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Tribological characteristics of piston ring and cylinder linear application of low friction TiN nanocomposite coatings

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KEYWORDS

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ABSTRACT

The piston ring and linear cylinder interaction can significantly affect mechanical friction losses in Internal combustion (IC). Therefore, it needs a coating that can reduce friction in the interaction of the piston ring and linear internal combustion. TiN is one of some materials that has been popularly used as a coating as it is a high hardness material, reasonable wear, and good corrosion resistance. This paper examines the friction behavior of TIN coatings in a vacuum. The tested sample was conducted under the dry sliding condition on a pin on a disc prepared as ASTM G99-05 standard. After testing the wear surface and traces of TiN wear, a Scanning Electron Microscope (SEM) was analyzed to observe wear on the TiN layer. The results showed that TiN has friction coefficient values in the range of 0.007-0.040. Based on FEM analysis, TiN had maximum stress of $5.137\text{x}10^6$ N/m^2 and a minimum of $5.186\text{x}10^3$ N/m^2. This proves that TiN has a high hardness and can be utilized as a coating material.

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1.0 INTRODUCTION

The tribological interaction between the piston ring and linear cylinder can significantly affect mechanical friction losses in the Internal combustion (IC) (Chaudhari and Sutaria, 2016). There are more than 30 energy consumption in IC engines. Those are located in the linear cylinder and piston ring system (Holmberg, et al., 2014). The maximum energy combustion in IC engines is thru friction inside the piston assembly, primarily because of the friction piston skirt and piston ring. Therefore, a machine with good performance is needed to improve vehicle performance and IC performance efficiency (Tyagi, et al., 2019). The friction caused by the piston and cylinder will also cause abrasion to the engine. Half of the power loss is attributed to friction between the piston, piston rings, and cylinder liner since friction losses are much higher in piston rings than in other sliding components (Vinoth et al., 2019). Abrasion is a wear mechanism that often appears and is often found in the industry.

Mechanical stress, temperature, and oxidation are some factors that control the frictional behavior of a material. This sliding friction will arise from these three interrelated factors and is also influenced by the load and speed. Chemical composition has a vital impact on the kind and physical traits of the tribolayer formation, which controls the frictional conduct and wears rate (Willey Y.H. Liew et al., 2013). This layer will provide a protective role to reduce friction on the material from the two surfaces. In the encompassing region, the kind of framed layer is typically an oxide, which is a consequence of the response between the layer and oxygen. Consequently, the fractional tension of oxygen during the shear is fundamental for a successful oxidation measure as the oxygen dispersion controls the oxidation rate into the metal cross section (Willey Y.H. Liew et al., 2013; Okechukwu et al., 2020). Internal combustion engine systems need to improve and optimize current energy conversion devices (Gsuo, Zuo, et al., 2020).

In recent years, IC systems has turned into an unwanted theme in the automotive industry. Natural issues become a massive justification for people, in general, to supplant IC with electric and hybrid systems because the minimization of petroleum product utilization has turned into an inexorably significant issue (Ferreira et al., 2020; Wardana et al., 2019).

Friction is one of the complicated phenomena accompanied by energy conservation. About 85%-95% of the energy due to friction is converted into heat energy (Ying and Yupeng, 2017). Changes in conditions such as relative speed, friction factor, and average load can cause variations in the heat field and frictional temperature to affect tribological behavior. Material protection using coating stuff is an essential and versatile choice, not only to improve the material performance but also can reduce the wear and tear that occurs on the material. Friction is a non-equilibrium technique that results in wear (Adiyanto, et al.,2018). The announced friction and wear rates regularly show wide varieties, even with ostensibly indistinguishable tests. This intricacy makes the tribological estimation a complicated problem (Novak and Polcar, 2014).

Since the mid-Sixties, titanium nitride (TiN) coating has been broadly used as a coating material cutting device. similarly to the usage of Titanium Nitride (TiN) as a coating for cutting tools, TiN is also used as a coating on system factors which include sliding bearings, seals, and valves (Mansor et al., 2021; Taufik, et al., 2018). Titanium-nitride (TiN) coatings have been created and utilized by the industry in different tribological applications, counting designing, fabricating, and transportation. TiN has ended up a commonly utilized coating because it has an excessive hardness, moderate wear, excellent corrosion resistance and has been utilized as a wear-resistant coating for cutting apparatuses and dies (Bahri, et al., 2015). TiN has been extensively utilized in the industry as a wear-resistant coating since of its excessive hardness, great erosion resistance, and suitable chemical stability (P. Chen, Xiang, et al., 2016).

