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FRICTION AND WEAR OF AMORPHOUS CARBON COATED STAINLESS STEEL UNDER PALM METHYL ESTER CONTAINED DIESEL OIL

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ABSTRACT

The popularity of plant-based biodiesel has been increasing nowadays. The methyl ester from various resources, such as Palm Methyl Ester (PME), are mixed with petroleum diesel and sold as biodiesel oil. On the other hand, amorphous carbon coatings have also been applied to mechanical components to improve the friction and wear performances such as those used in fuel injection system. This paper discusses the effect of PME and PME-contained diesel oil on friction and wear of amorphous carbon coated stainless steel balls sliding against stainless steel disk. The tests were conducted using a ball on disk tribometer at severe loading conditions. The results show that the wear of amorphous carbon coated ball decreases significantly with the increase of PME concentration in the diesel oil. When the tests were conducted in PME 100% oil, the wear scar diameter reduces 50% for a-C coated ball and 30% for a-C:H coated ball, compared to the wear scar diameter in pure petro diesel oil. Although clear differences in friction coefficients could not be seen, the results indicated that PME contribute to the reduction of wear of the coated ball, drastically. According to this results, the non hydrogenated carbon coating is more suitable to be used in PME contained diesel oil.

Keywords: amorphous carbon coating, palm methyl ester, friction, wear, stainless steel.

INTRODUCTION

The use of diesel fuel in automotive industry increases significantly in recent time, mainly because of its high efficiency. Particularly, the diesel fuel efficiency can reach up to 40% with the use of high pressure fuel injection system, with a pressure up to 200 MPa [1]. However, sustainability issues as well as environment concerns have been growing steadily nowadays and this require engines that not only consume low fuel but also produce low emission. Biodiesel is one of renewable sources of fuel that fulfill these criteria. Analysts predicted that world consumption of biodiesel and bioethanol will reach 135 billion gallons in 2018 [2].

The switch of fuel to biodiesel has several implications to automotive industry because, among others, biofuels affect the tribological performances of the mechanical components particularly those related to the fuel injection system [3, 4, 5]. On the other hand, solid lubricant coatings such as amorphous carbon coatings have also been applied to the mechanical components to improve the friction and wear performances, including the mechanical parts of the fuel injection system. Here, the ability of the bio-degradable oil in lubricating the mechanical contact of the components is affected by the type of amorphous carbon coating as well as the additives [6,7,8]. It is reported that the tribological properties of Diamond-like Carbon (DLC) coatings inside polyalpha olefin synthetic oil (PAO-4) are affected by temperature, besides additives [9, 10].

Although the effect of PME on friction and wear of metals has been studied by many researchers, there are still few discussions on the effect of PME on friction and wear of amorphous carbon coated metals. PME is mainly composed of triglycerides, glyceride, free fatty acids and non-glyceride substances. In the case of metal on metal contact, PME is found to have a beneficial effect. It is reported that PME acts like an anti wear properties on cast iron [11] and therefore it can be used as additive in lubricants. In other report, it is found that a 10% addition of PME into diesel oil resulted in 10% wear reduction of cast steel ball [12].

As far as it is concerned, discussion about friction and wear properties of amorphous carbon coating in PME and PME-contained diesel oil is still very limited. Nevertheless, there are several reports on the coating's tribological properties under lubrication of other bio-oil lubricants, such as the sunflower oil [13] and rapeseed oil [14]. It is found that the friction and wear performances of the coatings are improved in both bio-oils, especially when the temperature reaches 100^{o}C [13]. Donner-Reisel *et al.* [15] reported that the bio-fuel with a high unsaturated fatty acids fraction could reduce friction in a tribological systems with chemically inert DLC. However, the type of bio oil used in that case is not clarified.

In this paper, the friction and wear of amorphous carbon coated stainless steel under lubrication condition of palm methyl ester (PME) and PME contained diesel oil are investigated. Various concentration of PME in petro diesel fuel were prepared to investigate the effect of PME on the friction and wear performances of the material.

