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Study on tribology of liquid-solid formed CuPb$_{20}$Sn$_5$/Carbon steel bimetal

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Abstract

Taking CuPb$_{20}$Sn$_5$ as the research object, the CuPb$_{20}$Sn$_5$/Carbon steel bimetallic sample was prepared by the solid-liquid compound method, and the relationship between the microstructure and friction properties of the bimetallic CuPb$_{20}$Sn$_5$ layer. The results show that the Cu$_3$P and δ(Cu$_3$Sn$_8$) phases in CuPb$_{20}$Sn$_5$ are distributed in the α-Cu to improve the wear resistance of the alloy. The friction coefficient fluctuates in the range of 0.057 ~ 0.093, when the load was 150 N~350 N. When the speed exceeds 3.86 m s$^{-1}$, as the load increases, the friction coefficient first increases and then decreases, and the wear rate increases. When the load was less than 250 N, the wear surface of CuPb$_{20}$Sn$_5$ was smooth, and the material was basically free of wear. When the load was 300 N, the friction coefficient reaches the lowest point, and the third body friction layer was formed in CuPb$_{20}$Sn$_5$ layer, and the wear mechanism was slight adhesive wear. When the load was greater than 300 N, Pb will fall off the CuPb$_{20}$Sn$_5$ surface, and the friction coefficient increase, causing abrasive wear.

1. Introduction

The bimetal cylinder block of hydraulic plunger pump [1, 2] is composed of steel and copper. The copper layer forms a friction pair with the plunger as a wear resistant working surface [3], which bears alternating stress and internal surface friction during operation [4]. The main failure modes of the plunger pump include copper layer wear, bimetallic interface shedding and plunger card sluggish [5–7]. The wear of the friction pair surface directly affects the normal working of the hydraulic plunger pump cylinder [8–10]. In order to reduce wear failure, high-lead tin bronze with good wear resistance is often used as the friction pair material.

Lead-tin bronze [11] has good lubricating properties, low friction coefficient, high melting point [12, 13]. Pb cannot be dissolved in the α-Cu matrix and exists in a free state between the dendrites. During the friction process, a third body friction layer can be formed to achieve lubrication and anti-friction [14, 15], its widely used in oil-deficient or oil-free friction pairs [16]. Lead-tin bronze not only has a small friction coefficient and good wear resistance, but also has the characteristics of good thermal conductivity and high fatigue strength [17, 18].

The structure of the plunger pump cylinder is complex [19], the bimetallic bonding is difficult, and the solid-liquid casting method can effectively solve the forming problem [20–22]. However, there are few studies on the tribology of lead-tin bronze suitable for engineering. Yan [23] studied the influence of the size refinement and distribution of the lubricating lead phase in high-lead tin bronze on the wear rate by spray forming. Zeng [24] prepared carbon fibers by powder metallurgy to replace part of the tin and all lead in the tin bronze matrix, studied the tribological properties of short carbon fiber reinforced Cu-based composites. Tao [25] used laser cladding technology to successfully prepare five aluminum bronze coatings with different Fe and Ni contents on the surface of 316 stainless steel to improve its abrasion resistance.

In this paper, the CuPb$_{20}$Sn$_5$/Carbon steel bimetal is used as the testing, to study the wear resistance of the bimetallic copper layer and the friction disc under oil lubrication conditions. Under the synergistic effect of the oil film, explore the lubrication effect of the third-body friction layer, it can provide more theoretical support for the future application of the bimetal copper layer wear resistant materials. Based on this point of view, friction...
and wear tests and microstructure characterization of bimetallic samples were carried out to clarify the behavior mechanism of bimetallic copper layer during wear, and study the behavior of Pb in bimetallic CuPb20Sn5 layer.

