Kovove Mater. 49 2011 287–295
DOI: 10.4149/km_2011_4_287

Physical properties and wear behaviour of aluminium matrix composite reinforced with palm shell activated carbon (PSAC)

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Received 10 January 2011, received in revised form 8 February 2011, accepted 9 February 2011

Abstract

This study was aimed to investigate the influence of reinforcement content on the physical properties and wear behaviour of composite pure aluminium reinforced with palm shell activated carbon (PSAC). Pure aluminium was reinforced with 0 %, 5 %, 10 %, 15 % and 20 % by weight of PSAC and then compacted at 200 MPa followed by sintering at 500 °C for 2 h. Quantitative analysis on dry sliding wear behaviour was investigated by means of pin-on-disc wear testing machine. Wear rates of the composite were determined at fixed applied load (10 N) and sliding velocity (150 rpm). Optical micrograph showed that an increasing PSAC content had resulted in increasing of pores in the composites. The hardness and density decreased with the addition of PSAC content. They were reduced drastically with the amount of PSAC content more than 10 wt.%. The cumulative wear rate of the specimens was observed decreased with the amount of PSAC content less than 10 wt.% PSAC and increased with PSAC content more than 10 wt.%. The optimum content of PSAC was found to be 10 wt.% in order to achieve optimum wear resistance.

Key words: dry sliding wear, aluminium matrix composite, pin-on-disc, palm shell activated carbon

1. Introduction

Metal Matrix Composites (MMCs) have several advantages like isotropic properties, better specific strength, stiffness, hardness and wear resistance. They can be fabricated by casting and powder metallurgy. MMCs are well established in various applications such as cylinder liners, brake rotor discs, wear resistance materials such as cemented carbides and sporting equipment such as bicycle frame, golf head and chain wheels [1]. The difficulties of producing MMCs are always related to high temperature process and the mixing process of reinforcement and matrix. Therefore, many processing routes are developed to overcome the processing problems and the high cost of raw materials leading to extremely limited use [1].

There are several processing routes which have been developed like vortex route under vacuum [2], compocasting [3], infiltration process [4], spray process [5], powder metallurgy [6], Lanxide's process [7] and XD™ process [8]. These routes have their own advantages and limitations, and can be adopted by different product characteristics. Currently, the most cost-effective routes are casting and powder metallurgy. Powder metallurgy has many merits such as a simple process, high materials utilizing ratio, and lesser energy consumption; but sintered parts have generous porosity resulting in their dynamic mechanical properties being affected [9]. Most of the research works on wear behaviour of MMCs have focused on the particle reinforced composites. Several researchers focused on the wear behaviour of particle reinforced aluminium composites systems such as silicon carbide/aluminium composites, alumina/aluminium composites, graphite/aluminium composites, carbon char/aluminium composites, fly ash/aluminium composites, hematite/aluminium composites and bauxite/aluminium composites. Abrasive wear resistance of several alloys containing silicon carbide particles and different volume fraction has been investigated by a

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number of researchers [10–13], whereas the effect of ceramic particle such as alumina to wear behaviour of aluminium has been studied by Hosking et al. [14], Surrapa et al. [15], Wang and Hutching [16], Prasad et al. [17].

Muralli et al. [18] and Ejifor et al. [19] have studied wear behaviour on carbon char/aluminium system. Ramachandran and Murali [20] studied wear behaviour on hematite/aluminium system, whereas Ramachandran and Radhakrishna [21] have reported wear behaviour on fly ash/aluminium composite. Singh et al. [22] investigated wear behaviour on spinel/aluminium system. They observed that the wear resistance has been improved by the addition of reinforcement.

Based on the previous works, the main particulate reinforcements used in aluminium matrix composite are silicon carbide, alumina, graphite and fly ash. Actually, many other possible species are readily available or naturally renewable at affordable cost such as coconut shell char, mica, palm-kernel shell char and zircon [19]. However, no research has been focused on wear behaviour of palm shell activated carbon (PSAC) as reinforcement in metal matrix composite. PSAC is expected to be a potential reinforcement in aluminium matrix composite. PSAC is biomass by-product from palm oil factory that can be obtained locally. The idea proposed is to reduce the cost of starting material in fabrication of novel aluminium composite reinforced with local waste materials. From the practical perspective, the utilisation of PSAC as reinforcement in fabrication of metal composite is also important for the development of palm oil industry in Malaysia. It can help the government to formulate the right and appropriate strategies to promote sustainable approaches in generating higher value-added products from palm biomass and adopting of zero waste strategy.

Therefore, this study focuses on PSAC as reinforcement in pure aluminium fabricated by powder metallurgy technique. In this study, effects of different content of PSAC particles on porosity, density and hardness properties as well as wear behaviour of PSAC reinforced aluminium matrix composite were investigated.

