中國機械工程學刊第四十五卷第四期第 365~374 頁(民國一百一十三年)
Journal of the Chinese Society of Mechanical Engineers, Vol.45, No.4, pp365~374 (2024)

Effects of Nano-Diamond Additives on the Tribological Performance Improvement of Lubricating Grease for Ball Screw

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Keywords: Tribology, Four-Ball Wear Test, Ball Screw, Grease Life Test. Nano-Diamond

ABSTRACT

This study presents groundbreaking insights into the tribological performance enhancement of lithium soap-based greases through the novel use of Ultra Dispersed nano-Diamonds (UDD). Uniquely, we explore the synergistic effects of Oleylamine (OLA) as a dispersant and different particle sizes of UDD, a methodology not extensively investigated in prior research. Our comprehensive four-ball tests reveal that a 100 ppm concentration of UDD with OLA significantly lowers the grease temperature and reduces wear scar diameters on steel balls, a finding with considerable implications for industrial lubrication applications. Notably, the addition of 0.001 ml of UDD under a test load of 2934 N extended grease life from 1450 to 2100 seconds, demonstrating a substantial improvement over traditional grease formulations. These results underscore the potential of UDD additives in revolutionizing the performance and durability of lubricating greases.

INTRODUCTION

Ball screws are pivotal in various mechanical applications, valued for their low friction coefficient, high positioning accuracy, and long service life. These characteristics are especially critical in high-speed and high-frequency operations where the performance of lubricants plays a determining role. Recent advancements in enhancing lubricant efficacy have centered around the incorporation of nano-additives, with nano-diamonds (NDs) emerging as a promising candidate. Studies have shown that NDs can significantly improve the wear resistance and load-bearing capacity of lubricants (Gyoung-Ja Lee et al., 2017; A.K. Piya et al., 2024). However, these studies primarily focus on conventional lubricants, leaving a research gap in the application of NDs in specific formulations like lithium soap-based greases used in ball screws. Moreover, the role of dispersants in optimizing ND distribution and performance within these greases remains under-explored. Our study aims to bridge this gap by examining the effects of various dispersants and particle sizes of Ultra Dispersed nano-Diamonds (UDD) in lithium soap-based greases, offering insights into enhanced tribological performance for ball screw applications.

Ball screws have characteristics such as low friction coefficient, high positioning accuracy, long life, capability for high-speed forward and reverse rotation, and can be used as transmission components that convert linear motion to rotational motion and vice versa. Under high-speed and high-frequency conditions, the temperature rise of the lubricant is a critical issue. It is crucial to prevent the softening of the grease to avoid reduced lubrication performance or failure. During the movement on the track surface, the lubricant plays a vital role in isolating direct frictional contact between the balls and the track surface.

Lubrication is both a science and a specialized technology. During the industrial revolution of the 19th century, after the invention of the steam engine, large machinery composed of many mechanical parts emerged, necessitating stable and reliable lubrication to ensure normal operation. This sparked extensive research into lubrication theory. As time progressed, tribology gradually evolved into an interdisciplinary science involving physics, chemistry, fluid mechanics, and contact mechanics. The purpose of lubrication is to alleviate mechanical wear, reduce power loss and mechanical failure, thus saving resources and reducing costs. In recent years, numerous studies have incorporated nanoparticles as additives in lubricants, opening a new frontier for the application

Paper Received February, 2024. Revised March, 2024. Accepted March, 2024. Author for Correspondence: Hsiao-Yeh Chu.

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of nanomaterials. Their aim is to enhance wear resistance, reduce friction, increase load-bearing capacity, and even repair worn surfaces (Xu et al., 1996). For instance, the incorporation of nano-diamonds has been found to significantly bolster the load-bearing capacity of lubricants, contributing to the reduction of wear and friction (Liu and Chen, 2014). Additionally, the use of nanoparticles has been explored for their potential to create a protective film between contact surfaces, thereby improving lubrication and extending the operational life of the machinery (Shen et al., 2001). In addition to adding additives to lubricating grease, solid lubrication can also be applied directly to lubrication points, coated on surfaces, or incorporated into materials for modification. These methods are all designed to prevent direct contact between moving surfaces and thus avoid wear. Ball screws can be lubricated with either oil or grease, with the latter being more common. This is mainly because there is no dripping of lubricant when the nut moves, and it has a higher load-bearing capacity. Therefore, the lubricant used in ball screws is also grease, specifically the type used by industry manufacturers. The grease used in ball screws must maintain its film strength without breaking or collapsing under high load pressures and because it needs to move continuously along the track during operation, it must have a certain degree of resistance to environmental contaminants. Hence, developing suitable grease for ball screws is quite important.

