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Research Paper

TRIBOLOGICAL BEHAVIOR OF DUAL FUEL DIESEL ENGINE

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Significant efforts have been made to reduce the pollution caused by Direct Injection (DI) diesel engines during the past decades. One of the promising engineering solutions is the use of gaseous fuels as a supplement for liquid diesel fuel. These engines, which use conventional diesel fuel and gaseous fuel, are referred to as dual fuel engines. The main objective of the dual fuel combustion systems is to reduce particulate emissions and nitrogen oxides. One of the gaseous fuels used is natural gas, which is a clean burning fuel, economical and possesses a relatively high auto ignition temperature. The high auto ignition temperature of natural gas is a serious advantage against other gaseous fuels since the compression ratio of most conventional DI diesel engines can be maintained. Furthermore, the combustion of natural gas produces practically no particulates since natural gas contains less dissolved impurities (e.g., sulfur compounds). The current study investigates the tribological performance of dual fuel diesel engine used oil. A set of used oil samples was taken from the dual fuel diesel engine after 25 hrs, 50 hrs and 100 hrs of operation at full load. A standard ball on disc friction-wear testing machine was used to study the impact of the above mentioned used oils on the friction and wear of various engine components. The results showed that the dual fuel engine used oil showed a much better behavior than the traditional diesel engine used oil in terms of friction and wear behavior for the four different levels of operating times. The difference was more significant at the longer operation time. This can be attributed to the fact that the dual fuel engine is a cleaner engine; hence it produces lower soot content than the diesel fuel engine.

Keywords: Friction, Wear, Dual fuel engine, Oil

INTRODUCTION

The popularity of diesel engines has increased in the recent years due to their higher fuel efficiency and lower maintenance costs. Despite these advantages, high levels of exhaust NOx and particulate matter emissions from diesel engines are 50-80 times greater than emissions from spark-ignition engines.

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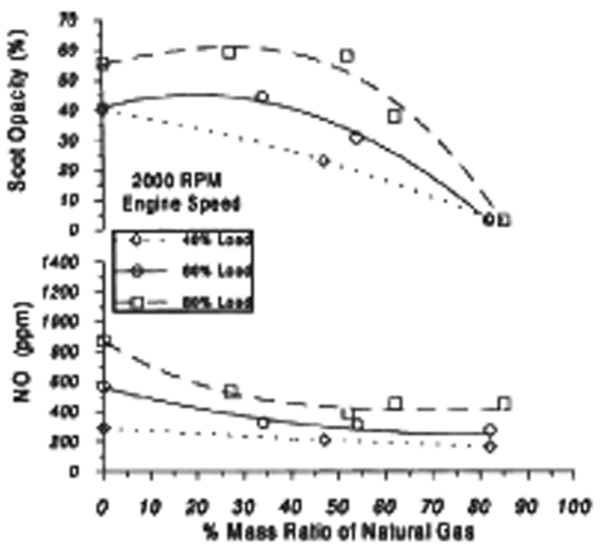
Contamination of lubricating oil by diesel soot is one of the major causes of increased engine wear. The diesel soot interacts with engine oil and ultimately leads to wear of engine parts. Significant amount of research has been done in an attempt to control NOx emissions. Some of these attempts include controlling the fuel injection system parameters, controlling in-cylinder charge conditions, EGR, and controlling fuel formulation. One of the promising engineering solutions is the use of dual fuel engines which use conventional diesel fuel and gaseous fuel (Barata, 1995; Daisho *et al.*, 1995; Dishy *et al.*, 1995; Karim, 2003; Lin and Su, 2003; Selim, 2003; Aldajah *et al.*, 2007; and Carlucci *et al.*, 2008). The main objective of the dual fuel combustion systems is to reduce particulate emissions and nitrogen oxides. One of the gaseous fuels used is natural gas, which is a clean burning fuel, economical and possesses a relatively high auto ignition temperature. The high auto ignition temperature of natural gas is a serious advantage against other gaseous fuels since the compression ratio of most conventional DI diesel engines can be maintained. Furthermore, the combustion of natural gas produces practically no particulates since natural gas contains less dissolved impurities (e.g., sulfur compounds).Significant research has carried out extensive theoretical and experimental investigationsconcerning the combustion processes occurring inside thecombustion chamber of a dual fuel diesel-natural gas compressionignition engine (Karim, 1991; Zhigang, 1992; Liu and Karim, 1997; Kusaka *et al.*, 1998; Pirouzpanah and Kashani, 1999; Poonia *et al.*, 1999; Karim and Karim, 2003; *et al.*, 2000; Krishnan *et al.*, 2003; Singh *et al.*, 2004; and Pirker *et al.*, 2009). Many researchers have proved that that dual fuel operation, with a high percentage of natural gas, is an efficient way to reduce soot concentration. Practically the gaseous fuel produces no soot, while it contributes to the oxidation of the one formed from the combustion of the liquid fuel (Morey and Mark, 2000).On the other hand, it is well known that the formation of nitric oxide is favored from the high oxygen concentrations and the high charge temperatures (Rakopoulos *et al.*, 1995; and Kouremenos *et al.*, 1997 and 1999). Papagiannakis studied the effect of natural gas mass ratio on the Nitric oxide concentration at the engine exhaust at 2000 rpm engine speed for various engine loads (Papagiannakis and Hountalas, 2003), Figure 1. The increase of natural gas mass ratio resulted in a decrease of nitric oxide concentration compared to the one under normal diesel operation. At high engine load and low mass ratios of natural gas there is a

