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Tribological evaluation of hybrid ceramic and surface-treated rolling bearings lubricated with oils heavily diluted by refrigerants

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Abstract

Heat pumps are increasingly recognized as a key technology not only for building and district heating but also for industrial decarbonization and significantly enhancing the overall efficiency of data centers. High-temperature heat pumps and advanced chiller systems operate under increasingly severe conditions including high pressure differentials, large speed variations, elevated temperatures, and significant oil dilution by refrigerants. These factors lead to mixed and boundary lubrication regimes in the rolling bearings used in refrigerant compressors. This study evaluates hybrid ceramic bearings and surface-treated steel bearings as alternatives to standard steel bearings. Component-level tests and functional bearing tests under oil dilution rates as high as 50% demonstrated that the tested Tribological Black Oxide (TBO) coating significantly improves running-in performance, reduces friction and vibration, while maintaining surface integrity. The post analysis of the tested bearings revealed that both TBO-coated and hybrid ceramic bearings exhibited strong resistance to the refrigerant dilution, whereas steel suffered from micropitting and adhesive wear. TBO-coated bearings clearly outperformed standard steel bearings. These findings suggest TBO as a cost-effective solution and hybrid ceramic bearings as a more robust option for demanding refrigerant compressor environments. Complementary investigations addressing lubrication modelling and fatigue life prediction are also cited at the end of this publication.

Keywords: Bearing; Coatings; Hybrid ceramic

1. Introduction

Heat pump systems are a key technology to achieve global decarbonization and energy efficiency goals [1]. Recently, the technology has gained even more attention in the area of data centers to recover the huge amounts of waste heat from the computers [2-3]. Advances in industrial heat pump design reveal a growing capability to provide output temperatures surpassing 100 °C, essential for thermal processes like drying and steam generation [4]. These high-temperature applications impose stringent demands on vapour-compression cycles, where the compressor is the main mechanical element.

Industrial heat pumps and large-scale district heating systems typically employ screw or centrifugal compressors. The most common compressor designs use rolling element bearings to support shafts and rotors, although hydrodynamic and magnetic bearings are also used in specific cases [5]. As shown in Figure 1, both centrifugal and screw compressors rely on rolling-element bearings to support shafts and rotors.

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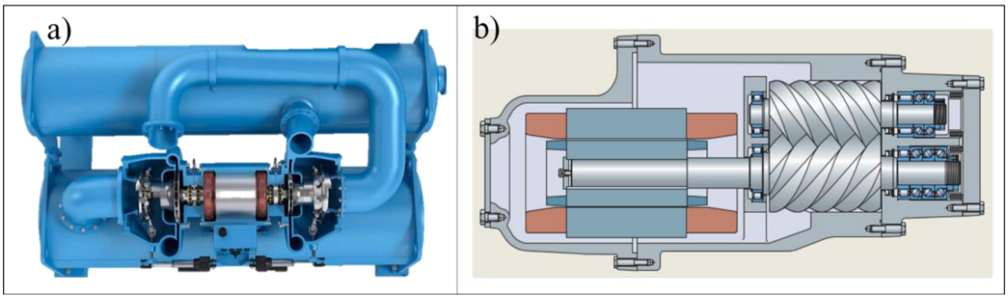

Figure 1. Typical compressor designs used in industrial heat pumps: (a) centrifugal compressor; (b) screw compressor. Rolling bearings in such systems operate under severe mixed lubrication conditions due to high oil-dilution and variable operating speeds

The main functions of the bearings in compressors are to accurately position shafts and impellers— to achieve narrow sealing gaps and thus high efficiency —while minimizing friction and internal heat generation. They must also maintain reliable performance across a wide speed range, including very low speeds during part-load operation. Expected lifetimes are often 50,000 to 100,000 hours. Considerable research has been devoted to predicting bearing performance under diverse operating conditions, culminating in advanced life models such as the Generalized Bearing Life Model (GBLM), which accounts for both subsurface and surface fatigue under thin-film and contaminated lubrication regimes [6-7]. Typical bearing designs used in refrigerant compressors include cylindrical roller bearings, angular contact ball bearings, and deep groove ball bearings. Figure 2 illustrates two advanced bearing variants: a tribological black oxide coated cylindrical roller bearing and a hybrid angular contact ball bearing with ceramic rolling elements and stainless-steel rings.

