate particles too. Additionally, intermediate particle and coarse particle provide combined shielding to the fine particle and base metal. Therefore, TPS exhibited less wear compared to DPS. In a meanwhile, TPS3 which contains 10 per cent coarse particles exhibited lowest wear rate among the three TPS composites. In general, the wear resistance of the SiC_p Al MMC can be improved over DPS by TPS reinforcement.

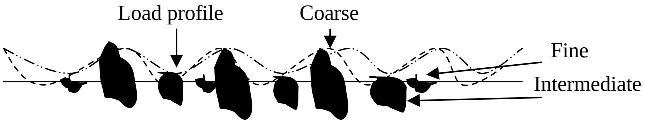
The wear rate vs sliding distance with trend line curve of developed composites (DPS and TPS) is shown in Figure 4.

Figure 2 Cumulative wear (mg) of developed Al matrix DPS and TPS composites tested under dry sliding condition

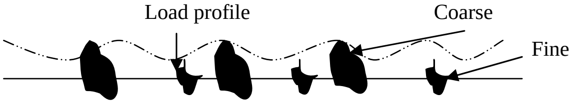


Notes: Speed, 2 m/s; load, 29.4 N

Figure 3 Hypothesis of dissemination of load in presence of intermediate particles inclusion

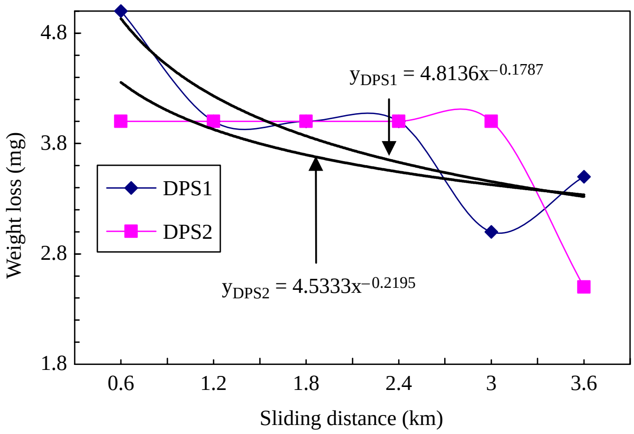


(a) TPS Composite with double shielding

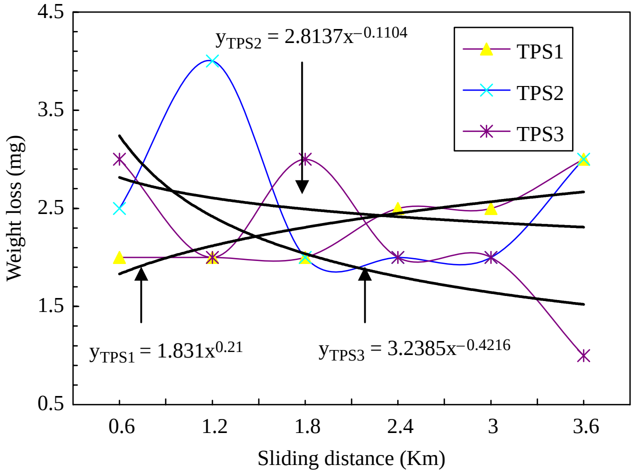


(b) DPS Composite with single shielding

Figure 4 Weight loss (mg) vs sliding distance (km) curve (with trend line) of composites tested under dry sliding condition



(a) Weight loss (mg) vs. sliding distance (km) of DPS composites



(b) Weight loss (mg) vs. sliding distance (km) of TPS composites

Notes: Speed, 2 m/s; load, 29.4 N

The trend line curve for both DPS1 and DPS2 are inclined and almost parallel. It can be seen that the wear rate of DPS2 is slightly lower than the wear rate of DPS1 composite. This is because the DPS2 contains more fine SiC_p (13 per cent) than DPS1 (7 per cent).

The wear rate vs sliding distance with trend line curve of TPS reinforced composites has been shown in Figure 4(b). Among the three TPS reinforced composite, the wear rate trend of TPS3 was lower than other two TPS composite. This is again showed that the TPS reduced the impact of particle size variation and disseminate the load from coarser particle to intermediate to the smaller particles via shielding mechanism. The co-factor (*C*) and power factor (*P*) for both trend lines have been shown in Table III.

