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Evaluating plain bearing performance in alternative fuel engine applications

Tribology

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ABSTRACT

As the transition towards decarbonization of internal combustion engines gains momentum, there is a growing emphasis on sustainable engine solutions. In fact this is calling for the embrace of alternative fuels including ammonia, hydrogen and methanol. These, however, put challenging demands on relevant engine parts – particularly on plain bearings – necessitating targeted research and adaptation efforts to ensure that plain bearings will meet the power density, durability and efficiency requirements of leading future applications.

Under the aspect of decarbonization, a major component in these considerations is the performance evaluation of plain bearings. Integral to this assessment is understanding how byproducts of combustion, fuel residues and different oil additives interact with the currently used bearing materials. This is essential to provide new robust plain bearing solutions for future demands like elevated water contents or ammonia contaminations in engine oils.

The interaction between lubricating oil and bearing material is of particular significance. New lubricant formulations, due to the introduction of alternative fuels, heralds a significant challenge. As such, the development of dedicated testing methods focusing on oil-material compatibility is imperative, illuminating potential chemical dynamics between bearing materials and oils under real-world conditions.

Tribological investigations as a central aspect for the bearing material characterization unravels a deeper understanding of wear and friction mechanisms within the engine. It also reveals potential influences of alternative fuel contaminations due to load capacities and degradation behavior of aged oils. In order to solidify these insights and move one step closer to their practical application, it is important that these findings are transferred to the hydrodynamic test rigs.

Learnings from lab tests, test bench tasks, and tribometer trials are used to bridge laboratory results with field applications. Such integration enables a holistic performance evaluation of plain bearings under multifarious conditions. The paper shows an evolutionary trajectory of bearing adaptation, opening doors to future research pathways, and illuminating the route towards more efficient, environment-friendly engine systems.

Databases are comprehensively created based on the robust foundation formed by the findings from laboratory and field trials. These have the potential to enable a form of virtual validation, simulating the behavior of plain bearings under a range of operating conditions and with different types of fuels. This virtual validation could not only expedite time-to-market by reducing the need for time-consuming physical tests. It could also enhance material lifespan by providing insights into potential wear and corrosion mechanisms and patterns. This would allow for future research and development efforts to be more targeted and efficient.

Upon presenting the findings, the audience is invited to gain enriched insights into the evaluation of plain bearing performance through diversified tribological tests. Equally paramount is imparting a sense of the criticality of probing oil-material compatibility, which forms a pivotal element in the validation process for essential engine components. It underscores the complexities of the transition towards alternative fuels, simultaneously signaling the progressive and sustainable development of new bearing solutions.

1 INTRODUCTION

In recent years, the need to reduce CO_2 emissions and combat climate change has led to a growing interest in the decarbonization of internal combustion engines. Developing and implementing sustainable engine applications is a crucial step in reducing the environmental impact of both the transportation and energy production industries. The transport industry, for example, particularly the marine sector, is one of the largest contributors to global CO_2 emissions. Conventional marine fuels, primarily heavy fuel oil (HFO) and marine diesel oil (MDO), are derived from crude oil and release significant amounts of carbon dioxide and other greenhouse gases when burned. The combustion process in large marine engines, such as two-stroke low-speed and four-stroke medium-speed diesel engines, is optimized for efficiency but inherently results in high emissions due to the carbon-rich nature of fossil fuels.

Decarbonizing internal combustion engines is a central theme. Alternative fuels like ammonia (NH_3), hydrogen (H_2), and methanol (MeOH) are considered potential solutions to reduce CO_2 emissions. Understanding the interactions between combustion products, fuel residues, and bearing materials, as well as their reactions with oils, is crucial to assess their impact on bearing performance.

Various regulations, like those set by the International Maritime Organization (IMO) to reduce CO_2 emissions in the marine sector, drive the decarbonization of internal combustion engines. These regulations set ambitious goals for reducing greenhouse gas emissions from international shipping to net-zero by or around 2050. To guide this transition, the strategy outlines indicative checkpoints: by 2030, a minimum 20% reduction in total annual GHG emissions, and by 2040, a minimum 70% reduction, compared to 2008 levels. All this makes the development and implementation of sustainable technologies and fuels in the shipping industry mandatory. [1]

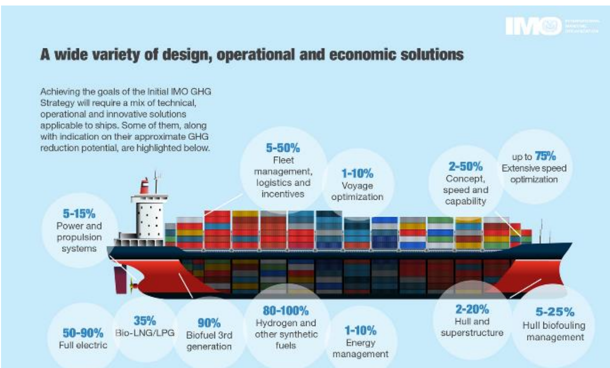

Figure 1 Potential CO2 savings by design changes [1]

Factors such as fuel availability, infrastructure, and the distinction between stationary and mobile engine applications will influence the choice of fuels, leading to a varied fuel mix across different engine applications (see Figure 2). For instance, stationary power generation units might use hydrogen, which requires high-pressure storage (700 bar) or low temperatures (-252°C) [2] but can be easily supplied via pipelines. A fuel supply via pipeline is a convenient solution to supply power generation plants. To transport hydrogen, existing pipeline infrastructure can be used to a certain percentage of hydrogen blended with natural gas. For transporting pure hydrogen, existing pipelines have to be modified or rebuilt for that purpose. Maritime applications needing extensive fuel supplies in limited space keep the fuel bunkering tank as small as possible to have the maximum loading capacity for transporting goods. This is necessary to keep the freighting costs relatively low. With this background, marine applications will likely prefer ammonia or methanol as potential fuel candidates, which are easier to liquefy and store.

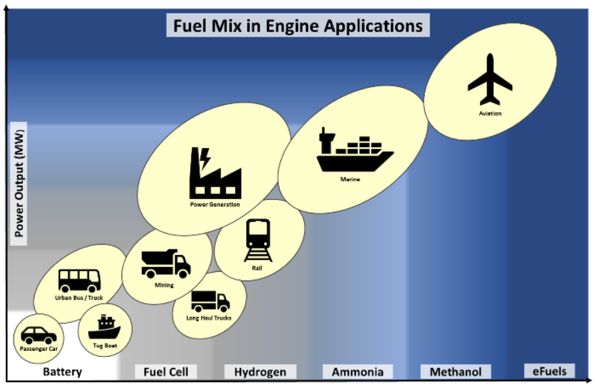

Figure 2 Expected fuel mix in future engine applications

Another significant aspect in the future of internal combustion engines is the growing demand for sustainable engine oils. Innovative, fully synthetic base oils not derived from fossil sources, such as polyesters and polyglycols, are gaining popularity. Polyester-based synthetic oils are synthesized through the polycondensation of organic acids and alcohols, resulting in a molecular structure that imparts several advantageous properties. One of the key attributes of these oils is their high viscosity index, which indicates minimal change in viscosity across a broad temperature range. Furthermore, polyester-based oils exhibit superior thermal and oxidative stability. Their robust molecular structure resists thermal degradation and oxidation, even at elevated temperatures, leading to prolonged oil life and extended oil change intervals. Therefore, these new oil formulations play a crucial role in material compatibility within the engine. The use of new additive formulations in these kinds of oils can bring completely new chemical interactions between oils and bearing materials, which can lead to unknown corrosion phenomena in the engine. Driven by sustainability but also due to the high oxidation stability and the higher costs for the use of these synthetic oils, the oil lifetime will be expanded.[3]

