SMOOTH SLIDING

Consulting company providing engineering services on issues related to sliding bearings

pMax Black™ - Strengthened Tri-metal Bearing Materials for High Performance Bearings

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1. Introduction

The properties of Engine bearing materials determine how a bearing functions under conditions of alternating load, intermittent metal-to-metal contact with the journal and in the presence of impurities transported in the oil.
The structure and the characteristics of the materials used in a high performance bearing are particularly important because of the severe conditions under which it must operate, including high loads and high rotation speeds.

Here are the main properties of materials for engine bearings:

- **Load capacity (fatigue strength)** is the maximum value of cycling stress a bearing can withstand without developing Fatigue cracks after an infinite number of cycles.
- **Wear resistance** is the ability of the bearing material to maintain its dimensional stability (oil clearance) under conditions of mixed lubrication regime and in the presence of foreign particles carried by the lubricant.
- **Compatibility (seizure resistance)** is the ability of the bearing material to resist physical joining with the crankshaft journal when it contacts the bearing surface.
- **Conformability** is the ability of the bearing material to accommodate geometry imperfections of the journal, housing or bearing itself.

- **Embeddability** is the ability of the bearing material to absorb small foreign particles transported in the lubricating oil.
- **Corrosion resistance** is the ability of the bearing material to resist chemical attack from the lubricant or substances that may enter and contaminate the lubricant.
- **Cavitation resistance** is the ability of the bearing material to withstand impact stresses caused by collapsing cavitation bubbles, which form because of sharp and localized drops of pressure in the circulating lubricant.

Thus, to achieve durability and reliability from an engine bearing, its materials should paradoxically combine contradictory properties: high strength (load capacity, wear resistance, cavitation resistance) with softness (compatibility, conformability, embeddability.) [1].

2. Tri-Metal Bearing Structure

The contradictory combination of strength and softness may be achieved if the bearing material has a composite structure.
Engine bearings are composed of a steel back, onto which is applied a relatively strong base (copper or aluminum) combined with a solid lubricant in the form of either a thin overlay or small particles distributed throughout the base material.

Bearing material having a thin overlay is called tri-metal, in contrast to materials without any overlay – bi-metal.

Typical tri-metal and bi-metal engine bearing construction is shown in Fig. 1:

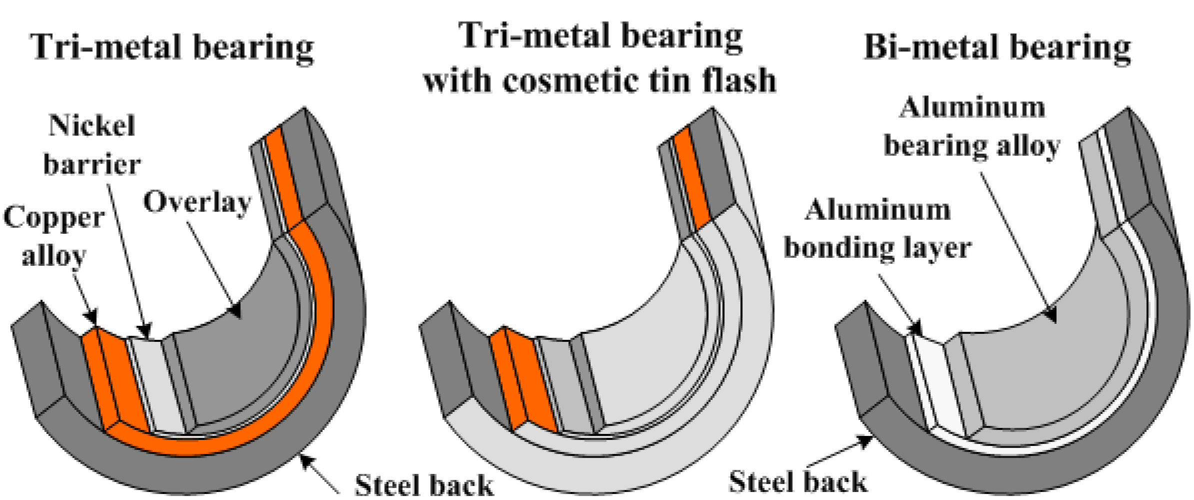

Fig.1 Engine Bearing Structure

Microstructure of a typical tri-metal bearing is shown in Fig. 2:

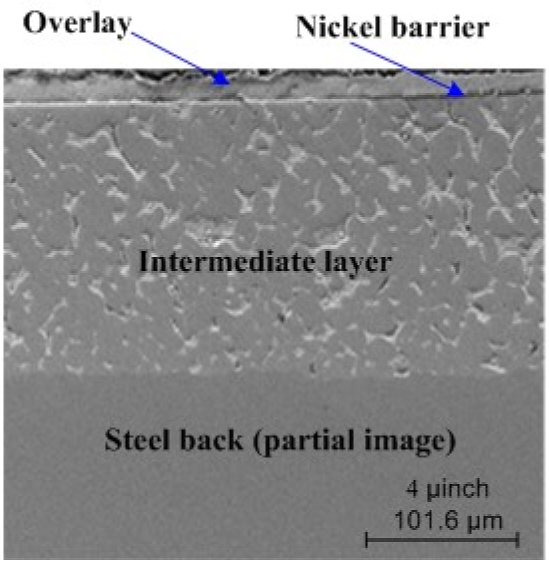

Fig.2 Microstructure of Tri-Metal Bearing

<u>Conventional tri-metal bearings are composed of the following layers [2]:</u>

- **Steel back** supporting the bearing structure and providing its rigidity and press fit under severe conditions of increased temperature and cycling loads.
- **Intermediate layer**, an alloy having minimal anti-friction properties (conformability, compatibility, embeddability), but high fatigue strength in order to provide bearing durability while working under alternating loads. It is applied onto the steel back surface by either casting or sintering. Its thickness is usually in the range of 0.008”-0.016”. The intermediate layer of conventional tri-metal bearings is composed of copper (the basic element), 22-25% lead and 2-3% tin. Lead in the form of separated particles distributed throughout the copper matrix serves as a solid lubricant and imparts anti-friction properties to the alloy. Tin forms tiny intermetallic inclusions with copper atoms which strengthen the material.
- **Nickel diffusion barrier (nickel dam)** is deposited between the intermediate layer and the overlay to prevent a migration of tin from the overlay into the intermediate material (copper). Diffusion of tin into copper decreases the tin content in the overlay, causing a deterioration of corrosion resistance of the lead-based overlay alloy. Nickel diffusion barrier thickness is about 0.00004”-0.00008”.

- **Overlay** which is commonly made of a leaded alloy containing 10% tin and 2-3% copper. The addition of tin increases the corrosion resistance of the alloy. Copper improves its fatigue strength (load capacity). Overlay thickness is typically in the range of 0.0005”-0.0008”. Lead based overlays, as well as nickel barriers, are deposited onto the intermediate layer by Electroplating.

3. High Performance Tri-metal pMax Black™ Structure with Increased Fatigue Resistance

The load capacity of a tri-metal bearing is determined by the fatigue strength of both the overlay and the intermediate layer.
The fatigue strength of the copper based intermediate layer is commonly higher than that of the soft lead based overlay. Therefore fatigue cracks initiate on the overlay surface. Overlay fatigue itself does not cause engine failure. However, bearings working with a fatigued overlay for an extended period of time will undergo partial flaking of their overlay. This will lower the oil film thickness and allow the possibility of destructive contact between the crankshaft journal and the bearing surface.