Figure 1: Soot Opacity and Nitric Acid as a Function of Gas Mass Ratio at 2000 rpm for Various Engine Loads



Source: Papagiannakis and Hountalas (2003) sharper decrease of NO concentration, compared to part load conditions, with increasing gaseous fuel percentage. A possible explanation for the reduction of NO concentration, observed in most cases is the less intense premixed combustion, the reduction of gas temperature due to the increase of the specific heat capacity, the slower combustion and finally the reduction of oxygen concentration due to the presence of natural gas mass ratiowhich replaces an equal amount of air in the cylinder charge.

Since soot formation is reduced it is expected to reduce engine wear. There are not many studies that investigated the impact of dual fuel system on the engine wear. In the current study, the main goal is to investigate quantitatively the tribological behavior of a dual fuel engine used oil with 90% natural gas mass ratio and at full load.

EXPERIMENTAL EQUIPMENT AND PROCEDURE

Test Engine

The research engine used in the present study is the research engine Ricardo E6 single cylinder variable compression indirect injection diesel engine. Full details of the engine are given in Table 1.

The engine is loaded by an electrical dynamometer rated at 22 kW and 420 V. The engine is fully equipped for measurements of all performance parameters and combustion noise data. The combustion pressure time history is measured by a water-cooled piezo-electric pressure transducer connected to the relevant amplifier. The liquid fuel flow rate is measured digitally by a multi-function micro processor-based fuel system, Compuflow

Table 1: Ricardo E6 Engine Specifications

Model	Ricardo E6
Type	IDI with the pre-combustion chamber
Number of Cylinders	1
Bore	76.2 mm
Stroke	111.1 mm
Swept Volume	0.507 liters
Max. Speed	50 rev/sec (3000 rpm)
Max. Power, Diesel	9.0 kW, Naturally Aspirated
Max. Power, Diesel	14.0 kW, Supercharged (0.5 bar)
Compression Ratio	Variable, up to 22
Injection Timing	Variable, 20°-45° BTDC

System. Two data acquisition systems are used to collect the important data and store it in two personal computers for offline analysis. The following parameters are fed into the first data acquisition system: liquid fuel flow rate, engine speed and torque, and air/oil/coolant/ exhaust temperatures. A computer program in μMACBASIC language is written to collect the data and manage the system and a workstation operating system has been used to run the program. The Experiments have been carried out after running the engine for some time until it reaches steady state and oil temperature is at 55 °C ± 5, and cooling water temperature is at 65 °C ± 5.

Test Oil

Used diesel engine oils from the Ricardo E6 single cylinder variable compression indirect injection diesel engine were evaluated in the present study. These tests evaluated the effectiveness of lubricating oils in reducing soot-related wear of overhead components in engines. Oils from two different tests were collected. Samples were collected after 25 hrs, 50 hrs and 100 hrs of operation time. In addition to the used oil, friction and wear tests were also conducted with fresh oil from the same batch as the oils used for the engine tests. The oil samples were collected for two types of fuel, diesel only and dual fuel. For each type of fuel, the engine parameters are kept constant according to the following listed levels:

- The engine speed: 20 rev/sec.
- The engine injection timing for the diesel pilot fuel: 35° BTDC.
- The engine load output torque: 10 N.m for both cases (diesel and dual fuel).
- The engine compression ratio and it is kept constant at 22.

