# High-strength Aluminum bearings without soft phase coated with PFAS free polymer

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**ABSTRACT**

The robustness requirements for bearings to meet the demands of increasingly efficient, clean, and power-dense engines has created a paradox for future bearing alloy developments. Traditional Al-Sn-Si based Al alloys have reached their limits with Peak Cylinder Pressures (PCP) reaching above 120bar in Flex-fuel Light Vehicles (LV). Bronze alloys are stronger but more expensive.

The development of a high strength Al alloy which encroaches on the historically dominant bronze alloys is a necessity to meet both commercial and performance targets of the market. The new high strength roll bonded Al-Mn-Mg alloy developed without a soft phase and coated with a PFAS free polymer addresses this compromise while resisting maximum specific loads up to 95MPa.

The absence of a soft phase is compensated by the PFAS free polymer that already meets the anticipated future restriction of PFAS chemical substances and ensures system robustness when operating under thin or disrupted film conditions. The new polymer solid lubricant gives the necessary seizure resistance needed for polymer coated bearings.

Rig and engine testing (900 hours MHD and 300 hours LV flex) have demonstrated a significant improvement in fatigue performance over the highest rated Al-Sn-Si bearing alloy without jeopardizing seizure and wear performance.

**INTRODUCTION**

OEM's are in constant pursuit of engine efficiency gains to meet increasingly stringent local and global environmental regulations. Advancements such as start/stop engine capability, turbocharging, mass reduction via downsizing, low viscosity oils and higher temperatures all help to achieve these goals; however, they all impact individual engine components, such as bearings, increasing the overall operating severity parameters such as seizure, wear, and fatigue. This necessitates technology and material advancements to meet these requirements in a cost-effective manner. Cylinder pressures observed from next generation medium duty diesel engines show trends exceeding 200bar, outpacing current Al alloy load capabilities. Alternative fuels popular regionally also impact bearing requirements.

Around 2003 the Brazilian market adopted the use of ethanol or "Flex-Fuel" engines as one path to achieving these goals. When considering the "Well-to-Wheel" cycle, ethanol is more environmentally friendly than gasoline. However, ethanol requires about 30% higher combustion pressures when compared to gasoline [1]. Turbocharged Flex-Fuel engines already reach 120bar cylinder pressures with potential to reach 130bar soon. When combined with the increased operating severity due to the technical advancements mentioned previously, bearing specific loads and severity has increased substantially over the last decade.

Polymer coatings have become crucial technology for increasing bearing survivability and robustness in thin film or mixed lubrication regimes. Consisting of a Polyamide-imide (PAI) resin with a combination of solid lubricants and other additives to increase seizure and wear performance, polymer coatings can often be tailored with additives to further enhance performance, such as wear resistance or thermal conductivity. A typical construction of a polymer coated Al alloy bearing shell can be seeing in Figure 1.

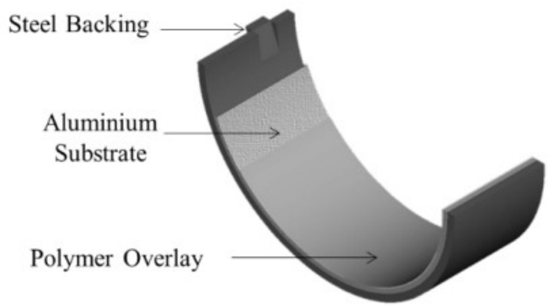


Figure 1: Schematic of steel backed, polymer coated, Aluminum bearing

Historically, Al-based alloys have been the cost-effective material choice for main and rod bearings demanding a balance of seizure and wear performance, limited mostly by fatigue strength. Al alloys require a blend of hard and soft phase properties to prevent seizure, wear, and increase debris embedment. This is typically accomplished by adding Sn, Si, Cu, and other elements in varying percentages and careful processing of the material. When the engine specific loading eclipses aluminum alloy capabilities a bronze substrate becomes necessary, increasing costs, requiring an electroplated or polymer overlay, and losing advantages of Al alloys, even though the bronze alloy performs adequately.

To address the issue of fatigue strength in Al alloys, a novel Al alloy was developed. This alloy, when combined with a polymer overlay, can achieve a significant improvement in fatigue strength compared to traditional products. This development is meant to bridge the gap between traditional Al alloys and bronze alloys, as shown in Figure 2. Because modern polymer overlays are functional coatings that should last the lifetime of the product, there is no need for the Al alloy to contain any soft phase. This has enabled a wider range of alloys to be considered for development. However, even if the polymer is worn, the new Aluminum substrate can handle eventual metal-to-metal similarly to bronze.