Experiment setup and data acquisition

The tests were conducted using a pin on disk tribometer. The schematic diagram of the tribometer is given in Figure-1. The ball is 8 mm in diameter and the disk is 30 mm in diameter and 5 mm in thickness. Two types of amorphous carbon coating were used; amorphous carbon (a-C) and hydrogenated amorphous carbon (a-c:H).

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The disk is not coated but polished with surface roughness Ra=0.03 μm.

During the friction tests, the sliding members were dipped into chamber containing diesel oil and diesel oil mixed with various volume percentage of PME. Therefore, the mixtures are defined according to the percentage of PME, i.e. PME 0%, PME 7.5%, PME 15%, PME 30%, and PME 100%. The PME itself is biodiesel oil and can be used as the substitute for petro diesel oil. The tests were conducted at severe loading condition. The applied weight was 15 N and the rotation speed was 100 rpm for the entire test. The tests were conducted for 9000 cycles. The friction force data was acquired using a load cell and a strain amplifier connected to personal computer. The wear scar of the ball was analyzed using optical microscope. The tests were conducted at ambient temperature of 27ºC.

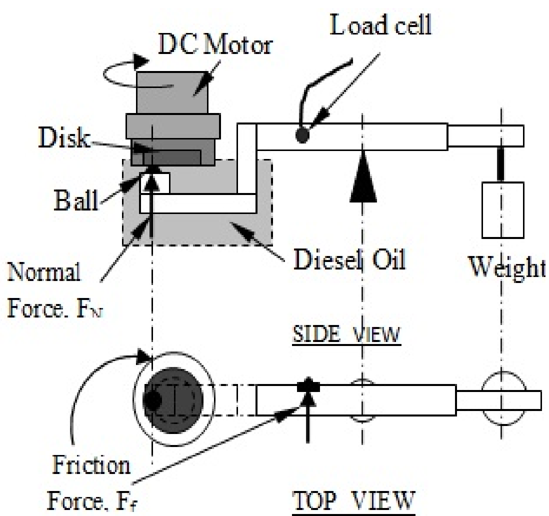
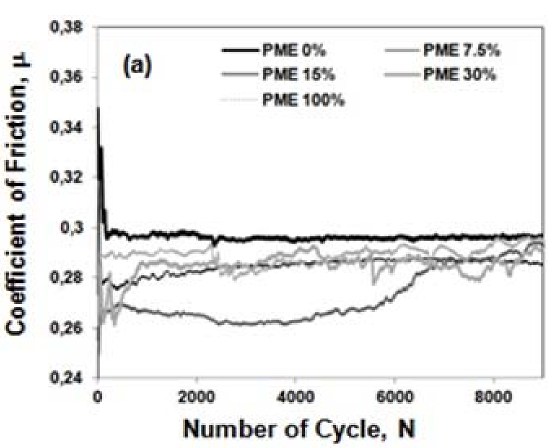


Figure 1. Schematic diagram of the pin on disk tribometer.



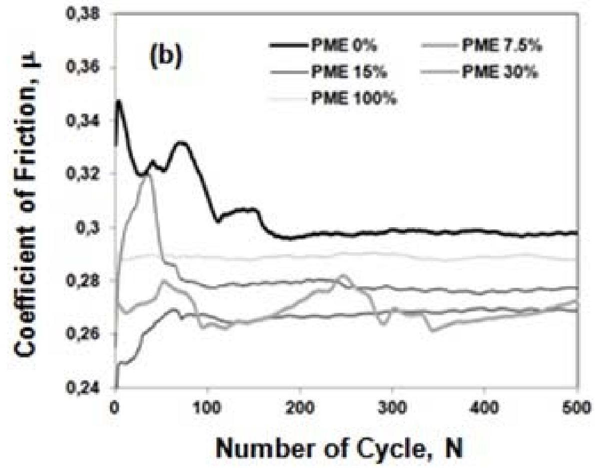


Figure 2. Effect of PME content in diesel oil on friction coefficient of steel/a-C coated ball (a) and the friction development for the first 500 cycles (b).