2. Experimental

2.1. Material and characterizations

Preparation of CuPb20Sn5/Carbon steel bimetallic samples by solid-liquid casting method, the pouring amount of the liquid Cu–Pb–Sn alloy is 500g. The liquid alloy liquid is poured into the preheated carbon steel substrate for air cooling to form a bimetallic interface. The anti-oxidation coating used on the steel substrate is a mixed coating of Na2B4O7 and (CH2OH)2 = 20:13. (CH2OH)2 volatilizes during preheating. Na2B4O7 melts into glass at 878 °C during preheating. It contains acidic oxide B2O3, so it can dissolve metal oxides and prevent oxidation of the steel matrix. The density of Na2B4O7 in the molten state is less than that of the copper alloy liquid, and it floats on the molten metal during the pouring process, and only plays a role of preventing oxidation during the preheating of the steel substrate, and has no effect on the interface formation. The preheating temperature of the steel matrix was 1150 ± 30 °C and the Cu–Pb–Sn alloy smelting temperature was 1200 ± 20 °C. The Cu–Pb–Sn alloy was subsequently poured into the preheated steel matrix to form a bimetallic composite interface. The composition of the steel after casting is 0.42% C, 0.21% Si, 0.68% Mn, 0.04% Cr, 0.02% Ni (wt.%), and the actual element content the CuPb20Sn5 obtained after the bimetallic samples in Table 1, which were detected by the German SPECTRO-MAXx spectrometer.

The size and sampling method of the steel/copper bimetallic sample is shown in figure 1. In the actual working condition of the plunger pump cylinder, the thickness of the friction surface of the plunger hole copper layer from the interface is 2 mm, so the friction and wear copper layer is taken as 2 mm. Two samples were taken from the symmetrical position, and they were used for microstructure and copper layer hardness test, friction

![Figure 1. The bimetallic cutting method. (a) Before cutting, (b) after cutting, (c) location of microstructure and friction and wear.](image1)

![Figure 2. Friction pair and samples size. (a) Bimetallic sample size, (b) schematic diagram of load and sensor, (c) friction disc size.](image2)

| Material | Pb     | Sn     | P      | Ni     | Zn     | Cu     |
|----------|--------|--------|--------|--------|--------|--------|
| CuPb20Sn5| 19.15  | 4.91   | 0.1    | 1.78   | 1.71   | Bal.   |

Table 1. Chemical composition of the matrix material (wt.%).
and wear testing. The hardness of the copper layer was tested with the HB-3000B Brinell hardness, and the hardness of the CuPb20Sn5 alloy was measured to be 63 ± 3 HBW. The CuPb20Sn5 alloy was etched with ammonia water, hydrogen peroxide, and distilled water (1:1:3), and the carbon steel was wiped with a 5% nitric acid alcohol solution. A Zeiss Smartzoom 5 optical microscope (OM) was used to observe of the bimetallic samples. CuPb20Sn5 phase and Wear scar morphology were studied by field-emission scanning electron microscopy (Hitachi SU 5000) operated at 15 kV combined with energy-dispersive spectrometry (EDS).

2.2. Test method
The bimetallic friction pair and the sample are shown in figure 2. The friction tests on the MRH-3A ring block friction and wear tester. The bimetallic copper layer is used as the friction material, and the friction disc material is GCr15. During the friction process, the friction disc rotates, and the bimetallic sample is fixed. Testing temperature of the friction and wear is room temperature, the lubrication state is oil lubrication, the lubricating oil used is 15W-40#, and the speed parameters are listed in table 2. The loads are 150, 250, 300 and 350 N, and the speed is 2.58 m s⁻¹, 3.86 m s⁻¹, 5.15 m s⁻¹. The same testing was repeated 3 times and the average value was taken. The friction coefficient was the average value after 20 min of friction.

Table 2. Friction and wear load and speed parameters.

| Program | 1# | 2# | 3# | 4# | 5# | 6# | 7# | 8# | 9# | 10# | 11# | 12# |
|---------|----|----|----|----|----|----|----|----|----|-----|-----|-----|
| Load N  | 150| 150| 150| 250| 250| 250| 300| 300| 300| 350 | 350 | 350 |
| Speed (m/s) | 2.58| 3.86| 5.15| 2.58| 3.86| 5.15| 2.58| 3.86| 5.15| 2.58| 3.86| 5.15 |

Before the testing, each sample was coarsely ground, finely ground, polished and cleaned, and the CuPb20Sn5 alloy surface roughness Ra ≤ 0.8, and its quality was called. After abrasion, it is washed with acetone and dried, and then weighed with a 1/10000 electronic analytical balance, the wear rate is calculated by the weight loss.

