

Article

Experimental Study on In Situ Storage of Grease-Lubricated Ball Screws

Peijuan Cui ^{1,2,*} , Zhanlin Hou ^{1,2}, Luman He ^{1,2}, Hui Zheng ³, Yifeng He ³, Yuanxun Fan ⁴, Linxue An ^{1,2} and Yuping Huang ^{1,2}

- ¹ Beijing Institute of Precision Mechatronics and Controls, Beijing 100076, China; zhanlin.hou@lasat.com (Z.H.); luman.he@lasat.com (L.H.); linxue.an@lasat.com (L.A.); yuping.huang@lasat.com (Y.H.)
² Laboratory of Aerospace Servo Actuation and Transmission, Beijing 100076, China
³ SINOPEC Research Institute of Petroleum Processing Co., Ltd., Beijing 100083, China; zhenghui.ripp@sinopec.com (H.Z.); heyf.ripp@sinopec.com (Y.H.)
⁴ School of Mechanical Engineering, Nanjing University of Science and Technology, Nanjing 210094, China; fanyx@mail.njust.edu.cn
* Correspondence: peijuan.cui@lasat.com

Abstract: Lubricating grease plays an important role in the rolling screw transmission of the actuation system and is particularly concerned with the performance stability of long-term storage in aerospace applications. In this article, a batch of ball screws that were lying flat in the warehouse for about eight years were selected to extract lubricating grease from the screw raceway after being stored in situ. The oxidation performance, friction performance and rheological properties of lubricating grease were tested and compared to those of fresh grease to analyze and summarize the performance changes in lubricating grease. The transmission efficiency, friction torque, and temperature rise of ball screws without removing the original grease and those filled with fresh grease after cleaning were tested and compared. The impact of grease degradation on the transmission performance of ball screws was analyzed to provide a reference for ball screw lubrication schemes and further accelerated storage experimental design.

Keywords: ball screw; lubricating grease; in situ storage; performance testing



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1. Introduction

Ball screws are one of the mainstream transmission mechanisms in the actuation system, and its lubrication method is grease lubrication. Lubricating grease can not only separate the rolling surface but also can absorb and transmit the frictional heat of the screw.

The lubrication space of the ball screw is relatively narrow, and the lubricating grease agglomerates and tightly adheres to the contact surface after volatilization and deterioration (as shown in Figure 1), such as the bottom of the screw raceway and nut raceway, between the steel balls and in the inverter pipeline, causing an increase in the working of the starting torque, which can affect the working performance of the servo actuator.



Figure 1. Agglomeration phenomenon of lubricating grease after long-term storage.

Researchers at home and abroad have conducted research on the correlation between the failure of lubricating grease and its components. The composition of the base oil, the refinement degree of the base oil preparation process, the reactivity of the thickener, the type of metal ions, and the composition of the composite formula can all affect the antioxidant properties of lubricating grease [1,2]. For the oxidation stability of lubricating greases with different metal–soap bases as thickeners, the higher the content of metal–soap-based thickeners in the same series, the stronger the oxidation stability of lubricating greases. Non-soap-based lubricating greases have better oxidation stability compared to metal–soap-based lubricating greases. Lubricating greases prepared from moderately refined base oils have better antioxidant capacity than greases prepared from unrefined or excessively refined base oils [3]. Different types of antioxidants have different antioxidant properties for the same lubricating grease. The synergistic use of phenolic amine and bisphenol antioxidants can make various types of lubricating greases exhibit good oxidation stability and thermal stability [4].

In addition, researchers also studied the relationship between the failure of lubricating grease and major external environmental factors, such as temperature, metal type and humidity. Temperature increases accelerate the oxidation of lubricants [5]. The thermal oxidation of lubricating grease not only damages its own lubrication performance, but its by-products also have an impact on the surface of the friction pair. Metal corrosion and lubricant oxidation are also interrelated. The interaction between lubricant oxidation byproducts and metal surfaces can lead to metal surface corrosion [6], and metal corrosion products can catalyze the oxidation of lubricants, leading to the formation of sludge deposits in lubricating grease. Different compositions of metal surfaces [7] and different valence states of metals [8] have different catalytic rates for lubricating grease. In addition, the presence of water also has adverse effects on the storage of lubricating grease. When lubricating grease is stored in an environment where water, the catalyst (copper) and hot air are present, as the storage time increases, the hydrolysis of the base oil becomes more severe, and the acid produced by hydrolysis further promotes hydrolysis, forming a vicious cycle [9].

Based on the above analysis, various components of lubricating grease are affected by factors such as temperature and humidity during atmospheric storage, which can easily cause base oil volatilization and oxidation deterioration, leading to performance degradation and decreased lubrication. Studying the performance changes in lubricating grease used for ball screws during in situ storage and its influence on the transmission performance of ball screws helps to explore the friction lubrication mechanism of lubricating grease under typical external factors (temperature, humidity, oxygen, etc.), locate the weak links of lubricating grease storage failure, and propose reasonable and effective lubrication solutions, thereby improving the reliability of servo transmission mechanisms, preventing transmission mechanism jamming failures, and improving system reliability, which has an important engineering value and theoretical significance.

2. Test Scheme Design

The lubricating grease sample selected in this article is Wide Temperature Aircraft Grease 7014 (referred to as Grease 7014, GJB 694-89, China). Grease 7014 is made by thickening sodium alkyl terephthalate into oil and refining it with antioxidant additives. It is suitable for the lubrication of electromechanical actuators (such as ball screws).

