Tribological Property of Surface Hybrid Composite Layer Fabricated on Aluminum Alloy 7075 by FSP

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Abstract. In this study, friction stir processing (FSP) has been used to fabricate aluminum alloy 7075 based surface hybrid composite with a mixture of SiC and MoS$_2$ reinforcement particles. The surface hybrid composite layer has been successfully fabricated at different content ratio of SiC and MoS$_2$ particles by one-pass FSP. The SiC and MoS$_2$ particles were distributed almost homogeneously over the nugget zone. The average Vickers hardness at nugget zone increased to about 190 at 100% SiC, and it decreased with increasing the MoS$_2$ content ratio in reinforcement. The wear weight loss of the surface hybrid composite depended on the applied load and the relative content ratio of SiC and MoS$_2$ particles. The surface hybrid composite of 75% SiC and 25% MoS$_2$ showed superior wear resistance among all tested samples. The wear failure was attributed to the combination of the combination of abrasive wear and delamination.

Introduction

Friction stir processing (FSP) has received considerable attention as an effective microstructure modification technique since 2000. In this case, a rotating tool with pin and shoulder is inserted in a single piece of material and then moves in a direction of interest. The tool serves two primary functions of heating and deformation work-piece material. The heated material softens which flows around the rotating, and then fills the cavity at the rear of the tool [1-3]. Through the aforementioned severe plastic deformation, the microstructural modification can be obtained. Up to now, FSP technique has been used to produce the fine-grained structure, surface or bulk composite for aluminum alloy, magnesium alloy, copper alloy, etc [1].

Compared to the traditional fusion surfacing techniques, such as laser beam and thermal spraying, FSP shows a special merit to fabricate surface composite, which can inhibit the formation of undesirable interfacial reactions between the matrix and the reinforcement [4]. Therefore, FSP technique has been used to fabricate surface metal matrix composites (SMMCs) in recent years, which can be divided into two types based on the type of reinforcement phase [5]. One is intermetallic compound, which is incorporated by the in-situ reaction. Qian JW etc. fabricated Al/Al$_3$Ti, Al/Al$_3$Ni SMMCs by FSP, where the formation of intermetallic compound reinforcement was produced by the in-situ reaction with the addition of Ti or Ni powders [5-7]. The other is reinforcement particles, which is distributed in the light metal matrix by severe mechanical mixing, where different reinforcement particles have been used, such as SiC, Al$_2$O$_3$, carbon nanotube, etc [5]. Although the incorporation of single reinforcement was beneficial to the improvement of wear resistance of the resultant SMMCs, some studies concluded that hybrid-SMMCs exhibited better wear resistance, which was reinforced by a combination of two or more different type of reinforcement particles, such as SiC and Al$_2$O$_3$ [4], SiC and MoS$_2$ [8,9], etc. For aluminum alloys, hybrid-SMMCs have been investigated to improve wear resistance of pure aluminum plate, 3xxx, 5xxx and 6xxx series aluminum alloys.
In the present study, aiming to investigate the effect of hybrid SMMCs on the tribological characteristics, the SMMCs were fabricated on aluminum alloy 7075-T6 by FSP with the mixture of SiC and MoS$_2$ reinforcement particles. The microstructure, hardness and tribological behavior of the hybrid SMMCs have been measured in details.

**Experimental Procedures**

AA7075-T6 alloy rolled plate of 6.9 mm thickness was used to fabricate surface composite, which composition is shown in Table 1. Mixtures of SiC and MoS$_2$ at different ratios were utilized as reinforcement. The average particle size of SiC particles was approximately 20 µm, and which of MoS$_2$ particles was about 5µm. The 120 mm ×80 mm ×6.9 mm strips were prepared by wire-electrode cutting. A square groove (2 mm deep and 2 mm wide) was made on each strip surface allowed particles to be incorporated into the matrix. High speed steel having screwed taper pin profile with shoulder diameter of 15 mm, pin diameter of 3 mm at the bottom and 6 mm at the top, pin height of 3 mm was used in FSP. A stirring tool having shoulder without pin was utilized to pack the groove filled with SiC and MoS$_2$ particles. After packing the groove, surface composite was fabricated by FSP. One-pass FSP were carried out at a ratio of tool rotation rate/traverse speed of 1500 rpm/33.5 mm.min$^{-1}$. The tool onward tilt angle of 2.5° was used along the center line in FSP with reduction of 0.5 mm.