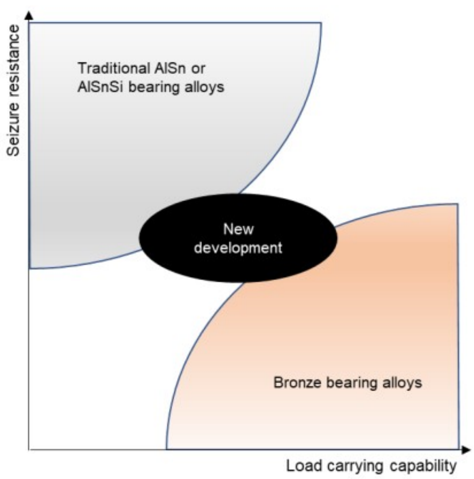


Figure 2: Target applications area for novel Al alloy

## HIGH STRENGTH ALUMINUM ALLOY WITH NO SOFT PHASE

As said, conventional Al-Sn and Al-Sn-Si bearing alloys present combination of hard and soft properties to prevent seizure and improve dirt embeddability, when running uncoated. These products are light, corrosion resistant and highly cost efficient with good balance to their fatigue resistance. However, requirements for increased load carrying capability pushes towards polymeric overlay, or to bronze bearings at a cost disadvantage over aluminum solutions.

The removal of soft phase elements such as Sn or Pb from Al alloys is key to achieving increased fatigue strength while also simplifying the strip manufacturing process. Products such as $AlSi_{11}Cu$ and $AlZn_5NiPb$ [2] have explored this direction, however these rely on an electroplated overlay to achieve the balance of soft phase properties. Given the decreased operation under hydrodynamic film conditions in modern engines, electroplated overlays could potentially wear to a greater extent, exposing the substrate, reducing seizure and debris tolerance. In this situation, the use of polymer overlays is ideal. The fatigue strength is provided from the high strength Al alloy composition, while the polymer provides superior soft properties and wear resistance compared to traditional leaded and lead-free electroplated overlays.

Outstanding advancements in functional polymer overlays [2] have facilitated an optimum combination: a high strength aluminum delivers desired product fatigue strength whereas the polymer overlay provides permanent functional overlays with enhanced balance of soft properties whilst achieving superior wear resistance compared to historical leaded and lead-free electroplated overlays, increasing bearing system security.

The alloy selection targeted global availability, high formability and recyclability [3]. A 3000 series composition Al-Mn-Mg [4] was utilized as the bearing substrate and roll-bonded onto low carbon steel to produce a bimetal strip. Prior to bonding, steel and alloy were degreased and dried for further bonding surfaces preparation. The steel was linished using impregnated abrasive belts and the aluminum alloy was scratch brushed with steel wire brushes. The two layers were rolled bonded to achieve at least 50% reduction on the alloy. A schematic of the bonding process is shown in Figure 3.

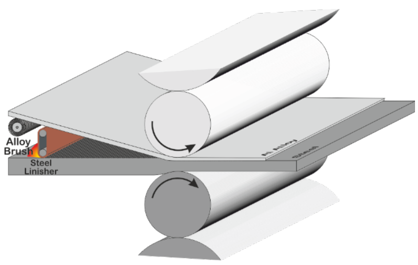


Figure 1. Schematic of roll bonding process

The coiled bimetal received a stress relieving heat treatment in a static oven. The bond integrity was assessed by means of a chisel and peel test. In this test a tab of alloy is chiseled using a cold chisel and then an attempt is made to peel the alloy from the steel. The amount of peel back is measured, and a quality assessment is made (figure 4).


Figure 4: Examples of chisel & peel back test pieces (a) Satisfactory alloy-steel adhesion (b) Unsatisfactory alloy-steel adhesion

Test bearings were manufactured using small batch production equipment and coated with a polymeric overlay. The polymer overlays are described in Table 1.

Table 1. Description of polymer overlays

| Polymer Overlay | Description |
|---|---|
| A | PAI, Al flakes, PTFE, Cerium Oxide, Silane |
| B | PAI, Al flakes, Melamine Cyanurate, Silane, Dispersant |

The hardness of the alloy and steel are measured throughout the process by means of a Vickers Hardness test [5].

## PFAS FREE POLYMERIC COATING

The group of chemicals based on Perfluoroalkyl and Polyfluroalkyl are known as PFAS substances. These chemicals have raised environmental concerns due to their complex chemical chains that do not breakdown easily in the environment. Several day-by-day products contain these chemicals which are starting to be banned from several industry segments e.g. food ware and packaging, hygiene products, automotive segment among others. The first generation of the polymer formulation used as coating for bearings had PTFE in its composition. PTFE work as solid lubricant. This substance is a PFAS related substance which will be subjected to a future ban.

The development of an Aluminum substrate without a soft phase requires a robust coating for emergency situations of oil film disruption e.g. transient conditions where direct contact with the shaft may occur. To cope with the future environmental requirements a new PFAS compliant polymer was developed with the use of a solid lubricant called Melamine Cyanurate (overlay B of table 1). This new solid lubricant replaced the PTFE with success when applied over the newly developed Al-Mn-Mg Aluminum alloy.