RESULTS AND DISCUSSION

The results of friction tests showing the relationship between coefficient of friction and the number of cycles are given in Figure-2 and Figure-3. For steel/a-C coated ball, it is seen that the friction coefficient is largest at PME 0% condition with an average value of 0.3 (Figure-2(a)). At this condition, the friction coefficient seems stable for the entire test cycle up to 9000 cycles. The friction coefficient for the same PME 0% condition for steel/a-C:H coated ball is relatively similar, i.e. 0.29 (Figure-3(a)). The friction behaviors for these PME 0% conditions for both steel/a-C and steel/a-C:H pairs were relatively similar at the first few hundred cycles, (Figure-2(b) and Figure-3(b). The stable friction coefficient value of 0.3, for both cases, were reached within the first 200 cycles. The friction coefficient value of 0.3 is considered normal for this condition. Podgornik et. al [16] observed a friction coefficient of 0.2 in the first 10000 cycles for the case of steel/DLC coating in diesel oil.

The friction behavior of the contact pairs for various concentration of PME can be observed more detail in the running-in process, which is shown in the first few hundred cycles of the sliding, as given in Figures-2(b) and 3(b). For the case of PME 0%, both combinations of steel/a-C coating and steel/a-C:H coating show a relatively high friction at running-in, which lasted for about 200 cycles. This is an indication that the coating layer broke immediately after the sliding started. The wear scar of the balls can be observed in Figure-4(a) and Figure-4(f) for a-C and a-C:H coated balls, respectively. For the case of a-C coated ball, the wear seems occurring uniformly across the contact area. The diameter of the wear scar is about 600 μm. In the case of a-C:H coated ball, the wear is not uniform across the contact area, although the dimension of the wear scar is relatively similar to that of a-C coated ball.

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The coefficient of friction become slightly lower with the present of PME in the diesel oil. However, this decrease seems independent on the percentage of the PME in the mixture. As observed in Figure-2(b) for the case of steel/a-C coated ball, 7.5% PME in the oil decrease the coefficient of friction slightly. Further increase of PME, 15%, only slightly decreases the friction coefficient further. But when the PME content were further increased, the friction coefficient increased again. Similar phenomena was also observed for the cases of steel/a-C:H coated balls. In the overall, it seems that there is an optimum value of PME concentration in the diesel oil which can produce lowest friction coefficient. In these cases, it seems that the value lies between 15% and 30% of PME in the diesel oil.

However, an important information is observed in the running-in process of the contact pairs. As observed in Figure-2(b) and Figure-3(b), the presence of PME in the oil has reduced and/or completely eliminated the running-in process. As stated before, for both cases of steel/a-C and steel/a-C:H, the running-in process were observed for the case of PME 0% and PME 7.5% condition. For example, in the case of steel/a-C coated ball (Figure-2(b)), the friction coefficient started at 0.34 for the case of PME 0% and required about 200 cycles to be stable at 0.3. With the presence of 7.5% PME in the oil, this running in process is shortened to less than 100 cycles. Furthermore, the presence of 15% PME in the oil has completely eliminated the running in process. The friction coefficient started at 0.24 and increases to 0.26 within 100 first cycles. At 100% PME, a stable friction coefficient of 0.28 was achieved from the beginning of the test. This results indicated that the presence of PME content in the oil has a positive effect for the friction behavior of the amorphous carbon coating. It is highly possible that the coating layer persisted for a longer time with the presence of PME component in the oil. Whereas without the PME, the layer broke immediately after the start of the sliding. However, a more careful analysis on this matter is necessary.