The co-factor value shown in Table III indicates initial point of trend lines. According to geometric rule of parallel transfer of line all the trend lines can be transferred along *Y*-axis and geometrically their initial points can be coincided at one point. In this case the value of co-factor (*C*) is not significant to determine wear characteristics. Beyond co-factor value, the only variable exist in a trend line is power factor. Hence, the increment or decrement order of a trend line depends on power factor (*P*) value. The range of power factor is from -1 to $+1$. Mathematically, the composite with power factor value near to -1 suppose to show decreasing order wear rate and the composite with power factor value near to $+1$ suppose to show increasing order wear rate. DPS2 exhibit higher negative value of power factor in compare to that of DPS1, hence it exhibited better wear resistance as shown earlier in Figure 2 and 4. Similarly, the power factor for TPS3 was higher negative than those of TPS1 and TPS2 composites which also determined the better wear resistance of this composite. This result agreed well with earlier explanation.

3.2 Friction behavior of DPS and TPS Al-MMC

The average friction coefficient of all composite materials on 3.6 km sliding distance has been shown and compared graphically in Figure 5. The friction coefficient varies from minimum 0.44 to maximum 0.61. During the tribo-tests, all composite materials showed relatively rough sliding behavior, with a friction coefficient that varied significantly. These friction data are extracted as ±1 standard digression. The average friction was measured from six tribo-tests, each involved with 0.6 km sliding. TPS3 average friction coefficient is likely to remain within the industry standard range 0.3-0.45 for automotive brake system (Chapman *et al.*, 1999). Average friction coefficient values of all composites are very near.

The variation of average friction coefficient values among DPS1, DPS2, TPS1 and TPS2 are very small and is within 0.05. This result coincide with the findings of Bonollo *et al.* (1994) which describes, the presence of reinforcing particle does not change the coefficient of friction significantly compared with the unreinforced matrix. However, TPS3 composite exhibited exceptionally low-friction coefficient value compared to other composites. The reason attributed for such behavior can be splitting coarse particles into fine particles. Along with 5 per cent fine and 5 per cent intermediate reinforcement these additional fine particle increased presence of huge fine particles and formed a thin layer. This phenomenon is likely to be occurred only in TPS3 composite due to optimum reinforcement combination.

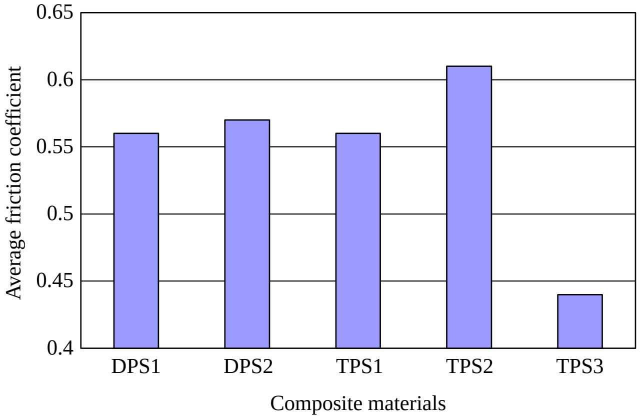
The friction coefficient curve with trend line of all composites represented as a function of sliding distance in Figure 6. Friction coefficient trend line of DPS1 and TPS3 are similar and almost parallel. This might be a reason both of them contains comparatively more amount of coarse particle (13 and 10 per cent).

TPS1 and TPS2, both composite contain 5 per cent coarse particle and their trend line also similar. It can be assumed coarse particle have significant influence to determine friction coefficient characteristics of a composite. DPS2 containing 13 per cent fine reinforcement exhibit negative trend line slope. The reason might be 13 per cent fine particle works as solid lubricant.