2. Experimental procedure

Figure 1 shows the SEM micrographs of pure Al particles and PSAC particles. Figure 1a,b obviously shows the flaky shape particles of pure Al and irregular shape particles of PSAC, respectively. The chemical composition of the aluminium powder and PSAC particles are listed in Tables 1 and 2, respectively. Composites containing up to 20 wt.% PSAC with an average particle size of 65 μm were prepared by a conventional powder metallurgy (PM) which involved the steps of mixing, compacting and sintering. The aluminium powder and PSAC particles were mixed using

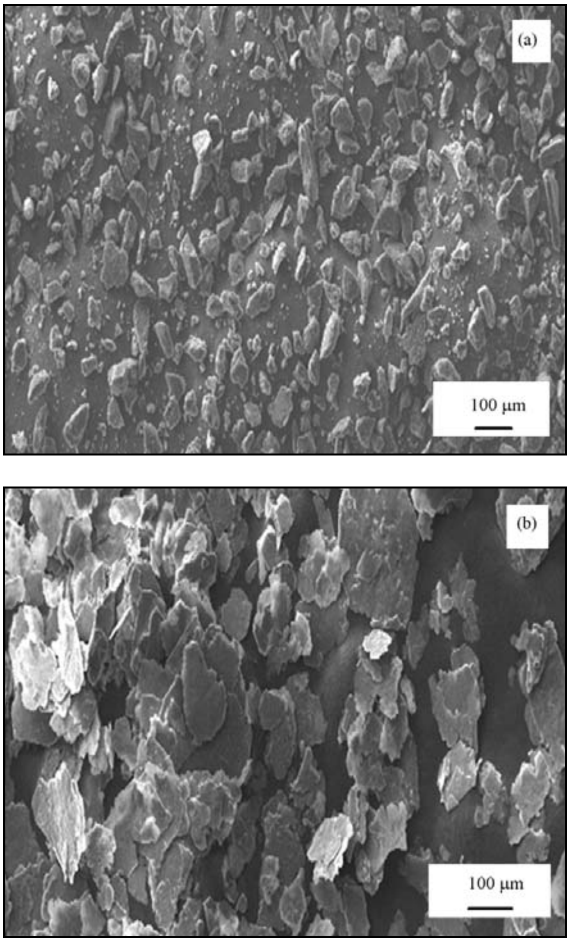

Fig. 1. SEM micrograph of: (a) PSAC particles, (b) aluminium particles.

Table 1. The chemical composition of pure aluminium powder (Al)

Element	Content
Fe	Max. 0.5 wt.%
Pb	Max. 0.03 wt.%
Al	Bal.

Table 2. The chemical composition of PSAC used as reinforcement in composite

Element	Content
Fe	0.05 ppm
Cu	0.1 ppm
As	0.05 ppm
C	Bal.

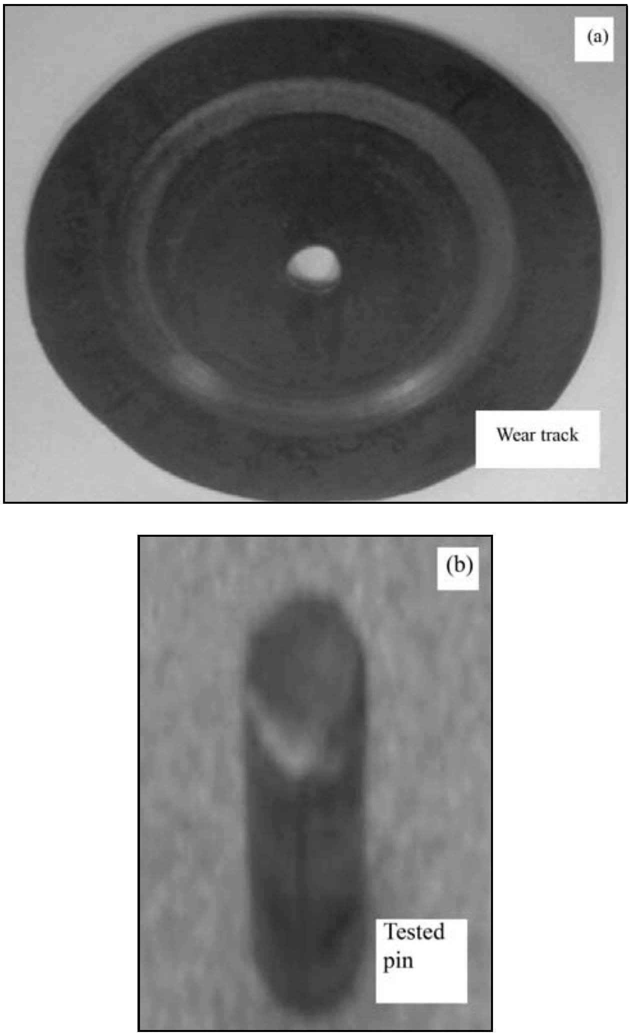

Fig. 2. Photographs of: (a) mild steel disc as mating surface, (b) typical pin sample after sliding wear tested.

a rotational mixer. The steel die was used to compact the mix powder into pin. The samples were cold pressed in a die at a pressure of 200 MPa and then sintered for 4 h at 600 ℃ in the carbolite furnace. After sintering, the porosity and density were determined according to the gravimetric method. The hardness test was performed using Vickers-hardness-testing machine. For microscopy analysis, the samples were prepared according to the standard metallographic procedures. Scanning electron microscope (SEM) and energy dispersive X-ray (EDX) from JEOL* JSM-6460LA were used to reveal the microstructures of the samples. The pin-on-disc dry sliding wear resistance test based on ASTM standard G99 [23] was used to evaluate the wear resistance of the pure aluminium and the composites.

