Dry Sliding Wear Behavior of A2218/Al3Fe Composites Fabricated by Plasma Synthesis Method

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The wear behavior of an A2218 alloy and an A2218/Al3Fe composite fabricated by the plasma synthesis method was investigated under dry sliding conditions. The wear tests were carried out at a sliding speed of 0.2 m/s and at the load range of 3–600 N. The variation of wear rate with applied load is composed of two regions for both materials and the two regions belong to mild wear. On the basis of observation and analysis on the worn surface, subsurface and the wear debris, the wear mechanism acting on each region was identified. At low loads, oxidative wear is the main wear mechanism and at high loads, the wear is controlled mainly by delamination and adhesive wear mechanism and oxidative wear is an additional wear mechanism. The A2218/Al3Fe composite exhibits an improved wear resistance at lower loads. On the contrary, at higher loads, due to the presence of the mechanical mixed layer on the worn surface of the A2218 monolithic alloy, both the monolithic alloy and composite exhibit similar wear rate.

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1. Introduction

Ceramic particle-reinforced aluminum based metal matrix composites (MMCs) show a superior combination of mechanical and physical properties, such as high modulus and strength, high temperature stability and excellent resistance to wear.1,2) The composites have been considered as potential application in the tribological field for such as piston, rotor brake and cylinder liner. When the particle reinforced MMCs are fabricated by casting route with ceramic particles such as SiC, TiC and Al2O3, incorporation of reinforcing ceramic particles into molten matrix is difficult due to poor wettability between molten metal and ceramic particles.3,4) Moreover, costs, machinability and incompatibility with environment such as recycling have so far hampered ceramic particle-reinforced MMCs to be utilized for their commercial applications in spite of their superior physical and mechanical properties.

In recent years, metal particle reinforced MMCs have taken great attention due to their easy fabrication and variety of property selection, and much work has been reported on the development of metal or intermetallic compound particle reinforced MMCs: in-situ Al/Al3Ti composites with centrifugal casting of Al–Ti alloys, squeeze casting of A380/Fe and A201/Al–Fe–V–Si particles, stir-casting of Al/quasicrystalline Al–Cu–Fe particles and in-situ Al/Al3Fe composites with the plasma synthesis method.5–9) The tribological behavior of ceramic particle reinforced aluminum matrix composites has been extensively studied for more than last 3 decades.10–17) But, up to now, the tribological behaviors of the metal particle or intermetallic compound reinforced aluminum matrix composites are limited.18–20)

The plasma synthesis method (PSM) is a kind of in-situ formation of intermetallic compounds in the matrix and it involves incorporation of metallic particles into a molten metal using a plasma jet. In the process, the particles are heated and accelerated in the plasma arc, which helps the incorporation of the particles into the molten metal and accelerates the in-situ formation of intermetallic compounds in the melt.

In the present work, in-situ A2218/Al3Fe composites were produced by the PSM. A2218 alloy is a heat-treatable Al–Cu–Mg–Fe–Ni forging alloy system and is used as engine pistons and cylinder heads. Thus, improved wear properties are required for the A2218 alloy. The intermetallic compounds such as Al3Fe are reported to be thermally stable in aluminum with higher hardness values. Thus, the combination of A2218 and Al3Fe can be expected to give good wear properties. The purpose of the present work is to study the dry sliding wear behavior of A2218/Al3Fe composites fabricated by the PSM.

2. Experimental

The commercial A2218 alloy was received from Dooray Air Metal Co. Ltd. The as-received A2218 alloy was extruded with a 35:1 extrusion ratio. The A2218 extruded bar was cut and remelted to make A2218/Al3Fe composites by the PSM. The fabrication processing was carried out by a ValuPlazTM Plasma Spray System (SULZER METCO Co., USA). The plasma spraying condition was 300 A of input current, 80 L/min of gas flow rate and 85 g/min of powder feeding rate. The temperature of the melt was held at 760°C. Details of fabrication experiments were given elsewhere.9) The chemical compositions of the as-received A2218 alloy and as-cast A2218/Al3Fe composites are given in Table 1. The as-cast A2218/Al3Fe composites were extruded at 390°C with a

