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Tribological properties of bronze–Cr–Ag alloy in seawater, NaCl solution and deionized water

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ABSTRACT

Tribological properties of bronze–Cr–Ag alloy sliding against AISI 52,100 steel were investigated in deionized water, 3.5 wt% NaCl solution and seawater. The friction coefficient and wear rate of the alloy follow the sequence: deionized water > NaCl solution > seawater. In NaCl solution and seawater, Cu_2O, $Al(OH)_3$, FeOOH and Fe_2O_3 form on the surface because of chloride corrosion. In seawater, $CaCO_3$ and $Mg(OH)_2$ are adsorbed on the surface. The above compounds play an important role in reducing the friction and wear. The study of tribocorrosion mechanism is beneficial for bronze–Cr–Ag alloy to be used in sliding bearing under seawater condition.

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1. Introduction

A large variety of bronzes have been widely used in many tribological applications [1–6]. As an important type of nickel–aluminum bronze, Cu–9Al–5Ni–4Fe–Mn is widely employed in marine applications due to the exceptional corrosion resistance and bearing properties [7–11]. However, the poor tribological properties limit its application in sliding bearing under seawater condition. Recently, it has been reported that a little Cr added in copper alloy can improve the hardness and wear resistance [12–15]. Meanwhile, the addition of Ag reduces the friction coefficient and wear rate of copper alloy effectively [16,17]. Hence, bronze–Cr–Ag alloy is a potential material which possesses both of good corrosion resistance and tribological properties [18–20].

In addition, numerous researchers have focused on the tribological characteristic of alloys in seawater environment. It has been investigated that Cu–6Sn–6Zn–3Pb bronze exhibits different tribological properties in seawater and distilled water [21]. Babbitt alloy 16-16-2 shows low friction coefficient and wear rate in seawater environment. During friction process, the formation of basic lead carbonate $Pb_3(OH)_2(CO_3)_2$ makes surface porous and adsorbs more seawater and therefore reduces the direct contact of the sliding couple [22]. It plays a critical role in remaining low friction coefficient. Moreover, the varying content of salts in seawater has obvious influences on the tribological properties of aluminum alloy [23].

Concurrently, the seawater corrosion can change the chemical composition and surface morphology of frictional surfaces. This has an influence on friction coefficient and wear rate of the materials [24–26]. However, the tribological characteristic and mechanism of the bronze–Cr–Ag alloy in seawater is not identified. It is also unknown whether the corrosion products of alloy and steel (counterface) have an influence on the tribological properties.

Based on the above consideration, the bronze–Cr–Ag alloy containing 2 wt% Cr and 8 wt% Ag was prepared by a vacuum hot-pressed sintering technique. Its tribological properties sliding against AISI 52,100 steel were evaluated in deionized water, 3.5 wt% NaCl solution and seawater. The influences of corrosion and various salts on the tribological properties were studied as well as the wear mechanism of the alloy in different liquids.

2. Experimental procedures

2.1. Sample preparation

The bronze–Cr–Ag alloy is prepared according to the composition in Table 1. All metal powders were mixed by a planetary ball-milling machine for 10 h at a rotational speed of 170 rpm (grinding media: WC/Co balls, ratio of the ball to powder: 2:1). The mixed powders were then placed in a BN-coated graphite mold, and sintered at 860 °C with an axial pressure of 38 MPa for 15 min. In the entire process, the vacuum degree of furnace chamber is 10^{-2} Pa. Finally, the specimens were naturally cooled to room temperature.

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Table 1
Composition of the bronze–Cr–Ag alloy (wt%).

Material	Cu	Al	Ni	Fe	Mn	Cr	Ag
Alloy	72.9	8.1	4.5	3.6	0.9	2.0	8.0

Table 2
Chemical composition of artificial seawater (g/L).

Compound	$MgCl_2$	$CaCl_2$	$SrCl_2$	KCl	$NaHCO_3$	KBr	NaF	NaCl	Na_2SO_4	H_3BO_3
Concentration	5.200	1.160	0.025	0.695	0.201	0.101	0.003	24.530	4.090	0.027

Fig. 1. XRD pattern of the hot-pressed sintering alloy.