2.1. Storage Conditions for Ball Screws

The inner circulation ball screw is wrapped with plastic protective film on the outside and placed flat on warehouse shelves for about 8 years. The warehouse is cool and ventilated, and the screw was not moved during this period. The specific storage situation is shown in Table 1.

The 7014 Lubricating Grease test sample was filled with 13 ball screws as described above and placed in the storage room simultaneously with the screws, meeting the in situ storage conditions. Part of the ball screws was retained for transmission performance

testing, while the remaining lubricating grease in the ball screws was removed for testing. The grease-removed ball screws were cleaned and filled with fresh lubricating grease for transmission performance testing.

Table 1. Storage situation of ball screw.

Order Number	Project	Conditions
1	storage location	Beijing
2	placement status	lay flat and stand still
3	lubrication status	filling with lubricating grease
4	packaging status	wrapped in plastic protective film
5	air circulation status	good
6	sunshine status	no sunlight exposure
7	transportation situation	no handling

2.2. Performance Testing of Lubricating Grease

Based on the results of pretesting and the summary in the literature, the main degradation types of lubricating grease can be determined. The main ways of lubricating grease degradation and failure are physical degradation and chemical degradation. Physical degradation refers to all physical changes that occur in lubricating grease during storage or use, which are highly sensitive to the shear effects under working conditions. The main failure modes include the destruction of thickeners (mechanical shear degradation), base oil separation, base oil evaporation, grease softening, and contamination by particles (water, metal). Chemical degradation refers to all chemical changes that occur during the lifespan, producing oxidation products such as ketones, acids, hydrogen peroxide, alcohols, etc., which are sensitive to aging and temperature. The main failure modes include the depletion of additives (antioxidants), thickener oxidation, and base oil oxidation.

As shown in Figure 2, the degree of physical and chemical degradation can be characterized by indicators such as appearance, oxidation properties, friction properties, and rheological properties. The changes in appearance of lubricating grease can be preliminarily observed and compared through human eyes, and a more detailed microscopic morphology can also be obtained through an electron microscope scanner (SEM) (ATA Scientific Pty Ltd., Caringbah, Australia) [10], transmission electron microscopy (TEM) (JEOL Ltd., Tokyo, Japan) [11], and atomic force microscopy (AFM) (Oxford Instruments Asylum Research, Oxford, UK) [12]. The appearance of lubricating grease was compared through human-eye observation, and the microstructure of lubricating grease was compared and analyzed through SEM testing in this article.

The oxidation performance of lubricating grease can be measured by the chemical composition of its components and the oxidation stability of the grease. Detection methods such as Fourier transform infrared spectroscopy (FTIR) [13], X-ray, gas chromatography–mass spectrometry (GCMS) [14], and chromatography (SEC) can analyze the chemical composition of lubricating grease, identify the consumption of additives in grease, and measure the oxidation level of grease. The oxidation stability of lubricating grease can be characterized by the oxidation induction period. High-pressure differential scanning calorimetry (PDSC) [15] can compare heat release and absorption and identify the oxidation induction time of lubricating grease at different temperature conditions.

The friction performance of lubricating grease is mainly characterized by the following two indicators: friction coefficient and wear resistance, which can be measured using micro friction and wear testing machines, the German abbreviation of which is SRV: Schwingung (vibration in English), reibung (friction in English) and verschleiss (wear in English) [16]. The four-ball machine can test the extreme pressure performance and wear resistance of lubricating grease. The rheological properties of lubricating grease include viscoelasticity and flowability, which can be measured by a rotational rheometer [17].

Due to the small amount of lubricating grease extracted from the ball screw raceway and considering the testing cost, the preferred testing scheme selected in Figure 2 is the one

with less grease extracted and more reasonable testing costs. To investigate the changes in appearance, oxidation performance, friction performance, and rheological properties of lubricating grease before and after in situ storage, multiple testing items were conducted, including SEM testing, FTIR testing, rheological testing, PDSC testing, and SRV testing, on fresh lubricating grease and lubricating grease filled in the in situ stored screws. Based on the design of the in situ storage device and the calculation of storage capacity, the testing items, execution standards, required sample size, and sampling methods are summarized, as shown in Table 2.

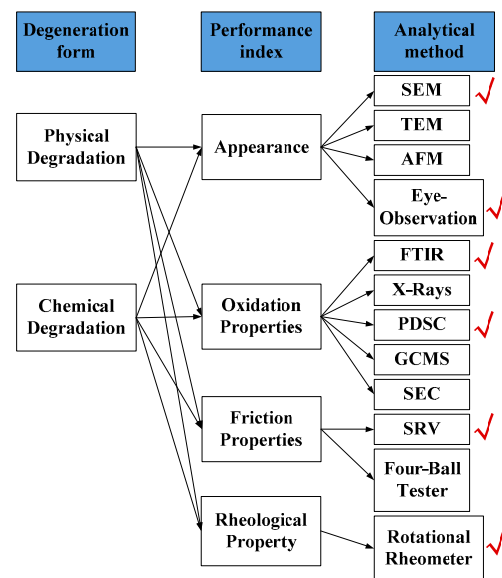


Figure 2. Block diagram of test scheme.

Table 2. The demand for samples in the in situ storage testing project.