Research on frictional heat play the essential role in the development of tribology. The pin-on-disk check is a standardized technique used to look at tribological properties (Meng et al., 2019; Sulaiman, et al.l, 2021). Tribology is the science and engineering of interacting surfaces that move relative to each other. It includes friction and wear, which might be unwanted and result in wasted squandered energy and decreased material life (Mushtaq, et al., 2021).

Several studies on the use of TiN as a coating material have been previously conducted. Research (Çomaklı, 2021) revealed that the structural and mechanical results obtained in the study showed that the multilayer film had a more acceptable grain size, and the film structure was more stable and more complicated than the monolayer layer. The study (Kong et al., 2020) also showed that adding a sealing layer using TiN would significantly increase corrosion resistance compared to CrN. Other authors (Q. Chen et al., 2019) reported the tribological behavior of TiN films in atmospheric and vacuum environments. Based on this research, it was found that the average friction coefficient in the atmosphere is 0.58 and in a vacuum is around 0.31. Therefore, TiN films are suitable for use in a vacuum environment.

On the other side, comparative study between TiN and AlCrN layers has also become one of the exciting topics that have been carried out by (W. Y.H. Liew et al., 2012). Based on the result, it was found that TiN gave a lower coefficient of friction than AlCrN. This research is also corroborated by several similar studies illustrating that TiN has a low friction coefficient value (Tanno and Azushima, 2009; Yao, et al., 2006; Ying and Yupeng, 2017; Zhang, Liu, et al., 2019).

Until today, most of the studies have referred to the application of TiN as a coating material. However, this research has not explicitly provided an overview of the application of TiN on the piston ring and linear cylinder. Therefore, it is interesting and essential to investigate the corrosion properties of the interaction between the piston ring and the linear cylinder coated with TiN. This paper determines the friction coefficient of the TiN coating on the piston ring and linear cylinder using a tribometer. On the other words, the main objective of this paper is to determine the tribological characteristic of TiN coatings in piston ring and linear cylinder applications. The surface and mechanical structure of the sample is also examined.

2.0 EXPERIMENTAL PROCEDURE

2.1 Materials

Figure 1 explain about the thickness of pin and disk specimen. In this research diameter of the pin is 4 mm and diameter disk is 60 mm. Thickness of 1 mm for pin and 5 mm for SCM 440. Composite material of SCM 440 is shown in **Error! Reference source not found.**. While, the Chemical composition and mechanical structure from the disk and pin are clearly presented through Table 1 and “Table 2.

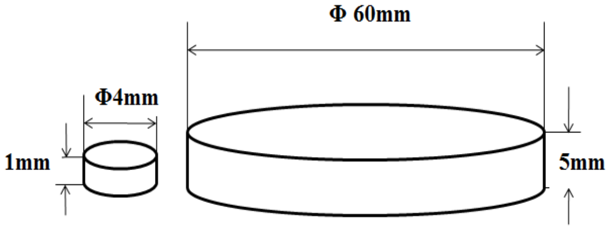

Figure 1: Schematic of pin and disk specimen

Table 1: Chemical composition of SCM 440

Element	Composition (%)
C	0.38 - 0.43
Si	0.15 – 0.35
Mn	0.60 – 0.90
P	<0.030
S	<0.030
Cu	<0.025
Ni	0.02 – 0.05
Cr	0.90 – 1.20
Mo	0.15 – 0.30

Table 2: Mechanical properties of the disk

Element Material	Tensile Strength (kgf/mm^2)	Yield Strength (kgf/mm^2)	Elongation	Hardness (HB)
SCM440	75	90	14%	255~ 321

Table 3: Mechanical properties of the pin (Wang et al., 2015)

Material	Thickness (µm)	Hardness (GPa)	Elastic modulus (GPa)	Contact pressure (GPa)
TiN	0.76	23.6	397	0.673

Sample preparation was put into alkaline solution (NaOH 50g/L; Na2CO3 25g/L) at 80°C, then washed with Acetone $(CH_3)_2CO$ and then ultrasonically cleaned for 15 minutes afterwards.

Table 4: Test setup

Specification	Conditions
Pin material	TiN
Disk Material	SCM 440 carbon steel
Load range (N)	2, 4, 6, 8, 10
Pressure range (MPa)	0.25-2.05
Speed range (m/s)	0.06-0.34

The TiN coating was carried out using a cathodic arc evaporation technique (CAE). This coating was carried out using a vacuum chamber with a diameter of 70 cm and a height of 70 cm. The metallic Ti-cathode has a water cooler with a diameter of 6 cm. The substrate for the deposition of the TiN layer used a sample of 304 L stainless steel with dimensions of 30x30x20 mm^3. Before carrying out the coating process, the model was first cleaned with acetone and propanol in an ultrasonic bath for 15 minutes. During the coating process, the coating pressure is kept constant at a pressure of 1Pa.

