CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 096

"Soft" sputter bearing, a new solution balancing performance and robustness

Mechanics, Materials & Coatings

Ping Li, Miba Precision Components (China) Co., Ltd.

Johann Nagl , Miba Gleitlager Austria GmbH
Emil-Sandor Bakk, Miba Glitelager Austria GmbH
Zhifeng Zhang, Miba Precision Components (China) Co., Ltd.
Oliver Feng, Miba Precision Components (China) Co., Ltd.

ABSTRACT

Driven by the need to reduce CO2 emissions, large-bore engines are undergoing advancements characterized by increased firing pressures, weight reduction, and a greater number of cylinders. Additionally, their duty cycles are transitioning from base load to peak load operations. As a result, the crank train is becoming more flexible, placing bearings especially main bearings under significant stress due to excessive edge loading and a higher frequency of mixed friction events (such as start-stop cycles), which elevate operational risks and can lead to seizure issues starting from the initial running-in phase of the validation program.

Furthermore, cleanliness issues have become increasingly critical. The oil film thickness is now much thinner, and periods of mixed friction are more prolonged compared to previous years, largely due to increased engine loads. Concurrently, bearing clearances have been reduced to optimize oil film pressure distribution.

In addition, due to the development and application of new 'carbon-neutral' or 'zero-carbon' fuels (e.g., LNG, methanol, hydrogen, ammonia), bearings are now required to be more resistant to corrosion than in previous years. These alternative fuels tend to have a higher corrosion potential compared with diesel. This is due either to a lower initial alkaline reserve in the lubricating oil or the presence of more water and acidic matter in their combustion products, which accelerates oil aging.

Therefore a bearing with an adequate performance (load & TbO) characteristics in combination with excellent robustness (tolerance to misalignment, dirt, mixed friction and corrosion) capabilities is desired to overcome the mentioned application requirements.

By now standard Electroplating bearings perfectly cover the robustness part, but show deteriorating performance with increased loadings, failing to achieve adequate TbO targets. In contrast, the state-of-the-art AlSn20 Sputter bearing has proven extraordinary long-term operation performance under highest loads but requires a clean and compliance operation environment. To provide a hassle-free solution to cope with the upgrading requirement from the engine developing and R&D experts, while having less demand on the manufacturing processes, a “soft” SnCuSb sputter bearing is developed balancing robustness and long-term durability. The mentioned coating will be available in combination with both leaded and lead-free bronze lining materials, offered in various dimensions to suit different applications, regions, and environmental regulations.

In this publication, the demands and challenges from the engines across different markets and regions will be recognized, the significance of bearing surface coating will be addressed, the structure of this new SnCuSb sputter bearing will be explained, the bearing material DVP will be presented, field experiences will be shared and working range and production availability will be introduced.

1 INTRODUCTION

1.1 Environmental regulations and the impact on engines

The global average temperature has been rising since the era of industrialization. 2024 is confirmed by the Copernicus Climate Change Service (C3S) to be the warmest year on record globally, and the first calendar year that the average global temperature exceeded 1.5°C above its pre-industrial level. Human-induced climate change remains the primary driver of extreme air and sea surface temperatures [1]. Conventional internal combustion engines consuming fossil fuels (gasoline, diesel, and heavy oil fuel) significantly contribute to global warming. Efforts to reduce greenhouse gas (GHG) emissions have been intensifying over the last decade in the application field of all sorts of engines to meet market demands and environmental regulations.

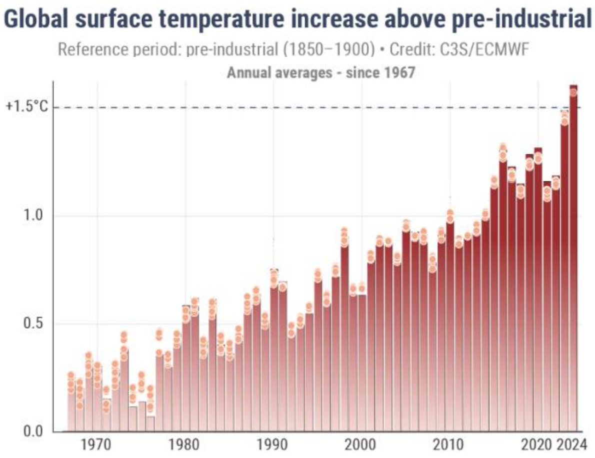

Figure 1. Global surface temperature increase above pre-industrial [1]

Although electric vehicles especially passenger cars and light vans show rapid growth during the last decade, it is expected that the conventional large bore engines (high-speed, medium-speed, and low-speed engines) will power the majority of fleets in long term due to their special application, high power, and possible emission reduction solution by means of engine retrofitting and utilizing of alternative fuels [2,3].

To cope with the requirements for reducing GHG emissions, a variety of programs are currently underway focusing on large bore engines.

In recent years and in the years to come, engines have been upgraded and will continue to be enhanced to improve fuel economy, efficiency, and emission performance through elevated firing pressure, weight reduction, and an increase in the number of cylinders. Meanwhile, cleaner energy sources such as liquefied natural gas (LNG), biofuels, and methanol are being utilized or tested in many engine applications.

In the long term, the combustion of renewable fuels, including methanol, ammonia, and hydrogen, has the potential to make internal combustion engines 'carbon-neutral' or 'zero-carbon' power sources. The development and application of related technologies will usher in a brand-new future for the internal combustion engine industry.

Taking the shipping industry as an example, as the International Maritime Organization (IMO) tightens its policies on carbon dioxide (CO2) emissions reduction, the sector is accelerating its transition away from fossil fuels as shown in Figure 2 [4]. For ship and marine power, pure electric drive or power exchange modes are suitable for short-distance inland waterway small and medium-sized vessels, while ocean-going large ships will need to rely on carbon-neutral or 'zero-carbon' fuels. Traditional heavy fuel oils are gradually being phased out due to their high carbon emissions, making way for new clean fuels. The adoption of alternative renewable fuels necessitates a comprehensive upgrade of the power system in terms of fuel infrastructure, technological adaptation, and performance enhancement.

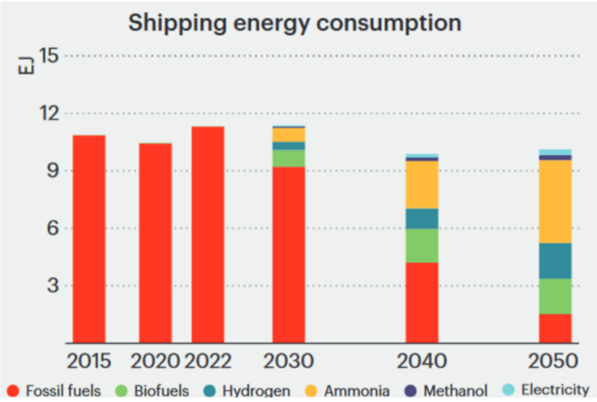

Figure 2. Shipping energy consumption, source: IEA

1.2 Demands and challenges from the engines

From a bearing manufacturer’s point of view, demands and challenges from the large bore engines especially high-speed engines for various applications, such as propulsion, gensets, mining, construction machinery, locomotives and special machinery are recognized, and corresponding R&D activities are taken.

Firstly, high-speed engines have been upgraded to improve fuel economy, efficiency, and emission performance through increased firing pressure, weight reduction, and an increase in the number of cylinders. In addition, the duty cycles of these engines are shifting from base load to peak load operation. As a result, bearings —especially main bearings — are significantly challenged by excessive edge loading (as shown in Figure 3) due to a more flexible crank train. Furthermore, an increased number of mixed friction events (start-stop operations) lead to higher operational risks, potentially resulting in seizure events (as shown in Figure 4) starting from the running-in phase of the validation program.

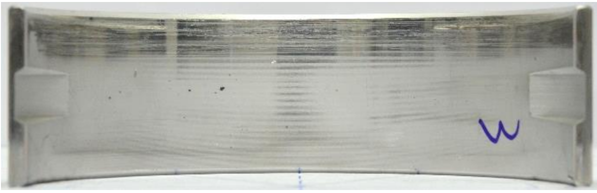

Figure 3. Unilateral edge loading of a main bearing lower shell in a high-speed diesel engine

Figure 4. Mixed friction in the bearing center of a main bearing lower shell in a high-speed diesel engine

Secondly, cleanliness issue is getting more critical (as shown in Figure 5) since from one hand the oil film thickness is much more reduced and mix friction periods are wider than years before due to the increased engine loads, from another hand the bearing clearance is getting smaller to have a better oil film pressure distribution.

Lastly, due to the development and application of new 'carbon-neutral' or 'zero-carbon' fuels (e.g., LNG, methanol, hydrogen, ammonia), bearings are now required to be more resistant to corrosion than in previous years. For example, methanol combustion easily generates formaldehyde, formic acid, and other acidic substances. These combustion byproducts can readily enter the crankcase and dissolve in the engine oil. The resulting fuel-related acids will neutralize the alkaline additives in the engine oil, rapidly depleting its alkaline reserve and potentially damaging the engine's lubrication system, especially components that are susceptible to acidic corrosion (as shown in Figure 6) [5, 6]. Regarding LNG, hydrogen, and ammonia, these fuels tend to have a higher corrosion potential compared to diesel. This is due either to a lower initial alkaline reserve in the lubricating oil or the presence of more water and acidic matter in their combustion products, which accelerates oil aging. An example of this issue is Lead (Pb) leaching from corroded bearings in large bore LNG engines, as illustrated in Figure 7.

