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Tribological Improvement of Lubricants Using Silicone Rubber Powders in Hydrogen Compressors

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Abstract: The development of eco-friendly alternative energy sources has become a global priority owing to the depletion of fossil fuels and an increase in environmental concerns. Hydrogen energy has emerged as a promising clean energy source, and hydrogen compressors play a crucial role in the storage and distribution of compressed hydrogen. However, harsh operating conditions lead to the rapid deterioration of conventional lubricants in hydrogen compressors, thereby necessitating the development of advanced lubrication technologies. This study introduces micrometer-sized silicone rubber powders as lubricant additives to enhance the lubrication performance of hydraulic oils in hydrogen compressors. We prepare silicone rubber powders by varying the ratio of the silicone rubber base to the curing agent and investigate their effects on interfacial properties, friction behavior, and wear characteristics. The findings reveal that the incorporation of silicone rubber powders positively influences the surface affinity, wettability, friction reduction, and wear resistance of the lubricants on the 304SS substrate. Moreover, we identify the optimal lubricant formulations, with a 15:1 ratio demonstrating the most effective friction reduction and a 5:1 ratio exhibiting the highest wear resistance. The controlled surface modification by the silicone rubber powder and the enhanced interfacial characteristics of the powder-containing lubricants synergistically contribute to the improved lubrication performance. These results indicate the potential of silicone rubber powder additives for the development of long-life lubrication solutions for hydrogen compressors and related applications, ultimately contributing to the advancement of sustainable energy technologies.

Keywords: Hydrogen compressor, Silicone rubber, Lubricant additives, Friction, Wear

1. Introduction

The depletion of fossil fuels and environmental pollution have made the development of eco-friendly alternative energy sources a global concern [1]. Among them, hydrogen energy has garnered significant attention as a next-generation clean energy source owing to its low pollutant emissions during combustion and high energy efficiency [2]. Hydrogen is the most abundant element on Earth, existing in the form of water and compounds, and can be produced using various methods. Hydrogen energy systems consist of several processes including hydrogen production, storage, transportation, and energy conversion.

Hydrogen compressors are essential components of hydrogen energy systems and are responsible for compressing the produced hydrogen to a high-pressure state for storage and distribution [3]. As hydrogen has a large volume in its gaseous state, high-pressure compression is indispensable for efficient storage and transportation.

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Generally, hydrogen is compressed and stored at pressures greater than 30 MPa [4]. The compression process generates high heat and pressure owing to friction and impact, resulting in harsh operating conditions for hydrogen compressors.

Hydrogen compressors are driven by various mechanisms such as reciprocating, centrifugal, and electric motors. Because of the characteristics of ionized hydrogen gas, internal components are prone to wear and corrosion. Moreover, extreme pressures, high temperatures, and impact loads significantly degrade the performance of lubrication systems. In these environments, conventional synthetic lubricants experience rapid performance deterioration, leading to adhesive wear, surface damage, and lubricant decomposition caused by the direct contact between metal surfaces.

To address these issues, extensive research has been conducted on improving the properties of lubricants using various additives. In particular, silicone rubber powders in the micrometer (μm) size range possess excellent thermal and chemical stability and low surface energy, exhibiting great potential as additives in extreme lubrication environments [5]. Silicone rubber powders can form protective films on metal surfaces and reduce wear by controlling surface roughness through regulated polishing action. Furthermore, they can enhance the interfacial properties of lubricants, thereby improving their wettability and adhesion to metal substrates.

This study aims to introduce micrometer-sized silicone rubber powders as lubricant additives to improve the lubrication characteristics of hydraulic oils in hydrogen compressors. Silicone rubber powders were prepared by adjusting the ratio of the silicone rubber base to the curing agent and were added to the base lubricant. The interfacial properties, friction, and wear characteristics of the prepared lubricant compositions were comprehensively evaluated to determine the optimal composition of silicone rubber powder additives.

