EFFECTS OF SHORT ALUMINA FIBER REINFORCEMENT ON MACHINABILITY OF ALUMINUM ALLOY

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ABSTRACT

Fiber-reinforced aluminum alloy composites were fabricated by squeeze casting, and the effects of the fiber reinforcement on the machinability of the alloy were investigated. Al-Si-Cu-Ni-Mg alloy was used as the matrix metal, and two kinds of short alumina fibers were used as the reinforcements. The cutting force values of the alloy were reduced by the fiber reinforcement under every cutting condition. The lower the hardness of the fiber in the composite was, the lower the cutting force of the composite was. The roughness of the machined surface decreased by the fiber reinforcement. This result and the in situ observation of cutting process revealed that the fibers in the composite suppress the formation of the built-up edge. The observation of chip forms indicated that the fibers in the composite facilitated the shear deformation of the chips because the fibers were easily sheared by the cutting. Continuous chips were formed after cutting the unreinforced alloy, while serrated chips were formed after cutting the composites. The lower the hardness of the fiber in the composite was, the lower the tool wear was.

1 INTRODUCTION

Aluminum alloy is attractive as a lightweight and oxidation-resistant material. The drawbacks of the alloy are its low strength and rigidity at elevated temperature, and poor wear resistance. Therefore, the application of the alloy as a heat and wear resistant material is still limited. The reinforcement of aluminum alloys with ceramic fibers has been proposed to improve the strength and rigidity at high temperature, and wear resistance of the alloys. The alumina fiber would be most suitable for improving the properties of the alloy, because its high temperature strength and hardness are superior. The alumina fiber-reinforced aluminum alloy composites have not only been fundamentally studied [1-5] but also made in trials or put into practical use [6]. However, there is a concern about a decrease in machinability of the aluminum alloy by reinforcing with alumina fibers, because alumina is difficult to machine. Although Saga et al. [7] reported the machinability of an alumina fiber-reinforced aluminum alloy composite, the effects of the fiber on the cutting mechanism of the aluminum alloy and tool wear characteristics when the composites were machined have not yet been sufficiently clarified.

In the present study, short alumina fibers having different properties were used as the reinforcements of the aluminum alloy, and a fiber preform was infiltrated with the aluminum alloy melt by squeeze casting in order to fabricate the composite. The effects of the fiber reinforcement on the machinability of the aluminum alloy were then clarified.

2 EXPERIMENTAL PROCEDURE

The JIS (Japanese Industrial Standards) -AC8A aluminum alloy (Al-12Si-1Mg-1Cu-1Ni) was used as the matrix metal. Two kinds of short alumina fibers (Denka Alsen B80L and B97N3, Denki Kagaku Kogyo Co.) were used as the reinforcements. Table I lists the chemical composition and properties of the fibers [8], showing that the composition and properties of the fibers are different. The composites fabricated using fibers A and B are labeled as the composites A and B, respectively.
The preforms were fabricated as follows. The fibers were dispersed using careful agitation in an aqueous medium containing polyvinyl alcohol (PVA) as the organic binder and SiO₂ sol as the inorganic binder. Dewatering was conducted by press forming, followed by drying at 373 K for 3 hours to drive off any residual free water and to obtain the strength due to the PVA. After drying, the preform was sintered at 1173 K for 1 hour to burn off the PVA and generate the strength due to the presence of the SiO₂ binder. The preform was 50 mm diameter and 30 mm thick. The fiber volume fraction in the preform was 15 vol%. The composite was fabricated by squeeze casting.

The preform was horizontally placed in the permanent mold, and the AC8A alloy melt (1073 K) was poured into the mold (673 K). A pressure of 40 MPa was quickly applied and maintained until the solidification was complete.

The test piece with a 40 mm diameter was machined from the composite, and then the machinability was examined by cutting the outside surface of the test piece. The cutting conditions are shown in Table 2. The cutting speed ranged from 50 to 150 m/min. Although these speeds are lower than that generally used for an industrial application (up to 3,000 m/min), the low cutting speed was determined based on the following two reasons. (1) Small enterprises often have only old lathes with a low cutting speed and the speed in the present study is based on the assumption of machining by such small enterprises, and (2) a low cutting speed generally promotes the formation of the built-up edge; the machining at a low speed would clarify the effect of the fiber reinforcement (effect of lowering the smearing of the aluminum alloy on the carbide tool). The cutting resistances (cutting force) were measured using an elastic disc-type tool dynamometer, and roughness of the machined surface was measured by a surface profiler. The machined surface and chip forms of the specimens were then observed. The width of the flank wear of the tool was measured by observing the flank of the tools after cutting the composite.