The fatigue of a copper based intermediate lining begins with the fatigue of its overlay. The overlay flakes out from the copper lining, resulting in a breaking of the oil film. This changes the lubrication regime from hydrodynamic to boundary. The load localizes at the contact area, causing a formation of small cracks on the lining surface .The cracks then propagate throughout the lining thickness, meet the steel back surface and continue to advance along the steel-copper boundary. As a result, parts of the intermediate layer detach from the steel surface [1]. Thus, both the strength of the overlay and the strength of the intermediate layer affect bearing operation and durability.
Load capacity for the pMax Black™ intermediate layer was reached (up to 17,000 psi) by changing two parameters: an increase of the tin content in the copper base alloy and a greater cold work treatment (cold rolling) of the steel-bronze strip.
Tin strengthens copper alloys. Intermediate layer alloys of conventional high performance bearings contain 2-3% tin. The hardness of such alloys is commonly 90-95 HV.
The hardness of the intermediate layer of pMax Black™ was increased (by 20-25%) to 110-115 HV. This was achieved by increasing the tin content of the copper alloy to 4-5%, and by a greater amount of cold work (cold rolling of the strip with an increased thickness reduction). The harder intermediate layer provides more reliable bearing operation under high load.
The main factor affecting the load capacity of a tri-metal bearing is the fatigue strength of the overlay. Therefore the primary focus for pMax Black™ was to develop an overlay having increased fatigue strength.

Consider the overlay properties that exert an influence on its fatigue strength:

- **Thickness of the overlay.** Fatigue strength of a thin overlay differs from fatigue strength of a bulk material. Such difference is caused by the supporting effect of the substrate onto which the overlay is deposited.

In the case of tri-metal bearings, the substrate is an intermediate copper based alloy. The overlay is adhered to the substrate surface. Therefore the overlay dimensions at the interface between the two materials cannot distort more than the dimensions of the intermediate material when a load is applied to the bearing.
Since the modulus of elasticity of the copper alloy (15*106 psi) in the intermediate layer is much higher than that of the overlay leaded alloy (2*106 psi), the stress in the overlay induced by the load is much lower than the stress in the intermediate layer. This is in accordance with the relationship: $\sigma = E*\varepsilon$ (E- modulus of elasticity, ε – the strain at the interface).
However, the ratio between the elasticity modules of the materials is equal to the ratio between the stresses only for ultra-thin overlays. The thicker the overlay, the less its surface is affected by the mechanical properties of the substrate material. The graph in Fig. 3 demonstrates the effect of the thickness of a lead base overlay on its fatigue strength. The data was obtained in experiments performed with the King test rig.

Conventional tri-metal bearings for street use engines have an overlay with a thickness of about 0.0007”.
The thickness of the overlay for highly loaded race use bearings should be less than that of street engine versions.
The pMax Black™ structure features an overlay of 0.0005”, which combines increased fatigue strength with good anti-friction properties.

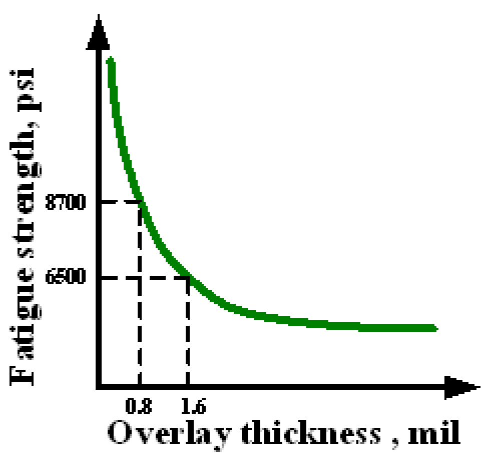

Fig.3 Effect of Overlay Thickness on its Fatigue Strength

- **Bulk strength/hardness** of the overlay material. Common overlay material is made of leaded alloy containing tin and 2-3% copper. Tin content exerts a negligible influence on the mechanical properties of the alloy. On the other hand, copper is added to increase the material strength and hardness.

Our tests prove that an increase of copper from 2.6% to 5.1% in a leaded alloy result in an increase of alloy hardness from 12.3 HV to 18.3 HV. Higher copper content also increases the fatigue strength of the overlay alloy.
In contrast to conventional high performance bearings, the pMax Black™ overlay material of King XP series high performance bearings contains 5% copper, providing higher fatigue strength.