Table III Wear rate trend line equation, cofactor values and power factor extracted from Figure 4

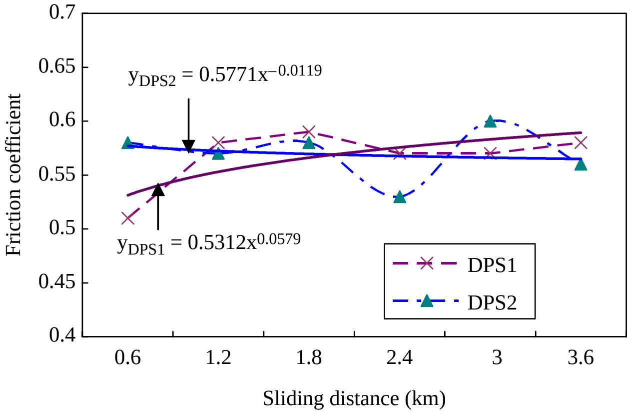
Composite material	Wear trend line equation	Co-factor value (*C*)	Power factor (*P*)
DPS1	$y = 4.8136x^{-0.1787}$	4.8136	-0.1787
DPS2	$y = 4.5333x^{-0.2195}$	4.5333	-0.2195
TPS1	$y = 1.831x^{0.21}$	1.831	0.21
TPS2	$y = 2.8137x^{-0.1104}$	2.8137	-0.1104
TPS3	$y = 3.2385x^{-0.4216}$	3.2385	-0.4216

Figure 5 Average friction coefficient of various MMCs tested under dry sliding condition

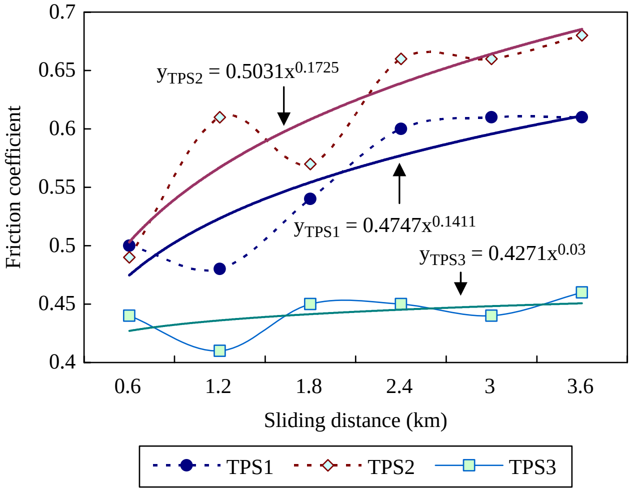


Notes: Speed, 2 m/s; load, 29.4 N

Figure 6 Friction coefficient vs sliding distance of composites tested under dry sliding condition



(a) Friction coefficient vs. sliding distance curve (with trend line) of DPS composites.



(b) Friction coefficient vs. sliding distance curve (with trend line) of TPS composites

Notes: Speed, 2 m/s; load, 29.4 N with trend line (power based)

The co-factor value shown in Table IV indicates initial point of trend lines. According geometric rule of parallel transfer of line all the trend lines can be transferred along *Y*-axis and geometrically their initial points can be coincided at one point. In this case the value of co-factor (*C*) is not significant to determine friction characteristics. Moreover, the co-factor values of all composites vary from 0.427 to 0.577 which indicates its less importance to determine friction characteristic. Beyond co-factor value, the only variable exist in a trend line is power factor. Hence, the increment or decrement order of a trend line depends on power factor (*P*) value. The range of power factor is from -1 to $+1$. As shown in Table IV, only DPS2 exhibit negative power factor value. The reason attributed for such behavior is existence of 13 per cent fine particles in DPS2 composite. Except DPS2, TPS3 exhibit smallest positive value of power factor among other four types of composite. The reason attributed for such behavior can be optimum combination of different size reinforcement combination. Thorough out long life cycle its change of coefficient friction, thus rupture likely to be less in compare to other composites.

3.3 Wear morphology of DPS and TPS Al-MMC

Figure 7 showed the SEM micrograph of wear worn surface of 20 wt% SiC_p reinforced DPS and TPS Al-MMC pin specimens after tribo-test. In Figure 7, DPS1 showed a fairly rough surface with many cracks while DPS2 showed a relatively smoother appearance with less number of cracks. It can also be seen that the DPS1 exhibited ploughing while DPS2 showed grooving. DPS2 composite, which contains comparatively more quantity of fine reinforcement, seems to be less wear damage compared to DPS1. Quantitative analysis of wear between DPS1 and DPS2 (Figure 2) also showed similar trend.

