International Journal of Innovative Research in Engineering
Volume 4, Issue 5(September-October2023), PP: 01-14.
www.theijire.com ISSN No: 2582-8746

# Wear Behavior of DLC Coated HSS with Hydraulic Fluids

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**How to cite this paper:**
Ashutosh Kumar Singh[1], Ayush Guha[2], "Wear Behavior of DLC Coated HSS with Hydraulic Fluids", IJIRE-V4I05-01-14.

https://www.doi.org/10.59256/ijire.20230405001



***Abstract:*** *The worldwide rotary pump market was estimated at around $5000 million in2020 and the market is supposed to increase by 20% toward the end of 2026, seeing a compounded annual growth rate of 3% over a period from 2022-2026. The scrapping of an engineered component made from non-renewable resources at an early stage in life due to wear goes against the ethics of the conservation of natural resources as the frictional processes lead to dissipation of a part of input energy. In this context many research works focused on analyzing wear behavior using various formulated and vegetable oils but no works investigated on using hydraulic oils as lubricant for wear preventative nature. The objective of the work was to obtain diamond-like carbon coating on high-speed steel samples and test them for better wear preventative behavior with different hydraulic fluids. The HSS ball sample of 12.7 mm diameter were used as a substrate on which the dlc coating was to be developed using then RF-PECVD technique. The developed DLC coating was characterized by conducting X-Ray diffraction which suggested the coating to be of amorphous structure, Raman spectroscopy which determined the content of graphite (sp2 ) to be 47% and that of diamond (sp3 ) to be 53%.Further nanoindentation was conducted to compare the hardness of the high-speed steel sample before and after coating which was 12.22GPa and 35.56GPa respectively. The four ball test was performed to investigate the anti-wearproperties of lubricating oil at specific conditions such as higher load, controlled temperature and constant rotating speed of the ball as per the ASTM D4172. The four ball results show that the coefficient of friction for samples reduces by around 36% when test oil 3 is used in uncoated samples and 48% in coated samples. Also, the wear rate for the test oil 3 for coated samples was found to be 0.7381x10-6 mm/Nm, which is the lowest wear rate among the other test oils. The outcome of the project is the reduction of coefficient of friction by 84% with respect to dry condition when test oil 3 is used. Therefore, it can be deduced that test oil 3 stands out as the most effective lubricant among the trio of test oils.In this direction , further work can be carried out by carrying out four ball tests with lubricant oils in combination with additives to it so as to enhance the base oil property and suppress undesirable base oil properties. Fabrication and manufacturing of the vane model can be done to validate the result with the help of experimental work.*

***Key Word:*** *DLC; HSS; Raman Spectrograph; AFM; 4-Ball Test, Hydraulic Oil.*

## I.INTRODUCTION

The hydraulic vane pump of fixed or variable displacement is subjected to different wear due to mixed friction, sliding wear, corrosion, cavitation, chemical effects while operating continuously for a longer period of time and thus the life as well as the efficiency is reduced [1]. Wear caused by the abrasion of small particles has been studied extensively, particularly in unlubricated systems [2]. The important parameters have been found to be the hardness of the surface being abraded and the hardness, size, shape and toughness of the abrasive particles. Abrasion with lubricated systems has also received considerable attention [3- 6]. Nowadays some pump producing industries use ceramic coatings like chromium oxide, aluminum oxide, titanium carbon nitride orzirconium as wear coatings to increase the life of the pump. Thanks to their outstanding corrosion resistance, hardness, thermal stability and other properties. Other than ceramic coatings Diamond like coating (DLC) also gained acceptance. Diamond-like carbon (DLC) coatings are perfectly suited to the most extreme wear conditions and high sliding speeds, even without lubrication. They minimize frictional losses, making them ideal for engine components such as fuel injection systems, valve trains and pistons. Numerous additional applications, spanning from pumps and compressors to bearing shells and rollers, as well as from textile machinery to medical technology, also make use of the remarkable sliding characteristics offered by DLC coatings.One of the solutions to minimize the wear would be to find desirable coating material with required properties appropriate for the base materials and suitable techniques of coating the materials[7]. Also anti-wear agents can be added in the hydraulic fluids. The bonding strength is also of importance as the vane pumps operate at higher speeds for longer duration [8,9].

## II.MATERIAL AND METHODS

**Specifications of HSS Balls:**
Weight of Ball : **8.8 gm** Diameter Of Ball : **12.7 mm**Hardness : **415 HV** Average Roughness: **0.93 µm**

**Selection of Coating Material**
**DIAMOND LIKE CARBON (a-C: H) Properties:**
- Extremely hard
- Low friction losses
- Ideal for high speeds

- Excellent abrasion protection
- Higher sliding velocity

Table No. 1 Carbon Based Coating

| | Me-DLC( WC-C:H) | DLC a-c:H | Doped DLC a-C:H | a-C:H sputtered C | ta-C |
|---|---|---|---|---|---|
| Method | PVD | PACVD | PACVD | PVD | PVD |
| Film nr. according VDI 2840 | 2.6 | 2.4 | 2.7 | 2.4 | 2.2 |
| Hardness(HV 0.05) | 800-2200 | 1500-3500 | 1500-2500 | 2000-4000 | 3000-8000 |
| Coefficient of friction | 0.1-0.2 | 0.05-0.15 | 0.05-0.1 | 0.05-0.1 | 0.02-0.1 |
| Internal Stress(GPa) | .1-1.5 | 1-3 | 1-3 | 2-6 | 1-3 |
| Thickness(μm) | 1-10 | 1-3 | 1-3 | 1-3 | 1-3 |
| Industrial use | +++ | +++ | +++ | +++ | +++ |
| Mass Production | + | +++ | ++ | +++ | +++ |

In Table No.1, various carbon based coatings are shown out of which the selected coating has been highlighted

**Specifications of DLC Coated HSS Balls**

- Coating Material: **Diamond Like Carbon (a-C:H)**
- Coating Technology: **PECVD**
- Weight Of Ball: **8.97 gm**
- Coating Thickness: **3 μm**
- Hardness: **1500-2500 HV**

**Coating Architecture Used-a-C:H Coating Architecture:**

In a typical sputter procedure, graphite targets can produce the hydrogenated a-C:H top coating. However, in order to provide the top layer appropriate hardness, this procedure must be reactive. Sputtered a-C:H typically has a hardness value that is significantly higher than a-C:H made using PECVD. However, as the coating would be too soft otherwise, reactive sputtering is required. The performance in terms of friction might arc toward ta-C for high-volume production. Although the delayed application method makes the coating more expensive, it is nonetheless used in high-volume manufacturing due to the coating's superior friction performance. Figure 1 shows HSS Balls before and after DLC coating.