2.2 Tribological Testing

The test sample was conducted under the dry sliding condition on a pin on disc and prepared as ASTM G99-05 standard.

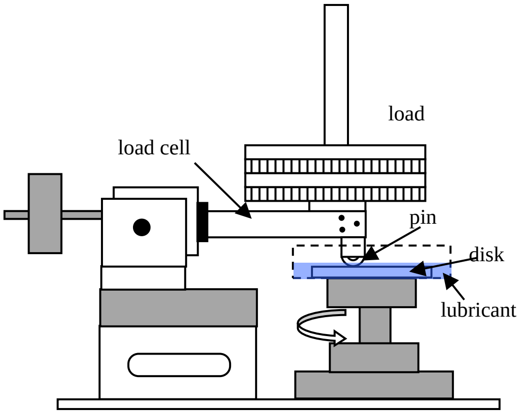

Figure 2: Schematic of the experimental apparatus

W is Normal Load and applied constant with angular velocity. Center of the disc (r) defined from the normal load exerted on pin surface. F_{app} is torque and the value is equal to $F_{T.}$ Friction force (fc) in the opposite direction and F_{Net} (net force) is difference F_T and F_C

$$F_T = F_{app} \tag{1}$$

$$F_C = \mu_s \mathrm{W} \tag{2}$$

$$F_T - F_C = F_{Net} \tag{3}$$

$$F_{Net} = \mu_d \mathrm{W} \tag{4}$$

$$F_{Net} = F_{tf} \tag{5}$$

$$\mu = \frac{F_{tf}}{W} \tag{6}$$

3.0 RESULTS AND DISCUSSION

Figure 3 appears the contact coefficient of the TiN test with five specific loads. Based on the chart in the picture, four friction coefficients continuously start after the speed is 0.10 m/s to 0.35 m/s. TiN has a friction coefficient between 0.007-0.040. Figure 3 indicates the coefficient of friction in the range between 0.007-0.040.

The coefficient of friction is initially high and will decrease towards a constant. The coefficient of friction at large loads (10N) is more significant than at small loads (2N, 4N, 6N, and 8N). The TiN coefficient of friction will increase as the load increases. In other research, also experienced the same phenomenon: at large loads, it will have a more significant coefficient of friction than at small loads (W. Zhang et al., 2020). In other words, the TiN coating can maintain pressure and reduce friction coefficient (Zhang, et al., 2019). The performance of the TiN tribology is strongly influenced by the atmosphere during the testing process (Q. Chen et al., 2019; Huq and Celis, 1999).

The influence of the atmosphere is very influential on the results of COF and wear. In short, the results indicate that the oxidation process dramatically affects friction and wear. Several studies have shown that the oxidation process can be inhibited by reducing the oxygen content to show low friction (Bahri et al., 2015; Willey Y.H. Liew et al., 2013). This study uses a vacuum so that the COF results from TiN will be better. It is because TiN has good tribological properties in a vacuum (Wang et al., 2015; Yu, Inagawa, and Jin, 1995).

The initial decrease in friction of coefficent TiN is thought to be due to the gradual evaporation of the adsorbate on the sample surface by friction heating in a vacuum. In a vacuum pressure of 1.3x10-1 Pa, the evaporation of the adsorbate can reach the limit under experimental conditions so that the friction of coefficent will decrease to a minimum, and the friction of coefficent value will experience a steady value (Yu et al., 1995).