<table>
<thead>
<tr>
<th>Zn</th>
<th>Cu</th>
<th>Mg</th>
<th>Fe</th>
<th>Si</th>
<th>Mn</th>
<th>Ti</th>
<th>Cr</th>
<th>others</th>
<th>Al</th>
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<td>5.77</td>
<td>1.56</td>
<td>2.47</td>
<td>0.50</td>
<td>0.34</td>
<td>0.10</td>
<td>0.02</td>
<td>0.23</td>
<td>0.15</td>
<td>Balanced</td>
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</table>

After FSP, the cross section of surface composite in nugget zone (NZ) was made by wire-electrode cutting. Microstructural observations were carried out using optical microscope and scanning electron microscopy (SEM, JSM-6460LV) with EDX. Microhardness of the cross section of NZ normal to the FSP direction was measured by use of a Vickers digital microhardness tester.

The tribological characteristics of the hybrid SMMCs on aluminum alloy 7075 were measured by dry sliding wear against a 4 mm diameter GCr15 bearing steel ball. The tests were carried out at normal loads of 10, 20, 50 N applied to the GCr15 balls. The reciprocating sliding rate was 0.1 m/s, and the total test period was 10 min. The friction coefficient of steel balls against the SMMCs was recorded by the tester software. The wear volume loss was measured with a surface profilometer (NanoMap 500LS). The ware morphology was examined by SEM (JSM-6460LV).

**Results and Discussion**

The optical macroscopic appearances of the cross section of nugget zone produced by one FSP pass are shown in Fig. 1. As expected, the mixture of SiC and MoS$_2$ reinforcement particles was incorporated in the aluminum alloy 7075 matrix, which was caused by the severe stirring action of the rotating tool. The density of reinforcement particles seemed to be higher on the advancing side than that on the retreating side. However, the distribution of reinforcement particles was uniform at the top of nugget zone. As compared to that, there existed some aggregation of reinforcement particles and voids at the bottom of nugget zone, which may be attributed to the inadequate plastic flow by one FSP pass [10]. This phenomenon was neglected because the tribological behavior of the hybrid SMMCs was measured.

The distribution of SiC and MoS$_2$ reinforcement particles in nugget zone was investigated further by SEM. The SEM photographs of the cross section of hybrid SMMCs were shown in Fig. 2. Both images clearly attested to the uniformly dispersion of both reinforcement particles, which was analyzed by EDS surface scanning results. Moreover, the interfacial adhesion was good between the reinforcement particles and the aluminum alloy 7075 matrix. As compared to the results in ref.[11], the MoS$_2$ particles was not seen by naked eyes in SEM images, and the SiC particles size was reduced obviously, which can be ascribed to the severe stirring action of rotating tool under axial load [3,11].
Figure 1. Optical macrographs of the cross section of hybrid SMMC after one FSP pass (AS: advancing side).

Figure 2. SEM micrographs of the nugget zone of different hybrid SMMC: (a) 67% SiC+33% MoS$_2$; (b) 50% SiC+50% MoS$_2$.

The Vickers hardness profiles along the cross section of nugget zone for the hybrid SMMC are presented in Fig.2. Two special characteristics were shown based on the variation of Vickers hardness. On the one hand, at the middle of nugget zone, the hardness was higher than that of aluminum alloy 7075 matrix, where the width was about 3 mm. With increasing the distance from the rotation center, the hardness decreased gradually, which happened in both advancing and retreating side. These zones belonged to the heat affected zone and thermo-mechanically affected zone. The decrease of hardness can be due to the recovery of work hardening [12]. In contrast, the increase of hardness in the nugget zone can be ascribed to the incorporation of reinforcement particles and grain refinement [3, 4, 11, 12]. Besides, the hardness profiles can be considered to reflect the homogeneity of reinforcement particles [12], the distribution of the hardness suggests a uniform dispersion of SiC and MoS$_2$ particles in nugget zone. On the other hand, the addition of MoS$_2$ particles led to the decrease of hardness at nugget zone. With the increase of MoS$_2$ content in reinforcement, the hardness decreased. The results were similar to those in ref. [11]. As compared to the hardness of hybrid SMMC with 100% SiC, that of hybrid SMMC with 50% SiC and 50% MoS$_2$ was reduced to about 165 HV, which can be attributed to the layered structure and softening properties of MoS$_2$ [9,11]. At the heat affected zone and thermo-mechanically affected zone without reinforcement particles, the variations of hardness was irregular.
In order to evaluate the triological behavior of hybrid SMMC on 7075 alloy matrix, dry sliding wear tests were conducted at the center of nugget zone along the advancing direction of the rotating tool. The variations of wear rate are illustrated in Fig. 4. As can be seen in this figure, the increase of applied load resulted in the increase of wear weight loss. As compared to the samples with 100% SiC, the addition of 25% and 33% MoS$_2$ decreased the wear weight loss, however, the addition of 50% MoS$_2$ improved the wear weight loss. These results concluded that the FSPed hybrid SMMCs showed better wear resistance when the MoS$_2$ content ratio in reinforcement was lower than 50%. Moreover, despite the fact that the hardness of surface composite layer with 100% SiC was higher than other samples, it showed lower wear resistance.

