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Multi-phase quasicrystalline alloys for superior wear resistance

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ABSTRACT

Highly wear-resistant alloys are important in many engineering and biomedical applications. In this research, a multi-phase quasicrystal-based alloy was developed using a rapid arc-melting technique. The alloy contains three characteristic phases, hard λ-$Al_{13}Fe_4$, quasicrystal icosahedral (i-phase), and ductile τ-AlCu. The Vickers micro hardness of each was 828, 795, and 552, respectively, with an overall hardness of 334 (HR15T). Due to the co-existence of these three phases, this alloy exhibits both hardness and ductility. As such, the new material has favorable wear and crack resistance. The approaches used in this study are beneficial for the future design and development of this class of quasicrystalline alloys.

1. Introduction

Since their discovery in 1984 [1], quasicrystals have attracted great interest regarding chemical catalysis, heat insulation, and surface coating applications. The unique structure of the icosahedral phase, not seen in conventional metals, leads to low thermal conductivity, absorption of infrared-light, low friction, and high hardness [2–4]. When fabricated as a coating, the combination of high hardness and low coefficient of friction improves resistance against scratches or wear [2]. Reports on use of the quasicrystalline phase in coatings are summarized in Table 1. More information about these materials can be found in the supplemental material (Table S1). As shown in the table, the most popular metallic elements are Al, Cu, and Fe. To date, there are many limitations to the application of quasicrystalline materials. For example, it has been reported that the bonding between quasicrystal coatings and the substrate is weak. Fabrication processes are usually complicated and expensive, and specifically they are difficult to fabricate over large areas. Furthermore, their poor load bearing capability can result in deflection and peeling of the coatings [5,6]. There has been increasing interest in fabrication of bulk quasicrystal-based alloys using less complicated processes with lower cost. However, quasicrystal-based alloys are known to be extremely brittle [7–9]. In this research, a simple process step was developed to fabricate bulk quasicrystal-based alloys. An arc-melting technique was selected due to its fast heating and cooling process and low cost [10]. Raw materials of aluminum, copper, and iron were used to make the quasicrystal-based alloy. These raw materials were selected because of their low toxicity, affordability, and abundance [11–17]. The quasicrystal alloy contained multiple phases: λ-$Al_{13}Fe_4$, i-phase, and τ-AlCu. This alloy has a unique combination of mechanical properties and exhibits favorable tribological performance. Detailed examination of wear was conducted, and the role of each phase in wear resistance is discussed in this manuscript.

2. Experimental details

2.1. Sample preparation

Aluminum (Al, EM Science) with purity of 99.99%, copper (Cu, J.T. Baker) with purity of 99.9%, and iron (Fe, Sigma-Aldrich) with purity of 99.98% were selected as the raw material elements. Beads of Al (65 at.%), Cu (20 at.%), and Fe (15 at.%) were mixed with the goal of making the $Al_{65}Cu_{20}Fe_{15}$ quasicrystal. This concentration was selected based on the phase diagrams in order to generate a combination ofλ-$Al_{13}Fe_4$, i-phase, and τ-AlCu phases. These phases were candidates for study of wear [23,24]. An as-cast alloy was fabricated by arc-melting and quenching in the water cooled copper crucible. Detailed information is available in the supplemental information. The raw materials were put into a copper crucible in an argon-filled vacuum chamber to avoid oxidation. Then, they were melted by arc with a DC current for 60 s. After turning off the DC current, the melted material was rapidly cooled to room temperature in 5 min by the flowing cooling water around in the walls of the copper crucible. In order to improve the uniformity, the solidified sample was flipped and re-melted. This process was repeated for 8 times in order to ensure uniformity. The as-cast

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Table 1
Comparison of reported quasicrystalline coatings.

No.	QC Phase	Substrate	Thickness/Ra [μm]	Friction	Hardness	Wear (Load, speed, distance, temp.)	Ref.
1	$Ti_{41.5}Zr_{41.5}Ni_{17}$	Stainless steel	200/0.2	0.4	631.5 $Hv_{10\ g}$	Wear loss 6 mg (10 N, 0.5 m/s, 100 m sliding)	[18]
2	$Ti_{60}Cr_{32}Si_8$	301 Stainless steel	−/−	1	590 $Hv_{10\ g}$	Wear rate 1.1 × 10^{-5} mm^3/Nm (35 N, 0.001 m/s, 36 m sliding)	[19]
3	$Al_{62}Cu_{26}Fe_{12}$ (QC coating)/$Fe_{68}Al_{30}Cr_2$ (Particle)	304 Stainless steel	500/−	–	826 $Hv_{25\ g}$	Wear loss 0.027 cm^3 (87.2 N, 300 revol.)	[9]
4	$Al_{62}Cu_{26}Fe_{12}$	Mild steel	−/1.25	0.27	858 $Hv_{100\ g}$	Wear rate 9 × 10^{-4} g/m(20 N, 0.136 m/s, 41 m sliding)	[20]
5	$Al_{56.5}Cu_{28}Fe_{15.5}$	Inconel disk	10/0.05	0.37 (150 °C)	–	Wear rate 1.68 × 10^{-4} mm^3/Nm (0.98 N, 0.12 m/s, 600 m sliding, 150 °C)	[21]
6	$Al_{65}Cu_{20}Fe_{15}$	304 Stainless steel	10/0.05	0.09	1376 Hv	Scratch width 13 μm (after 50 times scratches)	[22]

alloy was then annealed in a Cress Electric furnace at 700 °C for 30 min. Detailed information is available in the supplemental material. The annealing temperature was selected to increase the amount of i-phase based on the phase diagram [25,26]. Illustration of the overall sample manufacturing process is available in supplemental information.