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<th>Specimen</th>
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<tr>
<td></td>
<td>Fe</td>
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<td>A2218</td>
<td>0.16</td>
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<td>A2218/Al3Fe</td>
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Table 1 Chemical compositions of the A2218 alloy and A2218/Al3Fe composite.
Dry Sliding Wear Behavior of A2218/Al3Fe Composites Fabricated by Plasma Synthesis Method

Distributed homogeneously in the Al matrix of A2218 monolithic alloy. In the case of composites, Al3Fe intermetallic compounds were evenly distributed in the A2218 matrix alloy. The second phase compounds were analyzed by using XRD and SEM/EDS. The phases such as Al7Cu4Ni, Mg2Si and Al9FeNi were detected in the microstructures of an A2218 monolithic alloy. In the composite sample, an additional phase, Al7Cu2Fe was detected. The formation of Al7Cu2Fe was associated with the dissolution of Fe particles during fabrication of the composite materials.

3.2 Wear rates

Figure 3 shows the effect of applied load on the wear rates of the monolithic alloy and the composite in the load range of 3–600 N. The wear rate curves reveal that there exist two different regions, which are marked as region I and II in Fig. 3. In region I, the applied load is smaller than 50 N for both materials and the wear rate of the composite shows one order of magnitude lower values compared with the monolithic alloy. When the applied load exceeds 50 N, increase of wear rate becomes distributed homogeneously in the Al matrix of A2218 monolithic alloy. In the case of composites, Al1Fe intermetallic compounds were evenly distributed in the A2218 matrix alloy. The second phase compounds were analyzed by using XRD and SEM/EDS. The phases such as Al1Cu4Ni, Mg2Si and Al1FeNi were detected in the microstructures of an A2218 monolithic alloy. In the composite sample, an additional phase, Al1Cu2Fe was detected. The formation of Al1Cu2Fe was associated with the dissolution of Fe particles during fabrication of the composite materials.

3. Results

3.1 Microstructures of the test samples

Figure 2 shows the typical microstructures of the solution treated A2218 monolithic alloy and A2218/Al1Fe composite. It can be seen that very fine second phase compounds were distributed homogeneously in the Al matrix of A2218 monolithic alloy. In the case of composites, Al1Fe intermetallic compounds were evenly distributed in the A2218 matrix alloy. The second phase compounds were analyzed by using XRD and SEM/EDS. The phases such as Al1Cu4Ni, Mg2Si and Al1FeNi were detected in the microstructures of an A2218 monolithic alloy. In the composite sample, an additional phase, Al1Cu2Fe was detected. The formation of Al1Cu2Fe was associated with the dissolution of Fe particles during fabrication of the composite materials.
rapid. In region II, near linear functions of wear rate to the applied load are obtained. Further, both materials exhibited almost similar wear rates in this region.

3.3 Worn surface

The worn surfaces of the composites alloy pins at different applied loads are shown in Fig. 4. At a low load of 6 N, the worn surface appears smooth and consists of small grooves and few dimples. Generally, the width of the grooves and size of the dimples on the worn surface increase with increasing load. Figures 4(b) and (c) correspond to the load of 60 and 150 N, respectively. The worn surfaces are also smooth, and the width of groove becomes larger than that at the load of 6 N. In addition, larger dimples are easily found on the worn surface (Fig. 4(d)).

The worn surfaces of the monolithic alloy pins at different applied loads are shown in Fig. 5. The characteristics of the worn surface of the pins are similar to those exhibited in composites except at low load of 6 N. At low load of 6 N, large grooves appear on the smooth worn surface and very few dimples are found.

