# The development of a lead-free corrosion resistant bearing system for turbocharger applications

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**ABSTRACT**
A lead-free and corrosion resistant journal and thrust bearing system for turbocharger applications has been developed using a comprehensive lab and application-based approach to testing and analysis. The market and legislative drivers behind lead-free bearing technology are discussed, with the rationale for creating a corrosion resistant bearing system introduced. Brass, bronze and nickel aluminium bronze bearing materials were characterised in terms of their robustness and suitability to application within a turbocharger. All bearing materials were subject to lab-based corrosion testing within two respective application-representative aggressive media, namely a contaminated engine oil and an acid. Corrosion performance was adjudged by analysing post-test bearing microstructure, with the best performing materials evaluated further through tribological testing. The friction and wear performance of the bearing materials was determined by exposing the substrates to a complement of comprehensive test methods, so as to adjudge consistency of tribology performance in a wide range of simulated worst-case turbocharger environments. High resolution microscopy, interferometry and chemical analysis were utilised to characterise test samples. The findings from the research were compiled into a detailed matrix, with the most superior materials further subject to turbocharger-based corrosion and bearing endurance testing in order to correlate on-application and lab-based performance.

## 1. INTRODUCTION

Due to its exceptional dry lubricating properties (1), lead has long been regarded as a key constituent of copper-based bearing alloys used within the commercial internal combustion engine (ICE) and its associated component systems, such as the turbocharger (2). However, as a result of its toxicity (3), the use of lead in bearing alloys is being increasingly restricted by worldwide environmental legislation (4; 5; 6; 7; 8) and original equipment manufacturers.

Hence, alternative lead-free bearing alloys have been developed which are reported to provide either identical or superior performance to their lead-containing counterparts (1; 9). Such alloys contain alternatives to lead in the form of bismuth (1; 10) to provide dry lubrication performance or hard particles (9) for wear resistance, as an example. It is also common practice to design modern lead-free alloys with a consideration for corrosion resistance (1; 11; 9); a critical characteristic for bearing materials utilised within commercial ICE applications.

Bearing materials utilised within critical ICE tribosystems, such as the journal and thrust bearing system of the commercial turbocharger, are subject to increased stresses as a result of the pursuit of emissions reduction and fuel consumption improvement. Indeed, technologies such as start-stop, low viscosity oils (12; 13; 14) and extended oil drain intervals significantly increase bearing material durability requirements. Therefore, it is imperative that turbocharger manufacturers provide lead-free bearing systems which are capable of operating in the aggressive environments experienced within a commercial ICE system.

The intention of this article is to present the approach by which a wide range of lead free bearing alloys have been evaluated for use within a commercial turbocharger journal and thrust system on a start-stop ICE application. The bearing alloys have been characterised in terms of corrosion, friction and wear performance using a comprehensive and robust series of lab-based and system-based testing and analysis techniques. The testing has afforded the determination of the most superior lead free bearing alloys for use within a commercial turbocharger application.

## 2. EXPERIMENTAL

### 2.1. The turbocharger bearing system

Contained within the turbocharger bearing system are two journal bearings (Figure 1) which are located on a shaft within a bearing housing. The bearing system also encapsulates a thrust bearing (Figure 2), either side of which are located a thrust collar and slinger, respectively. The primary lubrication regime for the bearing system is hydrodynamic, but it will operate in the boundary and mixed regimes during start up, shut down and under very high contact stress conditions.

**Figure 1: Turbocharger journal bearing**

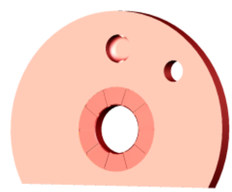

**Figure 2: Turbocharger thrust bearing**

### 2.2. Materials

The bearing material concepts utilised within this research are stated in Table 1 and were provided by Cummins Turbo Technologies. All materials were classified as lead free, when considering the maximum 0.1 % by weight limit stated within the European Commission's end of life vehicles (ELV) legislation (5).