Testing Project	Characterized Property	Executive Standard	Sample Size	Sampling Method
SEM	Microcosmic appearance	JY/T010-1996 [18] General rules for analytical scanning electron microscopy	0.1 mL	Repeat 3 times
FTIR	Oxidation performance	General rules for infrared analysis GB/T 6040-2019 [19]	0.5 g	Repeat 3 times
PDSC	Oxidation induction time	Standard test method for oxidation induction time of lubricating grease by pressure differential scanning calorimetry SH/T 0790-2007 [20]	0.12 g	Repeat 3 times at ten temperatures considering the loss during the transfer and weighing process of trace samples (sample loss at least twice)
SRV	Friction coefficient and wear resistance	Standard test method for measuring friction and wear properties of lubricating grease using a high-frequency linear-oscillation (SRV) test machine NB/SH/T0721-2016 [21] SH/T0784-2006 [22]	1.33 g	Repeat 3 times 90% sample loss
Rotational rheometer	Rheological properties	General rules of rheometry for rotational rheometer JY/T 0590-2020 [23] Operational manual of RheoPlus Manuel V2.0	0.7 mL	Repeat twice 90% sample loss

2.3. Performance Testing of Ball Screw Transmission

The ball screw transmission performance testing platform was equipped with a motor that provides a driving force according to the instructions of the controller, providing a stable loading driving torque. The torque was transmitted to the torque and speed sensor through the coupling, and real-time torque and speed information was obtained through data collection. The output torque was transmitted to the screw end through the connecting device. The magnetic powder brake provided a stable braking force through the controller. Through the swing rod device, the torque was converted into axial loading force. The real-time torque value was obtained from the tension pressure sensor. The axial force was transmitted to the screw nut through the connecting flange. The nut was connected to the guide rail, limiting the rotational freedom. Due to the long push rod and the connection to a heavier tension sensor, linear bearings were added to the push rod to achieve support.

The ball screw specimens with stored lubricating grease and the ball screw specimens filled with new grease after cleaning were sequentially installed on the ball screw transmission performance testing platform shown in Figure 3. The room temperature was $20\text{ }^{\circ}\text{C} \pm 5\text{ }^{\circ}\text{C}$. The maximum speed of the drive motor was greater than 4000 rpm. The travel of the loading mechanism was 60 mm. The maximum stable loading force was 12,000 N. The maximum speed for linear loading was 266.7 mm/s. After completing the test, the specimen was disassembled, and the next specimen was installed on the testing platform.

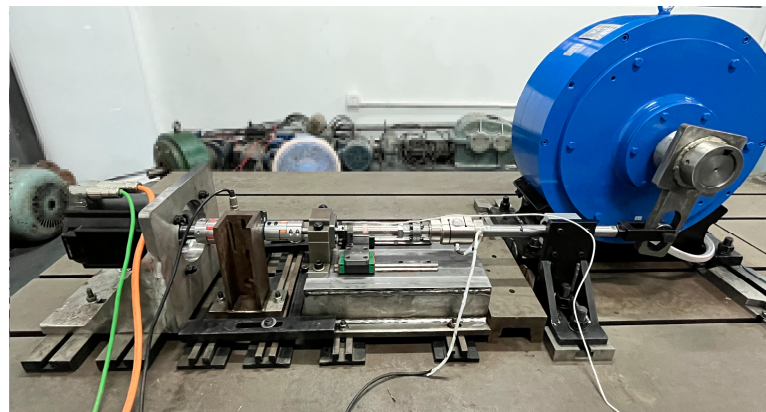


Figure 3. Ball screw transmission performance testing platform.

(1) Transmission efficiency and friction torque testing

The ball screw was simulated and loaded through the control system and tested under different operating conditions. At the same time, data such as the input torque and output axial force of the ball screw were collected. After the above operation was repeated multiple times (with the screw and nut going back and forth), the test data were exported. After the experiment was completed, abnormal data were removed, and the average of each cycle of experimental data was obtained. By calculating the input and output power, the efficiency and friction torque of other transmission links on the testing platform were deducted, and the transmission efficiency and friction torque of the ball screw were calculated. Finally, the variation diagrams of transmission efficiency and the friction torque of ball screws under different operating conditions were drawn.

(2) Temperature rise testing

Similarly, the ball screw was simulated and loaded through the control system and tested under different operating conditions. Meanwhile, the rising temperature data of the temperature sensor arranged on the nut were collected. When the temperature of the screw tended to stabilize or approached the melting point of the lubricating grease, the test was stopped. After the testing was completed, the temperature increase in the ball screws was plotted.

3. Test Results and Analysis

According to the testing plan described above, performance tests were conducted on lubricating grease and ball screws. It should be noted that all tests have been measured multiple times, and the results of the same test are relatively consistent. Therefore, one group of test results was taken as the final result for comparison.

3.1. Changes in the Performance of Lubricating Grease before and after In-Situ Storage

(1) Appearance

Based on the designed testing scheme, performance tests were conducted on samples of Grease 7014 before and after storage. The appearance of the original sample and the sample after storage is shown in Figure 4.

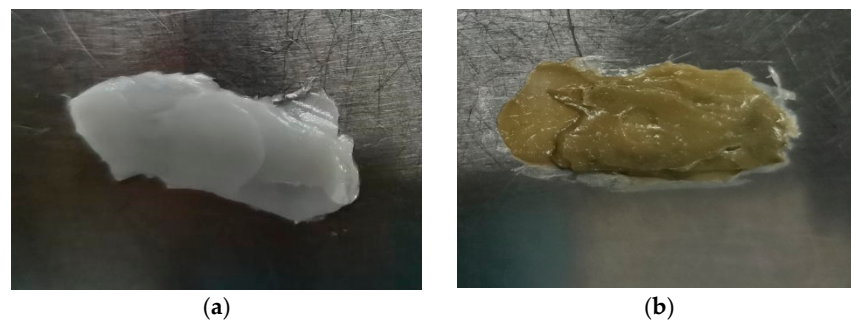


Figure 4. Appearance of Grease 7014. (a) Original sample; (b) sample after storage.

