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Effects of Coating and Lubrication on Friction and Wear for Metal-to Metal Application

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ABSTRACT

Friction and wear between sliding surfaces can lead to various issues in industrial applications, such as increased costs, reduced machine lifespan, loss of functionality, energy loss, and decreased system efficiency. To mitigate these problems, lubricants and coatings are commonly employed. This study aims to investigate the impact of coatings and lubrication on friction coefficient, wear volume loss, and lubricant temperature using the block-on-ring wear test. The effectiveness of different coatings (uncoated, DLC, CrN, and TiALN) and lubricants (anti-friction graphene oxide additive oil and strong nano engine oil additive) in reducing friction and wear is evaluated. The block-on-ring tests are conducted under varying loads (6-60 N), speeds (1450 rpm), lubricant volumes (40 ml), and durations (2-20 min). The coefficient of friction is measured using an inline load cell, wear volume loss is determined by weighing the blocks before and after the experiment, and lubricant temperature is monitored using thermocouples. The results indicate that the coefficient of friction decreases with increasing load, while the lubricant temperature rises. Coated blocks exhibit lower wear volume loss compared to uncoated blocks. Overall, the combination of CrN-coated blocks and anti-friction graphene oxide additive oil demonstrates the best tribological performance.

1. Introduction

Tribology is an important topic, especially in the engineering field. The word tribology is derived from the Greek word "tribos" meaning rubbing and can also be translated literally as "the science of rubbing" [1]. Tribology is also known as the science of friction, wear and lubrication [2]. Tribology played a central role in early technological evolution where people in ancient time developed wheel to reduce friction which made it possible for people to travel further and faster, and lubrication of sleds also made it easier to transport heavy building [3]. However, wear is not always undesirable

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since it helps in manufacturing processes involving abrasive processing which wear can be used to form and shape surfaces [4]. Friction is also important since it prevents people from sliding when walking and helps in braking action of a moving car. According to Ludema and Ajayi [3], the need to reduce or control friction and wear is increasing in modern societies. Friction is a system response and not a material characteristic [3]. Friction force is the resistance experienced by one object in moving of another object which it is in contact with [2]. The fundamental laws of friction are the friction force is perpendicular to the normal load, the area of contact and sliding speed does not affect friction force [2]. Next, according to Hutchings and Shipway [2], Coefficients of friction value vary from low to high and the value of it can affect the magnitude of frictional force. The value of μ usually in the range of 0.1 to 1, for common materials sliding without lubricants.

Wear is the exchange of material from one surface to another surface and can be considered when the movement of material happens within the same body or surfaces that induced damage to the surface [5]. Wear can also be known as loss of materials from the surface because of movement on the surface [6]. Sliding wear happens when two surfaces slide over one another. When surface slides with other surfaces wear will happen and reduce the volume of materials on the surface [2]. Lubrication is the application of a substance to improve the smoothness of movement of one surface over another, and the substance used is usually known as a lubricant [7]. Lubrication can help to reduce friction and wear on surfaces [1,8]. The two main factors that come into consideration when selecting the lubricant are usually the speed and load [7].

Coating is a layer of substance that has been deposited over the surface of a part to add beneficial properties to the surfaces [8,9]. Coatings can help to reduce friction and wear for metal-to-metal contact applications. Coatings can also help improve the hardness of the surfaces, improve thermal stability so that the surface can withstand a higher temperature and help improve the chemical stability of the surfaces [10]. Block on ring (ASTM G77) test is a sliding wear test that was used widely to test the wear characteristics of a material in different conditions and situations [11,12]. The work environment such as normal loading, friction, speed, and lubrication can heavily affect the wear characteristics of the materials. This tribometer is used for the testing of coatings, lubrications, greases, additives and sliding performance.

This study addresses the current gap in understanding the tribological performance of specific coatings and lubricants in industrial applications and contributes valuable insights for enhancing efficiency and reducing wear-related issues.

