Influence of contact pressure and sliding speed dependence on the tribological characteristics of an activated carbon-epoxy composite derived from palm kernel under dry sliding conditions

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Abstract: The objective of this work is to investigate the influence of contact pressure and sliding speed on the coefficient of friction and wear of an activated carbon-epoxy composite derived from palm kernel under dry sliding conditions. A wear mode map approach was employed to identify the transitions from mild to severe wear of the composite. The dry sliding test was executed by utilizing a ball-on-disc tribometer at different contact pressures and sliding speeds with a constant sliding distance and operating temperature. The results showed that, regardless of the sliding speed, the friction coefficient and wear rate of the composite increased drastically when a critical limit of contact pressure is exceeded. As for the sliding speed, both the friction coefficient and wear rate increased first and thereafter decreased at a higher speed of 500 rpm. A wear mode map is proposed to classify the boundary from mild to severe wear regimes. The predominant wear failures identified include micro-crack, fine grooves, debonding, delamination, debris, broken carbon, and fracture.

Keywords: activated carbon; agriculture waste; palm kernel; friction and wear; pressure and speed

1 Introduction

Nowadays, many alternative technologies including thin film coatings [1–4], green lubricants [5–9], and bio/eco-materials [10–13] have been introduced for sustainability owing to the global need to save energy by reducing the friction and wear of components or parts.

Globally, Malaysia is one of the largest producers and exporters of palm oil, accounting for 11% of the world's oil and fat production, and 27% of the export trade of oils and fats. The palm oil industry generates a large quantity of waste consisting of approximately 90% of biomass waste and only approximately 10% of palm oil [14]. The use of agricultural waste as a

new composite material has been observed to be renewable and relatively less expensive and ultimately could transform the waste effectively into wealth [15–17]. Therefore, this motivated us to investigate the potential of activated carbon derived from one of the largest wastes in the extraction of palm oils, called palm kernel, as a new tribological material. The palm kernel activated carbon, also known as palm oil extraction waste material, is composed of a carbonaceous, highly porous adsorptive medium with a similar atomic structure as graphite, but in a disorganized form [18]. Furthermore, this activated carbon in the form of composite has immense potential to be a self-lubricating material with a low friction coefficient and high wear resistance owing to the

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presence of remaining natural oils in the palm kernel [19–21]. In addition, Tahir et al. [19] observed that there was no significant impact of sliding distance on the friction coefficient of a palm kernel activated carbon reinforced polymer composite. However, a change in working temperature was observed to influence its tribological performances. Chua et al. [22] discovered that there is a potential use of the palm kernel activated carbon reinforced with polymer composite as a lubricant in solid state, which can reduce the friction coefficient and wear owing to the applied load.

There were few research studies that reported the effects of operating conditions on the tribological characteristics of an activated carbon-epoxy composite derived from palm kernel, such as applied load, temperature, and sliding distance. However, studies on the simultaneous effects of contact pressure and sliding speed are limited to exploring the tribological characteristics of an activated carbon-epoxy composite derived from palm kernel. Thus, the aim of this study is to investigate the influence of contact pressure and sliding speed on the friction coefficient and wear of an activated carbon-epoxy composite derived from palm kernel under dry sliding conditions. Furthermore, a wear mode map of the composite is proposed to identify the transition points from mild to severe wear and their correlation with contact pressure and sliding speed.

Tabor [23] discovered the idea of a wear map and was inspired by the innovative work of Frost and Ashby [24] on deformation maps. The development of a wear map is a useful way to study and represent mild to severe wear transitions of two materials sliding against one another under different parameters. Studies have demonstrated that wear failure changes with the severity of contact conditions [25]. Until now, there was no specific outline to develop a wear mode map, because the controlling variables vary with mechanism or parameter. Generally, the construction of wear mode maps can be divided into two types, involving empirical and physical modeling [26, 27]. Empirical data from experiments are plotted on appropriate axes and identified by the wear rate. Boundaries are drawn to separate classes of wear failure. Physical modeling consists of model-based equations, describing

the wear rate caused by each mechanism. However, only the empirical approach is used in this study.