- **Surface hardening.** The surface condition of a material is crucial to its fatigue strength. Fatigue cracks form on the surface and then propagate into the material bulk. The higher the hardness of the surface layer, the greater the load must be in order for cracks to initialize.

One of the most effective methods of increasing fatigue strength of a metal part is Shot peening. This is a cold work process in which a metal part is struck by a stream of small hard spheres (shot). They create numerous overlapped dimples on the part surface [3]. Shot peening produces a hardened compression stressed skin which resists the formation of fatigue cracks.
Unfortunately, shot peening is not effective as a treatment for soft leaded alloys, due to their low strain hardening effect.
An alternative and effective method of surface hardening lead based overlays has been developed by King Engine Bearings. This innovative technique enables the formation of an ultra-thin hardening of the overlay surface. It is an essential component of the pMax Black™ overlay.
All King XP series high performance bearings are manufactured with the pMax Black™ structure and its hardened pMax Black™ overlay. These bearings are easily recognizable by their distinctive dark black color. This is an attribute resulting from King's proprietary surface hardening process (Fig. 4).
The pMax Black™ overlay surface hardness has a nano-scale thickness. It is sufficient to suppress the formation of fatigue cracks on the overlay surface. It has proven its effectiveness in increasing the fatigue strength of high performance tri-metal bearings.

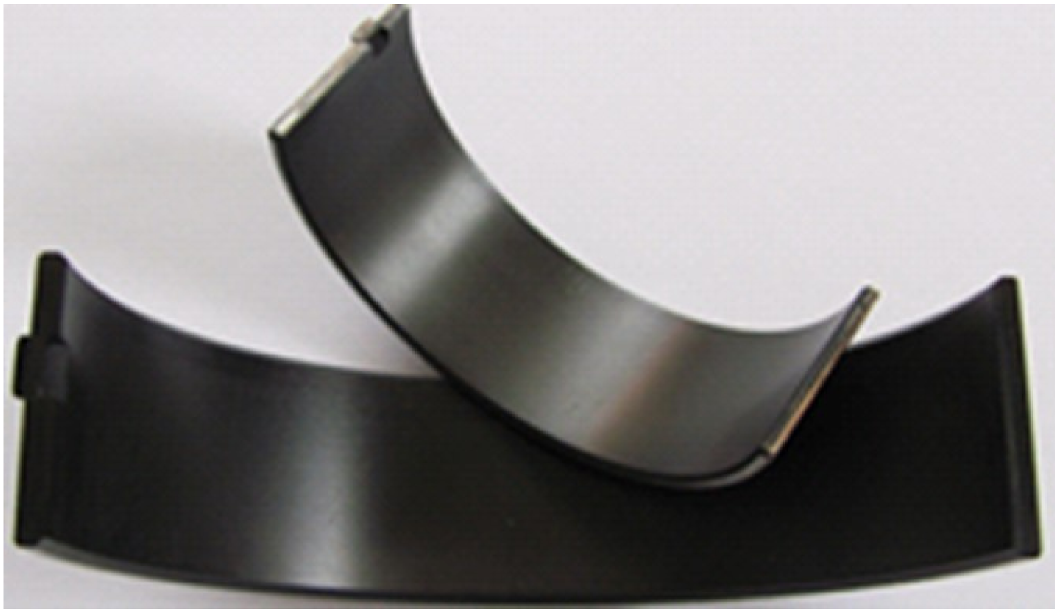

Fig.4 King pMax Black™ Bearings

4. Validation of pMax Black™ Structure

pMax Black™ was tested by two different methods:

- Test Rig
- Dynamometer

a. Validation of pMax Black™ in Test Rig Machine

The tests were performed in the test rig designed and manufactured by King Engine Bearings (Fig. 5)

