Short Communication

The Effect of Temperature on the Tribological Properties of Palm Kernel Activated Carbon-Epoxy Composite

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The aim of this study was to investigate the effect of temperature on the tribological properties of Palm Kernel Activated Carbon-Epoxy (PKAC-E) composite. All specimens were formed into 10 mm diameter pins of 30 mm length, using a hot compaction technique. Tribological testing was carried out using a pin-on-disc tribometer in dry sliding conditions by applying temperatures in the range of 27°C to 150°C, at constant sliding speed, applied load, and sliding distance. The results showed that both coefficient of friction (COF) and wear rate of the composite increased with operating temperatures. Abrasive wear and crack formation that would induce delamination wear were identified as the predominant wear mechanisms.

1. Introduction

Friction and wear are response acts of describing the contact of bodies in tribological aspects. Although friction and wear are related to each other in each state of contact with a system; it is not a simple relationship. Previous tribology studies have introduced several successful methods of controlling wear, such as film coating, multi-phase alloying, and composite structuring; as an addition to lubrication [1,2]. Wear can be further reduced by understanding the wear mechanisms to confirm the tribological characteristics of materials in terms of surface roughness, hardness, ductility, reaction conditions, and adhesive / abrasive transfer [1,3].

Previous researchers suggested several methods to reduce friction and wear by achieving an effective lubrication of all moving components (with minimum adverse impact on the environment), such as monitoring the wide range of operating conditions of load, speed, temperature, and chemical reactivity [4]. This would result in improvements in the tribological performance of engines, and consequently yield lower fuel and oil consumption, higher engine power output, reduced harmful exhaust emissions, better durability, reliability, engine life, lower maintenance requirements, and longer service intervals.

Besides using lubricating ideas, researchers also investigated the potential of metal matrix composites (MMC). This is because MMC can provide enhanced properties over monolithic materials, such as higher strength, stiffness and is much lighter. MMC has also shown significant improvements in tribological properties, including sliding wear resistance. Regardless of this, Singh and Chuahan [5] found that the incorporation of solid lubricant particles such as partial reinforcement in aluminium matrix increases the wear resistance of composites. Zhai et al. [6] also found that grain nano particles reinforced with aluminium has great potential applications as an effective solid lubricant for moderate loads and stress and can be easily used for the preparation of self-lubricating composites.

Nowadays, studies on natural fibres as a reinforcing component in polymer matrix have also been popular among researchers [7,8]. The use of natural wastes as a partial reinforcement / filler has also shown great promise for wear resistance applications. It has also been shown that the combination of hybrid ceramic reinforcements produces acceptable tribological properties, under optimized controllable parameters. These researchers found that fibres such as oil palm,

kenaf, coir, bamboo, sugarcane, betel nut, sisal, jute, cotton, basalt, and banana have promising potential in mimicking the behaviour of self-lubricating materials. Although the overall achievement is not as good as super low ideas (i. e. DLC coatings), there are some gaps which can be studied for improvement.

Synchronized with a natural fibre potential, Polytetrafluroethylene (PTFE) also shows acceptable results in high performance mechanical properties due to its unique properties like high chemical resistivity, low coefficient of friction and high temperature stability. However, PTFE shows poor wear and abrasion resistance. The wear resistance of PTFE can be significantly improved by the addition of suitable filler materials. In the past, researchers had studied PTFE filled with conventional filler materials like glass fibers, graphite, and carbon fibers [9]. However, those studied are also not enough to ensure that PTFE can sustain the functionality of the replaced materials without compromising the life cycles and its functions. Hence, significant effort is needed for developing novel composite materials by adding non-conventional filler materials possessing the potential of increasing wear resistance.

Recently, a substantial amount of research has shifted focus from monolithic materials to composite materials, in order to meet the global demand for lightweight, high performance, eco-friendly, wear and corrosion resistant materials. The advantages of composite materials are their permeability, cost effectiveness, and different strengthening mechanisms [10-12].