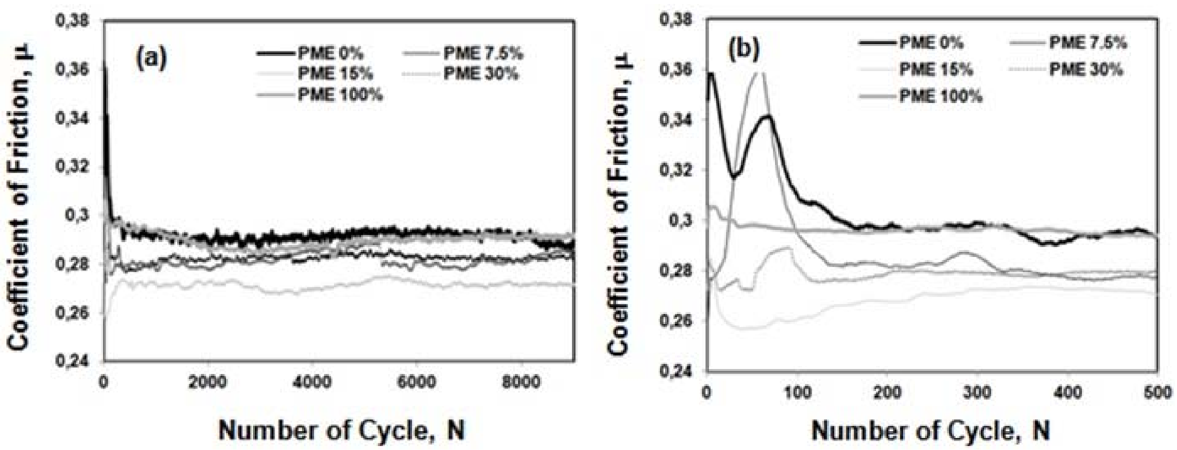


Figure 3. Effect of PME content in diesel oil on friction coefficient of a-C:H coated ball (a) and friction development at first 500 cycles (b).

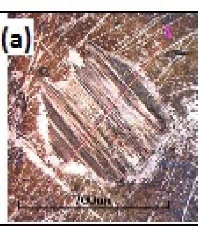
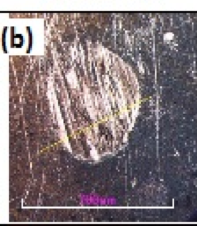
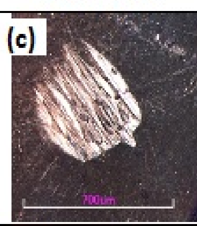
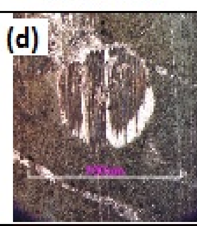
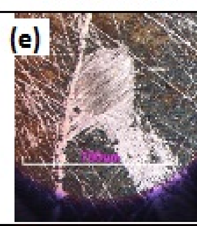
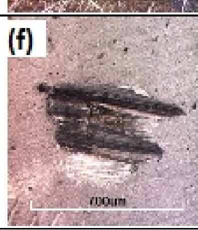
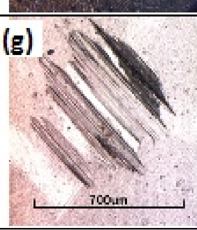
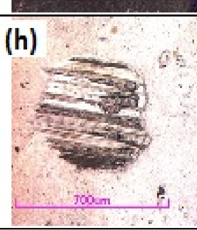
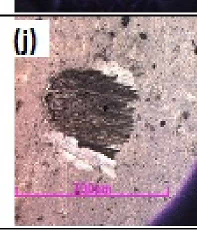
	PME 0%	PME 7.5%	PME 15%	PME 30%	PME 100%
a-C					
a-C:H					

Figure-4. Effect of PME content in diesel oil on the wear scar dimension.

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Therefore, the presence of PME in the diesel oil is beneficial to reduce the number of cycle required in the running-in process prior to stable friction stage. This is believed to have a significant effect to the wear of the material, as shown in Figure-4.