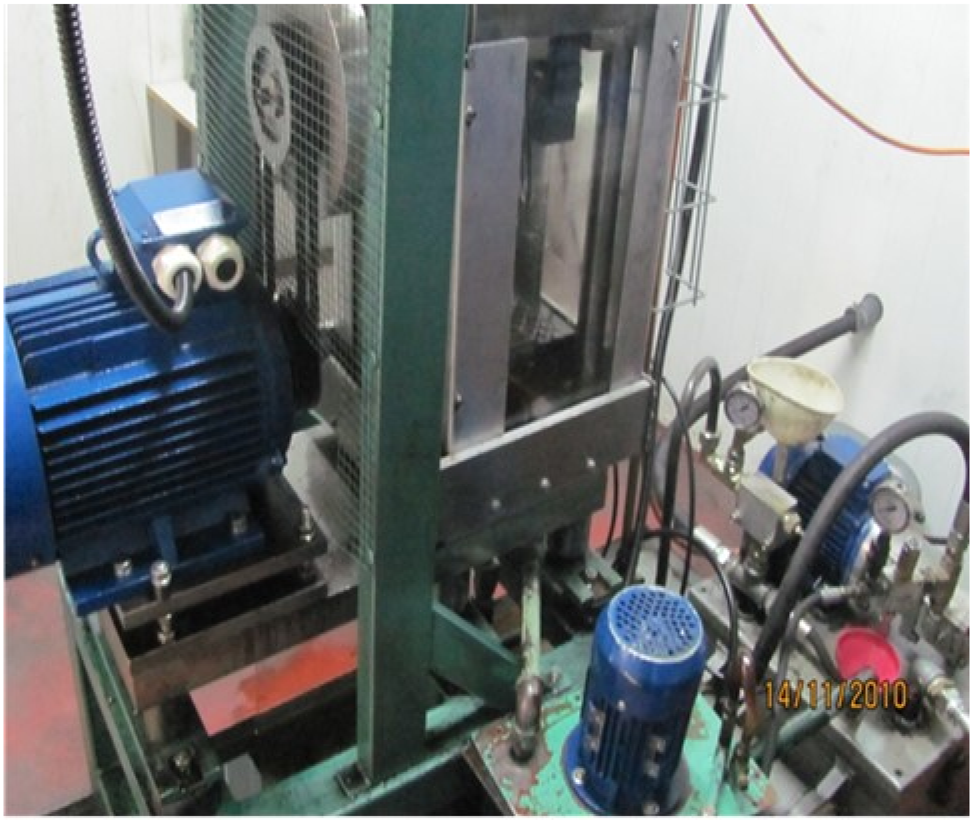

Fig. 5 Test rig machine of King Engine Bearings

The test rig uses an eccentric shaft located between two concentric shaft parts. The test bearing coupled with the eccentric shaft is mounted in the big end of the connecting rod. Rotation of the eccentric shaft results in reciprocating motion of the connecting rod [4]. The shaft is driven by an electric motor. The rotation speed of the test rig may be varied within the range of 1500-5000 RPM. Load is created by a hydraulic cylinder.

The experimental bearings were tested with a reciprocating load in the range of 9500 to 12,000 psi.

Test duration: 24 hrs;

Rotation speed: 3000 RPM

Number of cycles: 4,300,000

Note:

All our data regarding the load capacity of different materials was obtained in our test rig under similar test conditions. It is incorrect to compare load carrying capacity measured in different test rigs. There is no standardized scale method of bearing fatigue testing. Bearing manufacturers use different equipment and different test conditions, which produce different results for the same material. Therefore, only results obtained under the same conditions and in the same test machine may be compared.

The rig tests results:

The effects of increased copper content in the **pMax Black™** overlay alloy and of the surface hardening treatment on the load capacity of the bearings have been determined in a series of rig tests using King high performance bearing C 697.
The bearings were tested at a load of 9500 psi, which is above the load capacity of conventional tri-metal bearings.
The bearings with conventional overlay composition (Sn 10.3%, Cu 2.6%, Pb balance) and hardened surfaces passed the test without the formation of fatigue cracks. However, their sufaces did exhibit shiny areas of slight wear (Fig. 6A).
Also similar in appearance were the bearings with a non-hardened surface – but with an increased copper content in the overlay (5.1% Cu) (Fig. 6B).

