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Adhesive wear behavior of $Al_xCoCrCuFeNi$ high-entropy alloys as a function of aluminum content

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Abstract

The $Al_xCoCrCuFeNi$ alloys with different aluminum contents prepared by arc melting were investigated on their adhesive wear behaviors. With increasing aluminum content, both the volume fraction of BCC phase and the hardness value increase, and thus the wear coefficient decreases. Moreover, the wear mechanism changes from delamination wear to oxidative wear. For low aluminum content, $x = 0.5$, the microstructure is of simple ductile FCC phase and the worn surface is deeply grooved and undergoes a periodic delamination which produces big debris. For medium aluminum content, $x = 1.0$, the microstructure is a mixture of FCC and BCC phases, and the worn surface is deeply grooved in FCC region but smooth in BCC region. Delamination wear is still dominant although oxidative wear occurs in the smooth region. For high aluminum content, $x = 2.0$, the microstructure is of BCC phase and the worn surface is smooth and yields fine debris with high oxygen content. The high aluminum content gives a large improvement in wear resistance. This improvement is attributed to its high hardness, which not only resists plastic deformation and delamination, but also brings about the oxidative wear in which oxide film could assist the wear resistance.

Keywords: High-entropy alloy; Adhesive wear; Wear coefficient; Friction

1. Introduction

In recent years, an entirely new alloy field, high-entropy alloys with multiple principal elements in equimolar or near-equimolar ratios, has been explored by Jien-Wei Yeh et al. [1,2]. High-entropy alloys may contain at least five principal elements with the concentration of each element being between 35 and 5 at.%. Solid solutions with multi-principal elements will tend to be more stable at elevated temperatures because of their large mixing entropies [1]. The previous studies [1–6] have shown that high-entropy alloys might possess simple crystal structures, ease of nanoprecipitation, and promising properties in high hardness and superior resistance to temper softening, wear, oxidation and corrosion. Among these, $Al_xCoCrCuFeNi$ alloys have a gradual change from FCC phases to BCC phases, and hardness increase from 120 to 650 HV with increasing aluminum content. They are promising for the applications in structural and tool industries [5,6].

The wear performance of the alloys based on one principal element has been investigated widely. One of the most common forms of the coefficient of friction curves in adhesive wear test is characterized by an initial rise in the coefficient of friction, up to a peak value, followed by gradual decline to a steady-state value [7–13]. Fig. 1 shows a schematic diagram of this typical coefficient of friction versus sliding distance curve [13]. The factors influencing the friction curve of metallic materials include hardness, plastic deformation, work-hardening and evolution of crystallographic texture all of which can take place during the wear process [13,14]. Due to the importance of wear behavior of high-entropy alloys for their industrial applications, the adhesive wear behavior of $Al_xCoCrCuFeNi$ alloys is investigated in this paper.

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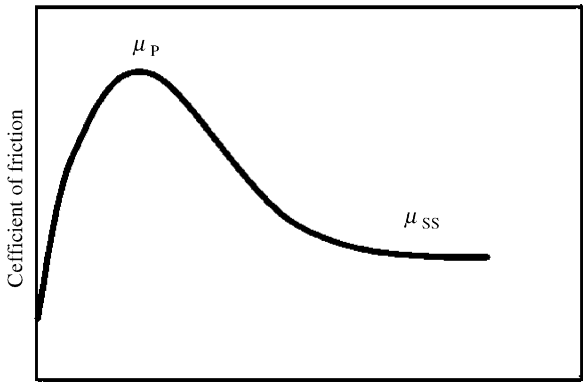

Fig. 1. Schematic diagram showing a typical coefficient of friction as a function of sliding distance. The friction curve increases rapidly to a peak value (μ_P) followed by a gradual decrease to a steady-state value (μ_{ss}).