**Table 1: Turbocharger bearing material concepts**

| Bearing Material Concept | Hardness (HV 5 kg) | Tensile Strength (MPa) | Yield Strength (MPa) |
|---|---|---|---|
| Lead-Free Bronze | 170 ± 12 | 207 | 83 |
| Lead-Free Brass A | 165 ± 3 | 650 | 550 |
| Lead-Free Brass B | 157 ± 9 | Data not available | |
| Nickel Aluminium Bronze A | 249 ± 5 | 700 | 460 |
| Nickel Aluminium Bronze B | 168 ± 5 | 760 | 415 |

The coupons used to conduct laboratory-based corrosion and tribology testing are stated in Table 2. The shaft / thrust collar material was AISI 8740, at a hardness of 52 HRC.

Details of the two types of turbocharger utilised in this study are stated in Table 3.

**Table 2: Test coupons**

| Test Type | Test Coupon | Component being Replicated | Dimensions (mm) | Critical Surface Ra (µm) |
|---|---|---|---|---|
| **Corrosion** | Block | Journal and thrust bearing | 16.2 x 16.2 x 6.3 (W x D x H) | 0.10 |
| **Tribology** | Disc | | 31.5 x 6.6 (ø x H) | 0.40 |
| | Block | | 16.2 x 16.2 x 6.3 (W x D x H) | |
| | Pin | Shaft / thrust collar | 6.4 x 21.0 (ø x H) | 0.15 |
| | Ring | | 35.0 x 8.7 x 26.5 (Outer ø x H x Inner ø) | |

**Table 3: Test turbochargers**

| Turbocharger Nomenclature | Journal Bearing Outer Diameter (mm) | Thrust Bearing Outer Diameter (mm) |
|---|---|---|
| **HE200WG** | 12.8 | 41.9 |
| **HE400WG** | 15.8 | 47.5 |

## 2.3. Method

Testing and analysis was completed according to the 7 step process highlighted in Figure 3. All material concepts were subjected to steps 1 – 4 and the best performing candidate(s) were further subjected to steps 5 – 6, with the final concept selected thereafter based on overall performance.

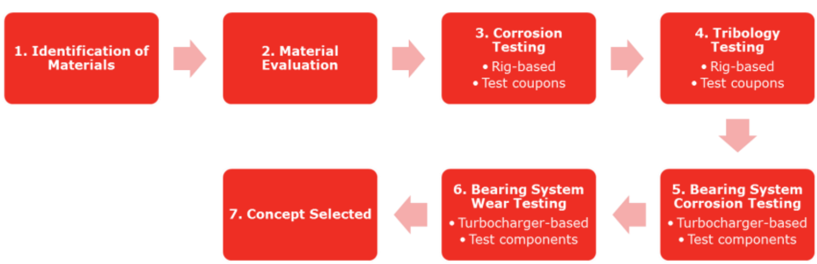


**Figure 3: Testing and analysis process**

### *2.3.1. Corrosion testing*

Laboratory-based corrosion testing was completed using a Grant QBH dry heater block, which housed individual test tubes. Bearing material concepts were subjected to corrosion testing in the form of the test coupons described in Table 2.

Each test coupon was allocated a test tube, to which 20 ml of corrosion media (Table 4) was added. 3 repeats per bearing material concept, per corrosion media type were conducted. The test temperature and duration for the laboratory-based corrosion testing are described in Table 4. Turbocharger-based corrosion testing was conducted on the best performing material concept(s) to provide confirmation of corrosion performance in a real-world, system-level test. Testing was conducted for 1000 hours using a HE400WG turbocharger and a Cummins standard endurance cycle, which utilised a heavily contaminated lubricant containing both iron-based wear debris and a high total acid number (TAN).

**Table 4: Corrosion test media and parameters**

| Corrosion Media | Details | Test Temperature (°C) | Test Duration (Hours) |
|---|---|---|---|
| Sulphuric acid | Undiluted sulphuric acid | 70 | 30 |
| Engine oil | Obtained from aggressive natural gas application | 100 | |

### *2.3.2. Tribology testing*

Tribology testing encapsulated four unique tests and was conducted using a Bruker UMT-3 tribometer. The test methods and conditions are stated in Table 5.

