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High strength tin-based overlay for medium and high speed diesel engine bearing tribological applications

Yi Zhang*, Ignacio Tudela, Madan Pal, Ian Kerr

Daido Metal Co. Ltd., the European Headquarters, Winterhay Lane, Ilminster TA19 9PH, UK

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ABSTRACT

Tin-based materials are often used as lead-free overlay for half shell bearings in medium and high speed diesel engines for their high resistance to cavitation and corrosion damages and excellent conformability and embeddability for engine tribological applications. Tin-based overlay also offers reasonable fatigue resistance but in order to satisfy the more and more exigent demand of future engine developments especially those fired by natural gases to minimize emissions, a multilayer tin–copper overlay system is herein proposed to overcome the structural weaknesses of traditional monolayer tin–copper overlay therefore provide enhanced tribological performances.

1. Introduction

Plain bearings are important components in internal combustion engines. They are designed to convert the reciprocating motion of the pistons into the rotary motion of the crankshaft. Bearings must be constructed to be strong enough to withstand the ever increasing fatigue loads involved but also soft enough to conform to variations in alignment. During the 720° firing cycle of an engine the bearing is required to resist wear under a range of different lubrication conditions while at the same time being soft enough to embed debris that could otherwise score the journal.

Scientists concentrating on plain bearing design in the past 50 years have found that bearing material selection for any given application is invariably a compromise of surface properties, mechanical strength, and corrosion resistance [1–4]. In order to satisfy increased engine demands, the modern plain bearing usually adopts a complex structure [5].

Plain bearings of internal combustion engine include a metallic copper or aluminium alloy, generally referred to as the lining, which is bonded to a steel backing. The copper or aluminium alloys provide a strong yet tribologically friendly layer that can withstand the loads subjected on the bearing in use. Plain bearings should also exhibit suitable seizure resistance as well as good embeddability and conformability, and for this purpose a soft coating, or overlay, is usually added on top of the lining layer [6].

Electroplated tin-based overlays have proven to be a highly effective replacement for use in large medium speed diesel (MSD) engines where their excellent sliding properties, and high corrosion resistance coupled with reasonable mechanical strength [6] make them extremely effective. However, environmental pressures driving towards lower NOx combustion and higher fuel efficiency are set to raise firing loads above the capability of many current materials in this market. At the same time the proliferation in use of gas fired engines, driven by the projected future availability of cheap gas from fracking is also driving up firing pressures. However the product lifecycle for MSD engines is very long which means the market is necessarily conservative when it comes to selecting new materials. The closer new materials can be to the existing materials the better. Finally alternative production methods such as PVD, although cost effective for smaller components, are uneconomic for bearings of this size range.

In this study a new multilayer tin–copper overlay system is proposed to overcome the structural weaknesses of traditional monolayer tin–copper overlays therefore provides enhanced tribological performances. Various tribometer tests were carried out on the newly developed multilayer overlay to verify the properties. The bearing structures after rig tests were also investigated to reveal the mechanism behind the performance improvements.

2. Experimental setup and specimens

2.1. Specimen

The newly developed multilayer overlay was deposited on a range of different test pieces, including standard semi-circular

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* Corresponding author. Tel.: +44 1460 256268; fax: +44 1460 256205.
E-mail address: Yi.Zhang@daidometal.com (Y. Zhang).

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bronze bearings or flat bronze test pieces. A benchmark monolayer overlay that is already commercially available was also deposited.

Prior to the application of overlay the bronze substrate was degreased in a commercial alkaline cleaner then etched in a 30 vol % hydrochloric acid and finally electrochemically covered by a 2–3 μm nickel to act as a diffusion barrier layer between the overlay and bronze substrate.

The benchmark monolayer tin–copper overlay was electroplated from an electrolyte containing fluoroboric acid, tin fluoroborate, copper fluoroborate and proprietary additive package at 3.5 A dm^{-2} and room temperature.

The novel multilayer tin–copper overlay was manufactured by the combination of electroplating and thermal annealing. The top and bottom tin–copper sublayers were electroplated from the same electrolyte under same conditions whilst an additional sublayer of nickel was inserted into the structure between the top and bottom tin–copper sublayers. The nickel sublayer was electroplated from Watt's bath at 4.0 A dm^{-2} at 50 °C. After plating the multilayer overlay was thermally annealed to convert the nickel sublayer into nickel–tin intermetallic compound sublayer. Table 1 shows the details of the benchmark monolayer and proposed multilayer overlay structures.

2.2. *Material characterization*

The cross-sectional microstructure before and after rig tests was characterised using a Scanning Electron Microscopy (JEOL 6610 LVSEM) at an accelerating voltage of 15–20 ke V which was also equipped with an Energy Dispersive X-ray Spectroscopy (EDX-Oxford Instrument AzTEC) for compositional and elemental mapping analysis.

