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NOVEL BISMUTH-BASED TRIBOLOGICAL COATINGS FOR HIGH PERFORMANCE INTERNAL COMBUSTION ENGINE BEARING APPLICATIONS

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ABSTRACT

Bismuth-based coatings are often used as lead-free overlay materials for half shell bearing of internal combustion engines due to their high resistance to fatigue and wear. The present work shows how different approaches can have an effect on the microstructure of said bismuth-based overlay coatings, consequently optimize their mechanical and tribological properties, enabling the manufacturing of bismuth-based overlays with wider thickness range and therefore further enhanced their performances for modern engine applications.

Keywords: bismuth, bearings, electroplating, internal combustion engines, tribology.

INTRODUCTION

Current bismuth-based coatings exhibit a great performance in terms of fatigue and wear resistance when applied as lead-free overlay materials in either both bronze-based (Kawachi, 2005) or aluminium-based (Kerr, 2007) bearings in high-load engines. Despite this, the emerging trends in the design of modern internal combustion engines (low friction components, thinner oil films, low viscosity lubricants, engine downsizing, turbo-boosting, stop-start cycles, etc.) aiming at reducing mechanical and parasitic power losses in order to achieve maximum fuel efficiencies and lower carbon footprints will lead to engine components operating in arduous and more demanding operating conditions. This will result in higher fatigue loads, higher operating temperatures and greater asperity contact, implying the potential occurrence of mixed-film or even boundary lubrication which would accelerate wear and seizure of the components.

In order to further improve the good tribological performance of current bismuth coatings in terms of wear and seizure, lubricant WS₂ particles were incorporated into the bismuth coating by using a novel sono-electroplating method (Tudela, 2014 A). The main objective was to incorporate a lubricant phase into the coating and modify the microstructure of the bismuth benchmark coating in order to enhance wear and seizure resistance and hence further improve the overall tribological performance of the coating.

METHODOLOGY

Bronze substrates with standard bismuth-based (STD Bi) coatings such as those currently used in the automotive sector (Kawachi, 2005; Kerr, 2007) were prepared by electrodeposition from an alkylsulfonic acid-based plating bath with a proprietary additive

package. Before the electrodeposition, the surface of the bronze substrates was electrochemically degreased with a commercial alkaline cleaner and anodically etched in an acid solution to ensure good adhesion of the STD Bi coating to the bronze substrate.

The novel bismuth-based coatings with WS_2 particles ($Bi+WS_2$) here presented were also prepared from the same bath formulation following the basic procedure previously described but with some differences. In this case, WS_2 particles were previously dispersed in the alkylsulfonic acid-based plating bath with the aid of ultrasound, and then $Bi+WS_2$ composite coatings were sono-electrodeposited in the bath (Tudela, 2014 A). Ultrasound was used due to the improvement in particle dispersion and incorporation into the coating that can be achieved in presence of ultrasonic cavitation (Tudela, 2014 B).

Focused Ion Beam - Scanning Electron Microscope (FIB-SEM) analysis of the STD Bi and $Bi+WS_2$ coatings was carried out with a FEI Nova 600 Nanolab Dualbeam system to study the of the surface morphology and crystal structure of all the bismuth-based coatings. Lubricated scratch tests were performed on all coating materials to evaluate the effect that the modification of the structure had on the Coefficient of Friction (CoF) of the STD Bi coatings. Tests were carried out with a UMT UMT Scratch Tester (Bruker) on bronze samples coated with 15 μm bismuth-based coatings where lubrication of the surface was achieved via one single drop of lubricant immediately before starting the test. The scratch test conditions were:

- Sliding distance: 10 mm
- Sliding speed: 10 mm/min
- Load: 0-200 N (progressive)
- Ball diameter: 6.3 mm
- Ball material: JIS SUJ2 - ISO 100Cr6
- Lubricant: SAE 10 oil

Wear and seizure tests were also performed on all coating materials to have an initial idea of the tribological performance of the novel coatings. The coatings (15 μm) were electrodeposited on special bronze samples (Fig. 1) to be used on a ring (shaft)-on-disk tribometer (Fig. 2). The test conditions for the wear and seizure tests are included in Table 1.