The pin-on-disc configuration was used for the dry sliding wear testing with the pin mounted vertically on the tester arm at one end and the other pin surface held against the rotating mild steel disc. The pure Al and composites were used as the pin, and the mild steel disc was used as the mating surface (Fig. 2a). Tested samples were coded as shown in Table 3. All tests were performed under applied load of 10 N. Figure 2b shows the typical wear test sample after 400 m sliding distance. Al and composites were tested at sliding speed of 150 rpm. Prior to the test, the flat surface of the pin was polished by sliding against 600grit SiC paper. The mild steel discs were ground to a constant roughness of about 0.40 micron *Ra* (arithmetic roughness), and measured using a roughness tester. The wear of the pins was recorded by measuring the mass loss of the pins using a micro balance of accuracy 10^{-5} g. Each measurement was made by interrupting the test every 100 m of sliding distance. All samples followed a single track of 50 mm in diameter and mild steel disc was changed for each surface of the pin tested. In order to determine the wear mechanism of the aluminium and its composites, the worn surfaces and cross-section of worn surfaces were observed by optical microscope and scanning electron microscope. The debris collected during experiments was examined by SEM with EDX analysis.

3. Results and discussion

3.1. Microstructure analysis

Microstructure was analysed in order to observe the phase distribution and porosity as well as PSAC/Al interface bonding of the samples. Figure

Table 3. Details of the composite samples used in the present study

Sample code	Weight percent of PSAC particle (wt.%)	Applied load (N)	Sliding velocity (rpm)
A	0	11.04	150
B	5		
C	10		
D	15		
E	20		

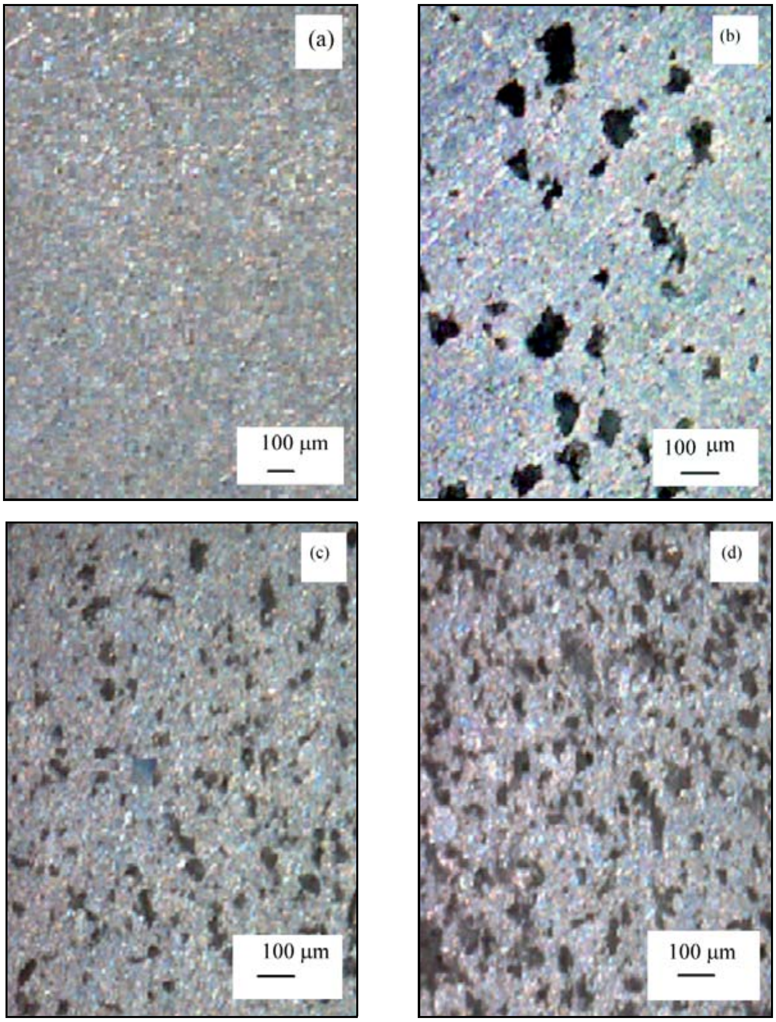

Fig. 3. Optical micrographs of: (a) 0 wt.% PSAC/Al, (b) 5 wt.% PSAC, (c) 10 wt. % PSAC, (d) 20 wt.% PSAC.