The potential of local waste materials as reinforcement substitutes in the fabrication of lightweight materials, such as metal matrix composites and polymer matrix composites, have attracted a great deal of attention from researchers; due to their self-lubricating properties and adoption of a zero waste strategy at an affordable cost [13-18]. Zamri et al. [13,14] found that graphite and porous carbon (also known as activated carbons, such as palm shell activated carbon), exhibited a potential to act as a self-lubricating material when reinforced in aluminium alloy to significantly improve wear resistance by increasing carbon content up to 10 mass%. Gomes et al. [19] stated in his study of carbon-carbon composites, that friction coefficient is almost independent of sliding speed, but is highly affected by test temperatures.

Based on the above discussion, there are a limited number of studies which investigated the potential of activated carbon materials as a new material for tribological applications. This fundamental study therefore aimed to further investigate the tribological effects of Palm Kernel Activated Carbon-Epoxy (PKAC-E) composite at different temperatures.

2. Methodology

2.1. Specimen preparation

In this study, the materials used were PKAC and high density epoxy (West system 105 epoxy resin 105-B) and slow hardener (West system 206-B). The PKAC was blended using a blender and sieved with a 1 mm sieve. The residual material (i. e., bigger than 1 mm) was re-blended and re-sieved. The fine PKAC
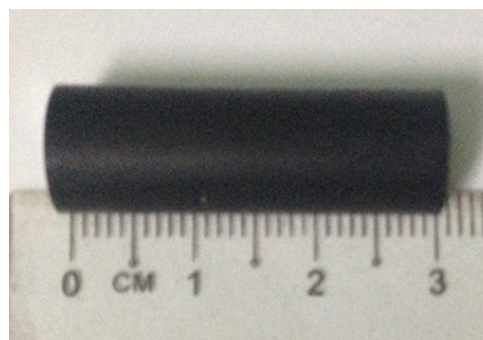

Fig. 1   Photo of PKAC-E composite after curing process

Table 1   Mechanical properties of the pin and disc materials at 27°C

Properties	[a] Pin (70 mass% PKAC+30 mass% Epoxy)	[b] Disc (EN-31 (AISI52100) high carbon alloy steel)
Hardness, H [GPa]	8.83	7.9
Porosity, [%]	1.21	-
Density, ρ [g/cm^3]	1.35	7.81

[a] Properties from laboratory measurements.

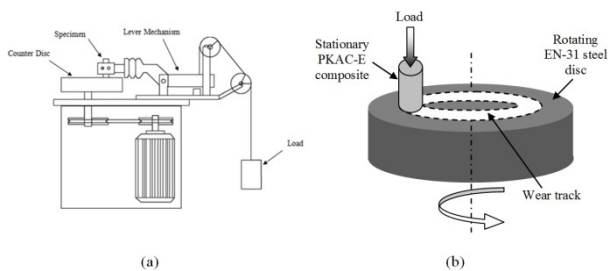[b] Properties from manufacturer.

Fig. 2 (a) Schematic diagram of a pin-on-disc tribometer and (b) illustration of the specimen placement
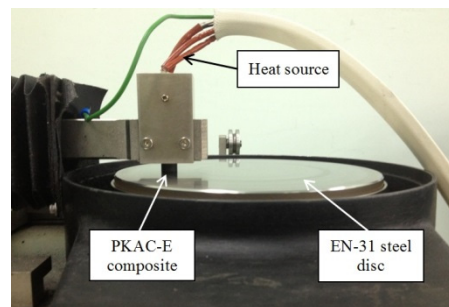

Fig. 3 Actual set up of a pin-on-disc test

Table 2 Dry sliding test operating parameter

Applied load, W [N]	Sliding speed, v [rpm]	Sliding Distance, L [m]	Temperature, T [°C]
49.05 (0.65MPa)	500 (2.618m/s)	2500	27, 60, 90, 120, 150

(size ≤ 1 mm) were then weighed by 70 mass% and mixed with epoxy 30 mass% (at a ratio of 4 : 1; resin: hardener). The mixed PKAC and epoxy were then placed in a mould, hot-pressed at 80°C and 2.5 MPa of compression pressure for about 10 minutes, and left to cool at room temperature for about 10 minutes before being pressed out. The pin specimens, sized 10 mm in diameter and 30 mm in height, were left to cure at room temperature for about a week. Figure 1 shows the specimen used in this study.