2. Methodology

This study was conducted to investigate the effects of various coatings and lubricants on friction and wear for metal-to-metal applications. This is because different coatings and lubrications have different properties that can affect the friction and wear of materials.

2.1 Block on Ring Test

The experiment uses a block on ring test machine model *Topech T- 01* to test for friction and wear of the block. The machine operates at 220 V / 50 Hz with a power rating of 280 W. The machine speed is 1450 rpm and weight of the machine is around 25 kg. The machine comes with several pieces of weight that can be added to control the amount of normal force that will be applied on the block and the rings.

2.2 Block and Ring

The block used in this experiment is made from SKD11 tool steel. The block has a density of 7.81 g/cm3. The diameter of the block is 14mm and the height of the block is 16 mm. The block was coated with coatings using PVD and HiPIMS method. Table 1 shows the properties of the coated block. The ring that was used in the experiment is made from ASTM 52100 bearing steel with hardness of 58 HRC. The diameter of the ring is 40 mm.

Table 1
Properties of the coated block

Coating	Hardness (HV)	Deposition method
DLC	891.25	PVD
TiALN	770.35	HiPIMS
Cron	678.39	PVD

2.3 Lubricants

The lubricants used in this experiment are anti-friction graphene oxide additive oil and strong nano engine oil additive. Table 2 shows the properties of the lubricants used in this experiment.

Table 2
Properties of the lubricants

No	Lubricants	Oil Viscosity (kg/ms)
1	Anti-Friction Graphene Oxide Additive Oil	0.03
2	Strong nano engine oil additive	0.02

2.4 Measuring Machine

The are several machines used in this experiment. Firstly, the Nikon MM-400/l measuring microscope was used to observe the wear occur on the block after the experiment. Next, inline load cell model LCM-100 was used in this experiment to measure the friction force. Digital k-type thermocouple model TM-902C was used to measure the temperature of the lubricants during the experiment. Digital weight scale model I-2000 was used in this experiment to measure the mass of the block before and after the experiment.

2.5 Experimental Procedures

The experimental procedure is the step-by-step directions for conducting the experiment to achieve the objective. The experiment was performed to collect data on the sliding wear of the block due to friction between the block and the ring. The test was done with only one sample of data collected for each combination of coating and lubricant. The experiment uses a rotating ring with a diameter of 40 mm which was rotated at constant 1450 rpm. The block was located at the top of the ring and mounted using a level arm system. The normal load applied through the level arm system ranging from 6 to 60 N. The duration of the experiment ranged from 2 to 20 min. Every 2 min, the amount of normal load was added by 6 N. Figure 1, shows the schematic of the block on ring setup.

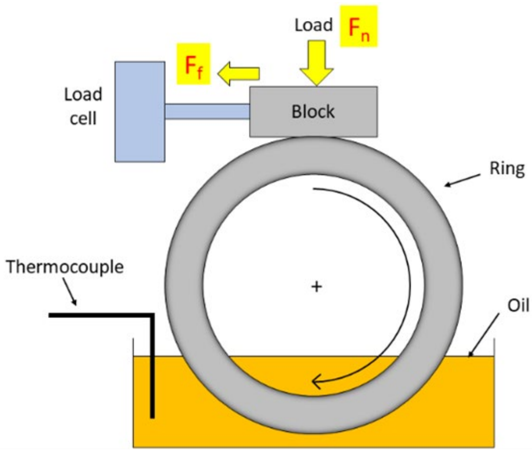

Fig. 1. Schematic of the block on ring

During the experiment, the ring was submerged slightly into the lubricant. The lubricant amount used in all the test is 40 ml. A digital k-type thermocouple was also submerged into the lubricant to measure the lubricant temperature. The lubricant temperature was recorded every 2 min. The block was mounted to a load cell to measure the friction force. Every 2 min, the friction force was recorded. The coefficient of friction (μ) was calculated by dividing the friction force (F_f) by the normal load (F_n) as in Eq. (1). The amount of wear was obtained by measuring the weight of the block before and after the experiment by using digital weight scale. The wear volume loss (W) was calculated by dividing the weight loss (m) by the density (ρ) of the block as in Eq. (2). The block was observed under Nikon MM-400/l measuring microscope to capture the wear on the block after the experiment. After the test was done, the test rig was cleaned using acetone to remove lubricants and any residual particles. The test was conducted until all combinations of blocks and lubricants were tested.