3a shows the matrix microstructure of unreinforced aluminium, whereas Fig. 3b,c,d shows the distribution of PSAC particles in the Al reinforced with 5, 10 and 20 wt.% PSAC, respectively. It can be seen that the PSAC particles were homogeneously distributed in an aluminium matrix. Large particles with irregular shape of PSAC have improved its distribution in an aluminium matrix. According to Hunt [24], powder metallurgy route that involves cold pressing and sintering can produce a homogeneous distribution. He reported the distribution of the reinforcement in powder metallurgy composite depended on the mixing procedure and compaction process as well as relative particle size and particle shape of matrix and reinforcement. If the matrix particles are larger than reinforcement particles, the reinforcement particles will agglomerate in between larger particles. Consequently, the distributions of the reinforcements are inhomogeneous.

Figure 4 shows a close up view of selected particle-matrix interfaces illustrating particles fragmentation leading to micro-pores at the particle/matrix interface. Figure 4a shows SEM micrograph of Al/10 wt.% $\mathrm{PSAC_p}$ showing good bonding between matrix and particle. Figure 4b shows SEM micrograph of Al/20 wt.% $\mathrm{PSAC_p}$ and its EDS showing a poor bonding between matrix and particle. From the EDS analysis, the presence of Al_2O_3 can be found at particle/matrix interface. The presence of Al_2O_3 may be due to the oxide "skin" that is invariably present on the Al particle surface [25, 26]. Poor bonding between matrix and particle is due to the powder metallurgy processing. During compaction process of composite with 20 wt.% of PSAC, it is seen that the green body that was produced from cold pressing was not enough dense because of the high PSAC particles content. Consequently, this condition produced the poor interface bonding between PSAC particles and Al matrix after sintering process.

3.2. Physical properties

Figure 5 shows the relationship between weight percent of PSAC particles and density of the PSAC/Al composites. The density was found to decrease with

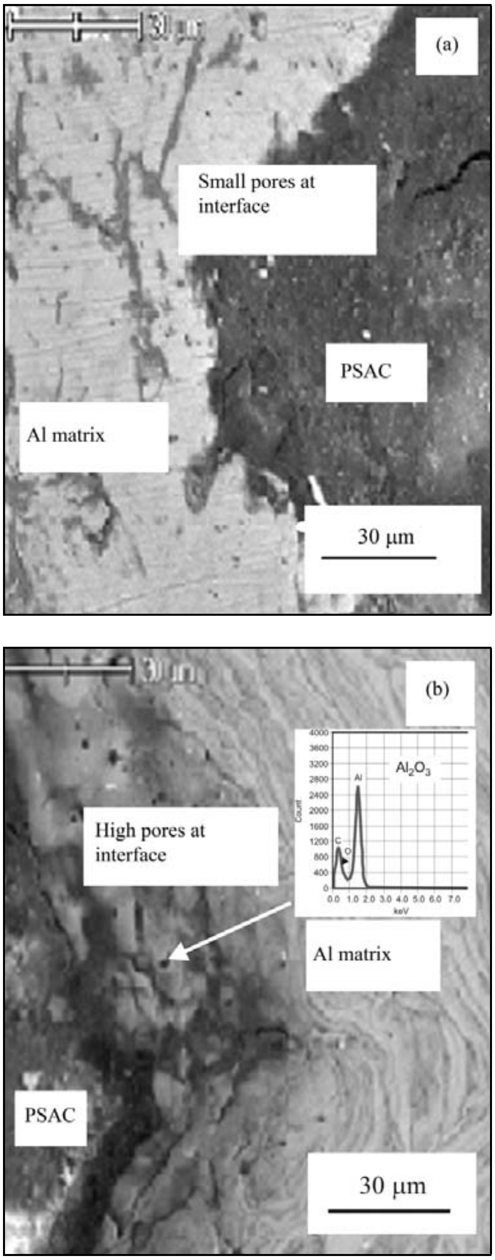

Fig. 4. Back scattered SEM micrograph of: (a) Al/10 wt.% $PSAC_p$, (b) Al/20 wt.% $PSAC_p$ and its EDS analysis.

increasing the weight percent of PSAC particles. The reduction of this composite density is due to a lower density and pores structure of PSAC particles. However, the density of sample without PSAC particles is 2.31 g cm^{-3} which is 85 % of pure aluminium (2.71 g cm^{-3}) as a comparison. The PSAC particles addition in Al matrix decreased the density of composites.

Figure 6 indicates PSAC particles addition has affected the sintered porosity in the PM composites. It is clear that the porosity of the P/M aluminium composite increased as content of PSAC increased.

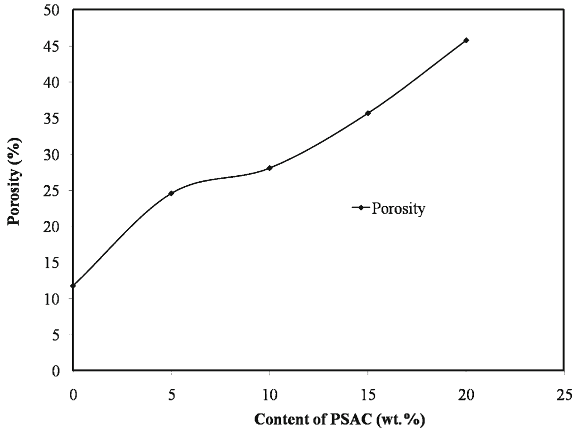

Fig. 5. The influence of PSAC particles content on the bulk density of the composites.