The density, surface roughness and hardness of the specimen were measured using densitometer, profilometer and Shore Hardness Durometer-D type, respectively. Besides, the porosity was measured based on the Archimedes principle.

2.2. Pin-on-disc test

The dry sliding test was performed, following ASTM standard [20], using a pin-on-disc tribometer. The disc was made from bearing material of EN-31 (equivalent to AISI52100) high carbon alloy steel. All tests were performed under different temperatures ranging from 27°C to 150°C at a constant sliding speed of 500 rpm (2.618 m / s) of 100 mm diameter of sliding track, applied load of 49.05 N (0.62 MPa), and a sliding distance of 2500 m. The heat was supplied and measured to the pin specimen. The average surface roughness of the pin specimen was about 0.40 μm ± 0.02; while for the disc, it was about 0.13 μm ± 0.02. The mechanical properties of the pin specimens and discs are shown in Table 1.

Prior to the sliding test, the disc specimen was cleaned using acetone in an ultrasonic bath. The pin was then mounted vertically on the tester arm at one end and the other pin surface was held against the rotating disc. The schematic diagram of the pin-on-disc tribometer and the actual placement image are shown in Figs. 2 and 3. Test conditions are summarized in Table 2.

The coefficient of friction (COF) and frictional force were measured using a personal computer (PC) based data logging system. The formula used was as follows:

$$\mu = F / W \tag{1}$$

Where, μ is the COF, F is the frictional force in unit N, and W is the applied load in unit N.

It was assumed that the disc had negligible wear, as there was no change in its weight. The wear of the pin was recorded by measuring the mass of the pin before and after the pin-on-disc test. The mass loss was determined by taking the difference in mass, and the mass loss (in mass units) was converted to volume by dividing the bulk density of the specimen. The specific wear rate was determined as follows:

$$V_{loss} = m_{loss} s / \rho \tag{2}$$

$$k = V_{loss} / (W \times L) \tag{3}$$

Where, V_{loss} is the volume loss in unit mm^3, m_{loss} is the mass loss in unit g, ρ is the bulk density in unit g / mm^3, k is the specific wear rate in unit mm^3 / Nmm, W is the applied load in unit N, and L is the sliding distance in unit mm.

2.3. Quantitative and Qualitative Analyses

The analysis in this study was made through quantitative and qualitative analyses. For the quantitative analysis, the results was based on the data logged PC for frictional coefficient, calculation of mass loss for specific wear rate, measurement of specimen surface roughness and hardness. Meanwhile, for the qualitative analysis, the surface morphology was observed using inverted microscope and Scanning Electron Microscopy (SEM). In addition, the chemical composition was determined using Energy-Dispersive X-ray spectroscopy (EDX).

3. Results and discussion

3.1. Friction and Wear Properties

From Figs. 4 and 5, it is clearly seen that the COF increased rapidly with operating temperatures. This might be due to frictional heating and failure of the epoxy bond. However, starting at 120°C, the COF seemed to be constant in the range of 0.7 to 0.8. It is believed that tribofilm starts to form on the counter surface after 120°C. Figure 6 clearly shows that the transfer film of the carbon element is generated at the counter surface. The transfer film of carbon materials is formed on the counter surface and helps to stabilize the friction between the surfaces. The tribofilm, generated from the preferential wear of the soft carbon material, results in a carbon based tribofilm adhering to the counter surface, which breaks the adhesive joints between the asperities and subsequently leads to a low or maintained friction [16,21].