*Fig 1 (a) HSS Balls*

*Fig 1 (b) DLC Coated HSS Ball*

**Selection of Oil:** One of the most crucial parts of a hydraulic system is hydraulic fluid. It carries out a variety of tasks, including power transmission, lubrication, heat transfer, and the transportation of contaminants, wear debris, and sludge. Given the significant roles that fluids play, choosing the right fluid is essential for maximizing the performance and lifespan of hydraulic pumps, motors, and other components.

**Fluid Properties to Consider while selecting Oil:** The most significant property is viscosity, which characterizes a fluid's resistanceto flow. Low viscosity fluids create boundary lubrication conditions with low film thickness, which can cause metal-to-metal contactand harm system components.

On the other hand, high viscosity, or strong resistance to flow, can cause slow operation and reduced mechanical efficiency. Elevated fluid temperature can be caused by energy losses from high viscosity.

Temperature directly affects viscosity, with system design, operating temperature, and ambient temperature all playing a role. Based on the operating temperatures, a suitable viscosity grade fluid needs to be chosen for each application. The viscosity of the fluid at working temperature must be within the range recommended by the system's components, particularly the pump. For choosing the fluid viscosity grade, minimum, normal, and maximum operating temperatures must be taken into account.[34-35]To maximize hydraulic system performance and component longevity, good AW characteristics are necessary.Inadequate AW characteristics can cause boundary lubrication regime scuffing and cold welding, which will remove surface material. [36].

**Various standard tests to consider:** ASTM D 943: Oxidation Characteristics of Inhibited Mineral Oils: considered useful in estimating the oxidation stability of lubricants. Uninhibited oils will usually fail within 200 h, while high quality oils can exceed 5000 h – 10.000 h. Longer the oxidation life is in the D 943 test, the longer the lubricant will perform in the field.

The Vickers 35VQ25 test assesses the anti-wear properties of hydraulic oil by analyzing weight loss in a 35VQ25 vane pump's cam ring and vane, with a requirement for a minimum of three cartridges undergoing 50-hour testing each. For a fluid to pass this assessment, the first three cartridges, or the initial four out of five, must demonstrate satisfactory performance. ASTM D665 A and B: To determine the rust preventive properties of turbine oils and other industrial lubricants ,particularly circulating systems .An outcome marked as "Pass" in this test signifies that, under conditions of moisture, the lubricant is unlikely to result in substantial rust formation within the equipment.

**Typical Properties of oil:**

**Table No. 2: Typical Properties of Lubricant Oil**

| NAMING CONVENTION | TEST OIL 1 | TEST OIL 2 | TEST OIL 3 |
|---|---|---|---|
| AW HYDRAULIC GRADE | 32 | 46 | 68 |
| ISO VISCOSITY GRADE | 32 | 46 | 68 |
| DENSITY@ 15°C,kg/m3 | 854 | 857 | 865 |
| Pour Point °C | -39 | -36 | -33 |
| Flash Point °C | 230 | 248 | 254 |
| Viscosity Index | 115 | 114 | 111 |
| Rust Test | Pass | Pass | Pass |
| Denison HF- Pump Test | Approved | Approved | Approved |
| Oxidation Stability,hrs D-943 | 5000+ | 5000+ | 5000+ |
| 33VQ25 Vane Pump Test | Pass | Pass | Pass |

Table No: 2 shows the different important properties of the oil like ISO Grade, Density, Viscosity and test results that were taken into consideration for selection of oils.From above data we can see that operating viscosity of the oil should be between 10 cSt and 108 cSt.The viscosity index of hydraulic system oil should not be less than 90. It has the ASTM D-943 of 5000+hrs for all the oils. It passes the 33VQ25 Vane Pump Test and Denison HF-Test has been approved for all the oils. Therefore we conclude that the test oil 032, 046 and 068 as shown in Figure 4.2 passes all the criteria for right oil selection.

*Fig. 2: Test oil 1,2 and 3*

**Characterisation and Experimentation**

**X Ray Diffraction:**

A crystal consists of periodically arranged atoms during a three-dimensional space. On the opposite hand, amorphous materials don't possess that periodicity and atoms are randomly distributed in 3D space. So, this forms the basis to differentiate between amorphous and crystalline structure of the coating. When there's periodic arrangement of atoms the X-rays are scattered only in certain directions once they hit the formed lattice planes which are formed by atoms. This may cause high intensity peaks that will have the width of the peaks lesser when compared to its height. Whereas in case of an amorphous structure the X-rays are scattered in many directions resulting in an oversized bump distributed during a wide selection (two Theta) rather than high intensity narrower peaks. As shown in Figure 3 no sharp peaks are observed in the intensity v/s two theta graph concluding amorphous structure of the coating.