2. Materials and Experiments

The following materials were used to evaluate the lubrication characteristics based on the manufacturing conditions of silicone rubber powder. Stainless steel 304 (304SS, Korea), Ethanol (C_2H_5OH), Acetone (CH_3COCH_3), Lubricant (PAO, 5W30), Silicone rubber (Sylgard 184).

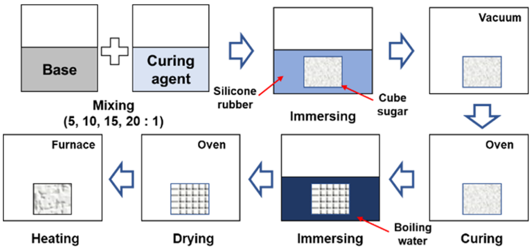

Fig. 1. Schematic illustration of the fabrication process of silicone rubber powder.

Fig. 1 illustrates the fabrication process for the silicone rubber powder. First, the silicone rubber base and curing agent were mixed in ratios of 5:1, 10:1, 15:1, and 20:1. The mixed silicone rubber solution was then dipped into granulated sugar. After removing the air bubbles in a vacuum chamber, the solution was cured for 3 h in a chamber heated to 80°C. Subsequently, the sugar particles coated with silicone rubber were immersed in boiling water to completely remove the sugar particles. The powder was dried for 2 h in a chamber heated to 80°C. Finally, the powder was heated for 6 h in a furnace to 300°C.

Powders prepared at various mixing ratios were added to the lubricant at a concentration of 1.5 wt%. The mixture was stirred at 300 rpm for 2 h and then ultrasonicated for 30 min to achieve a uniform dispersion.

Contact angle measurements were performed to evaluate the interfacial affinity of lubricants prepared at different ratios. A 10 μL drop of lubricant was placed on the surface of a 304SS substrate, and the angle formed by the oil droplet was measured.

A ball-on-reciprocating friction tester was used to assess the lubrication characteristics. A 304SS ball with a diameter of 1 mm was used as the counter tip. The friction tests were conducted under a load of 100 mN with a stroke of 2 mm at a speed of 8 mm/s for 5000 cycles.

After the friction tests, the wear width and depth were measured using a 2D profiler and the wear rate was calculated using the measured values. Additionally, the wear tracks formed on the surface of the 304SS substrate were analyzed using an optical microscope.

3. Results and Discussion

As shown in Fig. 2, microscopic characterization of the synthesized silicone rubber powders revealed a uniform size distribution of approximately 10-100 μm, regardless of the ratio of the base and curing agent used in the synthesis process. This uniform powder size distribution is crucial for achieving consistent friction performance because it ensures that the powders are evenly dispersed within the lubricant matrix and that the polishing action at the contact surfaces is well controlled.

The contact angle measurements presented in Fig. 3 provide insight into the surface affinity and wettability of the lubricants on the 304SS substrate. The base oil exhibited a relatively low contact angle of 22.65°, indicating its poor wettability and adhesion to the metal surface. In contrast, lubricants containing silicone rubber powder showed higher contact angles, ranging from 28.15° for the 5:1 formulation to 29.83° for the 10:1 formulation. This increase in the contact angle can be attributed to the presence of the silicone rubber powder, which alters the surface energy and enhances the wettability of the lubricant on the metal substrate. This improved wettability and adhesion are crucial for the formation of a robust tribofilm that can effectively separate contact surfaces and mitigate adhesive wear [6].

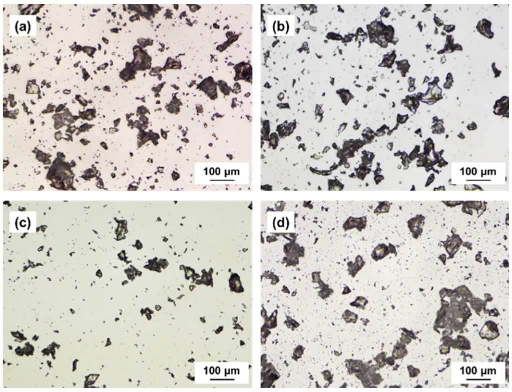

Fig. 2. Microscopic images of silicone rubber powders: (a) 5:1, (b) 10:1, (c) 15:1, and (d) 20:1 base-to-curing agent ratio.