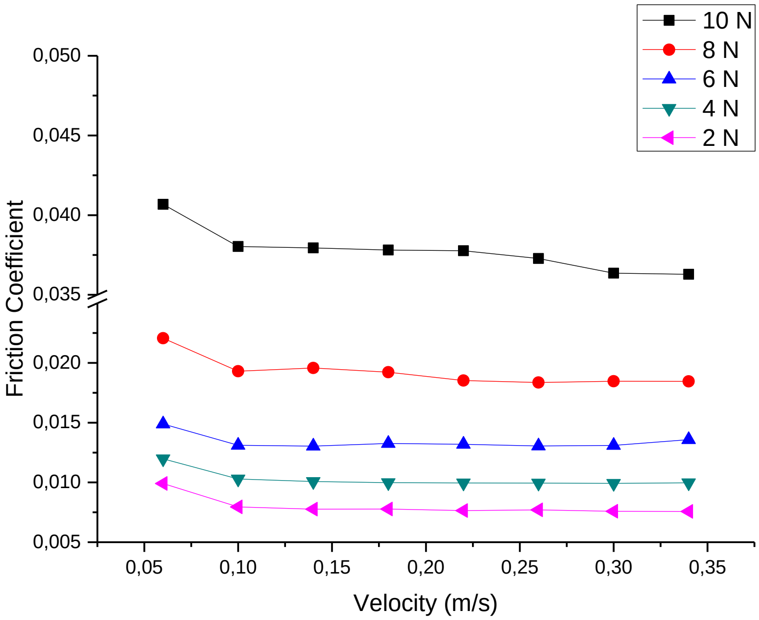

Figure 3: Friction coefficient of a load as a function of velocity with pin TiN

Through Figure 4, the wear debris is observed along the edge of the sliding track on TiN. Wear debris is caused by the generated oxidized particles. This makes a significant contribution to COF (W. Y.H. Liew, et al., 2012). Furthermore, Figure 4 shows that the wear debris has a thickness of 2,232 mm.

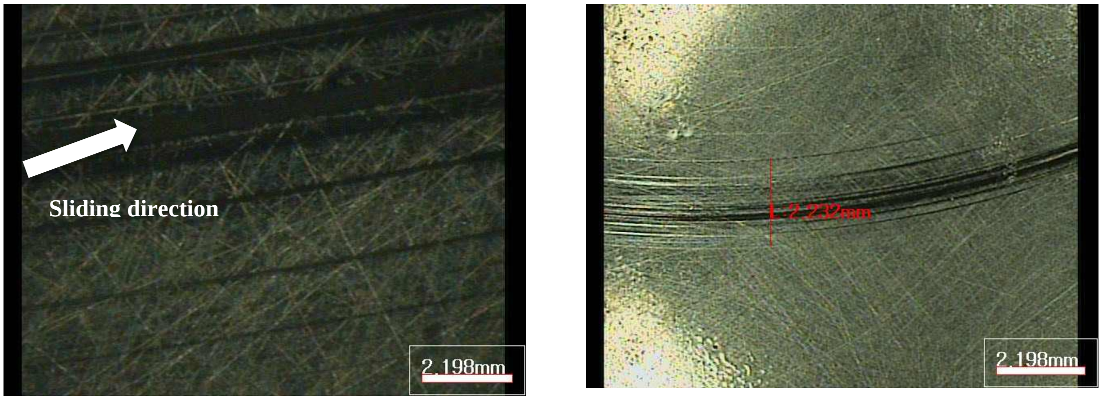

Figure 4: Sliding track on TiN

The SEM image of the wear track obtained after tribological corrosion analysis is shown through Figure 5. In detail, the sliding direction is vast and dense furrow due to excessive deformation and gluing, which will result in wear during the test. TiN has a multilayer coating, so that it has a higher load-carrying capacity than a monolayer (Çomaklı, 2021).