Figure 2. Typical bearings used in heat pump applications — Left: cylindrical roller bearing with tribological black oxide coating; Right: hybrid angular contact ball bearing with ceramic rolling elements and stainless-steel rings [8]

However, high-temperature heat pump applications introduce unique challenges to the rolling element bearing designs. Elevated temperatures, temperature differences, and application load increase the internal mechanical stresses during rolling contacts [4]. The ever increasing dilution rate of refrigerant in the lubricating oil, especially at high pressures, significantly reduces the lubrication film thickness [9]. Variable-frequency drives can further worsen the lubrication conditions by allowing very low-speed operation in part-load conditions. As a consequence, the combination of those application conditions cause tribological issues such as earlier and faster wear, and surface-distress to the functioning surface of a bearing, which results in a shorter bearing life. Additionally, certain refrigerants can generate chemically active or corrosive species, which further accelerate the bearing surface degradation [10]. These factors make rolling bearings one of the most critical machine elements in the evolution of heat pump technology [4].

Commercial solutions for demanding environments often rely on hybrid ceramic bearings and in some cases, stainless-steel variants are chosen for their wear resistance, and corrosion protection [11]. Yet, widespread adoption is constrained by comparatively high manufacturing and procurement costs. This paper presents recent efforts to develop and validate robust yet cost-effective rolling bearing materials and designs tailored to heat pump conditions characterized by severe oil dilution and extremely thin lubricant films.

2. Component testing

2.1. Experimental work

2.1.1. Materials and material combinations for the component test

Table 1 summarizes the material combinations that were subjected to the component tests. They were selected based on previous knowledge from lab testing as well as field experience. Two baselines (No. 1 and 2) were selected as reference points, which represent standard steel bearings and hybrid ceramic bearings, respectively. The steel substrates used in all experiments were fabricated from 100Cr6 bearing steel, which typically contains 0.98%–1.10% carbon, 1.30%–1.60% chromium, 0.15%–0.30% silicon, 0.25%–0.45% manganese, along with trace amounts of phosphorus (≤0.025%) and sulfur (≤0.025%). Number 3 to 5 contains combination of coatings, conversion layers and ceramic (Silicon Nitride) balls.

From the many existing bearing coating variants, two promising candidates were chosen, namely a special bearing grade Tribological Black Oxide (TBO) and Chromium Nitride (CrN), due to their distinctive properties in relation to poor lubrication conditions as encountered in refrigerant compressors. TBO is a chemically produced conversion layer formed through a modified black oxidation immersion process, developed specifically for bearing components. The process delivers an oxidation depth of approximately one micron on the steel surface and follows the principles of DIN 50938[12] and ISO 11408 [13], while incorporating proprietary specifications to achieve optimal tribological properties in demanding bearing applications. This layer can be produced in a very cost-efficient manner and has no risk of flaking or other potential threat to the bearing. TBO is known for its ability to form mixed iron oxides on the surface that enhances oil retention, reduces friction, and provides mild wear protection under poor lubrication conditions.

On the other hand, CrN is a hard ceramic coating with excellent wear resistance and chemical stability. It is produced in a more costly PVD vacuum setup where typically an initial very thin chromium deposition is triggered on the steel surface which then, adding a nitrogen atmosphere, continues its layer growth as CrN. Typical thicknesses can vary between 2 and 5 microns, while the tests used a layer thickness of 4 µm. CrN performs well under boundary lubrication regimes, especially in aggressive environments such as refrigerants, due to its inert surface and high hardness, which helps maintain surface integrity and reduce adhesive wear [14-15].

Table 1. List of material combinations, with No. 1 and 2 serving as baselines, while No. 3 to 5 represent combinations involving coatings

Combination No.	Ball material	Plate/Disc material
1	Steel	Steel
2	Ceramic (Silicon Nitride)	Steel
3	Tribological Black Oxide	Tribological Black Oxide
4	Ceramic (Silicon Nitride)	Tribological Black Oxide
5	Chromium Nitride	Chromium Nitride

2.1.2. Reciprocating sliding test

An in-house fretting wear rig was used to measure the coefficient of friction in reciprocating-sliding conditions (Figure 3). The contact configuration was ball on plate. The ball of 12.7 mm diameter was pressed against a flat plate. The surface topography was oriented perpendicular to the direction of the ball's movement [16]. The load applied was varied between 15.4 and 122 N, resulting in Hertzian contact pressures between 1 and 2 GPa. The oscillation frequency applied was 20 Hz with an amplitude of 100 µm. The tests were performed at room temperature for 1 hour with Mobilith SHC 100 grease. Each test was repeated two times.

