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"STUDY OF FRICTION AND WEAR CHARACTERISTICS OF NANOCOATED PISTON RINGS"

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ABSTRACT

Nanoparticle-based coatings can significantly enhance the performance and service life of internal combustion automobile engines by reducing friction and wear between critical engine components. In this research, the tribological properties of titanium dioxide (TiO_2) nanocoatings applied to piston rings are investigated. The nanocoating samples were prepared using the sol–gel dip-coating process with different dipping–drying cycles of 40, 50, 60, and 70. Tribological tests were conducted using a pin-on-disc tribometer under varying loads and sliding speeds. The experimental results demonstrate that TiO_2 nanocoatings exhibit superior friction-reduction and anti-wear characteristics compared to conventional chromium plating. A reduction in the coefficient of friction by approximately 4% and 8% was observed for coatings prepared with 60 and 70 dipping–drying cycles, respectively. Furthermore, the worn surface morphology was analyzed using scanning electron microscopy (SEM), confirming improved wear resistance of the nanocoated surfaces.

KEYWORDS: TiO_2 nanocoating, tribological properties, coefficient of friction, wear behavior, piston ring.

INTRODUCTION

Tribology is the science and technology concerned with the study of friction, lubrication, and wear of interacting surfaces in relative motion under applied loads. Owing to its wide scope, tribology is inherently multidisciplinary, integrating concepts from mechanical engineering, materials science, chemistry, physics, and applied mathematics. As a result, it is difficult for an individual researcher or engineer to possess comprehensive expertise in all aspects of this field.

For example, a lubrication engineer may have limited knowledge of bearing design, metal friction, and wear mechanisms, while specialists focusing on lubrication principles may not be fully acquainted with bearing materials and structural design considerations. Therefore, effective tribological solutions demand collaborative efforts among chemists, physicists, material scientists, mathematicians, and mechanical engineers.

The primary objective of tribological research is to control friction and minimize wear in machine components through the development of advanced lubrication technologies, formulation of improved lubricants, and identification of novel wear-resistant materials. The advancement of tribology depends on a strong interrelationship between tribological design principles and their practical implementation in engineering applications.

LITERATURE REVIEW

Peter J. Blau *et al.* [1] presented a comprehensive review of tribological studies related to automobile powertrain systems, including internal combustion engines, gearboxes, transmissions, drivelines, and other automotive components. Their study emphasized the integration of lubrication and surface engineering concepts into a unified automotive powertrain system. The authors also highlighted the replacement of conventional heavy-weight cast iron components with lightweight non-ferrous materials such as aluminum and magnesium to improve overall efficiency.

F. Gonzalez *et al.* [2] investigated nanocrystalline materials and reported that a reduction in grain size leads to a significant increase in the volume fraction of grain boundaries and triple junctions. The study demonstrated that nanocrystalline materials exhibit unusual mechanical, physical, chemical, and electrochemical properties compared to conventional polycrystalline and amorphous materials. Improvements in yield strength and toughness with reduced grain size make nanostructured materials suitable for advanced coating applications.

Narendra B. Dahotre *et al.* [3] reviewed engineering coatings for internal combustion engine applications, focusing on dimensional stability and tribological properties of coating materials. Their study discussed wear resistance, lubrication behavior, coefficient of friction, hot hardness, surface roughness, residual stresses, coating adherence, and cost performance.

The authors also highlighted laser-induced reaction nanocomposite coatings as promising candidates for automotive engine applications due to their damage tolerance and wear resistance.

P. Hariharan *et al.* [4] examined the tribological behavior and surface interface characteristics of Fe-based alloy coatings deposited using the HVOF thermal spray process. Powder particles in the size range of 40–80 µm were used to produce coatings with an average thickness of 400 µm. Microstructural analysis and micro-abrasive wear performance were evaluated using optical microscopy, video measuring systems, non-contact surface roughness testing, microhardness tests, and micro-abrasion wear tests. The results showed that the coatings provided high surface hardness and excellent wear resistance.

M. Josephson *et al.* [5] studied the development of a production process for nanostructured WC–Co coatings by reducing grain size to the nanometer scale and minimizing non-WC–Co phases. A comparison between nanostructured and conventional micro-grained WC–Co coatings revealed that the hardness of nanostructured coatings was nearly twice that of conventional coatings, along with improved wear resistance and cutting performance.

