Study of the mechanical behavior of leaded copper by scratch test and nanoindentation

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Abstract

Copper-lead was investigated by scratch tests under two set of experiments conditions: at progressive loads (0 – 200 N) and at two different constant loads (20 – 30 N). These tests were made to assess the adhesion properties to determine the critical normal load of copper-lead journal bearings material. The morphologies of material after scratches are synthesized by optical microscope. Nanoindentation studies of copper-lead provide the possibility of examining a variety of mechanical events due to porosity and pre-existing defects in material. The resulting data are analyzed in terms of load–displacement curves and various comparative parameters, such as hardness and Young's modulus.

Keywords: Antifriction coating, scratch test, nanoindentation, Friction.

Introduction

Journal bearings are one of the most important parts in rotating equipments; they are designed to allow free movement between two surfaces that are in sliding contact. Their materials are expected to have several good properties such as low friction coefficient, high load capacity, high heat conductivity, compatibility, high wear and corrosion resistance **[1-3]**.These properties directly affect the fatigue and wear life of journal bearings material. Their Tribological behavior has been the subject of much previous works reported in the literature (intensive research). However, the wear processes that occur are complex and not easy to understand. The durability and functionality of journal bearings material crucially depends on adhesion between the coating and the under laying substrate **[4-9]**. Despite the lack of fully satisfactory analytical mechanism, scratches are widely used to determine the adhesion, the scratch resistance and the hardness of coating and its substrate. However, not all the observed failure events in scratch testing are related to the detachment at the coating substrate interface and only certain, can be truly used as a measure of adhesion. Other types of failure, such as cohesive damage within the coating or substrate, may be equally important in evaluating the in-service behavior of an antifriction material of journal bearings **[10-13]**.Acutely investigation techniques of scratches such as acoustic emission, in situ microscopy, and coefficient of friction and penetration depth measurements are used to determine with precision the critical load and the mode of degradation of the specimen**[14, 15]**. However, scratch tests cannot be used to predict quantitative wear rates of materials and coatings. In order to overcome the demerits of these limitations, nanoindentation test is the absolute leader to perform this type. In fact, nanoindentation is an established method to investigate the mechanical properties of coated substrates. The response of a coated surface to load induced stresses and deformation allows the extraction of the integral mechanical properties **[16-19]**.In the present paper, the focus is devoted towards understanding of some fundamental mechanical behavior of conventional journal bearings materials and correlates the results with their tribological behavior.

2. Experimental

2.1. Material

In this study, Copper-lead bronze journal bearings material with a thickness of 0.25mm was used. Its chemical composition determined by mass spectroscopy is given in table1.

Matériau	Pb	Cu	Si	S	Ra
Copper-Lead	20.789	75.135	1.822	1.342	0.912

Tab. 1 Chemical composition of copper-lead journal bearings material.

2.2. Scratch tests

The scratch tests of copper-lead bearing materials were performed by the MILLENIUM 200 TRIBOTECHNIC device equipped with optical microscope, acoustic emission detection system, tangential friction force sensor. A Rockwell diamond stylus of tip radius 200µm ± 0.01 was used in the test. In progressive load mode, the sliding speeds, loading rate and frequency was chosen at a range of 15, 30, 60 and 90 mm/min, 300 N/min and 7 Hz respectively. The applied load grew from 0 N to 200N until a 7 mm long scratch pattern was produced. In constant load mode, the scratching speeds were 10 or 90 mm/min with applied loads of 20 or 30N the sliding distance was kept constant at 8 mm. During the experiments, the mechanical behavior, the values of critical loads were analyzed **[20, 21]**. Furthermore, in this work, normal and tangential forces were measured to allow the estimation of the friction coefficient.

2.3. Nanoindentation

Copper-lead journal bearings materials were tested using the Nano XP (MTS Nano Innovation Center, Oak Ridge, TN) nanoindenter equipped with a Berkovich diamond tip in the continuous stiffness mode (CSM) at a constant strain rate of 0.05 s^{-1} to continuously measure the indentation depth, the load, and the stiffness. The samples were indented at various points and the reported mechanical properties are from an average of 40 indents spaced by 50 µm apart at each location. The loads vs. indentation depth curves were acquired, and Young's modulus and hardness as a function of the indentation depth were calculated **[22]**.