Figure 5. Numerous particles scorings (upper) and seizure (lower) of main bearing lower shells in a high-speed diesel engine

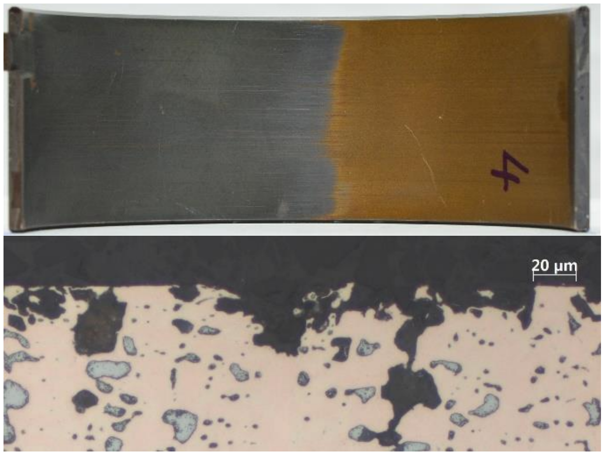

Figure 6. Delamination of the Polymer layer due to lead corrosion at the main loaded area of a conrod upper bearing from a high-speed methanol engine

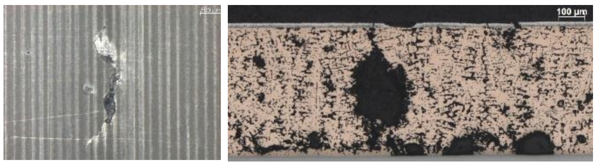

Figure 7. Weakened, cracked, and fractured bearing material due to lead corrosion in a high-speed gas engine

Therefore, a bearing that exhibits adequate performance characteristics — such as load capacity, wear resistance, and time between overhauls (TbO) —in combination with excellent robustness, including resistance to misalignment, dirt, seizure, and corrosion, is desired to meet the aforementioned application requirements.

Standard electroplated bearings currently excel in robustness but tend to exhibit inadequate performance under increased loads, failing to meet adequate fatigue life and TbO targets. In contrast, state-of-the-art AlSn20 sputter bearings have demonstrated extraordinary long-term operational performance under high loads. However, they require a clean and compliant operating environment to compensate for their sensitivity to dirt and misalignment.

To provide a hassle-free solution for engine development and R&D experts seeking an upgrade while reducing demands on manufacturing processes, a “soft” SnCuSb sputter coating balancing robustness and longevity has been developed. The mentioned coating will be available in combination with both leaded and lead-free bronze lining materials, in various dimensions suitable for different applications, regions, and environmental regulations.

In the main section of this publication, the significance of bearing surface coating will be addressed, the structure of the newly devoloped SnCuSb sputter bearing will be explained, the Design Verification Process (DVP) of this bearing type will be presented, field experiences will be shared, and working range and production availability will be introduced.

2 THE SIGNIFICANCE OF BEARING SURFACE COATING

2.1 Performance characteristics of an ideal plain bearing material

An ideal plain bearing material should possess the following performance characteristics [7]:

1. High load-bearing Capacity: The material should withstand high loads, maintaining mechanical strength and stable performance, particularly under high-alternative stress conditions to prevent premature failure and fatigue rupture.

2. High wear resistance: The material should have sufficient wear resistance to reduce wear during operation and extend the bearing's service life.

3. Good anti-seizure properties or friction compatibility: Friction compatibility refers to the ability of the bearing material to prevent cold welding and seizure with the journal material during relative motion. If fluid hydrodynamic lubrication is maintained between the bearing and the shaft journal, then even materials like steel would be very satisfactory bearing materials. However, during conditions such as startup, shutdown, heavy loads, shaft misalignment, and shaft deformation, the oil film is very difficult to be established, leading to mixed friction or even dry friction lubrication states. Under these circumstances, anti-seizure properties become very important. When direct contact occurs between the two moving surfaces, due to heat generation and rapid temperature rise, it can cause adhesion wear in mild cases and bearing seizure in severe cases. Material with good anti-seizure properties ensures safer running of the engines by mitigating risks of sudden operational failures due to sticking, smearing, or similar issues. In general, materials that are different and have a significant difference in hardness have better tribological compatibility.

4. Good conformability: Conformability refers to the ability of plain bearing materials to adapt to the flexure or misalignment of the shaft through elastic or plastic deformation. This adaptability ensures the bearing can continue to operate normally despite dimensional deviations, misalignment, as well as shaft and bearing deformation during engine operation. For various reasons, if the shaft and bearing are not parallel or if the shaft diameter is out of round, and the bearing's conformability is poor, the shaft and bearing will only contact at points. This results in significant edge loading, causing the bearing material to deteriorate quickly. Generally, the softer the bearing material and the lower its modulus of elasticity, the better its conformability.

5. Good embeddability: Embeddability refers to the ability of the bearing shell material to allow foreign particles to become embedded in its surface, thereby preventing or reducing damage to the shaft and bearing surface during operation. Even with careful maintenance, it is challenging to keep an internal combustion engine perfectly clean, and sometimes the engine must operate in dusty environments such as construction sites or mining areas. Therefore, it is difficult to prevent contaminant particles from entering the gap between the shaft and the bearing shell. This can significantly affect the lifespan of the shaft and bearing shell. Generally, the softer the bearing shell material, the better its embeddability.

6. Good corrosion resistance: Lubricating oil can easily oxidize at high temperatures, producing corrosive substances including organic acids

and oxides. Additionally, combustion gases and chemically treated cooling water may leak into the crankcase and further contaminate the lubricating oil. Some additives in the lubricating oil, especially those containing sulfur and phosphorus, may become harmful under high-temperature conditions, forming strong acids and oxides. These substances are likely to cause severe corrosion to the bearing and shaft surfaces, leading to pitting. This not only affects the formation of a continuous oil film but also allows small, corroded particles to act as abrasive particles, accelerating wear. Furthermore, these micro-pits can serve as points of fatigue initiation, leading to accelerated fatigue failure of the bearing. Generally, tin (Sn), aluminum (Al), and silicon (Si) have good corrosion resistance, while copper (Cu) and lead (Pb) exhibit poorer corrosion resistance.

Obviously, among all the aforementioned requirements, some are contradictory to each other. For example, materials with high hardness have high fatigue strength and load-bearing capacity, but they usually exhibit poorer surface characteristics such as anti-seizure properties, conformability, and embeddability. Therefore, in practice, there is no bearing material that can encompass all the desired properties. To reconcile these contradictions within the same bearing shell, multi-layer bearing structures have been developed. A thin surface coating provides the required surface properties, the intermediate alloy layer offers high fatigue strength and load-bearing capacity while maintaining good surface performance, and the high-strength steel backing layer provides the necessary stiffness and strength.

The task of material selection lies in making the most reasonable compromise based on the specific conditions and primary contradictions of the internal combustion engine, in order to meet practical needs [7, 8].

2.2 The significance of bearing surface coating and general technologies

Copper-based lining alloy with high load-bearing capacity is widely used as loaded shells—lower main bearing and upper rod bearing—in the large engines. Due to higher hardness and susceptibility to corrosion of the copper alloy, surface coating is essential to improve the bearings' multiple vital properties such as anti-seizure ability, conformability, embeddability, corrosion resistance, and wear resistance. Thanks to surface coatings, the robustness and longevity of bearing shells can be ensured.

The surface coatings are applied by a variety of technologies such as electroplating, polymer spraying and sputtering. The constitution of the bearings and specific benefits of these overlays will be discussed in the following sections.

2.3 Bearing types with electroplated overlay

Miba03 is a traditional tri-metal bearing type with Pb-based E-plated overlay and cast CuPb22Sn2 material providing corrosion resistance as well as dirt and particle tolerance with average load-carrying capability and wear resistance in its designated applications such as medium speed engines and locomotives. The cross section is show in Figure 8.

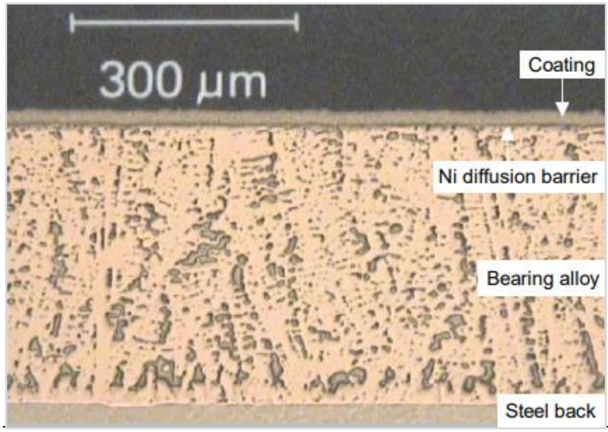

Figure 8. cross section of Miba03 material

To enhance the overall performance of the E-plated overlay in order to better adapt to the new demands arising from the medium-speed engines, a new type of E-plated Sn-based coating was developed years ago and has shown positive performance in various engine tests at customers' test benches and on fields [9].

Cross sections of bearing types utilizing this new E-plated overlay are depicted in Figure 9 (Miba4C) and Figure 10 (Miba4B). As shown a standard buildup of Miba4C comprises of steel back, leaded bronze lining, nickel intermediate layer and Sn-based overlay. The layer design of Miba4B is similar to Miba4C but with a lead-free high strength bronze lining material.