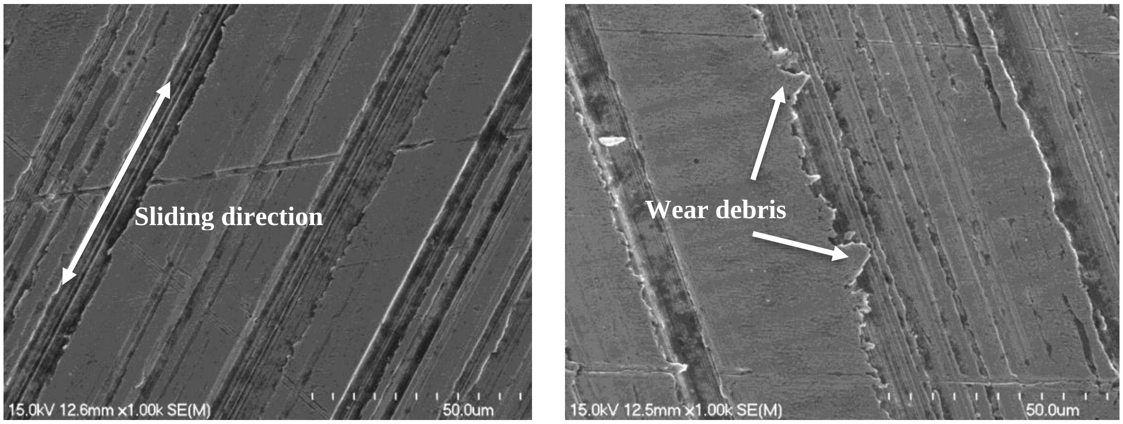

Figure 5: SEM images of the TiN surface

The arrows in each figure demonstrate the rotating and shear direction and the most topographic highlights of the worn surface. Figure 5 is due to hard protrusions on a softer surface that will remove material that can cause abrasive wear. In addition, the increase in surface temperature during the rubbing surface process will cause damage, debris, and scratches. The peeling and scratching damage on this surface shows the results of the coefficient of friction that occurs on the surface (Ali et al., 2016). The surface roughness of the contact friction is one of the foremost critical parameters in controlling the tribological process within the engine. In detail, It can be seen that the worn surface gets to be smooth and exceptionally smooth. Figure 5 shows that abrasive and corrosive wear is the primary wear mechanism of piston rings acting on cylinders lubricated only with acidic fuels (Tung and Gao, 2003). FEM analysis is used to provide answers in the form of stress, strain, and dislocation distributions formed due to loads and movements in the material (Kubica and Skoneczny, 2013)..

Figure 6 shows the graphical results of the numerical analysis in the form of a topographic map for SCM and TiN materials at a pressure of 2 N and a tribological friction pair simulation. Each color in the stress topographic map presented corresponds to a specific range of stress levels occurring on the surface. The consequences of the stress analysis for the chosen boundary conditions show the highest pressure for the tribological machine examined in the contact area between the SCM and the TiN layer shaped on the plate. The maximum pressure produced is 5.137x10^6 N/m^2 and a minimum of 5.186x10^3 N/m^2. The motion and pressure on the sample cause increased stress in the direction of the movement. In Figure 6 the maximum stress is visible on the pins that rub against the disk and occur during the tribology test. This FEA approach can predict wear and friction in the material (Bhat, et al., 2020).

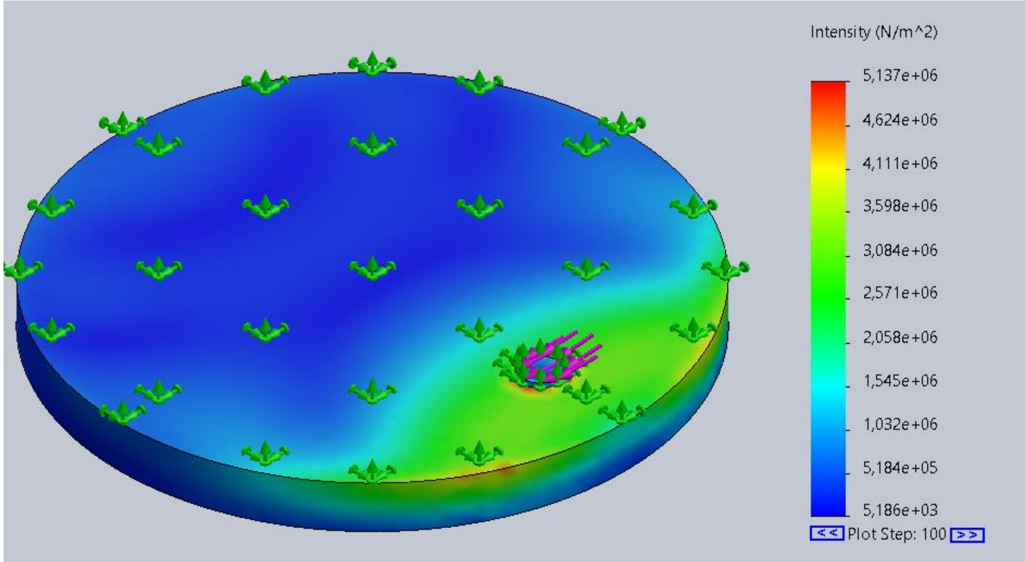

Figure 6: Distribution of principal stresses

CONCLUSIONS

The frictional behavior of TiN coating in dry sliding was studied. TiN gives a friction coefficient of 0.007-0.040. The friction coefficient decreases, and the bigger the load and velocity get fast so that the friction coefficient will be smaller. The friction coefficient characteristics produced by TiN indicate that the oxidation process dramatically affects friction and wear. The TiN coating can maintain pressure and reduce the friction coefficient. The maximum voltage produced is 5.137x10^6 N/m^2 and a minimum of 5.186x10^3 N/m^2. The motion and pressure on the sample motive elevated stress within the direction of the movement. The primary mechanism of frictional strength and wear is related to the hardness and wear resistance of the TiN coated. TiN-coated exhibits good corrosion resistance and has slight wear. This behavior can be seen from the small debris after the friction process and the low friction coefficient.

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