Rig and engine testing have confirmed the good compatibility of the new solid lubricant with the PAI polymeric matrix and new substrate, keeping friction, fatigue, wear and seizure properties in a similar range compared to the traditional Al-Sn-Si alloy coated with the first-generation polymer, having the advantage of using the existing manufacturing process and available equipment.

## RIG TESTING

The basic development of new bearings materials usually is subjected to rig testing before they can go on more complex and costly validation like engine testing. In this case, in-house rig testing was used to assess the basic properties like fatigue, seizure and wear of the newly developed material. Utilizing a steel-backed plain bearing half shell of standard size, all rig testing was conducted with dimensions that are comparable to those of current passenger car production parts. The conventional bearing materials were compared to the results of the developed alloy, as detailed in Table 2.

Table 2: Chemical composition of bearing materials

| Variant | Chemical Composition of bearing alloy |
|---|---|
| **Developed Al-Mn-Mg** | Al-Mn-Mg |
| **Conventional Al-Sn-Si-Cu** | Al-Sn-Si-Cu-Ni-Mn-V |
| **Conventional Cu-Sn-Bi** | Al-Sn-Bi-Ni |

## FATIGUE TESTING

The fatigue performance of bearing materials is evaluated using the standard in house fatigue test apparatus known as the 'Sapphire' fatigue rig. This test applies a load through an eccentric shaft and a hydraulic ram, thereby simulating the loading conditions experienced by bearings in practical applications. The testing protocol involves a duration of 20 hours during which the bearing shells undergo 3.6 million cycles. A schematic representation of the testing setup is provided in Figure 5, while the operating parameters are detailed in Table 3. The performance of the newly developed high-strength aluminum alloy was compared with a typical Al-Sn-Si-Cu alloy. Ten bearings from each material were submitted to testing under a controlled load, followed by a visual inspection to assess any signs of fatigue. A bearing is considered to have passed the test if no visible fatigue cracks are observed. Both materials were coated with a polymer overlay classified as 'B' grade, with a thickness ranging from 6 to 12 micrometers.

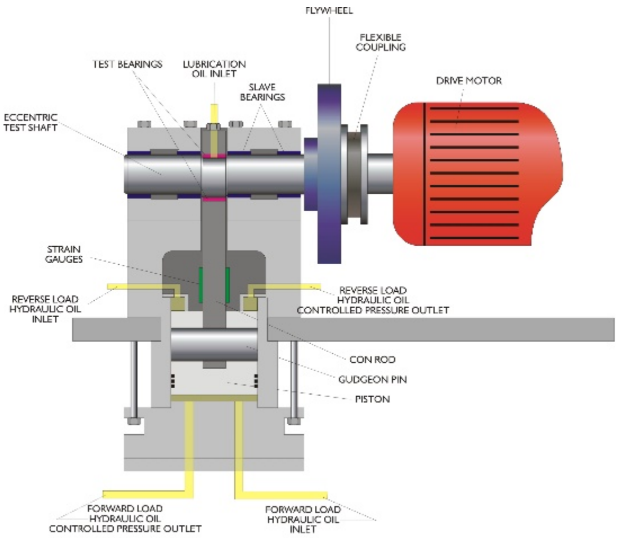


Figure 5. Schematic of Sapphire Fatigue Rig

Table 3. Sapphire fatigue test rig operating parameters

| Test Parameter | Value |
|---|---|
| Shaft | Hardened Steel |
| Shaft Finish (Ra) | Up to 0.25µm |
| Speed | 3000 rpm |
| Oil Temperature | 110 °C |
| Lubricant Oil | PAO Synthetic oil, |

## SEIZURE TESTING

The seizure performance of the bearing overlay was assessed utilizing a modified Sapphire test rig. In this setup, a slotted shaft of predetermined dimensions replaces the standard shaft without this feature. This modification disrupts the oil flow and alters the hydrodynamic behavior of the bearing system, thereby establishing severe testing conditions for seizure. The applied load is incrementally increased until seizure occurs. This testing process is fully automated, with both the applied load and bearing temperature data continuously recorded by a high-speed data logger. Seizure is identified when the load on the rig motor exceeds a specified threshold, at which point the system automatically shuts down to prevent further damage to the test rig. The developed alloy was evaluated in its coated condition, featuring a 'B' grade polymer overlay, and its uncoated state. The results were then compared to those of conventional Al-Sn-Si-Cu and Cu-Sn-Bi products.

## PARTICLE TOLERANCE TESTING

The product's operational capacity in the presence of metallic debris was examined through a particle tolerance assessment. This testing was conducted by the University of Kassel [6] utilizing a specialized rig designed to introduce steel particles with size varying from 700µm to 2100µm. The evaluation is based on visual inspection or instances of seizure, with a grading system ranging from pass to fail (1 indicates no damage, while 5 indicates seizure). Particle size was subsequently modified based on the outcomes of the preceding test, with increases applied following a pass rating and decreases following a failure. The test components utilized a light vehicle geometry, integrated within a series production connecting rod. The development of alloy bearings with a 'B' grade polymer overlay was assessed in the 'rod' position, while conventional Al-Sn-Si-Cu+'B' bearings were employed in the 'cap' position.