From Figure 4, it can be seen that the appearance of lubricating grease has undergone significant changes after in situ storage. The original sample is in a white uniform paste shape. After in situ storage, the color of the sample is uneven, showing a yellow-brown color, and some samples are black, which is related to the base oil of 7014 Grease, which contains ester oils with poor biodegradability.

(2) SEM Testing

SEM testing was conducted on the original sample and the sample after the storage of Grease 7014. The test results are shown in Figure 5.

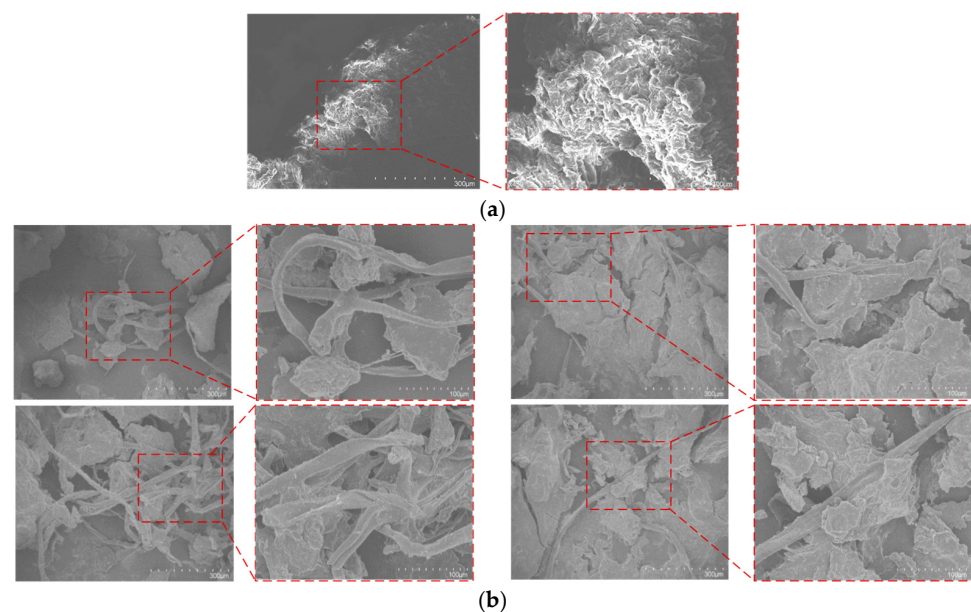


Figure 5. Microscopic morphology of Grease 7014. (a) Original sample; (b) sample after storage from different tests.

It is clear that the original sample in Figure 5a had a tightly connected overall structure, and the soap base of the thickener remained intact without any irregular broken structures. The overall structure of the sample after storage in Figure 5b was relatively loose, and the fiber skeleton structure was severely damaged. Only a small amount of irregular entanglement on the incomplete skeleton could be observed, with irregular block or sheet solid structures scattered around. Grease 7014 is a sodium-based lubricating grease; the thickener is a fiber-like structure; and its oxidation stability is relatively insufficient. Therefore, in a long-term in situ storage environment, the soap-based skeleton structure of the thickener of the sample after storage was severely damaged, which can affect the oil storage capacity of the base oil, cause the leakage and volatilization of the base oil and reduce the lubrication performance of the lubricating grease during storage.

(3) FTIR Testing

FTIR testing was conducted on the original sample and the sample after the storage of Grease 7014. The test results are shown in Figure 6, where the red line represents the original sample, and the blue line represents the sample after storage.

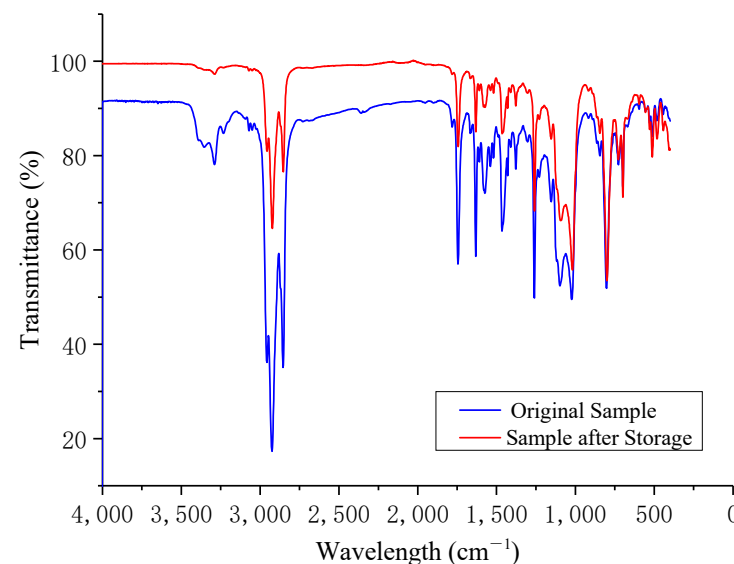


Figure 6. Infrared spectrogram of Grease 7014.