A B C

Fig.6 High Performance Bearings C 697 after King Rig Test (9,500 psi, 4,300,000 cycles)
A – copper content 2.6%, hardened surface
B - copper content 5.1%, non-hardened surface
C – copper content 5.1%, hardened surface (XP bearing)
Bearing performance improves significantly when both factors (higher copper content and surface hardening treatment) take place. The bearing completes the test in excellent condition: no fatigue cracks, no wear marks, no seizure (Fig. 6C).
For comparison purposes, a conventional high performance bearing (non-King bearing) was tested under the same conditions. The bearing was similar to King C 697. It had the same dimensions, but its overlay was conventional (copper content 2.8%, no surface treatment). The tested bearing is shown in Fig. 7.

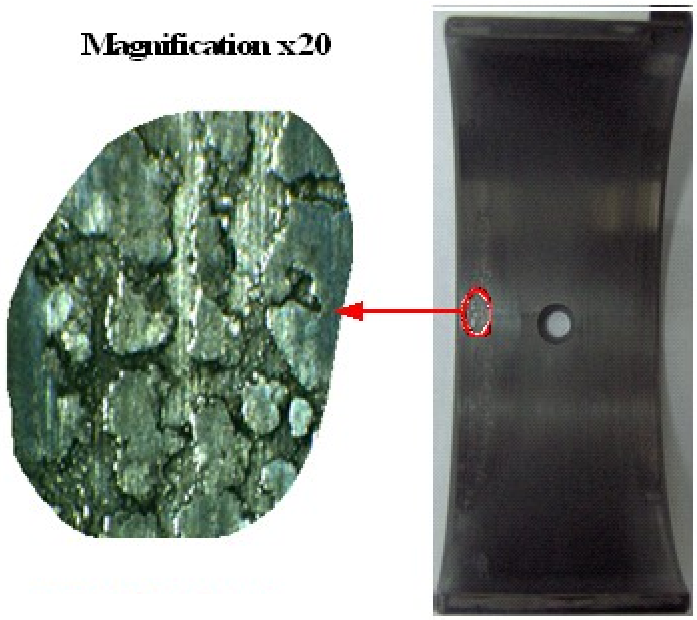

Fig. 7 Conventional high performance bearing (a competitor bearing similar to King C 697) after King rig test (9500 psi, 4,300,000 cycles)

Overlay fatigue cracks are clearly seen in the magnified picture.
It is evident that the load capacity of the bearing material was below the test load (9500 psi).
According to our rig tests, the conventional lead based overlay has a fatigue limit of about 8700 psi.

In order to determine the load capacity of the developed **pMax Black™** structure, King high performance bearings C 807XP were tested under different loads in the range of 9500 to 12,000 psi.
The bearings proved excellent performance under loads of 9500 psi and 10,200 psi (Fig. 8).
A further increase of load resulted in the formation of overlay fatigue cracks.

