Short Communication

Wear Behavior of Al$_2$O$_3$-Reinforced Aluminum Metal Matrix Composite in Water and in Ethanol

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Aluminum metal matrix composite disks reinforced with alumina (Al$_2$O$_3$) were slid against silicon carbide (SiC) pins in water and in ethanol to evaluate the wear resistance. The wear of the composite slid against SiC in water was higher than that in ethanol. Oxidized aluminum compounds were formed by tribo-oxidation on the composite disk surfaces worn both in water and in ethanol. The amount of the oxidized aluminum compounds deposited on the wear tracks in water was much larger than that in ethanol. The significant oxidative wear took place in water, while oxidative wear and wear due to plastic deformation took place in ethanol.

Keywords: aluminum metal matrix composite, wear, tribo-oxidation, water, ethanol

1. Introduction

Decreasing the weight of the material used for moving parts in a machine appears to increase the energy efficiency of the system. Ceramic-reinforced aluminum metal matrix composites are lightweight wear-resistant materials with good thermal conductivity, and have been used for automotive components such as engines and brakes$^1$. Diversified applications of aluminum metal matrix composites require the composites to have good wear resistance in various environments. Tribo-systems using water and ethanol as lubricants are considered to be environment-friendly. Aluminum metal easily reacts with water and alcohol$^{2,3}$. The reaction of aluminum with water afforded oxidized aluminum, such as Al$_2$O$_3$ and Al(OH)$_3$$^4$. Aluminum metal react with alcohol to form aluminum alkoxide [Al(OR)$_3$]$^5$. Alkoxyaloxane [AlO(OH)$_{1-x}$ (OR)$_x$] and aluminum oxide hydroxide (Al$_2$O$_3$$\cdot$H$_2$O) were formed by the thermal decomposition and the hydrolysis of the aluminum alkoxide$^6$. The formation of these reaction products on the surfaces of aluminum metal and aluminum matrix composites worn in water and in alcohol has been reported$^{6-12}$.

In the case of aluminum metal slid against SiC and stainless steel, the wear of the aluminum in water was much lower than that in ethanol$^{11,12}$. The amount of the deposited oxidized aluminum compounds in water was much larger than that in ethanol. The deposited oxidized aluminum film effectively prevented adhesive wear of the aluminum in water while severe adhesive wear took place in ethanol.

In this paper, we investigate the wear behavior of aluminum metal matrix composite lubricated in water and in ethanol. The corrosion resistance of the aluminum matrix composite in aqueous solution was strongly influenced by the reinforcement$^{13}$. Al$_2$O$_3$ did not influence the galvanic corrosion rate of the aluminum metal matrix composite in aqueous solution$^{13}$. To avoid the influence of galvanic corrosion on the wear behavior of the aluminum metal matrix composite in water, we chose Al$_2$O$_3$ particle as the reinforcement. We chose SiC as the mating material. The friction coefficient and specific wear rate of SiC in water were similar in magnitude to those in ethanol though SiC appeared to react with oxygen, water and alcohol to form silica, hydroxysilane and alkoxysilane on the sliding surface$^{14,15}$. There was small difference in lubricity for SiC between water and ethanol$^{14,15}$.

2. Experimental procedure

The Al$_2$O$_3$-reinforced aluminum metal matrix composite was prepared from a mixture of Al$_2$O$_3$ powder (purity: 99.99%, particle size: 300 mesh, density: 3.9 g/cm$^3$) and aluminum metal powder (purity: 99.9%, particle size: 300 mesh, density: 2.7 g/cm$^3$). The
Al$_2$O$_3$ concentration was 30 mass percent (mass%) and the aluminum metal concentration was 70 mass%. The mixed powder was sintered in a vacuum chamber using a spark plasma sintering apparatus (Model SPS-511S, Sumitomo Coal Mining Co.) at pressures of 90 to 107 MPa, at temperatures of 590 °C to 600 °C, and in a disk shape (diameter: 20 mm, thickness: 4 mm to 5 mm). Hereafter, we abbreviate and refer to the Al$_2$O$_3$-reinforced aluminum metal matrix composite sintered from 30 mass% of Al$_2$O$_3$ and 70 mass% of aluminum as the 30Al$_2$O$_3$-70Al composite.

In the sliding experiments, a 30Al$_2$O$_3$-70Al composite disk was slid against a SiC hemispherical pin (radius: 2 mm, chemical composition analyzed by energy dispersive X-ray spectrometers after carbon coating: C; 67.1 at%, O; 2.4 at%, Al; 0.4 at%, Si; 30.1 at%) in distilled water and in anhydrous ethanol (H$_2$O < 50 ppm) using a unidirectional pin-on-disk machine (Model 200, Implants Science Corp.). The sliding speed was 40 mm/s, the applied load was 0.245 N, the sliding duration was 2 h and the sliding distance was 288 m. The sliding tests in ethanol were performed in dry air (relative humidity < 20%). Each test was run three times.

The observations of the worn surfaces of the disks and pins were performed using a laser microscope (VK-9500, Keyence) and a field emission scanning electron microscope (FE-SEM, S-4300, Hitach). Microprobe X-ray photoelectron spectroscopy (XPS; Theta Probe XPS system, Thermo Fisher Scientific) analyses were done to examine the chemical composition of the worn surfaces.