**Table 5: Tribological test methods and conditions**

| | Test Name | | | |
|---|---|---|---|---|
| **Test Parameter** | **Minimum Oil Film Thickness (MOFT)** | **Thrust Wear** | **Dynamic Corrosion** | **Seizure** |
| **Test Method** | **Pin-on-Disc** | | | **Block-on-Ring** |
| **Upper Specimen** | Pin | | | Block (bearing) |
| **Radius of Curvature on Pin (mm)** | 150 | | | N / A |
| **Lower Specimen** | Disc (bearing) | | Corroded disc (bearing) | Ring |
| **Contact Diameter on Disc (mm)** | 15.75 | | | N / A |
| **Lubricant** | New 10W30 | | Used engine oil | New 10W30 |
| **Lubricant Volume (ml)** | 25 | | | 10 |
| **Lubricant Temperature (°C)** | 105 | | | |
| **Running-in Period Duration (minutes)** | 10 | | | |
| **Running in Period Applied Load (N)** | 8.5 | | | 50.0 |
| **Description of Remaining Test Cycle** | 10 minute linear ramp to 20.0 N; constant load | 10 minute linear ramp to 80.0 N; constant load | 10 minute linear ramp to 20.0 N; constant load | 5.0 N ramp every 5 minutes |
| **Frequency (Hz)** | 1.25 | 2.50 | 1.25 | 5.00 |
| **Total Test Time (minutes)** | 120 | | 240 | |

Each test type was repeated 3 times per bearing material concept. The contact stresses described in Table 5 were representative of those experienced in the journal and thrust bearing tribosystems found within a turbocharger operating under extreme, boundary lubrication conditions. A Bruker Contour GT-K0 interferometer was used to acquire wear volumes from tested substrates. The equipment possessed a lateral and vertical resolution of 2.2 μm and < 0.1 nm, respectively.

#### *2.3.3. Bearing system wear testing*
As noted in Figure 3, the bearing material concept(s) which provided the most superior corrosion and tribology performance were subjected to turbocharger-based bearing system wear testing. Such experimentation was performed using a HE200WG turbocharger on a gas stand, with two respective tests being conducted:

1. Repeat start-stop bearing wear
2. Bearing endurance

Both tests were aggressive in nature and were designed to replicate the worst case conditions experienced by a turbocharger on application, for extended periods of time. With regards to the former test cycle, the turbocharger operated at a turbine inlet temperature of 630 °C for 8 minutes, before shutting down for approximately 3 minutes. Following shut down, the turbocharger was restarted and the cycle repeated for a total of 330 hours. This test methodology evaluated the boundary lubricating capabilities of the journal and thrust bearing materials, together with their resistance to high temperature coking and corrosion.

The bearing endurance test was a Cummins standard method designed to evaluate the boundary lubrication performance of the turbocharger journal bearing system, when subjected to high sliding speeds and low oil film thicknesses. Over a 6 hour period, the test included cyclical changes in rotor speed from maximum release to that typically observed at application idle. The test method was repeated with different oil inlet pressures.

#### *2.3.4. Evaluation of substrates*
The material concepts were characterised using a Leica® DM LM microscope and a Philips™ XL30 Scanning Electron Microscope (SEM) in order to acquire both low and high magnification images of the surfaces of interest. The SEM was utilised to analyse the microstructure of the concepts before and after testing.

## 3. RESULTS

### 3.1. Concepts before and after lab-based corrosion testing
The microstructures of the bearing material concepts before being subjected to corrosion testing are shown in Figure 4. The Lead-Free Bronze concept comprised both tin and bismuth rich regions of varying dimension and distribution. The largest bismuth particle was ~ 10 μm in length.

