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ScienceDirect
Procedia Engineering 68 (2013) 600 – 606
Procedia Engineering
www.elsevier.com/locate/procedia

The Malaysian International Tribology Conference 2013, MITC2013

# Effectiveness of surface texturing for improving the anti-seizure property of copper alloy

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**Abstract**

It is well known that lead-bronze is widely used in the automotive industry owing to the high anti-seizure property. However, because of toxicity of lead, the automotive industry demands a lead-free copper alloy from the viewpoint of environment. Lead-free copper alloy, which has the anti-seizure property as high as lead-bronze, has not been yet well exploited. For this reason, the objective of this study is to improve the anti-seizure property of lead-free copper alloy using a laser surface texturing (LST). In this study, a ring-on-ring sliding friction tester was used to assess the effectiveness of LST on the anti-seizure property of lead-free copper alloy. The upper specimens were made of FCD700, while the textured bottom specimens were made of PBC2 (lead-free copper alloy). A Daphne Hydraulic Fluid 32 (Idemitsu) paraffinic oil was used as a lubricant. The sliding friction test was conducted with a running-in period for 10 min at a load of 50 N. Afterwards, the load was increased incrementally from 50 N to 1600 N, while the friction coefficient was measured simultaneously. The friction test results showed that the textured specimens have a better anti-seizure property compared to the non-textured specimens. Based on the obtained experimental results, it was concluded that the arrangement and area ratio of dimples play an important role in improving the anti-seizure property.


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*Keywords:* Seizure; surface texturing; copper alloy

## 1. Introduction

Lead-bronze is widely used in the automotive industry because of its high anti-seizure property, but the presence of lead in bronze is known to be toxic. Therefore, the replacement of lead-bronze with lead-free copper alloy is required from the viewpoint of environment since lead is toxic and cause serious problems. However, lead-free copper alloy has no anti-seizure property compared to that of the lead-bronze when it is utilized to produce mechanical components. Seizure occurs when two surfaces come into contact in relative motion where the

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doi:10.1016/j.proeng.2013.12.227

temperature of the interface reaches to a critical temperature [1]. Moreover, the seizure is accompanied by dramatic changes in friction force, wear rate and surface topography [2] and it does not occur immediately, but develops with increasing sliding time [3].

Surface texturing is a technique which allows to produce various precise geometries such as micro-groove [4], micro-dimple [5] and micro-convex [6]. Various techniques can be employed for the surface texturing including machining, ion-beam texturing, etching techniques and laser texturing [7]. It has been previously reported that the surface texturing reduces the friction by acting as a reservoir of lubricant and trapping of wear debris. It is expected that the dimples produced by laser surface texturing (LST) may be beneficial to improve the anti-seizure property of lead-free copper alloy as well. Therefore, the objective of this study is to improve the anti-seizure property of lead-free copper alloy by LST. The effect of surface texturing on the tribological properties has been studied in a previous study using a block-on-ring tester [8-9], where the block specimens were made of bronze (CuSn10P) with a hardness of 138 HB and the dimples on the surface were produced using a burnishing technique. The counter specimens were made of 42CrMo4 steel with a hardness of 40 HRC. A seizure resistance test was carried out at a constant normal load of 2700 N. The experimental results showed that the surface texturing can increase the lifetime of the analyzed assembly up to five times in comparison to non-textured [8]. Galda et al. reported the effect of surface texturing on lubrication regime transitions from mixed to hydrodynamic [9]. In their study, the block specimens were made of EN-GJS 400-15 cast iron with a hardness of 50 HRC and the dimples on the surface were produced using a burnishing technique. The ring specimens were made from hardened 42CrMo4 steel of hardness 32 HRC. It was shown that a dimple density smaller than 20% was beneficial for lubrication regime transitions. Recently, Qiu et al. reported the effects of laser surface texturing on the frictional characteristics of heat-treated 17-4PH stainless steel [10]. The dimples were designed with different sizes, densities and depth-to-diameter ratios. The textured specimens led to a lower friction coefficient compared to that of the non-textured specimens. However, some of the produced dimples affected the wear resistance. The effects and mechanisms of surface texturing on the friction and seizure properties have been studied by numerous researchers so far [11-13]. However, to our knowledge, there is no guideline for optimum designs of geometry and arrangement of the dimples, which improves the friction and seizure properties for a particular application with a replacement of lead-bronze with lead-free copper alloy. Hence, the purpose of this study is to confirm the effectiveness of LST on the anti-seizure property of lead-free copper alloy and to optimize the dimples geometry and arrangement for obtaing the lowest friction coefficient and the highest anti-seizure property.