The microhardness measurements were performed on the overlay cross section with a Mitutoyo MicroWizhard HM221 hardness tester. The indentation loads of different levels were applied to the test areas, depending on the hardness of the material to be measured, for 10 s, and then the hardness was determined by measuring the average length of the diamond diagonal left by the indenter.

2.3. *Tribological testing*

Fatigue resistance, wear resistance and seizure resistance were all measured on dedicated tribometers. In each case, as well as measuring the quantitative results, subsequent investigations were carried out using SEM, EDX and other equipment to determine the underlying mechanisms.

3. Results and discussions

3.1. *Material microstructure*

Fig. 1(a) shows the microstructure of the benchmark monolayer tin–copper overlay. The different sections of the bearing are highlighted as A, B C and D. A is the lead bronze substrate with lead islands clearly shown in white colour; B is the nickel barrier layer designed to separate the bronze substrate and the tin–copper overlay in order to avoid detrimental diffusion problems [7]; C is the benchmark monolayer tin–copper overlay. The intermetallic compound particles of Cu_6Sn_5 D are distributed in the matrix. The distribution of the intermetallic compound particles is uniform which acts as a precipitation strengthening phase in the matrix and makes the overlay suitable for engine bearing applications.

Table 1
Benchmark monolayer and proposed multilayer overlay structures.

		Monolayer	Multilayer
1st layer, top	Material	Sn–Cu (3 wt%)	Sn–Cu (3 wt%)
	Thickness	20 μm	8 μm
2nd layer, middle	Material	n/a	Sn–Ni (27 wt%)
	Thickness	n/a	4 μm
3rd layer, bottom	Material	n/a	Sn–Cu (3 wt%)
	Thickness	n/a	8 μm

An EDX linear compositional analysis was carried out in perpendicular direction from the overlay surface to the bronze lining as indicated by the red arrow in Fig. 1(b). The results indicate that a tin based overlay of approximate 20 μm was deposited over the bronze substrate with a nickel barrier layer of 2 to 3 μm in between. The overlay matrix is tin with a fraction of copper as the second phase to strengthen the matrix and improve the mechanical properties of the system [7].

The newly developed multilayer tin–copper overlay is shown in Fig. 2(a). Instead of a monolayer tin–copper overlay of Fig. 1(a) two tin–copper sublayers, C are separated by a tin–nickel middle sublayer, E. Again the overlay was laid on a nickel plated bronze substrate A. Another difference noticed between the monolayer overlay and the multilayer overlay is the distribution of intermetallic compound, D. In the monolayer structure the intermetallic compounds exists as particles and is uniformly distributed in the matrix. The intermetallic compound in the multilayer overlay on the other hand is no longer noted as the second phase in the matrix. Instead the majority of them migrated into the areas between the tin–copper sublayers and the tin–nickel middle sublayer after thermal annealing. It was also found that after thermal annealing some of the original nickel barrier layer B was converted into tin–nickel intermetallic compound layer B1. The nickel diffusion barrier B and the tin–nickel intermetallic layer B1 combined and functioned as an upgraded barrier layer in the multilayer system.

Fig. 2(b) shows the EDX linear compositional analysis results of the multilayer tin–copper overlay system. The analysis was again carried out in perpendicular direction from the overlay surface to the bronze lining as indicated by the red arrow. The upper 8 to 9 μm is a tin–copper sublayer with the composition being predominately tin after thermal annealing. The middle sublayer is approximate 4 μm comprising of mainly tin and nickel with some tin–copper intermetallic migrated from the top and bottom tin–copper sublayers. The lower sublayer is 8 μm of tin–copper. Unlike the nickel barrier layer shown in Fig. 1(b) the barrier layer in the multilayer system contains both nickel and tin–nickel intermetallic.

3.2. *Fatigue resistance*

The fatigue performance of the overlays was characterized by a dynamic load fatigue tribometer. The arrangement of the tribometer, the test conditions and the results are shown in Fig. 3. The tribometer applied a dynamic load to the test bearing by rotating an eccentric test shaft within the test bearing. High housing rigidity ensures excellent stability and this test can be performed under heavy specific loads that are two to three times the load in an actual engine. The dynamic load is applied as the results of oil film pressure between the bearing and the shaft due to the motion of the shaft. After the test the bearings were taken out, cleaned, visually examined with a × 10 loupe and the fatigue of the test piece was evaluated. The pass criteria was no visible fatigue cracks on the material surface.

The monolayer tin–copper overlay passed the 30 MPa test without any visible surface fatigue cracks. However it failed straightaway when the test load was increased to 40 MPa showing severe fatigue damage. Fig. 4 reveals the surface of the monolayer