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Sliding Wear Properties of Hybrid Aluminium Composite Reinforced by Particles of Palm Shell Activated Carbon and Slag

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Abstract

In present work, dry sliding wear tests were conducted on hybrid composite reinforced with natural carbon based particles such as palm shell activated carbon (PSAC) and slag. Hybrid composites containing 5 -20 wt.% of both reinforcements with average particles sizes about 125µm were prepared by conventional powder metallurgy technique, which involves the steps of mixing, compacting and sintering. Dry sliding experiments were conducted in air at room temperature using a pin-on-disc self-built attach to polisher machine. The disc which acted as the mating surface material was made of mild steel (120 HV) cut from commercial mild steel sheet (2 mm thickness) into 100mm diameter. The influence of the applied load was investigated under a constant sliding velocity of 0.1m/s with the applied loads at 3N, 11N and 51N. The contribution of the reinforcement content and the applied load as well as the sliding distance on the wear process and the wear rate have been investigated. The contribution of synergic factors such as applied load, sliding distance and reinforcement content (wt.%) have been studied using analysis of variance (ANOVA). All synergic factors contribute to the wear process of all tested composites. Among synergic factors, the applied load is the highest contribution to wear process on both composites (Al/PSAC and Al/Slag) and hybrid composite. The degree of improvement of wear resistance of hybrid composite is strongly dependent on the reinforcement content.

Keywords: Wear; Powder Metallurgy; Aluminium; Hybrid Composite;Reinforcement

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1 INTRODUCTION

Tribological properties of such materials depend on the matrix and the reinforcement phase, as well as the size, shape and concentration of the reinforcement particles. The main problem is optimization of the microstructure for the best tribological performance. This task is complicated and requires theoretical analysis. Apart from hard reinforcement particle in soft matrix composite, soft reinforcement particles in hard and strong matrix composites are widely used in sliding bearing applications. They possess low coefficient of friction and adapts to diverse operational conditions [1].

Alexeyev and Jahanmir (1993) have attempted to develop self lubrication theory based on quantitative analysis. Slip-line field analysis of plastic deformation was used to analyze the processes of deformation and flow of the soft phase toward the sliding surface. They found a general relationship for deformation and flow of soft phase. It was shown that the properties of hard matrix and soft reinforcement particles, as well as the shape and size of the particles, control the processes of deformation and flow of the soft phase. Solid lubrication was introduced from the solid lubricant cavities (reservoirs) dispersed within the material. These cavities are typically filled with graphite, MoS2 or soft metal such as Pb, Sn or Ag. The solid lubricant particles deformed by the sliding action of the mating surface and are squeezed out towards the surface, forming a soft interfacial film [1].

The presence of this film is believed to be responsible for the decreasing friction and wear. When the solid lubricant film is worn away, the resulting increase in friction accentuates plastic deformation of the surface layer and forces more material from second-phase particles towards the surface, thus re-forming the worn film. The beneficial effect of self-lubrication depends on the thickness of the film, the relative plastic properties of the film and the sub layer, and the pressure experienced by the soft film and sub layer [2]. There is very few studies have been done on the processes of film formation and destruction [3], [4]. The exact mechanism for the adhesion of the film and substrate remain unclear.

In order to understand the tribological behaviour of metal matrix self-lubricating composite, the basic mechanism of the formation of lubricating films must be developed. The early studies of wear behaviour on self-lubricating aluminium composite using graphite as solid lubricant have been done by several researchers [5]-[7]. However, study on the formation of lubricating film at worn and mating surface are did not discussed thoroughly until Liu et al. (1992). He attempted to describe the smearing process of the embedded graphite particles in aluminium 2014 alloy during sliding in great details based on qualitative analysis by optical microscope. They found that the reduction in friction and wear of the aluminium-graphite composites is resulted of the embedded graphite particles during sliding, forming a lubricating film on both the tribosurface of the composite and the steel mating surface.