2 Methodology

2.1 Material preparation

For preparing the specimens, the material used in this study is activated carbon derived from palm kernel, which is waste from the palm oil extraction process. Palm oil is composed of exocarp, mesocarp, endocarp, and endosperm. However, in the extraction process undertaken by the manufacturer, only the endocarp part, also known as the kernel, is used, which becomes activated carbon derived from palm kernel.

As shown in Fig. 1, a disc of diameter 74 mm and thickness 5 mm was produced by mixing 60 wt.% activated carbon derived from palm kernel (particle size 250 μm) with 40 wt.% epoxy, where the hardener to resin ratio is 1:4. The mixture was thereafter placed in a mold and pressed using a hot-press machine at a forming temperature and pressure of 80 $^{\circ}\text{C}$ and 2.5 MPa, respectively. The green composite was thereafter cured at room temperature of 23 $^{\circ}\text{C}$ for one week.

The hardness, density, and surface roughness of the materials were measured using a Type D shore hardness tester, densitometer, and profilometer, respectively. The Young's modulus was determined using a tensile test.

2.2 Tribological test

The dry sliding experiment was performed utilizing a ball-on-disc tribometer (Fig. 2), in accordance with

Fig. 1 Disc specimen of an activated carbon-epoxy composite derived from palm kernel.

Fig. 2 Schematic diagram of a ball-on-disc tribometer.

ASTM G99-05 [28]. All the tests were performed at different applied loads between 20 and 100 N, with a sliding speed in the range 200–500 rpm at a constant sliding distance of 3,000 m. The operating temperature was 27 °C. ASTM 52100 (EN31) chrome steel ball, as a counter surface, with two different diameter sizes 10 mm and 12.7 mm, was used in this study. Each test was repeated three times to reduce the experimental errors.

The nominal contact pressure, P_m , was calculated based on the Hertzian theory using Eqs. (1) and (2).

$$a = \left(\frac{3WR}{4E^*} \right)^{1/3}; \quad \frac{1}{E^*} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2} \quad (1)$$

$$P_m = \frac{W}{2\pi a^2} \quad (2)$$

where a is the contact radius (m), W is the applied load (N), R is the radius of the ball (m), E^* is the effective Young's modulus (E_1 =Young's modulus of the disc; E_2 =Young's modulus of the ball), ν is the Poisson's ratio (ν_1 =Poisson's ratio of the disc; ν_2 = Poisson's ratio of the ball), and P_m is the nominal contact pressure (Pa).

The friction coefficient, μ , was calculated using Eq. (3).

$$\mu = \frac{F}{W} \quad (3)$$

where F is the frictional force (N).

The test composite wear data were obtained by measuring the initial and final disc masses via the ball-on-disc test. The specific wear rate, k , was calculated using Eqs. (4) and (5).

$$V_{\text{loss}} = \frac{m_{\text{loss}}}{\rho} \quad (4)$$

$$k = \frac{V_{\text{loss}}}{(W \times L)} \quad (5)$$

where V_{loss} is the loss of volume (mm^3), m_{loss} is the loss of mass (g), ρ is the density (g/mm^3), k is the specific wear rate ($\text{mm}^3/(\text{N} \cdot \text{mm})$), and L is the sliding distance (m).

A summary of the operating parameters used in this study is presented in Table 1. The physical-mechanical properties of both disc and ball are listed in Table 2.

2.3 Development of wear mode map

In this study, an empirical approach was used to develop a wear mode map, where suitable axes of the map were to be decided. The appropriate axes were determined to be the sliding speed and nominal contact pressure.

All the experimental wear data were plotted on two different graphs as a function of the sliding speed and nominal contact pressure. Subsequently, the locations of wear transitions were identified using experimental observations and data trend analysis. Arrows indicate the onset of these wear transitions. The best fitting curves connecting all the transition

Table 1 The operating parameters for the dry sliding test.

