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Smearing-type wear behavior of $Al_{62}Cu_{25.5}Fe_{12.5}$ quasicrystal abrasive on soft metals

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ABSTRACT

The abrasive polishing behavior of $Al_{62}Cu_{25.5}Fe_{12.5}$ quasicrystal on Cu, Al and austenite stainless steel alloys were investigated, to compare with commonly used hard abrasives such as diamond, alumina and silica. The quasicrystal abrasive showed a dominating smearing-type wear mechanism, in sharp contrast to all the other three abrasives, as reflected by large indent size shrinking with respect to surface removal depth. The quasicrystal abrasive polishing, producing a flattened surface with minor depth removal, may open new application fields where low-wearing and fine surface finishing are demanded.

1. Introduction

Quasicrystals (QCs) have unique surface properties such as low coefficient of friction, low surface energy, and high corrosion resistance [1–4]. As measured by Kang et al. using pin-on-disk against diamond indenter [4], their coefficient of friction varies from 0.05 to 0.2 [4,5], while under the same tribological testing conditions, it is 0.42 for copper, 0.37 for aluminum and 0.32 for low-carbon steel. The low friction behavior is related to the intrinsic low surface energy property, resulted from the low electron density of states at Fermi level [6,7], which is much lower than that of a typical clean metal and significantly lower than that of an oxidized metal such as oxidized quasicrystals. Their Vickers hardness is about 6.5–11 GPa [1,4], higher than those of normal high-strength steels but close to that of silica. A high H/E ratio is generally indicative of good wear resistance [8]. Their H/E ratios are close to 0.05 GPa, which is similar to that of alumina and is among the highest in metallic compounds. In many aspects, QCs behave like covalent compounds. The combination of all these properties makes them suitable for non-stick oven coating [2]. Generally speaking, QCs are good wear resistant materials, and at the same time, do not wear much their counter parts principally due to the low friction property. Low-friction abrasives generally cause smearing-type wear during polishing [9,10], where plastic deformation smears out the irregular roughness and leaves a smoothened surface, without much surface material removal. On the other hand, via cutting-type wear, hard abrasive particles cut away the asperities on the worn surface, producing a fine surface at the expense of severe surface removal. It was especially noticed that when the frictional coefficient is low, only plastic deformation occurs without producing any wear debris [11].

Consequently, QCs should be useful in fields where low-wearing and fine surface finishing are demanded. In fact, QC particles have already been used as solid lubricant additives in engine oil [12], where the friction is reduced by avoiding intense abrasion while at the same time minimizing local scratching. Their applications can also be envisaged in harsh wearing environments such as oil pipe connectors and motors.

The present work explores the abrasive polishing behavior of Al–Cu–Fe QC particles on soft metals, to compare with commonly used hard abrasives such as diamond, alumina, and silica. The $Al_{62}Cu_{25.5}Fe_{12.5}$ QC [13] is used in our work for the low cost and easy availability. The wearing mechanism can be unveiled by following changes in wear rate and in surface morphology.

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2. Material and methods

2.1. Fabrication of quasicrystals abrasive

Ingots of the composition $Al_{62}Cu_{25.5}Fe_{12.5}$ were prepared by arc melting commercially available pure Al (99.99%), Cu (99.99%) and Fe (99.99%) metals in argon atmosphere. The master alloys were re-melted three times in order to achieve chemical homogeneity. From the alloy ingots, cylindrical rod samples of 3 mm in diameter were fabricated by cooper-mould suction-casting in argon atmosphere. The rod samples were then sealed in quartz tubes under vacuum and were annealed at 800 °C for 8 h, then furnace cooled.

The ingots were further crushed by ball-milling, using cemented carbide balls of 10 mm in diameter as the grinding medium. A ball-to-powder weight ratio of 15:1 was employed in this experiment. The rotation speed was 200 r/min. The grinding was carried out for 5 h in argon protection. Finally, the powders were sieved through 700 meshes (~20 μm). Structure, morphology and composition of the powders were characterized using X-ray diffraction (BRUKER D8 Focus, Cu K_α radiation) and scanning electron microscopy (JSM-5600LV). Table 1 lists the particle diameters measured by different methods.