$$\mu = \frac{F_f}{F_n} \tag{1}$$

$$W = \frac{m}{\rho} \tag{2}$$

3. Results and Discussion
3.1 Coefficient of Friction

Figure 2 and Figure 3 show the coefficient of friction when tested using strong nano engine oil additive and anti-friction graphene oxide additive oil respectively. From Figure 2 and Figure 3, when the normal load increases, the coefficient of friction decreases. The coefficient of friction decreases from 0.20-0.23 at 6 N load to 0.11-0.13 at 60 N for the strong nano engine oil additive. While for the anti-friction graphene oxide additive oil the coefficient of friction decreases from 0.19-0.21 at 6 N load to 0.11-0.13 at 60 N. Overall, the coefficient of friction graph showed the same downward trend on all the four blocks for both lubricants.

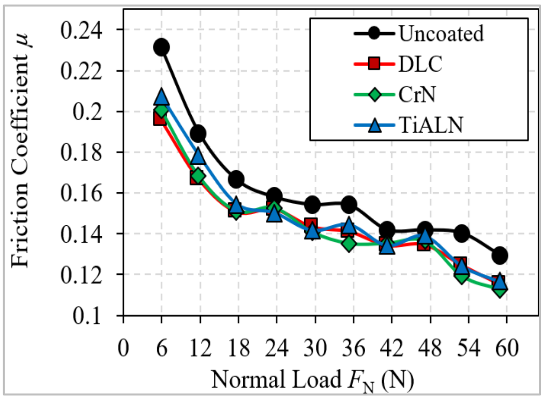

Fig. 2. Coefficient of friction for strong nano engine oil additive

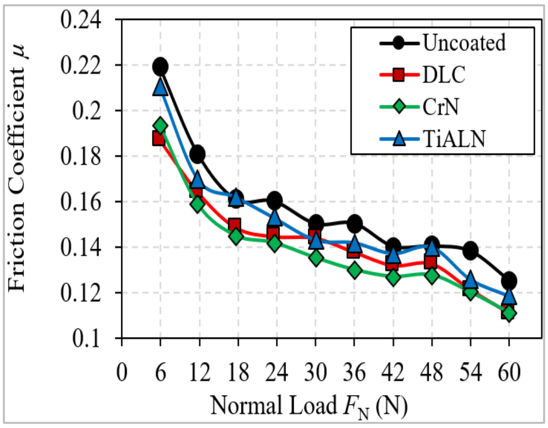

Fig. 3. Coefficient of friction for anti-friction graphene oxide additive oil

The relationship between the friction force and normal force is directly proportional, which means that if the normal force increases, the friction force will increase too. However, in this experiment it was found that when the normal force was increased by double or triple the amount, the friction force didn't multiply by double or triple the amount. This indicates that the lubricant film between the two sliding surfaces was in the mixed lubrication or hydrodynamic lubrication region that creates a wedge and clearance between the surfaces in motion which reduced the coefficient of friction. Study done by Huang *et al.,* [13] shows that coefficient of friction decreased as the normal load increased when tested the CrN coated piston ring with nano-diamond additive lubricants.