## WEAR TESTING

An in-house developed accelerated wear test rig, named "Viper," was employed to conduct wear testing, as illustrated in Figure 6. The test operates under boundary lubrication conditions as well as generates high specific loads.

The eccentric shaft rotates at 500 rpm working as the wear partner and a dead weight is used to maintain a consistent operating load. To establish a boundary-lubricated regime, heated oil is supplied throughout the test. The accelerated wear rig typical test conditions are summarized in Table 4. The bearing overlays are submitted to 60-minute test and the mass loss is evaluated by weighing the test pieces before and after the test.

Six bearings are evaluated, and the findings are statistically analyzed. Using the material known density, the mass loss is converted to a volume loss. A variety of overlay materials can be ranked in this manner.

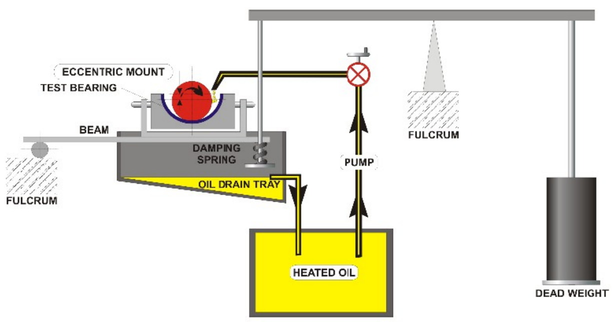


Figure 6. Schematic of Viper wear test

Table 4. Viper accelerated wear test rig operating parameters

| Test Parameter | Value |
|---|---|
| Shaft | Hardened Steel |
| Shaft Finish (Ra) | Up to 0.25µm |
| Speed | 3000 rpm |
| Oil Temperature | 110 °C |
| Lubricant Oil | Synthetic oil |

## ENGINE TESTING

Two engine tests were performed to confirm the fatigue capability of the new alloy. Test 1 was a 900-hour thermal shock performed on a 7.2L medium heavy duty EU6 DI (direct injection) diesel engine rated at 240 kW, while test 2 was a 300-hour durability on a 1.4L flex-fuel turbocharged DI engine that ran with 100% Ethanol. The engine parameters are shown in Table 5.

Table 5. Engine Tests parameters

| Engine Data | Value | |
|---|---|---|
| | Test 1 | Test 2 |
| Type | 7.2 L Diesel EU6 DI | 1.4L Flex-Fuel Turbocharged DI |
| Rated Power | 240 kW @ 2200 rpm | 110 kW @ 5500 rpm |
| Rated Torque | 1300 Nm @ 1500 rpm | 250 Nm @ 3000 rpm |
| Peak Cylinder Pressure (PCP) | 180 bar | 130 bar |
| Conrod bearing MSL | ~85MPa | ~72MPa |
| Conrod Bearing material - upper | Developed Al-Mn-Mg + Polymer coating | Developed Al-Mn-Mg +Polymer coating |
| Conrod Bearing material - lower | AlSn10Si4Cu2 | AlSn6Si2CuNiMnV |
| Test Regime | 900-hour thermal shock | 300-hour durability |

## RESULTS AND DISCUSSION

The absence of low melting point constituents in the developed alloy offers a range of significant advantages. It eliminates the necessity for an interlayer between the bearing substrate and the steel backing, a common requirement for tin-containing alloys to ensure adequate bond strength between the steel and the alloy. Interlayers, often composed of 99.5% pure aluminum foil, represent the weakest point in the composite structure, potentially compromising the fatigue performance of the final product. While enhancements can be achieved by utilizing a stronger aluminum alloy, such as Al-1Cu, for the interlayer, this practice is commonly applied in conventional aluminum-tin-silicon-copper products, however bringing more complexity to the manufacturing process Additionally, the parameters required for the roll bonding of the AlMn1Mg1 alloy to the steel backing have been established to fall within known limits, eliminating the need for modifications concerning surface preparation prior to bonding.

Existing literature [7] indicates that the bond strength achieved through cold roll bonding is directly proportional to the percentage of deformation experienced, with a minimum threshold deformation essential for obtaining a mechanical bond. It was determined during development that satisfactory bonding could be achieved with deformations exceeding 40%. Furthermore, the absence of a soft phase element provides another advantage related to the post-bonding heat treatment. In the case of aluminum-tin and aluminum-tin-silicon bearing alloys, a typical procedure involves annealing the bimetal after bonding to recrystallize the aluminum matrix. This process generally employs temperatures in the range of 270-350 °C to ensure that tin forms discrete particles or globules within the matrix helping increase fatigue resistance.