2. Experimental details

The $Al_xCoCrCuFeNi$ high-entropy alloys with different aluminum contents (x = 0–2.0 in molar ratio) were prepared in this study by arc melting and casting method. The method followed the same procedure as described in reference [3]. The alloy specimens were polished and etched with *aqua regia* (HNO_3:HCl = 1:3) for observation under an optical microscope and scanning electron microscope (SEM, JEOL JSM-5410). The chemical compositions of different phases were analyzed by SEM energy dispersive spectrometry (EDS). Hardness measurements were conducted using a Vickers hardness tester (Matsuzawa Seiki MV-1) under a load of 49 N and at a loading speed of 70 μm/s for 20 s. Scattering errors were within 3%. The adhesive wear behavior of the alloys was investigated by pin-on-disk sliding using a self-made wear testing machine under dry sliding conditions as shown in Fig. 2. Pins of 8 mm diameter and 25 mm height were worn for a pre-determined distance against a 75 cm diameter disk made of SKH-51 steel with a hardness of 890 HV, at a distance of 20 mm from center, sliding speed of 0.5 m/s and normal load of 29.4 N. The sliding distance for low and medium aluminum contents, i.e. x = 0.5 and 1.0, was 5400 m due to their high wear loss, whereas that for high aluminum content, i.e. x = 2.0, was 64,800 m due to its excellent wear resistance. Both pins and counterface were polished to 0.25 μm finish before each test. Wear debris and worn surfaces were characterized using SEM and EDS. An X-ray diffractometer (XRD, Rigaku ME510-FM2, Tokyo, Japan) was used for the phase identification with the 2θ scan ranging from 20° to 100° at a speed of $1^\circ\ \mathrm{min}^{-1}$. The typical radiation condition was 30 kV

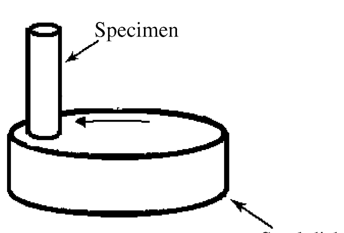

Fig. 2. Schematic drawing of wear test.

Table 1
Chemical compositions of cast $Al_xCoCrCuFeNi$ alloys in atomic percentage

x-Value	Al	Co	Cr	Cu	Fe	Ni
0.5						
Nominal	9.09	18.18	18.18	18.18	18.18	18.18
DR (BCC)	5.5	21.2	23.9	9.4	22.7	17.2
ID (Cu-rich)	12.5	5.5	4.0	59.2	5.2	13.6
1.0						
Nominal	16.67	16.67	16.67	16.67	16.67	16.67
DR (BCC)	25.5	16.1	17.2	7.4	14.6	19.2
ID (FCC + BCC)	13.0	17.3	18.3	17.5	20.0	13.9
ID (Cu-rich)	13.3	6.2	4.9	56.9	6.4	12.3
2.0						
Nominal	28.56	14.28	14.28	14.28	14.28	14.28
DR (BCC)	31.5	16.8	10.8	9.1	15.0	16.9
ID (Cu-rich)	15.1	3.4	4.2	68.2	4.0	5.1

DR, dendrite; ID, inter-dendrite.

and 20 mA with a copper target. Wear coefficient is defined as follows:

$$W_r = \frac{\Delta V}{F\int_0^{L_p} \mu d_L}$$

where W_r is the wear coefficient, ΔV the volumetric loss of the specimen (pin) after sliding for a distance L_p and obtained by dividing the weight loss of the specimen after sliding by its density, μ the coefficient of friction, L the sliding distance and F is the load.

3. Results and discussion

3.1. Microstructure and hardness of as-cast $Al_xCoCrCuFeNi$ alloys

In order to compare with the microstructure of the worn surface after adhesive wear test, the microstructure of as-cast $Al_xCoCrCuFeNi$ alloys was investigated first. Fig. 3 gives the typical microstructures of the alloys with different aluminum contents. Typical cast dendrite and interdendrite structures (defined as DR and ID in the figures, respectively) are observed in the alloys. The chemical compositions of the alloys analyzed by EDS are summarized in Table 1. Copper segregation is obviously seen in the interdendrite region. Fig. 4 shows the XRD analysis of crystal structure. It reveals that they consist of simple phases, FCC and BCC in the as-cast state. Thus for low aluminum content (x = 0.5), both the dendrite and Cu-rich interdendrite are of one simple FCC phase. As the aluminum content increases to x = 1.0, the dendrite region is of BCC phase and featured by the modulated structures of spinodal decomposition (defined as SD), while most region of the interdendrite is composed of FCC and BCC phases, and small region is the Cu-rich FCC phase. For high aluminum content (x = 2.0), the BCC dendrite is of spinodal structure and the small interdendrite is the Cu-rich FCC phase. It is clear that with the aluminum content increase, the volume fraction of BCC phase increases while the amount of interdendrite decreases. All these observations are in accordance with the microstructure analysis of $Al_xCoCrCuFeNi$