3. Results and discussion

3.1. The influence from progressive load

Scratch tests provide a qualitative measure for the tribological properties at the surface of the materials. Progressive load scratch tests were used to study the load deformation response over a continuous range of loads and to detect rupture transitions of the copper lead journal bearings materials. Their scratch response can be emphasized by progressive load (0 – 200N) scratch at a four different scratch velocities. Fig.1 shows the average critical loads of each four scratches. It discloses a comparatively good similarity in the size of the deformation pattern. It also clearly identifies the conformal cracks that arise after a short distance. Those cracks subsequently lead to continuous perforation of the material with conformal cracks at the border area. In addition, it also depicts cracks running perpendicular to the scratch edge and the scratch that remained inside the coating. By their aspect, those cracks are similar to tensile cracks which form in the wake of the moving indenter in duplex coatings **[23, 24]**.

In the case of conformal cracking, the C-shaped cracks are oriented in the direction of the advancing indenter. They form when the coating material over-scratches as a result of its plastic accumulation in front of the sliding diamond stylus (fig 2).In the case of tensile cracking, the C-shaped cracks are directed opposite to the advancing stylus because they result from the tensile zone behind the contact between the indenter and the coating material. The evolution of critical load as a function of scratching speed is displayed. Obviously, the adhesion between the steel substrate and the copper-lead antifriction material is perfect **[25]**.