## 2. Experimental methods

A schematic view of ring-on-ring sliding tester used in this study is shown in Fig. 1. The upper rotating specimen was fixed on a motor, while the stationary bottom one was fixed on a cup. The upper rotating specimen pushed toward to the bottom specimen, and the load and friction torque were measured using a load cell. The pedestal was supported by a hydrostatic bearing. The upper specimens were made of FCD700, while the textured bottom specimens were made of PBC2 (lead-free copper alloy) with outer and inner diameters of 44 mm and 27.6 mm, respectively. The average surface roughness ($R_a$) of the both specimens is about of 0.40 μm. It is well known that PBC2 alloy is superior to wear resistance and corrosion resistance. It is usually used to manufacture gears, walm gears, bearings, sleeves, impellers, etc. Thus, it is expected that the anti-seizure property of it can be improved by LST in order to substitute for lead-bronze.

The mechanical properties of FCD700 and PBC2 alloys are listed in Table 1. Table 2 shows the various dimple dimensions, angles and area densities used in this study as illustrated in Fig. 2. It can be seen from Fig. 2 that the dimples were arranged radially from the center of the specimen and on the concentric circle. It can also be seen from Fig. 2 that the relative position of each dimple was square in pattern 1 (see Fig. 2(a)), while the dimples were located in the lattice configuration in patterns 2 and 3 (see Fig. 2(b and c)). In addition, the patterns 1 and 2 have the same parameters except for the arrangement of dimples. The patterns 2 and 3 have different area ratio of dimples as shown in Table 2. The friction tests were conducted with three different textured specimens and their friction and anti-seizure properties were compared to that of the non-textured specimens at an incrementally applied load. The friction test conditions are given in Table 3. The lubricant used in this study was a Daphne Hydraulic Fluid 32 (Idemitsu) paraffinic oil and its physical properties are listed in Table 4. The volume of oil used in each test was about of 50 ml, which was poured enough to immerse the upper specimen into the cup. The sliding friction test was conducted with a running-in period of 10 min at a load of 50 N. Afterwards, the normal load increased incrementally from 50 N to 1600 N, while the friction coefficient was measured simultaneously.

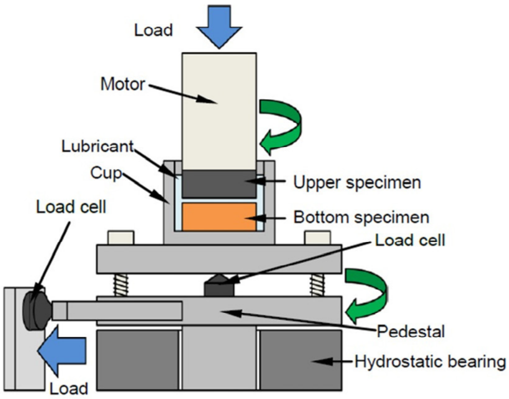

Fig. 1 Schematic view of ring-on-ring sliding tester.

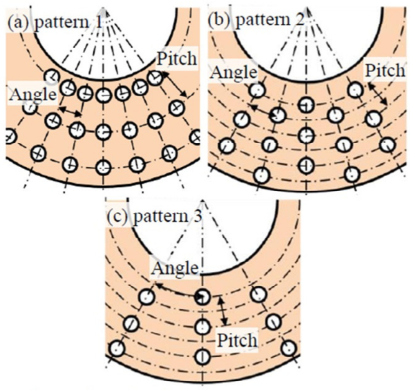

Fig. 2 Schematic of dimple pattern arrangement, (a) pattern 1,(b) pattern 2 and (c) pattern 3 specimens.