Figure-4 shows the wear scar of the amorphous coated stainless steel balls under various conditions of PME percentage in the diesel oil. For the case of PME 0% diesel oil (Figure-4(a)), the width of wear scar is about 600 μm in the case of steel/a-C pair. As the content of PME in the oil increases, the width of wear scar gradually decreases. At PME 100%, the width of wear scar was 300 μm (Figure-4(e)), a 50% decrease.

Similar phenomena is also observed for the case of steel/a-C:H coated ball. Figure-4(f) shows that the wear is severe causing deep grooves along the sliding direction, as shown in Figure-5. The length of the longest grove is about 700 μm at PME 0%. At PME 100%, the diameter of the wear is about 500 μm, about 30% smaller compare to that at PME 0%.

Figure-6 shows the comparison between the worn surface of steel/a-C coating in PME 0% diesel oil and that in PME 100% oil. In PME 0%, it can be seen that the wear is severe with a relatively large and deep grove (Figure-6(a)). A different condition is shown in Figure-6(b). The wear groves are relatively smaller and the worn surface seems smoother. Therefore, it is suggested that a-C type of coating is more suitable to be used in PME contained diesel oil.

In both cases of a-C and a-C:H coated ball, the coatings on the worn surface has been completely removed at the end of the test. This is considered normal in severe loading condition. In the future, it is necessary to conduct the test using small loading condition in order to find out the wear resistance of the amorphous carbon coating in PME lubrication environment.

This results indicated that application of amorphous coating are beneficial for the fuel system components, as suggested in Ref. [16]. Here, it is shown that the coatings improved the wear resistance of the steel ball in the PME blended biodiesel. This could be caused by the anti wear characteristic of the PME component, as suggested by Fazal *et al.* [12]. Amorphous carbon coatings also improve the friction and wear properties with other types of biodiesel such as rapeseed oil [14].

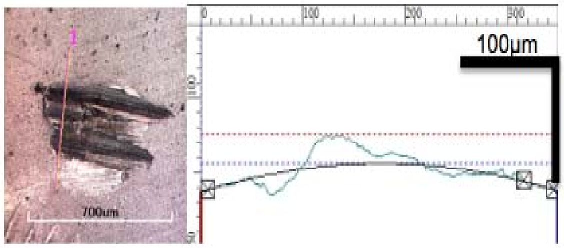

Figure-5. Cross section of a-C:H coated ball's worn area at PME 0% condition. The cross section refers to the magenta line of the worn scar.

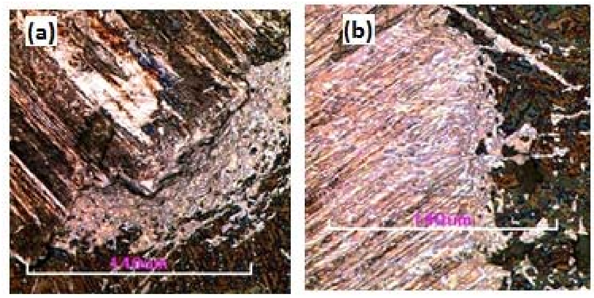

Figure-6. Effect of PME on wear of a-C coated stainless steel ball; PME 0% (a) and PME 100% (b).

CONCLUSIONS

The friction and wear characteristics of steel/a-C and steel a-C:H tribo pair in PME contained diesel oil have been investigated. The results show that the wear of coated balls decreases by 50% for the case of steel/a-C pair and 30% for that of steel/a-C:H pair as the effect of PME mixture in the diesel oil. It is also concluded from the results that this wear reduction is caused by the running-in behavior of the tribo pair. The presence of PME component in the oil have decreased or the running in process. It seems that the PME component provides an anti wear characteristic to the tribo pair, preventing excessive wear of the material, especially at severe loading condition. However, in order to clarify the role of PME component in reducing the wear, further investigation is necessary.

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