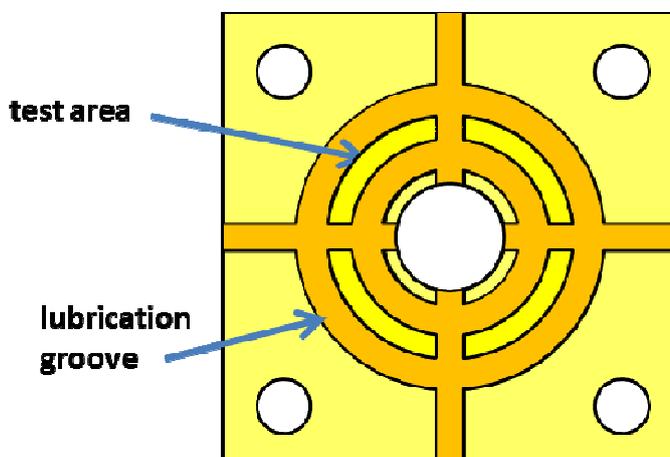


Fig. 1 - Samples used for wear and seizure tests in TE92 rotary tribometer

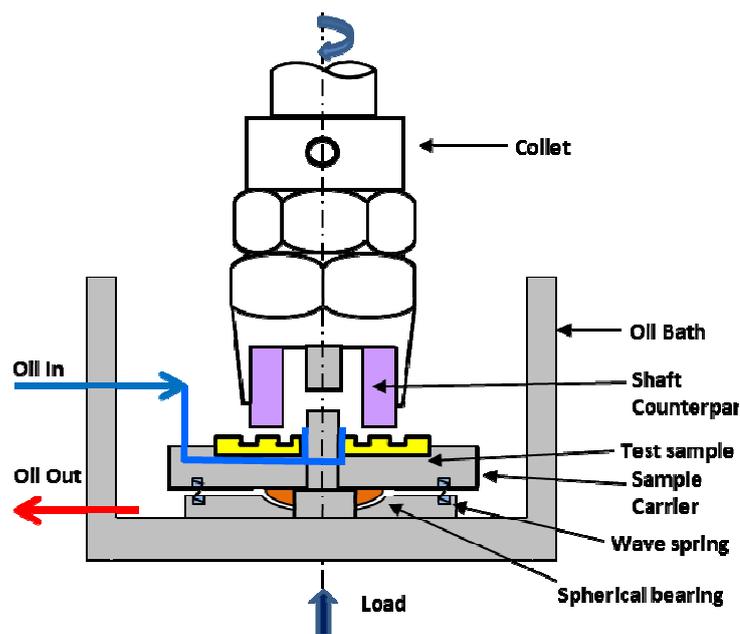


Fig. 2 - Diagram showing experimental set-up for wear and seizure tests conducted in TE92 rotary tribometer

Table 1 - Operational conditions for wear and seizure tests conducted in TE92 rotary tribometer

	Wear tests	Seizure tests
Sample dimensions	Outer diameter = 27.2 mm Inner diameter = 22 mm	
Load	1MPa increase every 2 minutes up to 12MPa, then constant at 12 MPa	1 MPa increase every 5 minutes
Sliding speed	0.05 mm/s	2 mm/s
Lubricant	SAE10 oil	
Inlet lubricant temperature	60 °C	
Lubricant flow rate	5 ml/min	20 ml/min
Sliding distance	400 m	until seizure
Shaft counterpart	case hardened EN36	
Shaft hardness	500~600 Hv10	
Shaft roughness	0.3µm (R _{max})	0.5µm (R _{max})