The microstructures of the two Lead-Free Brass concepts were similar in appearance, containing manganese silicide particles of differing size and distribution. The greatest particle width within Lead-Free Brass A and B were approximately 15 μm and 10 μm, respectively. The latter alloy also contained some non-uniform dimensioned bismuth rich particles, which were approximately 5 μm in length.

The microstructures of the Nickel Aluminium Bronze concepts were dissimilar in appearance. The particles rich in iron, nickel and aluminium contained within Nickel Aluminium Bronze A differed in dimension, with the largest approximately 10 μm in width. Such particles were not present within Nickel Aluminium Bronze B.

Figure 4 also provides the post laboratory-based corrosion test microstructures of the bearing material concepts. The main findings from corrosion testing are provided in Table 6, together with an overall corrosion rating for each bearing material concept.

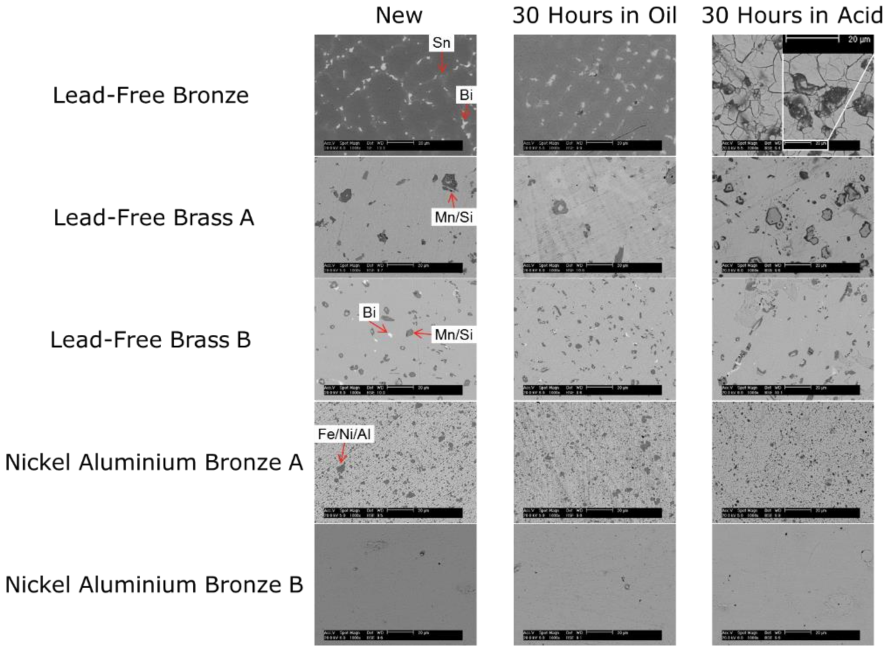


**Figure 4: Microstructure of bearing material concepts before and after corrosion testing (all images at 1000 x magnification)**

**Table 6: Corrosion testing results**

| **Bearing Material Concept** | **Observations from Corrosion Testing in Oil** | **Observations from Corrosion Testing in Acid** | **Overall Corrosion Rating** |
|---|---|---|---|
| **Lead-Free Bronze** | Significant removal of bismuth and tin rich regions | | Significant |
| **Lead-Free Brass A** | Mild dezincification | Damage to interface between Mn/Si rich regions and matrix | Mild |
| **Lead-Free Brass B** | Mild dezincification and limited bismuth removal | Mild dezincification and limited bismuth removal | Mild |
| **Nickel Aluminium Bronze A** | No corrosion observed | Limited removal of Fe/Ni/Al rich regions | Minimal |
| **Nickel Aluminium Bronze B** | No corrosion observed | | Minimal |

## 3.2. Tribology testing

### *3.2.1. Wear*

The wear performance of the bearing material concepts when subjected to the four tribology tests stated in Table 5 are reported in Figure 5 – Figure 8. Note that no recordable wear data was obtained from the steel test samples in all experiments.