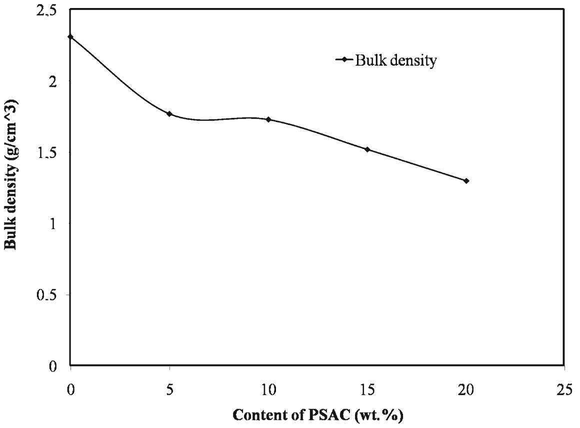

Fig. 6. The influence of PSAC particles content on the porosity of the composites.

Sample of pure Al has the lowest percentage of porosity which is 11.8 % but sample with 20 wt.% PSAC/Al has the highest porosity. These results have similar trends with the finding reported by Jha et al. [27]. They found that by increasing the graphite contents in Al, the porosity of composites also increased.

Figure 7 shows the relationship between the weight percent of PSAC particles and the macro-hardness of PSAC/Al composite. The hardness decreases slightly with the increasing weight percent of PSAC particles. This is related to the amount of PSAC particles content in the Al matrix. It is prominent that the surface hardness of PSAC/Al composite is reduced when PSAC particles are added. Pure Al has the highest hardness value, which is 62.7 HV. Meanwhile, a sample 20 wt.% PSAC/Al that contains the highest PSAC particles indicated the lowest hardness (17.2 HV). These results have similar trends with the findings reported by Lin et al. [28]. They found that by in-

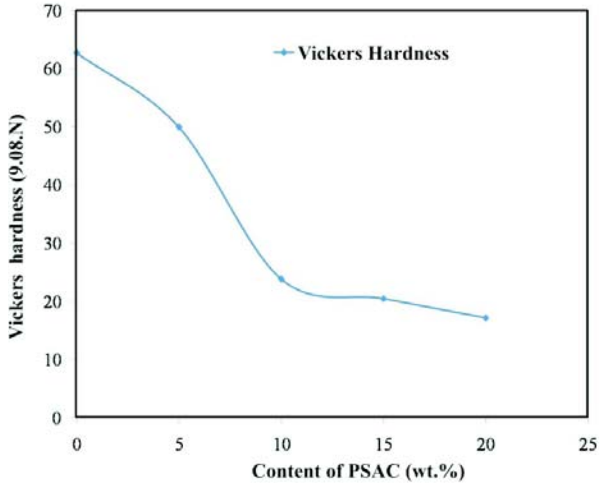

Fig. 7. The influence of PSAC particles content on surface hardness of the composite.

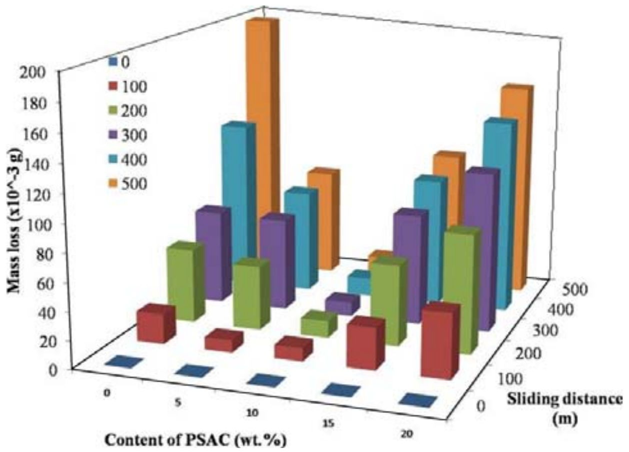

Fig. 8. Relationship between the mass loss with a content of PSAC particles and the sliding distance.

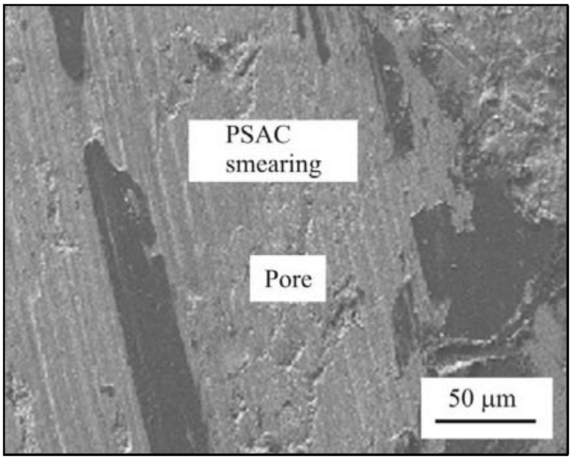

Fig. 9. Micrograph of top view of typical worn surface of sample containing 10 wt.% of PSAC.

