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Effect of DLC coating on tribological behavior of cylinder liner-piston ring material combination when lubricated with Jatropha oil

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Abstract

The expansion of modern engines would have been unfeasible without advanced lubricant chemistry and proper lubricant formulation. Introduction of diamond like carbon (DLC) coatings opens further possibilities in improving performance of engine and transmission components, which cannot longer be achieved only by lubricant design.DLC coatings show extremely good promise for a number of applications in automotive components as they exhibit excellent tribological properties. In this paper, the tribological performance of hydrogenated amorphous carbon (a-C: H)DLC coating with Jatropha oil was evaluated using a four ball Tribometer also with commercial synthetic lubrication oil (SAE 40) used as base lubricant. Experimental results demonstrated that the hydrogenated amorphous carbon (a-C: H)DLC coating exhibited better performance with Jatropha oil in terms of wear and friction under similar operating conditions compared to the uncoated stainless. Thus, usage of hydrogenated amorphous carbon (a-C: H)DLC coating with Jatropha oil in the long run may have a positive impact on engine life.

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*Keywords:*Hydrogenated amorphous carbon (a-C: H)DLC Coating; Bio-lubricant; Wear; Friction

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Nomenclature

I_d	D peak intensity of RAMAN spectra
I_g	G peak intensity of RAMAN spectra

1. Introduction

Increasing environmental awareness and demands of lowering energy consumption are strong driving forces behind the development of the transport vehicles of tomorrow. By reducing friction and wear of engine components, the efficiency and lifetime of a vehicle can be significantly increased. Surface treatments and coatings contribute to a better lubrication with oils and can participate significantly in achieving these goals. In modern engines, it has become increasingly more common to deposit thin wear resistant low friction coatings composed of amorphous carbon, also known as diamond like carbon (DLC), on the components in question. DLCcoatingsmain advantages are low friction, good anti-wear properties, adhesive protection, extreme hardness, high elastic modulus,excellent corrosion resistance, high thermal and chemical stability [1]. It has diamond like structure consists of both SP^3 and SP^2 bonding. The mechanical property like hardness, elastic modulus largely depends on the relative amount of these two types bonding. Higher % of SP^3 bonding gives better mechanical property [2,3].The mechanism by which DLC coating reduces the friction coefficient is it forms a transfer layer into the counter surface and transfer layer forms a tribo-film with lubricant thus minimize the friction coefficient.

Also the development of modern engines would have been unfeasible without proper lubricant formulation and advanced lubricant chemistry [4].Vegetable oil based bio-lubricants are renewable and biodegradable in nature. The biodegradability of bio-lubricant is the strongest point in the case for their automobile use. Bio-lubricants are shows potential source as alternative include lower toxicity, high viscosity index, increased equipment service life, high load carrying abilities, good anti-wear character and excellent coefficient of friction [5]. Both boundary and hydrodynamic lubrication can be obtained from the bio-lubricant due to its long chain free catty acid and polar groups of the natural plant oil.

The main aim of this paper is to provide information to the engineers, policy makers, industrialists and researchers who are interested in DLC coatings with bio-lubricants for automotive applications. This paper presents the tribological performance of hydrogenated amorphous carbon (a-C: H)DLC coatings tested against steel and hydrogenated amorphous carbon (a-C: H)DLC coatings with Jatropha oil and commercial oil (SAE 40). Three different types of combinations used in this experiment for investigate the tribological performance of hydrogenated amorphous carbon (a-C: H)DLC coatings such as steel/steel combination, steel/a-C: H DLC combination and a-C: H DLC/a-C: H DLC combination.

2. Experimental method

2.1 Preparation of tribological samples

In this experiment was only concern with most friction prone area of engine like piston ring and cylinder liner. Those parts are generally made by stainless steel. The test balls used in this experiment were made of stainless steel and meet ASTM A276-98b 440C stainless steel specifications. The test balls had a diameter of 12.7 mm. Hydrogenated amorphous carbon (a-C: H) DLC films were deposited on stainless steel balls by an ion beam deposition method. Prior to the installation of these samples in the deposition system, the substrates were ultrasonically cleaned in the bath solution of water and metal cleaning agent, rinsed in deionized water and ethanol, and then dried in hot air. Table 1 shows the properties of substrate and coating materials.