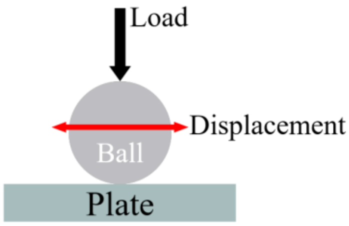

Figure 3. Schematic representation of the ball-on-plate configuration indicating the applied load and displacement direction for the reciprocating sliding test

2.1.3. Ball-on-disc test

A WAM (Wedeven Associates Machine Inc., USA) test rig was used to evaluate the friction performance under low-kappa (thin-film) lubrication under combined rolling and sliding conditions. The rig simulates a bearing raceway and rolling element contact with a ball-on-disc configuration (Figure 4). A 20.64 mm diameter ball and a disc were driven independently to obtain different slide-to-roll ratios. The rotational speeds of the ball and disc, along with the load and test temperature, were managed by a computer and can be adjusted according to a predetermined test sequence. The frictional force between the ball and disk was continuously monitored.

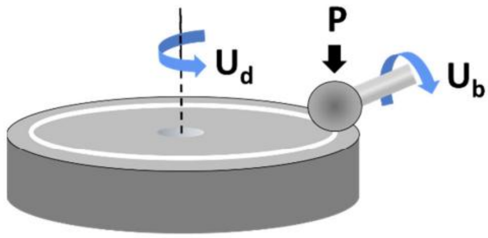

Figure 4. Configuration of the ball-on-disc test showing applied load and rotational directions of disc and ball

The test conditions are specified in the Table 2. The disc's rotational speed was set to achieve mixed lubrication, with a lubrication parameter lambda (λ) of 0.3. Lambda is defined as the central film thickness relative to the initial surface roughness (Rq) of the uncoated disk. To maintain fully flooded conditions, the Durasyn 164 lubricant was continuously delivered onto the rotating disc. Two repetitions were followed for each material combination listed in Table 1.

Table 2. Experimental conditions applied in the ball-on-disc test

Roughness, Rq	Oil	Oil temperature	Contact load (contact pressure)	Speed	Slip-to-roll ratio	Test duration
Disc: 140 ± 15 nm Ball: 50 ± 10 nm	Durasyn 164 (PAO)	100 ºC	150 N (~ 1.5 GPa)	0.8 m/s for lambda 0.3	5%	70 hours

2.2. Results

2.2.1. Reciprocating sliding test

Figure 5 illustrates the friction behaviour of all coatings, with the coefficient of friction averaged over the final 22,000 cycles of the 72,000-cycle test. This range was chosen because all coatings exhibited stable friction values after the initial running-in phase. Figure 6 presents optical images of the resulting wear scars.

When tested against a TBO-coated ball, the TBO-coated plates showed a wear depth of approximately 1.5 µm, indicating complete removal of the original TBO layer having around 1 µm depth. In contrast, testing against a ceramic ball resulted in a wear depth of around 0.5 µm, suggesting that the TBO layer underwent running-in but remained present in the tested area. This combination also yielded the lowest friction among all tested pairs.

In other cases, the surfaces were primarily polished without significant material loss. Among all coatings, CrN exhibited the highest friction coefficient.

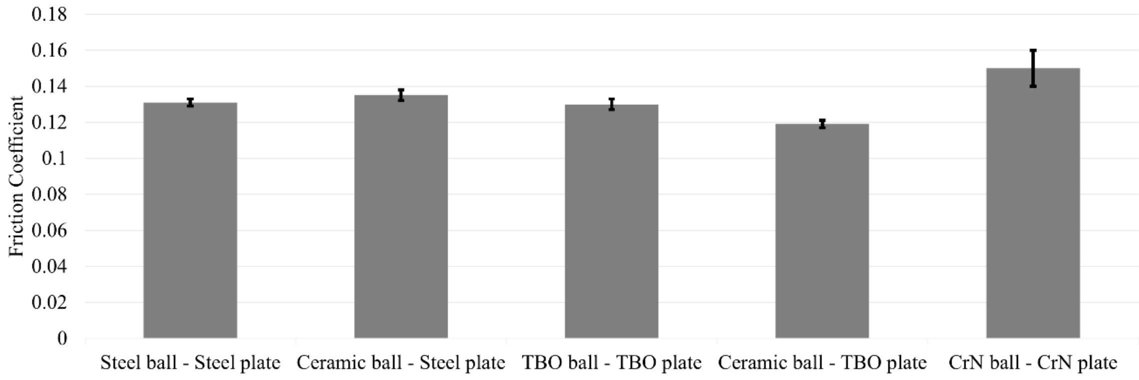

Figure 5. Friction coefficient results from reciprocating sliding test (averaged over 2 tests per combination)