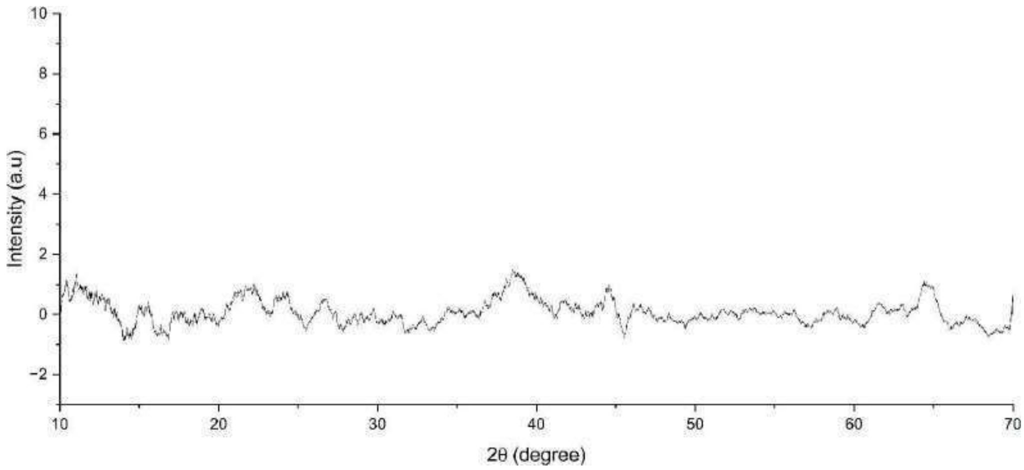



*Fig 3: X Ray Diffraction Graph Intensity v/s two theta**Specifications Of The Machine***

**X-Ray Tube**

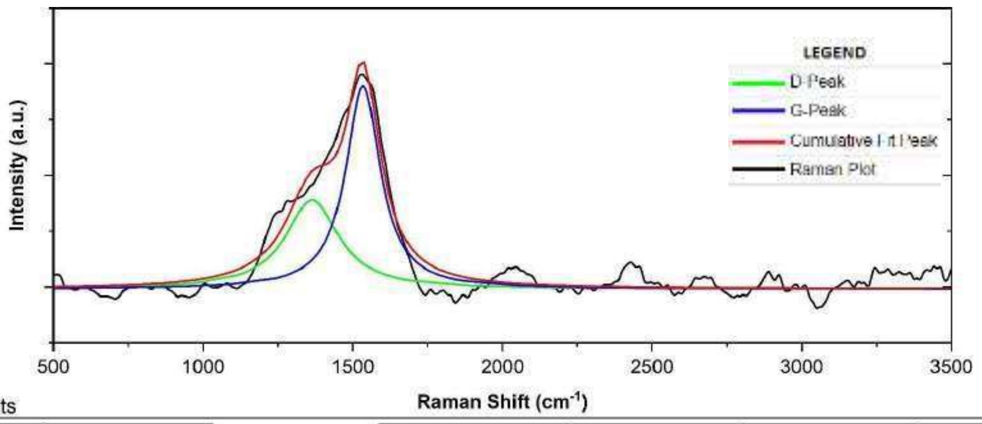
Table 3: Specifications of X ray Tube

| Description | Specification |
|---|---|
| TYPE | Sealed Type |
| ANODE | Cu |
| FOCUS SIZE | 1 x 10mm (2.0kW) or 2 x 12mm (2.7kW) |
| RATING | 2.0kW or 2.7kW |

Table No 3: shows the important specifications of X Ray Tube used for X Ray diffraction. These specifications are important in determining the nature of the coating.

**Raman spectroscopy**

DLC is a metastable amorphous carbon composed of a disordered network with $sp^2$ and $sp^3$ bonds. By modulating the ratio of $sp^2/sp^3$ bonds, the properties can be altered. To ensure the correct content of $sp^2$ and $sp^3$ in the obtained coating, Raman Spectroscopy is performed on the samples. The extent of defects (diamond- $sp^3$) in the graphite material ($sp^2$) can be obtained from the integrated intensity ratio of the D band and G band ($I_D/I_G$) obtained from the Intensity v/s Raman Shift plot of the material. Higher the value of $I_D/I_G$ higher the defect in the system, and hence, higher the content of diamond in the coating




Fitting Results

| Peak Index | Peak Type | xc | Area Intg | FWHM | Max Height | Area IntgP |
|---|---|---|---|---|---|---|
| D-Peak | BWF | 1364.03 | 5246.61664 | 217.14395 | 15.9752 | 40.09456 |
| G-Peak | Lorentz | 1534.26 | 7838.99208 | 140.38541 | 36.39305 | 59.90544 |

*Fig 4 Raman Spectroscopy plot of the DLC Coating (Intensity vs. Raman Shift)*

The graph in Figure 4 of Intensity vs. Raman Shift was plotted on the Origin shift to obtain the D-Peak and G-Peak heights. The D-Peak was observed at a Raman Shift of 1364.03 $cm^{-1}$ and G-Peak was observed at a Raman Shift of 1534.26 $cm^{-1}$. The ratio $I_D/I_G$ shows a ratio of 0.88. This shows that the coating has 47% content of Graphite ($sp^2$) and 53% Diamond ($sp^3$). This amount is acceptable for the required application.

Table 4 Specifications of Raman Spectrometer

| Description | Specification |
|---|---|
| Make | Witech Make |
| Model Name | Alpha 300 RAS |
| Laser | 532 nm |
| Laser Source | ND YAG (Neodymium doped yttrium aluminum garnet ) |

Table 4 shows the important specifications of the Raman Spectrometer. 532 nm wavelength laser was used in the experiment.

Nano Indentation: Nanoindentation has become an essential non-destructive technique for determining mechanical properties under extreme conditions. The method has been effectively utilized to determine the elastic modulus and hardness. Researchers have extensively employed this robust approach to explore the mechanical properties of polymers and their composites. Nanoindentation has proven to be a proficient technique in capturing localized mechanical alterations within nanocomposites.

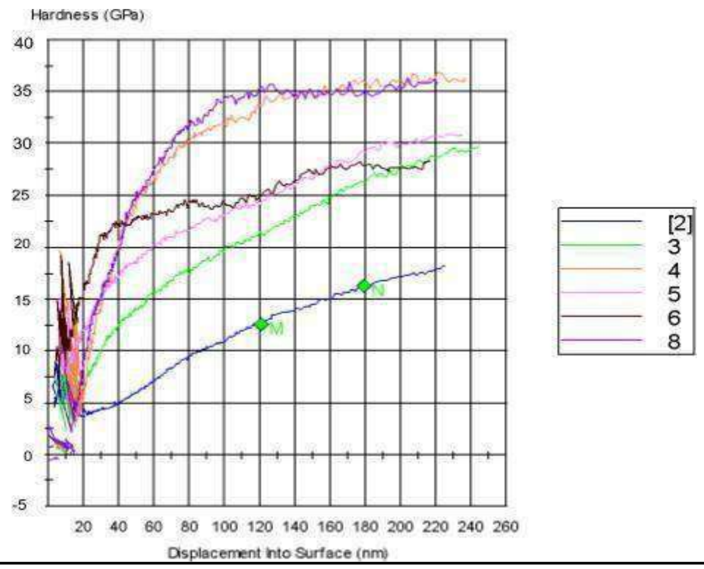



*Fig 5(a) Hardness for uncoated balls*

Fig 5(b) Hardness for coated balls

From Figure 5 (a) & (b) we can verify that hardness for uncoated sample is 12.22GPa and DLC coated sample is 35.56GPa and therefore the hardness has increased around three times after coating.