TPS1 composite material exhibited abrasion with few cracks while TPS2 composite exhibited deep grooving with less crack. TPS2 composite, which contains comparatively more quantity of fine reinforcement, showed less wear damage. Wear worn surface of TPS3 composite seems to be better than TPS2 due to the mild abrasive wear and minimum cracks. This TPS3 composite showed soother appearance as the SiC particles distribution is more homogeneous compared to other composites. TPS3 exhibit abrasive wear with very few cracks.

4. Conclusions

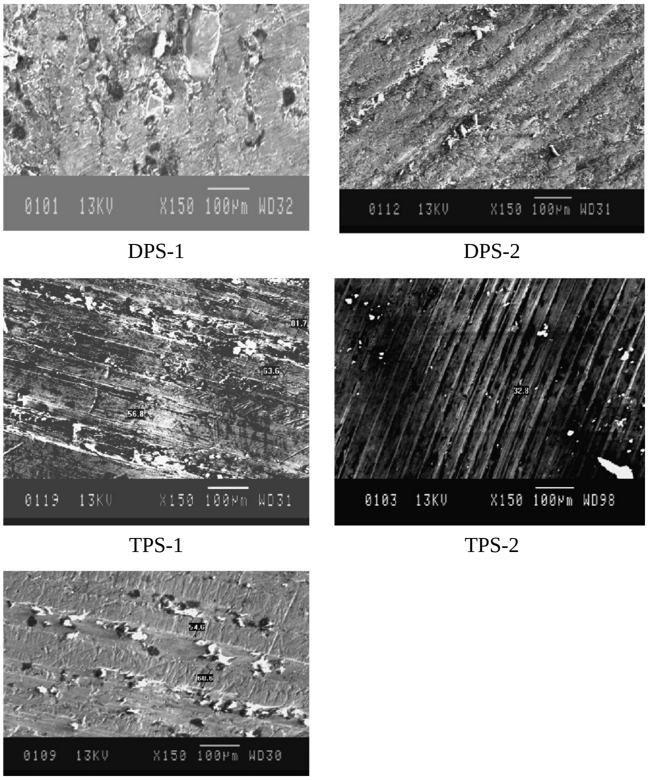
The tribological behaviour of DPS and TPS SiC reinforced Al-MMC is studied for better understanding of wear and friction of DPS and TPS composites. Both quantitative and qualitative tests results of wear showed that the TPS composite is better than DPS composite. It is anticipated that when a composite is integrated with small, intermediate and large SiC particle sizes (which is known as TPS) within the same composite could be an effective method of optimizing the wear resistance properties of the developed material.

The average friction coefficient results due to particle size variations (reinforcement combinations of DPS and TPS) are almost similar except TPS3 composite. However, the TPS3 composite showed very low-friction coefficient value compared to other composites. Wear worn surface of TPS3 composite seems to be better than TPS2 due to the mild abrasive wear and minimum cracks.

Table IV Friction coefficient trend line equation, co-factor and power factor extracted from Figure 6

Composite material	Friction coefficient trend line equation	Co-factor value (*C*)	Power factor (*P*)
DPS2	$y = 0.5771x^{-0.0119}$	0.5771	-0.0119
TPS3	$y = 0.4271x^{0.03}$	0.4271	0.03
DPS1	$y = 0.5312x^{0.0579}$	0.5312	0.0579
TPS1	$y = 0.4747x^{0.1411}$	0.4747	0.1411
TPS2	$y = 0.5031x^{0.1725}$	0.5031	0.1725

Figure 7 SEM micrograph of wear worn surface of 20 wt% SiC_p reinforced Al-MMC pin specimens tested under dry sliding condition



DPS-1 DPS-2

TPS-1 TPS-2

TPS-3

Notes: Speed, 2 m/s; load, 29.4 N

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