From Figure 6, it can be seen that both the original sample and the sample after storage showed characteristic peaks of silicone oil at 1260 cm^{-1} , 1098 cm^{-1} , and 1023 cm^{-1} , and amide at $3260\sim 3360\text{ cm}^{-1}$. However, after in situ storage, the amide characteristic peak of the sample changed significantly, with a new characteristic peak appearing at 1740 cm^{-1} , which is a stretching vibration peak of $\text{C}=\text{O}$, the in-plane bending vibration characteristic peak of $-\text{OH}$ in the carboxyl group was 1429 cm^{-1} , and the stretching vibration peak of $\text{C}-\text{O}$ in the carboxyl group was displayed at 1260 cm^{-1} . The above characteristic peaks correspond to the presence of carboxyl groups in the lubricating grease thickener. The reduction in these three peaks in the screw grease may indicate that the carboxyl groups in the thickener participate in the oxidation reaction and generate other oxidation products, indicating that the lubricating grease undergoes oxidation during storage. At 2919 cm^{-1} and 2851 cm^{-1} , asymmetric stretching vibration characteristic peaks and symmetric stretching vibration characteristic peaks of $-\text{CH}_2-$ are displayed, respectively. Due to the large amount of $-\text{CH}_2-$ in the base oil, an increase in the peak value here indicates an increase in the relative content of the base oil. It is speculated that there is precipitation of the base oil, which indirectly reflects a decrease in the content of the thickener, which is a relatively large proportion of the lubricating grease except for the base oil. From the above analysis, it can be inferred that under long-term storage, the lubricating grease thickener in the screw pair undergoes an oxidation reaction, causing a change in its chemical structure.

and resulting in a decrease in the thickener content and oil storage capacity. The base oil seeps out and oxidizes, resulting in a decrease or loss of lubrication performance. Overall, during the lubrication and storage process, the grease thickener may be affected by oxidation–reduction reactions or structural damage, which can affect its oil storage and drainage capacity, resulting in a decrease or failure of the lubrication performance.

(4) Rheological Testing

The rheological properties of Grease 7014's original sample and the sample after storage were tested, and the test results are shown in Figures 7 and 8. The blue line represents the original sample, and the red line represents the sample after storage.

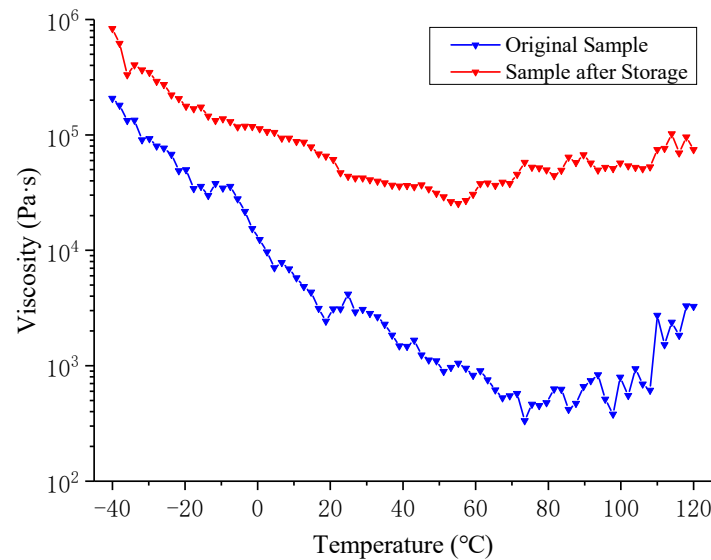


Figure 7. Viscosity–temperature curve of Grease 7014.

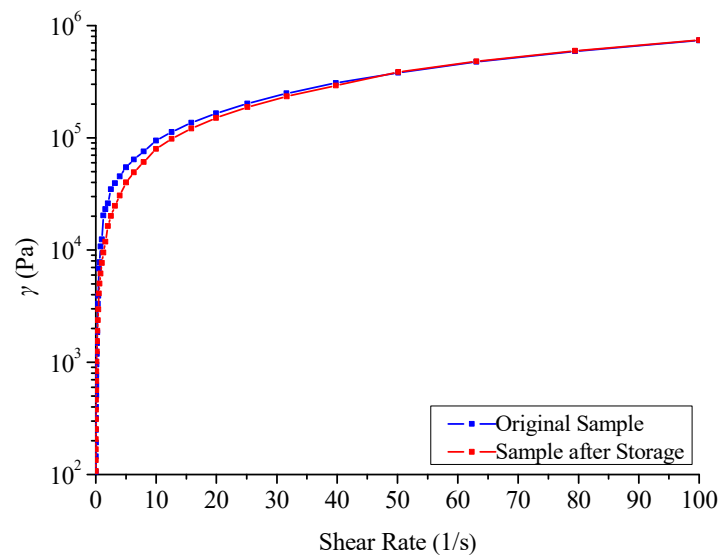


Figure 8. Shear curve of Grease 7014.

From Figure 7, it can be seen that the trend of the viscosity–temperature curve of the original sample and the sample after storage is consistent. The viscosity first decreases and then stabilizes with the increase in temperature. After the temperature reaches 100 °C, the viscosity of the lubricating grease increases slightly. The starting viscosity of the sample after storage at −40 °C is significantly higher than that of the original sample, and the viscosity difference increases with the increase in temperature. The viscosity of the sample

after storage at 25 °C is about 10 times that of the original sample, and the viscosity of the sample after storage at 70 °C is about 1000 times that of the original sample. This might be because, during storage, the base oil in the lubricating grease precipitates and loses, or its components evaporate, resulting in an increase in its viscosity.