Referring to Figure 5, the Lead-Free Brass bearing material concepts did not experience any measureable wear after MOFT testing. The greatest volume of wear and standard deviation was experienced by Nickel Aluminium Bronze B. The wear scar volumes on the Lead-Free Bronze and Nickel Aluminium Bronze A concepts were approximately 50 % and 70 %, respectively, of which was measured on the Nickel Aluminium Bronze B material concept.

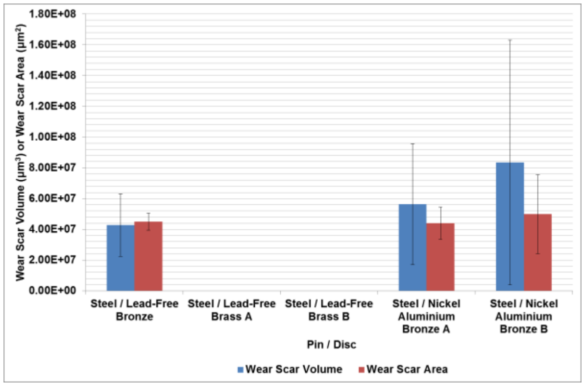


**Figure 5: Wear data for bearing concepts subjected to MOFT testing**

Nickel Aluminium Bronze A and Lead-Free Brass B possessed no measurable wear after being subjected to thrust wear testing (Figure 6). The greatest wear volume and standard deviation was obtained from the Nickel Aluminium Bronze B concept. Although the wear volume measured on the Lead-Free Bronze material concept was approximately half that of Aluminium-Bronze B, it possessed a similar wear scar area. The wear measured on the Lead-Free Brass A concept was approximately 3 % of which was measured on the Nickel Aluminium Bronze B concept.

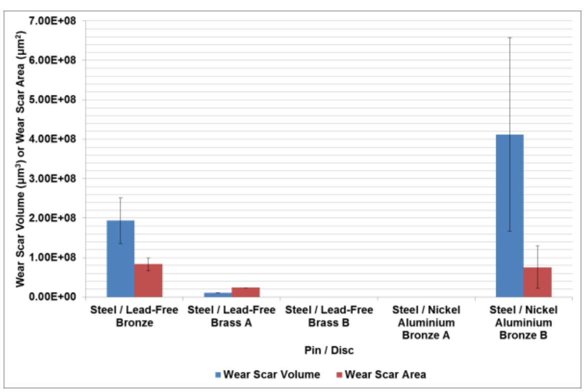


**Figure 6: Wear data for bearing concepts subjected to thrust wear testing**

As can be observed in Figure 7, after being subjected to dynamic corrosion testing, the greatest wear scar volume and area were possessed by the Lead-Free Bronze and Nickel Aluminium Bronze B material concepts. The wear volume measured on the Nickel Aluminium Bronze A material concept was approximately 3 % of that measured on its Nickel Aluminium Bronze counterpart. No measurable wear was recorded from the Lead-Free Brass material concepts.

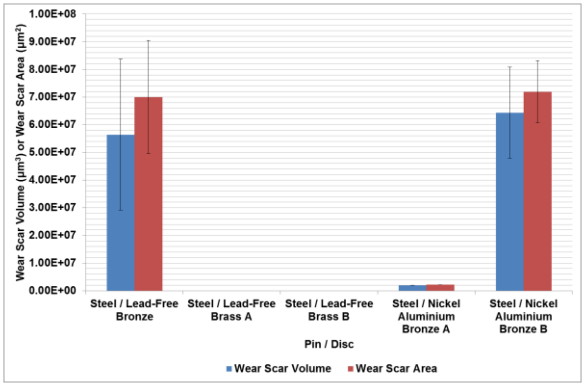


**Figure 7: Wear data for bearing concepts subjected to dynamic corrosion testing**

All bearing material concepts possessed minimal recordable wear scar areas after being subjected to seizure testing, as shown in Figure 8. The Lead-Free Bronze and Nickel Aluminium Bronze A material concepts possessed the greatest wear scar volumes measured after seizure testing. However, the standard deviation of the former was approximately 3 times that of the latter. The lowest measurable wear was obtained from the Lead-Free Brass B material concept, with Lead-Free Brass A also possessing a low level of wear. The volume of wear measured on Nickel Aluminium Bronze B was approximately half that of Nickel Aluminium Bronze A.