To achieve optimal tribological properties and minimize the risk of seizure when wearing through the overlay into the high-strength copper-based lining materials, Miba selected sulfides as a tribology improver. The presence of sulfides dramatically reduces the welding tendency to steel (crankshaft). This material offers tribological properties almost equivalent to those of high-leaded bronze materials in seizure load programs as depicted in Figure 11. Specific testing conditions will be described in section 5.

With both the lining alloy and overlay free of Lead, Miba4B offers an environmentally friendly solution to meet the increasingly stringent regulations.

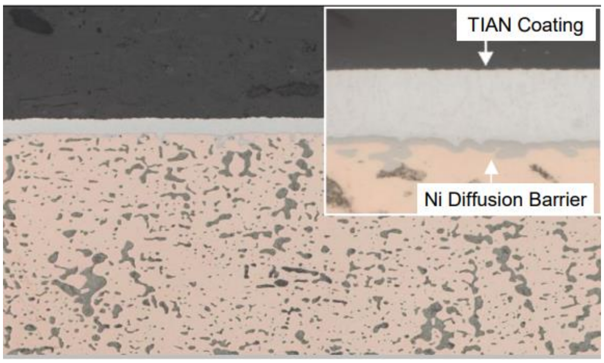

Figure 9. cross section of Miba4C material

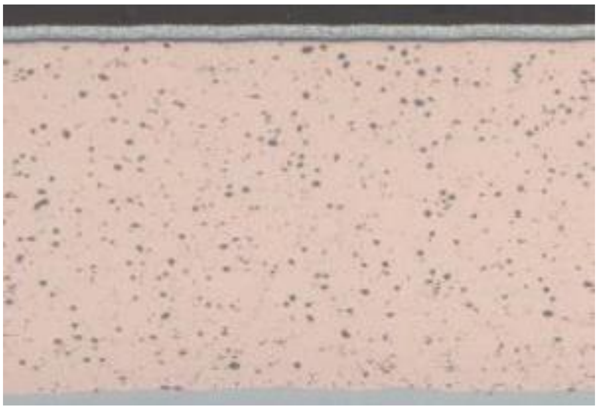

Figure 10. cross section of Miba4B material

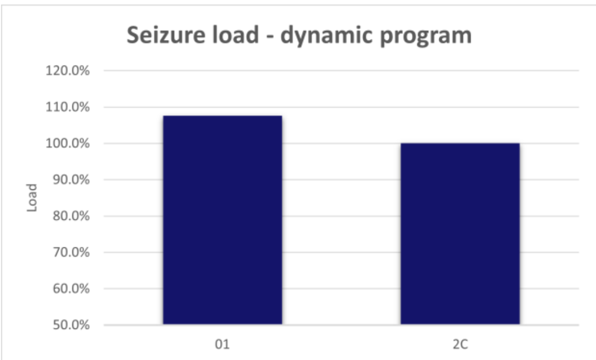

Figure 11. Dynamic seizure load of leaded bronze (PbBz) lining material (Miba01) and Pb-free lining material (Miba2C)

2.4 Bearing types with Sputtered (+Polymer) overlay

The aluminum based AlSn20 sputtered overlay has a long and successful history in truck and high-power high-speed engines as loaded shell in both conrod and main bearings configurations. It provides excellent wear resistance, load ability, and cavitation resistance under high loads owing to its high hardness and fine grain size.

Standard Miba bearing type with aluminum-based sputtered overlay is Miba37, Miba 61 and Miba6G. Figure 12-14 show the respective cross sections.

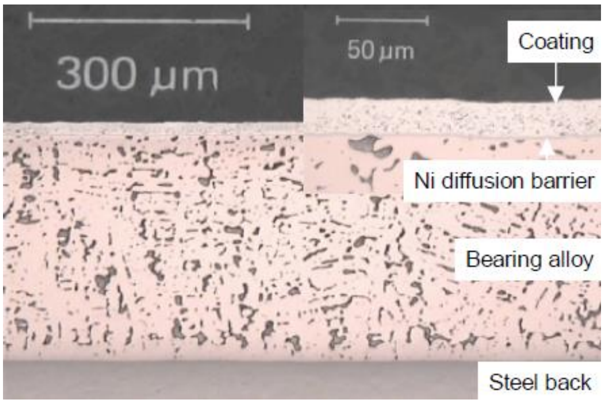

Figure 12. Cross section of Miba37 material

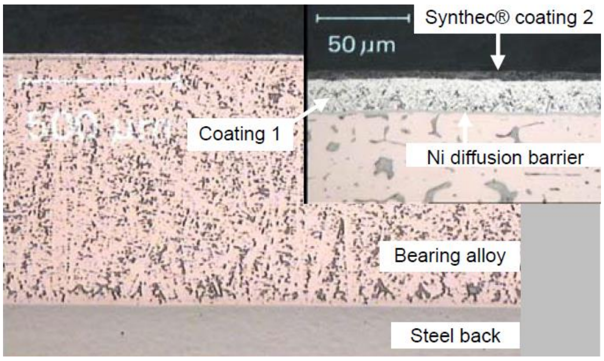

Figure 13. Cross section of Miba61 material

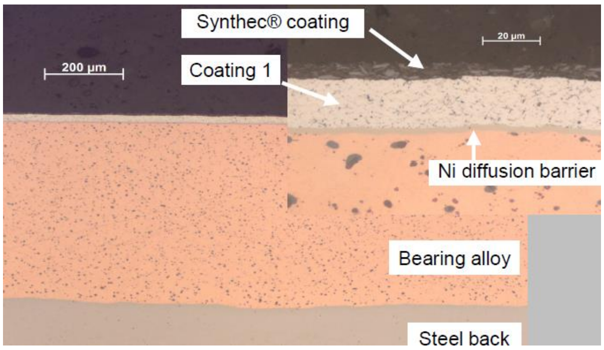

Figure 14. Cross section of Miba6G material

On bearing types Miba61 and Miba6G, 6µm polymer layer is added on the sputter layer to improve the running in characteristic and adaptability for frequent start-stop application where boundary lubrication or mixed lubrication is supposed to occur. This two-layer design is widely applied in truck and high-speed high-load engines worldwide. The difference of Miba61 and Miba6G bearing lies on the lining alloy. Miba6G has a lead-free lining while Miba61 with a leaded bronze lining.

2.5 Bearing performance with different overlay

Figure 15 and Figure 16 depict how bearing types perform differently from each other in terms of different overlay built on the same PbBz lining alloy (Miba01).

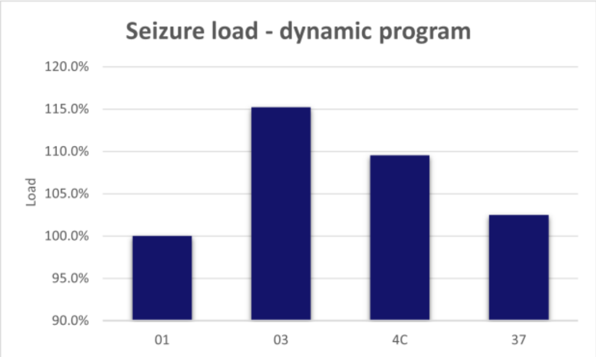

Figure 15. Dynamic seizure load of PbBz bearings with different overlays

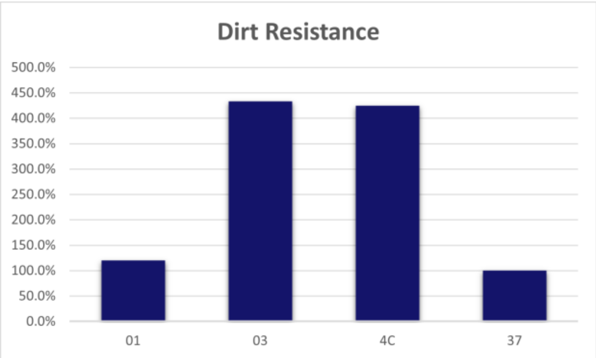

Figure 16. Dirt resistance of PbBz bearings with different overlay

It is shown in the bar charts that the dynamic seizure load has increased by a maximum of 15% and the dirt resistance has been boosted to 433% when E-plated overlay (Miba03 and Miba4C) is added on the PbBz lining alloy. The apply of sputter layer does not add much value to the tribological properties but provide good corrosion resistance due to its Al-based material and high load ability owing to its high hardness and fine grains.

Based on the integration of Numerical Hydro-Dynamic (NHD) calculation, laboratory testing, test rig results, and field experience, the following spider web showing performance characteristics of the existing bearing families can be derived. The scale of 1 to 5 in Figure 17 represents performance characteristics of the specific bearing type. 5 indicates the highest, 1 indicates the lowest performance.

The meanings of the five dimensions of bearing's performance characteristics are:

- "Load/wear" means load ability and long-term operational performances of the bearing.
- "Start/stop" refers to the bearing's performances during the mix friction condition or dry friction condition such as fast start without pre-lube.
- "Emergency" relates to bearing's adaptability to misalignment, deformation, dirt particles, and seizure.
- "Corrosion" reflects bearing's resistance to aggressive lubrication or environments such as acidic oils, high sulfur-containing fuels, etc.
- "Cavitation" means the ability of bearing shell to resist cavitation, which is primarily determined by material hardness. Prolonged exposure to cavitation can lead to continuous erosion of local bearing material, significantly impacting long-term performance and durability.