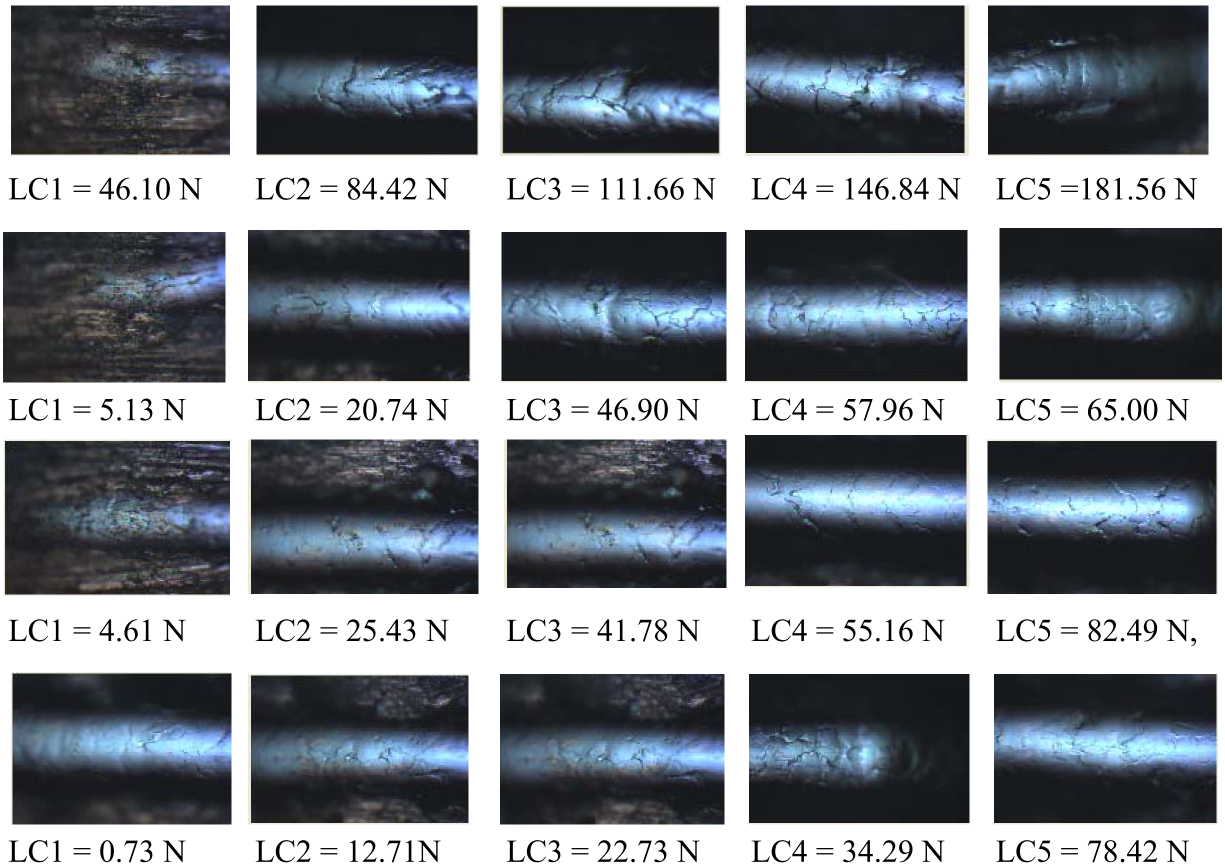


Fig.1 Images showing surface morphologies of copper-lead journal bearings material after scratch deformation with progressive load at 15, 30, 60 and 90 mm/min respectively.

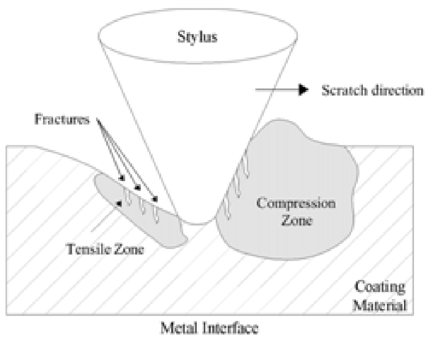


Fig. 2 Stress field distribution around the stylus during a progressive load scratch test: conformal cracking and tensile cracking.

3.2. The progressive load influence

Fig.3 illustrates the results of evolution of copper- lead due to two different velocities (10 and 90 mm/min) with three different constant normal loads (20 and 30 N). Fig.3 (a) show that the friction responses increase with increasingly scratch speeds at the normal load of 20N and it increase conversely with scratch velocities for the normal load of 30N(fig.3 (b)).However, fig. 3 (c) and (d) reveal respectively that The friction coefficient are sensitive to normal loads compared to scratch velocities. These results are apparently similar with those reported in the literature for similar journal bearings material **[25]**. Similarly, optical microscope is used to examine the scratch surfaces morphologies of copper-lead at different constant loads (fig.4). The examinations of the morphologies of the residual scratch patterns confirm the aforementioned considerations. With increasingly normal scratch loads, the widths increases that always produced more rupture. The damage has the forms of cracks that spread inside the scratches. It is also important to mention how coatings rupture events tend to produce some discontinuous ductile perforations of the copper-lead material.