RESULTS

Fig. 3 displays FIB-SEM images from the surface and the cross-section of the different bismuth-based coatings here evaluated. Electrodeposited STD Bi coatings exhibited a smooth surface morphology (Fig. 3A) consisting of pyramid-alike crystals that improve the lipophilic

properties and oil wettability of overlay in bearing applications (Kawachi, 2005). These crystals mostly presented the classical columnar-like structure (Fig. 3B) commonly observed in thick electrodeposited coatings (Paunovic, 2010). The surface of the Bi+WS₂ composite coatings was slightly rougher, as the surface was covered with large nodular structures (Fig. 3C). Bismuth crystals were again pyramid-like bismuth crystals, although in this case they seemed smaller. Further evaluation of the cross-section of the Bi+WS₂ composite coating (FIG. 3D) showed that the coating consisted of rounded and finer Bi crystals with no presence of the lengthy columnar-alike structures observed in the pure Bi coatings.

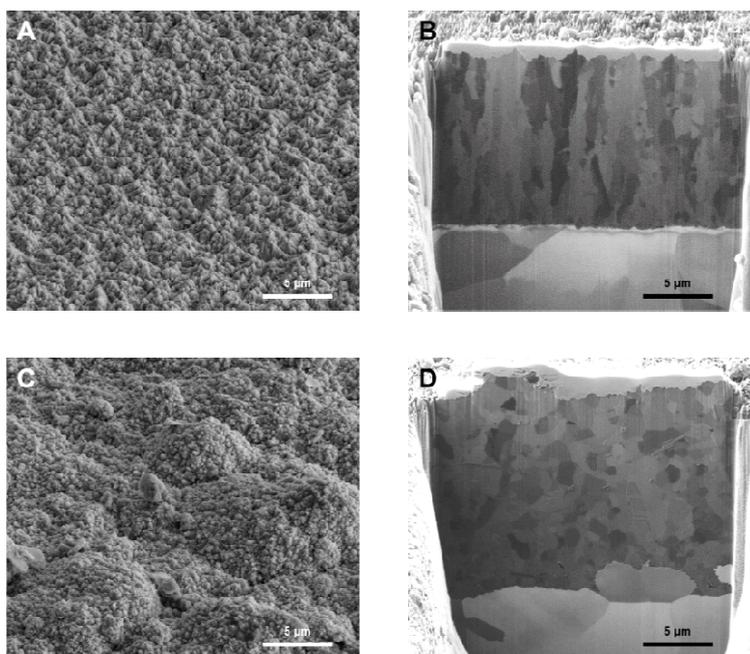


Fig. 3 - FIB-SEM images of STD Bi (A: tilted view of surface, B: *in situ* cross-section) and Bi+WS₂ (C: tilted view of surface, D: *in situ* cross-section) coatings electrodeposited on bronze substrates

CoF curves obtained in the scratch tests performed on STD Bi and Bi+WS₂ composite coatings are displayed in Fig. 4. CoF measured for the Bi+WS₂ composite coatings was significantly lower than CoF measured for the STD Bi coatings, demonstrating the improvement in terms of CoF that can be achieved when soft lubricant particles such as WS₂ are successfully incorporated into electrodeposited metal coatings.

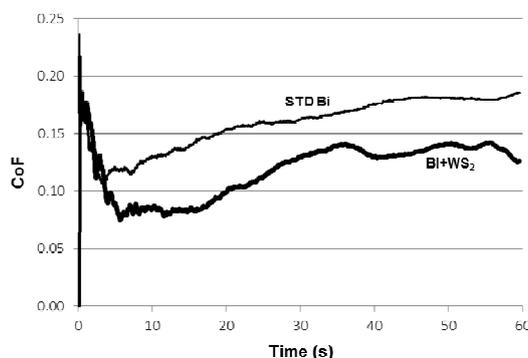


Fig. 4 - CoF curves obtained during lubricated scratch tests performed on 15 μm STD Bi and Bi+WS₂ coatings electrodeposited on bronze substrates.