Tin exhibits limited strength, and when present in semi-continuous bands, results in reduced fatigue resistance. In contrast, the newly developed high-strength aluminum alloy, does not necessitate recrystallization; instead, a stress relief heat treatment cycle is employed. Development trials have demonstrated that the bond quality achieved during the roll bonding process, along with the subsequent stress-relieving heat treatment, is adequate for the manufacture and operation of bearings. No issues concerning bond strength have been reported during the fabrication of components and common bond tests like the one previously described in figure 4. An illustration of the microstructure of the polymer-coated bimetal is presented in Figure 7.

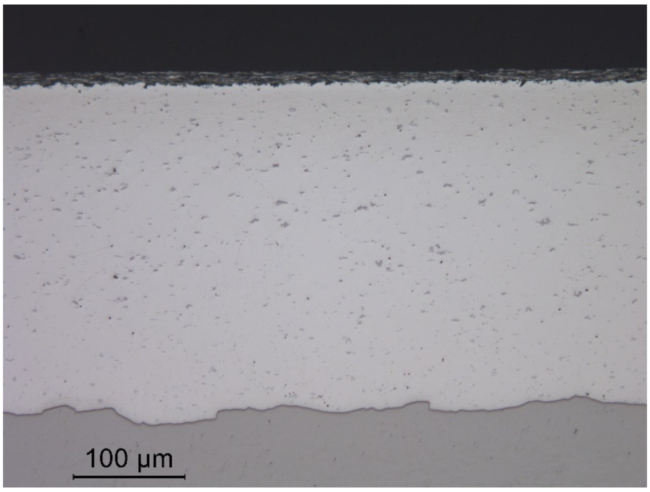


Figure 7. Development alloy microstructure with polymer coating

An important concern that was investigated pertains to the stability of substrate hardness over time when subjected to elevated temperatures. Conventional Al-Sn-Si-Cu alloys usually exhibit a reduction in substrate hardness under such conditions, prompting a temperature soak test to determine whether the newly developed high-strength Al-Mn-Mg alloy exhibits similar behavior. Both the newly developed alloy and the conventional Al-Sn-Si-Cu bearings were subjected to a laboratory oven set at 160°C for durations ranging from 1 hour to 500 hours, after which hardness measurements were taken. The findings, illustrated in Figure 8, indicate that both the conventional and developed alloys exhibit comparable patterns in hardness loss over time, suggesting that the newly developed alloy does not present a heightened risk of strength degradation at elevated temperatures when compared to existing products.

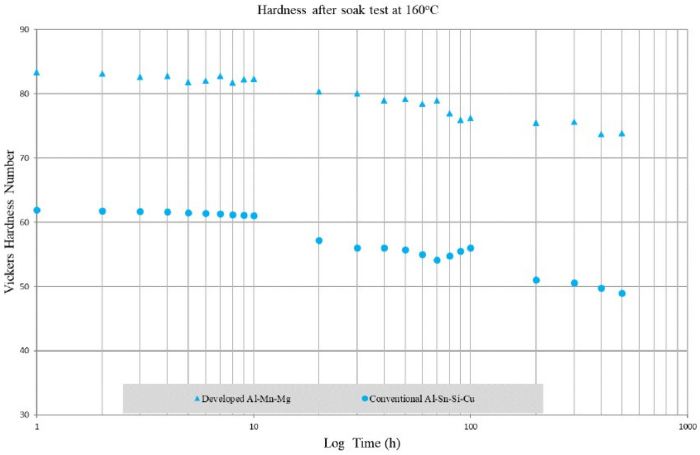


Figure 8. Bearing Hardness after soak test at 160oC

The hardness of the alloy substrate that was developed was assessed following the production of the bearings and the application of a polymer coating. The measured hardness of this alloy was determined to be between that of the Al-Sn-Si alloy and the Cu-Sn-Bi alloy, with values ranging from 70 to 95 HV, as illustrated in Figure 9. This hardness exceeds that of Al-Sn-Si alloys, attributed to the higher levels of retained cold work and the absence of a soft phase. While elevated hardness is typically associated with increased strength, including fatigue resistance, it is crucial for the material to maintain its ability to adapt to the shaft's shape during operation; thus, substrates exhibiting very high hardness (>150 HV) are not considered optimal in this context.