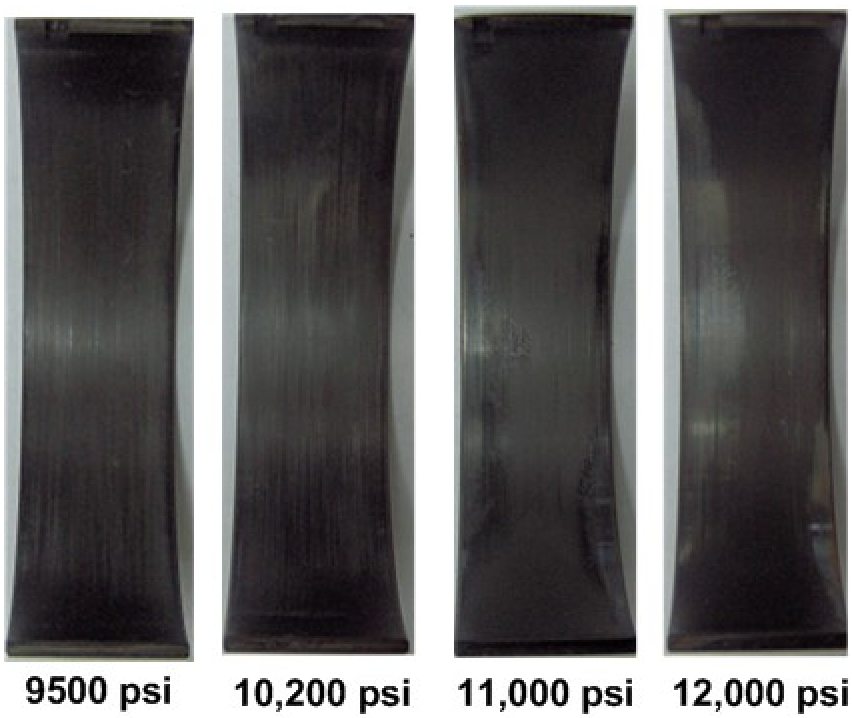

Fig.8 King C 807XP Bearings after King Rig Test at Different Loads (4,300,000 cycles)

The test were repeated several times. According to their results, the fatigue strength of pMax Black™ was determined: 10,200 psi. It is 17% greater than the fatigue limit of conventional tri-metal bearings.

A conventional high performance bearing similar to King C 807XP was tested at a load equal to the fatigue resistance of pMax Black™.
A photograph of the tested bearing is presented in Fig.9.
In contrast to King XP series bearings, the conventional high performance bearing has a large area of overlay fatigue cracks. The cracks are shown in the magnified image (Fig. 9).

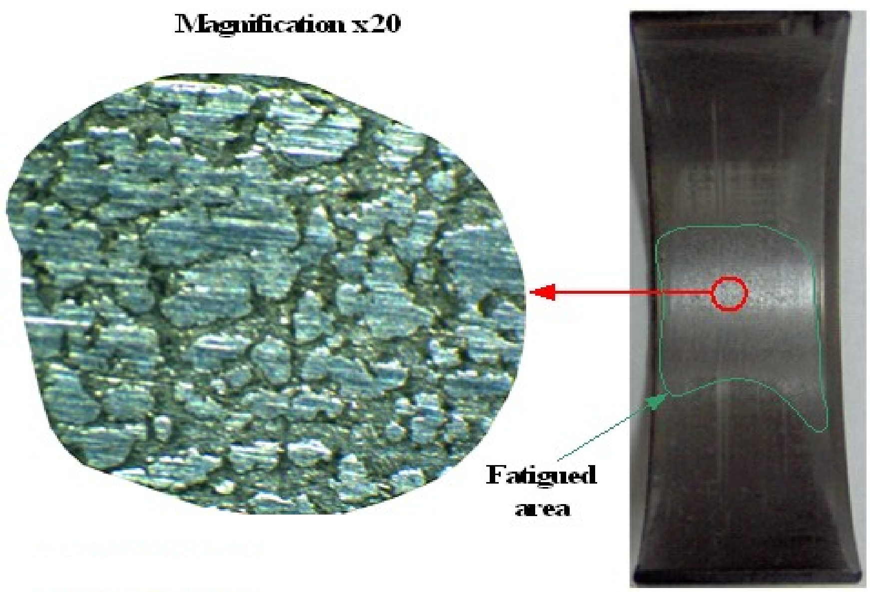

Fig.9 Conventional High Performance Bearing (non-King, similar to King C 807XP) after King Rig Test (10,200 psi, 4,300,000 cycles)

b. Validation of pMax Black™ in dynamometer

The tests were performed on King's Power Test dynamometer.
Tested engine: high performance Chevy 355.
King bearings: CR 807XP (connecting rod bearings) and MB 557XP (main bearings) were installed in the engine.