3. Results and discussion

3.1. CuPb20Sn5 layer friction coefficient and wear rate
It can be seen from figure 3(a) that the linear velocity from 2.58 m s⁻¹ to 5.15 m s⁻¹ under the load of 150N to 350N, the friction coefficient fluctuates in the range of 0.057 to 0.093. When the linear velocity is 2.58 m s⁻¹, the friction coefficient increases with the increase of the load. When the load increases from 300 N to 350 N, the increase rate is 21.25%. Under the conditions of linear velocity of 3.86 m s⁻¹ and 5.15 m s⁻¹, with the increase of load, the friction coefficient of CuPb20Sn5 layer shows a trend of first increasing and then decreasing. When the linear velocity is 3.86 m s⁻¹, the load greater than 150 N, the friction coefficient is the lowest value of 0.062.

Figure 3(b) shows that the CuPb20Sn5 layer wear rate at constant linear velocity increase with the increase of load. When the load exceeds 300 N and the speed exceeds 3.86 m s⁻¹, as the load and speed continue to increase,
the increase in the wear rate becomes larger, increasing from the original 30.8% to 45.8%. In the range of
2.58 $\sim$ 3.86 m s$^{-1}$ linear velocity, the increase of the wear rate of CuPb$_{20}$Sn$_{5}$ layer is small. After the linear
velocity exceeds 3.86 m s$^{-1}$, the wear rate increases significantly.

Figure 4. The microstructure of the CuPb$_{20}$Sn$_{5}$ layer uncorroded. (a) CuPb$_{20}$Sn$_{5}$ layer, (b) bimetallic interface, (c) Fe–Cu atomic interdiffusion.

Figure 5. Pb size distribution in CuPb$_{20}$Sn$_{5}$ layer. (a) Pb distribution (b) quantity statistics.

Figure 6. CuPb$_{20}$Sn$_{5}$ layer composition phase. (a) CuPb$_{20}$Sn$_{5}$ BSE, (b) A point EDS in (a), (c) B point EDS in (a), (d) C point EDS in (a).
3.2. Analysis of friction and wear mechanism

Figure 4 shows the uncorroded microstructure of the bimetal interface and the CuPb20Sn5 layer. Figure 4(a) shows that the Pb in the CuPb20Sn5 layer surface is freely present on the α-Cu matrix, and the distribution is relatively uniform, and no defects exist on the surface, ensuring the wear process interference of impurity factors. Figure 4(b) shows that there is no defect in the interface, figure 4(c) shows that forming a metallurgical bond, that the interface falls off does not exist during the wear process.

Figure 5 can be seen that most of the area of Pb is concentrated within 900 μm², and most of them are concentrated in 10–450 μm², indicating that the overall Pb particles are relatively small. For friction and wear, round and free state of Pb is beneficial to the improvement of the wear resistance of CuPb20Sn5 layer. The number of Pb particles within 900–7200 μm² is 180, of which 53 are more than 1800 μm². Pb mainly exists in the dendrites in the α-Cu, and the Pb with larger area are easy to fall off during the wear process, which is harmful to the wear conditions.

Figure 6 is the EDS point scan of each phase in the CuPb20Sn5 layer. The CuPb20Sn5 layer is mainly α-Cu, (α + δ), Cu₃P, and Pb phases, of which δ(Cu₃₁Sn₈) and Cu₃P is a hard phase, which can increase the hardness and wear resistance of the CuPb20Sn5 layer. Pb is insoluble in α-Cu and exists in the free state between the branches of the dendrites. It plays a self-lubricating role in the alloy improve the wear resistance. Figures 7(a)–(c) are the components of Pb, Cu₃P, and δ(Cu₃₁Sn₈) phases.

According to the change trend of friction coefficient and wear rate under different working conditions, under the two conditions of linear velocity of 3.86 m s⁻¹ and 5.15 m s⁻¹, with the increase of load, the friction coefficient of CuPb20Sn5 layer first increases and then decreases. The greater the linear velocity, the more obvious the trend. Therefore, the samples with a linear velocity of 5.15 m s⁻¹ and a load of 150, 250, 300, and 350 N were selected, to observe the wear scar, as shown in figure 7.