As shown in Figure 17, bearings with different coatings exhibit significant differences in performance. E-plated tri-metal bearings present excellent robustness but have insufficient load-carrying ability and cavitation resistance. Bearings with hard sputtered layers exhibit extraordinary load-carrying capacity, wear resistance, and cavitation resistance. However, its weakness lies in the adaptability to misalignment, deformation, dirt particles, and seizure. Adding a polymer layer on top of the sputtered overlay improves the bearing's ability to cope with frequent start/stop conditions.

As discussed in section 2, further adaptability is required for bearing to cope with dimensional deviations, misalignments, deformations, and cleanliness issue during engine operation especially prominent in large engines. Meanwhile adequate load ability and longevity are indispensable. Which means, in between the robust Sn-based EP layer and the high-performance Al-based sputtered coating, a bearing type that showing appropriate load ability and excellent robustness is in great need. This specific demand has led to the development of the "soft" sputter layer.

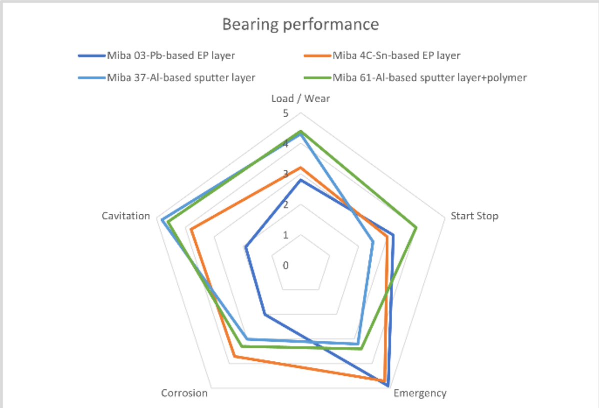

Figure 17. a) Bearing performance of different overlay built on the same PbBz lining alloy

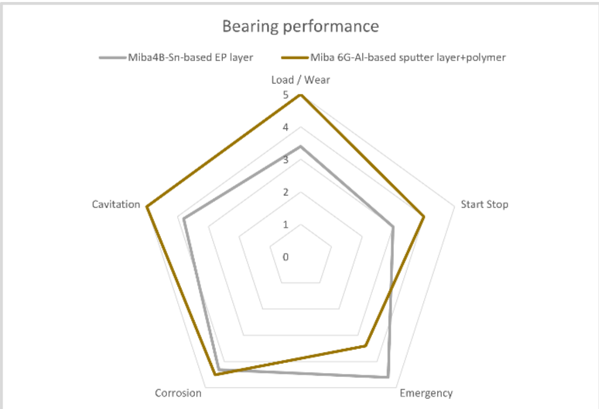

Figure 17. b) Bearing performance of different overlay built on the same Pb-free bronze lining alloy

3 MIBA "SOFT" SPUTTER BEARINGS

3.1 "Soft" sputter bearings Miba3B/3H

The "hard" Al-based sputter bearings use a stiff matrix material with good load carrying ability containing soft additional Sn phases to improve sliding properties. The newly developed "soft" Sn-based SnSbCu sputter bearings Miba3B, on the contrary, deploy a soft resilient matrix with embedded hard phases to take over the load. This new generation of Sn-based sputter bearings closes the gap between the soft electroplated overlay and the hard Al-based sputter layer in response to the ever-increasing robustness and longevity demands arising from the high-speed engines.

As shown in Figure 18, Miba3B bearing consists of steel back, lead bronze lining, 2µm intermediate nickel layer and a sputtered Sn-based surface coating on the inner surface. Miba3H, the lead-free version is shown in Figure 19. The layer design is like Miba3B but with a lead-free lining material to cope with higher load demands, provide corrosion resistance property against aged engine oil and fulfill the possible more restrict environmental obligations concerning element Pb.

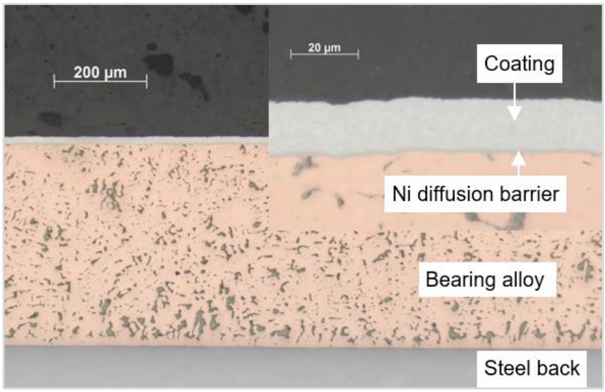

Figure 18. Cross section of Miba3B bearing

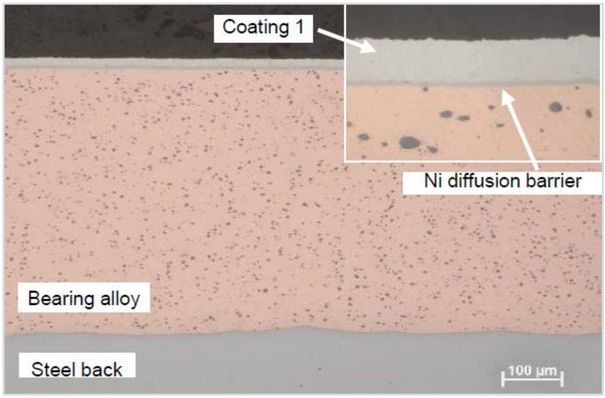

Figure 19. Cross section of Miba3H bearing

The soft Sn matrix is reinforced by means of solid solution strengthening, second phase strengthening, and grain boundary strengthening as a result of well-designed composition formula and optimized process parameters. It can be seen in Figure 20 that there are dense and uniform CuSn second phases embedded on the Sn-matrix. All of these strengthen effects enable the sputtered Sn-based overlay possesses remarkably higher hardness and loading-carrying ability in comparison to the cast or E-plated Sn-based material.

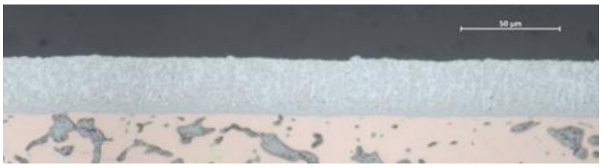

Figure 20. Detailed view of the overlay

3.2 Hardness comparison

As shown in Table1, the E-plated Pb based overlay has a Vickers hardness of 15 HV. It is relatively soft compared to other materials, which can be beneficial for applications where a softer surface is needed to cope with dimensional deviations, misalignments, deformations, and cleanliness issue during engine operation and prevent damage to mating components.

With a Vickers hardness of 30 HV, the E-plated Sn-based overlay is moderately soft. It offers a balance between wear resistance and the ability to conform to mating surfaces and dirt tolerance, making it suitable for a range of applications where moderate load and high robustness are required.

The sputtered Al-based overlay has a Vickers hardness of 86 HV, making it significantly harder than the other types listed. The higher hardness provides better resistance to wear and exhibits highest load ability, which is advantageous in applications where load-carrying ability and longevity are critical.

The Sn-based sputter layer possesses a typical Vickers hardness of 56 HV, which is a substantially increase compared to the E-plated overlays but lower than the hard sputtered Al-based overlay. It offers a good combination of wear resistance and robustness, making it suitable for various engine applications where a balance of properties is needed.

Table 1. Typical hardness of different overlays

Bearing type	Vickers hardness, HV
Miba03-E-plated Pb based overlay	15
Miba4C-E-plated Sn-based overlay	30
Miba37-Sputtered Al-based overlay	86
Miba3B-Sputtered Sn-based overlay	56

However, hardness data only reflects part of the performance characteristics of overlays. The comprehensive performance in applications requires further, in-depth evaluation through various tests within Miba and plentiful engine tests at customer sites. Test processes and field experiences will be discussed in section 4 and section 5 respectively.

4 DVP OF THE “SOFT” SPUTTER BEARINGS

4.1 Test program set-up

Based on Miba’s understanding of bearing performance expectations for high-speed engines’ applications (Table 2), a full-scale validation programs of the bearing including test rig tests and laboratory tests are designed as depicted in Table 3 [10].

The used hydro pulsating test rig is shown in Figure 21. Detailed test program descriptions are elaborated in reference 10.

Table 2. Bearing performance expectations for high-speed engines

Performance characteristics	Expectations
Load	Up to 95 MPa
Sliding Speed	Up to 18 m/s Average14/s
Bearing Life	Up to 60k hours
Start-Stop	Up to 1k times
Dirt resistance	Medium
Cavitation resistance	Medium

Table 3. Test programs set up

Bearing Performance	Load, speed, duration	Performance indicator
Load (wear, fatigue)	75MPa&100MPa, 12m/s, 15hours	Wear-break in
Load (wear, fatigue)	75MPa&100MPa, 12m/s, +55hours	Wear-long term
Start / stop	2.4MPa, speed ramps from 0 to 1.8m/s, 1800 cycles	Wear
Seizure load	Step load, 12m/s, until failure	Failure load
Conformability / misalignment sensitivity	75MPa, 12m/s, 15hours	Load distribution, seizure inclination
Embeddability / dirt resistance	75MPa, 16m/s, times of shocks until failure	Times of survived dirt shocks
Cavitation	Lab test	Mass loss
Oil-material compatibility	Lab test	Layer formation Weight loss
Aging effect	Lab test	Hardness change

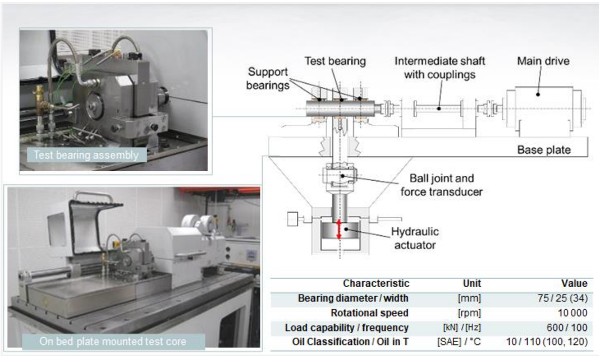

Figure 21. Operating principle of hydro pulsating test rigs

The following sub-sections will show a direct comparison of the “soft” sputter bearing with existing reference bearings typically used in high-speed engines.