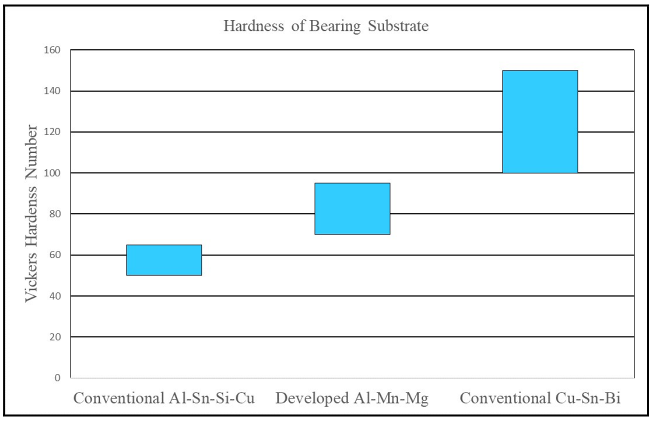


Figure 9. Hardness of bearing substrates

## RIG TESTING RESULTS

The novel high-strength aluminum product exhibited favorable results during rigorous fatigue performance assessments conducted on a 'Sapphire' rig, as previously described. Comparative analysis between the developed alloy combined with a polymer overlay designated as 'B' and the conventional Al-Sn-Si-Cu alloy with the same polymer overlay revealed a remarkable 100% pass rate at a stress level of 124 MPa for the experimental material, while the conventional material achieved a 10% pass rate at a lower stress threshold of 117 MPa. Furthermore, when subjected to elevated test loads, the conventional alloy components experienced seizure within the 20-hour testing cycle. The comparative results are graphically represented in Figure 10, while Figure 11 illustrates the typical visual conditions of the samples post-testing. This improvement in fatigue performance is significant when contrasted with the traditional Al-Sn-Si-Cu alloy. To further evaluate the robustness of the fatigue properties of the developed alloy, certain test specimens were intentionally subjected to higher than standard temperatures, resulting in a reduction of their hardness below the proposed specified range of 70-95 Hv. These specimens, which recorded a pre-test hardness of 68 Hv, also achieved a 100% success rate at 124 MPa. This observation suggests that the fatigue performance of the high-strength developed alloy remains robust within the designated hardness specification range.

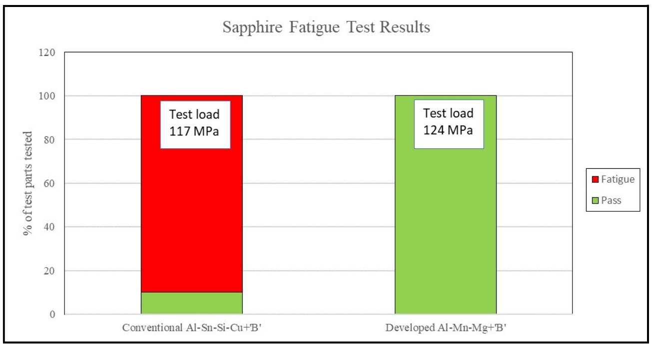


Figure 10: Fatigue Test Results

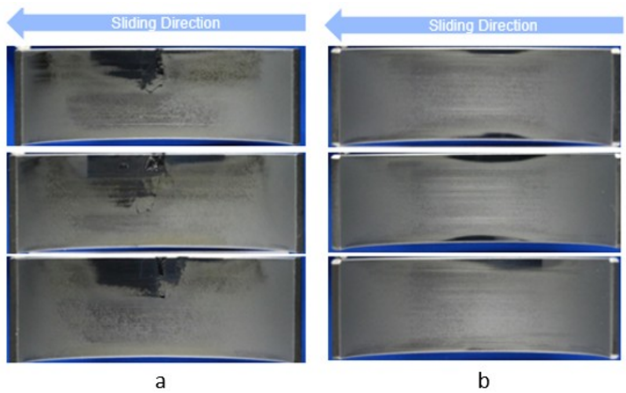


Figure 11. Examples of Sapphire fatigue tested bearings (a) Conventional Al-Sn-Si-Cu + 'B' polymer coating (b) Developed Al-Mn-Mg+'B' polymer coating

The seizure performance of the developed alloy was observed to lie within the parameters established by contemporary research, particularly when compared with conventional bearing materials that are coated with the 'B' polymer overlay, as illustrated in Figure 12.

This finding underscores that while the developed alloy exhibits commendable fatigue resistance, it also possesses an adequate level of seizure performance necessary to attain the requisite balance of properties for an effective bearing product.

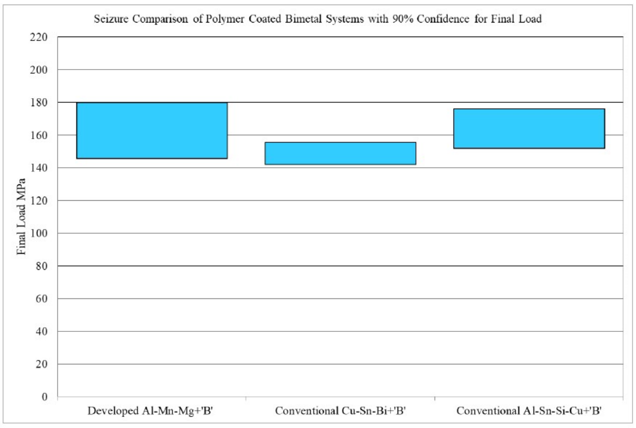

Figure 12. Results of 'Sapphire' seizure tests

The uncoated version of the developed alloy also was tested to ascertain its emergency running capabilities in the event of unforeseen degradation of the polymer overlay. The results indicated that the performance of the developed alloy is comparable to other lead-free bronze alloys; however, it did exhibit seizure at a lower load than those materials that feature a soft phase, as demonstrated in Figure 13. It is essential to highlight that the manufacture of the developed alloy will be conducted exclusively in conjunction with polymer overlay.