All these potential changes in the internal combustion engine system necessitate adapting the performance of bearings to new requirements arising from the use of alternative fuels like methanol, hydrogen, and ammonia. Overall, analyzing the performance of bearings in environmentally friendly engine applications provides detailed insights and helps expand knowledge of the challenges and opportunities in this field. The following chapters will explain the approach of evaluating the bearing performance in these alternative fuel applications to ensure that future bearing applications will meet the demands of the next generation of internal combustion engines.

2 ALTERNATIVE FUELS

Implementing alternative fuels in internal combustion engines presents specific challenges that can affect combustion processes and the functionality of essential components such as plain bearings (see Table 1). Each alternative fuel has unique chemical and physical characteristics, resulting in differences in combustion patterns and the production of particular byproducts. These substances, along with unburned fuel recidues, may enter the engine lubricant through blow-by gases, potentially changing the oil's chemical makeup and its interaction with bearing materials. Subsequently, the properties of the three most pertinent future fuels for internal combustion engines (Hydrogen, Ammonia and Methanol) will be discussed more in detail.

Fuels	Energy density [MJ/L]	Wear	Corrosion	Cavitation	Storage
Hydrogen	8,0	+++ (knocking)	+	++	Gas Liquid
Methanol	15,7	++	+	+++	Liquid
Ammonia	11,3	++	++	++	Liquid
SAF	35	0	0	0	Liquid

Table 1 Overview of the Characteristics of Alternative Fuels [4]

2.1 Hydrogen (H_2)

The combustion characteristics of Hydrogen in internal combustion engines present both opportunities and challenges. One notable advantage is hydrogen's wide flammability range, allowing it to combust over a broad spectrum of fuel-air mixtures. This flexibility enables the engine to operate on lean mixtures, where the fuel quantity is less than the stoichiometric amount required for complete combustion with a given air volume.

Hydrogen’s unique combustion characteristics present also specific challenges in internal combustion engines, particularly concerning the phenomenon of knocking. Knocking arises from the spontaneous auto-ignition of the air-fuel mixture ahead of the flame front, leading to abrupt and erratic pressure surges within the combustion chamber. These pressure fluctuations can induce significant mechanical stress on engine components, notably the bearings, potentially resulting in accelerated wear or even catastrophic failure. [5]

Ester oils can help prevent knocking in hydrogen-fueled internal combustion engines (ICEs) due to their superior thermal stability, lubricity, and deposit-control properties. Knocking in hydrogen engines primarily occurs due to the fuel’s high flame speed, low ignition energy, and tendency to pre-ignite in the presence of hot spots, oil residues, or deposits. The use of ester oils address these issues.

One key advantage of ester-based oils is their excellent thermal stability. Hydrogen combustion leads to higher combustion temperatures compared to conventional fuels, increasing the risk of oil degradation and deposit formation. Traditional mineral-based oils and some synthetic oils can break down under these extreme conditions, forming carbonaceous residues that can act as ignition sites for premature combustion. Esters, however, have a strong molecular structure with high oxidation resistance, meaning they resist breakdown at elevated temperatures. This helps maintain a clean combustion chamber, reducing the likelihood of knocking caused by deposits. [3]

Besides the mechanical hurdles, the combustion of hydrogen is from a chemical point of view the least complex of the alternative fuel candidates. While the primary combustion product of hydrogen is just water vapor, the high combustion temperatures can facilitate the formation of nitrogen oxides (NO_X) when hydrogen is burned in air. The elevated water and NO_X-content in the blow-by gas stream can lead to high oxidation and degradation of the oil additives. This can effect the corrosivity, against lead-containing materials, of the ester oils used especially in the hydrogen fueled ICE.

2.2 Ammonia (NH_3)

Compared to hydrogen combustion, one of the primary challenges associated with ammonia is its low flame speed and high ignition temperature. Furthermore, ammonia has a narrow flammability range of approximately 15–28% by volume in air, which complicates its application in internal combustion engines (ICE). These characteristics can result in incomplete combustion and diminished engine efficiency. To address the flammability issues of ammonia, a pilot fuel, such as diesel, can be employed to initiate the ignition process. Typically, a range up to 10% diesel fuel by volume can be used to achieve effective ammonia combustion.

In addition to the utilization of hydrogen, the use of ammonia as a fuel introduces a bunch of complex challenges, particularly regarding chemical interactions. Due to the low flammability of ammonia, there is a significant likelihood of unburned ammonia infiltrating the crankcase via blow-by gas. Consequently, the interaction between ammonia and various materials, especially copper, becomes a critical area of focus. Ammonia's ability to form stable copper complexes results in highly corrosive behavior towards these materials.

Moreover, it is not only copper materials that are affected by the reaction with unburned ammonia in the blow-by stream. The additives in engine oil also have the potential to react with ammonia and lose their effectiveness. Furthermore, the copper-ammonia complexes can act as catalysts for the oxidation of engine oils, leading to the rapid depletion of anti-oxidant additives and severe sludging of the oil.

Other scientific studies examining the behavior of engine oils under ammonia exposure have demonstrated that the tribological properties of engine oils are adversely affected. When investigating the failure load and friction coefficient of oils in both fresh and aged conditions (according to ASTM D7421), ammonia-aged engine oils exhibit a significant reduction in load-carrying capability and tribological performance.[6, 7]

While ammonia represents an interesting alternative fuel option for internal combustion engines, its unique chemical and combustion characteristics pose significant technical challenges that must be addressed to ensure efficient and reliable operation.

2.3 Methanol (CH_3OH)

Methanol is a promising alternative fuel for internal combustion engines (ICEs) due to its advantageous properties. Unlike hydrogen and ammonia, methanol is a liquid at room temperature, facilitating handling and storage similar to conventional fossil fuels. Its high octane rating enables higher compression ratios in engines, enhancing thermal efficiency and power output. Consequently, methanol combustion closely resembles that of traditional fuels like diesel, offering benefits for retrofitting large engines.

To align methanol combustion with net-zero transport policies, modifications in production processes and exhaust gas treatment are necessary. Green methanol must be produced using renewable energy sources and CO_2 as a carbon source. To maintain a closed carbon loop, CO_2 should be captured from atmospheric sources or through carbon capture processes. This requires capturing CO_2 from engine exhaust gases, which may demand additional space.

Beyond these technical challenges, methanol's corrosive properties can affect engine components. It can corrode copper materials and carbon steel, potentially causing issues in critical engine parts. Incomplete combustion of methanol can produce carbonic acids, such as formic acid, introducing additional corrosive elements into the engine system. This may lead to problems like lead leaching from lead-containing bearing materials.