4.2 Wear test

The test conditions are depicted in Figure 22. The test loads are 75MPa and 100MPa respectively. The surface speed of the bearing is 12m/s, and the test system is lubricated by SAE10 lube oil with an inlet temperature of 110°C.

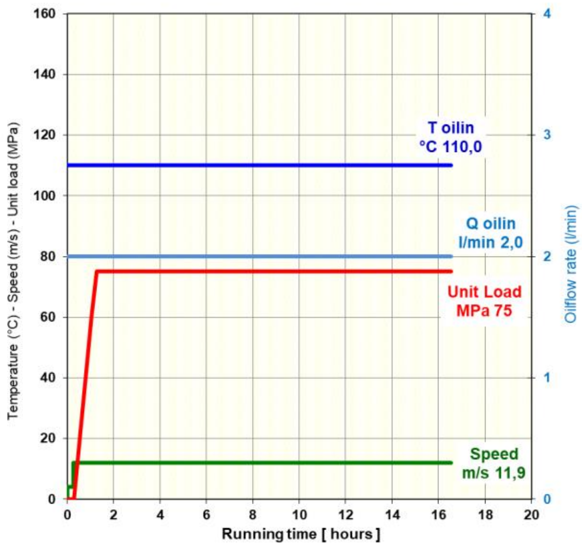

Figure 22. Typical test condition _ Wear test

The wear of the bearing coating is measured in the bearing main loaded area. The average value of the wear at bearing edge and center is taken as the final wear result.

The break-in wear test last for 15 hours, followed by thickness measurements and additional 55 hours long-term testing.

Figure 23 displays the "average wear at the main loaded area" under the conditions of 75MPa pressure and 12m/s speed. The y-axis shows the average wear, measured in micrometers (µm), and expressed as a percentage, while the x-axis categorizes the data by different sample groups.

The blue portion of each bar indicates the wear measured after break-in with a duration of15 hours, and the orange portion on top represents additional wear accumulated after an additional 55 hours.

Miba3B bearing shows obviously improved break-in and long-term wear resistance against traditional Miba03 E-plated bearing and Miba4C the Sn-based E-plated bearing. Miba37, the hard sputter bearing, is the best performer with a wear value of only 24.5% of that of the Miba03 bearing at break-in and nearly no wear during the 55hours long-term test.

There is higher wear on Miba61 bearing in the break-in phase because the polymer overlay is cured at lower temperature and is designed to be running in layer. After the Synthec layer is wear through, Miba61 has the same level wear compared to Miba37.

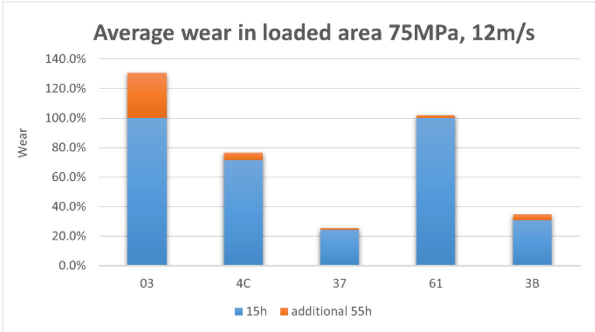

Figure 23. Test rig result _ Wear at 75MPa

Figure 24 shows the wear results at higher pressure which is 100MPa to represent the load condition in high load high speed engines.

The Miba03 bearing shows the maximum wear among all the bearings after 15 hours break-in test and 20% increase in wear after the additional 55 hours test. While the bearings with sputtered overlay exhibit much less wear compared to the Miba03 bearing. It is observed that the increase in shear force caused by elevated pressure has a significant impact on the wear amount of the soft E-plated overlay.

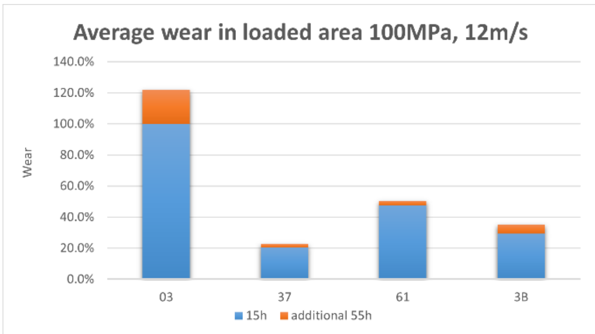

Figure 24. Test rig result _ Wear at 100MPa

4.3 Start-stop test

This program is designed to evaluate the performance and durability of a bearing under conditions that simulate frequent engine start and stop cycles, where mixed friction or even boundary lubrication predominates.

Over the course of 1800 cycles, the test sample experiences a constant load of 2.4 MPa, while the sliding speed ramps up linearly from 0 to 1.8 m/s (Figure 25). The oil in use is SAE10 with an inlet temperature of 120°C. Result interpretation is done via the average wear at bearing edge and centerline position of the main loaded area.

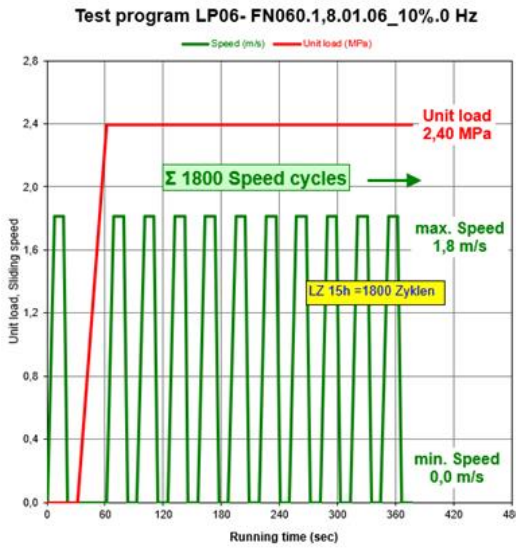

Figure 25. Test condition _ start/stop test

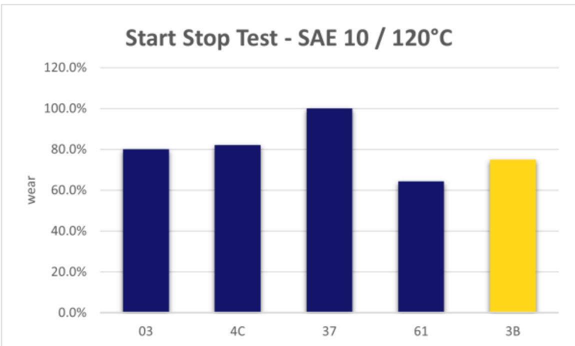

Figure 26. a) Test rig result _ Start stop

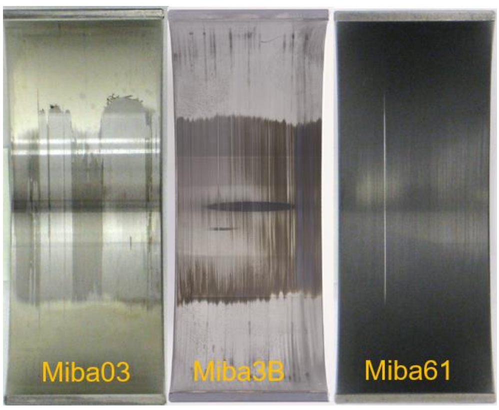

Figure 26. b) Tested bearings _ Start stop

As depicted in Figure 26, the E-plated bearings and the Sn-based sputtered bearings exhibit similar levels of wear. The Miba37 bearing shows the highest wear, most likely due to tin release caused by the high temperatures generated from mixed friction. An additional polymer layer applied as an emergency lubricant on the Miba61 enhances its performance, making it the best bearing type among those available.

4.4 Static seizure load test

In this test program, the bearing static seizure load will be identified under conditions of high temperature and limited oil supply to the main loaded area. The oil used is SAE 10, with an inlet temperature of 120°C to accelerate the test. The oil supply volume is 1.1L/min and the sliding speed is 12 m/s. After a short time running in with dynamic load, the bearing is loaded starting from 0 MPa static load until seizure occurs (Figure 27).