Figure 4 shows the comparison of the average coefficient of friction of nano engine oil and graphene oxide oil. From Figure 4, the average coefficient of friction of the uncoated, DLC and CrN block was lower when tested using graphene oxide oil. However, the average coefficient of friction of the TiALN block was lower when tested using the nano engine oil. The reason TiALN coated block shows a higher average coefficient of friction when tested using graphene oxide oil when compared to nano engine oil may be due to the rough surface of the ring that was being used during the test. After each experiment, the ring was supposed to be polished before starting the next test or a new set of rings can also be used. The higher average coefficient of friction probably indicates that the ring was not polished properly before the test was done because when compared to the uncoated, DLC and CrN block, the trend shows that the graphene oxide oil should perform better than nano engine oil. However, since only one sample of data was collected, it is not confirmed if the same trend will happen if the test is repeated for the second and third sample when testing the TiALN coated block. Study done by Huang *et al.,* [14] found that TiALN coatings have a higher average surface roughness value of 0.85 µm when compared to CrN coatings that have an average surface roughness value of 0.63 µm. The study also found that TiALN exhibited higher average coefficient of friction compared to CrN coatings under both dry and lubricated conditions when tested at all 5 N, 10 N and 20 N load.

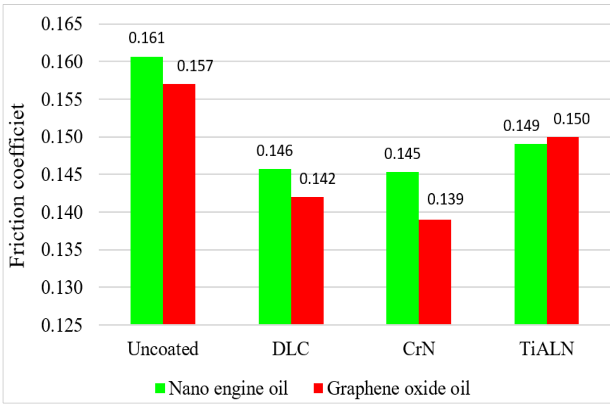

Fig. 4. Comparison of average coefficient of friction

Wear volume loss is the amount of volume and weight difference due to the sliding wear that occurs during the block on ring test. The wear volume loss was calculated using Eq. (2). Table 3 and Table 4 show the difference between wear volume loss of the block tested using strong nano engine oil additive and anti-friction graphene oxide additive oil respectively. Figure 5 shows the comparison of the wear volume loss of the block tested using strong nano engine oil additive and anti-friction graphene oxide additive oil. From this figure, the wear volume loss for all the block was lower on the graphene oxide oil when compared to the nano engine oil. Next, the CrN coated block shows the lowest wear volume loss while the uncoated block shows the highest wear volume loss. It can be concluded that the block with coatings has more resistance to wear when compared to the uncoated block. Research done by Huang *et al.,* [14] shows that TiALN has a higher wear rate both in dry and lubrication conditions when compared to CrN, which means that TiALN experienced a more rapid wear that results in higher wear volume loss. Another study done by Paskvale *et al.,* [15] also shows that CrN coated steel has a lower wear coefficient when compared to TiALN coated steel.

Table 3
Wear volume loss of the block tested using strong nano engine oil additives

Block	Initial mass (g)	Final mass (g)	Mass difference (g)	Wear volume loss (g)
Uncoated	16.612	16.279	0.033	4.225
DLC	16.570	16.552	0.018	2.305
CrN	16.581	16.567	0.014	1.793
TiAln	16.590	16.563	0.027	3.457

Table 4
Wear volume loss of the block tested using anti-friction graphene oxide additive oil

Block	Initial mass (g)	Final mass (g)	Mass difference (g)	Wear volume loss (g)
Uncoated	16.510	16.481	0.029	3.713
DLC	16.580	16.563	0.017	2.177
CrN	16.611	16.600	0.011	1.408
TiAln	16.609	16.594	0.015	1.921