From Figure 8, it can be seen that the trend of the shear force versus shear rate curve of the original sample and the sample after storage is basically consistent.

(5) PDSC Testing

PDSC testing was conducted on the original sample and the sample after storage of Grease 7014, and the test results are shown in Figure 9.

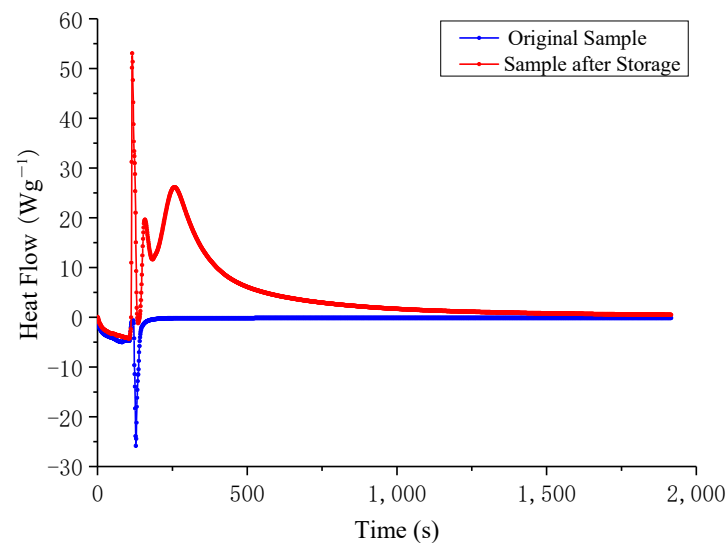


Figure 9. PDSC testing (210 °C) of Grease 7014.

From Figure 9, it can be seen that the original sample of PDSC (210 °C) > 60 min has a good high-temperature antioxidant performance. After in situ storage, the PDSC (210 °C) of the sample was 1.59 min, indicating poor high-temperature antioxidant performance. This might be due to the gradual consumption of antioxidants during storage, resulting in a decrease in the antioxidant performance of lubricating grease.

(6) SRV Testing

SRV testing was conducted on the original sample and the sample after storage of Grease 7014, and the test results are shown in Figure 10. Due to the poor lubrication performance of 7014 Lubricating Grease after storage, it can only be maintained for 70 s. After 70 s, the test results exceeded the testing range of SRV, so the experimental results were only retained for 70 s.

From Figure 10, it can be seen that both the original sample and the sample after storage failed to complete the SRV test, with the original sample lasting approximately 47.9 s while the sample after storage lasted for about 22 s after the start of the experiment. The friction coefficient of the sample sharply increased, exceeding the limit set by the instrument, and the experiment was forced to terminate. From the SRV results, it can be seen that the anti-fretting wear performance of the sample still needs to be improved. The decrease in the anti-friction and wear performance of lubricating grease affects the intensification of friction and wear in the transmission mechanism. For rolling screw transmission mechanisms, the debris formed by wear accumulates in the raceway to a certain extent, causing serious failure modes such as mechanism jamming. Therefore, it is necessary to add an appropriate amount of extreme-pressure anti-wear agents to improve the lubrication performance of lubricating grease products.