Whereas, Alexeyev and Jahanmir (1993b) attempted to describe the process of film formation in self-lubricating composites and deformation of the film based on the quantitative analysis by the slip-line field method. Their results indicated that the size of second-phase particles in the composite, the relative shear yield limits of the matrix and the soft phase, and the thickness of the film controls the tribological performance of these composites [1].

Lin et al. (1998) studied the process and tribological behaviour of Al6061/graphite particulate composite. They found that the tribological behaviour of the composite depends on the hardness of the matrix, the rate of release graphite particulates, the structure of the solid lubricating film deposited on the wearing material, and the structure of Al chip clusters [8].

Recently, Goto and Uchijo (2005) attempted to clarify the wear mechanism of Al-Si alloy impregnated graphite composite under dry sliding. They used the composite containing a large amount of graphite (56 vol. %). They found that the composite has good self-lubricating performance in the moist air under dry sliding. The compacted films consisting of graphite and metallic wear particles are formed on the disk sliding surface due to smearing particles. The films prevent the sliding surfaces from metal-to-metal contact. A pin-lifting phenomenon is observed in the early stage. The entrance of wear particles onto the contact surfaces causes the pin lifting, leading to an apparent decrease in wear [9].

Based on literatures, there are some research focuses on the role of soft reinforcement particle in hybrid composite. The soft reinforcement likes graphite and carbon fibre, whereas the hard material likes Saffil fibre in hybrid composite. Gurcan and Baker (1995) found that the hybrid composite 11% Saffil/20% SiCp/AA6061 and the composite 60% SiCp/AA6061 showed the best performance in wear resistance after testing against P400 SiC grit adhesive bonded paper. When tested against BS817M40 (EN24) steel, only small improvements were noted for 11% Saffil/AA6061 and 20% SiC/AA6061. However, hybrid composite 11% Saffil/20% SiCp/AA6061 and the composite 60% SiCp/AA6061 recording low wear rates [10].

Riahi and Alpas (2001) found that the hybrid composites of A356 Al-10% SiC-4% Gr and A356 Al-5% Al2O3-3% Gr showed more stable tribo-layers on the contact surfaces of the graphitic composites compared to non-graphitic composites and the A356 Al alloy. The graphitic composites showed higher load and speed transition from mild-to-severe wear compared to non-graphitic composites and the A356 Al alloy. However, the hard constituents in the tribo-layers were the scuffing damage that they inflicted on the counterface [11].

Fu et al. (2004) found that the hybrid composite of aluminium containing Saffil/SiC showed the better wear resistance under dry sliding at high temperature and high load compared to Saffil/Al and Saffil/ Al2O3/Al. The dominant wear mechanism was abrasive wear under mild load and room temperature, and the dominant wear change to adhesive wear as load or temperature increased. However, under lubricated condition, Saffil/Al showed the best wear resistance among them. The dominant wear mechanism of the composites was micro-ploughing but micro-cracking also occurred to them to different extents [12].

Jun et al. (2004) found that the hybrid composite of Al-12Si alloy reinforced with 12 vol. % Al2O3 showed a critical transition load from mild wear to severe wear improved to the range between 196 and 245 from 147 to 196 N for the monolithic Al-12Si alloy. Moreover, the addition of 4 vol. % carbon short fibre in the 12 vol. % Al2O3/ Al-12Si composites enhanced the further the critical transition load to the range between 245 and 294 N. Carbon fibre was more efficient in improving wear resistance of the hybrid composites at high applied load. Analysis of worn surfaces and subsurface regions indicated that the fibres had no significant effect on wear mechanisms of Al-12Si alloy. When applied load is below the critical load, dominant wear mechanisms were ploughing grooves and delamination. The unpeeling delamination layer was damaged and the dominant wear mechanisms shifted to severe wear when applied load exceeds the critical load [13].