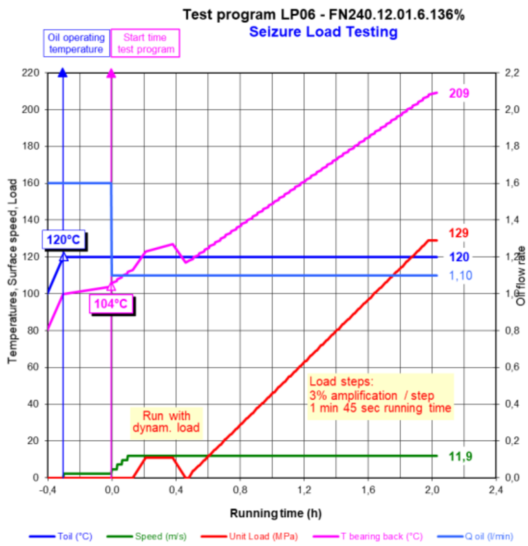

Figure 27. Test condition _ static seizure test

As shown in Figure 28, the E-plated bearing materials, Miba03 and Miba4C, demonstrate excellent seizure resistance. However, Miba 37 and Miba 61 exhibit relatively lower seizure resistance due to their hard sputtered overlays or polymer layer. Miba3B show obviously higher seizure load than Miba37 and slightly lower seizure load than the E-plated Sn-based bearing Miba4C.

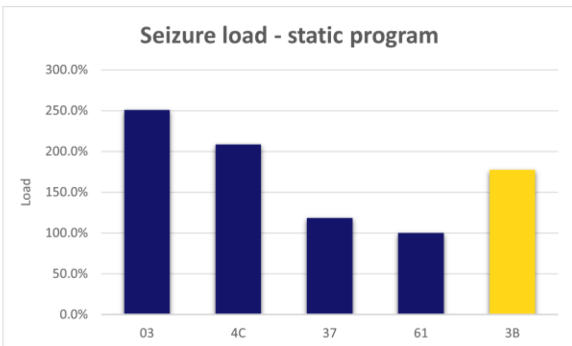

Figure 28. Test rig result _ Seizure load (static)

4.5 Dynamic seizure load test

The dynamic load program is to identify the seizure load in case of high temperature and limited oil supply to the main loaded area. The loading frequency is 50Hz. The other parameters are the same as the static seizure load test.

As depicted by Figure 29, all the bearing types show performance significantly above the application needs. It is worth mentioning that Miba3B achieved almost identical seizure load value as the E-plated bearing Miba4C.

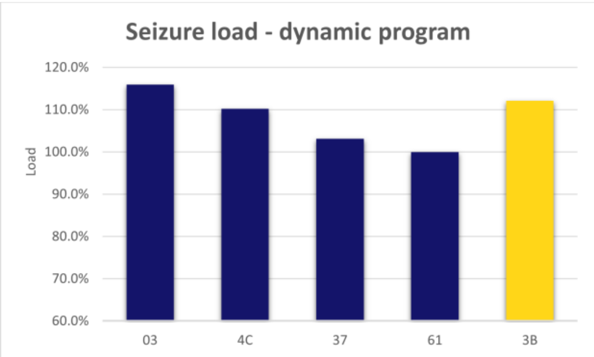

Figure 29. Test rig result _ Seizure load (dynamic)

4.6 Dirt resistant test

This test program aims to evaluate the robustness of bearing materials against impacts from hard particles. The test bearing, with a diameter of 48 mm and a width of 12 mm, is subjected to a specific unit load of 75 MPa at a speed of 16 m/sec in an environment using SAE 10 oil at 95°C. Hard mineral particles are introduced directly into the oil feed line through a revolving device.

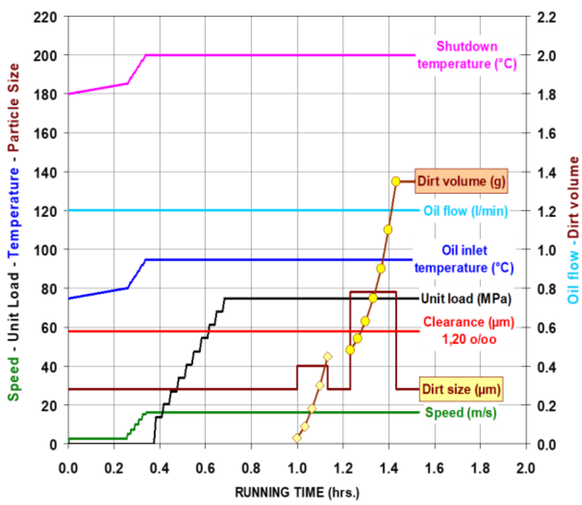

Figure 30. Test condition _ dirt shock test

As depicted in Figure 30, the test is divided into three phases:

- In the initial phase, the system undergoes start-up and maintains continuous operation for 20 minutes under consistent contamination conditions. The contaminant particles have a maximum size of 25µm, equating to 43% of the bearing clearance, which simulates engine performance in a very dirty environment.

- Following this initial phase, the test proceeds with five consecutive injections of dirt, each with progressively increasing volume. The maximum particle size is escalated to 40µm, now representing 69% of the bearing clearance, thereby intensifying the severity of the testing conditions.

- After a brief recovery period, the final series of seven injections commences. These injections feature a maximum particle size of 78µm, which is 135% of the bearing clearance, with the volume also increasing incrementally. This stage reflects even more extreme initial dirt conditions.

The bearing needs not only a good wear resistance but also an extreme tribological behavior to withstand this severe test conditions.

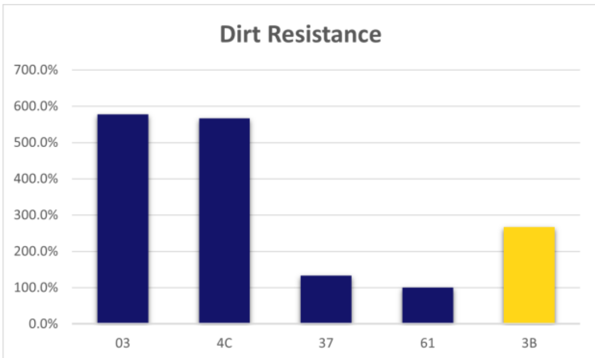

Figure 31. Test rig results _ dirt shock test

As shown in Figure 31, the E-plated bearings Miba03 and Miba4C exhibit superior performance in withstanding dirt shocks. The Miba03 material endured all 13 shocks without failure and the Miba4C performed almost as well. The hard sputtered bearings Miba37 and Miba61 can survive from smaller particles and fewer dirt shocks which enables them to meet the standard application requirements. Impressively, Miba3B bearing shows a significant improvement over other sputtered bearings and suggesting a heightened resilience to cleanliness issues.

4.7 Misalignment (conformability) test

As stated in the introduction section, conformability of the bearing is required to cope with edge loading caused by dimensional deviations, misalignments, and deformations during engine operation especially prominent in high-speed engines. Under these kinds of non-ideal conditions, the bearing system can either adapts and distributes the load on a wider area quickly or fail by seizure.

The misalignment test is designed to identify this adaptation capabilities in case of local overloading. An inclination of 40µm is applied across the 34mm length of the bearing, which is subjected to a unit load of 75MPa and a sliding speed of 12m/s. The use of SAE 10 oil, along with an inlet temperature of 110°C, further decreases the oil film thickness, thereby accelerating the testing process. The condition of the bearing after this rigorous test is illustrated in Figure 32.

The Miba03 and Miba3B bearing types demonstrate perfect adaptation ability, allowing the tested bearings to survive the challenging conditions. In contrast, the Miba37 exhibits reduced robustness under edge loading, resulting in damage due to severe adhesive wear.

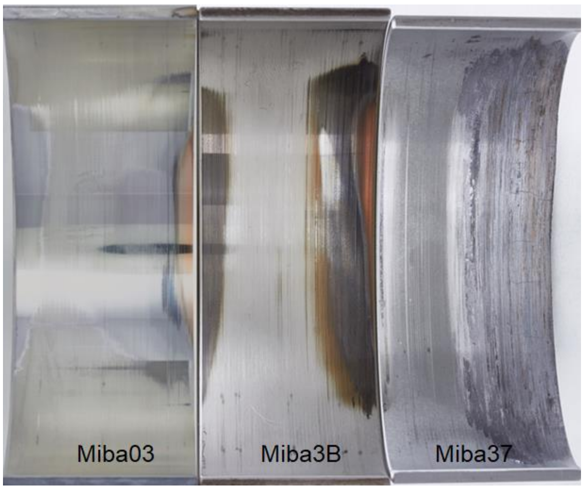

Figure 32. Test rig result _ misalignment

4.8 Cavitation test

The cavitation resistance of a bearing is highly related to the material hardness. In the cavitation test, an ultrasonic oscillator operating at a frequency of 20 kHz is employed, using an aqueous solution as the contact medium. The extent of material loss, measured by weight reduction after a specified testing duration, serves as the key indicator of the test outcome.

As showed in Figure 34, Miba37 bearing with highest coating hardness delivers the least weight loss as expected. Miba3B bearing show substantially improved cavitation resistance in comparison with the E-plated bearings and the polymer bearing.