Table 1. Properties of substrate and coating materials

Properties	Substrate	Coating
Specification	440C stainless steel	a-C: H
Hardness	540 Hv	3000 Hv
Roughness	0.03 – 0.04 Ra	0.03 – 0.04 Ra
Thickness		1.6 μm

2.2 Lubricant properties test

There are two different types of lubricant sample were investigated in this study. Jatropha oil and commercial synthetic lubrication oil (SAE 40) was used as a reference lubricant. Table 2 shows the properties of lubricants sample.

Density: DMA 35 portable density meter was used to measure the density. The samples were tested at 40^{0}C. Only 2 ml of each sample was used per test.

Viscosity index (VI): ASTM D2270 was used to calculate the viscosity index. For this method 40^{0}C is used to determine kinematic viscosities and 100^{0}C is used to determine the VI. The experiments were done by using a Stabinger Viscometer (SVM 3000)

Table 2. Properties of Lubricants Sample

Properties	SAE 40	Jatropha oil
Kinematic Viscosity at 40˚C (mm^2/s)	40.444	35.077
Kinematic Viscosity at 100˚C (mm^2/s)	8.4289	7.8036
Viscosity Index	191.7	202.8
Density (Kg/m^3)	898.4	985
Oxidation Stability 110˚C,h	24.36	7.34

2.3 Friction evaluation

A 40 kg beam type load cell was used to measure the frictional torque. The load cell was fitted at a distance of 100mm from the center of the spindle. The coefficients of friction in these experiments were calculated according to IP-239 standards as shown in Eq. [1], where μ is the coefficients of friction, T is the frictional torque (N-m), W is the applied load (N), and r is the distance from the center of the contact surface on the lower balls to the axis of rotation, which was determined to be 3.67mm. A similar calculation was used by Husnawan[6], et al. and Thorp [7].

$$\mu = \frac{T\sqrt{6}}{3Wr} \quad (1)$$

2.4 Wear tests

The tests were carried out at a load of 40 kg (392.4N) and at 1200 rpm for 1 h and 100˚C. The wear scar diameter of the three balls was measured using a scanning electron microscopy (SEM).

Fig. 1. Four ball Tribometer.

2.5 Test procedures

The four ball wear tester (Fig. 1) is the predominant wear tester used by the oil industry to study lubricant chemistry. In this experiment, test method used to investigate wear preventive characteristic was ASTM D4172 (load 392.4N, 1200 rpm, 3600 sec and 100˚C). Balls were thoroughly cleaned in an ultrasonic bath with acetone and n-heptanes. The test lubricant was introduced into the oil cup assembly and confirmed that the oil filled all of the voids in the test cup assembly. The lubricant was then heated to the desired temperature. When the set temperature was reached, the drive motor, which was set to drive the top ball at the desired speed, was started. After the 3600 seconds test period, the heater was turned off and the oil cup assembly was removed from the machine. After the tests, the bottom balls were placed on a microscope base that was designed to hold the balls during microscopic evaluation. The three bottom balls in the wear test were evaluated, and the average diameter of the circular WSD (wear scar diameter) formed was measured.

3. Results and discussion

Variations in the coefficient of friction (μ) with respect to time (sec) for three material combinations steel/steel, steel/a-C:H and a-C:H/a-C:H combinations when lubricated with Jatropha oil and SAE 40 are shown in Fig. 2. The a-C:H/a-C:H combinations gives the lowest coefficient of friction (~0.065) compared to steel/steel combination (~0.12) and steel/a-C:H (~0.075). The steel/a-C:H material combinations shown very uniform coefficient of friction(Fig. 2b)and values closed to the a-C: H/a-C: H combinations values under same test condition. The coefficient of friction for a-C: H coated material was approximately 40-45% lower than that of uncoated material with Jatropha oil. This can be explained that the a-C: H DLC coating reduces the wear rates is it forms a transfer layer into the counter surface and transfer layer forms a tribo-film with lubricants. In the case of Jatropha oil, under same testing conditions result shown almost similar coefficient of friction as observed for SAE 40. The reason for the mostly lower friction with Jatropha oil lies in the large amount of unsaturated molecules and polar components (fatty acids) in the oils. Indeed, this affects their lower oxidation stability, but increases the lubricity.