In another report, Hui et al. (2004) found that the hybrid composite of 12 vol.% Al2O3/ Al-12Si containing carbon fibres attained superior wear resistance over entire range of test temperatures. The critical transition temperature from mild wear to severe wear of the composites reinforced with only 12 vol. % Al2O3 fibre improved to the range between 250-300 and

150-200 0C for the monolithic aluminium alloy. But, the critical transition temperature of the hybrid composites reinforced with Al2O3 and carbon fibres improved further to the range between 350 and 400 0C. The wear rate of the hybrid composite 12 vol.% Al2O3/ Al-12Si decreased with the increase of carbon fibre volume fraction up to 6 vol. %. Analysis of worn surfaces and subsurface regions indicated that reinforcing fibres have no significant effect on wear mechanisms of Al-12Si alloy. The dominant wear mechanisms shifted to severe adhesion at test temperatures above the critical transition temperature [14].

Basavarajappa et al.(2007) found that the hybrid composite of Al 2219 alloy containing 15SiCp and 3 graphite showed less degree of subsurface deformation in comparison Al 2219/15SiCp non-graphitic composite. They found that the subsurface deformation was increased with increasing sliding speeds in the mild wear region. In another report, Basavarajappa et al.(2007) applied statistical analysis such as analysis of variance (ANOVA) to study the role of graphite during dry sliding wear of hybrid composite Al/SiCp/Gr. They found that graphite particles are effective agents in increasing dry sliding wear resistance of Al/SiCp composite [15], [16].

Benal and Shivanand (2007) found that the hybrid composite of Al 6061 alloy wear resistance increases with increased the ageing durations. However, in both as-cast and heat-treated hybrid composites, the wear rate increased when the sliding distance increased [17]. It is difficult to deduce the effects of reinforcement from literature because in the reported studies experimental conditions such as load and sliding velocity spread over very wide range and these studies employ many different kind test apparatus. Based on previous studies on wear behaviour of hybrid composite shows that most of studies using SiC and alumina particles as hard reinforcement and remain using commercial graphite and carbon fibre as soft reinforcement, but no study using natural material base reinforcement.

In present work, dry sliding wear tests were conducted on hybrid composite reinforced with natural carbon based particles such as palm shell activated carbon (PSAC) and slag. Both of particles are softer than aluminium matrix. The contribution of the reinforcement content and the applied load as well as the sliding distance on the wear process and the wear rate have been investigated. The contribution of synergic factors such as applied load, sliding distance and reinforcement content (wt.%) have been studied using analysis of variance (ANOVA).

2 MATERIALS AND EXPERIMENTAL PROCEDURE

The hybrid composite materials used in this work were prepared by powder metallurgy technique, the matrix was pure aluminium and the reinforcement was palm shell activated carbon particles and slag particles. The chemical composition of aluminium powder is 0.5 wt.% Fe, 0.03 wt.% Pb and 99.7 wt.% aluminium. The chemical composition of PSAC particle is 0.05 ppm Fe, 0.01 ppm Cu, 0.05 ppm As and 99.99 ppm C. The chemical composition of Slag is 4.8 wt.% Si, 5.48 wt.% O and 89.72 wt.% C. Hybrid composites containing 5 -20 wt.% of both reinforcements with average particles sizes about 125 µm were prepared by conventional powder metallurgy technique, which involves the steps of mixing, compacting and sintering. Aluminium powders were mixed using rotational mixer with various contents (wt.%) of reinforcement according composition as shown in Table 1. After mixing, the powders were compacted into pin shape (8 mm diameter and 10 -12 mm length) in a simple die and compaction carried out at a pressure of 200 MPa (the optimum pressure for aluminium is 25 – 250MPa). The green compacts removed from the die were sintered in Carbolite furnace at a temperature of 500°C for 2 hr and then allowed to cool to room temperature in the furnace itself. The sintered cylindrical pin (Ø8 mm x 12 mm) specimens are ready to conduct wear test

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Table 1: Ratio of mixture for each composition

Composition Material	Percentage of weight (% wt)				
	C0	C5	C10	C15	C20
Alp	100	95	90	85	80
PSACp	0	5	10	15	20
Slag	0	5	10	15	20
Hybrid (PSAC/Slag)	0	2.5/2.5	5/5	7.5/7.5	10/10

Dry sliding experiments were conducted in air at room temperature using a pin-on-disc self-built attached to the polisher machine. The disc which acted as the mating surface material was made of mild steel (120 HV) cut from commercial mild steel sheet (2mm thickness) into 100 mm diameter. The influence of the applied load was investigated under a constant sliding velocity of 0.1m/s with the applied loads at 3N, 11N and 51N.