Jeremy (Zheng) Li [6] investigated the anti-corrosive performance of coating materials using computational simulations to study fundamental corrosion mechanisms. The proposed simulation model demonstrated potential for predicting coating behavior and performance. Experimental studies were also conducted to validate the computational results.

Simon C. Tung *et al.* [7] provided a detailed review of tribological aspects of automotive powertrain systems, including engines, transmissions, drivelines, and associated components. The authors emphasized that the application of tribological principles and the integration of lubrication and surface engineering are critical for enhancing vehicle performance and efficiency, leading to significant advancements in powertrain tribology.

Rajiv Asthana *et al.* [8] investigated nanomaterials as an emerging class of materials designed for tailored properties. The study highlighted the potential of nanomaterials to exhibit exceptional strength-to-weight ratios and enhanced resistance to wear, friction, corrosion, and thermal degradation, making them suitable for advanced engineering applications.

S. Prabhu *et al.* [9] studied CrN coating deposition on piston rings and piston heads using physical vapor deposition (PVD). Experimental investigations conducted on a spark ignition engine showed a reduction in friction and an improvement in wear characteristics. The results indicated an increase in engine power by 0.76%, torque by 0.67%, and a reduction in surface roughness by more than 63%.

E. Sanchez *et al.* [10] examined the microstructure and phase composition of Al_2O_3 coatings deposited on stainless steel substrates using atmospheric plasma spraying. Characterization techniques such as SEM, TEM, and XRD were employed. The results revealed that nanostructured coatings exhibited superior hardness and wear resistance compared to conventional coatings.

Kenneth Holmberg *et al.* [11] studied the friction and wear behavior of coated surfaces through simulation and modeling techniques. Their work focused on diamond-like carbon (DLC) thin films, explaining friction and wear mechanisms, scale effects, and parameters influencing tribological performance. The study provided a foundation for surface optimization through stress simulation and fracture analysis.

Andrzej Adamkiewicz *et al.* [12] investigated piston ring wear in large marine compression ignition engines through inspections conducted via cylinder liner scavenge ports. Visual inspection and clearance measurements were used to assess piston ring gaps. The study concluded that the increase in piston ring gap with operating hours can serve as a reference parameter for evaluating wear trends during subsequent inspections.

Based on the literature survey, it is evident that nanocoatings significantly enhance tribological performance by improving friction reduction and wear resistance. The following conclusions can be drawn from the reviewed studies:

1. Nanocoatings have been successfully implemented in various applications, such as hydrophobic nanocoatings for water-repellent surfaces in mobile devices and hydrophilic coatings for specialized surface functionalities.
2. Apart from diamond-like carbon (DLC) and thermal barrier coatings (TBC), limited research has been reported on the application of nanocoatings in internal combustion engine components.
3. Nanocoatings demonstrate excellent friction-reduction and anti-wear characteristics, indicating strong potential for their effective implementation in engine applications.

4. Wear prediction through numerical simulation is feasible using Archard's wear model, which is based on contact pressure distribution and material properties.

EXPERIMENTAL

A. Fabrication of TiO_2 Nanocoating by Sol–Gel Technique

In materials science, the sol–gel process is a widely used technique for producing solid materials from small molecular precursors and is particularly suitable for the fabrication of metal oxide coatings. Figure 1 illustrates the schematic procedure of the sol–gel technique employed for TiO_2 nanocoating deposition.

The sol was prepared by maintaining a constant molar ratio of titanium isopropoxide ($C_{16}H_{36}O_4Ti$), ethanol (EOH), and distilled water at 1:5.63:1.58. The solution was magnetically stirred for 30 min at room temperature to ensure homogeneity. Subsequently, nitric acid (HNO_3) of 0.5 M concentration was added as a catalyst to initiate hydrolysis and condensation reactions.

Prior to coating, the metal substrates were thoroughly cleaned to remove surface contaminants. The cleaned substrates were immersed in the prepared sol for 1 min and then withdrawn for drying under ambient conditions. The dipping and drying cycle was repeated for 40, 50, 60, and 70 cycles to ensure uniform and adequate deposition of the TiO_2 nanocoating.