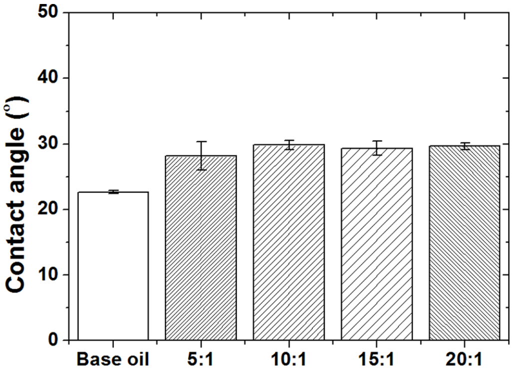

Fig. 3. Contact angles of lubricants on 304SS substrate.

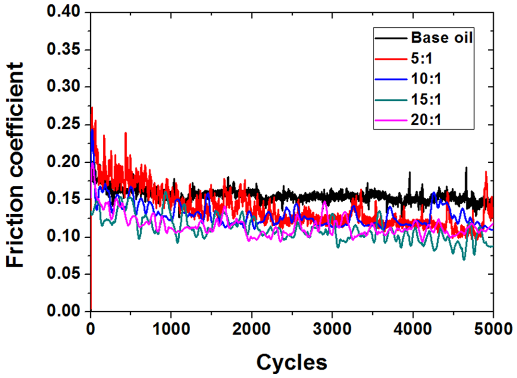

Fig. 4. Friction coefficient variations over 5000 sliding cycles.

The friction coefficient variations shown in Fig. 4 provide important information regarding the lubrication mechanism and lubricating effect over extended sliding cycles. The base oil exhibited an initial friction coefficient of 0.2, which gradually decreased to 0.15 after 300 cycles, possibly due to the formation of a thin tribofilm facilitated by the inherent anti-wear additives in the lubricant. However, the subsequent fluctuations and the final friction coefficient of 0.15 after 5,000 cycles suggest that the tribofilm is not sufficiently stable or robust to maintain effective lubrication under the applied conditions. In contrast, lubricants containing silicone rubber powder exhibited distinct friction behaviors, indicating the influence of powder additives on the lubrication mechanism. The 5:1 lubricant started with a high initial friction coefficient of 0.25 and steadily decreased to 0.12 by the end of the test. This trend can be attributed to the gradual formation of a tribofilm composed of silicone rubber powders and the controlled polishing action, leading to the removal of initial asperities and the establishment of a protective tribofilm on the contact surfaces. The 10:1 lubricant showed a similar initial friction coefficient of 0.24, but rapidly decreased to 0.14, indicating the rapid formation of a tribofilm owing to the polishing action of the silicone rubber powders [7]. The subsequent fluctuations and the final friction coefficient of 0.11 after 5,000 cycles suggest a dynamic equilibrium between the removal and continuous replenishment of the tribofilm, maintaining effective lubrication. The 15:1 and 20:1 lubricants exhibited lower initial friction coefficients of 0.13 and 0.2, respectively, compared to the other formulations. This can be attributed to the optimized concentration and dispersion of the silicone rubber powders, which enabled rapid tribofilm formation and enhanced surface protection at the onset of sliding. The relatively large fluctuations observed in the 15:1 lubricant for up to 1,000 cycles may be due to the temporary instability of the tribofilm, which is eventually overcome, leading to a stable friction coefficient of 0.09 after 5,000 cycles. The 20:1 lubricant also exhibited a similar trend, with an initial decrease to 0.12 within 300 cycles, followed by variations in the friction coefficient, resulting in a final friction coefficient of 0.11 after 5,000 cycles.

The average friction coefficients summarized in Fig. 5 demonstrate the effectiveness of silicone rubber powder additives in reducing friction and improving the lubrication performance. The base oil exhibited the highest average friction coefficient of 0.15, whereas the 5:1 and 10:1 lubricants showed moderately reduced values of 0.13. The 15:1 and 20:1 lubricants exhibited the lowest average friction coefficient of 0.11, indicating a superior lubrication performance.