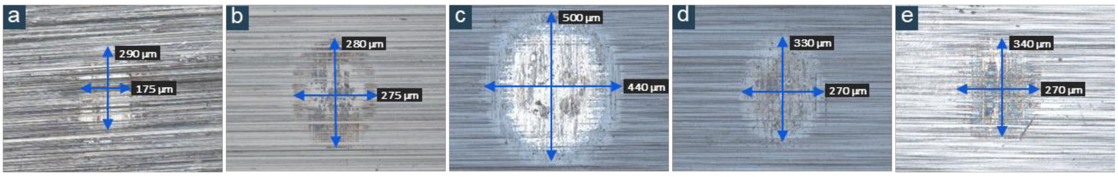

Figure 6. Optical images taken after the reciprocating sliding tests on a) steel plate (vs. steel ball), b) steel plate (vs. ceramic ball), c) TBO plate (vs. TBO ball), d) TBO plate (vs. ceramic ball), e) CrN plate (vs. CrN ball)

2.2.2. Ball-on-disc test

The WAM test results illustrated in Figure 7 present the friction coefficient both at the beginning and at the end of two separate tests for the ball–disc material combinations listed in Table 1. The initially high friction values are attributed to the running-in phase during which surface asperities interact and wear down, leading to smoother contact and reduced friction over time. From the data, it is evident that the CrN–CrN combination exhibited the highest friction, both at the start and end of the tests. In contrast, the TBO–TBO and Ceramic–TBO combinations showed similar and significantly lower friction values, indicating better tribological performance under poor lubrication.

The Steel–Steel and Ceramic–Steel combinations demonstrated intermediate friction levels, with Ceramic–Steel showing lower friction at the start of the test compared to Steel–Steel, likely due to the smoother surface and lower adhesion of the ceramic ball.

Although the CrN-coating is known for its hardness and wear resistance, it lacks self-lubricating phases and is prone to oxidation at elevated temperatures [17], which contributes to its high friction under poor lubrication conditions. On the other hand, the TBO layer possesses high lubricant wettability, which enhances the formation and retention of lubricating films on the surface. This property, combined with the ability of TBO layers to smoothen the raceway during the running-in phase, helps to reduce friction even in low-lubrication environments. In other words, the ceramic component adds thermal stability and abrasion resistance, while the TBO layer improves lubricity and minimizes adhesive interactions with the counter face.

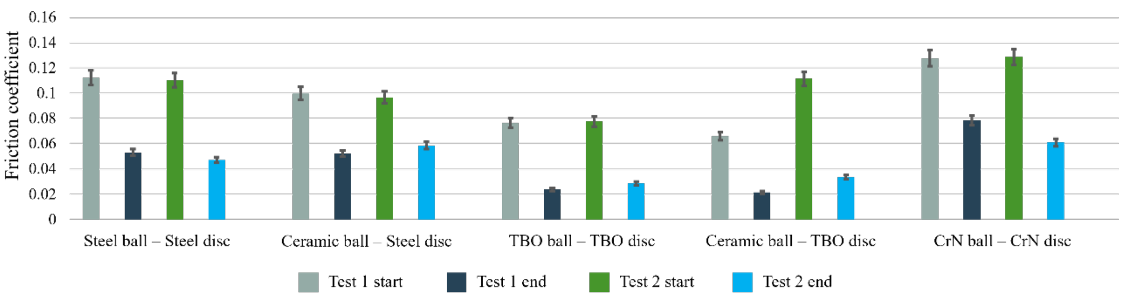

Figure 7. Results of ball-on-disc tests with combined rolling-sliding motion for two repetitions per material combination. Friction coefficient values represent averages for the first and last hour of the 70-hour test period, denoted as ‘start’ and ‘end’ in the graph

The wear depth for both ball and disc components across all tested material combinations is presented in Figure 8. The TBO–TBO and Ceramic–TBO variants exhibited approximately 0.8 µm wear within the TBO layer, remaining well below its initial (~1.0 µm) thickness, thereby confirming layer presence after the test. In the Ceramic–Steel combination, the ceramic ball showed negligible wear, and the steel disc displayed only surface polishing without considerable material removal. Conversely, the CrN–CrN combination demonstrated measurable wear (~0.35 µm) on the ball, whereas disc wear was negligible.