When two objects in contact move relative to each other (or tend to move) under external force, a tangential force known as friction occurs at the contact surface. The continual loss of material from the working surfaces due to relative motion or the destruction of the surface layer when a solid comes into mechanical contact with other objects or media is termed wear. When friction and wear occur, introducing a substance between the two moving surfaces to reduce friction and wear facilitates easier movement and prolongs service life, a phenomenon known as lubrication (Holm, 1958). In 1958, Holm used Electrical Contact Resistance (ECR) for foundational research on testing techniques. Since the measurement of surface contact resistance is directly related to the behavior of the frictional contact surface and is sensitive to surface contact measurement, it has been widely used in the study of frictional contact behavior of oil films. In 1987, Fukunaga compared the use of grease and lubricating oil on gears using contact resistance. He found that the contact resistance of lubricating oil was higher than that of grease. Additionally, he discovered that after a period of operation, the grease, subjected to high temperatures and gear pressure, allowed the base oil to flow into the gears, forming a protective oil film and thereby increasing the contact resistance (Fukunaga, 1987). Nano-diamonds are directly converted from exploding explosives, where the carbon atoms in the unoxidized oxygen balance reaction of the explosives regroup and rearrange to form nano-diamonds. These products have a concentrated particle size distribution (4~10 nm). Xu, Zhao, and Xu synthesized nano-diamond particles using the explosion method, i.e., detonation of explosives, and added them to paraffin-based oil to analyze the tribological performance of these two-phase lubricants. Their experimental results demonstrated the excellent load-bearing capacity, wear resistance, and friction reduction properties of nano-diamond particles. They also found that nano-diamond particles could penetrate between two meshing sliding surfaces and roll between two friction surfaces like ball bearings. The diamond particles get polished and form a boundary lubrication film, preventing direct contact of the friction surfaces. The surface hardness also increases due to the work-hardening effect produced by the ball bearing action. Shen, Luo, and Wen discussed the tribological properties of oils with added nano-diamond particles of 5-6 nm in diameter. They observed that adding spherical nano-diamond particles to the base oil increased the viscosity and formed a thicker lubrication film compared to the base oil without added nano-diamond particles. The coefficient of friction also decreased with sliding distance. Research has also shown that the addition of nanoparticles to base oils can result in increased viscosity and the formation of a thicker lubricant film, further contributing to the improved tribological properties of the lubricant (Macleod and Michalczewski, 2016). By examining the span of literature on lubrication science, one can see the progression from fundamental principles to the cutting-edge use of nanotechnology to address contemporary challenges in tribology (Yulin, 2005). Recent advancements have introduced the concept of using hollow nanoparticles as solid-state lubricants, offering new possibilities for friction reduction and wear resistance in various applications (Rapoport et al., 1997).

EXPERIMENTAL DETAILS

Preparation of Lubricating Grease with UDD

The lubricating grease chosen for this experiment was provided by a company through academic-industrial cooperation, known as Grease E, a lithium soap-based grease commonly used for ball screw lubrication in the industry. Its component characteristics are summarized in Table 1. The Industrial Technology Research Institute assisted in blending UDD into Grease E, using various dispersants to mix Grease E with UDD of different concentrations (ppm) and particle sizes. This modified the lubricating grease, which was then tested for extreme pressure properties and grease life using the four-ball test.

Table 1. Composition of Grease E Used in the Experiment

Actual Name of the Lubricant	HIWIN Grease G05
Color	Brown
Base Oil	Mineral Oil
Thickener	Lithium Soap-Based
Applicable Temperature Range (°C)	-15~120
Penetration (NLGI)	2
Viscosity (cSt) at 40°C	200
Drop Point (°C)	190

Four-Ball Test

The four-ball test, as delineated in the ASTM D-2266 standard, was selected for its effectiveness in evaluating the wear resistance and extreme pressure performance of lubricating greases - key parameters in assessing the efficiency of ball screw lubrication. This test method is particularly suitable for our study as it simulates the typical stress and wear conditions experienced by ball screws in industrial settings.

In this test, three steel balls are fixed in a triangular formation and a fourth ball is rotated against them under a specific load. The test measures the wear scar diameter on the three stationary balls after a set duration, providing quantitative data on the wear protection offered by the grease. By incorporating Ultra Dispersed nano-Diamonds (UDD) into the grease, we aim to observe their impact on reducing wear scars, thereby indicating enhanced protective capabilities against mechanical wear. The choice of this test method allows for a direct comparison of the tribological performance of the grease with and without UDD additives under controlled, yet industrially relevant conditions.

Moreover, the four-ball test offers insights into the effectiveness of different dispersants and particle sizes of UDD in the grease. By examining the wear scar diameters, we can infer the optimal combination of dispersant and UDD particle size that yields the best tribological performance. This is particularly crucial as the dispersion of nano-additives in the grease is a significant factor affecting their performance. The results from this test are expected to guide the formulation of more effective lubricating greases for ball screws, enhancing their longevity and reliability in high-demand applications.

The configuration of the four-ball fixture and the upper and lower test pieces are shown in Fig. 1, with the left side of the Fig. representing the lower test piece fixture housing three steel balls with a diameter of 12.7 mm; the right side shows the upper test piece fixture holding one steel ball locked above the three balls. This upper ball is driven by a fixed-speed spindle powered by an electric motor. The three fixed balls in the lower fixture are pressed upwards against the upper ball by a lever that can adjust the load. This setup allows the torque transmitted to the three fixed balls to be measured and converted into a friction coefficient. At the start of the test, the lower test pieces are stationary while the upper test piece rotates counterclockwise driven by the machine's driving shaft, but there is only pure sliding, no rolling, between the upper ball and the lower three balls. Fig. 2 illustrates the four-ball fixture assembled on the multifunctional wear testing machine.