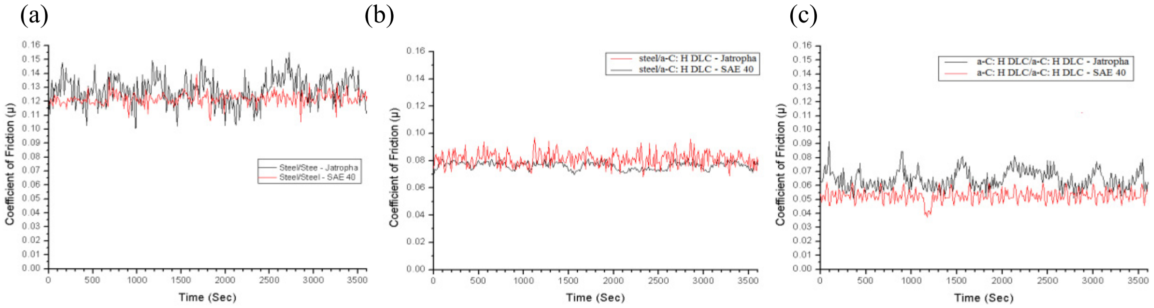

Fig. 2. Variation in coefficient of friction with Jatropha oil and SAE 40 at (a) steel/steel; (b) steel/a-C: H; (c) a-C: H/a-C: H combinations.

The Wear scar diameters (WSD) results for steel/steel, steel/a-C:H and a-C:H/a-C:H combinations with Jatropha oil and SAE 40 are shown in Fig. 3. The significance improvement in WSD was found for steel/a-C:H for both Jatropha oil and SAE 40, which is approximately 45% lower as compared to steel/steel combination. The a-C:H/a-C:H combination, shown slightly higher wears rates compared to steel/a-C:H combinations (4%). This can be explained that the a-C:H DLC coating forms a transfer layer into the counter surface. Transfer layer contained a fine distribution of graphite nano particles. Distorted coating film and graphitization process took place within the wear track region of the coating under thermal and strain effects from the repeated friction [8].

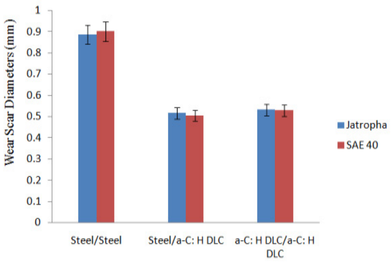

Fig. 3. Wear scar diameters (WSD) of steel/steel, steel/a-C: H and a-C: H/a-C: H combinations with Jatropha oil and SAE 40.

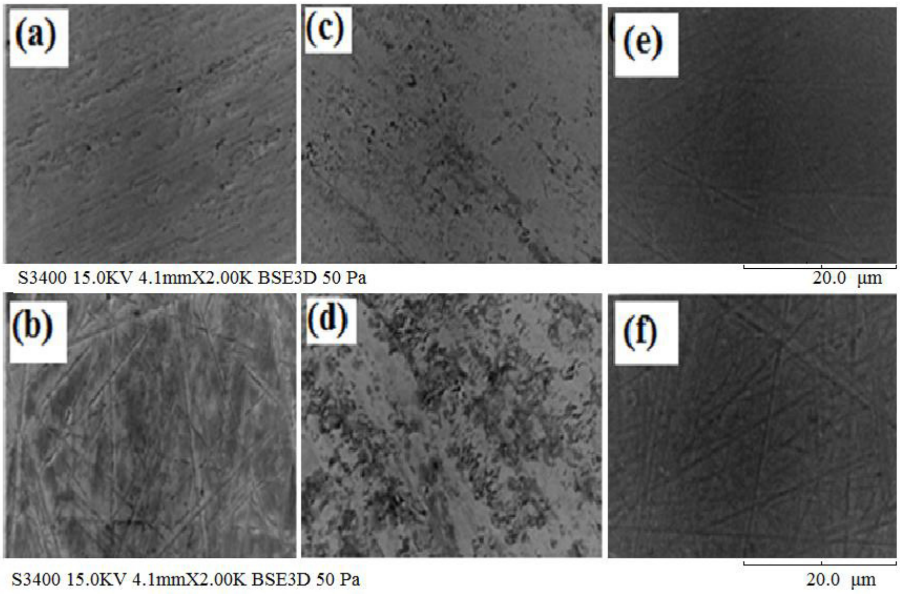

Fig. 4.SEM images of the steel balls worn surfaces tested against (a) steel/steel combination with SAE 40; (b) steel/steel combination with Jatropha oil; (c) steel/a-C:H combination with SAE 40; (d)) steel/a-C:H combination with Jatropha oil; (e) a-C:H/a-C:H combination with SAE 40; (f) a-C: H/a-C:H combination with Jatropha oil.