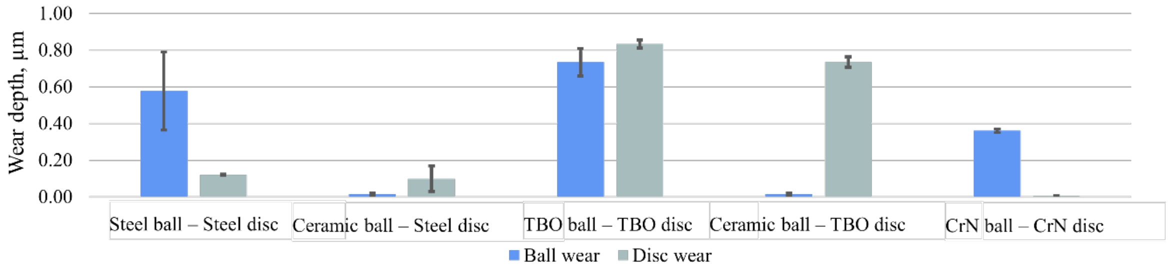

Figure 8. Wear depth measured in the track of ball and disc from the ball-on-disc test

2.3. Conclusions from component tests

Based on the reciprocating sliding and ball-on disc (WAM) test results, TBO treated surfaces demonstrated excellent tribological performance under rolling–sliding conditions, but limited durability under pure sliding. In the WAM tests with combined rolling and sliding, both TBO–TBO and ceramic–TBO combinations retained the layer and exhibited the lowest friction coefficients after running-in. The coating combination of CrN–CrN consistently showed the highest friction and measurable ball wear, confirming its poor lubricity and wear resistance despite high hardness. The ceramic versus steel test displayed negligible wear on the ceramic ball and only polishing on the steel disc, indicating good tribological compatibility under poor lubrication conditions.

In summary, the TBO layer performance showed lowest friction and good tribological suitability for rolling bearing applications operating under poor lubrication conditions, while the combination of ceramic balls on steel offers a particularly good balance of moderate friction and minimal wear. Therefore, these material combinations were implemented in the bearings for the functional tests described in the following section, where their functionality and suitability for operation in an oil–refrigerant mixed environment will be discussed.

3. Functional bearing tests

3.1. Test setup and conditions

The functional bearing tests were designed to check the performance of the bearings under challenging but realistic lubrication conditions where the oil was heavily diluted by the refrigerant. The test setup is shown in Figure 9. The setup consists of a hermetically sealed test cell in which the bearings to be tested can be mounted on a simple shaft (Figure 9a). The shaft is driven via a magnetic coupling. Angular contact ball bearings were used for the test, which were axially loaded using a hydraulic cylinder, whereas the speed was controlled using a drive motor. A continuous supply of oil-refrigerant mixture in the test cell was maintained using a circuit shown in Figure 9b. The oil and refrigerant were introduced in the targeted proportions into the pressure vessel and thoroughly mixed through the circulation within the system. Using a viscosity sensor system, the dilution rate was maintained during the test.

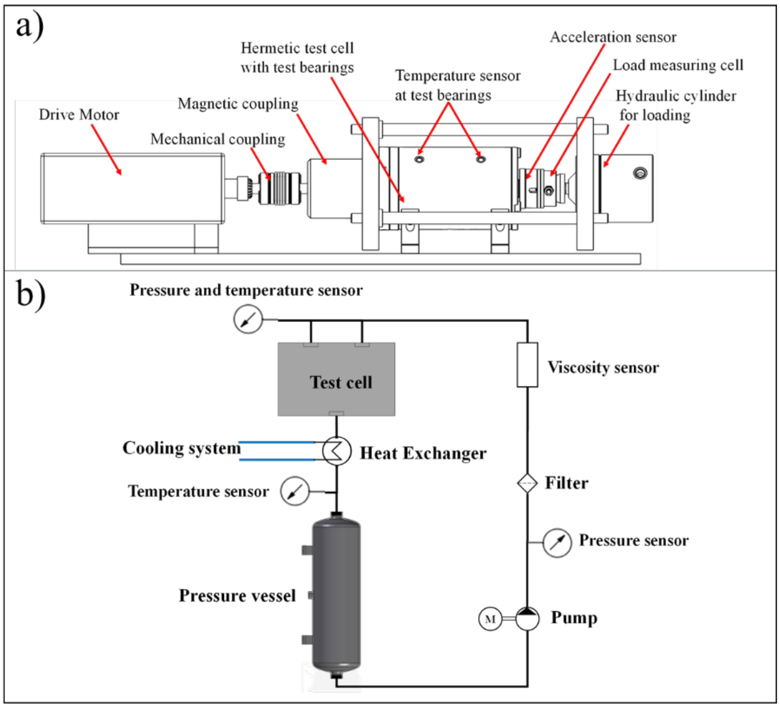

Figure 9. Functional bearing test rig - a) test cell and drive, b) oil-refrigerant mixture circuit