After completion of the coating process, the substrates were annealed at 450 °C for 45 min to remove residual solvents and enhance coating adhesion. The samples were then allowed to cool naturally for 24 h before further characterization and testing.

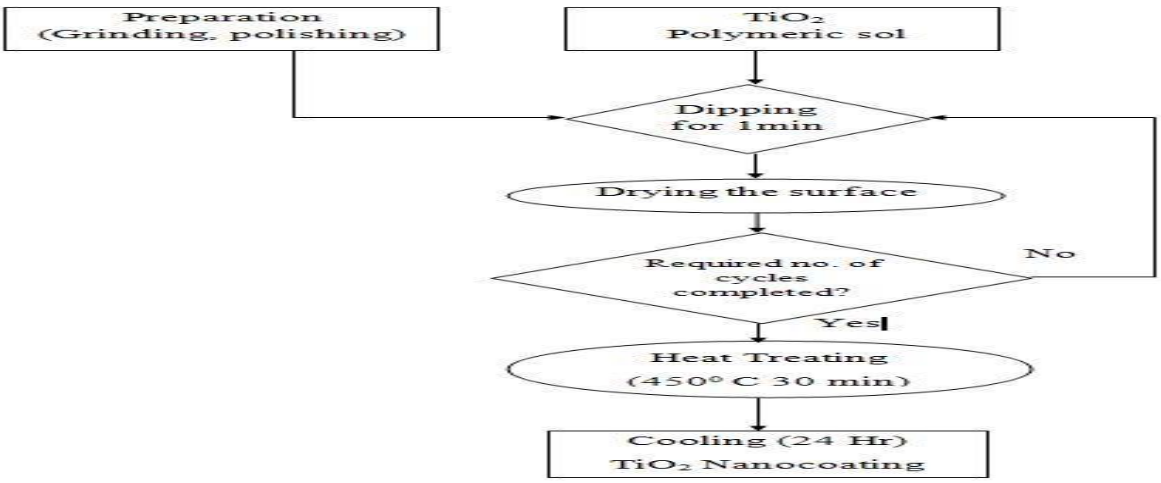


Fig.1 Sol gel technique for TiO_2 Deposition.

B. Materials

The materials selected for tribological testing were chosen to represent the actual material configuration used in internal combustion engine components. SAE 8620 steel, commonly used for piston ring applications, was selected as the pin material and was tested in both uncoated and TiO_2 nanocoated conditions. Gray cast iron, which is widely used for cylinder liner and bore applications, was selected as the disc material.

The pin-on-disc tribometer was employed to evaluate the friction and wear behavior of the selected material pair. Table I presents the details of the pin and disc specimen materials used for the tribological tests.

Table 1: Specimens.

Specimens	**Material**	
Disks	Grey Cast Iron, hardness=130-180BHN, d=165 mm, t=8mm, E=66-157GPa, ν=0.26	
Pins	A	Steel SAE 8620 without any coating
	B	Steel SAE 8620 with conventional chromium platting
	C	Steel SAE 8620 with TiO2 nanocoating (with 40 deposition Cycle)
	D	Steel SAE 8620 with TiO2 nanocoating (with50 deposition Cycle)
	E	Steel SAE 8620 with TiO2 nanocoating (with60 depositionCycle)
	F	Steel SAE 8620 with TiO2 nanocoating (with70 deposition Cycle)

C. Tribometer Test Procedure

Tribological tests were conducted using a pin-on-disc friction and wear testing machine designed and developed by Ducom Instruments. The tribometer was configured to operate under pure sliding contact conditions using a standard pin-on-disc arrangement, wherein the test pin was slid against the rotating disc counterface.

The fabricated pin specimens were tested against the prepared disc specimens under normal loads of 9 kg, 15 kg, and 20 kg. The disc was rotated at speeds of 1000, 1500, and 2000 rpm. All experiments were performed at room temperature for a test duration of 10 min with a continuous supply of 15W–40 lubricating oil to simulate engine lubrication conditions.

The coefficient of friction and wear rate were continuously monitored and recorded using a strain-gauge-based data acquisition system integrated with the tribometer. After completion of the tests, the worn surfaces of the pin specimens were examined using scanning electron microscopy (SEM) to analyze wear mechanisms and surface morphology.