The wear of the pins was recorded by measuring the weight loss of the material a micro balance of accuracy 10-5g. Each measurement was made by interrupted at 100m, 200m, 300m, 500m and 1000m. The weight loss recorded was converted to a volume loss by dividing by the calculated density of materials. All specimens followed a single track of 65mm diameter and the mild steel disc was changed for each surface of tested pin. The tests were repeated at least twice under the same operating conditions. Before each measurement, the pin was blown dry in air. Three readings were made for each weighing and the mean taken. In order to investigate the degree of influence of sliding distance, applied load and content of reinforcement to wear characteristic, the results have been treated based on statistical analysis of average and analysis of variance (ANOVA).

3 RESULT AND DISCUSSION

3.1 Statistical analysis

Table 2 shows the design sliding wear test and the experimental results. The wear rate of the composite depends on the content of reinforcement (0 to 10 wt. %), sliding distance (0 – 300m) and applied load (3 to 51N) simultaneously. In order to investigate the degree of influence of sliding distance, applied load and content of reinforcement to wear characteristic, the results have been treated based on the statistical analysis of average and analysis of variance (ANOVA).

Table 3 shows the statistical analysis significant data for wear results. Table 3 column 4 shows the correlation between the above synergic factors in present study is medium or less and does not have significant influence on the wear of all composites except two cases. One case is refer to significant influence and high correlation of applied load on the wear rate for all composite as shown in table 3 (column 4 & 6) indicated for PSAC (r=0.581, Sig=0.001), Slag (r=0.591, Sig=0.001) and Hybrid (r=0.600, Sig=0.001) whereby the analysis carried out for significant level of 1%. Another case is refer to significant influence of content on the wear rate for hybrid composite (r=0.446, Sig=0.020) whereby the analysis carried out for significant level of 5%.

The synergic contribution effects of load on wear rate, for different reinforcement content and sliding distance have been shown in table 3. Results from regression analysis in table 3 indicated that from 3 synergic factors on wear rate of composites, only 2 synergic factors (load and content) shows significant contribution. In the case of load factor, significant contribution for PSAC (F=12.753, Sig=0.001), Slag (F=13.432, Sig=0.001) and Hybrid (F=14.043, Sig=0.001). In the case of content factor, the contribution significant only for Hybrid (F=14.040, Sig=0.020).

Table 2: Design test for statistical analysis and their experimental results

Test	Load L	Sliding Distance SD	Reinfor. content Cont.	Wear rate PSAC/Al	Wear rate Slag/Al	Wear rate Hybrid/Al
	(N)	(m)	(wt. %)	(x10-4 g/m)	(x10-4 g/m)	(x10-4 g/m)
1	3	100	0	162	162	162
2	3	100	5	75	9	17
3	3	100	10	313	4	14
4	3	200	0	190	190	190
5	3	200	5	290	22	44
6	3	200	10	650	16	27
7	3	300	0	250	250	250
8	3	300	5	670	60	80
9	3	300	10	860	25	54
10	11	100	0	216	216	216
11	11	100	5	88	11	36
12	11	100	10	95	29	65
13	11	200	0	536	536	536
14	11	200	5	464	36	196
15	11	200	10	122	56	102
16	11	300	0	681	681	681
17	11	300	5	670	161	271
18	11	300	10	102	76	127
19	51	100	0	410	410	410
20	51	100	5	860	62	205
21	51	100	10	2240	246	269
22	51	200	0	810	810	810
23	51	200	5	2090	184	376
24	51	200	10	3330	1391	423
25	51	300	0	1580	1580	1580
26	51	300	5	3240	259	553
27	51	300	10	3530	1932	526