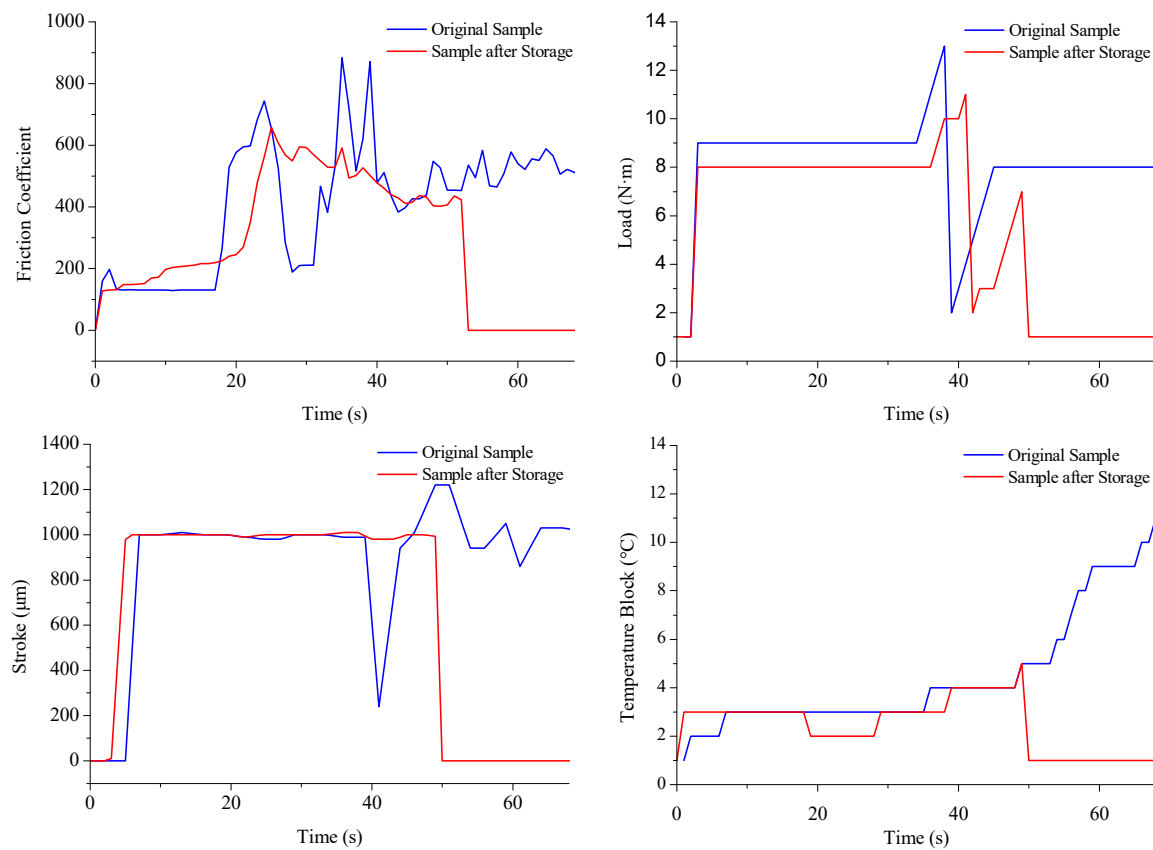


Figure 10. SRV testing results of Grease 7014.

3.2. Influence of Deterioration of Lubricating Greases on the Transmission Performance of the Ball Screw

(1) Transmission efficiency testing

The curve of the transmission efficiency of ball screws with the change in axial force is shown in Figure 11. It can be seen that, at the same speed, the transmission efficiency first increased with the increase in the axial force. When the axial load reached 5000~7000 N, the transmission efficiency reached its highest point and then showed a downward trend. The transmission efficiency of ball screws filled with new grease is significantly higher than that of ball screws with retained grease stored.

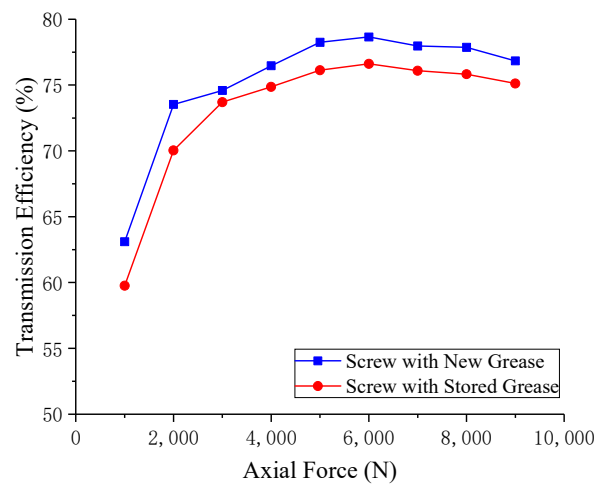


Figure 11. Transmission efficiency variation curve of ball screws at 4000 rpm.

(2) Friction torque testing

The curve of the friction torque of the ball screws with the change in axial force is shown in Figure 12. It can be seen that at the same speed, the friction torque increases with the increase in the axial force. Under certain rotational speed conditions, the friction torque of the ball screw with stored lubricating grease increases by about 0.1–0.2 Nm compared to the ball screw with new grease.

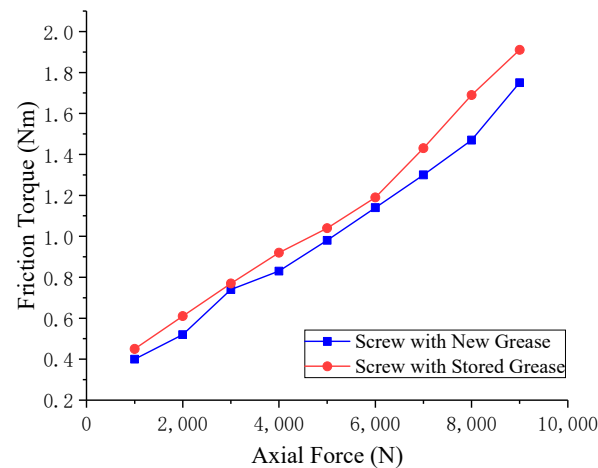


Figure 12. Friction torque variation curve of ball screws at 4000 rpm.

(3) Temperature rise testing

The temperature increase in the ball screws at speeds of 2000 rpm and 4000 rpm and axial loads of 3000 N and 6000 N are shown in Figures 13 and 14. As the axial force increases, the rate of temperature significantly increases, and the temperature increase rate of the ball screw with stored grease is significantly higher than that of the ball screw with new grease.

When the speed is 4000 rpm, the axial load is 6000 N, and both sets of ball screws cannot reach thermal equilibrium before the lubricating grease begins to melt. The temperature of the screw rises to 145~152 °C in a short period of time, and white smoke and an irritating odor appear. At a speed of 2000 rpm and an axial load of 6000 N, the ball screw with new grease reaches thermal equilibrium at around 130 °C, while the ball screw with stored grease cannot reach thermal equilibrium before the grease melts. It was indicated that the heat dissipation capacity of the ball screw significantly decreased after the grease deteriorated.

Under the same operating conditions, the ball screw with new grease runs relatively smoothly, with a gentle increase in temperature and a certain degree of curvature in the temperature rise curve. However, the ball screw with stored grease generates more intense heat, and the temperature rises sharply at high speeds and high loads, presenting a straight line in the temperature rise curve. In harsh working conditions, the ball screw with new grease reaches the melting point of the grease, and the time for smoking and irritating odors to appear is significantly later than that of the ball screw filled with stored grease. And, under the same operating conditions of 2000 rpm and 6000 N, the ball screw with new grease can reach a steady-state temperature, while the temperature of the screw filled with stored grease continues to rise and does not show a stable trend when it reaches the melting point of the lubricating grease. It was indicated that after the performance of the lubricating grease deteriorated, the ability to absorb and transfer heat decreased, which could not effectively help the ball screw pair dissipate heat and maintain the normal working temperature of the screw, so the damage was caused by the overheating of the ball screw. Therefore, the degradation of lubricating grease has a significant impact on the operation and lifespan of ball screws.