2.2. Abrasive powders and polishing pastes

In order to reveal the characteristics of the QC abrasive, three kinds of common polishing abrasives were compared with, including diamond, alumina and silica. The diamond paste was produced by Zhengzhou Research Institute for Abrasives & Grinding Co. Ltd., and the diamond particle size is about 10 μm as given by the company (Table 1). Alumina and silica particles were the products of Shenyang Shihua Powder Material Co., Ltd.. Their sizes are shown in Table 1. The size distributions of the four kinds of abrasives particles were measured using Mastersizer 2000 (Malvern, UK) laser diffractometer. The alumina, QC and silica polishing pastes were prepared by ourselves, using the same lubricant paste (containing mainly stearic acid and Vaseline) from Zhengzhou Research Institute for Abrasives & Grinding Co. Ltd. The abrasive-over-paste concentration was fixed to 10 weight percent (wt. %), the same as in the bought diamond paste.

2.3. Workpiece materials

For the workpieces, four relatively soft metals were selected, Al–5Cu (wt.%), pure Cu, Cu–6Sn (wt.%), and 18Cr–8Ni (wt.%) austenite stainless steel. Their properties are shown in Table 1. They were machined to a cylindrical form, Φ40 mm in diameter and 12 mm in height. The initial workpiece surfaces were grounded by SiC abrasive papers with 800, 1500, and finally 2000 grits, successively. In order to study the wear mechanism of the different abrasives, micro-indentation was carried out by using normal loads of 0.25 N, 0.49 N, 0.98 N, 1.96 N, 2.94 N, 4.91 N and 9.81 N on an HV-1000 Vivtorinox hardness tester for each workpiece materials. Rhombohedral indents of various sizes were produced with the different loads. Indent morphology was observed by using scanning electron microscope (Zeiss Supra 55 (VP)).

2.4. Polishing tests

Polishing tests were carried out on a commercial polishing machine PhoenixBeta/Vector, Buehler Ltd., using 10 N vertical load and Buehler-TriDent™ polishing pad (Fig. 1). To enhance the weight loss, a high rotational speed of 350 rpm was chosen. The workpiece holder had a fixed rotational speed of 60 rpm. The average linear sliding speed of the workpiece with respect to the polishing pad was 2 m s^{-1}. The duration of each polishing test was 1.5 min and a fixed amount of the abrasive paste was added, 0.2 g. After each 3 min interval, the weight loss of the workpiece was measured by an electronic balance with sensitivity reaching 0.0001 mg. The indent morphologies were observed on SEM. The roughness of the worn surface was measured by a non-contact optical profiler, NewView 5022 (Zygo, USA).

2.5. AFM

Only pure aluminum samples were scanned with atomic force

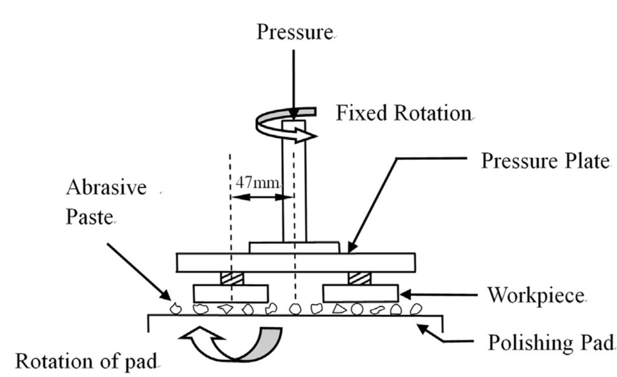

Fig. 1. Schematic diagram of the polishing test.

Table 1
Properties of workpieces and abrasives.

Material	ASTM	Hardness (GPa)	Elastic modulus (GPa)	H/E	K_{IC} (MPa $m^{1/2}$)	Diameter measured by mastersizer 2000 (μm)	Diameter estimated by SEM (μm)
Pure aluminum	–	0.25[a]	68	0.004			
Pure copper	C11000	1.0[a]	110	0.009			
Al–5Cu	2024	1.6[a]	73.1	0.022			
18Cr–8Ni	S30400	2.1[a]	200	0.010			
Cu–6Sn	C51900	2.4[a]	109	0.022			
Diamond	–	88–100 [14]	800–925 [14]	0.10–0.13	6–7 [15]	Ave:9–10 90% < 13.3	–
Al_2O_3	–	15.2–20.3 [16]	36 6[16]	0.04–0.06	2.2–3.5 [17,18]	Ave:8–10 90% < 13.7	~8
SiO_2	–	8.5 [19]	70–94 [20]	0.12–0.17	1.1–1.5 [19,20]	Ave:10–16 90% < 36.8	~10
QC	–	6.5–11 [1,4]	168 [21]	0.05–0.06	1.5 [1,2]	Ave:8–12 90% < 26.3	~8

[a] Vickers hardness measured by the present authors at a load of 200 g.