Methanol contamination in engine oil, resulting from blow-by gases entering the crankcase, can adversely affect mechanical performance. The presence of low-boiling-point substances in the oil increases the risk of cavitation and tribological issues in bearings. This effect can also occur with high water content in engine oil. Alternative fuels, including methanol, tend to produce higher water content during combustion compared to traditional diesel fuel. This water vapor can condense in the crankcase if it enters through blow-by gases, raising the water content in the oil.

The integration of alternative fuels into internal combustion engines introduces numerous technical challenges, necessitating thorough examination of critical components like bearings to maintain optimal engine performance throughout its lifespan. The adoption of new fuels introduces a multitude of unknown variables, rendering traditional testing setups potentially inadequate for comprehensively understanding bearing behavior under these novel conditions. In response, Miba is pioneering innovative testing methodologies to assess bearing performance in engines operating with alternative fuels.

3 PERFORMANCE EVALUATION OF SLIDEING BEARINGS

To ensure that bearings perform optimally across all future applications, it is crucial to evaluate and, if necessary, modify them to accommodate evolving operational parameters. Achieving this promptly is essential to minimize the time required to introduce innovative bearing solutions to the market. This necessitates the development and implementation of appropriate testing methodologies that can accurately replicate potential engine scenarios.

The procedures for testing and assessing various bearing designs encompass laboratory evaluations, such as analyses of corrosion resistance, evaluation of the cavitation resistance and assessments of long-term stability. Additionally, studies of tribological properties are conducted, focusing on the formation of tribo-layers at frictional interfaces. Test bench activities are also performed to simulate conditions like start/stop cycles, hydrodynamic performance, and tolerance to contaminants. (see Figure 3)

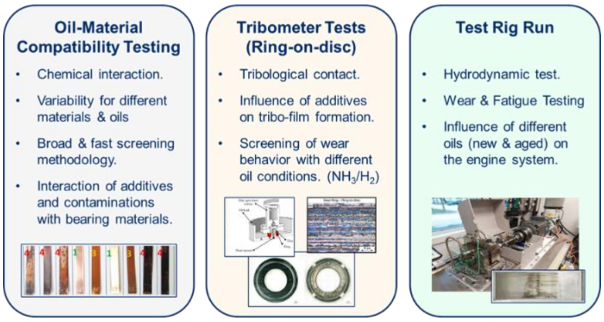

Figure 3 Overview of the Miba bearing testing strategy

By employing these comprehensive testing strategies, it is possible to gain a thorough understanding of bearing behavior under diverse conditions, thereby facilitating the development of high-performance bearings suited for future applications.

3.1 Oil-Material Compatibility Tests

As internal combustion engines transition from conventional diesel to alternative fuels, Miba, as a bearing manufacturer, must adopt a comprehensive approach when evaluating the entire engine system. This includes not only the combustion process but also the selection and behavior of engine oils, which are essential for ensuring long-term bearing durability and performance.

Choosing the right engine oil is critical for bearing reliability. If the lubricant's additive composition is not optimized, or if oil degradation accelerates due to interactions with alternative fuels, combustion byproducts, and unburned fuel blow-by, bearing lifespan may be significantly reduced. Corrosive reactions, cavitation effects, and changes in oil properties can all negatively impact bearing function. Therefore, oil formulations must be carefully matched to bearing materials for each specific application to maintain performance under evolving operating conditions.

To systematically analyze potential chemical interactions between bearing materials and engine oils in both fresh and aged states, specialized test methods have been developed. These methods rely on static oil-material compatibility tests and incorporate established industry standards, such as ASTM D130 and VDMA 24570 (see Figure 4). During testing, bearing material samples—both pure metals and composite alloys—are immersed in fresh or artificially aged oil at controlled temperatures between 60°C and 180°C. The required oil volume for testing a single material is approximately 15–20 mL. Throughout the experiment, material samples are periodically weighed to measure material loss, while visual inspections assess surface changes as indicators of corrosion susceptibility. [8, 9]

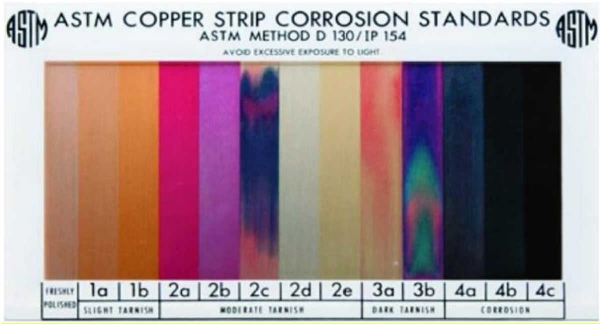

Figure 4 Oil-Material Compatibility Tests for Copper according to ASTM D130

This laboratory setup allows researchers to simulate long-term chemical interactions between lubricants and bearing materials under controlled conditions. While it does not fully replicate real engine environments, it provides valuable insights into potential degradation mechanisms, helping engineers predict long-term material performance. By exposing lubricants in various aging states to these tests, it becomes possible to study how corrosion behavior changes under different operational scenarios.

Initial Oil-Material Compatibility Tests (OMCT) have shown that the visual appearance of copper test coupons does not always correspond with actual corrosive interactions. The formation of passivating layers can reduce the reactivity of tested materials, leading to misleading results. Additionally, when testing materials other than copper, or when evaluating different bearing alloys, the standard methodology becomes insufficient for detailed investigations of real-world interactions.

To improve the accuracy of these tests, advanced laboratory techniques are required to perform detailed oil analyses and extract critical data from the experimental setup. High-precision equipment such as inductively coupled plasma optical emission spectrometry (ICP-OES), Fourier-transform infrared spectroscopy (FT-IR), viscosity measurements, and titration methods (for determining total base number (TBN) or water content in oil samples) are employed. These techniques enhance analytical precision by detecting trace metal dissolution and chemical changes such as additive breakdown.

To further enhance this research, Miba is developing a small-scale artificial oil aging system designed for oil volumes below 200 mL. This system replicates oil degradation by exposing samples to air oxidation, combustion byproducts, and alternative fuel residues (see Figure 4). The goal is to understand how these factors impact lubricant stability and bearing material integrity over time. In addition to static oil-material compatibility tests, tribometer experiments are being conducted to evaluate the tribological effects of aged oils and various fuel compositions on bearing performance.

Figure 5 Oil aging tests in laboratory scale

This testing approach provides a rapid and resource-efficient method for screening a wide range of materials and lubricants within a relatively short timeframe. The results offer valuable insights into chemical interactions between lubricants and bearing materials, helping engineers optimize formulations and material choices for future applications.

Currently, real-world data on fired engines operating with alternative fuels remains limited, particularly for long-duration engine tests. This makes it crucial to conduct effective laboratory investigations to gain an early understanding of how alternative fuels and combustion byproducts interact with lubricants and, subsequently, with bearing materials.