Table 1 Physical properties of tested materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Vickers hardness (Pa)</th>
<th>Density (g/cm$^3$)</th>
<th>Roughness (Ra) (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>2.78 × 10$^8$</td>
<td>2.7</td>
<td>0.015</td>
</tr>
<tr>
<td>30Al$_2$O$_3$-70Al composite</td>
<td>1.09 × 10$^9$</td>
<td>3.0</td>
<td>0.086</td>
</tr>
<tr>
<td>SiC</td>
<td>2.69 × 10$^{10}$</td>
<td>3.2</td>
<td>0.046</td>
</tr>
</tbody>
</table>

Fig. 1 Scanning electron microscope images of unworn surfaces ((a) and (b) 30Al$_2$O$_3$-70Al composite disk, (c) SiC pin)

Fig. 2 Specific wear rates of aluminum metal (A1070) metal disks and 30Al$_2$O$_3$-70Al composite disks slid against SiC pins

Fig. 3 Laser microscope 3D images of worn surface of the 30Al$_2$O$_3$-70Al composite disks ((a) disk worn in water (b) disk worn in ethanol)

3. Results and discussion

Figure 2 shows the specific wear rates of the 30Al$_2$O$_3$-70Al composite disk and aluminum metal (A1070) disk in water and in ethanol. In Fig. 2, each value is the average of three experiments. The wear of others; 0.02%) for comparison are summarized in Table 1. Scanning electron microscope (SEM) images of the unworn surfaces of the 30Al$_2$O$_3$-70Al composite disk and SiC pin are shown in Fig. 1. In Fig. 1 (a) and (b), the gray area is the aluminum matrix and the white particles are Al$_2$O$_3$. There are several visible grooves and pits that formed during sintering and polishing on the unworn SiC pin surface (Fig. 1 (c)).
the 30Al2O3-70Al composite disk in ethanol was lower than that in water, while the wear of the aluminum metal (A1070) in ethanol was remarkably higher than that in water. The addition of Al2O3 particles to the aluminum metal resulted in a reduction of wear. The wear of the 30Al2O3-70Al composite disk in water was about 7/10 of that of the aluminum metal (A1070). The wear of the 30Al2O3-70Al composite in ethanol was about 1/300 of the wear of the aluminum metal (A1070). The specific wear rates of the SiC pin slid against the 30Al2O3-70Al composite in water and that in ethanol were 1.2 × 10^-6 mm^3/Nm and 3.9 × 10^-7 mm^3/Nm, respectively.

Figure 3 shows three-dimensional (3D) profiles of the wear tracks of the 30Al2O3-70Al composite disk measured using a laser microscope. Several pits were observed on the wear track formed in water (Fig. 3 (a)). The depth, width and surface roughness of the wear track formed in ethanol were smaller than those formed in water (Fig. 3 (b)). Figure 4 shows SEM images of the 30Al2O3-70Al composite disks and SiC pins worn in water and ethanol. The adhesive substances, which appeared to be masses of the fine powder, were observed on the almost entire wear track in water (Fig. 4 (a), (b)). On the wear track formed in ethanol, adhesive substances (dark gray area) and the plastically deformed aluminum matrix were observed (Fig. 4 (d), (e)). The amount of the adhesive substances on the wear track formed in ethanol was much less than that formed in water. The surfaces of the SiC pins worn in water and in ethanol were smooth (Fig. 4 (c), (f)). Severe adhesion of aluminum to the mating SiC pin was not observed.

XPS analysis of the worn and unworn surfaces of the 30Al2O3-70Al composite indicated that the adhesive substances on the worn surfaces were oxidized aluminum. Figure 5 shows Al2p XPS peak profiles of the unworn surface and worn 30Al2O3-70Al composite disk surface after Ar+ etching for 600 seconds. The spot size of the analyzed area was 100 µm. On the wear track, the analyzed areas were center of the track. In Fig. 5, the Al2p peaks of 71.5 eV and approximately 74 eV were assigned to metallic aluminum and Al-O bond, i.e., the oxidized aluminum compounds, respectively. Various oxidized aluminum compounds, such as Al(OH)3, Al2O3 and Al2O3·H2O, are indistinguishable in the Al2p peak profile4). The Al2p peak of 74 eV in Fig. 5 comprised reinforcement and other oxidized aluminum compounds. The peak area ratio of the metallic aluminum to the oxidized aluminum compounds decreased after the sliding test. The peak area ratio of the metallic aluminum to the oxidized aluminum compounds of the
unworn surface, that of the wear track formed in water, and that of the wear track formed in ethanol were 0.82, 0.08 and 0.49, respectively. The atomic percent of the Si derived from the SiC pin on the wear track formed in water and that formed in ethanol were only negligible trace amounts.

The results of our SEM observation and XPS analyses suggested that the oxidized aluminum compounds appeared to have been formed by tribo-oxidation of the aluminum matrix during sliding and that the amount of the oxidized aluminum compounds deposited on the wear track in water was much larger than that in ethanol.

In water, remarkable oxidative wear took place. Previously, we reported that tribochemically formed oxide masses were embedded in a matrix of the composite and that the detachment of the embedded oxide masses resulted in the formation of pits. Similarly, the pits observed on the wear track in water (Fig. 3(a)) appeared to have been formed by the tribo-oxidation products.

Oxidative wear and wear due to plastic deformation took place on the 30Al2O3-70Al composite worn in ethanol. The wear due to plastic deformation such as ploughing, cutting and adhesion were significantly reduced by the addition of the Al2O3 particle to the aluminum metal. Consequently, the wear of the 30Al2O3-70Al composite in ethanol was much lower than that of the aluminum metal (A1070).

4. Summary

Oxidized aluminum compounds formed on the 30Al2O3-70Al composite disk surface worn in water and in ethanol by tribo-oxidation. The amount of the oxidized aluminum deposited on the wear track in water was much larger than that in ethanol. The formation of the oxidized aluminum caused the oxidative wear of the 30Al2O3-70Al composite. For these reasons, the wear of the 30Al2O3-70Al composite disk slid against the SiC pin in water was higher than that in ethanol.

5. References