Fig. 5 illustrates the variations of friction coefficient for the as-received aluminum alloy 7075 and hybrid SMMCs. As can be seen in Fig. 5, the mentioned two-stage trend can be distinguished from the friction coefficient curves for all the tested samples. At the beginning of the test, the friction coefficient increased to a peak value, and then decreased to a lower relatively steady state value, which was similar to the results reported in some literatures [12]. This can be ascribed to the increase of tangential force, used to overcome the highly adhesive contact between the tested sample surface and steel ball [8, 12]. As compared to the hybrid SMMCs, as-received aluminum alloy 7075 showed the highest friction coefficient at all the tested applied load.
For the hybrid SMMCs, the variations of friction coefficient seemed irregular. The sample with 50% SiC and 50% MoS$_2$ showed the lowest value at all tested load. However, the variations of friction coefficient for other three kinds of hybrid SMMCs were different at different applied load. At a applied load of 10 N, the sample with 67% SiC and 33% MoS$_2$ showed higher value, followed by the sample with 75% SiC and 25% MoS$_2$, and the sample with 100% SiC. In contrast, at an applied load of 50 N, the sample with 100% SiC showed higher value. In addition, the fluctuation of
the friction coefficient was higher for the latter two kinds of hybrid SMMC samples, which may be ascribed to the periodical accumulation and delamination of wear debris on the worn track [8, 12].

The worn surface at an applied load of 10 N for different hybrid SMMC samples is presented in Fig. 6. For all the tested samples, there mainly existed two kinds of worn morphology. One was the abrasion grooves, and the other was the delamination of wear debris. Besides, some white oxides were shown on the worn surface. As compared to other three samples, the worn surface for the sample with 75% SiC and 25% MoS$_2$ exhibited comparatively smooth, on which some fine grooves and little delamination were formed. This sample showed similar hardness with the sample with 100% SiC. As can be seen in Fig. 6 (a), (c), and (f), the increase of MoS$_2$ content in reinforcement caused the increase of delamination. Although MoS$_2$ particle was beneficial to the formation and retention of the solid lubricating film on the sliding surface, which prevented metal-to-metal contact and kept friction coefficient low [11], its addition decreased the hardness. Therefore, when the content of MoS$_2$ in reinforcement was superfluous, the load bearing of SiC particles may be inhibited, which increased the direct load contact of the steel ball with the soft aluminum alloy 7075 matrix, and so decreased the wear resistance of the hybrid surface composite.

Figure 6. SEM micrographs of the worn surface after sliding time of 10 min at a applied load of 10 N for hybrid ratio of: (a) 100 SiC; (b) 75% SiC and 25% MoS$_2$; (c) 67% SiC and 33% MoS$_2$; (d) 50% SiC and 50% MoS$_2$.

Conclusions

In this study, the microstructural and tribological properties of aluminum alloy 7075-T6 based surface hybrid composite were investigated by incorporating a mixture of SiC and MoS$_2$ particles by friction stir process. The conclusions are as following:

(1) SiC and MoS$_2$ particles were successfully incorporated into aluminum alloy 7075 matrix by one FSP pass, which were distributed uniformly at the top of nugget zone.

(2) The average Vickers hardness at nugget zone increased to about 190 at 100% SiC, and it decreased with increasing the MoS$_2$ content ratio in reinforcement.

(3) The existence of MoS$_2$ particles with the content ratio of 25% was beneficial to the decrease of wear weight loss and friction coefficient. The increase of the MoS$_2$ content ratio in reinforcement enhanced the wear weight loss.
(4) The wear failure of FSPed hybrid SMMC with a mixture of SiC and MoS$_2$ particles was ascribed to the combination of abrasive wear and delamination.

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