The SEM images of the area around the wear scar and the worn surfaces of the ball specimens for different material combinations with Jatropha oil and SAE 40 are shown in Fig. 4. In this experiment, lubricant occurred in boundary lubricationregime thereby, adhesive wear, abrasive wear, corrosive wear and fatigue wear were observed in to the rubbing zone. The mostly the wear phenomenon were adhesive wear, abrasive wear and the appearance of the worn surfaces seems to present corrosive product of black color when Jatropha oil used as lubricants. This may be explained from the fact that at high temperature, Jatropha oil can be oxidized and thereby produces different types of corrosive acids that enhance corrosive wear [9-11]. Steel/steel combination (Fig. 4a and b) shows several distinctive worn regions, slight adhesive wear with fewer grooves on steel surfaces. Mild wear occur during the test with steel/a-C: H combinations (Fig.4c and d). In the case of a-C: H/a-C: H combination, exhibitedno measurable wear (as observed in the SEM), with the coating being almost intact and original substrate topography still visible (Fig.4e and f).

As measured, the wear of the steel/a-C:H contacts was small with both oils, and the SEM analyses confirmed this behavior. Some signs of adhesion could be found in the contacts, the surfaces were very smooth. However, in steel/a-C:H combination the steel balls experienced, despite signs of a thin adhered wear-debris layer (Fig. 4d), rather low wear when lubricated with Jatropha oil. In contrast, relatively high wear was observed when steel/steel combination with Jatropha oil (Fig. 4b). Fig. 4f shows a distinctive layer with an amorphous-like appearance that is formed on the surface. The layer is obviously soft, as is typical for many tribo-chemical layers [12, 13], and can be the result of severe plastic deformation and smearing. Moreover, a-C: H coated materials combination with steel and it self-exhibit smooth worm surface when lubricated with Jatropha oil and no measurable wear found (as observed in the SEM). It is well known that a-C:H DLC coating is a layer by layer structure and between each layer there is a week Van der Waals force, therefore these layers can slide easily among each other.

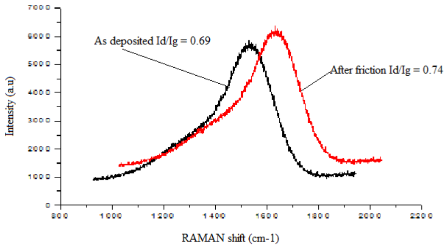

Fig. 5. RAMAN analysis of the as deposited a-C: H DLC coating

RAMAN analyses have been done for a-C: H/a-C: H combination when lubricated with Jatropha oil before and after testing to show the changes due to friction as shown in Fig. 5. From RAMAN spectrograph it shows that I_d/I_g ratio increases for the wear surface of a-C: H coating compared to as deposited coating surface. Intensity of D peak usually stronger for wear surface compared to as deposited surface, which conforms that the ratio SP^3 to SP^2 bonded carbon configuration of the DLC film decreases. The increase in I_d/I_g ratio or shift to higher wave number of the G band peak position is related to the reduction of the SP^3 region. According to the RAMAN analysis it is clear that wave number shift to right and intensity slightly increases. Here I_d/I_gratio increases from the as deposited a-C: H coating. In this present work I_d/I_gratio is close to 0.699 of as deposited coating and after testing I_d/I_gratio is increased to 0.74. This is clear indication of high degree of graphitization in this test condition.

4. **Conclusion**

The experimental results show that the a-C:H DLC coating with Jatropha oil reduced coefficient of friction and wear loss. For investigation of different material combinations, the a-C: H/a-C: H combinations resulted in the lowest coefficient of friction (~0.065) compared to steel/steel combination (~0.12) and steel/a-C: H (~0.075) combinationwith Jatropha oil. The steel/a-C:Hmaterial combinations shown very uniform coefficient of friction and a-C:H/a-C:H combination exhibit smooth worm surface with Jatropha oil. The coefficient of friction for a-C:H DLC coated material was approximately 40-45% lower than that of uncoated material. Also when in contact with a steel surface and a-C:H DLC coating gives superior wear resistance in Jatropha oil compared to steel/steel contact.

The large amount of un-saturated and polar components in the Jatropha oil significantly improved the tribological properties of the a-C:H coating. Therefore, hydrogenated amorphous carbon (a-C: H)DLC coating exhibited better performance with Jatropha oil in terms of wear and frictionunder similar operating conditions compared to the uncoated stainless steel. Thus, usage of hydrogenated amorphous carbon (a-C: H)DLC coating with Jatropha oil in the long run may have a positive impact on engine life.

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