RESULTS AND DISCUSSION

A. Anti-Friction Properties

To ensure the repeatability and reliability of the experimental results, the coefficient of friction (COF) was measured using a pin-on-disc tribometer under normal loads of 9 kg, 15 kg, and 20 kg. Each test was conducted for a duration of 10 min at disc rotational speeds of 1000, 1500, and 2000 rpm, with a continuous supply of 15W–40 lubricating oil.

Figure 3 illustrates the variation of the coefficient of friction with disc speed at a constant load of 9 kg. The horizontal axis represents the disc speed in revolutions per minute, while the vertical axis denotes the coefficient of friction. The uncoated pin (Sample A) consistently exhibited a higher coefficient of friction across all test speeds compared to the coated specimens.

Among the coated samples, the TiO_2 nanocoated pin prepared with 70 dipping–drying cycles (Sample F) demonstrated the lowest coefficient of friction and outperformed the conventionally chromium-plated pin (Sample B). In contrast, the TiO_2 nanocoated samples prepared with lower numbers of coating cycles (Samples C, D, and E) showed relatively higher friction values when compared to Samples B and F.

Overall, the TiO_2 nanocoated pin with 70 coating cycles exhibited an improvement of approximately 8% in friction reduction at a load of 9 kg, indicating superior anti-friction performance under lubricated sliding conditions.

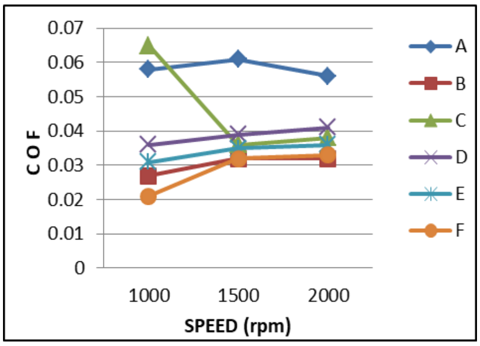


Fig. 3 Coefficient of friction at 9Kg load.

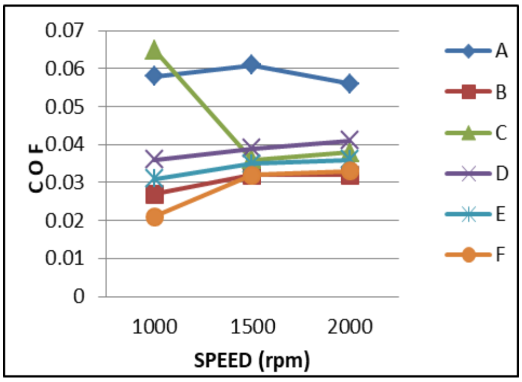
Figure 4 shows the variation of the coefficient of friction with disc speed at a normal load of 15 kg. The TiO_2 nanocoated pins prepared with 60 and 70 dipping–drying cycles (Samples E and F) exhibited lower coefficients of friction compared to the conventionally chromium-plated pin (Sample B).

Considering the results obtained from all three test conditions, it is observed that TiO_2 nanocoatings with higher coating cycles provide improved frictional performance. Sample E demonstrated an average reduction in the coefficient of friction of approximately 4% relative to the chromium-plated pin, while Sample F showed an improvement of about 8%, indicating superior friction-resistance characteristics under increased loading conditions.

RESULTS AND DISCUSSION

A. Anti-friction Properties

In order to confirm the repeatability of experimental data, the coefficient of friction was measured using the pin on disk tribotester under 9kg, 15kg and 20kg load conditions for 10 minute at 1000, 1500 and 2000 rpm speed condition with continuous supply of 15W40 lubricating oil. The coefficient of friction at various speeds at 9 kg load is as shown in Fig. 3.The x-coordinate shows speed of disk in rpm whereas y-coordinate shows coefficient of friction. Coefficient of friction for uncoated pin A is always higher than coated pin. The pin F, TiO_2 (70 cycles) nanocoating exhibits better results than conventional chromium platted pin B. The pin C, D, E exhibits poor frictional resistance than the pin B and pin F. TiO_2 (70cycle) sample possess near about 8% improvement in frictional resistance at 9 kg load.