2.2. Characterization

The annealed alloy had a cobblestone appearance with a rough surface. Once made, the alloy was cut and mechanically polished with a polisher (STRUERS, DAP-3) for the phase analysis. Subsequently, the alloy was examined for surface morphology using an optical microscope (Keyence VHX-2000), a scanning electron microscope (SEM, VEGA3-SB), and an atomic force microscope (AFM, Nano-R™). Chemical characterization was performed through X-ray diffraction (XRD, Rigacu) and the energy-dispersive spectrum (EDS).

2.3. Mechanical testing

After annealing, both the sample and a bearing steel reference were polished for hardness measurement. The hardness values were obtained in different phases using a Vickers microhardness indenter (Tukon 1102) at 25 g-force load. Afterwards, the overall hardness of the annealed alloy and the bearing steel (using E52100 as a reference sample) was measured with a Rockwell hardness tester (Wilson 2000) with a 1/16″ ball penetrator at 15 kg applied load. For scratch tests, the surfaces of the two polished samples were cleaned with methanol and dried in an oven for 30 min. A scratch test was conducted using a tribometer (CSM Instruments) and a tungsten carbide stylus (20 μm diameter) as a counterpart. The normal loads of 1 N and 2 N were applied at a 10 mm s^{-1} scratch speed in a linear mode at room temperature. Fig. 1(a) is the schematic of the scratch test. The scratch tracks were examined using a scanning electron microscope (SEM) which detects secondary electrons and a profilometer (KLA-Tencor P-6 stylus).

2.4. Tribotests

During the scratch and wear tests, the coefficient of friction (COF) of the annealed alloy and the bearing steel sample was recorded in the computer connected to the tribometer. Similar to the scratch test, the bearing steel and the annealed alloy were polished and cleaned before the wear test. A 6 mm diameter tungsten carbide ball was used as a counterpart in a dry rotating, sliding mode as shown in Fig. 1(b). The wear tests were conducted at room temperature under the following conditions: a normal load of 5 N, sliding speed of 3 mm s^{-1}, and a total sliding distance of 25 m. A low sliding speed was selected in order to reduce the effect of heating in the contact region. A SEM and a profilometer were employed to investigate the worn surface on the wear tracks.

3. Results and discussion

3.1. Multi-phase alloy

To generate quasicyrstals, the as-cast alloy produced through arc-melting was annealed at 700 °C for 30 min. Analysis was conducted using a scanning electron microscope (SEM) and X-ray diffraction (XRD). Results in Fig. 2(a–d). Fig. 2(a–d) and S2 all show the surface of the polished annealed alloy. They have three different colors: dark gray, gray, and light gray. To identify the nature of these phase, EDS

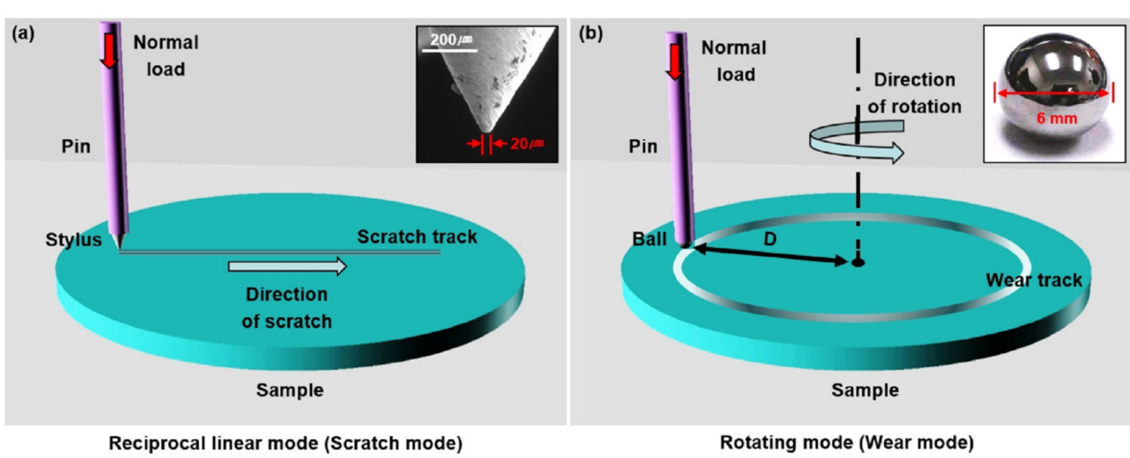

Fig. 1. Diagrams of experimental set-up. (a) a schematic of a scratch test with a 20 μm tungsten carbide shape stylus in a dry linear scratch mode and (b) a schematic of wear test with a 6 mm tungsten carbide ball in a dry rotating sliding mode at room temperature.