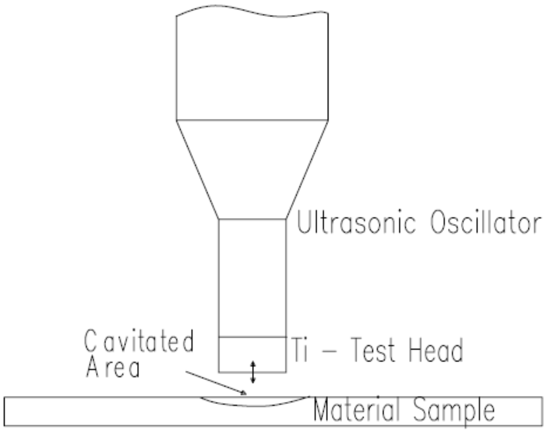

Figure 33. Test configuration _ cavitation test

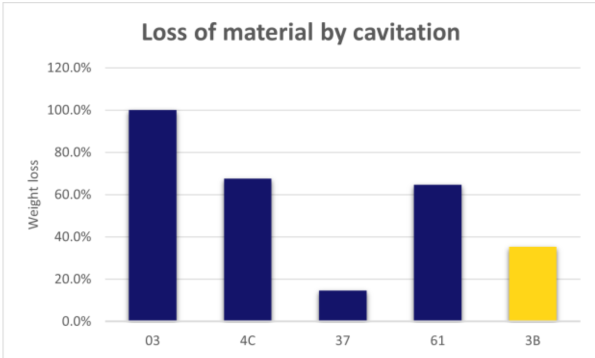

Figure 34. Cavitation test result

4.9 Oil-material compatibility test

As mentioned in the introduction section, the use of new fuels imposes higher demands on the material's ability to resist lead corrosion. To assess the resistance of different base materials to lead leaching, leaded bronze material (Miba01) and lead-free lining material (Miba2C) were placed in a selected oil and cooked at 160°C for varying durations, with a maximum time of 216 hours. The results showed that the Miba2C material had almost no weight loss, while the Miba01 material experienced a weight loss of 0.0103g due to lead corrosion as depicted in Figure 35.

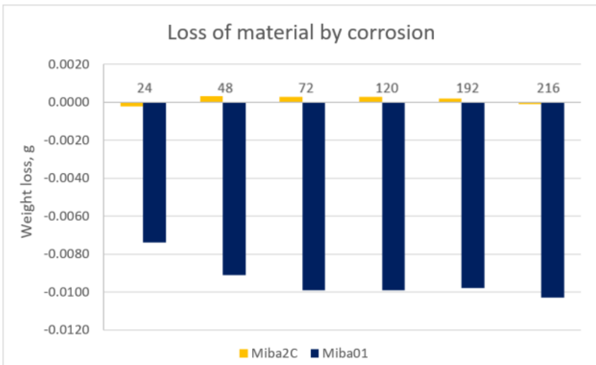

Figure 35. Test result _ Corrosion of lead

To verify the sensitivity to active sulfur, Miba4C and Miba3B bearing samples were placed in a selected diesel engine oil and heated at 115°C, 130°C, 145°C, and 160°C respectively for 140 hours. Both Miba4C and Miba3B materials exhibit similar results as showed in Figure 36. At lower temperatures, no black corrosion products are formed on the surface, but as the temperature increases to 145°C and 160°C, black sulfides are visible on the surface. This visibility of black sulfides is due to the reaction between the copper in the coating and the active sulfur in the oil at higher temperatures and longer durations.

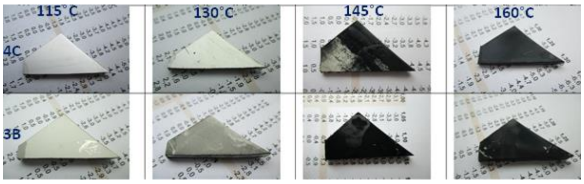

Figure 36. Test result _ Corrosion of copper

The above tests are standard oil-material compatibility tests designed to simulate long-term chemical interactions between lubricants and bearing materials under controlled conditions of temperature and duration.

Figure 37. Set up of the artificial oil aging test

While in a real engine operating environment, oil aging and degradation are influenced by various factors beyond temperature and time, such as air oxidation, nitrification, alternative fuel residues, and their combustion byproducts. To better understand the impact of these factors on oil stability and bearing material performance over time, an artificial oil aging system was developed (Figure 37). This system replicates oil degradation by exposing bearing samples to air oxidation, nitrification, fuel residues, and combustion byproducts. Testing of these "soft" sputter bearings using this new system will be conducted soon.

4.10 Aging effects of Sn-based overlays

Sn-based materials generally exhibit aging behavior when exposed to heat, whether cast in bulk or deposited as thin coatings [11]. Their microstructure changes due to diffusion process and their hardness decreases. A relatively simple laboratory test involves heat treatment in a hot air furnace for up to several thousand hours. Although this test ignores the effects of oil and friction, it provides a good understanding of the diffusion processes and mechanical stability of the overlay materials, allowing for a time-lapse study of bearing life. Figure 38 illustrates the loss of hardness in tin-based coatings during heat treatment at various temperatures.

When comparing overlays that are chemically identical but produced by two different kinds of processes (sputtering and E-plating), it is generally observed that sputtered overlays tend to be harder therefore more resistant to wear, particularly over extended periods of operation, as a consequence providing better support for load ability and temperature stability.

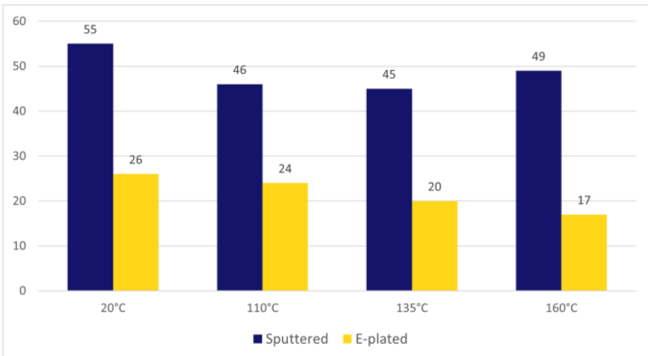

Fig. 38. Hardness of Sn-based sputtered and E-plated coatings after heat treatment at 110, 135 and 160°C for 1000 h. The reference samples stored at room temperature (20°C) represents the overlay condition as coated.

4.11 Results summary and interpretation

An interpretative overview is presented in Figure 39 using the spider web diagram. Please be aware that these rankings are for high-speed high-performance engines, and they may differ for different applications since the requirements and targeted bearing types are different.

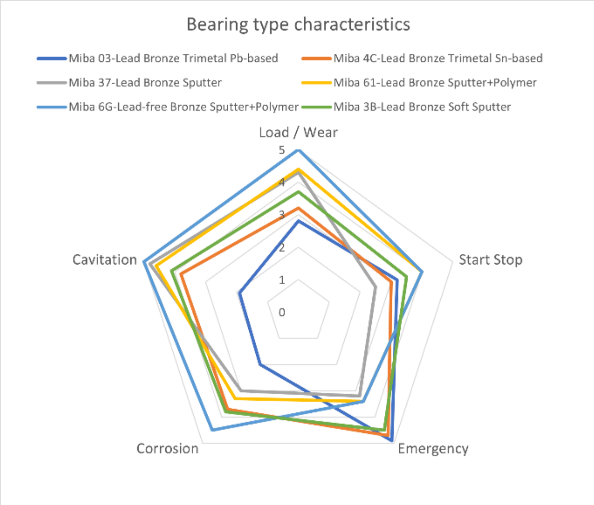

Figure 39. Bearing type performance

The distinctions between E-plated and high-performance sputter bearings are apparent. E-plated bearings excel in tribological performance, offering superior resistance to misalignment, contamination, and oil starvation conditions. This contrasts with the exceptional hydrodynamic performance characteristic of Miba37—the hard sputter bearings.

In high-speed engines, where engine cleanliness or the quality/design of the adjacent bearing components may not be optimal, the emergency operational characteristics of bearings become crucial. Miba3B bearings possessing higher load-carrying ability than the E-plated bearings and much enhanced emergency capability compared to the traditional hard sputter bearings, offering balanced robustness and longevity, making it a perfect bearing type for operational safety against particle contamination, misalignment, and oil starvation in high-speed application.

5 FIELD EXPERIENCES

The Sn-based “soft” sputter bearing type was released for engine tests in large high-speed engines fueling by diesel and gas.

As illustrated in Table 4, the Miba3B bearing has been widely adopted across several typical high-speed engines for different applications. Field experience to date corroborates the test rig findings, demonstrating the bearing's low wear rates, high resistance to cavitation, and excellent tolerance to misalignment, mixed friction, and initial contamination.

Miba3H bearing, a Pb-free version of the "soft" sputter bearing with enhanced corrosion resistance, excellent load-bearing capability, and similar tribology property as the leaded bearing, is currently undergoing testing at the customer site.

Table 4. Field experiences of Miba3B bearing

Application Fuel	Unit load, Surface speed Running hours	Bearing position Bearing OD
Genset Gas	45Mpa, 18m/s ~12,000hours	MB + CB ~350mm
Genset Gas	52Mpa, 15m/s ~33,000hours	MB + CB ~210mm
Propulsion Diesel	77MPa, 16m/s ~1000hours	MB ~130mm
Propulsion Diesel	62MPa, 19m/s ~500hours	MB ~150mm
Locomotive Diesel	52MPa, 14m/s ~8700MWh	MB + CB ~275mm

Figure 40a shows a lower main bearing that has been in operation for 12,000 hours in a high-speed gas engine used for genset (45MPa, 18m/s). The bearing remains in excellent condition, displaying smoothed main loaded area without any signs of material fatigue or mixed friction. The wear is minimal, with the maximum value reaching only 3µm at the edge area.

Figure 40b depicts the pristine dendritic structure of the coating in the reference area. Figure 40c demonstrates smoothed running surface with minimal wear and slight structure change in response to the high local temperatures and mechanical stress caused by edge loading, enabling a better tribological properties at the loaded area.