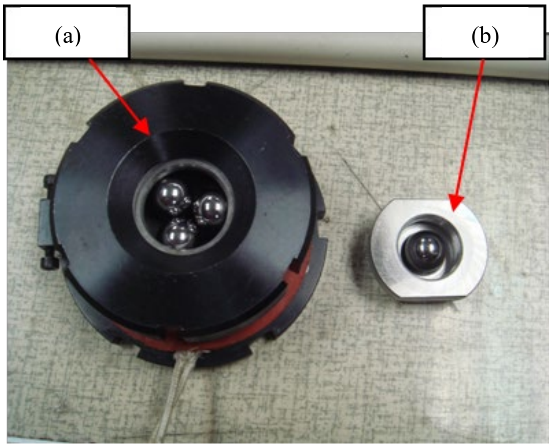
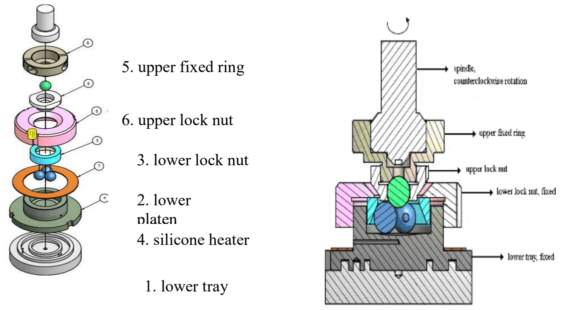


Fig. 1. Assembly of the Four-Ball Fixtures for the (a) Lower balls, (b) Upper ball.

The criteria for the grease's extreme pressure performance, according to ASTM D-2266, are determined by the size of the wear scars on the three lower balls after the experiment. The average wear scar diameter is measured with an optical microscope to determine the performance.

The conditions for the four-ball test were set according to the ASTM D-2266 standard for the experiments in this thesis. The steel ball specimens were standard four-ball test chrome steel balls, with specifications conforming to AISI Standard E-52100 (JIS Standard SUJ2), a diameter of 12.7 mm, and a hardness range of Rockwell hardness HRC 60~64. Their elemental composition is summarized in Table 2. The experimental conditions of the four-ball test according to the ASTM D-2266 standard are as follows:

1. The steel balls used for the experiment have a diameter of 12.7 mm (1/2 inch).
2. The temperature for the experiment is 75±2°C.
3. The rotation speed for the experiment is 1200±60 rpm.
4. The load applied for the experiment is 391±2 N (40±0.2 kgf).
5. The duration of the experiment is 60±1 minute.



(a) (b)

Fig. 2. (a) Exploded-view drawing of the Four-Ball test adapter, (b) Combination drawing of the Four-Ball test adapter mounted on a wear testing machine.

Grease Life Test

In assessing the longevity of lubricating grease enhanced with Ultra Dispersed nano-Diamonds (UDD), we adopted the ASTM D-3336 standard for grease life testing, with specific modifications tailored to our research objectives and constraints. While the ASTM D-3336 provides a comprehensive framework for evaluating grease life under high-temperature conditions, its prolonged test duration poses practical limitations for experimental efficiency. To address this, we made two critical modifications to expedite the testing process while preserving the test's integrity and relevance.

Firstly, the quantity of grease injected into the bearing was reduced. This modification intensifies the operational stress on the grease, accelerating the breakdown process and allowing us to observe the grease's performance over a condensed timeframe. It simulates a more severe usage scenario, testing the grease's resilience under heightened stress, which is particularly relevant for industrial applications where lubricants may be subjected to extreme conditions.

Secondly, we increased the load applied during the test. This change further simulates high-stress conditions, providing insights into the grease's performance under increased mechanical pressures. Such conditions are representative of many real-world applications, particularly in heavy machinery and high-load mechanical systems, making our findings more applicable to industrial contexts.

These modifications, while deviating from the standard testing protocol, are carefully considered to maintain the test's relevance to real-world applications and enhance the practicality of our research. By accelerating the wear process, we can more efficiently evaluate the potential of UDD additives in extending the life of lubricating greases under extreme conditions, offering valuable insights for their application in demanding industrial environments. The testing equipment used remains the Falex-6 multifunctional wear tester.

The bearing fixture is shown in Fig. 3, with Fig. 4(a) representing the overall fixture assembly and Fig. 4(b) detailing the test fixture components. After locking the rotating shaft and the bearing to be tested, the assembly is placed inside the lower fixture, and the top cover is locked onto the lower fixture. The bearing's outer ring is secured within the lower fixture, remaining stationary while the inner ring rotates with the drive shaft and does not move. The temperature sensor is then placed in the temperature hole to measure the temperature of the bearing's outer ring. At the beginning of the test, the lower fixture is stationary, and the upper rotating shaft driven by the machine turns counterclockwise. Fig. 4 is a composite and system diagram of the overall fixture drawn using drawing software.