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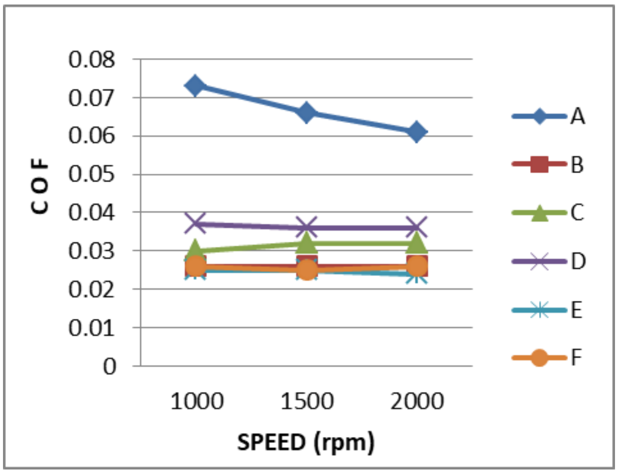

Fig. 4 Coefficient of friction at 15Kg load.

Figure 5 illustrates the variation of the coefficient of friction with disc speed at a normal load of 20 kg. The uncoated pin (Sample A) exhibited the highest coefficient of friction, indicating inferior tribological performance under higher loading conditions. In comparison, the TiO_2 nanocoated pins prepared with 60 and 70 dipping–drying cycles (Samples E and F) showed lower friction values than the conventionally chromium-plated pin (Sample B).

Overall, the experimental results confirm that TiO_2 nanocoatings with higher coating cycles provide superior friction-resistance characteristics compared to chromium plating, particularly under increased load conditions.

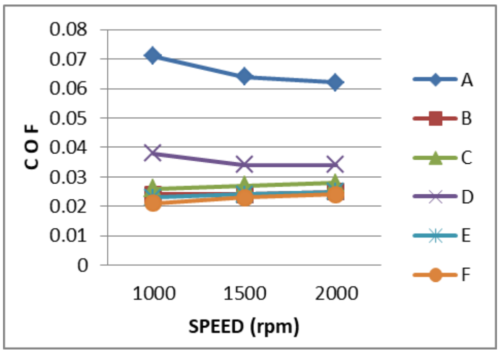

Fig. 5 Coefficient of friction at 20Kg load.

B. Anti-Wear Properties

The anti-wear performance of the test specimens was evaluated using two complementary methods on the tribometer. In the first method, the wear depth of the pin was measured using the load cell sensor integrated with the tribometer, from which the wear rate was calculated. In the second method, a gravimetric approach was adopted, wherein the weights of the pin specimens were measured before and after the tribological tests using a precision weighing balance.

The measured mass losses of the pin specimens before and after testing are presented in Table II. Under the present test conditions, no significant difference in wear was observed between the chromium-plated pins and the TiO_2 nanocoated pins. It should be noted that all experiments were conducted at room temperature, whereas actual internal combustion engine components are exposed to substantially higher operating temperatures. Since temperature has a strong influence on wear mechanisms, its effect cannot be fully captured under ambient test conditions.

Modern tribometers provide the capability to independently control the temperatures of both the pin and disc specimens. Incorporating temperature-controlled testing in future investigations would enable a more realistic evaluation of wear behavior under engine-like operating conditions.

Table 2 Weights of pins

Sample	Weight before test	Weight after test
A	25.834 gm	25.821 gm
B	26.248 gm	25.845 gm
C	25.625 gm	25. 621 gm
D	25.694 gm	25.692 gm
E	25.638 gm	25.636 gm
F	25.614 gm	25.612 gm

B. Analysis of Specimen Surfaces

Scanning electron microscopy (SEM) was used to examine the worn surfaces of both coated and uncoated specimens. As observed in Figs. 6 and 7, the worn surfaces exhibit deep grooves, pits, and spall formations, which are attributed to adhesive and contact fatigue mechanisms. The wear process involves progressive material removal characterized by fiber thinning, subsequent fracture, and eventual detachment of fragmented material from the surface.