The maximum uncertainties in the measured quantities were 2% in the engine speed, 4% in the engine torque, 6% in the mass of fuel, 1° in the fuel injection angle, 0.01 in the engine compression ratio.

LPG level and engine operation conditions for the collected oil samples

- For diesel fuel case, the engine used only pure diesel fuel with an output torque of 10 Nm and is kept constant at engine speed of 20 rev/s (1200 rpm). The engine ran for 100 operating hours with sampling of engine oil every 25 hours (Table 2).
- For dual fuel case, the engine used 10% by mass liquid diesel fuel as a pilot fuel and the rest of fuel is the gaseous fuel (LPG) fed in the intake of the engine and mixed with the engine intake air. The LPG fuel is a mixture of 50% Propane and 50% Butane. The mass of liquid diesel fuel and the gaseous fuel were kept constant such that the engine produces 10 Nm of torque output (similar to diesel fuel case).

Table 2: Oil Sample Designations

Oil Sample Designation	Engine Operation Time (hrs)
A	0
B	25
C	50
D	100

Friction and Wear Testing

Bench-top friction and wear tests were conducted with a ball on flat test rig. The contact configuration consists of afixed ballloaded against a rotating flat. An adequate amount (about 10 ml) of oil being evaluatedwas added such that the contact areabetween the ball and the flat was fully flooded and well lubricated.Tests were conducted with well-polished bearing gradeAISIM-50 ball with a diameter of 12.7 mm (0.5 in.). The ballshave a hardness of 7.3 GPa (61 Ra) and a surface finish of about0.06 μm Ra. The flat was made of H13 stainless steel with a hardness of 6.2 GPa and an approximate surface roughness of 0.1 μm Ra.

All of the tests were conducted for 1 h at a constant load of 52 N, rotating speed of 100 rpm, and ambient room temperature. The friction coefficient was continuously monitored duringeach test.At the conclusion of each test, the flat and ball specimens were thoroughlycleaned with hexane. The wear scar dimensions on thestationary balls were measured with an optical microscope, whereas the flat wear track dimensions were measured using a profilometer which gave the depth and width of the wear track, the flat wear volume V_f was calculated from $V_f = w * h * (\pi d_t)$ where w is the wear track average width, h is the wear track average depth and d_t is the wear track diameter. The wear volume (V_b) from each ball was calculated from $V_b = (\pi d_4)/64r$, where d is the wear scar diameter, and *r* is the ballradius. Wear mechanisms of the wear track on the flat sample were assessed by SEM.

RESULTS AND DISCUSSION

It is well-known that soot causes oil thickening or viscosity increase, which isusually addressed by lubricant additive formulators (Bardasz *et al.*, 1995; Selby, 1998; and Parry *et al.*, 2001). Inaddition to soot being responsible for the viscosity increase,oxidation of the lubricant after exposure to the engine testenvironment is also expected. Such oxidation will contribute, in part, to the oil thickening. Again, oils are usually formulatedwith anti-oxidant additives so as to retard the oxidationprocess. It is well established that using a dual fuel system will reduce the amount of soot; hence reduce the wear in the engine components. Two groups of tests were executed during the current study; the first was for the dual fuel engine which contained four samples of oil collected at 0, 25, 50 and 100 hrs of engine operation time. The second group was for the diesel fuel engine which contained oil samples collected at 0, 25, 50 and 100 hrs of engine operation time. Ball on flat testing rig was used to test the friction and wear behavior of the above mentioned oil samples. Figure 2 shows the friction behavior of the diesel engine oil samples. It can be seen clearly that oil samples with longer operation time have higher friction coefficient. The least friction value was for the new oil. This can be attributed to the increased soot content. Figure 3 shows the friction coefficient for the dual fuel case. Friction values for the dual fuel are less than the diesel engine oil.