Table 1. Mechanical properties of FCD700 and PBC2 materials (quoted by JIS G5502 and JIS H5120, respectively)

| Material | Tension strength [N/mm²] | Proof strength [N/mm²] | Brinell hardness [HB] |
|---|---|---|---|
| FCD700 | ≥ 700 | ≥ 420 | 180 ~ 300 HB(10/3000) |
| PBC2 | ≥ 195 | ≥ 120 | ≥ 60 HB(10/1000) |

Table 2. Dimple dimensions

| Pattern | Size [μm] | Depth [μm] | Pitch [μm] | Angle [deg] | Area ratio [%] |
|---|---|---|---|---|---|
| 1 (square) | 100 | 100 | 400 | 0.36 | 10 |
| 2 (latice) | 100 | 100 | 160 | 1.5 | 10 |
| 3 (latice) | 100 | 100 | 160 | 3.1 | 5 |

Table 3. Test conditions

| | | |
|---|---|---|
| Rotating speed | [m/s] | 0.56 |
| Load | [N] | 50 ~ 1600 |
| Temperature | [ºC] | RT |
| Lubricant | [ml] | 50 |

Table 4. Physical properties of lubricant

| | | | |
|---|---|---|---|
| Density | [g/cm³] | | 0.868 |
| Viscosity | [mm²/s] | @ 20 ºC | 55.87 |
| | | @ 40 ºC | 31.89 |
| | | @ 100 ºC | 5.456 |

## 3. Results and Discussions

Figure 3 shows the variation in friction coefficient for the non-textured, patterns 1, 2 and 3 specimens as a function of normal load. An increase in friction coefficient was observed in all the specimens at normal loads between 200 N and 400 N. Therefore, another friction test was conducted and halted when the normal load reached 400 N. In the result of observation of the surface after friction test, no seizure was observed on the surface. Thus, it was concluded that the seizure did not occur at a normal load of 400 N. It is considered that the increase in friction coefficient may be attributed to the shift of the lubricated regimes from mixed to boundary. The friction coefficient of all the specimens decreased with continuing the friction test at a normal load of higher than 400 N. It is suggested that the decrease in friction coefficient may also be attributed to the surface smoothing. The average surface roughness *(*$R_a$*)* of the specimens after the test were of about 0.12 μm. So it was considered that the surface was polished at the boundary lubrication and many wear debris were present in the sliding surface. The friction coefficient of the non-textured and pattern 1 specimens increased abruptly at 1200 N and 1100 N, respectively. In the case of pattern 1, the friction coefficient reached the highest value and started decreasing till the end of the friction test. In the case of pattern 2, the friction coefficient decreased until the end of the test. In the case of pattern 3, the friction coefficient increased again at a normal load of 1200 N, but the increase in friction coefficient was gradual compared to that of the non-textured and pattern 1 specimens. It was found from the obtained results that the LST can improve the friction behavior of the combination of FCD700 and PCB2.

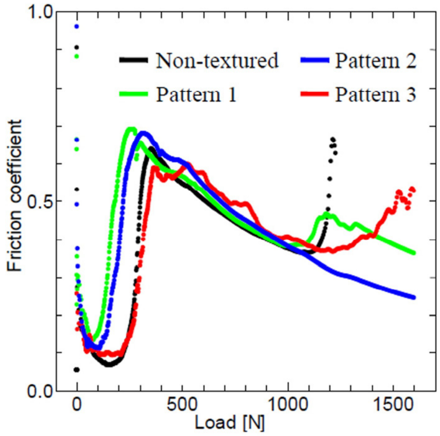


Fig. 3. Variation in friction coefficient with respect to load for the non-textured and patterns 1, 2 and 3 specimens.

Figure 4 shows the optical microscope (OM) images of the non-textured and textured bottom specimens after the friction test. In the case of non-textured specimen shown in Fig. 4 (a), severe wear was not observed in comparison with the textured specimens since the friction test was halted at a normal load of about 1200 N because of high friction. In patterns 1 and 3 as shown in Figs. 4(b and d), where it is evident that the dimples are disappeared, which may be attributed to the severe wear. It can be determined from these results that the seizure and severe wear occurred in those two patterns 1 and 3. However, in pattern 2 as shown in Fig 4(c), the seizure did not occur since severe wear was not observed on the surface. The observed minor seizure property of pattern 2 compared to those of the pattern 1 may be attributed to the high number of dimples at the contact interface, while it may also be attributed to the different angle and area ratio compared to that of the pattern 3.