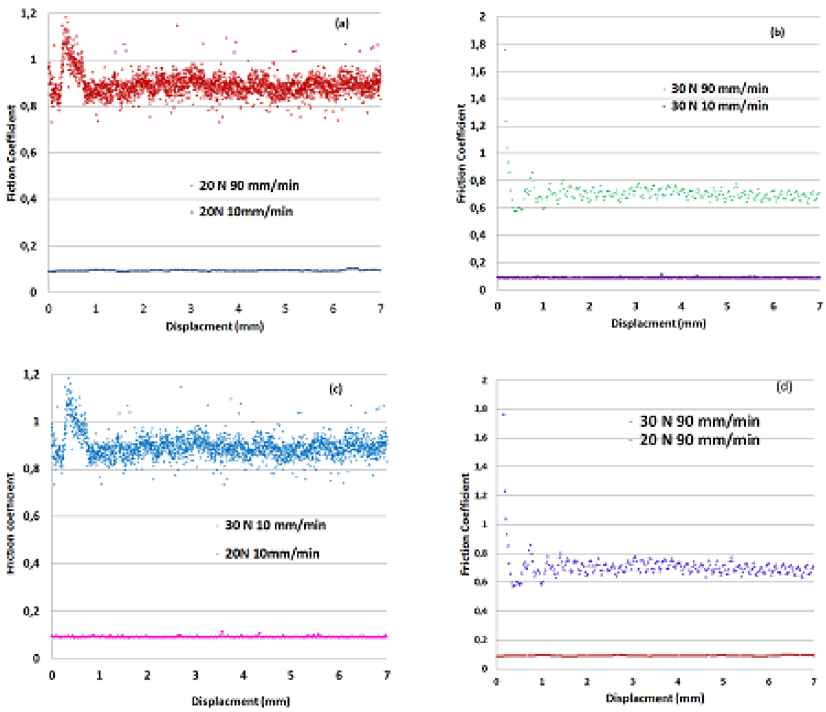


Fig.3 The influence of scratch loads (20 and 30N) and scratch speeds (10 and 90 mm/min) on friction response of copper lead journal bearings material.

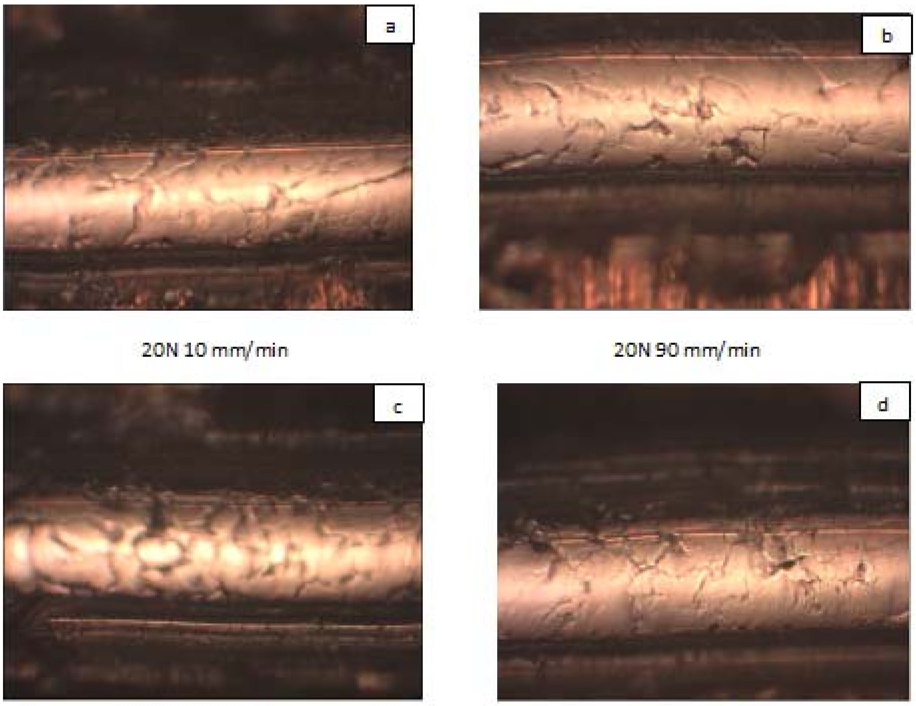


Fig. 4 Images showing surface morphologies of copper-lead journal bearings material after scratch deformation with different constant normal load.

3.3 Nanoindentation

The mechanical properties were investigated by nanoindentation methods for the determination of a typical load versus indentation depth curve of a copper-lead material. The maximum indentation depth is approximately 3000 nm at load of 180 mN. Discontinuities first occur during indentation depth of 2300 nm at load of 97 mN and then at indentation depth of 2600mn at load of 144 mN. 40 indentations were made on the copper–lead material, out of witch twelve tests (30% of tests) show event at depth 2000 – 3000 nm. The origin of this phenomenon is not clear. We assume that the occurrence of the discontinuities 'pop-in' was related to porosity of copper-lead material (5% of microstructure). It is probably by due to the pre-existing defects in this material, the presence of native oxide at the surface, that also fractures under the indenter which triggers an abrupt 'sinking' of the indenter into indentation material **[26]**.