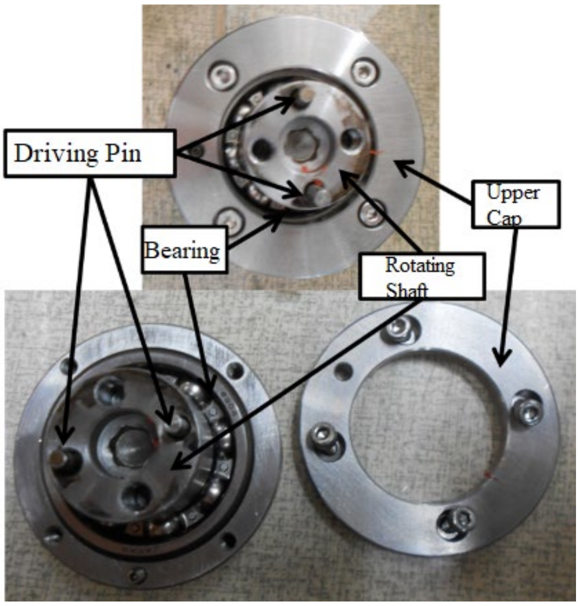
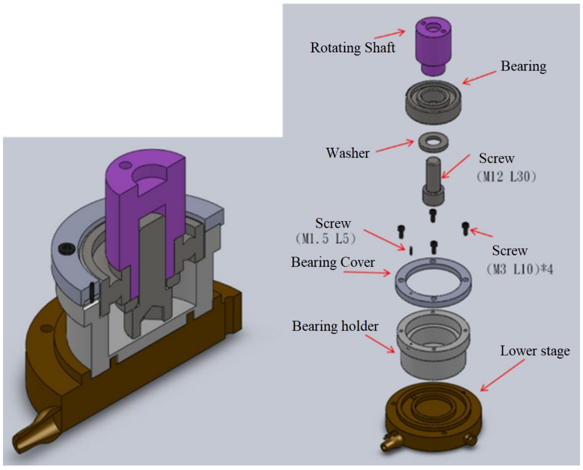


Fig. 3. Grease life test rig pictures

The conditions for the grease life test are modified from the ASTM D-3336 standard for estimating the life of lubricating grease. The bearing is a 6204 open-type deep groove ball bearing, and its specifications are shown in Table 3 [7]. The experimental conditions for the grease life test are as follows:

1. The bearing used for the experiment is a 6204 open-type deep groove ball bearing, and all lubricant inside the bearing must be completely removed.
2. The temperature for the experiment is room temperature.
3. The rotation speed for the experiment is 2500±60 rpm.
4. The load applied for the experiment is 2934 N.
5. The duration of the experiment is until a significant rise in test temperature or friction torque (friction coefficient) occurs, at which point the test stops, and the elapsed test time is used as the basis for grease life.



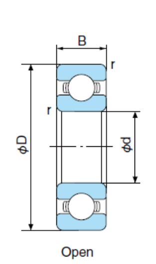
(a) (b)

Fig. 4. Grease life test fixture: (a) Cross-sectional view of the fixture assembly; (b) Detail Component diagram.

Table 2. Composition of Steel Balls in the Four-Ball Test

Component Name		Steel Ball
Material Name		SUJ2
AISI Code		52100
Elements and Contents (wt %)	C	0.98~1.10%
	Si	0.15~0.35%
	Mn	0.25~0.45%
	P	0.025%
	Ni	0.25%
	Mo	0.10%
	Cu	0.35%
	Cr	1.30~1.60%
	S	0.025%

Table 3. Specifications of Open Type Deep Groove Ball Bearing 6204 [7]。

	d	20 mm
	D	47 mm
	B	14 mm
	R (min.)	1 mm
	Rated Dynamic Load, Cr	12800 N
	Rated Static Load, Cor	6600 N

RESULTS AND DISCUSSION

Changes and Comparisons of Temperature, Electrical Resistance, and Friction Coefficient

After the Four-Ball Test Fig. 5 shows the average friction coefficient from the four-ball test with Grease E, with varying UDD particle sizes, all using OLA as a dispersant and at a concentration of 100 ppm. It is observed that as the UDD particle size increases from 38 nm to 200 nm, the average friction coefficient gradually decreases, especially between 38 nm and 68 nm where the reduction is more significant. Beyond 68 nm up to 200 nm, the decrease is marginal, indicating an approach towards an optimum value. Fig. 6 compares the average friction coefficient for a particle size of 200 nm and concentration of 100 ppm when using two different dispersants, PEHMA and OLA. It is evident that the average friction coefficient obtained with OLA as a dispersant is less than half of that with PEHMA, indicating that OLA is superior in dispersing UDD and bonding with metal surfaces. Fig. 7 compares the time it takes for the friction coefficient to start increasing in the four-ball test with different UDD particle sizes, all using OLA as a dispersant at a concentration of 100 ppm. The grease with 38 nm UDD particles shows the longest duration before a rapid increase in friction coefficient during testing, and this duration decreases gradually as the UDD particle size in the OLA dispersant increases.

