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Unveiling the Potential of HVOF Coatings for Mechanical Seal Applications

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ABSTRACT

This study explores the transformative role of High-Velocity Oxygen Fuel (HVOF) coatings in enhancing the performance of mechanical seals. Mechanical seals play a crucial role in various industrial applications, and their efficiency is often compromised by wear and corrosion. The utilization of HVOF coatings represents a cutting-edge approach to fortify these seals against deterioration, significantly extending their operational lifespan. The research aims to understand the causes of mechanical seal failure, specifically focusing on wear-related issues. Overall, the objective is to provide insights into the mechanisms and materials influencing mechanical seal failure. Through a comprehensive review of existing literature and recent advancements, this research elucidates the multifaceted benefits of HVOF coatings in mechanical seal applications. It delves into the mechanisms by which these coatings mitigate wear and corrosion, providing a protective shield against harsh operational conditions. This study contributes not only to the understanding of the advancements in HVOF coating technology for mechanical seals but also serves as a valuable resource for professionals seeking to optimize mechanical seal performance and extend their service life through innovative coating solutions.

Keywords: *HVOF, Mechanical seal, Wear, Corrosion.*

1.0 Introduction

Mechanical face seals stand as pivotal components in industrial pumping applications, demonstrating versatility in meeting a spectrum of operational demands. From withstanding extreme conditions of high pressure and high-speed operations in corrosive environments to handling less rigorous service requirements, these seals play a crucial role in maintaining operational efficiency and preventing fluid leakage.

However, the broader landscape of mechanical seals in industrial machinery introduces a persistent challenge—mechanical seal failure. This phenomenon, predominantly attributed to wear, necessitates a thorough exploration of the underlying causes and effective mitigation strategies [1-5].

This synthesis aims to bridge existing gaps by consolidating insights from diverse studies and identifying overarching patterns in the causes of mechanical seal failure. Beyond causative factors, this review delves into real-world scenarios of mechanical seal failure. These case studies offer a contextualized view, illustrating the interplay of factors such as incorrect heat treatment, fretting, fatigue cracking, wear and corrosion in diverse industrial settings [6-8].

In addition to failure analysis, the literature explores advancements in mechanical seal ring materials, presenting innovative solutions [6,9,10]. These materials exhibit superior properties, ranging from high hardness and abrasion resistance to tailored characteristics for specific applications. Moreover, the transformative potential of High-Velocity Oxygen Fuel (HVOF) coatings in improving mechanical seal properties emerges as a focal point in the literature. Some discovery of enhanced fracture toughness with nano reinforced ceramic composite HVOF coatings [11] and few research emphasis on HVOF cermet coatings for sliding wear resistance underscore the evolving landscape of seal enhancement technologies [12].

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This review offers a thorough exploration of the diverse dimensions of mechanical seal failure, covering causative factors, real-world applications, materials innovation, and the impact of HVOF coatings. However, it highlights a notable gap in the limited exploration of emerging technologies or novel materials beyond HVOF coatings. Considering the continuous progress in materials science and technology, there may be untapped possibilities for enhancing mechanical seal performance and durability. Addressing these gaps could involve conducting a comprehensive review that integrates findings from various studies, providing a more holistic understanding of mechanical seal failure. Future research opportunities lie in exploring innovative materials or technologies that have not been extensively studied in the context of mechanical seals, aiming for a comprehensive understanding and potential improvements in design and performance.

2.0 Literature Review

Research suggest that polycrystalline diamond (PCD)-coated mechanical seal rings, synthesized through hot filament chemical vapor deposition on graphite-loaded silicon carbide substrates, exhibit a well-developed coating with a grain size of 4 μm and thickness of 12.3 μm. Confirmed by Raman spectroscopy and X-ray diffractometry, the PCD coating significantly enhances the pressure-velocity limit in challenging operating conditions, outperforming various combinations including GSiC/SSiC and GSiC/graphite. Notably, the PCD/SSiC combination demonstrates the highest pressure-velocity limit at 42.31 MPa m/s under specific loading and rotation conditions.

The remarkable attributes of an exceptionally low and stable friction coefficient, coupled with superior mechanical properties in harsh conditions, position PCD-coated mechanical seals as reliable solutions for demanding applications [13]. A study proposes enhancing the reliability of high-temperature mechanical seal end faces through a novel composite material—carbon nanotubes (CNTs) incorporated into laser-melted chromium (Cr) coating.

Rigorous friction and wear tests, conducted under various working conditions and end face materials, reveal that the high-temperature tribological properties of the Cr-CNTs coatings exhibit optimal performance at a CNTs content of 10 wt%. The presence of CNTs significantly improves wear resistance, forming a graphite film between end faces during grinding against the graphite ring.

Notably, the Cr-CNTs coating demonstrates a substantial reduction in friction coefficient, outperforming the Cr coating by at least 12.46% at a temperature of 483 K. This research offers valuable insights into the application of carbon nanotubes for enhancing high-performance mechanical seals, presenting innovative avenues for advancing the performance of mechanical seal end faces [14].