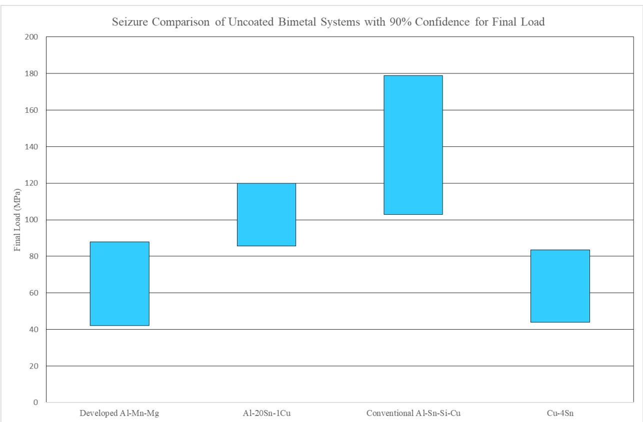

Figure 13. Uncoated seizure test results

The conducted test of particle tolerance assessments resulted in successful results with bearings passing the test with particles up at 2100µm as showed in Figure 14.

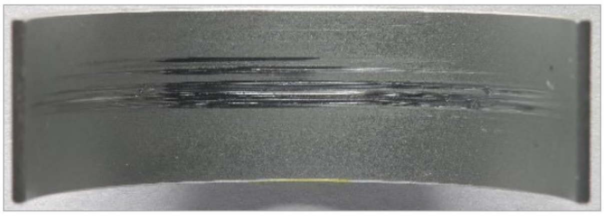
Figure 14: Development alloy+"B" after particle tolerance testing (2100 µm size particle)

The findings from the accelerated wear test, which compared the newly developed high-strength aluminum alloy with an Al-Sn-Si and a Cu-Sn-Bi product, indicated that the new material fell within the performance range of existing products. All materials were evaluated with a B grade polymer overlay, as illustrated in Figure 15.

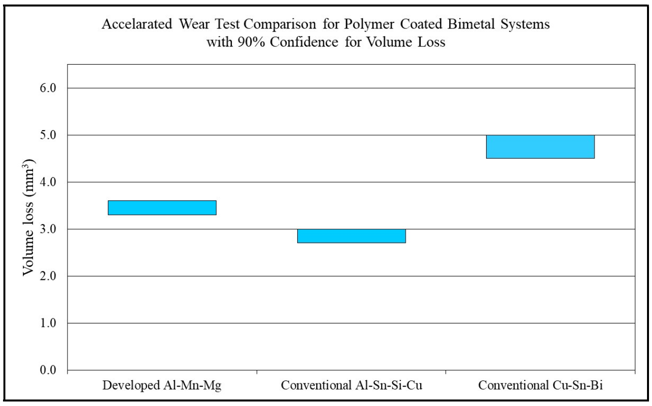

Figure 15: Accelerated Wear Test results

**ENGINE TESTING RESULTS**

The outcomes from the evaluation of diesel engine (900-hour thermal shock) and flex-fuel (300-hour durability) were favorable. The current version of the diesel engine utilizes lead-free bronze bearings that are coated with polymer, whereas the flex-fuel engine employs lead-free bronze bearings as well, however, these are coated with an electroplated tin. The alloy used in development was positioned in the upper con-rod, and the test components were polymer coated for both engine versions. The visual aspect of the tested bearings was good, with no damage or substrate exposure, see Figure 16.

The successful replacement of a bronze-based bearing product by an aluminum one is a promising outcome. Comparative analyses were conducted to measure bearing wear. In the case of the Diesel engine test, the polymer coated bearing was the reference material. The substrate comparison was between bronze (Cu-Sn-Bi) and the newly developed aluminum. In the case of the flex-fuel engine test running with Ethanol (E100), the coating comparison was between electroplated tin overlay against polymer. The substrate comparison was the same as the diesel one.

In the case of the diesel engine, the wear range was the same; however, for the flex-fuel variant the polymer coating demonstrated a marginally superior performance compared to electroplated tin, as depicted in Figure 17.

In the context of diesel engine testing, the mean hardness of the aluminum alloy post-examination was determined to be 74HV, compared to a pre-test mean hardness of 75HV under a 5kg test load. For the flex-fuel test, the average hardness of the component after testing was recorded at 72HV, while the pre-test average was 74HV. In summary, the reduction in hardness observed under both test conditions was remarkably similar and minimal hardness loss was experienced denoting a good stability for the newly developed Aluminum substrate.