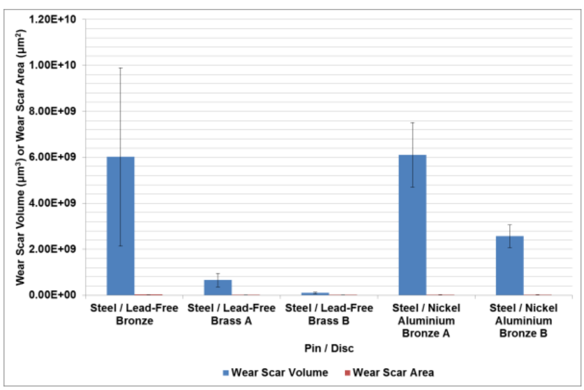


**Figure 8: Wear data for bearing concepts subjected to seizure testing**

### *3.2.2. Friction*

As shown in Figure 9, during MOFT testing, the steel / Lead-Free Bronze tribosystem provided the lowest frictional response throughout experimentation, with the coefficient of friction reducing from ~ 0.15 at the start to 0.11 at the end of testing. The four remaining steel / bearing tribosystems possessed analogous frictional response during MOFT testing, with a starting and final friction coefficient of ~ 0.15.

Referring to Figure 10, frictional response decreased throughout thrust wear testing for the Steel / Nickel Aluminium Bronze B and Steel / Lead-Free Bronze tribosystems, with the latter providing the lowest, and the former the greatest, final friction coefficient. The two Steel / Lead Free Brass tribosystems provided stable friction coefficients of ~ 0.13 throughout testing, whereas the frictional response of Steel / Nickel Aluminium Bronze A fluctuated between 0.15 and 0.11.

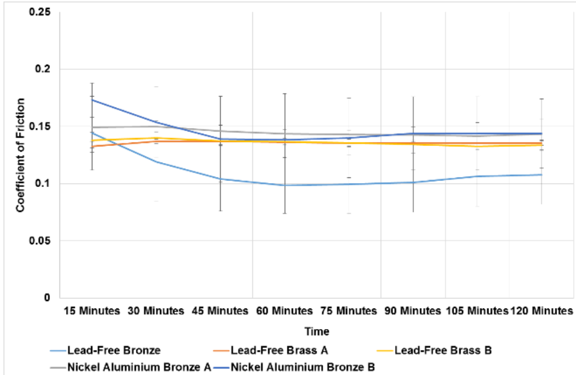


**Figure 9: Frictional response from steel / bearing material concept tribosystems during MOFT testing**

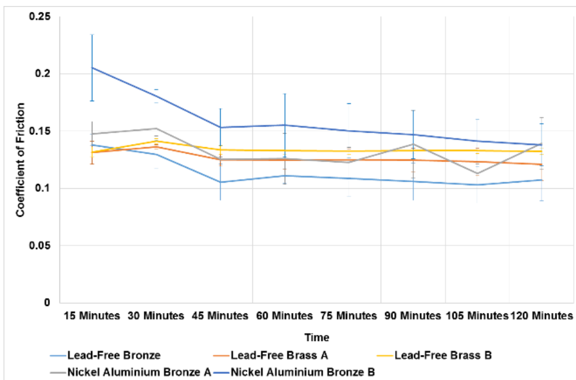


**Figure 10: Frictional response from steel / bearing material concept tribosystems during thrust wear testing**

During dynamic corrosion testing (Figure 11) the five tribosystems exhibited similar behaviour, whereby frictional response initially increased from ~ 0.11 and subsequently reduced throughout the test. The Steel / Lead-Free Bronze tribosystem provided the greatest frictional response reduction, with a final μ of 0.07.