**Atomic Force Microscopy**

The images were processed with line by line leveling to normalize the Z range. The data from these images will be analyzed and information about roughness, feature height, and grain analysis will be explored. The 3D images show exaggeration in the Z range in order to display the features on the sample. The color change indicates the height of the sample in the Z range from the dark brown being at zero and the bright yellow being the highest point in the sample.

AFM images give 3-Dimensional array of numbers.The quality of analysis depends on the quality of AFM images. The AFM images gives surface roughness,height analysis and grain analysis

Surface roughness includes a set of four standard equations that are used to calculate roughness of the sample surface:

Eq. 1. Surface Roughness: □□ = ∑ |□□−□̅| /□, □̅= ∑ □□ / □=471.72nm Eq. 2. Root Mean Square: □□ = √ (∑ (□□−□̅)/ □)=597.07nm

Eq. 3. Mean Value: □□ = □̅− □□□n=198.59nm

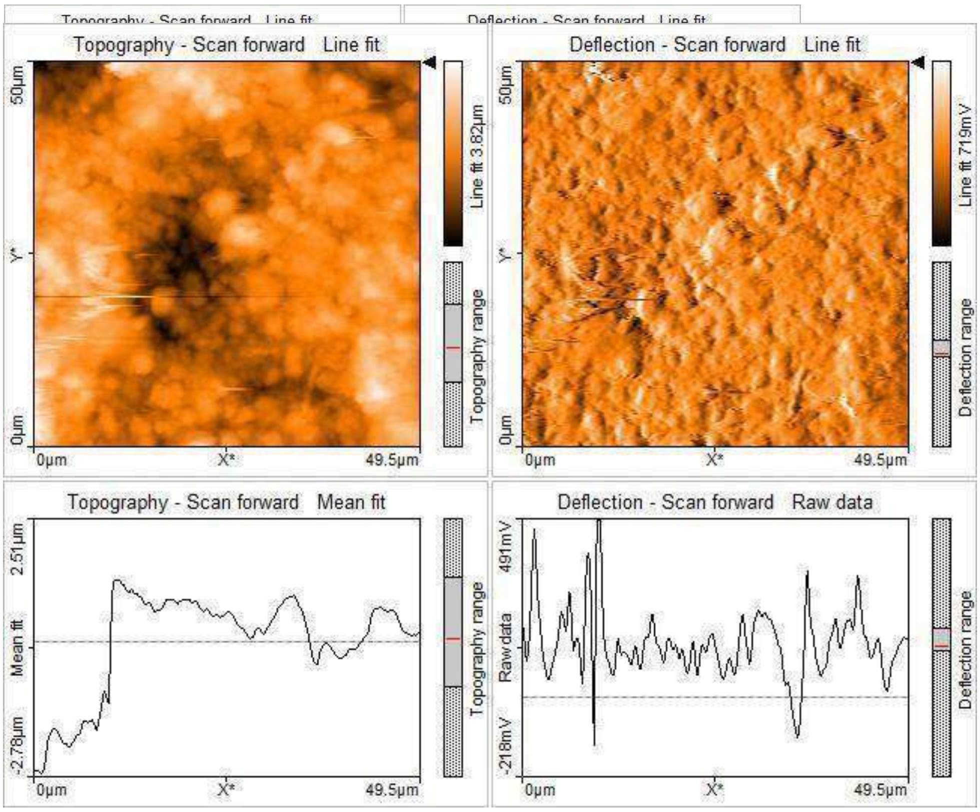



*Fig 6 AFM of DLC coating*

As in Figure 6 and Table 5 Sq root mean square roughness was found to be 597.07nm, Sp maximum peak found was 2193.2nm , Sv valley depth -1943.1nm , Sa arithmetical mean height was 471.72nm.

Table 5 Surface parameters using Atomic Force Microscopy

| **Area Roughness** | |
|---|---|
| Area | 2.496 $nm^2$ |
| Sa | 471.72 nm |
| Sq | 597.07 nm |
| Sy | 4.1363 µm |
| Sp | 2193.2 nm |
| Sv | -1943.1 nm |
| Sm | 198.59 pm |

**Specifications of the Machine**

Table 6 Specifications of Atomic Force Microscope

| Description | Specification |
|---|---|
| XY scan range | 100 µm (tolerance +/- 10%) |
| Z range | 15 µm (tolerance +/- 10%) |
| Power | AC 100 – 240V - 47-63Hz |

Table 6 shows the important specifications of the AFM machine.

**Experimentation - Four Ball Test**

Lubrication is widely used in machines, automotives and industries to eliminate surface to surface contact of components of machines and engines. Lubrication increases the efficiency as well as the working life and protects against the corrosion and wear. [38] Wear affects the life of components; if wear of components increases, life of that component decreases. [39] This inter-relationship between component performance and component lubricant is an important diagnostic tool to evaluate the component's health and performance. The components are affected by adhesive and abrasive wear of various other components and due to this contamination abrasion of surface of vanes, cam-rings and rotor. [40] The contaminations were identified as abrasive due to the observed marks and debris produced between the surfaces being tested.The primary role of a lubricant is to diminish friction, wear, corrosion, temperature, pollutants, and impacts. Anti-wear additives eliminate the metal-to-metal contact by addition of lubricant film forming agents that protect by direct contact of surfaces and abrasive wear phenomena. [41] The addition of anti-wear additives is used for enhancingthe anti-friction and anti-wear properties of lubricants.