The wear rates presented in Fig. 6 provide quantitative insights into the protective function of lubricant formulations against surface wear. The base oil exhibited the highest wear rate of 1.84×10^{-8} mm^3/N·mm, which can be attributed to the absence of an effective tribofilm and the prevalence of severe adhesive wear mechanisms. In contrast, the lubricants containing silicone rubber powders showed lower wear rates compared to the base oil, ranging from 1.41×10^{-8} mm^3/N·mm for the 5:1 formulation to 1.74×10^{-8} mm^3/N·mm for the 15:1 formulation. This reduction in wear rate can be attributed to the formation of a robust tribofilm owing to the controlled polishing action of silicone rubber powders, which effectively minimizes direct metal-to-metal contact and mitigates adhesive wear [8].

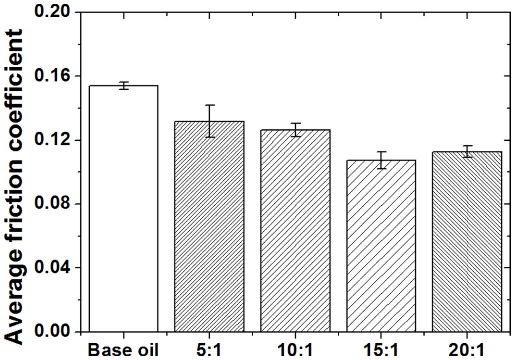

Fig. 5. Average friction coefficients of lubricant formulations.

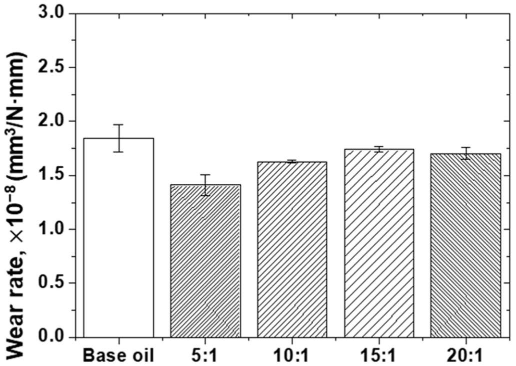

Fig. 6. Wear rates of lubricant formulations.

The microscopic analysis of the wear tracks shown in Fig. 7 provides direct visual evidence of the predominant wear mechanisms and the effects of the lubricant formulations. The base oil wear track exhibited severe plowing, surface damage, and irregular features, indiack, despcating extensive adhesive wear owing to inadequate lubrication and excessive material transfer between the contact surfaces [9]. In contrast, the 5:1 lubricant wear trite having the narrowest width, showed a rough surface texture and fine features, suggesting a complex interplay between adhesive wear and abrasive wear induced by silicone rubber powders. While the powders contribute to controlled abrasion and initial asperity removal, thereby promoting tribofilm formation,

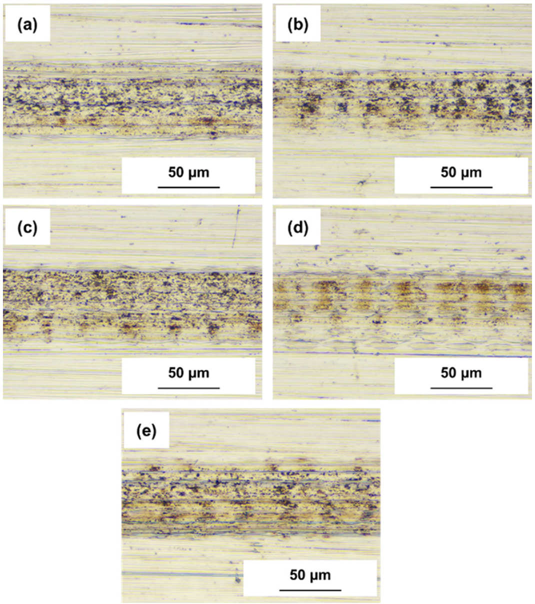

Fig. 7. Microscopic images of wear tracks: (a) base oil, (b) 5:1, (c) 10:1, (d) 15:1, and (e) 20:1 lubricant formulations.