Figure 2: Friction Behavior of the Diesel Engine Oil Samples A, B, C and D

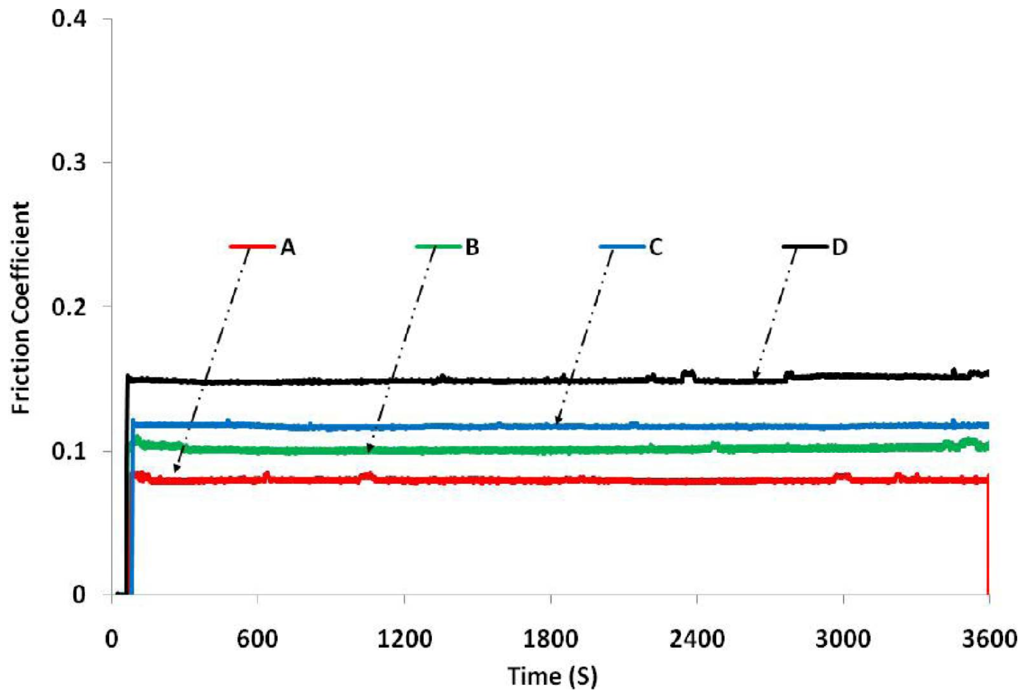


Figure 3: Friction Behavior of the Dual Fuel Engine Oil Samples A, B, C and D