Test parameter	Unit	Value
Applied load, W	N	20, 40, 60, 80, 100
Ball's diameter, d	mm	10.0, 12.7
Sliding speed, N	rpm	200, 300, 400, 500
Sliding distance, L	m	3,000

Table 2 Physical-mechanical properties of the ball and disc materials before testing.

^b Properties	^a Disc (60 wt.% activated carbon + 40 wt.% epoxy)	^b ASTM 52100 (EN31) chrome steel ball
Hardness, H	8.36 GPa	7.45 GPa
Young Modulus, E	7.61 GPa	210 GPa
Poisson's ratio, ν	0.23	0.3
Density, ρ	1.4 g/cm ³	7.81 g/cm ³
Surface roughness, R_a	0.4 μm	0.022 μm

^a Properties from laboratory measurements.

^b Properties from manufacturer.

points were thereafter traced and illustrated on the graph of a wear mode map (sliding speed vs. nominal contact pressure). These curves represent the mild to severe wear transition boundary of the material.

2.4 Surface morphology observation

The surface morphology of the worn surfaces was observed using 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 coefficient and wear rate properties

Figure 3 presents the data on the friction coefficient and wear rate of an activated carbon-epoxy composite derived from palm kernel. It can be observed that, at the beginning, the friction coefficient decreases with contact pressure, although the wear rate remains almost constant. Subsequently, at a certain level of contact pressure, the friction coefficient and wear rate increase significantly. This could indicate that, when the contact pressure was raised, the real surface contact area also increased, causing more plastic deformation to the asperities, resulting in energy dissipation. This caused the frictional force to increase, while maintaining the wear rate. This study used Coulomb's friction law $F = \mu W$. The law was originally defined in a general per area form: $\tau = \mu q$, where τ is the friction per area and q is the normal pressure. This law is only applicable at low normal pressures. When the frictional force continues to increase, the rate (friction coefficient) at which it increases with respect to normal load decreases. Applying additional pressure, therefore, cannot flatten asperities further, and the contact area is constant at higher pressure. Therefore, friction should remain constant for higher pressure, as the law states, and only depend on the material strength. However, when the contact pressure increases to the critical limit, the friction coefficient and wear rate rise drastically owing to the critical surface energy. This could be explained by the fact that the frictional heat raises the temperature of the friction surfaces, which leads to a reduction in the material strength and will eventually result in surface softening

Fig. 3 Effect of contact pressure on the (a) friction coefficient and (b) wear rate of an activated carbon-epoxy composite derived from palm kernel at different sliding speeds. The error bar is for the standard deviation.

of the polymer composite or a decreased hardness of the composite, as discussed in our previous publication [29].

As for the sliding speed, both the friction coefficient and wear rate increase first and thereafter decrease at a higher speed of 500 rpm. This is due to frictional heating as discussed above. However, at a higher sliding speed of 500 rpm, there is a significant decrease in the friction coefficient and wear rate. Raising the sliding speed results in increasing the surface temperature, which reduces the adhesion between the composite surfaces and steel ball [30]. This behavior can be rationalized within the frame of the adhesive theory of friction to provide better self-lubrication and protection to surfaces. This can be explained by the fact that the tribolayer, produced by the initial wear of the carbon substance, was caused by a tribofilm adhering to the contact surface, which dissolves the adhesive joints between the asperities [31, 32]. From Fig. 4(a), the formation of a transfer layer, as observed on the counter surfaces, could have accounted for the decrease in friction coefficient and wear rate owing to

Fig. 4 SEM micrograph and EDX spectrum of the counter surfaces (a) tested at 88 MPa, (b) 111 MPa, and (c) as-received chrome steel ball.

the surface contact changes from carbonized-steel to carbonized-carbonized materials. Another possible explanation for the increase in the friction coefficient and wear rate, at a certain level of contact pressure for the sliding speed of 500 rpm, is the deterioration of this transfer layer, thus forcing the counter surface of the protective layer to disappear. This also signifies that the contact surface has experienced high abrasion owing to the ploughing between the contact surfaces, which might have influenced the increment of the friction force and wear rate [33]. Figure 4(b) shows a higher-magnification micrograph of the damaged regions, where abrasive wear starts materializing on the counter surface. Consequently, this may have caused the increase in the friction coefficient and wear rate of the composite at contact pressure, which led to the removal of the material. Figure 4(c) shows the SEM micrograph and EDX spectrum of the counter

surface for the as-received chrome steel ball, where the carbon element is not as much as in Figs. 4(a) and 4(b).