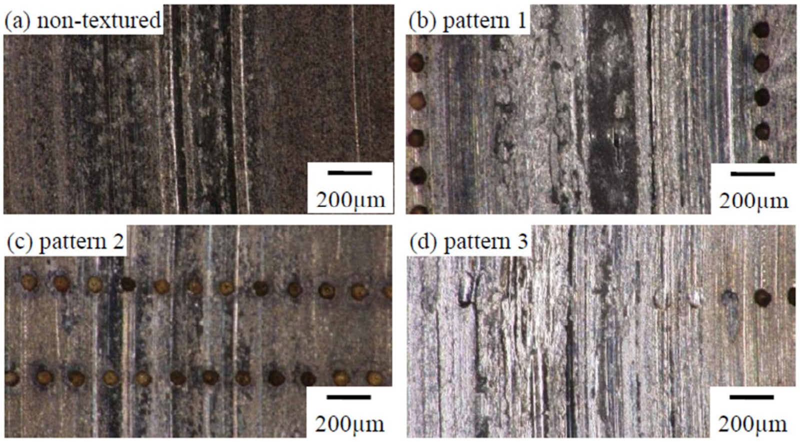


Fig. 4. OM images of the non-textured (a) and patterns 1(b), 2(c) and 3(d) PBC2 specimens after friction test for about 4 min (1200 N) and 5 min (1600 N), respectively.

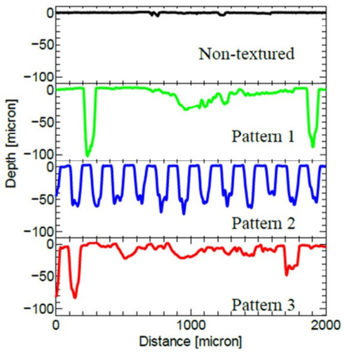


Fig. 5. Cross-sectional profile of the non-textured and patterns 1, 2 and 3 PBC2 specimens after friction test for 4 min and 5 min, respectively.

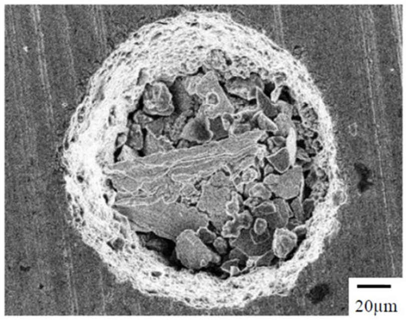


Fig. 6. SEM image of the pattern 2 PBC2 specimen after friction test.

Cross-sectional profiles of the wear track which was measured using a laser microscope are shown in Fig. 5. In the case of non-textured specimen, scratch traces in depth of 5 μm were observed. In the case of pattern 2, shallowed dimples were observed. In the cases of patterns 1 and 3, the wear traces much larger than the initial diameter of the dimple (100 μm) were observed. The maximum depth of the wear trace was 25 μm, which was shallower than the initial depth of the dimple (100 μm). Outside of the wear track in the case of pattern 1, the depth of dimple was not changed as compared with before the test. Therefore, it is considered that disappearance of dimples did not occur by wear, but by trapping the wear debris. In the friction tests of patterns 1 and 3, no LST effect was observed since the dimples were full with wear debris and particles. Figure 6 shows the scanning electron microscope (SEM) image of a single dimple of the pattern 2 after the friction test. It can be clearly seen that wear debris were trapped in the dimple.

Figure 7 shows the energy-dispersive X-ray spectroscopy (EDS) images of the FCD700 upper specimens that slid against the bottom non-textured, pattern 1, 2 and 3 specimens. It can be seen that the adhesion wear was observed on the specimen surfaces that slid against the patterns 1 and 3. Also, a small amount of the adhesion wear was observed on the specimen surfaces that slid against the non-textured and pattern 2 specimen surfaces as well. In the specimens that slid against the patterns 1 and 3, the adhesion was observed strongly on the wear track, on the other hand it was not observed strongly in the specimen that slid against the pattern 2. Hence, it is considered that this difference is caused by the occurrence of seizure.

After friction test, the FCD700 specimens were analyzed using an EDS system as shown in Fig. 8. It can be seen that a small amount of Cu was detected in all the specimens which was transferred from the bottom specimen PBC2. In the case of FCD700 specimen that slid against the pattern 2, it was observed the smallest amount of Cu element compared to those of the specimens which slid against the patterns 1 and 3. Therefore, it is considered that the adhesion wear was controlled by the design of dimple geometry and arrangement. From the results, the effectiveness of LST on the improvement of the anti-seizure property was observed on the pattern 2. It was also found from the experimental results that the arrangement and area ratio of the dimples play an important role in improving the anti-seizure property.