Figure 7 shows a graph of specific wear rate against temperature. The wear rate gradually increases with temperature. It is believed that as the temperature increases, there is a thermal activated process between the PKAC and the epoxy in the composite. The thermal activated process occurred because of the thermal degradation of epoxy binder which was paralyzed and oxidized. It degraded as gasses and other degraded products. This situation resulted in a decrease in material hardness, which could potentially increase wear. From Fig. 8, it can be seen that the average hardness of the PKAC-E composite began to decrease after the 90°C operating temperature. At 150°C, the PKAC-E lost almost 30% of its original hardness. This was supported by Brostow et al. [22], who found that temperature had a direct impact on the wear of polymers.

3.2. Wear Mechanisms

Not much wear was observed on the pin surfaces below 60°C. Figure 9 shows the wear track of the PKAC-E composite at 90°C. It is clearly seen that parallel groves were formed by abrasive wear, which caused roughening of the test pin surface and resulted in rapid increases of COF as shown in Fig. 5. However, at high temperatures, specifically at 150°C, surface fatigue occurred with crack formations, as shown in Fig. 10. If
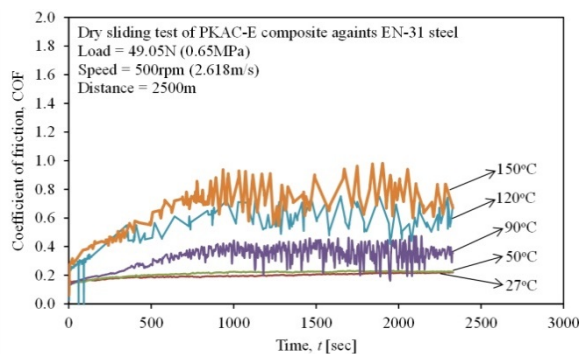

Fig. 4 Coefficient of friction at different operating temperatures of PKAC-E composite
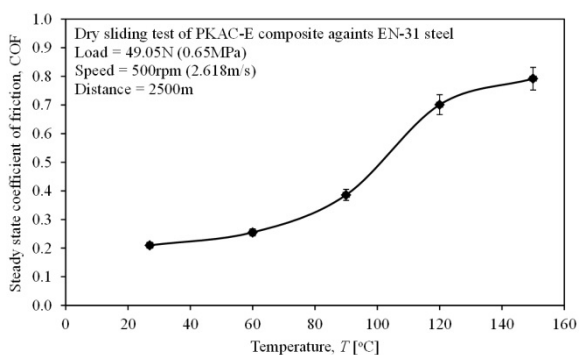

Fig. 5 Average steady state coefficient of friction of PKAC-E composite at different operating temperatures
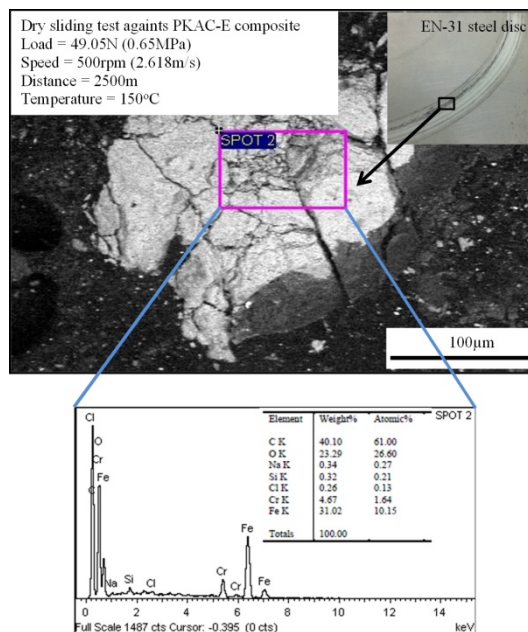