The four-ball tester is used to investigate the anti-wear properties of lubricating oil at various conditions such as higher load, controlled temperature and constant rotating speed of ball, Investigate the comparison of depletion of the anti-wear additive and properties of fresh and different working life cycle lubricant oils using four ball tester and make interrelationship between the working life of lubricating oil and performance of sliding components. [42]

**Standard Used**

American Society for Testing and Materials (ASTM D4172) Temperature : 75 degree celsius Speed : 1200 rotations per minute
Duration : 60 minutes
Load : 392 Newtons

**Experimental Procedure**

The tests are carried out in accordance with the standard test methods for measurement of wear preventive properties of Lubricating Fluids, using an ASTM D4172 standard. Newly coated balls with a Diamond-Like coat are used for each set of tests. The coated steel balls are placed into the oil cup assembly and the oil cup is tightened using a torque wrench to prevent the bottom coated steel balls from moving during the experiments as shown in Figure 5.5 (a), 5.5 (b) and 5.5 (c). The upper spinning ball is locked inside the collet and tightened into the spindle. The test lubricant is introduced into the oil cup assembly. It must be ensured that the oil fills all of the voids in the test cup assembly.

The oil cup assembly components are installed into the frictionless disc in the four-ball machine and, to avoid shock, the test load of 392 newtons is applied slowly. The lubricant is then heated to the desired temperature of 75º C. When the set temperature is reached, the drive motor, which is set to drive the top ball at the 1200 revolutions per minute. After the 1-hour test period, the heater is turned off and the oil cup assembly is removed from the machine. The test oil is then drained from the oil cup and the scar area is wiped using a tissue. The bottom balls are then placed on a microscope base that is designed to hold the balls during microscopic evaluation. On each of the three lower balls, measurements of the wear spot are made with a microscope and compared.

## III.RESULT

The final results of each characterization performed of the Diamond-Like Coating of high speed steel ball samples and thefour ball test performed on both coated and uncoated samples will be discussed in this chapter.

Table 7: Four ball test results

| SampleID | Type | Frictional torque in Nm | Scar diameter in mm | | | |
|---|---|---|---|---|---|---|
| | | | Ball 1 | Ball 2 | Ball 3 | Average |
| Test oil 1 | Uncoated | 0.14 | 0.628 | 0.615 | 0.620 | 0.621 |
| | Coated | 0.13 | 0.558 | 0.571 | 0.568 | 0.565 |
| Test oil 2 | Uncoated | 0.17 | 0.593 | 0.591 | 0.584 | 0.589 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | Coated | 0.12 | 0.538 | 0.533 | 0.529 | 0.533 |
| Test oil 3 | Uncoated | 0.09 | 0.602 | 0.561 | 0.569 | 0.577 |
| | Coated | 0.07 | 0.480 | 0.471 | 0.476 | 0.475 |

Utilizing four ball tribometers, a total of six experimental setups were conducted. These setups encompassed three tests involving uncoated ball samples and three tests involving coated ball samples. Each test was performed using one oil sample at a time. The outcomes, presented in Table 7, revealed a consistent reduction in the wear scar diameter for all oil samples when the ball sample was coated, in comparison to the uncoated condition.

Upon analyzing the differences in the average wear scar diameter for each oil sample, it was evident that test oil 3 exhibited the most effective reduction in wear scar diameter when compared to test oil 2 and test oil 1.Visual examination of the wear scar images resulting from the tests on the balls, captured through optical microscopy, is depicted in Figures 7 to 12.

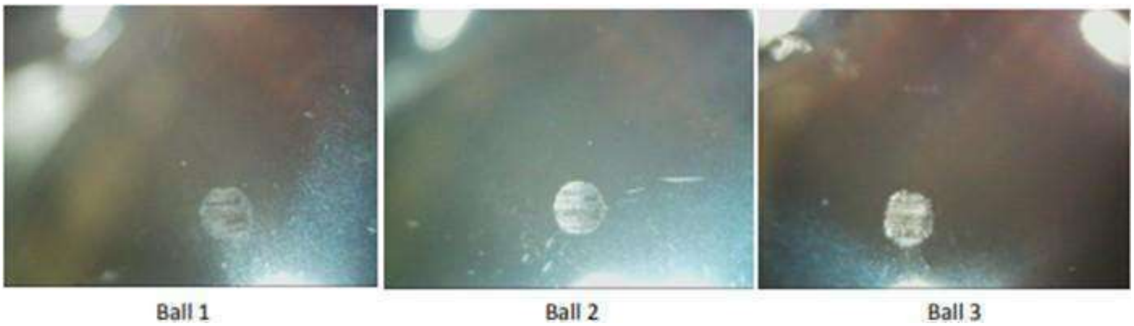



*Fig 7 Wear scar for uncoated - test oil 3 samples*


*Fig 8 Wear scar for coated - test oil 3 sample*


*Fig 9 Wear scar for uncoated - test oil 2 sample*


*Fig 10 Wear scar for coated - test oil 2 sample*


*Fig 11 Wear scar for uncoated - test oil 1 sample*


*Fig 12 Wear scar for coated - test oil 1 sample*

This explains that oil sample 3 displays the nature of slowest wear rate in the four-ball test and hence is successfully able to display good wear preventive behavior. This nature of slow wear rate of test oil 3 as compared to other samples occurs as it provides higher shearing stability which means that during the life cycle the viscosity loss is the least than in thecases of test oil 2 and test oil 1.

## IV.DISCUSSION

There are a total of six experimental setups that are performed using four ball tribometers which include three tests using the uncoated ball samples and three coated ball samples and each test done with one oil sample at a time. As per the result as shown in Table 7 it is observed that for all the oil samples the wear scar diameter obtained has reduced effectively when the ball sample is coated as compared to uncoated. Observing the differences of the average wear scar diameter for each oil sample it is clearly observed that oil sample test oil 3 reduces the wear scar diameter most effectively in comparison with test oil 2 and test oil 1. Figure 6.1, 6.2, 6.3, 6.4, 6.5, 6.6 shows wear scar images of the tested balls generated by optical microscopy

This explains that oil sample 3 displays the nature of slowest wear rate in the four-ball test and hence is successfully able to display good wear preventive behavior. This nature of slow wear rate of test oil 3 as compared to other samples occurs as it provides higher shearing stability which means that during the life cycle the viscosity loss is the least than in thecases of test oil 2 and test oil 1.