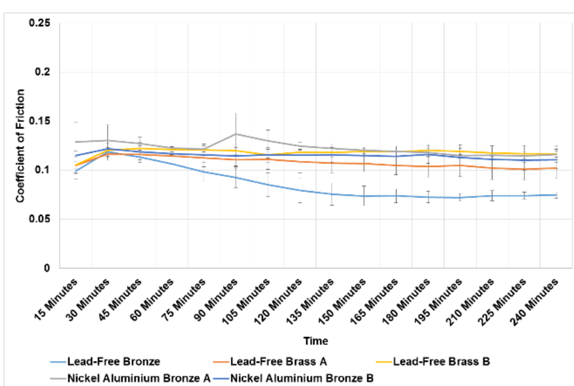


**Figure 11: Frictional response from steel / bearing material concept tribosystems during dynamic corrosion testing**

As can be observed in Figure 12, all tribosystems under evaluation exhibited similar frictional responses during seizure testing, whereby the coefficient of friction initially increased within the first 15 minutes of the test, before decreasing to a lower friction coefficient. The greatest frictional response was observed with the Steel / Lead-Free Brass tribosystems, respectively, with a final coefficient of friction of ~ 0.20. The lowest observed final frictional response was ~ 0.12, exhibited in the Steel / Nickel Aluminium Bronze tribosystems.

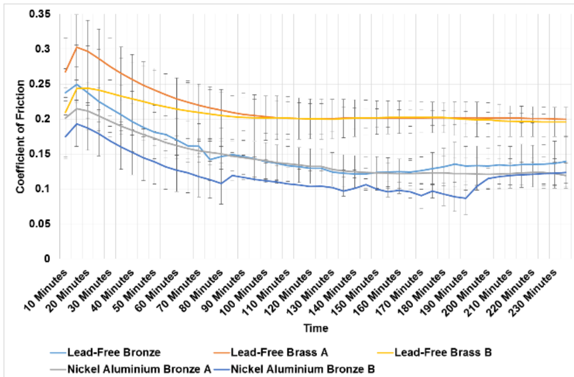


**Figure 12: Frictional response from steel / bearing material concept tribosystems during seizure testing**

## 4. DISCUSSION

The application of lead-free bearing technology to modern turbocharger tribosystems is a complex problem. This is because a commercial turbocharger bearing must continuously support applied loads without failure, whilst operating in corrosive environments and interacting with high speed ferrous-based components. The diverse range of lead-free bearing alloys evaluated herein have been subjected to a robust series of accelerated laboratory-based tests which simulated the worst-case environments found within a modern turbocharger.

### 4.1. Corrosion performance

Corrosion performance is a fundamental requirement of a bearing material because any change in the following may result in failure of other critical components within the turbocharger or failure of the turbocharger itself:

1. The dimensions or mass of the journal or thrust bearing
2. The friction, wear or mechanical properties of the journal or thrust bearing

The observed trend of superior corrosion resistance afforded by the Nickel Aluminium Bronze concepts can be accredited to the nickel (15) and aluminium (16) content within the alloy, with the latter forming a protective layer on the substrate (17). As reported elsewhere (17; 16), the dezincification witnessed in the brass materials under investigation must be minimised due to the potential for subsequent decrease in bearing performance. The unsuitability of the Lead-Free Bronze for use within corrosive environments is demonstrated by the reduction in both the dry lubricant and strength-affording (18) constituents of the alloy.

### 4.2. Tribological performance

Accelerated laboratory-based tribology testing has long been employed within the bearing industry to efficiently determine the most suitable bearing material for a given application (11; 9; 12; 10; 14; 19). The use of such a testing approach in this article has afforded a cost-effective method of evaluating bearing material performance *and* ensured a high level of data accuracy and repeatability.