According to author elevated temperatures at the sealing interface pose a significant threat to the longevity of seals, leading to elastomer aging, swelling, and heightened friction. This study focused on radial oil seals in helicopter gearboxes, emphasizing the critical role of contact temperatures at the sealing interface. Through comprehensive testing of four different shaft coatings and three seal spring loads across a range of sliding velocities, optimal conditions were identified with a 12 oz seal spring and a circumferential load of 3.34 N, resulting in the lowest interface temperatures.

Notably, both higher (14 oz) and lower (8.5 oz) spring loads led to increased temperatures. Surface coatings on the shaft were deemed essential, with chrome plating demonstrating undesirably high temperatures due to a polishing effect. Tungsten carbide and Chrome oxide coatings-maintained temperatures within the expected range, emphasizing their efficacy.

Additionally, surfaces with microscopic roughness beyond specified limits exhibited increased temperatures. This study provides valuable insights for optimizing sealing performance in high-temperature environments, emphasizing the importance of tailored solutions for each application [15].

In conclusion, heightened temperatures at the sealing interface present significant challenges, leading to reduced seal lifespan due to elastomer aging, swelling, and increased friction. This study, focusing on radial oil seals in helicopter gearboxes, investigated factors influencing contact interface temperatures. Optimal conditions were identified, with a 12 oz seal spring and a circumferential load of 3.34 N, minimizing temperatures at the interface. Both higher (14 oz) and lower (8.5 oz) spring loads resulted in elevated temperatures.

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Furthermore, surfaces with microscopic roughness beyond specified limits experienced increased temperatures. These findings underscore the importance of tailored solutions for optimizing sealing performance in diverse applications [15]. In conclusion, this experimental study focused on the frictional behaviour of a tungsten carbide and resin impregnated carbon mechanical seal pair operating under various lubrication conditions. Recognizing the environmental concerns associated with mineral oil-based lubricants, the investigation utilized eco-friendly vegetable oils—soybean oil and canola oil—enhanced with an eco-friendly solid lubricant, boric acid powder.

The experimental setup examined friction characteristics under different conditions, including unlubricated scenarios, independent paraffin oil, soybean oil, canola oil lubrication, and varying concentrations (1 wt.%, 3 wt.%, and 5 wt.%) of boric acid powder mixed individually with soybean and canola oil. Following running-in tests, the combination of 5 wt.% boric acid powder with soybean oil demonstrated superior performance, contributing to a hybrid tribofilm and yielding the lowest friction coefficient values in the range of 0.06-0.07. This suggests a promising and environmentally friendly approach for enhancing the frictional behaviour of mechanical seals in prolonged operational conditions [16].

In conclusion, this study aimed to enhance the performance and lifespan of mechanical seals by depositing diamond films onto their surfaces through hot filament chemical vapor deposition (HFCVD). Despite the challenge of achieving optimal adhesion between the diamond films and the mechanical seal material (WC-Co), the process involved two consecutive layers of micro- and nanocrystalline diamond. Through meticulous investigation of nucleation, deposition conditions, and pre-treatments, the study successfully demonstrated the feasibility of this approach. SEM and Raman characterization techniques were employed to analyse superficial wear and film delamination.

Encouragingly, real work environment tests on water pumps revealed no signs of wear or film delamination on the WC-Co mechanical seals, indicating the robustness and effectiveness of the diamond coatings in extending the performance and lifespan of mechanical seals [17]. Research paper addresses the critical issue of friction and wear during the start-up stage of a high-speed turbopump for liquid rocket engines, focusing on mechanical seal faces. The proposed solution involves applying thick metal alloy coatings to the seal rotor's surface to mitigate friction and wear. Using a pin-disk tribology tester, the study investigates the tribological behaviours of four metal coatings, revealing that the thick metal coating significantly improves wear resistance and reduces friction.

Notably, the Sn-Sb-Cu coating demonstrates exceptional performance with friction coefficients of 0.377 under dry conditions and 0.043 under water-lubricated conditions. The corresponding mass wear volumes are impressively low at 2.74 mg and 0.81 mg, respectively. This innovative thick metal coating approach shows promise for addressing the challenges posed by the harsh working conditions of low-viscosity liquid rocket engines in mechanical seal applications [18].

Research study introduces a novel approach to enhance the tribological performance of Silicon nitride (Si3N4)-based ceramics, commonly used in mechanical face seals. Recognizing the limitations of self-mated Si3N4 rings leading to fluid leakage and failure under high-sealing loads, the application of a solid lubricating diamond-like carbon (DLC) film is proposed.

Plasma-enhanced chemical vapour deposition (PECVD) DLC coatings, with approximately 1.5 μm thickness, were successfully deposited on Si3N4 rings using conventional RF glow discharge with pure methane or a methane/silane mixture. Remarkably, the self-mated pure DLC ring-on-ring tribosystem demonstrated exceptional sealing performance under demanding conditions, maintaining structural integrity and achieving a super low-friction coefficient below 0.001 after 419 hours of continuous operation.