Fig. 2. Optical micrograph of the microstructure of the sintered alloy.
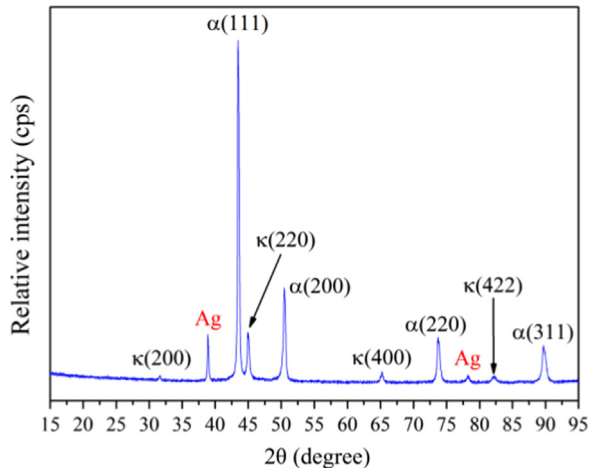
2.2. Friction and wear tests

Here, the friction and wear tests included: (1) comparative study of the tribological performances of the alloy in deionized water, 3.5 wt% NaCl solution and artificial seawater; (2) study of the influence of seawater composition on the tribological properties of the alloy. The seawater used here was prepared according to the standard ASTM D1141-98 (2008) as listed in Table 2. The pH value of prepared seawater was adjusted to 8.2 by HCl solution (0.1 mol/L) and NaOH solution (0.1 mol/L).

A CFT-1 reciprocating friction tester was used to carry out the friction and wear tests in the three liquids at 25 °C. The AISI 52,100 bearing steel ball (hardness: 60 HRC and diameter: 4 mm) was used as friction couple. All tests were conducted under various sliding speeds (0.017, 0.033, 0.050, 0.067 and 0.083 m/s) with 15 N load and various loads (10, 15, 20, 25 and 30 N) with 0.05 m/s sliding speed for 30 min. The wear rate (W) was calculated by the equation $W = V/SP$ (V: wear volume, S: sliding distance (m) and P: applied load (N)). A Micro Xam-3D surface profiler was used to measure the wear volume (V). Reported values represent an average of four tests under the same testing parameters. After friction tests, the liquids on the specimens surfaces were gently absorbed by cotton. Then, the specimens were naturally dried in atmosphere environment. Before analysis, the worn surfaces were cleaned well with acetone.

2.3. Sample characterization

The bending and compressive strengths of the alloy were measured with a DY-35 mechanical testing machine at 25 °C. The Vickers hardne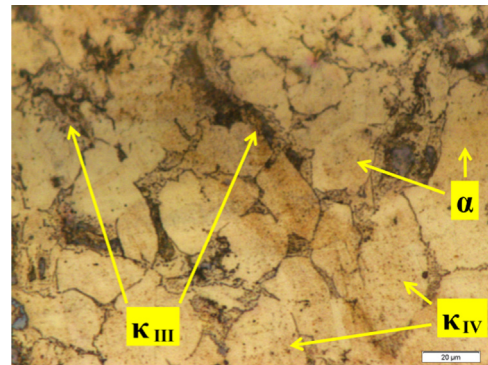ss was measured with a MH-5 Vickers hardness instrument with a load of 2 N and a dwell time of 10 s. The X-ray diffractometer was used to identify the phase constituents of the alloy. Microstructural characterization was performed with scanning electron microscopy (JSM-5600LV). The chemical states of the worn surfaces were examined with a PHI-5702 multifunctional X-ray photoelectron spectroscope. The chemical composition was analyzed using energy dispersive spectroscopy.

3. Results and discussion

3.1. Material characterization

The X-ray diffraction pattern of the prepared alloy is given in Fig. 1. It mainly consists of α phase (Cu-rich, fcc crystal structure) and κ-phase precipitates (Ni–Fe–Al complex). By observing the spectrum, it can be seen that the peaks of Ag can be detected. At the sintering temperature (860 °C), most of the added Ag (8 wt%) dissolve into the phases of the bronze. Then, the solubility of Ag in bronze reduces along with the dropping temperature. A large amount of Ag separated out from the bronze. However, the peaks of Cr cannot be observed. This is due to Cr content being low and the peaks of Cr overlapping the peaks of κ (220), κ (400) and κ (422).

Fig. 2 shows the optical micrograph of the microstructure of the alloy etched by corrosive solution (10% $FeCl_3$ and 90% CH_3OH by mass). The light region is α phase. The $κ_{III}$ phase (based on NiAl) is darker and has lamellar morphology. The $κ_{IV}$ phase (based on Fe_3Al) disperses in α phase as fine precipitates.

3.2. Friction and wear properties

Fig. 3 shows the friction coefficient of the alloy with various loads at 0.05 m/s and various sliding speeds under 15 N in the three liquids. It can be seen that, under the same testing parameters, the alloy has the highest friction coefficient in deionized