The consistently excellent wear response exhibited by the two Lead-Free Brass bearing material concepts indicates their ability to be utilised as either a journal or thrust bearing and can be accredited to the manganese silicides within these alloys (20). Such constituents of the brasses supported the applied load placed upon the bearing material, separating the soft matrix from the steel counterpart (20). Referring to (9), it can be inferred that the greater wear performance possessed by Nickel Aluminium Bronze A compared to Nickel Aluminium Bronze B was as a result of the considerable increase in hard particles within the matrix of the former alloy (Figure 4) and its intrinsic mechanical properties (Table 1). Nickel Aluminium Bronze A appeared particularly suited to the application of a thrust bearing due to its low wear response in the associated test. The lack of hard particles within the Lead-Free Bronze concept and its low strength (Table 1) resulted in inferior wear performance compared to all concepts except Nickel Aluminium Bronze B.

The frictional response of a system can be accredited to the force required to shear adhesively bonded junctions and deformation of interacting surfaces (21). Therefore, it can be inferred that the consistently low frictional response afforded by the steel / Lead-Free Bronze tribosystem can be attributed, in part, to the significantly lower strength of this bearing material concept (Table 1) compared to the four other concepts under evaluation. The noticeably greater frictional response of the steel / Lead-Free Brass tribosystems during seizure testing highlights the additional energy required to deform such copper alloys when subjected to extreme conditions.

Although the dynamic corrosion and MOFT test conditions were very similar, the improved wear performance possessed by Nickel Aluminium Bronze A during the former test can be accredited to the corrosion products generated on contact surfaces during testing (22). It can therefore be inferred that the reduction in frictional response experienced by all tribosystems in dynamic corrosion compared to MOFT testing can be accredited in part to a decrease in the energy required for the generated corrosion products to undergo shear and deform, compared to nascent bearing material surfaces (22).

### 4.3. On-application performance

As a consequence of possessing a combination of excellent wear, stable frictional response and satisfactory corrosion performance when subjected to a wide range of laboratory-based tests, the two Lead-Free Brass concepts were selected for turbocharger-based corrosion and wear testing in the form of journal and thrust bearings.


**Figure 13: Turbocharger-based corrosion testing**

Whereas a leaded bronze material experienced significant corrosion in the form of pitting during turbocharger-based corrosion testing, there was no measurable corrosion of the Lead-Free Brass A surface, as shown in Figure 13. Indeed, the microstructure of the tested Lead-Free Brass A surface was comparable to its new state exhibited in Figure 4. When subjected to turbocharger-based wear testing, the Lead-Free Brass B journal bearings had experienced acceptable levels of abrasive wear, with examples of the resultant turbine end journal bearing condition shown in Figure 14.


**Figure 14: Lead-Free Brass B turbine end journal bearing post turbocharger-based wear testing**

Therefore, it can be stated that the observed laboratory-based tribology and corrosion performance of the two brass bearing material concepts has been realised in aggressive real world testing through effective modelling of the environments experienced by the turbocharger bearing system using worst-case fundamental test methodologies. Due to the high quality of acquired results, together with a low cost and short time duration associated with laboratory-based accelerated testing, it is envisaged that greater quantities of turbocharger-based experiments will be replaced with laboratory-based tests in the future.

## 5. CONCLUSIONS

A comprehensive series of laboratory-based and turbocharger-based testing has been conducted in order to evaluate the corrosion and tribological performance of a wide range of lead-free bearing alloys for use within a turbocharger.

Although the Nickel Aluminium Bronze A concept provided the most superior corrosion resistance of all alloys under evaluation due to the formation of a protective layer on the surface of the substrate, both Lead-Free Brass concepts possessed the greatest wear resistance because of hard manganese silicides present within their microstructure. The lowest overall frictional response was afforded by the steel / Lead-Free Bronze tribosystem, predominantly as a result of the low relative strength of the bearing concept, compared to the other alloys under investigation. As a result of excellent overall performance, the Lead-Free Brass concepts were selected for turbocharger-based corrosion and wear testing.

A high level of correlation in terms of bearing material corrosion and tribology performance was realised between laboratory-based and turbocharger-based testing. It is envisaged that a greater quantity of laboratory-based experiments will supersede their turbocharger-based equivalents due to an increase in data quality, reduction in test costs and decrease in test duration.

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