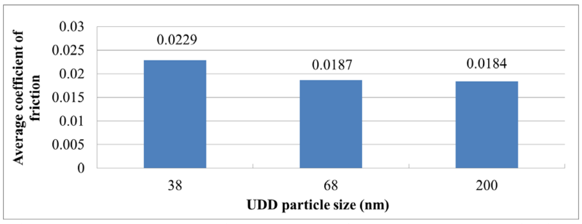


Fig. 5. Comparison of the average friction coefficient of UDD with different particle sizes at the same dispersant OLA and a concentration of 100 ppm.

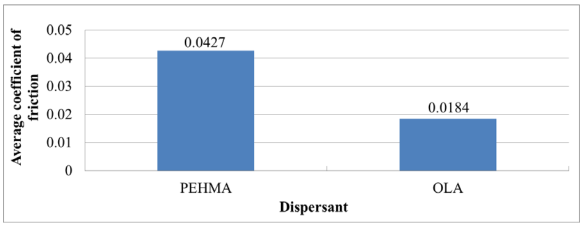


Fig. 6. Comparison of the average friction coefficient of UDD with different dispersants for the same particle size of 200 nm and concentration of 100 ppm.

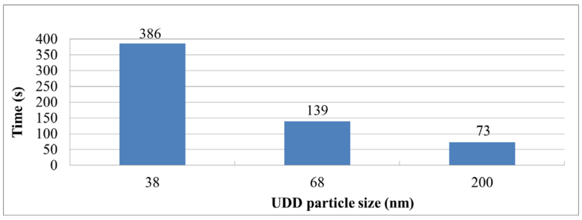


Fig. 7. Comparison of the time at which the friction coefficient begins to rise rapidly for UDD of different particle sizes with the same dispersant OLA and a concentration of 100 ppm.

Optical Microscope Images of Steel Ball Surfaces after the Four-Ball Test

Fig. 8 illustrates that the average wear scar diameter for greases with added UDD is smaller than that of Grease E. The best performance is shown by the grease with OLA as a dispersant, 200 nm UDD particle size, and a concentration of 100 ppm. Fig. 9 compares the average wear scar diameter for Grease E with UDD added using PEHMA as a dispersant at an average particle size of 117, 200, and 1000 nm, and a concentration of 100 ppm. It is found that the wear scar of the grease with 1000 nm UDD particles is significantly larger than the other two sizes, with the 200 nm particle size showing the smallest scar. This might be because larger particles do not easily enter between surfaces to form a protective layer. With smaller particles, the protective layer formed is too thin, leading to quick removal, rendering the layer ineffective. The 200 nm particles are more likely to penetrate between surfaces and form a thicker protective layer, achieving a better lubrication effect. Fig. 10 compares the average wear scar diameter for Grease E with different UDD particle sizes added using OLA as a dispersant at a concentration of 100 ppm, where the 200 nm particle size shows the smallest wear scar. Fig. 11 compares the average wear scar diameter for Grease E with 200 nm UDD particles added using both OLA and PEHMA as dispersants at a concentration of 100 ppm, revealing that the wear scar for the grease with OLA as a dispersant is slightly smaller than that with PEHMA.

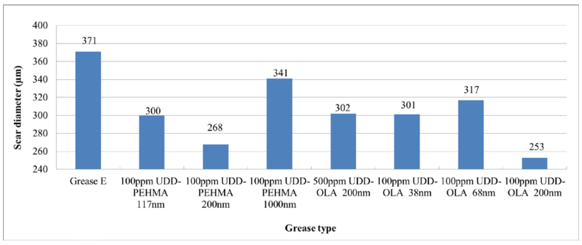


Fig. 8. Comparison of the average wear scar diameter of all greases in the four-ball test.

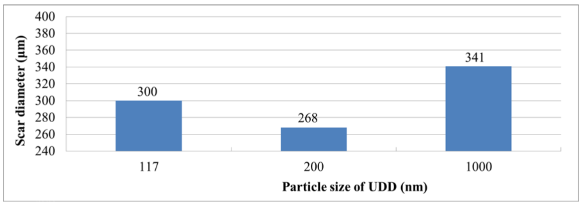


Fig. 9. Comparison of the average wear scar diameter of UDD with different particle sizes using the same dispersant PEHMA and a concentration of 100 ppm.

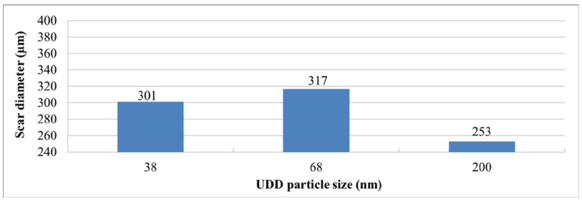


Fig. 10. Comparison of the average wear scar diameter of UDD with different particle sizes using the same dispersant OLA and a concentration of 100 ppm.

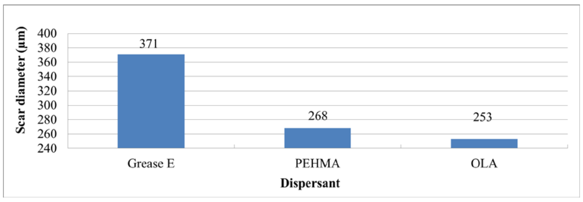


Fig. 11. Comparison of the average wear scar diameter of UDD with different dispersants for the same particle size of 200 nm and concentration of 100 ppm.