Following the outcomes of the component-level evaluations, the material combinations listed in Table 3 were selected for subsequent functional testing. The selection rationale and detailed descriptions of these materials are provided in the preceding section (2.1.1). The three bearing variants correspond to standard steel bearings, hybrid ceramic bearings, and Tribological Black Oxide (TBO) treated bearings, respectively. In the latter case, standard steel served as the substrate for the application of the TBO layer.

Table 3. List of material combinations for the functional bearing tests

Combination No.	Ball material	Ring material
1	Standard Steel (100Cr6)	Standard Steel (100Cr6)
2	Ceramic (Silicon Nitride)	Standard Steel (100Cr6)
3	Tribological Black Oxide	Tribological Black Oxide

The bearings were subjected to the conditions listed in Table 4. The refrigerant R1234ze was selected as a representative working fluid due to its relevance in typical industrial and commercial applications. R1234ze is a medium pressure, low Global Warming Potential HFO, used as a replacement for R134a in refrigeration, air-conditioning and heat pump applications [18-19]. It was also selected in accordance with inputs from OEMs and is used both for screw and centrifugal compressor-based machines. The speed and load were higher than in most application cases. The oil was chosen to be representative of common application cases. The combination speed, load, oil viscosity and temperature were specifically chosen to accelerate the test, yet to keep the tribological regime and failure modes same as the common applications.

Table 4. Functional bearing test conditions

Refrigerant	Lubricant	Dilution rate	Calculated Kappa at 50% dilution	Temperature	Speed	Load	Testing Time
R1234ze (HFO)	Fuchs Reniso Triton SEZ 100 (100 cSt at 40 °C)	50% refrigerant concentration by weight	Approximately 0.089 to 0.13	85 ºC	10,000 rpm (i.e. n*dm value of 0.66 million rpm*mm)	13.7 kN (~2.0 GPa Hertzian contact pressure for the 'Steel-to-Steel' inner ring raceway contact)	740 hours

3.2. Results

The tribological performance of all three variants, namely standard steel bearings, hybrid ceramic bearings, and TBO coated bearings, was evaluated. Figure 10 illustrates that the hybrid ceramic and standard steel bearings resulted in higher system friction torque, approximately 37%, whereas the TBO variant exhibited a comparatively lower value of around 30%.

Under boundary lubrication conditions ($\lambda \ll 1$), the surface asperities share the load, and the material stiffness determines how the contact forces are distributed across the surface area. Ceramics rolling elements have a higher elastic modulus and therefore lead to narrower contact areas, elevated Hertzian stresses and results in increased friction [20]. In case of steel bearings, the bare metal asperities come into direct contact during boundary lubrication. When those microscopic peaks stick (adhesive interactions), they resist sliding, leading to adhesive shear and elevated friction under thin-film conditions [21]. Conversely, TBO features a conversion oxide layer that provides a uniformly low-shear contact interface and resilient microtexture, reducing boundary friction without forming a tribo-film [22].

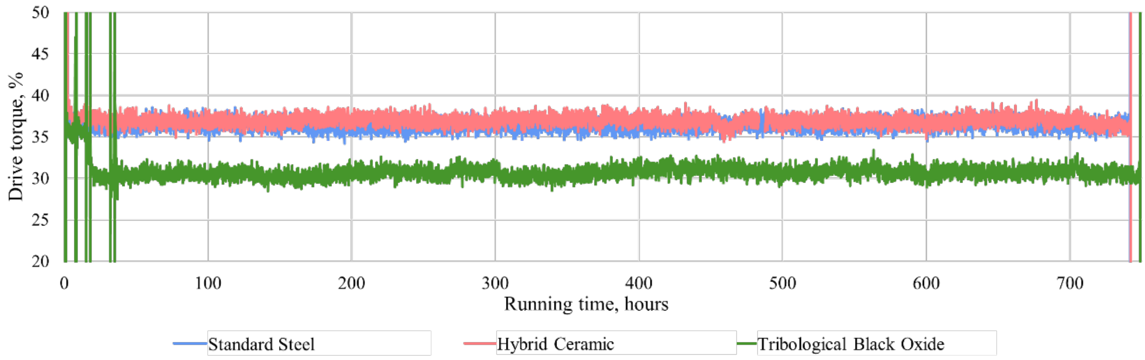

Figure 10. Drive torque evolution for standard steel bearings hybrid ceramic bearings, and TBO-coated bearings under mixed lubrication conditions