One practical example of this research is the study of copper-containing alloys exposed to unburned ammonia in the blow-by gas stream. This project, conducted in collaboration with Innio Jenbacher, and AC²T, examined the effects of ammonia exposure on gas engine lubricants. In these experiments, oil samples used in gas engines were artificially aged under two different conditions: one with air oxidation and another with defined amounts of ammonia in the air. After aging, these oils were tested with Miba bearing materials, including Miba 2C, a lead-free bronze alloy.

The analysis of these aged oils revealed that ammonia exposure significantly increased corrosivity toward copper, as indicated by elevated levels of dissolved copper in the oil compared to air-aged samples. (see Figure 6)

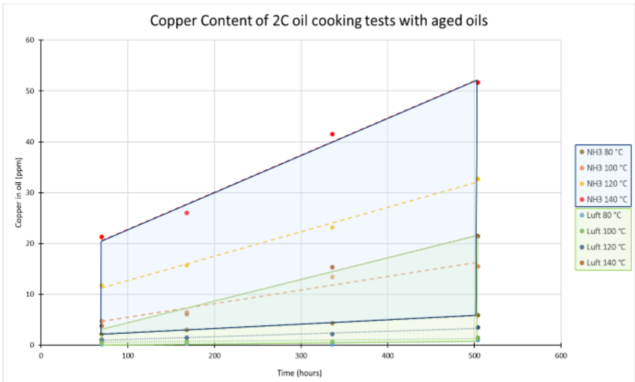

Figure 6 Copper content in air and ammonia aged oil after OMCT

This testing procedure is not exclusively applicable to alternative fuel combustion concepts. It can also be used to evaluate new engine oil formulations, including various Group V oils such as ester-based lubricants, to assess their long-term compatibility with bearing materials.

Tests conducted with different ester-based oils under conditions of increased water content in the crankcase — simulated by raising the humidity of the aging gas stream — have demonstrated significantly higher corrosivity toward lead-based materials compared to conventional lubricants.

The primary objective of these studies is to translate laboratory findings into real-world applications by replicating corrosion mechanisms observed in operational engines. Miba aims to incorporate these results into test bench experiments to refine the development of next-generation bearing materials and lubrication strategies. These advancements will help meet future demands for enhanced corrosion resistance in evolving engine technologies.

3.2 Tribological Tests

To better understand the tribological interactions between various material-oil combinations and assess their influence on bearing performance in engine applications, comprehensive tribological studies are conducted. These tests provide valuable insights into tribofilm formation, the effects of aged engine oils — especially in combination with alternative fuels — and potential tribocorrosion mechanisms. Such findings help optimize bearing performance and durability across different operating conditions.

A ring-on-disc tribometer is used for tribological testing, evaluating different bearing materials with application-specific engine oils (see Figure 7). Throughout the tests, the temperature, the coefficient of friction and the contact potential are continuously measured. Contact potential monitoring allows for real-time detection of tribologically active boundary layers, which can influence wear protection and friction behavior. [10, 11]

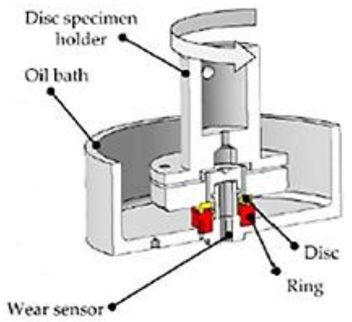

Figure 7 Setup of a ring-on-disc tribometer [11]

The ring-on-disc tribometer offers precise control over test parameters, enabling the simulation of good comparable conditions by adjusting factors such as load, speed, temperature, and the type of lubrication. This allows for an accurate assessment of material performance under conditions similar to those found on the big hydrodynamic test rigs.

During the tests, a ring made of the bearing material is mounted onto a rotating platform. A stationary disc, typically made of a reference material which is normally steel, is then pressed against the disc under a defined force. By systematically varying the load or speed, different operating scenarios are simulated, providing insights into how each material-oil combination performs under stress. The coefficient of friction is continuously tracked, as it serves as a direct indicator of lubrication efficiency and wear behavior. Lower friction coefficients generally indicate improved lubrication and smoother interactions, which are essential for reducing energy loss and enhancing bearing longevity.

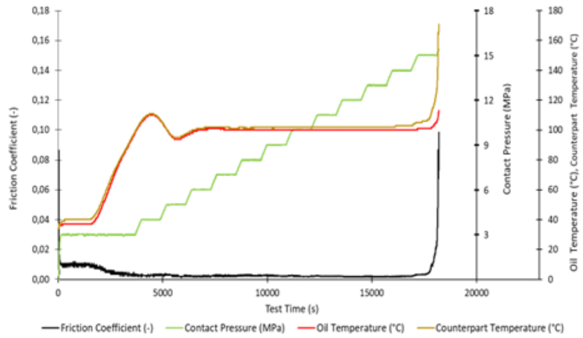

Figure 8 Tribometer experiment with Aluminum-Tin material

Contact potential measurements can further enhance the understanding of tribological behavior. As tribofilms form, they alter the electrical conductivity at the contact interface (see Figure 8). These protective films, composed of reaction products from the lubricant additives like ZDDP and the steel counterpart, play a crucial role in minimizing wear. By measuring contact potential, the formation of these tribolayers can be monitored in real-time, providing valuable data on their effectiveness and stability. (see Figure 9)

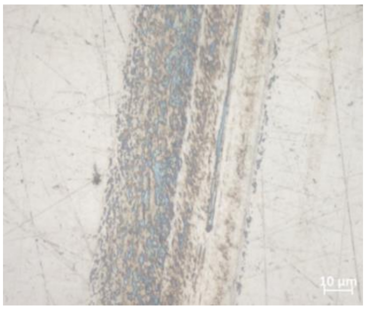

Figure 9 Optical microscopic picture of a tribofilm on the steel counter part

The tribometer also allows for the investigation of wear patterns and chemical interactions using advanced surface analysis techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDX). These methods help identify wear mechanisms, assess tribofilm composition, and better understand the frictional behavior of different material-oil combinations (see Figure 10).

Additionally, the ability to test oils in various aging states allows the study of oil degradation effects on bearing materials. This is particularly relevant for engines utilizing alternative fuels, which may introduce unique byproducts that influence lubrication performance. By replicating such conditions, potential challenges associated with specific fuel-oil combinations can be identified, leading to the development of more resilient materials and optimized lubrication strategies.

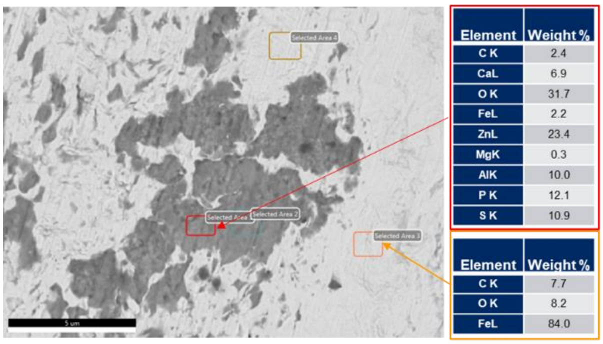

Figure 10 SEM & EDX Analysis of a tribofilm (red) compared to the reference material (orange)

Findings from these tribological investigations directly contribute to the enhancement of bearing designs and lubrication formulations, ensuring improved performance and longevity. Understanding optimal material-oil pairings allows for the development of bearings that withstand high-temperature environments and function effectively in the presence of alternative fuel byproducts.