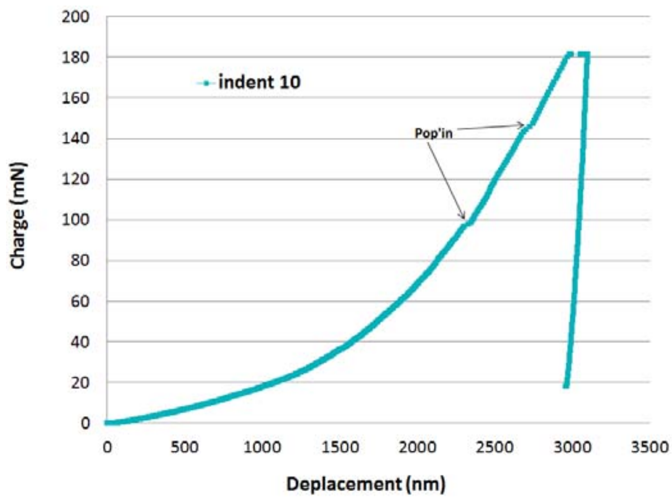
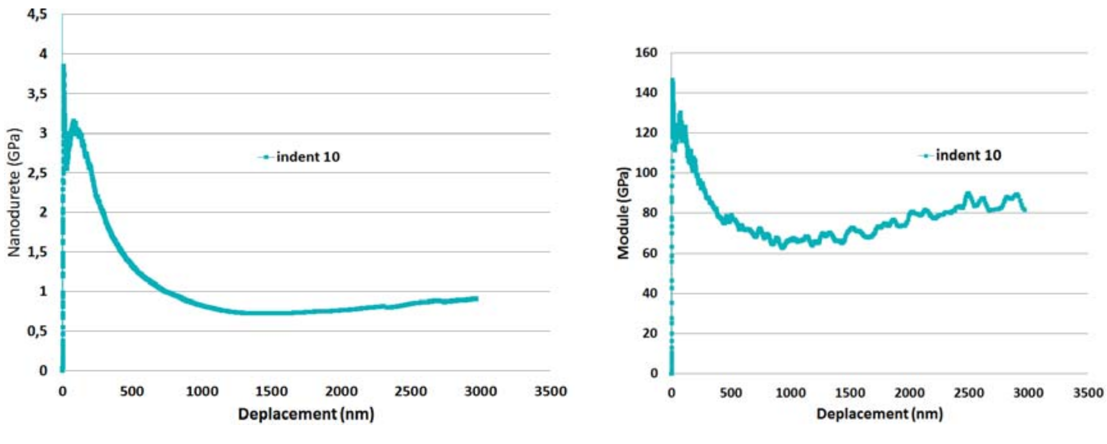


Fig. 5 Load depth curve obtained on the copper lead material, showing the discontinuities.

The hardness and the elastic modulus of copper lead material are function of the indentation depth and is illustrated in fig.6 (a) and (b) respectively. The hardness decreased abruptly at the depth corresponding to the discontinuity event and eventually became constant (≈0.7GPa) for further increases in indentation depth. Similarly, the elastic modulus did unexpectedly decreased and stabilize at a value 80 GPa for further increases of the indentation depth.



a b

Fig.6 Curve for (a) hardness and (b) Young's modulus with respect the indentation depth for copper-lead material.

Conclusion

In our attempts to understand the deformation behavior and mechanical properties of copper-lead journal bearings material, we tested this material under two analysis experiment methods: scratch tests and nanoindentation. The following conclusions can be drawn:

- Intrinsic effects from the microstructure caused local fluctuations in the scratches;
- Experiments have shown that the damage mechanisms can change when scratches interact;
- We also showed how the presence of confine defects such porosities and native oxide on the material surface leads to abnormal affect and greatly modify the shape of the curve load-depth.

The results clearly demonstrated that a microstructure of materials can have significantly further potential implications o the evaluation of tribological damage.

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