3.4 Subsurface

Figure 6 shows the optical microstructures of the worn subsurface of the monolithic alloy at the applied load of 6, 60 and 150 N, respectively (the arrow mark indicates the sliding direction). The microstructures clearly reveal a MML (mechanical mixed layer) and plastic flow along the sliding directions. Systematic observation showed that the MML exhibits discontinuity in the worn specimens. The thickness of the MML increases with increasing in the applied load. Figure 7 shows the optical microstructures of the worn subsurface of the composite alloy at the applied load of 6, 60 and 150 N, respectively. The microstructures clearly reveal bending of flow lines along the sliding directions. Unlike the worn subsurface observed in monolithic alloy pins, the formation of MML cannot be seen in the worn subsurface of the composite pin. Instead, smooth surface of Al$_3$Fe particles are protruded on the
worn subsurface. Further, with increasing the applied load, Al$_3$Fe particles are elongated along the flow line and cover the worn subsurface. To confirm the formation of MML on the worn subsurface of the composite pins, SEM/EDS analysis was performed on the worn subsurface for the both pins. Figure 8 shows the typical results of SEM/EDS. In the monolithic pin, the peaks of O, Al and Fe, which are the main compositions of MML, are clearly detected. On the contrary, in the composite pin, the peaks of Al and Fe are clearly detected and the peak of O is very weak. This indicates that the formation of MML on the worn surface of the composite pin is very retarded.

3.5 Debris

The observation and analysis of the wear debris can contribute to the understanding of the wear mechanism. In the present work, the wear debris generated during wear tests was collected. SEM observation, EDS and XRD analysis were used to reveal the morphology of the wear debris and its constituent. XRD patterns of the wear debris of the monolithic alloy and composite at different loads are shown in Fig. 9. The wear debris of the monolithic alloy contains Fe, Al, Fe$_2$O$_3$ and Al$_2$O$_3$ in the entire range of the applied load for the monolithic alloy. With increasing applied load, the peaks of oxide such as Fe$_2$O$_3$ and Al$_2$O$_3$ decrease and Fe and Al peaks become obvious. It is noted that the three main peaks of $\alpha$-Fe overlap those of Al. However, according to the results obtained by other investigators, $\alpha$-Fe should be present in the debris generated in a wear system composed of aluminum alloys and steel. In addition, the broadening of Al peaks,
which are overlapped by $\alpha$-Fe peaks in the present XRD patterns, also suggests the presence of Fe in the wear debris.\textsuperscript{21, 22)} The wear debris of composite is somewhat different compared with that of monolithic alloy. The wear debris of the composite at the load of 6 N contains only oxides such as Fe$_2$O$_3$ and Al$_2$O$_3$. With increasing applied load, the Fe and Al peaks become obvious. In addition, the peak of Al$_3$Fe (more precisely Al$_{13}$Fe$_4$) becomes clear. Figures 10 and 11 show the SEM micrographs of the wear debris of the monolithic alloy and composite, respectively. The wear debris of the monolithic alloy is composed of fine powders and irregular shape of platelets or flakes in the whole range of applied load. With increasing applied load, the size of the platelets or flakes becomes larger and their amount increases. The similar features are observed for the debris of the composite except for the debris obtained at the low load of 6 N, where debris is composed of only fine powders.

Figure 12 shows the results of EDS quantitative analysis performed on wear debris of the monolithic and composite, respectively, and plotted with the applied load. High levels of O, Al and Fe are contained in the debris of both materials in the whole range of applied load. The level of O decreases with increasing the applied load for the debris of both materials and especially high level of O is obtained for the debris of the composites at the load of 6 N, which corresponds well to the results of XRD analysis and SEM observation. The relative level of Fe increases with applied load while opposite behaviors appears for the relative level of Al. It is noted that the level of Fe and Cr for monolithic debris shows similar behavior with applied load, while the level of Fe increases and level of Cr remains constant with increasing applied load for composite debris. This indicates that Fe comes from not only steel counterpart but also Al$_3$Fe particles in the composite pin.