Fig.10 High performance Engine Chevy 355

Test conditions:

- Torque: 390 ft-lb
- Rotation speed: 5000 RPM
- Power: 371 HP
- Test duration: 100 hrs
- Number of cycles: 30,000,000

Test results:

Two types of King connecting rod bearings C 807XP were tested: full surface bearings and bearings with a reduced surface area (a groove with a width of 1/3 of the full surface).
The two types of bearings, after dynamometer testing, are shown in Fig. 11.

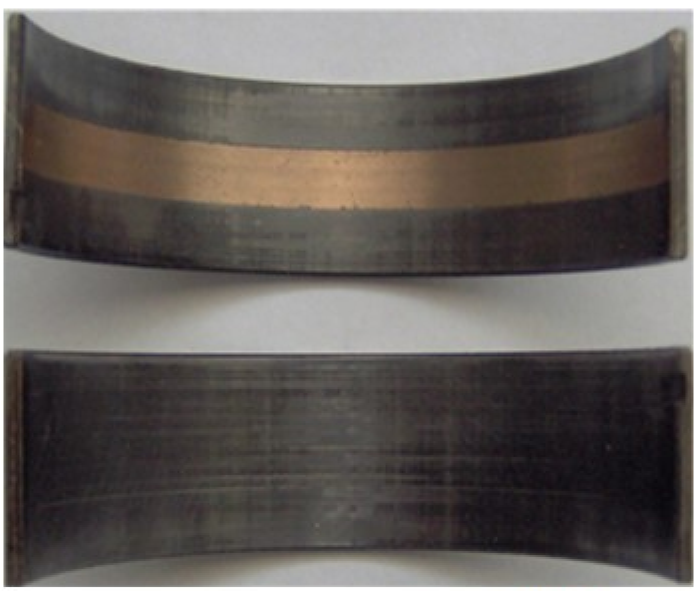

Fig. 11 King high performance C 807XP bearings after dynamometer test

5. Conclusions

- A new tri-metal bearing material for high performance applications – pMax Black™ – has been developed by King Engine Bearings.
- The intermediate layer of pMax Black™ is stronger than that of conventional high performance bearings due to a combination of cold work and an increase of tin content from 2-3% to 4.5%. The hardness of the intermediate layer has increased from 94 to 112 HV.
- The pMax Black™ overlay has higher fatigue strength due to its lower thickness and higher copper content (increased from 2-3% to 5%). Its hardness is 18.3 HV. This is a significant increase compared to conventional high performance overlays - their hardness is 10.3-14.2 HV.
- Fatigue resistance of the pMax Black™ overlay has been additionally increased by a proprietary surface hardening technique developed by King Engine Bearings. The treatment produces a hardened overlay surface of nano-scale thickness. The hardened surface suppresses the formation of fatigue cracks.
- The experiments using King's test rig demonstrated that fatigue resistance of the pMax Black™ overlay is 10,200 psi. This is 17% greater than that of conventional tri-metal bearings (8700 psi).
- **pMax Black™** XP series bearings have been successfully tested on the King Engine Bearings dynamometer in a high performance Chevrolet 355 engine. It has been proven that even the bearings with a narrowed surface (2/3 of the original) passed the test.

6. References

[1] Dmitri Kopeliovich (2011), The Proper Selection of Engine Bearing Materials, AERA., April-June 2011, p.48-62
[2] Dmitri Kopeliovich (2013), Engine bearing materials, SubsTech (Substances&Technologies), Available from http://www.substech.com/dokuwiki/doku.php?id=engine_bearing_materials
[3] Dmitri Kopeliovich (2013), Shot peening, SubsTech (Substances&Technologies), Available from http://www.substech.com/dokuwiki/doku.php?id=shot_peening
[4] Dmitri Kopeliovich (2013), Engine bearing fatigue test, SubsTech , Available from http://www.substech.com/dokuwiki/doku.php?id=engine_bearing_fatigue_test