Vibration data (Figure 11) reinforces these findings. The standard steel bearings exhibited peak fluctuations above 500 mg, which later stabilized around 250 to 300 mg, indicating active asperity collisions and stick-slip events. Hybrid ceramic bearings showed similar but marginally lower amplitudes, reflecting reduced but persistent contact instability. Despite higher torque, the inherent hardness and thermal stability of ceramics helped to maintain structural rolling contact integrity under severe mixed lubrication conditions, reducing the risk of catastrophic failures compared to steel. The TBO bearings produced the lowest and most consistent vibration levels 100 to 150 mg, which indicates smoother contact with lower shear disruptions.

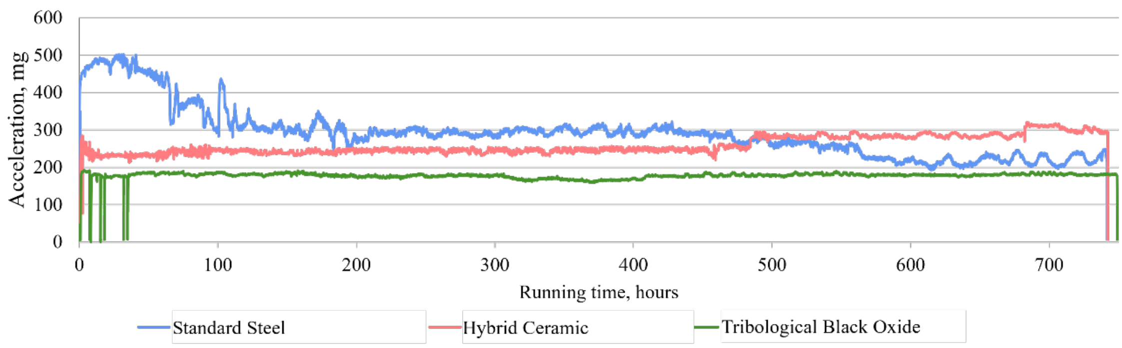

Figure 11. Acceleration (vibration) level for the three raceway materials during the 740-hour functional testing

Raceway surface analysis via Scanning Electron Microscopy (SEM), as shown in Figure 12, revealed distinct differences in wear morphology among the bearing variants. The standard steel bearings, involving direct Steel-Steel contact, exhibited pronounced surface distress (micro-pitting), and wear scars indicative of adhesive rupture. In hybrid ceramic contact, machining grooves were maintained on the steel rolling contact surfaces accompanied by mild polishing, suggesting reduced but persistent asperity contact. The combination of ceramic balls and steel rings appeared to mitigate deep surface damage, thereby supporting enhanced durability under high-stress operating conditions [23]. Under TBO-TBO contact, the TBO conversion layer promoted rapid surface smoothening during early operation, reducing the asperity interaction and friction compared to steel-steel or steel-ceramic contacts. It is part of the designed function of TBO that part of its layer thickness will be worn during running-in to enhance the overall surface quality, while the remaining layer will remain as protective and oil-retaining film. Moreover, the TBO layer provides a stable, low-shear interface that minimizes micro-pitting and smearing under boundary lubrication conditions, consistent with SEM observations, which revealed only mild polishing within the rolling tracks (Figure 12e). An Energy Dispersive X-ray (EDX) spectroscopy analysis in the raceway confirmed an oxygen-rich residue that persisted after testing. This residual layer maintained tribological benefits and continued lubricant wettability, which in turn contributed to a better vibration and torque performance. The observed trends aligned closely with those reported in section 2.2.2, reinforcing the earlier conclusions. Beyond friction reduction, TBO offers light protection against corrosion [12] and hydrogen ingress outside the contact zones [24].