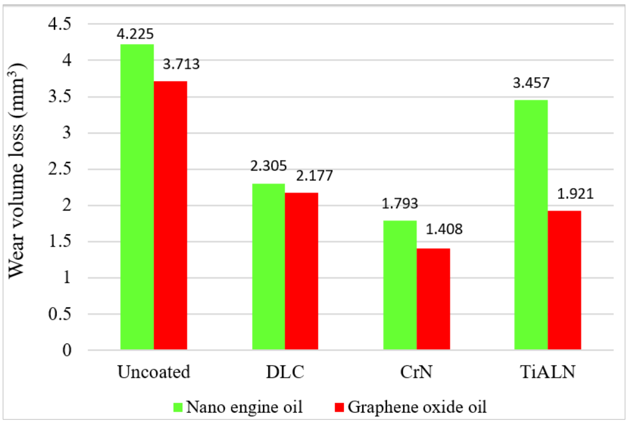

Fig. 5. Comparison of wear volume loss

Figure 6 and Figure 7 show the wear scar left on the block after the block ring test using nano engine oil and graphene oxide oil. The main cause of wear is sliding wear based on the scar wear that occurs on the block as seen in Figure 6 and Figure 7. From the figure, adhesive wear or scuffing was also observed where there were some removals of material from the surface. This occurs due to small contact areas at the sliding interface which results in high contact pressure, leading to adhesion between the surface and remove a large chunk of material from the surface such as in Figure 6 (a). According to Straffelini [16] low adhesion may result in lower friction and wear. Since uncoated blocks show a higher coefficient of friction and wear rate, it may indicate that a higher adhesion occurs at the contact surface. Overall, the uncoated block has a bigger wear scar when compared to the coated blocks.

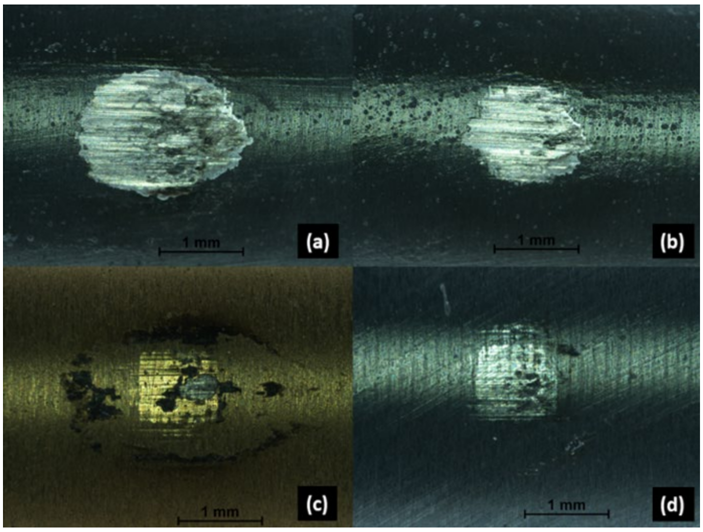

Fig. 6. Wear scar after block on ring test with nano engine oil (a) uncoated (b) TiALN (c) CrN (d) DLC

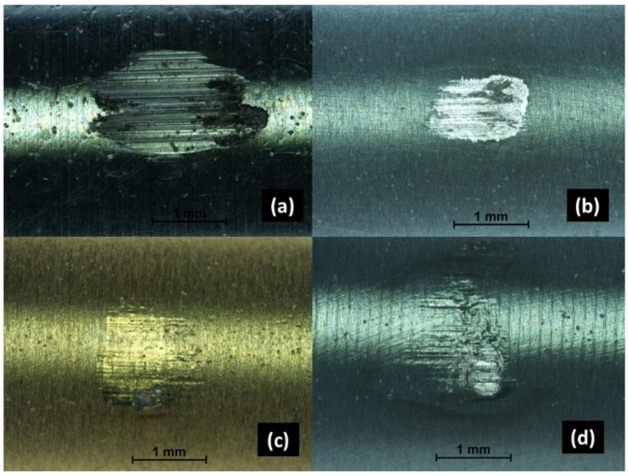

Fig. 7. Wear scar after block on ring test with graphene oxide oil (a) uncoated (b) TiALN (c) CrN (d) DLC