On the basis of analysis in table 3 (column 3 & 6), the main synergic factors is applied load whereby PSAC (Beta=0.581, Sig=0.001), Slag (Beta=0.591, Sig=0.001) and Hybrid (Beta=0.600, Sig=0.001) influence the wear rate either increases or decreases. In other word, 1 unit applied load increases 0.581 unit wear rate for Al/PSAC, 1 unit applied load increases 0.591 unit wear rate for Al/Slag and 1 unit applied load increases 0.600 unit wear rate for Al/PSAC/Slag (hybrid). The applied load contributes to the wear rate is 58.1%, 32.3% and 33.4% for Al/PSAC, Al/Slag and Al/PSAC/Slag (hybrid) respectively as shown in table 3 column 7.

The second main synergic factor observed influences the wear rate is content (Beta=0.446, Sig=0.0200) only in the case Hybrid composite. In other word, 1 unit content increases 0.446 unit wear rate for Al/PSAC/Slag (Hybrid). The content of the reinforcement contributes to wear rate of Al/PSAC/Slag (hybrid) is 16.7%. For other composites show the lower (below than 10%) contribution. The synergic factors such as sliding distance have contribution on wear rate of all composites but in low (below than 10%) contribution except for Al/PSAC/Slag (hybrid) (10.8%) is better than other composite.

The influence percentage of each factor for each composite is more and the less same and it shows that the incorporation of PSAC and Slag in hybrid composite under study will influence in increasing the wear resistance. But the wear mechanism that occurs in hybrid composite dry sliding should be predicted in order to understand the wear behaviour.

3.2 The effect of synergic factors on wear behaviour of hybrid composite

Fig. 1 to 4 show the experimental results of sliding wear test on the specimen content of reinforcement (0 to 20 wt.%) tested at sliding distance (0 – 1000m) and applied load (3 to 51N). The main objective of this study is to clarify the effect of PSAC particles and Slag particles on wear resistance of aluminium. On the basis of previous results, the hybrid composite that reinforced with PSAC/Slag show the significant influence of reinforcement content (16.7%). Fig. 1 shows the variation of cumulative wear rate with content of reinforcement (PSAC/Slag) tested under different applied load. The wear rate of hybrid composite decreased with increasing reinforcement content (wt.%) and reached its minimum at certain wt.% for all tested applied load.

Table 3: Statistical analysis significant data for wear results

Source of variances	Adjusted R square	Beta	P. corr.	F	Sig.	p (%)[#]
PSAC[x]						
L[a]	0.581	0.581	0.581**	12.753	0.001	58.1
SD[b]	0.064	0.316	0.316	2.774	0.108	6.4
Cont.[c]	0.036	0.064	0.064	0.104	0.750	3.6
Slag[y]						
L[a]	0.323	0.591	0.591**	13.432	0.001	32.3
SD[b]	0.087	0.349	0.349	3.475	0.074	8.7
Cont.[c]	0.031	0.096	0.096	0.23	0.635	3.1
Hybrid[z]						
L[a]	0.334	0.600	0.600**	14.040	0.001	33.4
SD[b]	0.108	0.377	0.377	4.133	0.053	10.8
Cont.[c]	0.167	0.446	0.446*	6.197	0.020	16.7

Method: enter (All requested variables entered),
[x] Dependent variable: Wear rate (PSAC),
[y] Dependent variable: Wear rate (Slag),
[z] Dependent variable: Wear rate (Hybrid),
[a] Synergic factor: L (load) ,
[b] Synergic factor: SD (Sliding distance),
[c] Synergic factor: Cont. (Content of reinforcement),
[#] Contribution percentage of synergy factor,
**Correlation is significant at the level 0.01 level (2-tailed),
*Correlation is significant at the level 0.05 level (2-tailed)