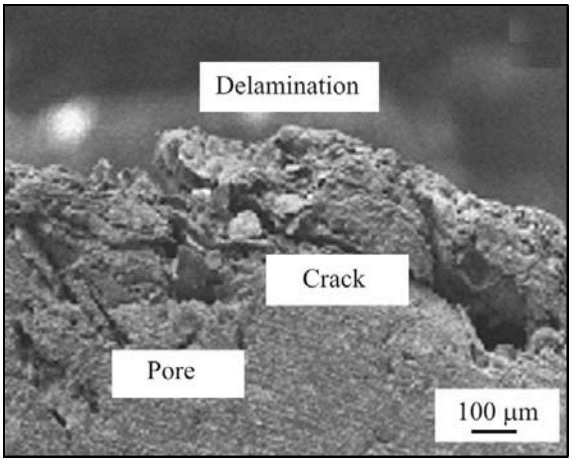

Fig. 10. Micrograph of cross section of sample containing 20 wt.% of PSAC parallel to sliding direction.

creasing the graphite contents in Al, the hardness of composites decreased.

3.3. Wear behaviour

Figure 8 shows the mass loss of Al/PSAC composite versus PSAC content and sliding distance at a constant load of 10 N and a constant sliding velocity of 150 m s^{-1}. It was found that the mass loss of the composite decreased with increasing PSAC content up to 10 wt.%. This can be possibly due to the strain hardening strengthening mechanism by PSAC in matrix pure aluminium. Another reason for the wear rate decreases can be due to the squeezed PSAC film that is smearing in between the sliding surfaces (Fig. 9). The pores and softness properties of PSAC can contribute to the entrapment and smearing the PSAC in contact surface leading to self-lubrication which reduces contact stress. However, the mass loss of the composite increases when the PSAC content is more than 10 wt.%. This can be possibly due to the higher PSAC content leading to the higher porosity of PSAC/Al composite as well as reducing its hardness. Another reason for increasing the wear rate could be due to the presence of pores at PSAC/Al interfaces that lead to delamination of tribolayer (Fig. 10). The results also show that the mass loss increases with increasing of sliding distance, but the rate of mass loss is different for each composite. The wear rate (g m^{-1}) is calculated from the slope of mass loss versus sliding distance. The lowest wear rate is given by the composite containing 10 wt.% of PSAC.

Figure 11 shows the cumulative wear rate versus PSAC content after 500 m sliding distance at constant load of 10 N and a constant sliding velocity of 150 m s^{-1}. The cumulative wear rate of pure Al is found higher than composites due to deformation and damage accumulation process in pure aluminium. Cu-

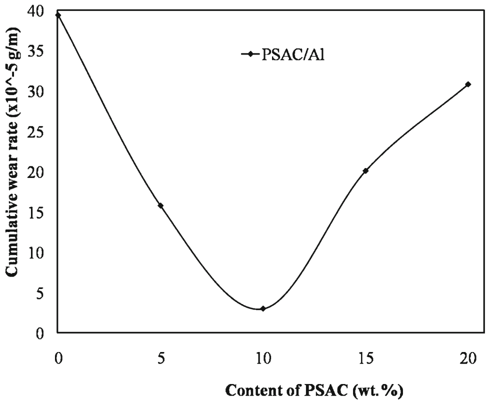

Fig. 11. Cumulative wear rate against weight percent of PSAC particle after 500 m sliding distance tested at 10 N/150 rpm.

mulative wear rate of the composites was reduced by increasing PSAC content up to 10 wt.%. Hence the composites exhibit better wear resistance than pure Al at the content of PSAC particles less than 10 wt.%. This result shows that the effect of reinforcement on the wear resistance is good due to the presence of PSAC particles as self lubricant at the contact surface between the composite and the mating surface. However, cumulative wear rate increases when the content of PSAC is more than 10 wt.%. This result is due to higher porosity in the composite and it affects composite ability to support the load. Based on the above result, the presence of PSAC particles in small quantities (10 wt.%) can reduce the wear rate but large quantities are the worst for the composite.