Moreover, continuous data evaluation enables ongoing improvements in material technologies. By systematically analyzing tribological performance, new materials and surface coatings can be designed to offer superior resistance to wear and friction-related challenges, ultimately contributing to more efficient and durable engine components.

3.3 Hydrodynamic Test Rigs

Bearing test bench analyses are essential for evaluating the wear resistance and load-bearing capacity of bearings under controlled conditions (see Table 2). To obtain precise and reliable results, bearings are tested under various loads and rotational speeds, with key parameters such as applied force, sliding velocity, and lubrication properties carefully adjusted to reflect real-world operating conditions. The performance of the bearings is assessed through wear measurements, determining material loss at both the highly stressed central load zone and the bearing edges. This approach provides a detailed understanding of wear distribution and overall bearing durability.

A comprehensive evaluation of the bearing will be conducted, encompassing optical inspection, cross-sectional analysis, and Scanning Electron Microscopy coupled with Energy Dispersive X-ray Spectroscopy (SEM/EDX) analysis. These methods will aid in understanding potential failure mechanisms within the bearing and correlate them with phenomena observed in practical applications.

To ensure accurate simulation of actual engine conditions, test parameters — including load intensity, rotational speed, and oil temperature — must be fine-tuned for each specific application. This alignment allows for the realistic replication of in-field stresses and operational demands.

Bearing Performance Expectation	High Speed Engine	Medium Speed Engine
Load	< 95 Mpa	< 49 Mpa
Sliding Speed	<18 m/s Average14/s	< 15 m/s Average11m/s
Bearing Life	< 60k hours	< 60k hours
Start-Stop	< 1k times	< 1k times
Dirt resistance	Medium	High
Cavitation resistance	Medium	Medium

Table 2 Expected bearing performance in different applications [4]

Beyond standard wear testing programs, extended-duration studies can be conducted to evaluate the long-term wear characteristics of bearings. While these tests maintain identical operating conditions to conventional wear tests, they are executed over prolonged time frames to distinguish between initial wear behavior and progressive material degradation (see Table 3). This differentiation is critical for predicting bearing lifespan and assessing long-term reliability.

Test Criterion Engine Type and test condition, time (h)	Purpose	Interpretation
Load / Wear Medium speed 75 MPa, 12 m/sec, 15 h	Wear robustness	Wall thickness cracking
Wear / Fatigue Medium Speed 75 MPa, 12 m/sec , 70h	Long term wear rate	Wall thickness crack propagation
Load / Wear High Speed 75 MPa, 20 m/sec, 15h	Wear robustness	Wall thickness cracking
Seizure Test Step Load, 12m/sec	Tribological robustness	Failure load
Misalignment Medium & High Speed 75 MPa, 12 m/sec, 15 h	Conform-ability	Load distribution Seizure inclination
Continuous dirt Medium & High Speed 75 MPa / 16 m/sec	Dirt sensitivity	Number of shocks
Corrosion Medium & High speed Oil cooking test	Sensitivity Environment oil additives	Layer formation Thickness of reaction layer
Cavitation Medium and High Speed Hardness / Ultrasonic	Material robustness cavitation	Hardness Weight loss

Table 3 Bearing test programs

A critical aspect of bearing evaluation involves analyzing material behavior under mixed-friction and boundary lubrication conditions. Start-stop tests replicate engine startup cycles by introducing speed fluctuations under constant load, subjecting bearings to dynamic friction transitions and measuring their ability to withstand repeated variations in lubrication conditions.

In addition, static and dynamic load assessments play a key role in determining the operational limits of bearings. These tests subject bearings to systematically increasing loads until failure occurs, identifying the load capacity threshold and providing insights into seizure resistance under extreme conditions.

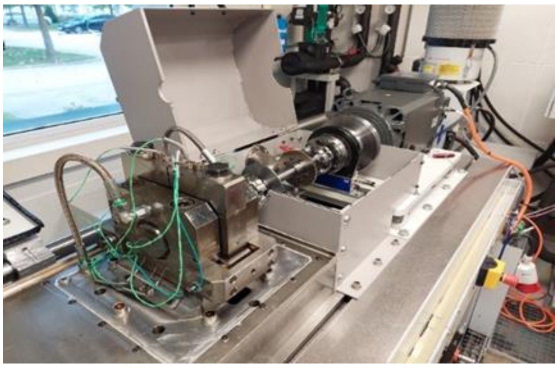

Figure 11 Bearing test bench

To further assess bearing material resilience, dirt resistance tests are conducted to examine the impact of abrasive contaminants. Bearings are operated under predefined load and sliding speed conditions while hard particles, such as silicate debris, are introduced into the oil circulation system. These tests simulate real-world contamination scenarios where bearings must function effectively despite exposure to foreign particles and wear debris.

Misalignment and adaptability studies evaluate bearing performance under localized overload conditions, particularly susceptibility to edge-loading effects. Such conditions can arise due to installation misalignment or crankcase deformations, leading to uneven stress distribution. During these tests, bearings operate under controlled load and rotational speed, while the drive shaft is intentionally misaligned to induce edge loading. The results help assess how well the bearings accommodate deviations and maintain functionality under these challenging conditions.

In addition to standard wear testing, it is crucial to assess bearing performance using lubricants aged with alternative fuels and their combustion by-products. This evaluation involves the lubricating oils from already existing field or laboratory applications like single cylinder engine test benches (SCE) as well as oil from artificial ageing processes that simulate the oxidative and thermal stresses experienced during engine operation with alternative fuels. By incorporating these aged oils into bearing test benches, we can closely replicate real-world conditions and observe the effects on bearing wear and durability. By integrating these artificially aged oils into hydrodynamic test rigs, we can evaluate bearing performance under conditions that closely mimic those encountered with alternative fuels. This approach provides valuable insights into the long-term wear characteristics and failure mechanisms of bearings operating with aged lubricants, thereby informing the development of more resilient bearing materials and lubrication strategies for future engine applications.

An example of the testing procedure is the investigation of the behavior of an ammonia-aged oil in combination with AlSn-alloy bi-metal bearings. In this test, the bearings were operated on the test rig using both fresh gas engine oil and the same oil after being aged for approximately 300 running hours in a single-cylinder engine with ammonia combustion (containing approximately 500 ppm free ammonia and 750 ppm water in the oil). The bearings tested with fresh oil exhibited only minor running-in wear during the standard load and wear program. In contrast, the bearings tested with the ammonia-aged oil, under identical testing conditions, showed significantly increased wear and distinct surface markings, indicating an impact of the aged lubricant on bearing performance. (see Figure 12). The significant deterioration in bearing performance observed with ammonia-aged oil necessitates further investigation.

Figure 12 Comparison of a Miba 15 (AlSn-Alloy) test rig bearing running on a fresh gas engine oil and an ammonia aged oil

The bearing test benches are essential for evaluating material performance across various engine operating scenarios. The insights gained from these evaluations significantly contribute to the development of efficient, high-performance, and durable bearing technologies, thereby supporting advancements in modern engine systems.