Figure 40. a) A lower main bearing (Miba3B) underwent 12000 hours test in a high-speed genset

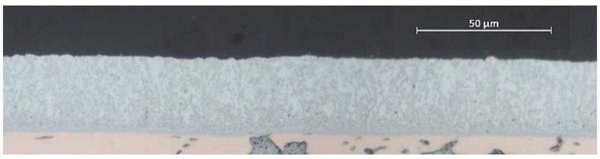

Figure 40. b) Detailed view of the sputter layer at the reference area

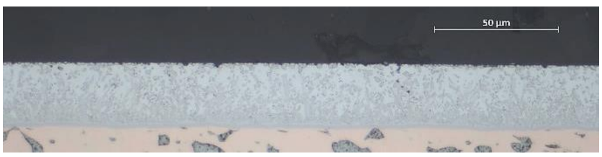

Figure 40. c) Detailed view of the sputter layer at the edge-loaded area

In a high-speed diesel engine (62MPa, 19m/s) used for propulsion, the former solution Miba61 bearing (Figure 41a) exhibits strong mixed friction after a 100-hour test due to not ideal crankshaft condition. In contrast, the Miba3B bearing (Figure 41b) adapted perfectly to the crankshaft and completed the 500-hour test with only slight wear, measuring just 4 µm.

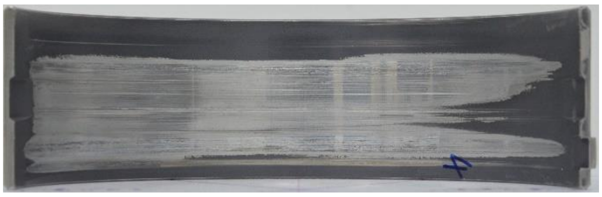

Figure 41. a) A lower main bearing (Miba61) underwent 100hours test in a high-speed propulsion engine

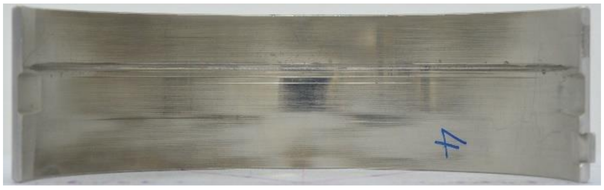

Figure 41 b) A lower main bearing (Miba3B) underwent 500hours test in a high-speed propulsion engine

Figures 42 and 43 compare the appearance of different types of bearings, Miba03 and Miba3B, after long-term operation in the same type of engine (52MPa, 14m/s) utilized in locomotives.

As shown in Figure 42a and Figure 43a, the previous Miba03 solution for lower main and upper rod bearings experienced high wear and moderate cavitation damage. Both bearings operated under dirty conditions, ruling out the possibility of using Miba37. The adopted Miba3B bearings, however, demonstrate significantly improved resistance to cavitation attack, along with good conformability and embeddability, as illustrated in Figure 42b and Figure 43b.

Figure 42. a) A Miba03 lower main bearing underwent 4389 MWh operation in a locomotive

Figure 42. b) A Miba3B lower main bearing underwent 8330 MWh operation in the same locomotive as Figure 42a

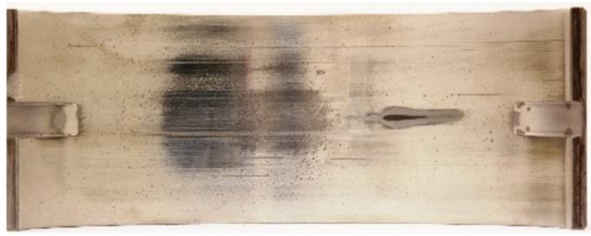

Figure 43. a) A Miba03 upper rod bearing underwent 2250 MWh operation in a locomotive

Figure 43. b) A Miba3B upper rod bearing underwent 7500 MWh operation in the same locomotive as Figure 43a

6 WORKING RANGE AND PRODCUTION AVAILABILITY

The three Miba bearing plants—Miba Europe, Miba China, and Miba USA — each possess the capability to manufacture the Miba3B bearing type, with their respective operational ranges outlined in Table 5.

Table 5. Working range at three production sites

Sites	Parameter	Limitation
Europe	Max. OD	355 mm
China	Max. OD	255 mm
USA	Max. OD	278 mm
All sites	Thickness	Only given by mech. manufacturing
All sites	Width	Only given by mech. manufacturing

Due to the complexity of the sputtering process, Artificial Intelligence (AI) based model has been developed to predict the quality of the parts. These models were trained from the historical data collecting from all production sites by using machine learning techniques. The AI predictive quality system is now operational and will be improved, evaluated, and monitored continuously [12].

7 CONCLUSIONS AND OUTLOOK

The key points of this paper can be summarized as follows:

- Further adaptability is required for bearings to cope with dimensional deviations, misalignments, deformations, and cleanliness issue during engine operation especially prominent in large engines due to engine upgrading in response to the ever-increasing emission regulations. Meanwhile adequate load ability and longevity are indispensable.

- Surface coatings, applied by a variety of technologies such as electroplating, polymer spraying, and sputtering, are essential for enhancing multiple critical properties of bearings. These properties include anti-seizure ability, conformability, embeddability, corrosion resistance, and wear resistance, all of which contribute to improving the robustness and longevity of the bearings.

- The E-plated bearings currently excel in robustness but fail to achieve adequate fatigue life and TbO targets. In contrast the AlSn20 Sputter bearing has demonstrated extraordinary long term operation performance under high loads but sensitive under rough conditions.

- Miba3B bearing with Sn-based “soft” sputter layer presents low wear rates, high resistance to cavitation, and excellent tolerance to misalignment, mixed friction, and initial contamination in both the test rigs and field operation. It closes the gap between the soft E-plated overlay and the hard Al-based sputter layer in response to the ever-increasing robustness and longevity demands of the upgraded large-bore engines.

- Miba3H bearing, a Pb-free version of the "soft" sputter bearing with enhanced corrosion resistance, excellent load-bearing capability, and similar tribology property as the leaded bearing, is currently undergoing testing at the customer site. This bearing type expands and optimizes Miba’s product portfolio, enabling an advanced solution to the requirements arising from the alternative fuel engines and environmental legal obligations (ROHS, REACH).

However, the interactions between the bearing and related parts—such as the mating surface of the shaft, the lubricating oil, and the fuel — are extremely complex. To address this, Miba has been developing new test methods tailored to the unique requirements of engines using alternative fuels, including methanol, ammonia, hydrogen, and e-fuel. These methods focus on tribological behavior, material compatibility, and design considerations, aiming to facilitate the widespread adoption of these fuels and support the transition towards more sustainable transportation systems [13].

8 DEFINITIONS, ACRONYMS, ABBREVIATIONS

C3S: Copernicus Climate Change Service

GHG: Greenhouse Gas

IMO: International Maritime Organization

CO2: carbon dioxide

LNG: Liquefied natural gas

DVP: Design Verification Process

Sn: Tin

Al: Aluminum

Si: Silicon

Sb: Antimony

Cu: Copper

Pb: element Lead

PbBz: leaded bronze

USP: unique selling proposition

NHD: Numerical Hydro-Dynamic

MB: main bearings

CB: conrod bearings

AI: Artificial Intelligence

9 REFERENCES AND BIBLIOGRAPHY

[1] https://climate.copernicus.eu/copernicus-2024-first-year-exceed-15degc-above-pre-industrial-level

[2] Hager, G. 2023. Joint development of the bearing system for AVL's new high-speed engine platform, *CIMAC 2023*, Busan, South Korea, 023.

[3] Auer, M. 2023. MAN energy solutions - four-stroke engine solutions for low-carbon and carbon-free fuels, *CIMAC 2023*, Busan, South Korea, 049.

[4] https://ammoniaenergy.org/articles/iea-ammonia -key-to-decarbonising-shipping-by-2050/

[5] Otto, K. 1986. Steel Corrosion by Methanol Combustion Products: Enhancement and Inhibition, *1986 SAE International Fall Fuels and Lubricants Meeting and Exhibition*.

[6] https://www.infineuminsight.com/en-gb/articles/Fuelling-a-more-sustainable-future/?utm_campaign=Infineum+Insight+Dec24+email+-+resend+to+Non-Openers&utm_medium=email&utm_source=Infineum+Insight

[7] Li, ZG. 2003. *Slide bearings of internal combustion engines*, 1st ed., Shanghai Jiao Tong University Press, Shang Hai, China.

[8] Aufischer, R. 2013. Modular bearing designs to cope with the new engine designs demanding high performance, Modular Bearing Designs to Cope with the New Engine Designs Demanding high performance, Lead-free solutions and robustness, *ICEF 2013*, Dearborn, Michigan, USA.

[9] Zhang, Z.F. 2023. Bearing testing and validation to optimize bearing design for different engine applications, *CIMAC 2023*, Busan, South Korea, 049.

[10] Forstner, C. and Mairhofer, G. 2007. Application oriented bearing testing, *CIMAC 2007*, Vienna, Austria, 246.

[11] Nagl, J. 2016. Adaptive Tin-Based Journal Bearing Overlays for Future Generations of High and Medium-Speed Engines, *CIMAC 2016*, Helsinki, Finland, 320.

[12] Nickel, F. 2023. DPLE – Digital product lifecycle engineering for hydrodynamic bearings, *CIMAC 2023*, Busan, South Korea, 009.

[13] Zunghammer, A. and Kirchhamer, S. 2024. Plain Bearing Performance in Applications Utilizing Alternative Fuels, *DGMK 2024,* Hamburg, Germany, 13.

10 CONTACT

Hellen.li@miba.con