The trend of wear rate of hybrid composite tested under 3 N is decreased slowly and reached its minimum at wt.% = 10%, but afterwards slowly increased with increasing wt.%. Whereas, the wear rate of hybrid composite tested under 11 N decreased gradually and reached its minimum at wt.% = 15%, but afterwards increased slowly with increasing wt.%. Moreover, the wear rate of hybrid composite tested under 51N decreased drastically and reached its minimum at wt.% = 15%, but afterwards increased gradually with increasing wt.%. In other words, the optimum content of reinforcement in hybrid composite sliding tested under 3N applied load is lower than sliding under 11N and 51N. This trend due to the roles of reinforcement in order to improved the wear resistance of the hybrid composite. The previous finding of present work that show significant contribution of reinforcement content on wear resistance of hybrid composite has been proved by this trend. Fig. 3 generally shows that higher applied load made higher cumulative wear rate at all wt. %. This trend shows the significant contribution of applied load on hybrid composite has been proved.

Fig. 2, Fig. 3 and Fig. 4 show the variation of mass loss with sliding distances at applied load of 3N, 11N and 51N respectively. Fig. 4 shows the examples of wear curves of the hybrid composite specimens with various wt.%. The hybrid composite with low wt.% underwent large mass loss during early stage of the test. After a certain sliding distance, the mass loss linearly increased with sliding distance. The sliding distance (or duration) for the transition from initial wear to steady-state wear was identified by two factors, firstly by an abrupt and steep reduction in the frictional force. Based on these measurements, the wear curves are characterized by two distinct straight lines of different slopes, which correspond to initial wear and steady-state wear conditions. At the beginning of the test, the hybrid composites with higher wt.% (5 to 15%) of reinforcement showed steady-state wear tested under 3N and 11N but not with highest wt.% (20%) reinforced content. However, initial severe wear does occur at the beginning of the test for all hybrid composite specimens tested under 51N. The effects of the wt. % of reinforcement on the wear are found to be different for the initial wear and the steady-state wear.