3.2 Wear mode map

Figure 5 is translated from Fig. 3, where the data values are separated by each sliding speed in order to trace the transition points from mild to severe wear. Figure 6(a) presents the wear mode map for the activated carbon-epoxy composite derived from palm kernel. It was developed based on transition points from the wear rate values as shown in Fig. 5. In this study, the wear mode map can be divided into two regimes: mild wear and severe wear. In the mild wear regime, the values of wear rates are relatively low and the surface damages are mild; in the severe wear regime, the wear rates are relatively high and the surface damages are severe [34]. From the wear mode map, regardless of the sliding speed, it was observed

Fig. 5 Transition points from mild to severe wear of an activated carbon-epoxy composite derived from palm kernel at different sliding speeds of (a) 200 rpm, (b) 300 rpm, (c) 400 rpm, and (d) 500 rpm. The error bar is for the standard deviation.

that increasing the value of contact pressure led to severe wear. When the composite operated at a higher level of sliding speed, the transitions from mild to severe wear occurred at lower contact pressure. However, after 400 rpm, a considerably slow change from mild to severe wear occurred, where the composite material showed better wear performance. This mild to severe wear transition was further confirmed by worn surface morphology.

Figure 6(b) shows the SEM micrograph of wear failures for the activated carbon-epoxy composite derived from palm kernel in both mild and severe wear regimes. In the mild wear regime, micro-crack (marked as “Cr”), fine grooves (marked as “Fg”), and debonding (marked as “Db”) were observed. In contrast, in the severe wear regime, predominant wear failures were identified as delamination (marked as “Dl”), debris (marked as “De”), broken carbon (marked as “Bc”), or fracture (marked as “Fr”). Fracture, delamination, and breaking of carbon led to the separation of carbon and resinous regions, which

resulted in higher material removal rate. Consequently, a high amount of debris was observed. Owing to the combined high action of contact surface and sliding speed, the surface of the composite generated friction, which led to the removal of wear debris. Moreover, a further increase in the sliding speed and contact pressure led to an increase in the temperature, which resulted in surface softening and elastic-plastic deformation, changing to plastic formation [35]. Thus, the severe wear manifested itself as massive surface damage accompanied by the generation of fine debris particles.

Figure 7 shows the most recent studies on the tribological performance of commercial and other agricultural waste-based polymeric composites for the purpose of comparison. An activated carbon-epoxy composite derived from palm kernel shows a lower friction coefficient and better wear resistance than other synthetic polymers and their composites. Moreover, the friction coefficient and wear resistant are similar to those of graphite/epoxy composite.

Fig. 6 (a) A wear mode map and (b) identified wear failures of an activated carbon-epoxy composite derived from palm kernel (Cr = micro-crack; Fg = fine grooves; Db = debonding; Dl = delamination; De = debris; Bc = broken carbon; Fr = fracture).

Fig. 7 (a) Coefficient of friction and (b) specific wear rate of synthetic and other agricultural waste-based polymeric composite under dry sliding conditions and tested at room temperature. The error bar is for the standard deviation. (Note: PKAC/E is an acronym for activated carbon-epoxy composite derived from palm kernel).

4 Conclusions

In summary, regardless of the sliding speed, initially, when the value of contact pressure increases, the friction coefficient decreases although the wear rate remains almost constant. When the contact pressure exceeds a critical limit, the friction coefficient and wear rate of the activated carbon-epoxy composite derived from palm kernel rapidly increase and lead to severe wear. However, both the friction coefficient and wear rate decrease at a higher speed of 500 rpm. Furthermore, a wear mode mapping approach was also undertaken to represent the mild to severe wear transitions. Predominant wear failures included micro-crack, fine grooves, debonding, delamination, debris, carbon broken, and fracture.

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