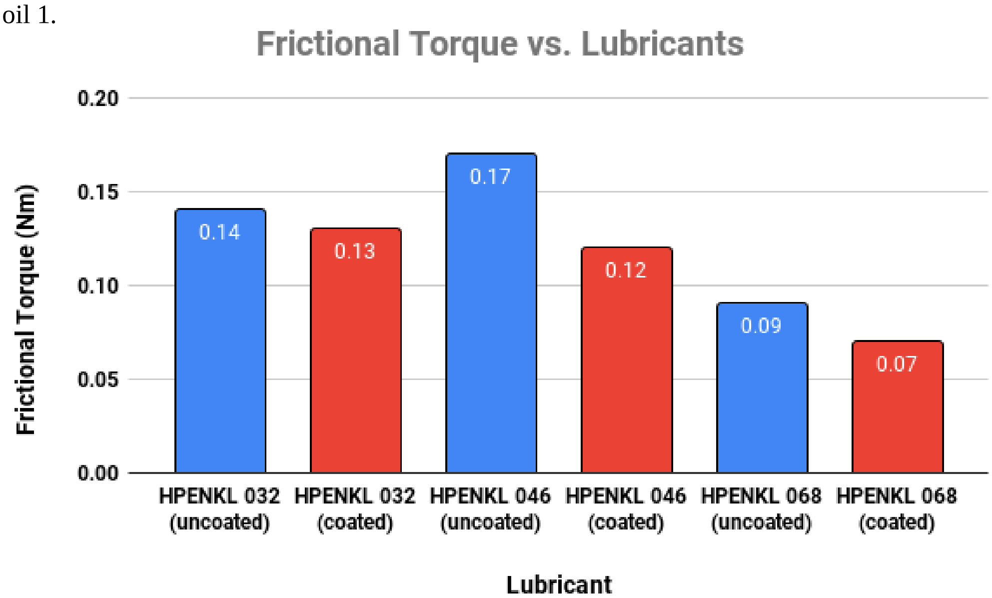



*Fig 8 Comparison of friction torque for different lubricants*

The graph in Figure 8 shows that frictional torque is minimum when test oil 3 oil is used as compared to other lubricants. Moreover, DLC coating shows further reduction in frictional torque as compared to uncoated condition.

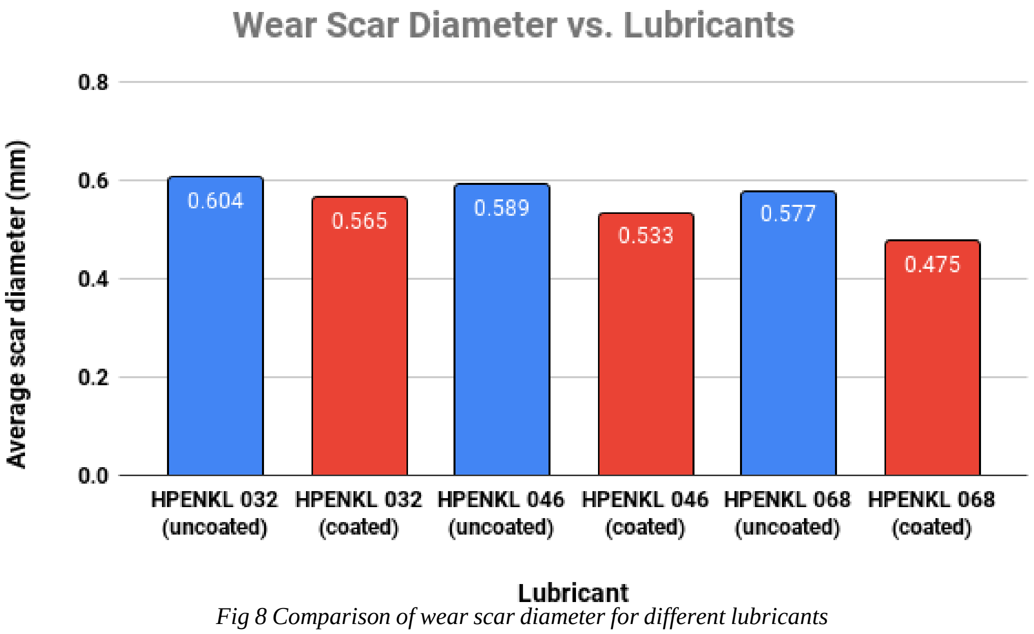



*Fig 8 Comparison of wear scar diameter for different lubricants*

More the scar diameter, the more the wear. The graph in Figure 6.8 shows that wear is minimum when test oil 3 oil is used as compared to other lubricants. Moreover, DLC coating shows further reduction in wear as compared to uncoated condition.Wear can be also evaluated by another parameter, called the wear rate. Tests are done with 1 h duration, with a constant rotational speed of 1200 rpm. Deleanu, L [43] calculated sliding distances for 1 h: L1200 = 1641.6 m (v = 01456 m/s or rpm). It is possible that the graph of the WSD dependence on test parameter is not relevant due to the difference in the sliding distances, and so, on the basis of the literature [43], the wear can be also evaluated by another parameter, called the wear rate, where:

□ =□□□ [□□/□·□]

Where WSD is the wear scar diameter average for a test, F – the load applied on the four balls, L – the sliding distance.

The product F·L is the mechanical work done by the tribosystem, in other words, the wear rate shows the loss of material volume or mass for the mechanical work unit performed by the system.