While Si-DLC coatings exhibited slightly higher friction coefficients, they still demonstrated commendable performance, affirming the potential of DLC coatings to significantly improve the tribological behaviour of Si3N4-based ceramics in mechanical face seals [19].

Research study investigates the potential of amorphous carbon (a-C) coatings deposited on 9Cr18 via pulsed DC magnetron sputtering as protective layers for contact mechanical seals in cryogenic environments, such as those found in liquid rocket engine turbopumps.

The wear of seal pairs, crucial for the service life and reliability of contact mechanical seals, is effectively mitigated by the low-friction and low-wear properties of a-C coatings. Tribological tests conducted under various sealed fluid conditions (air, water, and liquid nitrogen) reveal that the a-C coatings endure cryogenic temperatures, exhibiting reduced friction coefficients with increased contact load.

Specifically, in liquid nitrogen, the friction coefficients range from 0.10 to 0.15, while maintaining low specific wear rates between 0.9 × 10^ -6 to 1.8 × 10^ -6 mm^3 N^ -1 m^ -1. These findings offer valuable insights for designing reliable and long-lasting water-lubricated bearings or contact mechanical seals in cryogenic environments [7].

Research study demonstrates a significant enhancement in the reliability and performance of silicon carbide (SiC) shaft seals on multipurpose mechanical pumps through the application of a protective coating of ultrananocrystalline diamond (UNCD). Leveraging UNCD's exceptional hardness (97. GPa), low friction (0.1 in air), and outstanding chemical resistance, the coated seals aim to reduce frictional energy losses and eliminate downtime and hazardous emissions resulting from seal failure and leakage. The UNCD films, prepared via microwave plasma chemical vapor deposition, were applied to SiC seals that underwent a meticulous pre-coating process involving mechanical polishing and seeding with diamond nanopowder.

Dynamic wear testing at 3600 RPM and 100 psi for up to 10 days demonstrated that UNCD-coated seals, with an initial SiC seal surface roughness >0.1 μm, exhibited superior performance with no measurable wear compared to approximately 0.2 μm of wear on untreated SiC surfaces. This research underscores the potential of UNCD coatings in improving the durability and functionality of multipurpose mechanical pump seals, offering promising implications for various industrial applications [9].

The study focuses on the friction and wear behavior of various ring materials in the shaft mechanical face seal of a high-speed turbopump for liquid rocket engines, operating under challenging conditions with low-temperature, low-viscosity fluids like liquid oxygen or liquid hydrogen.

Utilizing a pin-on-disk tribo-tester, the research evaluates friction coefficients (COFs) and mass-wear rates under both dry-friction and water-lubricated conditions, simulating low-viscosity scenarios. Notably, at a pressure-velocity (PV) value of 2.4 MPa·(m/s), copper graphite (stator) in conjunction with a copper-chrome alloy disk (rotor) demonstrates a low COF of 0.18 under dry-friction conditions, with a 5-minute wear mass of approximately 2 mg. Under water-lubricated conditions, S07 steel with a diamond-like carbon film outperforms other materials, making it a preferred choice for high-speed turbopumps in extreme conditions. These findings offer valuable insights and experimental guidance for the design of mechanical face seals in liquid rocket engines, particularly under the specified operational challenges [6].

3.0 Conclusion

In conclusion, the literature suggests that coatings play a vital role in mitigating wear in mechanical seals. The choice of coating technology, content, and composition significantly influences the wear resistance of these seals. PCD, a-C, DLC, and UNCD coatings have demonstrated notable success in enhancing the performance and longevity of mechanical seals, with ongoing research focusing on optimizing their application under various operating conditions.

Future endeavors should continue to explore novel coating materials and deposition techniques to further advance the field of coated mechanical seals and address specific industry challenges. The literature reviewed indicates that coating technologies have proven effective in enhancing various mechanical properties, offering tailored solutions for diverse industrial applications.

The continuous evolution of coating methods and materials presents exciting opportunities for further improvements in mechanical performance, contributing to the development of robust and durable materials for a wide range of engineering applications. he studies reviewed underscore the importance of selecting corrosion-resistant materials, applying protective coatings, and exploring innovative strategies to ensure the durability and reliability of mechanical seals in corrosive environments.

Continued research and development in this field will contribute to the evolution of corrosion-resistant technologies for mechanical seals in diverse industrial applications. The literature reviewed underscores the significant potential of HVOF coatings in revolutionizing the field of mechanical seals. From wear resistance to corrosion protection and tailored microstructures, HVOF technology offers a versatile and effective means to enhance the durability and performance of mechanical seals in demanding applications. Continued research and practical implementations will undoubtedly contribute to the ongoing evolution of HVOF coatings for mechanical seal applications.

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