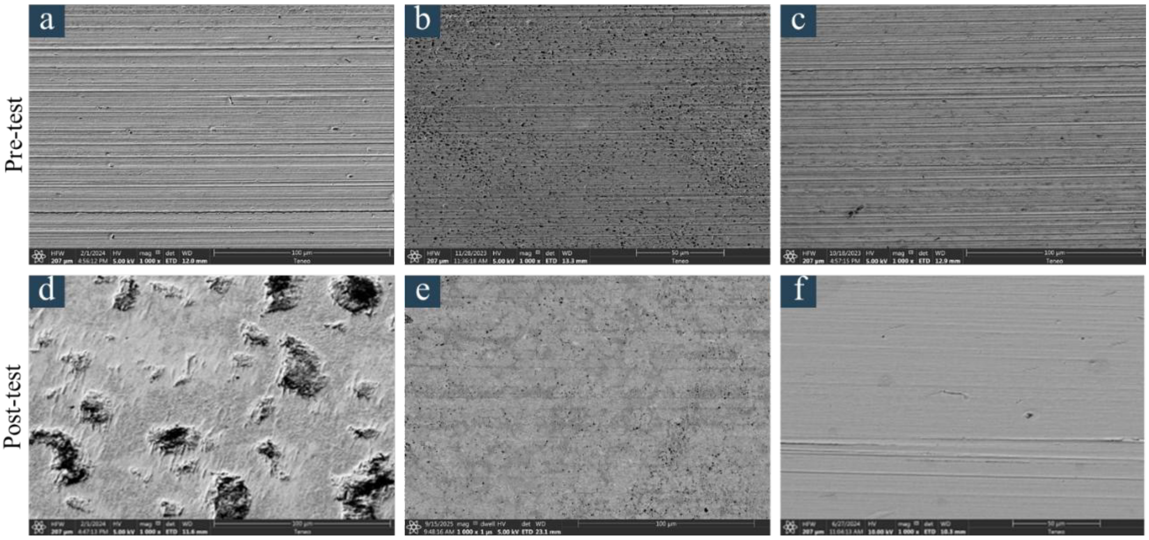

Figure 12. Pre-test and post-test SEM comparison: (a–c) initial raceway surfaces of steel, TBO, and hybrid ceramic; (d–f) corresponding surfaces after 740-hour test. TBO and hybrid ceramic have undergone mild polishing and steel sustained severe pitting and adhesive wear.

4. Conclusions

The study reported here focused on the tribological behavior of different material combinations in rolling element bearings used in heat pump compressors operating under mixed or boundary lubrication conditions. A two-phase approach was employed in the experimental studies: first, component-level tests were conducted to characterize tribological behavior under pure sliding and rolling–sliding contact.

The results were used to select promising material combinations for the second testing phase in which three bearing variants were subjected to functional bearing tests: standard steel bearings; hybrid ceramic bearings with balls made of sintered silicon nitride; and bearing-grade Tribological Black Oxide (TBO) treated bearings in which the base material was standard steel.

The functional bearing tests revealed that TBO-treated bearings achieved the lowest drive torque and most stable vibration levels, while hybrid ceramic bearings exhibited slightly higher but consistent torque and vibration levels. Conversely, standard steel bearings showed the highest torque and vibration fluctuations.

Surface analysis using SEM and EDX confirmed severe micropitting and wear on the raceways of the standard steel bearings; for the hybrid ceramic bearings, the raceways of the steel rings showed only minor polishing and mild polishing was observed on the TBO treated steel-surfaces, with the oxygen-rich layer remaining intact. These results demonstrate that rolling contact surfaces treated with TBO significantly reduce friction and wear relative to steel surfaces, while hybrid ceramic bearings deliver superior durability even under extreme conditions.

Hybrid ceramic bearings are ideal for highly stressed compressor environments requiring the longest possible service life, high speeds, or resistance to electrical damage in VFD-driven systems. On the other hand, TBO-treated steel bearings offer a cost-effective solution that ensures safe running-in under thin-film conditions and minimizes friction and vibration. Together, these technologies represent a solution portfolio for reliable, energy-efficient, and high-performance heat pump compressors, aligned with global decarbonization and efficiency goals.

5. Related investigations / complementary work

In addition to the experimental validation work presented in this study, complementary research work comprises advanced predictive modeling and testing methodologies for bearings in refrigerant compressors. These include mixture laws for oil–refrigerant systems, lubrication film thickness calculations for mixed lubrication regimes, and bearing life models based on surface-initiated fatigue mechanisms [4], [10], [25]. The SKF Generalized Bearing Life Model (GBLM) has been recently extended to hybrid bearings with standard steel [20], [26] as well as stainless steel rings, improving life prediction accuracy under low-viscosity and contaminated conditions. Ongoing work also explores additional steel variants and surface treatments, forming a comprehensive framework for optimizing bearing design and material selection in next-generation high-temperature heat pump applications.

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