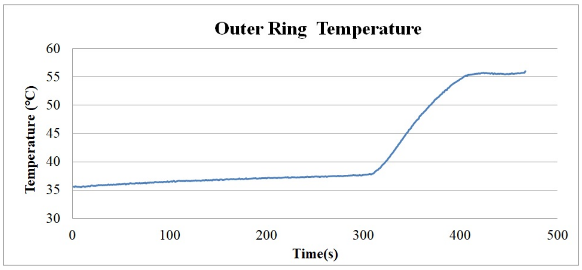
The findings of our study offer significant advancements in the understanding of nano-diamond additives in lubricating greases. We observed that incorporating 100 ppm concentration of UDD with Oleylamine (OLA) as a dispersant notably reduces the temperature of the grease and the wear scar diameter on steel balls. This is in alignment with the studies conducted by Kulkarni (Kulkarni et al., 2024), who reported enhanced wear resistance in lubricants due to nano-additives. However, our research extends these findings by demonstrating that the choice of dispersant, OLA in this study, plays a crucial role in optimizing the distribution and efficacy of nano-diamonds within the grease.

Furthermore, our observation that the 200 nm particle size UDD offers the best performance in terms of wear scar reduction and grease temperature aligns with the findings of Singh et al. (Singh et al., 2021), who emphasized the importance of particle size in the performance of nano-additives. Nonetheless, our study uniquely contributes to the field by specifically focusing on UDDs in lithium soap-based greases for ball screws, a context not extensively explored in previous studies.

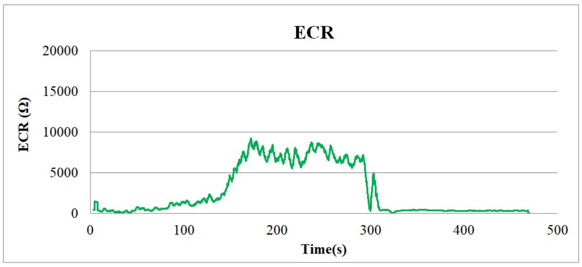
Dry Friction Test for Bearing Life Experiment

The dry friction test for bearing life experiment analyzes the lifespan performance of lubricating grease through a bearing life test, initially using a bearing without lubricant as a baseline for comparison with conditions where lubricant is added. Besides comparing the duration of bearing life, the test also captures the outer ring temperature of the bearing, the Electrical Contact Resistance (ECR) values, and the friction coefficient to observe differences during the process.

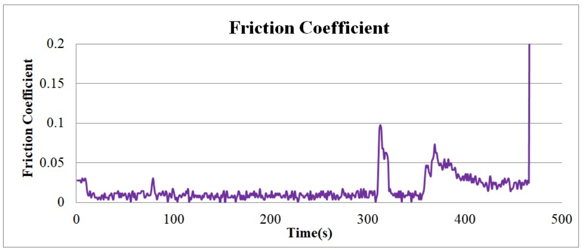
Fig. 12 depicts the experiment conducted on a bearing cleansed of all grease, in a greaseless state, under a load of 125 N. The graph shows that around 460 seconds, the friction coefficient sharply increases, and the ECR value drops to nearly zero, indicating bearing failure due to lack of lubrication. After the test, the bearing's retainer is found to be broken, as shown in Fig. 13. From Fig. 12, it is also observed that the ECR gradually increases after the start of the experiment, indicating the gradual formation of scratches on the steel ball surface. After 100 seconds, a significant amount of wear debris starts to form, leading to three-body wear (Third-body wear) between the steel ball and the track surface, reducing the direct contact area; thus, the ECR quickly rises significantly. However, since the wear debris is in a rolling and sliding state between the surfaces from 100 to 290 seconds, the increase in the friction coefficient is not pronounced. After 290 seconds, the friction coefficient and ECR sharply rise and fall, respectively, indicating severe wear with large wear particles that no longer enter between the wear surfaces, but continue to abrade the steel ball, track, and even the separator. The outer ring temperature initially rises sharply to about 55°C, and due to drastic changes such as retainer breakage (as shown in Fig. 13), the bearing seizes, causing the friction coefficient to rise vertically at around 460 seconds, and the experiment is stopped at this point.



(a)



(b)



(c)

Fig. 12. (a) Temperature; (b) Electrical contact resistance (ECR); and (c) Friction coefficient of the outer ring of a bearing under a no-oil condition and with an applied load of 125 N.

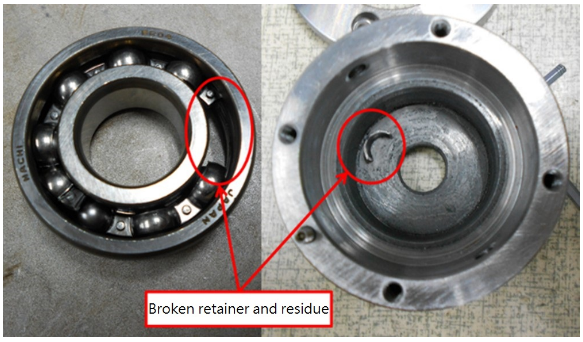


Fig. 13. Photo of the damage and fracture of a bearing cage under dry friction conditions.