4. Discussion

4.1 Wear regime

Aluminum alloys are well known to exhibit two types of sliding wear behavior, that is, mild and severe wear, which was first proposed by Archard and Hirst.\textsuperscript{23} A transition from the mild wear to the severe wear occurs when the applied load or sliding speed exceeds a critical value.\textsuperscript{24, 25} The severe wear involves massive surface damage and a large scale material transfer to the counterpart surface. Plastic deformation and fracture have been confirmed as being the main causes of severe wear.\textsuperscript{26} Alpas and Zhang reported that three main regimes existed with increasing load for A2014 alloy and its composites reinforced with SiC particle, and A6061 alloy and its composites reinforced with Al$_2$O$_3$ particle.\textsuperscript{12} At low loads (regime I), the particles support the applied load, and the wear resistance of the composites is at least an order of magnitude better than that of monolithic alloys. In the intermediate load range (regime II), the wear rate of the composites is comparable to that of monolithic alloys and increases gradually with increasing load. A second transition occurs at the end of regime II, and then severe wear becomes dominant (regime III). The transition takes place when the surface temperatures exceed a critical value and this region involves massive surface damage and material transfer to the counterpart surface. In regime III, the wear rate of the composites is better than that of monolithic alloys and increases rapidly with increasing load. In the present work, two regions exist apparently with the variations of the wear rate with the applied load. In general, the wear rate or wear mechanism of the materials in dry sliding wear are influenced by the experimental conditions such as applied load, sliding speed, atmosphere, temperature and counterpart materials. Under the experimental conditions used in the present work, the A2218 alloy and its composite reinforced with Al$_3$Fe exhibited two typical regions with the applied load. The wear features such as worn surface, subsurface and wear debris displayed gradual change from region I to region II. Further, presence of oxide powders in the debris in region II, the presence of MML on the worn surface in monolithic alloy, and the absence of severe plastic deformation and shear fracture in region II, which are evidences for severe wear, indicated that the two regions in this work all belonged to mild wear and correspond to regime
I and regime II, respectively, reported by Alpas and Zhang. However, the dominant wear mechanism appears somewhat different in different regions of the mild wear.

4.2 Wear mechanism

The wear tests showed that the wear rate exhibited different characteristics in the different regions. Therefore, the wear should be controlled by different mechanisms. In region I, for the composite, XRD analysis showed that the wear debris produced in this region contains a great amount of oxides of Al and Fe. In addition, the wear debris was very fine powder and dark in color, indicating that oxidative wear is the main wear mechanism. As for the monolithic alloy, the similar features were obtained but small amount of Al and Fe was contained in the debris and small flaky particles were observed in the debris. Further, large grooves were found in the worn surface. It was confirmed that the composition of grooves had similar composition of MML formed in worn subsurface. This indicates that delamination of MML also plays an additional effects. In region II, both materials showed similar wear characteristics except for formation of MML in the worn subsurface. The wear debris contained many shiny metallic flakes together with some small and dark powders. The metallic flakes had two kinds of compositions: some particles had similar composition with MML and the others had similar composition of bulk materials. This indicates that the delamination took place not only at MML but also at the subsurface bulk materials of the pin. XRD analysis showed that the wear debris produced in this region contains Al₂Fe. Further, plastic deformation of the pin materials can be seen on the worn surface and shear fracture trace is observed on some large debris, indicating the occurrence of adhesive wear. Thus, in this region, delamination and adhesive wear mechanism is dominant and oxidative wear is the additional wear mechanism.

It is reported that MML plays an important role in the wear of aluminum alloys and its composites against steel counterpart. MML is a mixture of $\alpha$-Al, $\alpha$-Fe, $\alpha$-Al₂O₃, and AlFe or Al₁₃Fe₄ created during the sliding process and shows much higher hardness than that of corresponding matrix materials. Venkataraman et al. showed that the width of MML increased with increasing load in mild wear and removal of MML is responsible for the onset of severe wear. However, Alpas and Zhang reported that the MML exists only under the low load conditions. The absence of MML at worn subsurface of monolithic alloy was considered as the reason that the wear resistance of monolithic alloy is worse than that of composite. However, many recent reports show that the MML layer forms on the worn surface of aluminum alloys and the composites. In the present work, MML can be always observed for the monolithic al-

Fig. 8 Results of SEM/EDS of subsurface regions at a load of 60 N for (a), (b) A2218 and (c), (d) A2218/Al₁₃Fe.
loy. On the contrary, MML cannot be clearly observed for the composite. The reason for the absence of MML on the worn surface of the composite pin is not still obvious. However, the presence of Al<sub>3</sub>Fe particles is one of the possible reasons. During dry sliding wear, the hard Al<sub>3</sub>Fe particle are protruded onto the worn surface without fracture, and furthermore, with increasing the applied load, the Al<sub>3</sub>Fe particles are elongated along the flow lines and cover the worn surface (Fig. 7). Thus, the fine particles of α-Al, α-Fe and α-Al<sub>2</sub>O<sub>3</sub>, cannot be compacted easily onto the matrix of worn surface.