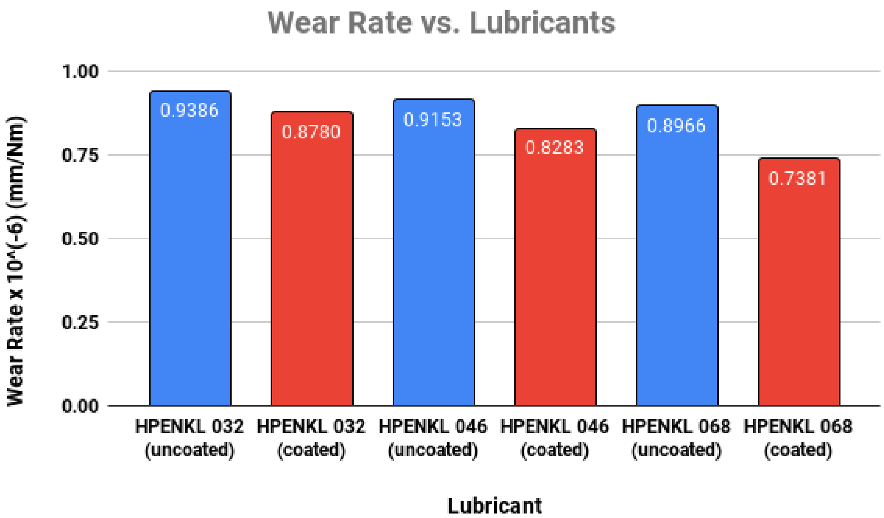



*Fig 9 Comparison of wear rate for different lubricants*

The graph in Figure 9 shows that wear is minimum when test oil 3 oil is used as compared to other lubricants. Moreover, DLC coating shows further reduction in wear as compared to uncoated condition.

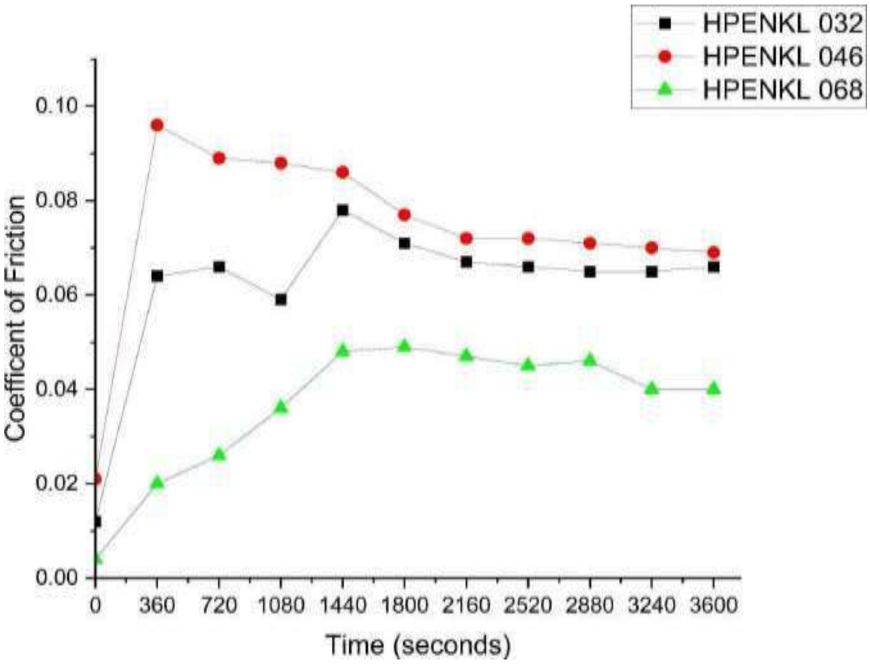



*Fig 10: Coefficient of friction for uncoated samples*

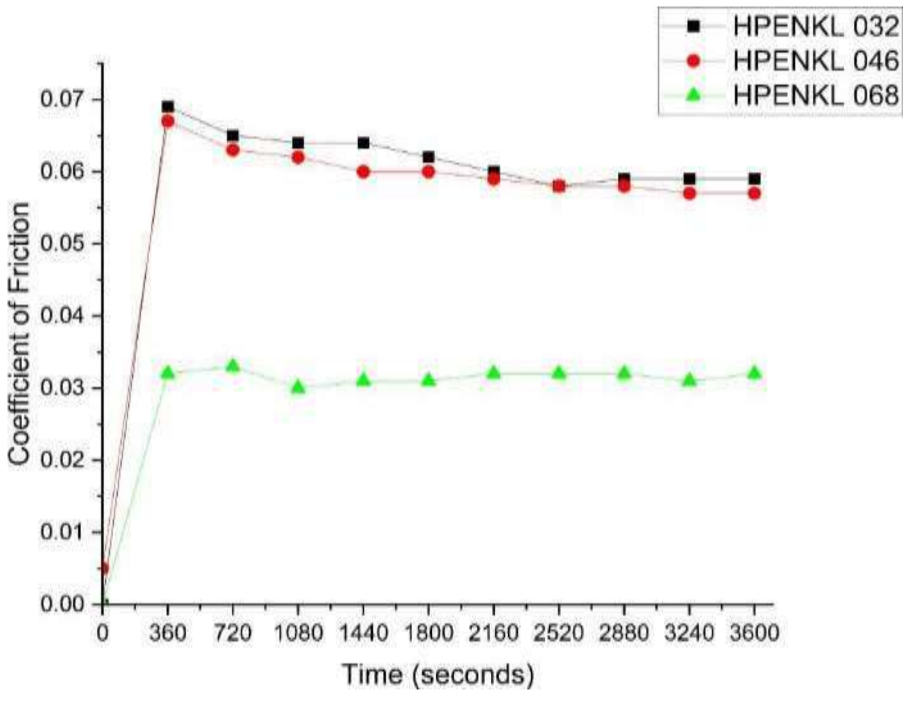



*Fig 11: Coefficient of friction for coated sample*

Figure 10 shows the coefficient of friction for uncoated samples during the one hour of four ball wear testing. Figure 11 shows the same for coated samples. The coefficient of friction increases as the test starts and gets fairly constant after sometime. For both the conditions, coated and uncoated the coefficient of friction is least of test oil 3 oil. The high viscosity of test oil 3 helps in reducing this value as compared to other two lubricants. The coefficient of friction values for test oil 1 and test oil 2 are almost similar and thus, do not show much difference. When comparing the two graphs, an overall decrease in coefficient of friction is evident in the case of coated samples. This shows that the DLC coating has helped in reducing the coefficient of friction.