Grease E Test for Bearing Life Experiment

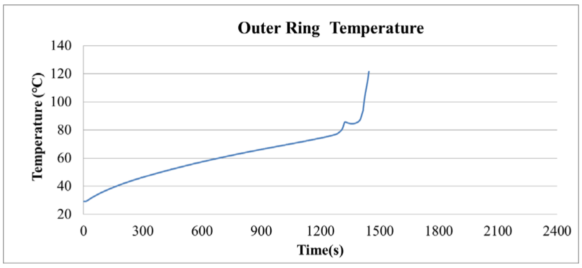
Life tests usually require a very long time and multiple experiments to obtain a life curve. Due to time constraints and the inability to test continuously over several days, this thesis accelerates the grease life test by adding a small amount of lubricating grease and increasing the load.

Fig. 14 shows the experiment conducted by injecting 0.001 cc of Grease E into the cleansed bearing and applying a load of 2934 N. At the beginning of the experiment, the ECR rises sharply, and the friction coefficient drops rapidly, indicating initial lubrication by the small amount of grease present. However, after 100 seconds, the ECR no longer rises and quickly falls, with a corresponding gradual increase in the friction coefficient, indicating that the load is too high for an effective lubricating film to be established, and the lubrication effect diminishes. During this phase, the outer bearing temperature is continuously rising. At approximately 1450 seconds, the friction coefficient starts to rise sharply, and the ECR drops to single digits, with the outer bearing temperature also rising rapidly, signaling the end of the experiment as the lubrication effect of the grease has failed, leading to bearing damage.

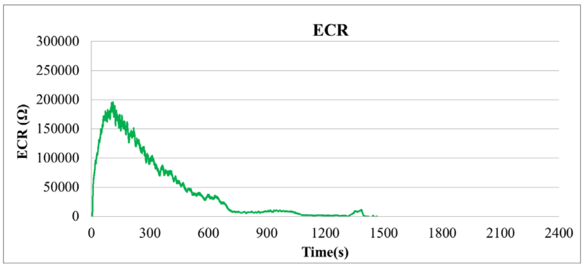
Bearing Life Test with 100 ppm UDD-OLA

Grease E with 200 nm Particle Size Having established that injecting 0.001 cc of Grease E into the bearing with a load of 2934 N results in a grease life of approximately 1450 seconds, the original Grease E is replaced with the grease that showed good lubrication effects with added UDD in the four-ball test. The same load is applied to observe if the life span of the grease compared to Grease E is extended or differs.

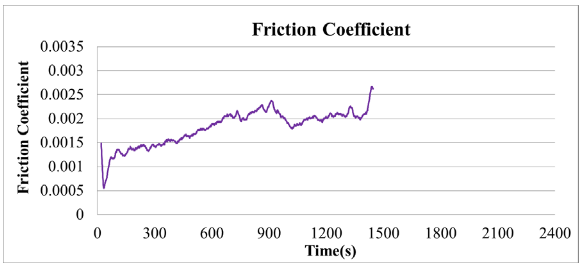
Fig. 15 shows the experiment using 0.001 cc of Grease E with added 200 nm UDD-OLA particles at a concentration of 100 ppm, injected into the cleansed bearing under a load of 2934 N. At the start of the experiment, the ECR rises, and the friction coefficient drops rapidly to about 0.001, which is almost half the stable friction coefficient of 0.002 for Grease E, and remains stable until the grease fails, leading to bearing damage. The friction coefficient is very stable throughout, indicating good anti-extreme-pressure lubrication effect of the grease under very high loads. The fact that the friction coefficient remains stable even as the ECR drops suggests that the lubricating film has become thinner due to the high load, reducing the ECR but not significantly affecting lubrication. Presumably, UDD particles coated on the surface strengthen the contact resistance of the surface, resulting in a longer grease life. Fluctuations in ECR after 1200 seconds are likely due to wear particles forming between the surfaces, leading to three-body wear. During this phase, the outer bearing temperature is continuously rising. At about 2100 seconds, the friction coefficient begins to rise sharply, and the ECR drops to single digits, with the outer bearing temperature also rising rapidly, indicating that the lubrication effect of the grease has failed at this point.



(a)



(b)

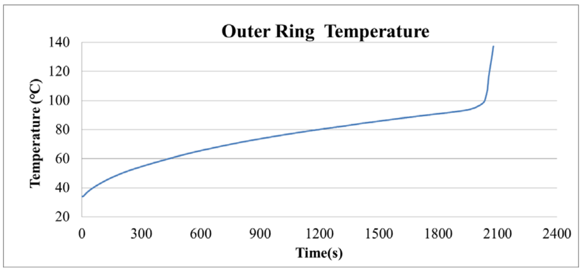


(c)

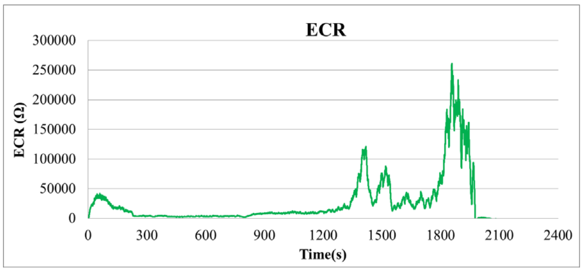
Fig. 14. Temperature, ECR, and friction coefficient of the outer ring of a bearing injected with 0.001 c.c. of Grease E and under an applied load of 2934 N.