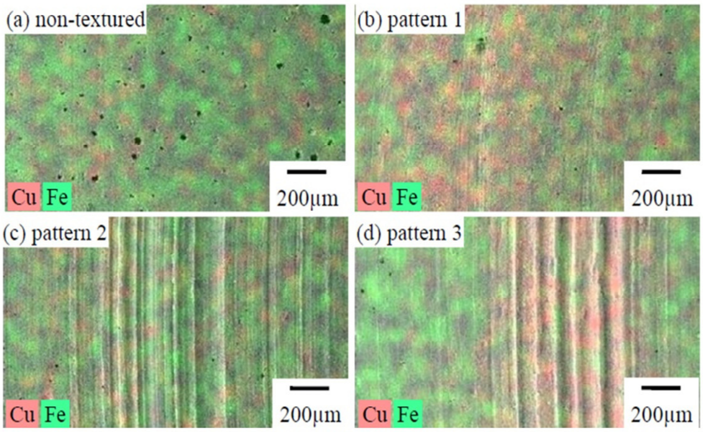


Fig. 7. EDS images of the non-textured (a) and patterns 1(b), 2(c) and 3(d) FCD700 specimens after friction test for about 4 min (1200 N) and 5 min (1600 N), respectively.

Cross-sectional profiles of the wear track generated on the FCD700 specimens are shown in Fig. 9. In the cases of specimens that slid against the non-textured and pattern 2 specimens, a small amount of scratch traces were observed. On the other hand, in the cases of the specimens that slid agains the patterns 1 and 3, the wear traces in depth of about 10 μm were observed on the sliding surface. The comparison of the specimens that slid against the patterns 1 and 3, the width of the wear traces of the specimen that slid against the pattern 3 is wider than that of the specimen that slid against the pattern 1, but the depth of the wear traces in the specimen that slid against the pattern 3 is shallower than that of the specimen that slid against the pattern 1. For this reason, it is difficult to estimate that which parameter is dominant to improve the anti-seizure property. Therefore it needs to be investigated in the near future.

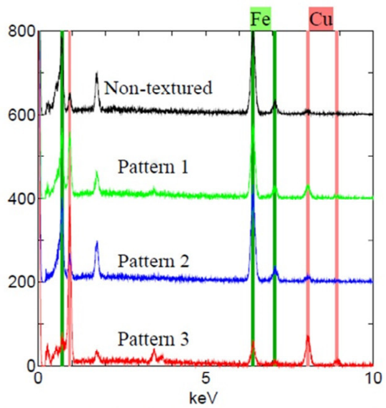


Fig. 8. EDS analysis of FCD700 specimens after friction test.

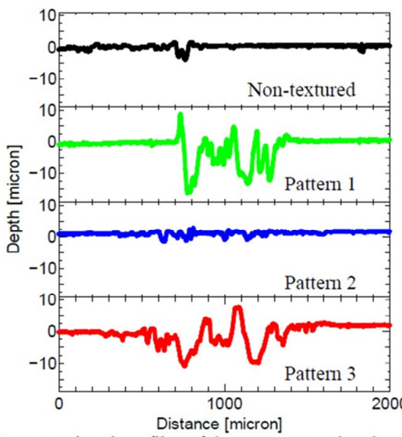


Fig. 9. Cross-sectional profiles of the non-textured and patterns 1, 2 and 3 FCD700 specimens after friction test.

## 4. Conclusions

In this study, the effectiveness of laser surface texturing for improving the anti-seizure property of lead-free copper alloy was investigated. The following conclusions are obtained from the experimental results:

(1) LST was effective in improving the friction and anti-seizure properties of lead-free copper alloy.

(2) The arrangement and area ratio of the dimples play an important role in improving the anti-seizure property. However, the pattern 2 was beneficial for improving the frictional and seizure properties of lead-free copper alloy, while the patterns 1 and 3 were detrimental.

(3) It was confirmed that wear debris were trapped in the dimple after friction test.

(4) Adhesive wear was observed on the surface of the FCD700 in all cases.

(5) Further experimental investigations are required in order to understand the mechanism of the improved anti-seizure property by laser surface texturing.

## Acknowledgement

This work was supported by a “JSPS KAKENHI Grant Number 23360077”.

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