The test bench will elevate technical capabilities to the next feasible level, representing a new generation of testing equipment compared to existing setups. Tests conducted within the current framework of component scaling aim to facilitate the realization of bearings that meet the demands of future carbon-neutral large engines.

3.4 Cavitation test rig

To enhance Miba's testing capabilities, new test rigs are being developed to simulate and address future demands on bearings used in engines powered by alternative fuels. One area of focus is the impact of water or methanol contamination in the crankcase, introduced via the blow-by gas stream, and the potential accumulation of these substances in the engine oil. Given that water and methanol have low boiling points and high vapor pressures, they are prone to causing cavitation within the engine environment. Cavitation refers to the formation and collapse of vapor-filled cavities in a liquid, which can lead to significant damage to bearing surfaces and potentially result in complete bearing system failure.

To investigate this phenomenon, a new cavitation test rig will be developed. This test method is based on the ASTM G32 standard for cavitation erosion using an ultra sonic apparatus (see Figure 13). It employs an ultrasonic horn and a test specimen of the bearing material immersed in a container of the test liquid, maintained at a controlled temperature. This setup allows for the assessment of how changes in oil composition, due to contaminants like water and methanol, affect bearing performance under cavitation conditions. [12]

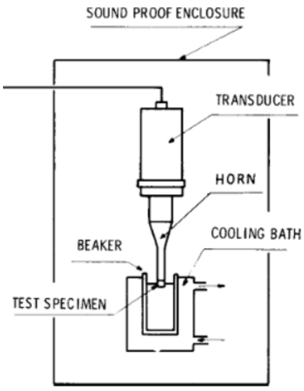

Figure 13 Schematic of vibratory cavitation erosion apparatus according to ASTM G32 [12]

By simulating these conditions, the test rig provides valuable insights into the cavitation behavior of bearings in engines utilizing alternative fuels. This information is crucial for developing bearing materials and designs that can withstand the challenges posed by such contaminants, ensuring the reliability and longevity of bearing systems in future engine applications.

To adapt this test to bearing-relevant conditions, several modifications have been introduced. The test specimen is paired with a highly cavitation-resistant counterpart, separated by a defined gap. Instead of the commonly used water as the testing fluid, different field and artificially aged engine oils with elevated amounts of methanol or water are utilized. The test operates at higher temperatures, ranging between 60°C and 140°C, with adjustable oscillation frequency and energy levels.

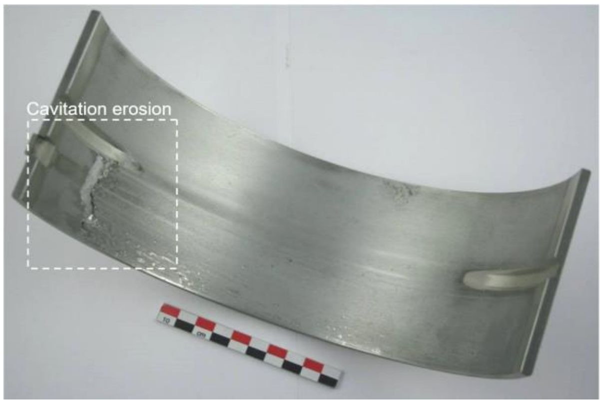

Figure 14 Bearing with severe cavitation erosion

The emergence of new fuels and applications necessitates the development of advanced tribological systems. To lead in understanding these systems and provide optimal bearing solutions, it is essential to utilize our testing capabilities to gain a comprehensive understanding of bearing mechanisms. The current testing approach for new bearings allows for detailed investigations into issues arising from the introduction of alternative fuels in combustion engines. This knowledge not only helps reduce the risk of severe engine problems but also enables customers to evaluate bearings in new engine applications more quickly, thereby shortening the time to market for innovative engine technologies.

4 INTEGRATING LABORATORY AND FIELD RESULTS

In performance testing, it is crucial not only to generate data within a test facility but also to integrate these results from various tests into practical applications. This integration aims to provide customers with valuable insights into system performance. To ensure that the knowledge gained aligns with engine experiences, to harmonize laboratory findings with field engine results. To achieve this, a collaborative FFG funded project involving Miba, Innio Jenbacher, and AC²T was initiated to explore the correlations between tribological laboratory tests and actual engine applications (FFG application number 909590). The project encompasses defining critical system parameters, conducting model tests and laboratory analyses, developing a simulation model, and aligning this model with real-world applications through field data generation and validation.

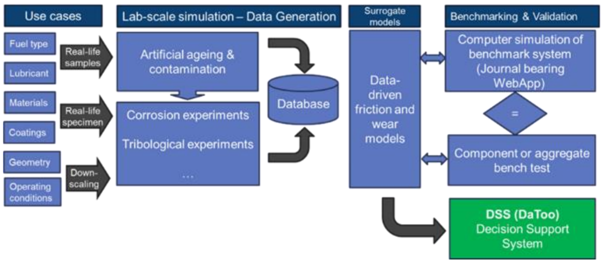

Figure 15 Schematic overview of the DaToo project to create a decision support system

The project's objective is to establish comprehensive requirements and system specifications for bearing materials operating in environments where oil is mixed with alternative fuels. This involves detailing construction aspects, identifying the types of loads the materials must withstand, and determining the environmental conditions they will encounter. Additionally, criteria for the end of these materials' service life will be defined. The project will also assess how these materials and associated processes impact human health and the environment. The focus will be on a selected range of bronze materials, various fuels, and lubricants. A key methodology will involve downscaling real-world system loads into manageable laboratory test conditions, informed by existing literature and preliminary studies to define the concentration range of alternative fuels in lubricants.

Developing and implementing model tests will require creating specific procedures and analysis methods to identify expected interactions between the fuel, lubricant, and material system. Laboratory methods must be developed to accurately replicate these interactions and characterize their effects. Initial testing phases will include laboratory aging and other tests based on a thorough review of existing literature and previous project findings. Establishing suitable analytical methods will be crucial for characterizing any changes in the states of both lubricants and materials. This stage will also address the current lack of expert knowledge regarding how ammonia and hydrogen interact with lubricants and produce new combustion products. Screening tests will be pivotal in determining the range of changes in lubricant quality, providing an opportunity to adapt and refine methods as necessary.

Mathematical models will be created using data obtained from these preliminary tasks. These models will precisely represent the relationships between process data and important target variables such as friction, wear, and corrosion rates. They will serve as predictive tools, forecasting damage rates and changes in the lubricants over time. These predictions will then be used to parameterize a bearing model. One of the critical goals of this modeling effort is to determine whether specific lubricants, when exposed to ammonia or hydrogen, will experience a significant reduction in lifespan or lead to operational infeasibility due to potential environmental damage or inefficiencies.

Generating the data to support these models will utilize standard methodologies and well-accepted techniques for inducing artificial aging and conducting tribological model tests. The quality of the data generated is crucial, as it will form the backbone of the hybrid models being developed. This data generation process will also necessitate prioritizing different interaction processes and may require compromises on certain details. Methodological adaptations will be possible, thanks to feedback loops established between the data generation phase and the model testing phase.