3.2 Lubrication Temperature

Lubricant temperature was measured using the thermocouple submerged in the lubricant during the block on ring test. Figure 8 and Figure 9 show the trend of lubricant temperature against normal load for nano engine oil and graphene oxide oil respectively. From Figure 8 and Figure 9, when normal load increases, the lubricant temperature also increases. The lubricant temperature increases from 35.1-36.0 degree Celsius at 6N load to 62.4-68.2 degree Celsius at 60N for the strong nano engine oil additive. While for the anti-friction graphene oxide additive oil the lubricant temperature increases from 35.0-39.0 degree Celsius at 6N load to 60.2-65.1 degree Celsius at 60N. Overall, the lubricant temperature graph showed the same upward trend on all four blocks for both lubricants. This was because the heat produced due to friction between the two sliding couples accumulated in the lubricant over time resulting in the increase of the lubricant temperature. Research done by Kašparová *et al.,* [17] using the block on ring test also shows the same upward trend for the lubricant temperature as the time and sliding distance increase.

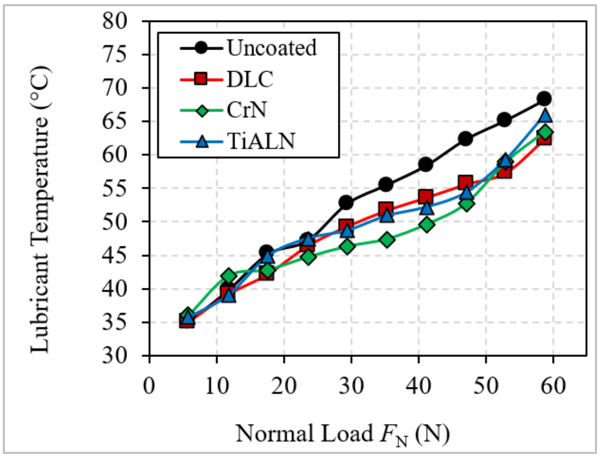

Fig. 8. Lubricant temperature of nano engine oil

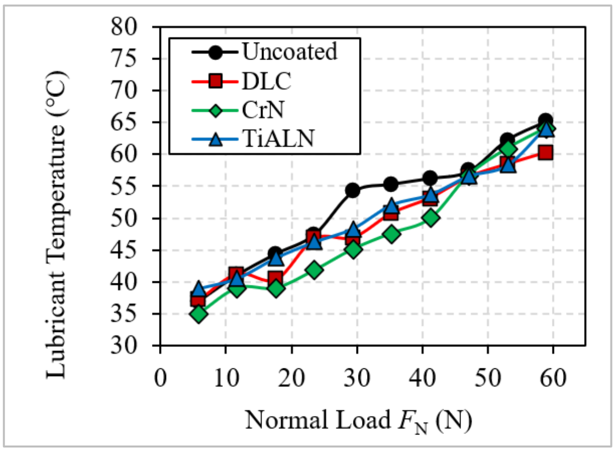

Fig. 9. Lubricant temperature of graphene oxide oil

Figure 10 shows the comparison of the average lubricant temperature of nano engine oil and graphene oxide oil. From Figure 10, the average temperature of the graphene oxide oil was lower than nano engine oil when running the block on ring test using uncoated, DLC and CrN block. However, the average temperature of the nano engine oil was lower than graphene oxide oil when running the block on ring test using TiALN coated block due to lower average coefficient of friction as seen in Figure 4. Next, both nano engine oil and graphene oxide oil show the lowest average lubricant temperature when running the block on ring test on CrN coated block while the uncoated block shows the highest average lubricant temperature. This may occur due to higher coefficient of friction when running the test using uncoated block that produce more heat which in turned increase the temperature of the lubricant. Overall, comparing the average coefficient of friction graph and average lubricants temperature graph, the trend shows that higher coefficient of friction resulted in higher average lubricant temperature which indicates that higher coefficient of friction produced more heat at the sliding interface.