the residual adhesive wear mechanisms manifest as material transfer and surface roughness. The 10:1 and 20:1 lubricant wear tracks exhibited smoother surfaces compared to the 5:1 lubricant, albeit with wider widths, indicating the dominance of abrasive wear mechanisms owing to the uniform polishing action of the well-dispersed silicone rubber powders. This polishing action effectively removed surface asperities and promoted the formation of a protective tribofilm, reducing adhesive wear and improving the surface quality. However, traces of adhesive wear were still observed in certain regions, suggesting the need for further optimization of lubricant formulations. The 15:1 lubricant wear track appeared relatively smooth, indicating an effective surface protection and minimal adhesive wear. However, some embedded or fragmented silicone rubber powders were observed, suggesting non-uniform powder dispersion within the lubricant matrix and localized abrasive wear. This localized abrasive wear may contribute to the slightly higher wear rates observed for these formulations compared with the 5:1 lubricant, despite their excellent friction performance [10].

The observed friction behavior can be attributed to the synergistic effect of the controlled polishing action of the silicone rubber powders and the enhanced surface wettability and adhesion of the powder-containing lubricants. The polishing action of the powders promotes gradual removal of the initial surface asperities, facilitating the formation of a robust tribofilm composed of powders and lubricant additives [11]. This tribofilm effectively separated the contact surfaces, minimized direct metal-to-metal contact, and mitigated the adhesive wear mechanisms. Furthermore, the improved wettability and adhesion of the powder-containing lubricants, as is evident from the increased contact angles, contribute to the stability and replenishment of the tribofilm. The enhanced adhesion allows the lubricant to maintain intimate contact with the surfaces, continuously supplying new powders and additives to replenish the tribofilm worn away during sliding.

Among the investigated formulations, the 15:1 lubricant formulation exhibited the lowest friction coefficient, whereas the 5:1 formulation exhibited the lowest wear rate. This performance can be attributed to the balanced concentration and dispersion of silicone rubber powders, which enables efficient tribofilm formation and maintenance while minimizing localized abrasive wear and adhesive wear mechanisms.

In summary, the use of silicone rubber powder as a lubricant additive can effectively improve the lubrication performance and wear resistance of base oils by controlling the polishing action to promote the formation of the robust tribofilm and enhance surface wettability and adhesion. The 15:1 lubricant formulation exhibited the lowest friction coefficient, whereas the 5:1 formulation exhibited the lowest wear rate. The 15:1 formulation achieved low friction through the controlled polishing action of well-dispersed silicone rubber powders; however, it exhibited a slightly higher wear rate owing to localized abrasive wear caused by powder agglomeration. On the other hand, the 5:1 formulation effectively suppressed adhesive wear despite its relatively higher friction coefficient, possibly due to the higher strength of the powder resulting from the higher ratio of the curing agent, achieving the lowest wear rate.

4. Conclusion

In summary, this study investigated the potential of micrometer-sized silicone rubber powders as lubricant additives for improving the lubrication performance of hydraulic oils in hydrogen compressors. The silicone rubber powders were synthesized by varying the base to curing agent ratio, and their effects on the interfacial properties, friction, and wear characteristics were comprehensively evaluated. The incorporation of silicone rubber powders enhanced the surface affinity and wettability of the lubricants, reduced friction coefficients, and improved wear resistance compared to the base oil. The optimal lubricant formulations were identified, with the 15:1 ratio exhibiting the lowest friction coefficient and the 5:1 ratio showing the lowest wear rate. The friction reduction was attributed to the controlled polishing action of the powders and the formation of a stable tribofilm, while the wear resistance was influenced by the suppression of adhesive wear and the strength of the powders. These findings highlight the effectiveness of silicone rubber powders as lubricant additives and their potential for application in hydrogen compressors and other mechanical lubrication fields. Further research on the optimization of powder concentration, dispersion stability, and long-term performance is recommended to develop robust and reliable lubrication technologies for extreme operating conditions.

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