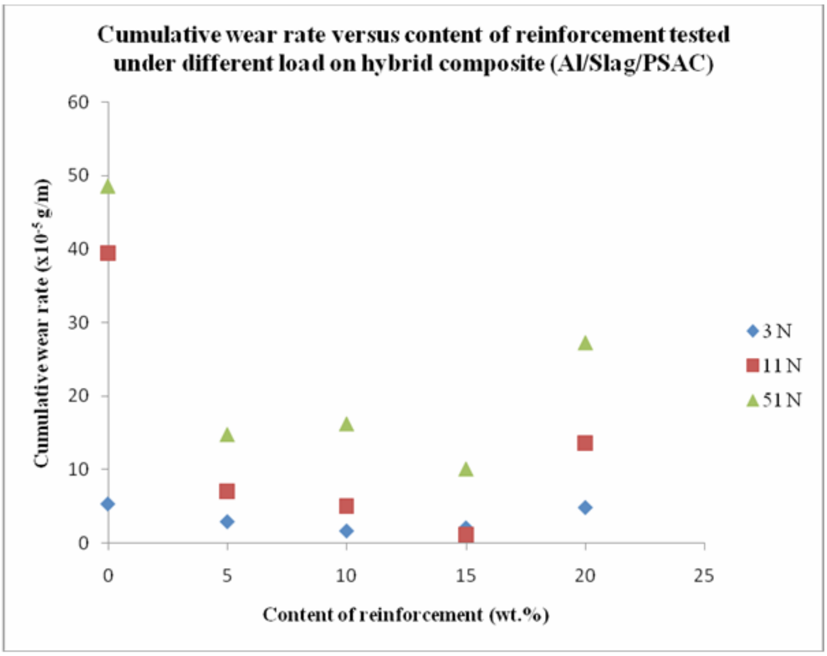

Figure 1: Variation of Cumulative Wear Rate with Content of Reinforcement

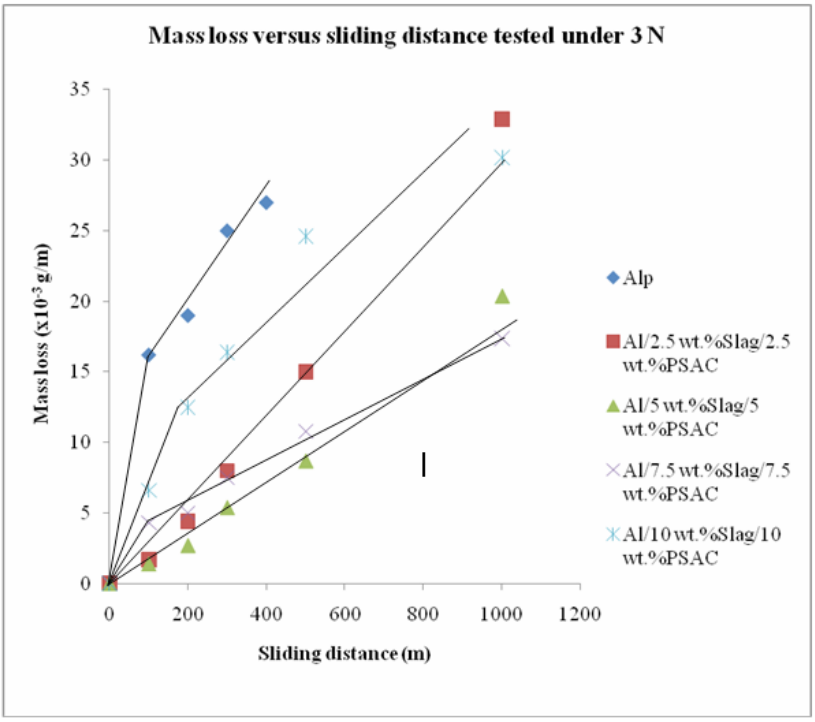

Figure 2: Variation of Mass Loss with Sliding Distance at a Load of 3N

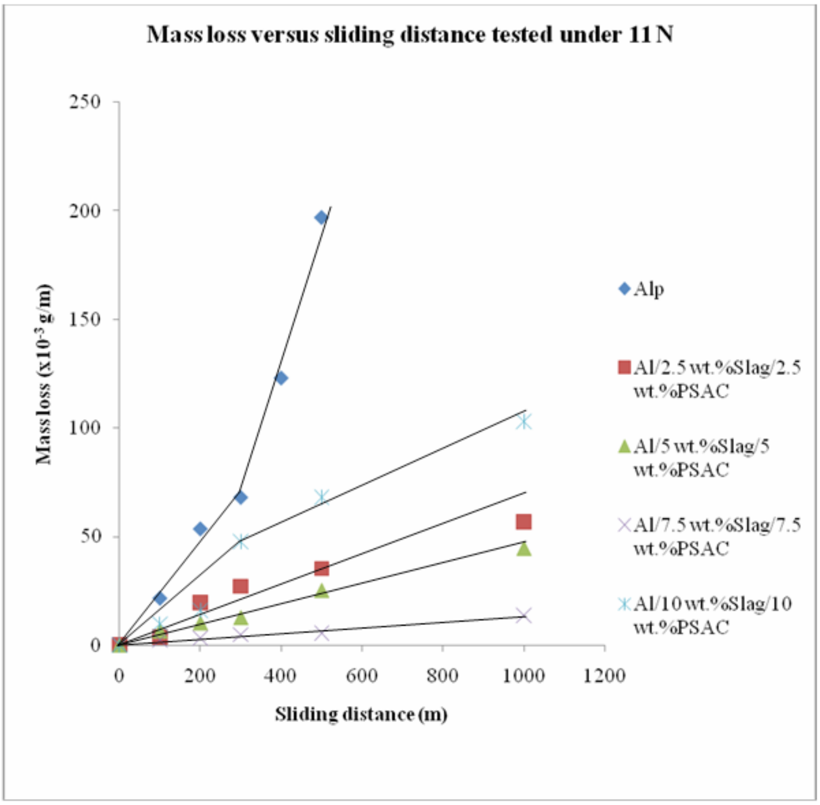

Figure 3: Variation of Mass Loss with Sliding Distance at a Load of 11N

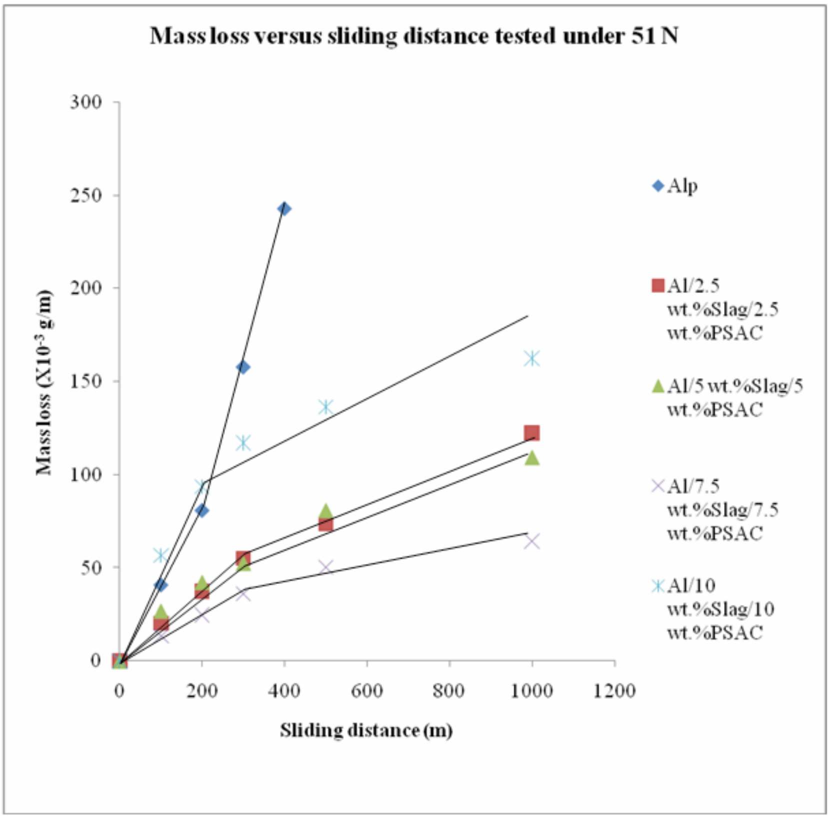

Figure 4: Variation of Mass Loss with Sliding Distance at a Load of 51N

4 CONCLUSION

Dry sliding wear tests using a pin-on-disc were conducted on hybrid composite reinforced with natural carbon based particles such as palm shell activated carbon and slag. The contribution of the reinforcement content and the applied load as well as the sliding distance on the wear process and the wear rate have been investigated. The following conclusions can be drawn from this study:

All synergic factors contribute to the wear process of all tested composites.

Al/PSAC composite presents a contribution of applied load (58.1%), reinforcement content (3.6%) and sliding distance (6.4%). Al/Slag composite presents a contribution of applied load (32.3%), reinforcement content (3.1%) and sliding distance (8.7%). Meanwhle, among synergic factors, the applied load is the highest contribution to wear process on both composites (Al/PSAC and Al/Slag) and hybrid composite.

Al/PSAC/Slag hybrid composite presents a contribution of applied load (33.4%), reinforcement content (16.7%) and sliding distance (10.8%).

The degree of improvement of wear resistance of hybrid composite is strongly depends on the reinforcement content. Initial severe wear does not occur for hybrid composite with wt.% = 10% (5% PSAC/ 5% Slag) and wt.% = 15% (7.5% PSAC/ 7.5% Slag) under applied load 3N and 11 N but not under 51 N. For hybrid composite with wt. % = 20% (10% PSAC/10% Slag), initial severe wear does occur at the beginning test under all applied load. The reinforcements effectively prevent the initial severe wear of hybrid composite at optimum content (7.5% PSAC/ 7.5% Slag) under optimum applied load (11N). The effect of the wt. % of reinforcement found to be different for initial wear and the steady-state wear.

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