The average wear measured on STD Bi and Bi+WS₂ coatings after wear tests is displayed in Fig. 5. The novel composite coating exhibited higher wear resistance when compared with the

STD Bi coating, as wear loss in the composite coatings was $\approx 16\%$ lower than in the benchmark material.

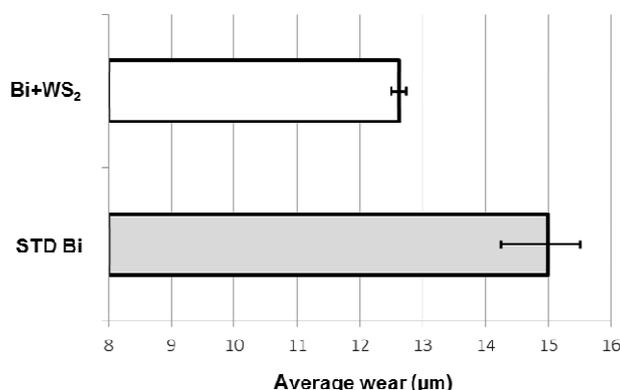


Fig. 5 - Wear measured on 15 µm STD Bi and Bi+WS₂ coatings electrodeposited on bronze substrates after wear tests

The average maximum load without seizure measured on STD Bi and Bi+WS₂ coatings during seizure tests is displayed in Fig. 6. Remarkably higher loads without seizure were reached when testing the Bi+WS₂ composite coatings than when testing the STD Bi coatings. In addition, the measured loads were significantly more consistent for the novel composite coatings than for the benchmark coatings, indicating the improvement in terms of seizure resistance and reliability achieved in bismuth coatings when WS₂ particles are successfully incorporated into them.

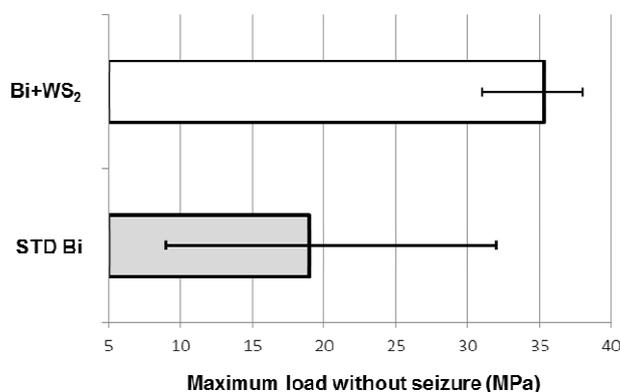


Fig. 6 - Maximum loads without seizure measured on 15 µm STD Bi and Bi+WS₂ coatings electrodeposited on bronze substrates during seizure tests

DISCUSSION

The incorporation of WS₂ particles into bismuth coatings with the aid of ultrasound during electrodeposition results in novel composite coatings with lower CoF and enhanced wear and fatigue resistance. This improvement would mainly be caused by the presence of the WS₂ particles and its characteristic layered structure (Erdemir, 2000). The particles would act as a solid lubricant, potentially forming a WS₂-rich tribofilm when released from the bulk coating after continuous and repeated sliding (Rapoport, 2001). This thin WS₂-rich film would protect the contact surface, preventing the increase of the friction force (Rapoport, 2003) and hence improving the seizure resistance. The improve in wear resistance would not be directly associated to the incorporation of the WS₂ particles themselves, but to the grain refinement and structure modification achieved with their presence in the plating bath (Tudela, 2015).

CONCLUSION

The tribological performance of a Bi+WS₂ composite coating has been evaluated and compared with the performance of a STD Bi coating such as those currently used as overlay coatings in bearing applications in automotive market. The novel composite coatings exhibits a new crystal structure consisting of well-rounded grains instead of the classical columnar structure commonly observed for benchmark bismuth coatings. This new structure, combined with the presence of the lubricant particles, results in novel coatings with lower friction and enhanced seizure and wear performance, making this novel composite coating a suitable option the next generation of bismuth-based materials for overlay applications in bearings for internal combustion engines.

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