Table 6.2: Average Coefficient of Friction of different samples

| **Oil** | **Average Coefficient of Friction** | |
|---|---|---|
| | **Uncoated Samples** | **Coated Samples** |

| | | |
|---|---|---|
| **Test oil 1** | 0.0667 | 0.0619 |
| **Test oil 2** | 0.0718 | 0.0601 |
| **Test oil 3** | 0.0438 | 0.0316 |

Table 6.2 shows average coefficient of friction of different samples. A significant reduction in coefficient of friction by around 48% is observed for the test oil 3 in coated samples and 36% for uncoated samples. The high viscosity of test oil 3 helps in reducing this value as compared to other two lubricants. This makes this lubricant better than the other two in terms of reducing friction. Also, coating the samples with DLC has helped in further reducing the coefficient of friction by 28% for test oil 3, making it suitable for the required applications.

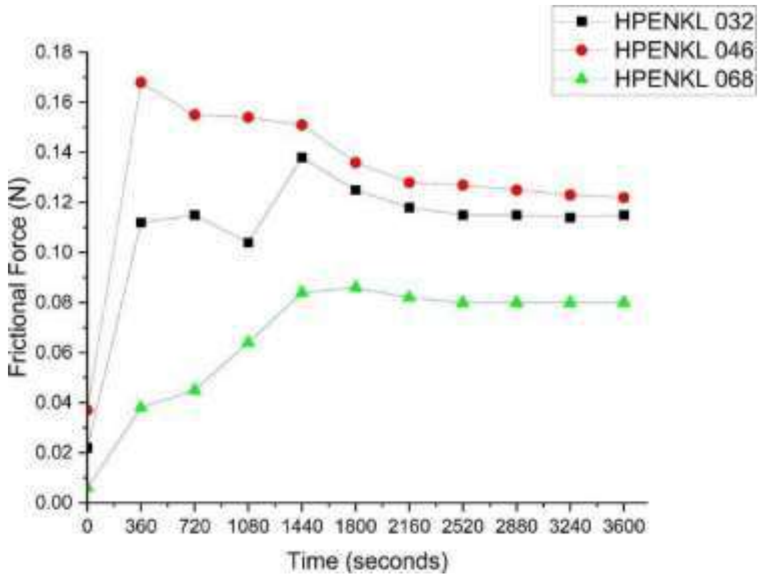



*Fig 12: Frictional Force for uncoated samples*

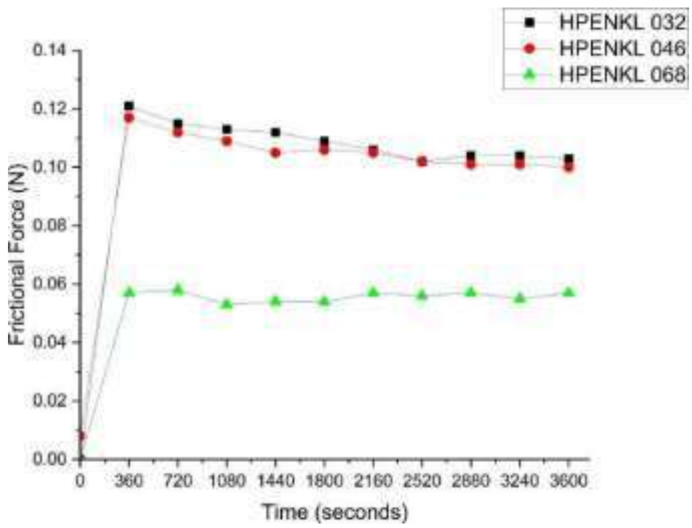



*Fig 13: Frictional Force for coated samples*

Figure 6.12 shows the frictional force for uncoated samples during the one hour of four ball wear testing. Figure 13 showsthe same for coated samples. The frictional force increases as the test starts and gets fairly constant after some time. For both the conditions, coated and uncoated the frictional force is least of test oil 3 oil. The high viscosity and low coefficientof friction of test oil 3 helps in reducing this value as compared to other two lubricants. The frictional force values for test oil 1 and test oil 2 are almost similar and thus, do not show much difference. When comparing the two graphs, an overall decrease in frictional force is evident in the case of coated samples. The reduction of frictional force helps in reducing the wear that occurs due to abrasion. This shows that the DLC coating has helped in reducing the frictional force and wear.

Table 6.3: Average Frictional force of different samples

| Oil | Average Frictional Force (N) | |
|---|---|---|
| | Uncoated Samples | Coated Samples |
| Test oil 1 | 0.1171 | 0.1089 |
| Test oil 2 | 0.1389 | 0.1058 |
| Test oil 3 | 0.0719 | 0.0558 |

Table 6.3 shows the average frictional force of different samples. A significant reduction in frictional force by around 48% is observed for the test oil 3 in coated samples and 40% for uncoated samples. The high viscosity of test oil 3 helps in reducing this value as compared to other two lubricants. This makes this lubricant better than the other two in terms of reducing friction. Also, coating the samples with DLC has helped in further reducing the frictional force by 23% for test oil 3, making it suitable for the required applications.

## V.CONCLUSION

The following are the conclusions that are made from the results obtained of the characterization tests and then the best hydraulic fluid for high wear preventative properties is found out. ● DLC Coating of thickness 3 µm was successfully deposited at Oerlikon Balzers facility on HSS Ball substrate, procured from Ducom Instruments using RF-PECVD technique. ● Surface topography, carbon and graphite content, amorphous structure and hardness were verified using AFM, Raman Spectroscopy, XRD and Nano-indentation respectively. ● Viscosity, density and flash point of the lubricants were verified as per the Hindustan Petroleum Ltd. datasheet. ● From the four ball test it was deduced that oil sample test oil 3 shows the best wear preventative properties as compared to other oil samples as it was able to bring the wear scar diameter to the lower range when DLC coating was applied to that of uncoated.

The research work can be extended by carrying out four ball tests with lubricant oils in combination with additives to it so as to enhance the base oil property and suppress undesirable base oil properties. The research work can further be extended by performingdebris analysis of the hydraulic oil post four ball test to have better understanding of the abraded particles in the test oil. Fabrication and manufacturing of the vane model can be done to validate the result with the help of experimental work.

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