When the load is less than 250 N, the wear surface of CuPb20Sn5 layer is smooth, there are slight wear marks and a small amount of wear debris. Most of the contact area is the contact between the small metal protrusions, and the sample and the steel ring are in contact through the oil film. At this time, the CuPb20Sn5 layer is basically free of wear. When the load is 300 N, the third body friction laye to form on the wear surface. The formed stable Pb film interacts with the oil film, and the wear surface becomes smooth. This load is not enough to destroy the lubricating film and form wear debris. At this time, the wear mechanism mainly with slight adhesive wear. Due
to the lubricating effect of the third body friction laye, the friction coefficient at 300 N in figure 3 has a tendency to decrease.

When the load increases to 350 N, the surface temperature of the friction pair interacting gradually increases, and Pb is gradually squeezed out of the \( \alpha \)-Cu surface, causing the friction coefficient to appear again increases, the formed third body friction laye will also be destroyed to form wear debris and cracks, resulting in brittle fracture and peeling of the lubricating film, which will increase the amount of wear rapidly, and the wear rate will increase to \( 18.258 \cdot 10^{-9} \text{mm}^3 (\text{N} \cdot \text{m})^{-1} \), the friction coefficient has also increased to 0.093, and the friction surface of \( \text{CuPb}_{20}\text{Sn}_5 \) layer has furrows, as shown in figure 7(d).

Pb has a face-centered cubic structure, and its shear strength is low. During friction, it can effectively reduce the friction coefficient through the self-shearing of lead between the friction pairs. In the friction direction, due to the shear force, it transfers to the surface enrichment. In addition, Pb has good lipophilicity and can play a better synergistic lubrication effect with lubricating oil. Figure 8 shows a scan of the element surface of the wear resistant. It can be seen that Sn and P elements are also distributed in Pb, and shows that the friction process also plays a role in reducing wear [18, 26].

Wear intensifies with the increase of load, this is due to the fact that the hard particles of \( \text{Cu}_3\text{P} \) and \( \delta \) on the friction surface have little effect when the load is low, and as the load increases, the pressing depth of the micro-convex point on the friction surface increases, the actual contact area between the friction pairs increases, and the number of hard particles at the contact surface also increases, which deepens the depth of the furrow, and the slight adhesive wear turns into severe wear, resulting in an increase in the wear rate.

4. Conclusions

(1) The friction coefficient fluctuates in the range of 0.057 \( \sim \) 0.093 when the load was 150 N–350 N and the linear velocity is 2.58 m s\(^{-1}\)–5.15 m s\(^{-1}\). When the linear velocity exceeds 3.86 m s\(^{-1}\), as the load and linear velocity increases, the friction coefficient first increases and then decreases, and the wear rate increases.

(2) When the load was less than 250 N, the wear surface of \( \text{CuPb}_{20}\text{Sn}_3 \) layer was smooth, and the material was basically free of wear. When the load was 300 N, the friction coefficient reaches the lowest point, and the third body friction layer was formed in \( \text{CuPb}_{20}\text{Sn}_3 \) layer, the wear mechanism was slight adhesive wear. When the load was greater than 300 N, the third body friction layer will fall off the \( \text{CuPb}_{20}\text{Sn}_3 \) layer, and the friction coefficient will increase, causing abrasive wear.

(3) The \( \text{CuPb}_{20}\text{Sn}_3 \)/Carbon steel bimetallic interface forms a metallurgical bond. The \( \text{CuPb}_{20}\text{Sn}_3 \) structure is \( \alpha\)-Cu, \( \alpha + \delta \), \( \text{Cu}_3\text{P} \), and Pb phases, which \( \delta \) (\( \text{Cu}_3\text{Sn}_4 \)) and \( \text{Cu}_3\text{P} \) are hard, it forms the third body friction layer with Pb to improve the wear resistance of the alloy. The area of Pb is concentrated in the range of 10–450 \( \mu \text{m}^2 \), and the particle morphology is fine and round.
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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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