Fig. 6 SEM micrograph and EDX spectrum show that the transfer film of the carbon element was generated at the counter surface
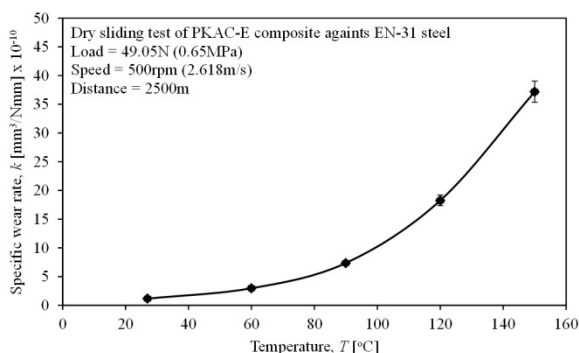
Fig. 7   Specific wear rates of PKAC-E composite at different operating temperatures
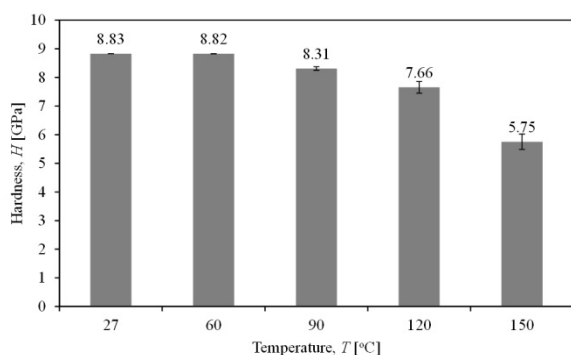

Fig. 8   Average hardness of PKAC-E composite at different operating temperatures
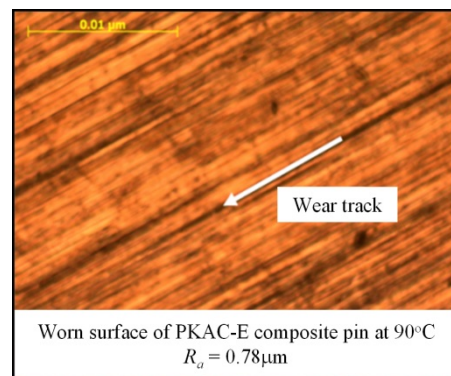

Fig. 9   Optical micrograph of worn surface of the PKAC-E composite at 90°C
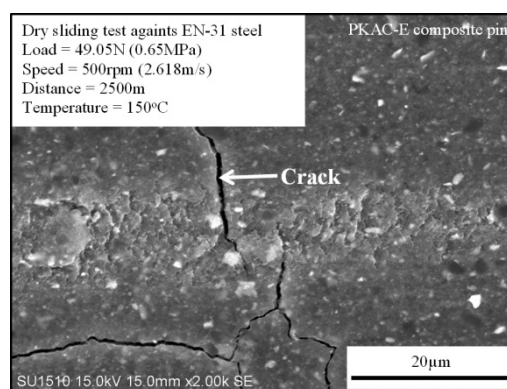
Fig. 10   SEM micrograph of worn surface on the PKAC-E composite show crack formations at 150°C

this situation continued, it would induce delamination wear. Gomes et al. [19] stated that fatigue effects and frictional heating were also responsible for causing surface damage and matrix fracture. Nirmal et al. [7] stated in their review that delamination wear was predominantly due to polymer swelling. Delamination usually occurs with mild signs of pitting, peel off, and cracks in worn surfaces.

4. Conclusion

In conclusion, the results showed that the COF and wear rate of PKAC-E composite increased with operating temperatures. Rapid increase of COF was clearly seen after 90°C due to frictional heating and failure of the epoxy bond. However, starting at 120°C, formation of tribofilm on the counter surface resulted in a constant COF. The wear rate kept increasing because of the thermally activated process which resulted in a reduction in hardness; thus causing the failure of the epoxy element in the composition. Abrasive wear and crack formations that would induce delamination wear were identified as the predominant wear mechanisms.

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