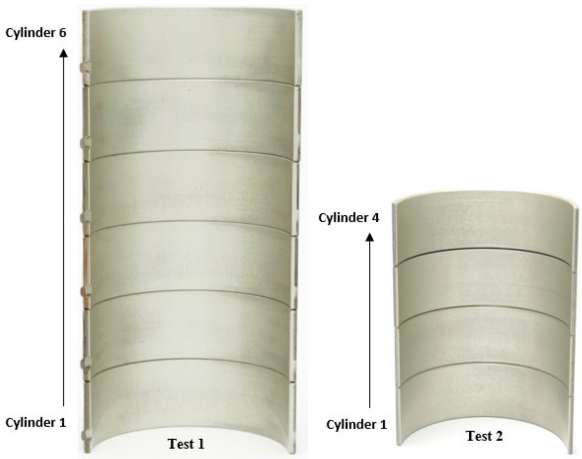


Figure 16. Developed Al-Mn-Mg alloy engine parts after testing. Diesel engine after 900-hour thermal shock (test 1) and Flex-fuel engine after 300-hour durability (test 2).

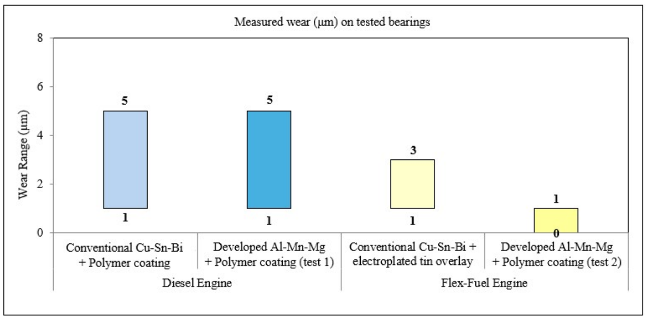


Figure 17. Wear range comparison

A light vehicle development engine, which is close to go into production, equipped with the new alloy and coated with polymer “B”, rated at 180kW, running with 0W20 oil grade, have also confirmed the good performance seeing in rig testing. Another development engine, this time a MHD, also equipped with the new alloy and coated with polymer “B”, experiencing loads close to 100MPa for the upper conrod bearings, have also demonstrated good results.

## SUMMARY

The development of a new Aluminum alloy without a soft phase demonstrated to suitably work as bearing material. The manufacturing process demonstrated that production parameters could be updated to process the material without major concerns, using existing process and equipment. The fact that no interlayer is needed - which is usually necessary to achieve good bonding or to avoid phases migration - was an advantage to the process. Bonding strength was strong enough to keep the material well adhered as suggested by quality checks and test results. The increased hardness of Al-Mn-Mg compared to traditional Al-Sn-Si alloy did result in higher fatigue resistance. Even after some running time and temperature input to the new material, the hardness was kept to high levels meaning that fatigue resistance difference over highest rated Al-Sn-Si would be kept during the bearing life. Bench and engine test results consistently confirmed the fatigue advantage of the new material while keeping other important properties like seizure and wear at similar levels. The new alloy demonstrated to be a good candidate for highly loaded engines where conventional Aluminum alloys are at the fatigue limit or even bronze replacement in traditional MHD applications, maintaining fatigue resistance at safe levels.

## REFERENCES

1. FERRARESE, A. et al, “The Interaction of Piston-Ring-Cylinder on Flex Fueled Engines”, SAE 2010-36-0327I, 2010.
2. PRATT, G.C. Material for Plain Bearings, International. Metallurgical Review, 18:2 62-88 (1973), doi: 10.1179/imtlr.1973.18.2.62
3. GEORGE, S. L. & MAGIDI-CHICUBA. Intermetallic and dispersoid structures in AA3104 aluminium alloy during two-step homogenization. Scientific Reports, 14:2958 (2024), doi: 10.1038/s41598-024-51890-2
4. EN 515:2017 Aluminium and aluminium alloys. Wrought products. Temper designations.
5. ISO 6507-1 Metallic Materials – Vickers Hardness test – Part 1: Test method
6. University of Kassel, Institute for Machine Elements and Tribology, 16.03.2022
7. STEINLAGE, G.A., BOWMAN, K.J., TRUMBLE, K.P. A comparison of three mechanical models for cold roll bonding metal laminates. Journal of Adhesion Science and Technology, 10:3, 199-229 (1996), doi: 10.1163/156856196X00355

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## ACKNOWLEDGEMENTS

The authors would like to thank the entire product development team at MAHLE UK. Most notably Sylvia Campbell, James George, Jeff Carter, Jonathan Fair and Falko Langbein.

## DEFINITIONS AND ABBREVIATIONS

PCP – Peak Cylinder Pressure

MHD – Medium Heavy Duty

LV – Light Vehicle

PFAS - Group of chemicals based on Perfluoroalkyl and Polyfluroalkyl

OEM – Original Equipment Manufacturer

PTFE – Polytetrafluoroethylene