Validation of the Decision Support System (DSS) created through this work will be conducted in two stages. Initially, the system will be validated using tribometers under new experimental parameters. Necessary adjustments will be made before proceeding to the second validation stage, which involves bearing tests. These bearing tests will selectively verify predictions for various lubricant-fuel mixtures. Meticulous planning will ensure that the validation process covers a broad spectrum. Additionally, field tests will be conducted using samples from large-scale engine tests. These field tests aim to analyze how combustion products affect both the lubricants and the materials used. Applying the DSS to these test systems will further verify the system's predictive accuracy and reliability.

This collaborative project endeavors to bridge the gap between laboratory research and real-world engine applications by developing predictive models and validation methods for bearing materials in alternative fuel environments. The outcomes aim to enhance system performance understanding and provide valuable insights for practical applications.

5 MATERIAL DEVELOPMENT

The transition to alternative fuels in internal combustion engines introduces complex chemical and mechanical changes that necessitate significant advancements in material and coating technologies. These challenges are multifaceted and not entirely predictable, encompassing issues such as increased corrosion of specific elements like copper, water ingress into the oil leading to heightened cavitation tendencies, and reduced load-bearing capacity of oils due to aging mechanisms distinct from those associated with fossil fuels. Consequently, certain materials and coatings must be adjusted or newly developed to ensure optimal performance in engines operating with alternative fuels.

Currently, several new bearing material developments are underway that, while not specifically designed for alternative fuel applications, may meet requirements that enhance bearing performance in such engines. For instance, Miba has developed an advanced bearing base material to comply with existing mandates for lead-free bronze materials, anticipating potential restrictions on lead usage under the European REACH regulation [13]. This bronze material, known as Miba 2C (see Figure 16), utilizes a different solid lubricant embedded within the bronze matrix to replace metallic lead compounds. This innovation not only exhibits excellent tribological behavior comparable to standard high-leaded bronze materials but also addresses existing challenges of lead corrosion in engines. Elevated total acid numbers (TAN) in engine oil, resulting from excessive lubricant oxidation and the formation of carbonic acids — which can react with lead in the material — pose significant risks. Such conditions may arise from the use of various fuels, including aggressive gas sources like untreated bio or landfill gas.

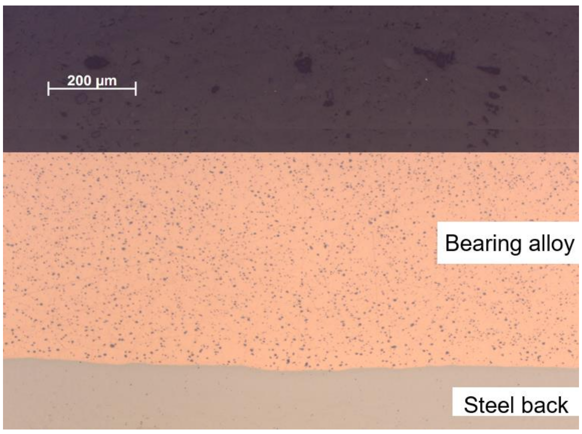

Figure 16 Cross section of Miba 2C (InnoAlloy lead free bronze material)

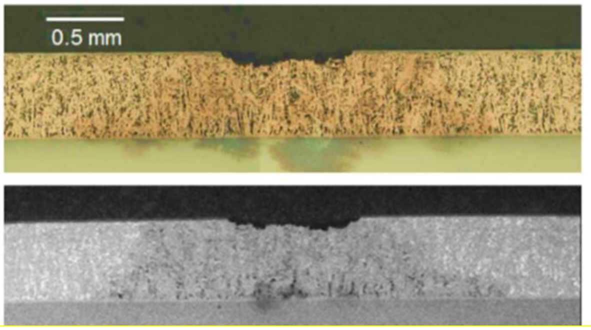

Figure 17 Cross section of lead leaching on a bearing in a gas engine application

Another approach to protect bearing materials involves the application of a coating layer. Initial laboratory tests have demonstrated that bronze bearings with an electroplated overlay are significantly less affected by copper corrosion in static oil cooking tests (see Figure 19). The TIAN overlay, an electroplated tin-antimony-based layer with a nominal thickness of 20 to 30 micrometers, exhibits favorable tribological properties and serves as a corrosion-resistant barrier for the underlying bronze material (see Figure 18).

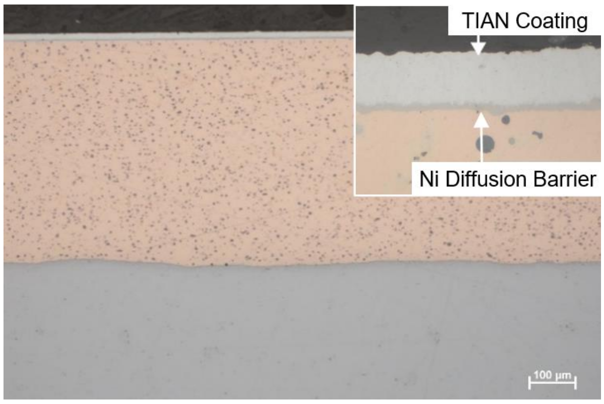

Figure 18 Cross section of a Miba 4B bearing (lead free bronze material with SnSbCu overlay)

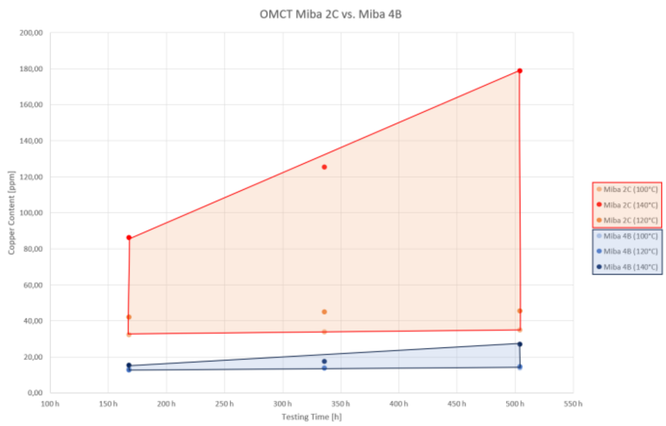

Figure 19 Comparison of Miba 2C (lead free bronze) and Miba 4B (lead free bronze + TIAN overlay) in the static corrosion test with ammonia aged oil.

Overall, the further development of bearing materials will require detailed research to meet the demands of future engine applications. The creation of new bearing types may become essential. By integrating field experience with new insights from laboratory tests, emerging requirements can be assessed and addressed with relatively short industrialization timelines.

6 CONCLUSION AND OUTLOOK

The forthcoming advancements in performance enhancement, fuel efficiency, and environmental regulations, including the adoption of alternative fuels, will significantly influence engine components, necessitating ongoing development of bearing materials and designs. Traditional diesel fuel is set to be supplanted by emerging technologies, presenting new challenges for internal combustion engine manufacturers. The increasing diversification of fuel types in various applications underscores the importance of flexibility in developing new technologies. In this context, Miba must continually expand its internal testing capabilities and devise innovative testing methods to address the challenges of the coming years (see Figure 20).