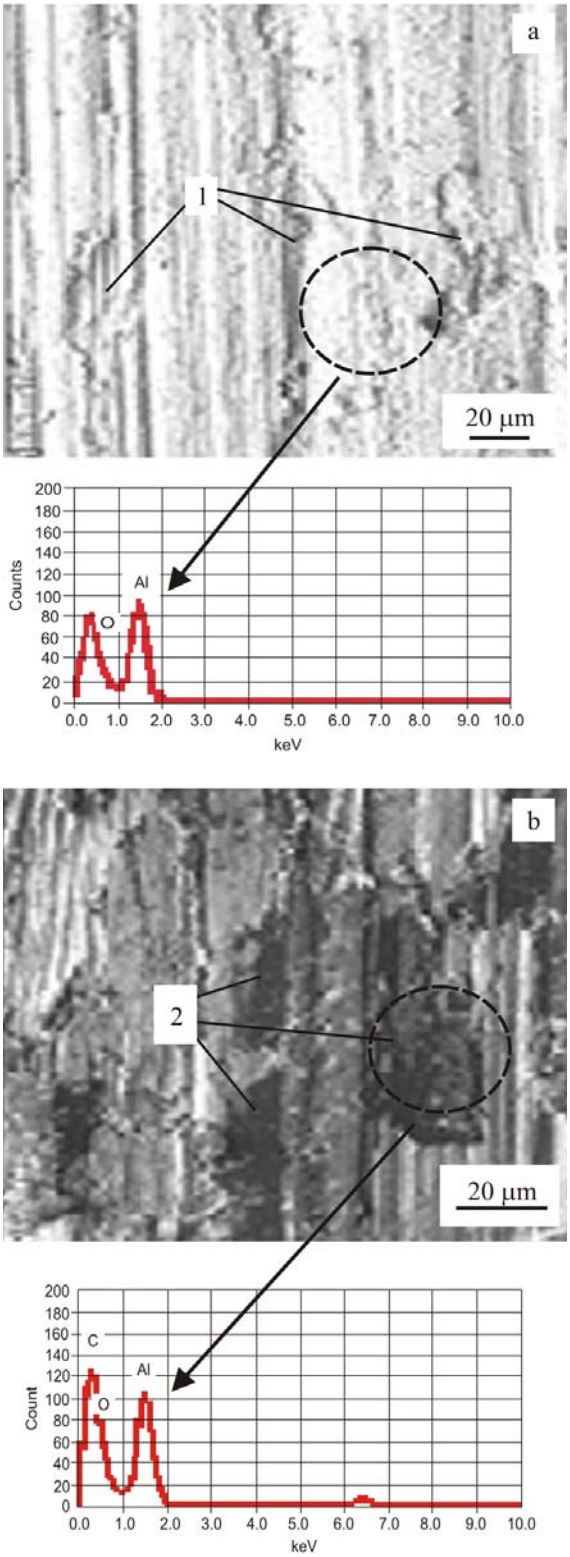

Fig. 12. SEM and EDX of worn surfaces: (a) 0 wt.% PSAC/Al, (b) 10 wt.% PSAC/Al.

3.3.1. Surface analysis

In order to understand the influence of PSAC particles on wear behaviour, the worn surfaces of the samples were studied under optical microscope and SEM with EDX. Figure 12b shows micrograph of worn surfaces showing wear tracks of Al with 10 wt.% of PSAC. There is a mixed mode of abrasive-adhesive wear mechanism. Ploughing phenomena and presence of grooves on the worn surface and no black film can be seen in pure Al as shown in Fig. 12a. This result shows that the damage process is due to the plastic deformation (position 1 in Fig. 12a). Figure 12b shows the prominent black film of PSAC that is smearing during sliding and was confirmed by EDX (position 2 in Fig. 12b). Figure 13a shows the worn surface of the composite containing 5 wt.% PSAC indicating the presence of grooves and a little black film on it. Figure 13b shows the worn surface of the same composite which reveals the increasing of black film smearing on the surface as well as on the grooves. Moreover, Fig. 13c shows the worn surface of the composite containing 15 wt.% PSAC revealing the black film and the presence of damage on the surface (position 4), whereas the worn surface of the composite containing