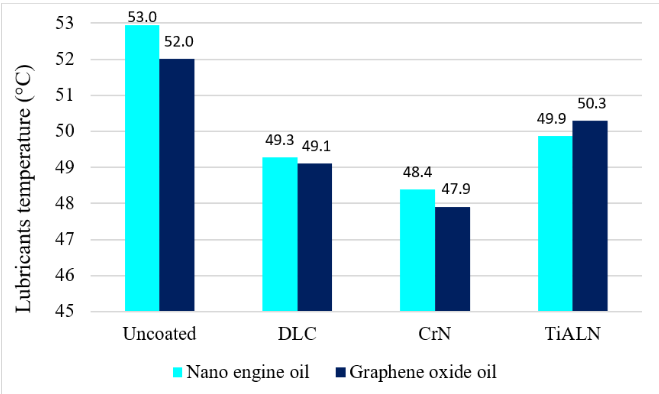

Fig. 10. Comparison of average lubricants temperature

3.3 Discussion

For this study block on ring test was successfully utilized to test the effects of coating and lubrication on friction and wear for metal-to-metal application. The usage of coating and lubricant have shown to help reduce the coefficient of friction. According to Ghatrehsamani and Akbarzadeh [18], the coefficient of friction of dry sliding of steel on steel was about 0.60-0.80. By using coating and lubricant, the coefficient of friction was observed to be reduced to 0.11-0.13 at 60N load when tested using block on ring test. Based on a study done by Paskvale *et al.,* [15], the coefficient of friction for 100Cr6 balls sliding on CrN and TiALN coatings lubricated in Polyalphaolefin (PAO) is 0.11 and 0.14 respectively. Another research done by Ghiotti and Bruschi [19], also found that both DLC and CrN coatings have a lower coefficient of friction compared to TiALN coating when tested using pin-on-disk rig.

Furthermore, wear volume loss was also reduced when coating and lubricant were used. The wear volume loss of CrN, DLC and TiALN coated block were 57.7%, 45.4% and 18.2% lower when compared to uncoated block when tested using nano engine oil. In addition, the wear volume loss of CrN, DLC and TiALN coated block were 62.1%, 41.4% and 48.3% lower when compared to uncoated block when tested using graphene oxide oil. Based on research performed by Ziberov *et al.,* [20], DLC coated microtool show a better wear resistance and microtool life when compared to TiALN coated microtool when performing micro milling under minimum quantity lubricant (MQL) conditions. Another research done by Sulaiman *et al.,* [21] using block on ring test ASTM G77 found that AISI 304L steel coated with DLC have a lower surface roughness when compared to uncoated and TiALN coated steel. This indicates that DLC coated steel has a lower wear when compared to uncoated and TiALN coated steel since high surface roughness value indicates that the surface experienced severe wear [21,22].

Next, averages lubricant temperatures when tested using coated block was lower when compared to the uncoated block. For nano engine oil, there were about 8.7%, 7.0% and 5.8% average lubricant temperature difference when compared between CrN, DLC and TiALN coated block to the uncoated block. For graphene oxide oil, there were about 7.9%, 5.6% and 3.3% average lubricant temperature difference when compared between CrN, DLC and TiALN coated block to the uncoated block. Uncoated block has the highest average lubricant due to higher coefficient of friction when compared to coated block that generate more heat at the sliding interface. From this study, the best coatings and lubricants based on the effectiveness in reducing friction and wear can be determined. Overall, combination of CrN coated block and graphene oxide oil showed the lowest average coefficient of friction, lowest wear volume loss and lowest average lubricants temperature.

4. Conclusions

The effects of coating and lubrication on friction and wear for metal-to-metal application is studied in this study. All the objectives are achieved in this study. The effects of coatings and lubrication on the coefficient of friction, wear volume, and lubricant temperature are successfully studied using the block on ring test. Furthermore, coefficient of friction was observed to be reduced to 0.11-0.13 at 60N load when tested using block on ring test with use of coating and lubricant. Next, wear volume loss for blocks coated with CrN, DLC and TiALN coatings were found to be lower when compared to the uncoated block. Furthermore, the average lubricant temperature when tested using blocks coated with CrN, DLC and TiALN coatings were also lower when compared to the uncoated block. Finally, the best coatings and lubricants based on the effectiveness in reducing friction and wear are also determined from this research where combination of CrN coated block and anti-friction graphene oxide additive oil show the best tribological characteristics.

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