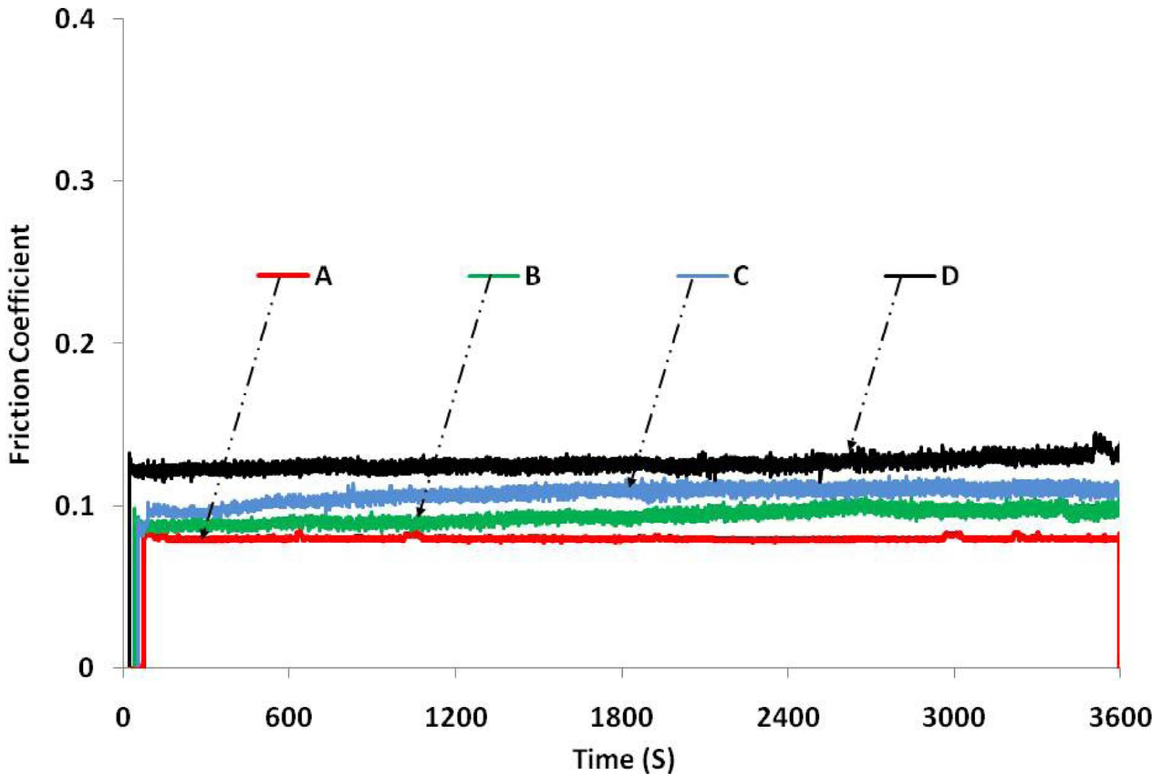


Figure 4: Ball Wear Volume

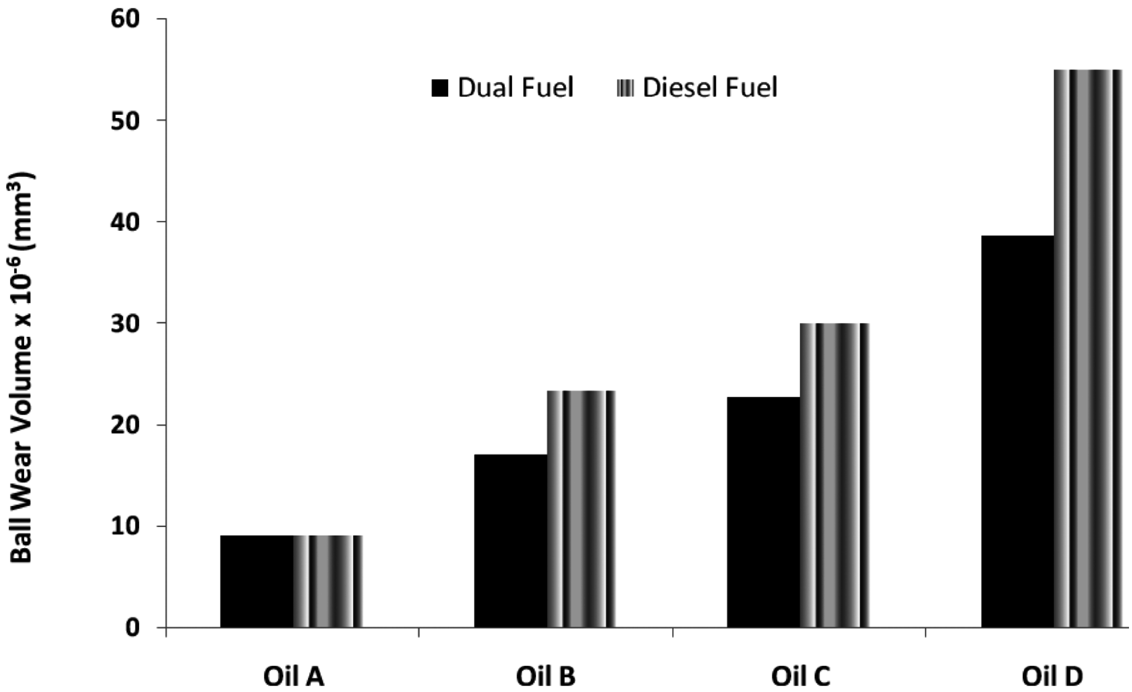
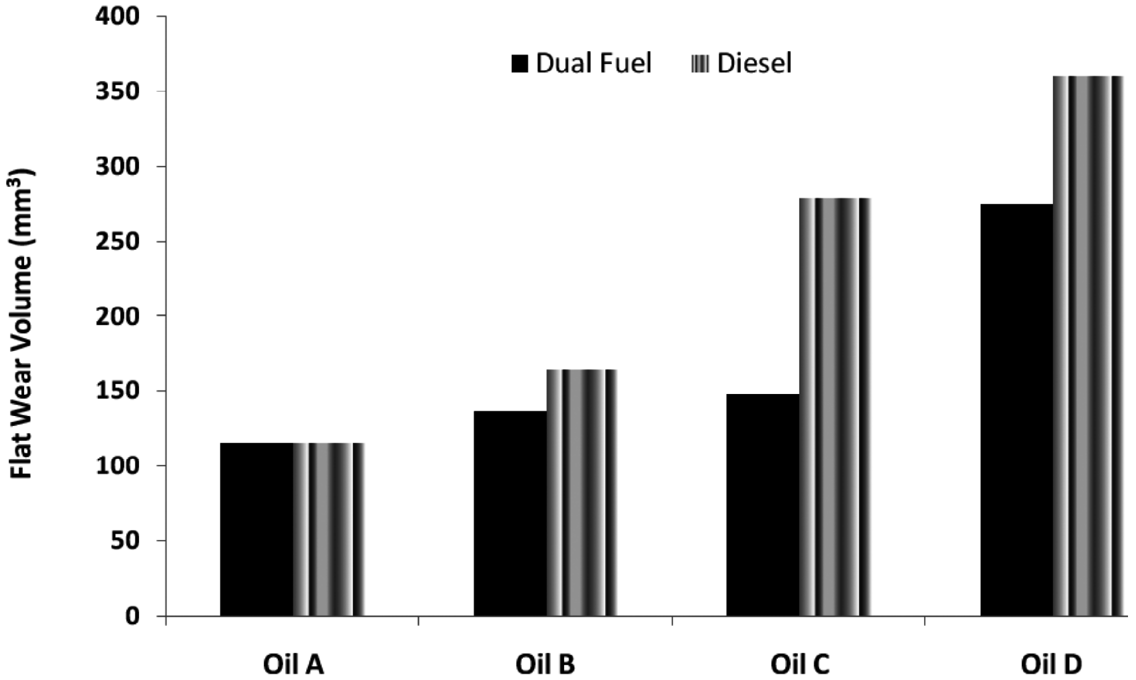