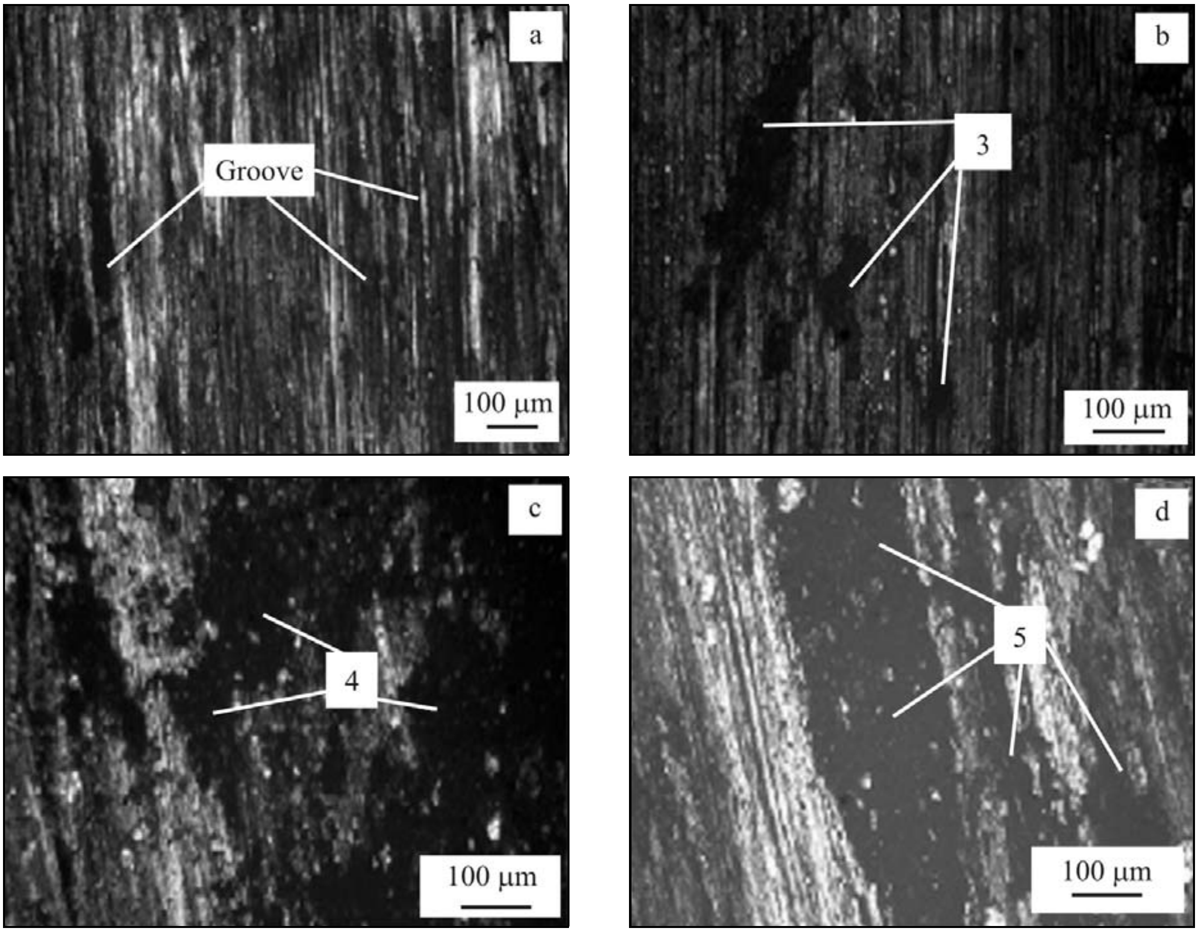

Fig. 13. Optical micrographs of worn surfaces showing wear tracks of Al/PSAC composite: (a) Al/5 wt.% PSAC; (b) Al/10 wt.% PSAC; (c) Al/15 wt.% PSAC and (d) 20 wt.% PSAC.

20 wt.% PSAC shown in Fig. 13d shows the presence of severe damage as well as wide grooves and black film (position 5 in Fig. 13d).

Based on this observation, it is believed that the amount of PSAC content has influenced the wear behaviour of the Al/PSAC composite. The presence of black film smeared on the worn surface of composite containing 10 wt.% PSAC can reduce the wear rate due to the smeared film that plays as self lubricant. According to Chawla, N. and Chawla, K. K. [29], the addition of ceramic particles to a metal matrix can lead to improving the wear resistance and they report that as the weight percent of reinforcement becomes larger, the fracture toughness of the composite reduces significantly. If the fracture toughness is inadequate, the particles will fracture and contribute to the wear process.

Moreover, it was taught that the PSAC particles could act as solid lubricant particles. The PSAC particles deform by the sliding action of the mating surface and they are squeezed out toward the surface, forming a soft interfacial film. The presence of this film is believed to be responsible for the observed reduced wear.

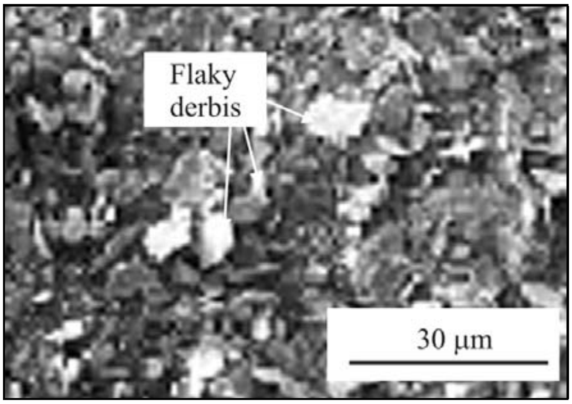

Fig. 14. Micrograph of large flaky debris.

On the contrary, at the highest content (20 wt.% PSAC), the presence of severe damage on the worn surface as a result of the poor bond between Al and PSAC has decreased the ability of surface structure to support the applied load and reduce the wear resistance. Consequently, some of PSAC particles pull out from worn surface as well as plastic deformation of the matrix made the surface crack and subsurface crack tend to delamination process. Figure 14 shows the presence of large flaky debris due to the delamination process.

4. Conclusions

The effects of different content of PSAC particles on porosity, density and hardness properties as well as wear behaviour of PSAC reinforced aluminium matrix composite were investigated. The conclusions are as follows:

1. PSAC reinforced pure Al composite is successfully fabricated by powder metallurgy technique. The microstructure showed that increasing PSAC content had resulted in increasing of pores in the composite.

2. It was observed that porosity increased, whereas hardness and density decreased with the addition of PSAC content. Hardness and density reduced drastically when the amount of PSAC content was more than 10 wt.%.

3. The cumulative wear rate of the samples was observed to decrease with the addition PSAC content less than 10 wt.%, but it increased with the addition PSAC content more than 10 wt.%.

4. The optimum content of PSAC in order to achieve better wear resistance is 10 wt.%.

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