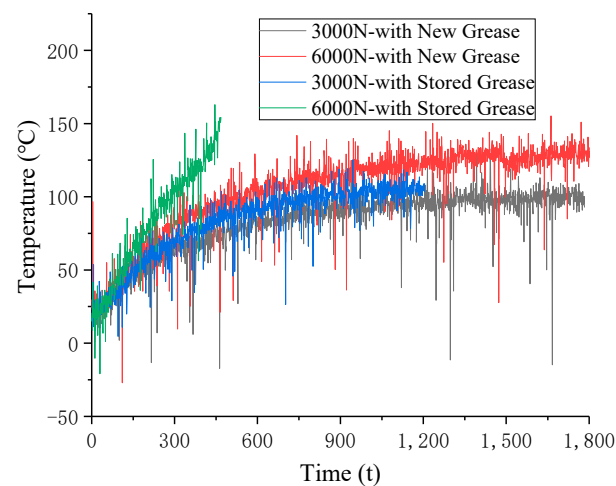


Figure 13. Temperature variation curve of ball screws at 2000 rpm.

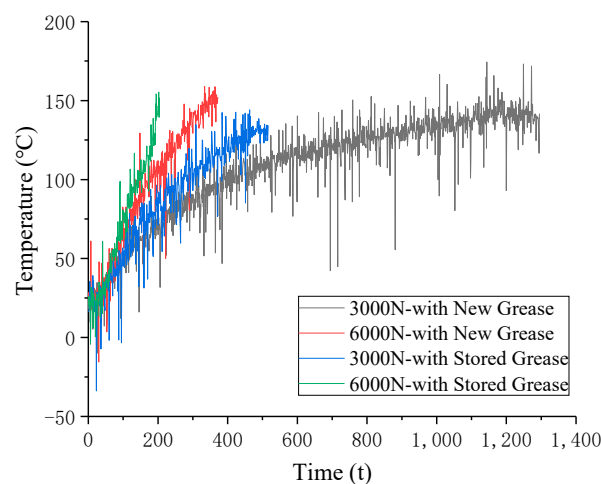


Figure 14. Temperature variation curve of ball screws at 4000 rpm.

4. Conclusions

This in situ storage experiment on grease-lubricated ball screws aimed to analyze the performance changes in lubricating grease in the transmission mechanism of the actuating system after long-term storage and its influence on the transmission performance of ball screws. Through the above tests and relevant data analysis, the following conclusions are drawn:

- (1) There are two main reasons for the failure of the lubricating grease studied in this article during storage. Firstly, the base oil in the lubricating grease contains ester oil, which is easily degraded by bacteria in the environment; on the other hand, there is a loss of the base oil during storage. Both reduce the effective lubricating components and lead to a decrease in lubrication performance. Based on the above analysis, it can be seen that after eight years of in situ storage, lubricating grease underwent continuous oxidation reactions in the temperature and humidity environment of our research institute, resulting in a decrease in various performance indicators.
- (2) The degradation of lubricating grease not only significantly reduces the transmission efficiency and friction torque of the ball screws, increasing the risk of wear and jamming of the ball screws, but also leads to a decrease in the heat dissipation capacity of the ball screw pair, which cannot maintain the normal working temperature of the screw, resulting in damage to the screws caused by overheating. Therefore, the degradation of lubricating grease has a significant impact on the operation and lifespan of ball screws.

- (3) The performance degradation results of lubricating grease after 8 years of in situ storage can provide an understanding of the failure mechanisms and failure modes of accelerated storage tests. A comparative test was conducted on the performance of the transmission mechanism in a degraded state (8-year in situ storage) and a normal state. The results showed that 8-year storage could cause changes in transmission efficiency and temperature rises but would not lead to a significant decrease in performance. Generally, unopened lubricating grease can be stored for about 5 years, while perfluoropolyether-based lubricating grease can be stored for 10 years or even longer. Lubricating grease should be sealed and stored. If conditions permit, it can be sealed with nitrogen gas and stored in a cool, dry, and ventilated environment. Lubricating grease packaging should be used as soon as possible after opening, and the use of small packaging is encouraged. Keeping the surface flat after using lubricating grease can reduce oil separation during storage and help extend the shelf life.
- (4) These performance changes in lubricating grease provide an experimental basis for the ball screw lubrication scheme. Synthetic lubricating grease with the slow degradation and volatilization rates of base oil, the slow consumption rate of antioxidants, and the strong antioxidant ability of thickeners needs further research and trial production. Through methods such as comparison, investigation, and composition compounding, key technologies for improving the storage stability of main components, such as base oils and thickeners, should be broken through, thereby improving the stability of lubricating grease and extending its storage life.
- (5) The results of the storage simulation test have significance in guiding the accelerated storage test design of lubricating grease. Based on the test results of this article, the rheological property detection results should be considered as the data basis for the accelerated degradation model, the oxidation induction period in the later stage of degradation as the modeling basis, and other indicators to explain the degradation mechanism from a microscopic perspective.

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Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Hui Zheng and Yifeng He were employed by the company SINOPEC Research Institute of Petroleum Processing Co., Ltd. The remaining authors declare that the re-search was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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