Figure 5: Flat Wear Volume



Optical microscopy was used to measure the wear scar diameter on the worn balls. The wear volume of the balls are shown in Figure 4 which shows that the balls used in the diesel engine oil experienced higher volume rate than the ones for the dual fuel engine case. Similarly, Figure 5 shows the flat wear volume for all tests.

The flats used for the diesel engine oil experienced a much higher wear volume than those used for the dual fuel engine. This can be attributed to the increased soot content in the diesel engine oil which is responsible for increasing the oil viscosity, oil oxidation number and agglomerated soot which causes abrasive

Figure 6: Flat Ear Track for Diesel Engine Used Oil Sample D

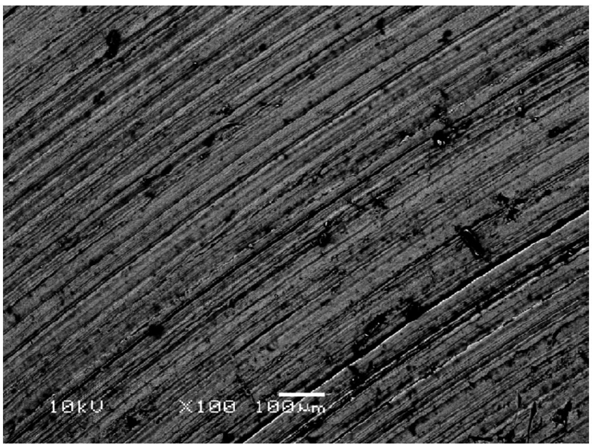
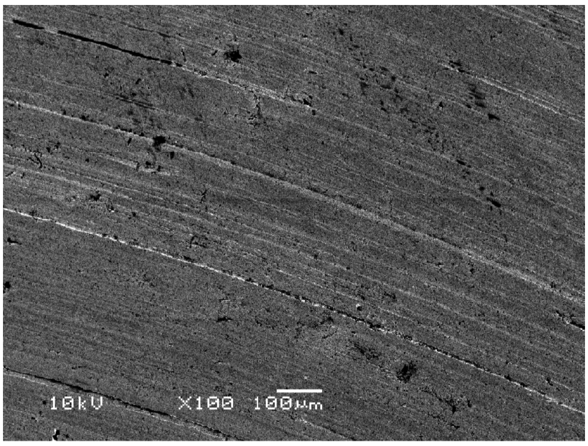


Figure 7: Flat Wear Track for Dual Fuel Engine Used Oil Sample D



wear. Figures 6 and 7 show the flat wear track micrograph for the diesel engine used oil sample D and the Dual fuel engine used oil sample D respectively. It can be seen from both images that the dominant wear mechanism is abrasion. However, it is more sever in the case of Diesel engine used oil.

CONCLUSION

The current study utilized a standard bench top ball on flat testing machine to study the impact of dual fuel engine used oil tribological behavior. The Dual fuel engine used oil showed a much better behavior than the traditional diesel engine used oil in terms of friction and wear behavior at four different levels of operating times.

The difference was more significant at the longer operation time. This can be attributed to the fact that the dual fuel engine is a cleaner engine; hence it produces lower soot content than the diesel fuel engine. It is very well known that soot can affect the engine oil at many levels. It can increase the viscosity and agglomerated particulates which are responsible to the increased engine wear. The SEM images of the wear tracks showed that the dominant wear mechanism is abrasion which was more sever in the case of diesel engine used oil.

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