Results show that the addition of UDD extended the life of the grease from 1450 seconds to 2100 seconds under a load of 2934 N. This significant increase in grease life not only corroborates the findings of Deepika (Deepika, 2020) regarding the longevity benefits of nano-additives but also underscores the specific effectiveness of UDD in high-load applications. This insight is particularly valuable for industrial applications where lubricants are subjected to extreme stress, highlighting the potential of UDD-enhanced greases in such scenarios.

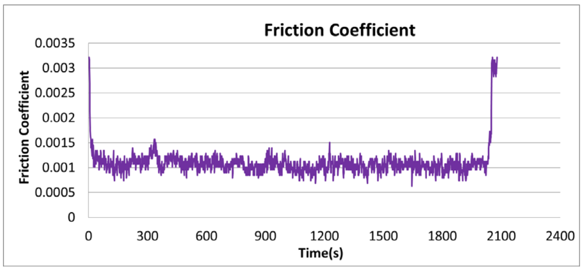
Overall, our study not only supports existing literature on the benefits of nano-diamonds in lubricants but also provides new insights into the synergistic effects of particle size, dispersant type, and concentration in enhancing the tribological performance of lithium soap-based greases. These findings have important implications for the development of more efficient and durable lubricants for high-stress mechanical applications.



(a)



(b)



(c)

Fig. 15. Temperature, ECR, and friction coefficient of the outer ring of a bearing injected with 0.001 c.c. of Grease E mixed with 100 ppm of UDD-OLA with particle size 200 nm, and under an applied load of 2934 N.

CONCLUSION

1. The four-ball test data shows that with OLA as the dispersant at the same concentration, the temperature for 200 nm particles is lower than

that for 68 nm and 38 nm.

2. Regarding wear scars on the steel balls, the scars from Grease E without added UDD are much larger than those with added UDD. With OLA as the dispersant at the same concentration, the 200 nm particle scars are smaller than those for 68 nm and 38 nm.
3. Overall, the smallest wear scars are seen with the addition of 200 nm particle size grease, particularly at a concentration of 100 ppm with 200 nm particle size, which performs better.
4. The grease life test data indicates that under a high load (2934 N), the bearing injected with 0.001 cc of Grease E failed at about 1450 seconds due to lubrication failure, resulting in bearing damage. In contrast, the bearing injected with 0.001 cc of Grease E with added 100 ppm UDD-OLA of 200 nm particle size, lasted until about 2100 seconds before lubrication failure occurred, demonstrating that adding UDD can significantly extend the life of the grease.

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奈米鑽石添加劑對滾珠螺桿用的潤滑脂磨潤性能提升之研究

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摘 要

本研究主要是針對適用於滾珠螺桿的潤滑脂添加奈米鑽石添加劑後對磨潤性能提升效果之研究。滾珠螺桿具有摩擦係數小、定位精度高、壽命長、摩擦係數低、可高速正、逆向轉動、以及可作為直線運動及旋轉運動之變換傳動元件等的特點。而在高速高頻的狀況下，潤滑劑的溫升將是非常值得注意的事情，對於避免油脂軟化導致潤滑性能降低甚至不良，是相當重要的。潤滑劑在軌道面運動時，潤滑劑在隔離滾珠與軌道面之直接摩擦接觸之功能上，扮演著非常重要的角色。

所以藉由廠商提供目前市面上常用的鋰皂基油脂，在其中改變不同分散劑及超分散奈米鑽石(UDD，Ultra-Dispersed nano-Diamond)的粒徑來了解這些參數對磨潤性能的影響。本論文從兩方面來探討與評價磨潤性能。首先以四球實驗來進行鋰皂基油脂和有添加 UDD 之油脂的抗極壓性能研究，並分析其各油脂之磨潤性能和鋼球上之磨痕大小，以尋找到適合之添加 UDD 之比例。接著藉由經四球實驗所得知之有添加 UDD 效果最好之油脂與鋰皂基油脂來進行油脂壽命實驗，來分析此兩種

油脂在使用壽命上之差異性。

經實驗的數據與光學顯微照片結果顯示以 OLA 為分散劑，添加濃度 100 ppm 粒徑為 200 nm 的 UDD 於油脂裡，可以有效地降低油脂的溫度與鋼珠的磨痕直徑。在油脂壽命方面，有添加 0.001 c.c.之 UDD 於鋰皂基油脂，在測試荷重為 2934 N 情況下，油脂壽命與未添加之原鋰皂基油脂相比，壽命可自 1450 秒增加到 2100 秒，顯示有添加 UDD 之油脂可以顯著地延長測試軸承之使用壽命。