The microhardness of the MML at some applied loads of the monolithic alloy was measured (Table 2). It is found that the hardness of the MML is lower than that of Al<sub>3</sub>Fe in the composite pin, but substantially higher than the bulk hardness and hardly changes with increasing load. Thus, owing to the formation of the MML in the monolithic alloy and the presence of Al<sub>3</sub>Fe in the composite, the similar wear behaviors were obtained for both materials in region II.

### 4.3 Wear rate

For wrought aluminum alloys such as A2014, A6061 and A7075, the differences in the wear rate between monolithic alloys and their composites reinforced with ceramic particles have been reported a lot in the literatures. In general, a great improvement in wear resistance has been revealed by the addition of ceramic particles. On the contrary, the opposite results have been also reported. Roy et al. observed a decrease by a factor of 3–4 in the wear rate by 10–20 vol%
SiC particle and Narayan et al.\textsuperscript{13} concluded that the wear resistance of the unreinforced alloy is better than that of the composites for A2014/Al$_2$O$_3$ composites. Gui et al.\textsuperscript{17} reported that Al–Cu–Mn/SiCp composites produced by spray deposition exhibited an improved wear resistance for whole range of applied load, but the improvement was not significant. As for the metal or intermetallic compounds reinforced aluminum matrix composites, the reported matrix alloy system is very limited and has confined to pure aluminum on the study of wear properties. Chen et al.\textsuperscript{18} reported that the wear rate of Al/NiAlp is comparable to that of Al/SiC. Wu \textit{et al.}\textsuperscript{19} suggested that large blocky Al$_3$Ti has a deleterious effect on the wear resistance of MMC made from the TiO$_2$–Al–B$_2$O$_3$ system. The present wear tests indicated that the A2218/Al$_3$Fe composite produced by the PSM exhibits an improved wear resistance at lower loads (region I) in comparison to the monolithic alloy by an order of magnitude even though similar wear rates were obtained at higher loads (region II) for both materials.

5. Conclusions

Dry sliding wear behaviors of an A2218 alloy and an A2218/Al$_3$Fe composite fabricated by the plasma synthesis method were investigated under the load range of 3–600 N at constant sliding velocity of 0.2 m/s. Based on the microstructural analyses of the worn surface, subsurface and the wear debris, the following conclusions can be drawn.

(1) The variation of wear rate with applied load is composed of two regions for both materials and the two regions belong to mild wear under the dry sliding condition used in the investigation.

Fig. 11 SEM micrographs of wear debris of the composite at different loads. (a) 6 N, (b) 6 N, high magnification, (c) 60 N, (d) 60 N, showing fractures of the debris, (e) 150 N.
In region I, oxidative wear is the main wear mechanism. In region II, the wear is controlled mainly by delamination and adhesive wear mechanism and oxidative wear is an additional wear mechanism.

MML is formed on the worn surface of the A2218 monolithic alloy for the whole range of the applied load. On the contrary, formation of the MML on the worn surface of the A2218/Al₃Fe composite is not observed.

The A2218/Al₃Fe composite exhibits an improved wear resistance at lower loads (region I) in comparison to the monolithic alloy by an order of magnitude.

**REFERENCES**


Table 2:

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<th>Materials</th>
<th>MML in A2218</th>
<th>Al₃Fe in composites</th>
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<td>Microhardness</td>
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<td>432</td>
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</table>

![Fig. 12 Changes of compositions of the debris with applied load by EDS analysis. (a) O, (b) Al, (c) Fe, (d) Cr.](image-url)