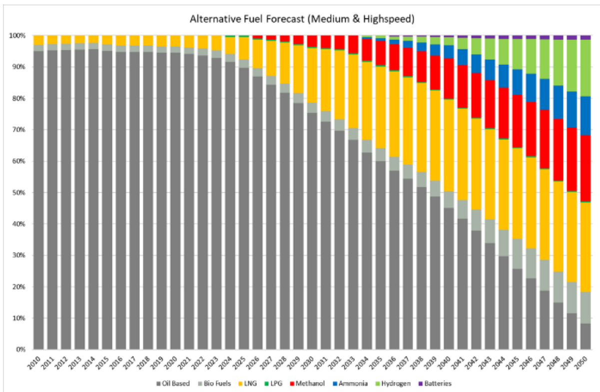

Figure 20 Forecast use of alternative fuels in medium and highspeed engine applications [14, 15]

To meet future demands for alternative-fueled internal combustion engines, new testing approaches are essential. Focus must extend beyond technical aspects like combustion concepts and peak cylinder pressures to encompass emerging challenges in future applications.

In addition to mechanical challenges, attention must be given to potential chemical interactions in future scenarios. Fuels such as ammonia and methanol have a high potential to interact with various engine parts, leading to corrosion. Combustion by-products can also introduce challenges; for instance, high water content in exhaust gases, combined with an increased frequency of start-stop cycles, can lead to condensation and, consequently, severe cavitation. The production of NO_X gases or carbonic acids can increase engine oil acidity, causing lead leaching in components. In addition to modifications in the combustion system, it is also essential to consider the impact of emerging engine oil formulations. The transition to Group V base oils, along with adjustments in additive packages, may introduce new interactions with bearing materials, potentially affecting their performance. All these factors must be considered in future engine designs.

To support our customers in these new developments, a comprehensive testing concept encompassing multiple layers — laboratory tests, tribometer assessments, and bearing test benches — enables the evaluation of future bearing material requirements and their optimization. By expanding expertise in bearing material studies, such as artificial oil aging concepts and lab-scale cavitation testing, Miba is well-prepared to address upcoming challenges in engine development.

With this data and growing in-house competence, the transformation phase can be approached using entirely new methods to qualify new materials. Implementing advanced standardized testing models, combined with field validations and the development of data-based systems, will facilitate early detection of emerging challenges.

Continuous development of new bearing designs and materials will be essential to meet the requirements of new engine developments. The trend toward highly corrosive environments for critical engine parts necessitates revolutionary new materials capable of withstanding harsh conditions. This corrosive environment — such as that resulting from ammonia and its by-products — may lead to the need for new copper-free materials with better performance than the well-known aluminum-tin alloys. Given that such development requires time, a proactive approach to investigating new engine conditions will be important in the future.

Laboratory data from test rigs or artificial oil aging can aid in understanding the mechanics of alternative-fueled engines, but this data has limited significance if not validated in real-life engines. Therefore, intensive cooperation between engine manufacturers and engine part suppliers is of utmost importance to handle future challenges in this area. Because the current field population of alternative-fueled engines is still extremely small, information based on real field data is limited. Miba is constantly seeking cooperation partners from engine manufacturers and engine oil suppliers to gain this important data and continue providing a benchmark in bearing technology.

7 DEFINITIONS, ACRONYMS, ABBREVIATIONS

Al: Aluminium (Element)

C: Carbon (Element)

Ca: Calcium (Element)

CH_3OH: Methanol

CO_2: Carbon dioxide

Cu: Copper (Element)

DSS: Zinc Decision Support System

EDX: Energy-Dispersive X-ray Spectroscopy

Fe: Iron (Element)

FT-IR: Fourier-Transform Infrared Spectroscopy

GHG: Green House Gas

HFO: Heavy Fuel Oil

ICE: Internal Combustion Engine

ICP-OES: Inductively Coupled Plasma Optical Emission Spectrometry

IMO: International Maritime Organisation

MDO: Marine Diesel Oil

MeOH: Methanol

Mg: Magnesium (Element)

NH_3: Ammonia

NO_X: Nitrogen oxides

O: Oxygen (Element)

OMCT: Oil-Material-Compatibility Test

P: Phosphorous (Element)

Pb: Lead (Element)

ppm: Parts Per Million

S: Sulfur (Element)

Sb: Antimony (Element)

SCE: Single Cylinder Engine

SEM: Scanning Electron Microscopy

Sn: Tin (Element)

TAN: Total Acid Number

TBN: Total Base Number

ZDDP: Zinc Dithiophosphate

Zn: Zinc (Element)

8 REFERENCES AND BIBLIOGRAPHY

[1] 2023 IMO Strategy on Reduction of GHG Emissions from Ships, https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx

[2] Holleman A. F., Wiberg N., 2017 Lehrbuch der Anorganischen Chemie, de Gruyter, Berlin, New York

[3] Synthetic base oils, https://www.fuchs.com/es/en/products/product-program/automotive-lubricants/automotive-news/synthetic-base-oils/

[4] Zhang, Z.F. 2023. Bearing testing and validation to optimize bearing design for different engine applications, CIMAC 2023, Busan, South Korea, 025

[5] Hydrogen combustion, explained, https://www.airbus.com/en/newsroom/stories/2020-11-hydrogen-combustion-explained?utum.com

[6] ASTM D7421-23 Standard Test Method for Determining Extreme Pressure Properties of Lubricating Oils Using High-Frequency, Linear-Oscillation (SRV) Test Machine

[7] Agocs, A. & Rappo, M. & Obrecht, N. & Schneidhofer, C. & Frauscher, M. & Besser, C. (2023). The Impact of Ammonia Fuel on Marine Engine Lubrication: An Artificial Lubricant Ageing Approach, Lubricants, 11. 165. 10.3390/lubricants11040165.

[8] ASTM D130-19 Standard Test Method for Corrosiveness to Copper from Petroleum Products by Copper Strip Test

[9] VDMA 24570:1999-03 Fluid power - Rapidly biologically degradable hydraulic fluids - Method of test for copper-alloy corrosion

[10] Pondicherry, K. & Grün, F. & Summer, F. & Gódor, I. & Laine, E. & Offenbecher, M., 2013. Comprehensive study of ZDDP-tribofilms formed

under soft contact conditions, 5th World Tribology Congress, WTC 2013. 4. 3551-3553.

[11] Summer, F., 2018. Damage Equivalent Test Methodologies as Design Elements for Journal Bearing Systems, Lubricants, 5. 10.3390/lubricants5040047.

[12] ASTM G32-10 Standard Test Method for Cavitation Erosion Using Vibratory Apparatus

[13] Lead in copper and bronze alloys, https://www.beulco.com/business-areas/beulco-industry/material/reach-regulation-ban-on-lead-in-brass-alloys/

[14] DNV GL Energy Transition Outlook 2024: Main Report, A global and regional forecast to 2050, 2024

[15] ABS Pathways to sustainable shipping report: Projected marine fuel use to 2050

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