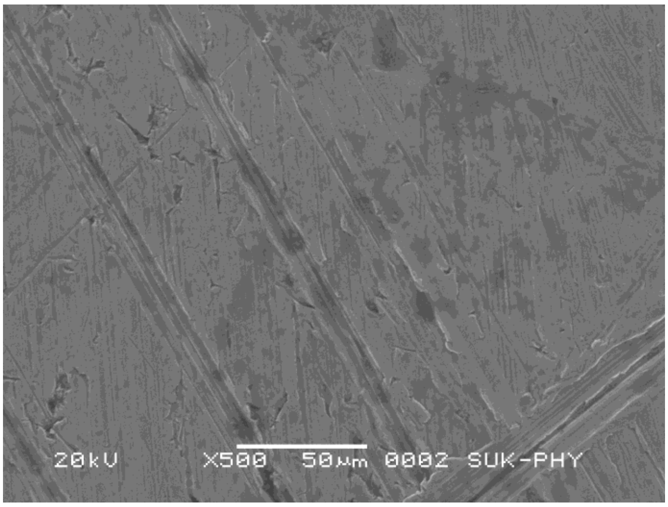

Fig. 6 SEM image of worn surface of uncoated pin.

Fig. 7 SEM image of worn surface of chromium coated pin.

Fig. 8 SEM image of worn surface of TiO_2 Cycle 60 (Pin E) nanocoated pin.

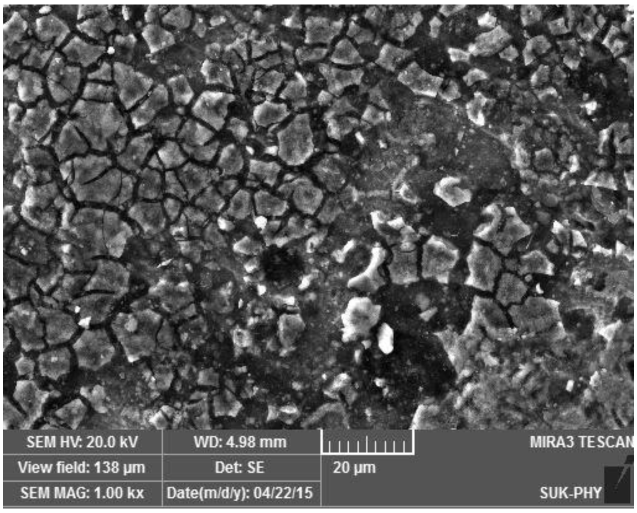

Fig. 9 SEM image of worn surface of TiO_2 Cycle 70 (Pin F) nanocoated pin

TiO_2 nanocoated specimens exhibited lower wear depth compared to chromium-plated samples. As shown in Figs. 8 and 9, the worn surfaces of TiO_2 nanocoatings appear smoother and free from severe scuffing. Material removal occurred gradually, contributing to enhanced wear resistance and improved load-carrying capacity. Consequently, the specific wear rate remained more stable for the nanocoated specimens.

Wear surface analysis further revealed that increasing the number of deposition cycles enhanced the friction-resistance characteristics in the presence of engine oil. An increase in disc speed resulted in a thicker lubricating film, which improved wear resistance but slightly increased frictional forces. Conversely, increasing the applied load reduced the lubricant film thickness. Therefore, maintaining an adequate lubrication film thickness is essential to achieve minimum friction and improved tribological performance.

CONCLUSIONS

Based on the experimental and analytical investigations carried out in this study, the following conclusions are drawn:

Titanium dioxide (TiO_2) nanocoatings were successfully deposited on piston ring material using the sol–gel technique, with effective coating performance achieved for deposition cycles of 60 and above. Both experimental results and numerical analysis indicate that the anti-wear and anti-friction characteristics of TiO_2 nanocoatings are comparable to, and slightly superior to, those of conventional chromium plating. This suggests that TiO_2 nanocoatings can serve as a viable alternative to chromium coatings when an adequate coating thickness is maintained.

A. The TiO_2 nanocoating prepared with 70 deposition cycles exhibited approximately 8% lower coefficient of friction compared to conventional chromium plating, resulting in reduced frictional losses.

B. The presence of the TiO_2 nanocoating on the contact surface reduces interfacial shear stress, thereby contributing to lower friction and improved wear resistance.

C. The anti-wear performance of TiO_2 nanocoatings was found to be comparable to that of chromium plating, with a dimensional wear coefficient of approximately 9.56×10−89.56 \times 10^{-8}9.56×10−8.

D. An increase in applied load on the pin led to a reduction in lubricant film thickness, highlighting the importance of maintaining adequate lubrication conditions for optimal tribological performance.

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