<table>
<thead>
<tr>
<th>Fiber</th>
<th>A</th>
<th>B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical composition ((\text{Al}_2\text{O}_3/\text{SiO}_2))(%)</td>
<td>80/20</td>
<td>97/3</td>
</tr>
<tr>
<td>Mineral composition ((\text{Mullite}/\alpha\text{- Al}_2\text{O}_3))(%)</td>
<td>5/0</td>
<td>7/36</td>
</tr>
<tr>
<td>Average diameter (μm)*</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Density (Mg/m³)</td>
<td>3.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Hardness (HV)</td>
<td>1500</td>
<td>2000</td>
</tr>
</tbody>
</table>

Table 1: Properties of short alumina fibers [8]

<table>
<thead>
<tr>
<th>Cutting tool</th>
<th>Carbide(H1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake angle</td>
<td>5°</td>
</tr>
<tr>
<td>End cutting edge angle</td>
<td>15°</td>
</tr>
<tr>
<td>Nose radius (mm)</td>
<td>0.8</td>
</tr>
<tr>
<td>Cutting speed (m/min)</td>
<td>50, 100, 150</td>
</tr>
<tr>
<td>Cutting depth (mm)</td>
<td>0.1, 1.0</td>
</tr>
<tr>
<td>Feed rate (mm/rev)</td>
<td>0.1, 0.2</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>None</td>
</tr>
</tbody>
</table>

Table 2: Cutting conditions.

3 RESULTS AND DISCUSSION

3.1 Microstructure and hardness of composites

Figure 1 is optical micrographs of the parallel section of composites. The dark phases observed in the micrograph are the short alumina fibers. No agglomeration of the fibers or porosity is observed in the composite, indicating that the melt infiltration into the fiber preform was perfectly accomplished. The fibers were in a random planar arrangement as well as the fibers in the preform. The difference in
the fiber distribution between in the composites A and B were hardly observed. The matrix of every composite was α aluminum (bright area observed in the micrograph) in which the fine eutectic silicon particles were mainly dispersed. As a result of the fiber volume fraction measurement in the composites using the Archimedian principle, it was 15 vol%, which is the same as the fiber volume fraction in the preforms.

Vickers hardness of the composite A and B was respectively 112 HV and 130 HV, while that of AC8A alloy was 90 HV.

3.2 Machinability of Composites

Figure 2(a) shows the effect of the cutting speed $v$ on the cutting force $F_c$ of the AC8A alloy and composites. Since the serrations (variation in $F_c$) were observed during the cutting, the mean values of $F_c$ were shown in Fig. 2(a). Under every cutting condition, $F_c$ decreased due to the fiber reinforcement. It is reported that dispersing the hard phases in the aluminum alloy facilitates the shear deformation of the alloy due to the stress concentration in the hard phases during the cutting process [7]. The results that occurred in the present study can be expressed by the same mechanism; the fibers in the composite act as stress-concentration sites and facilitate the shear deformation of the alloy. Furthermore, the $F_c$ of composite A was lower than that of composite B under every condition. This is probably due to the fact that the hardness of fiber A was lower than that of fiber B.

Figure 2(b) shows the effect of the cutting speed $v$ on the surface roughness (maximum height), $R_z$, of the AC8A alloy and composites. For every cutting condition, the $R_z$ values of composites were lower than those of the AC8A alloy. The surface roughness of composites A and B were similar.

![Figure 1: Optical micrographs of (a) composite A and (b) composite B.](image)

![Figure 2: Effect of cutting speed on (a) cutting force and (b) surface roughness (maximum height) of the AC8A alloy and composites ($t = 1.0$ mm, $f = 0.1$mm/rev).](image)
The cutting force and the surface roughness have a relationship with the formation of the built-up edge \[9\]. Therefore, we investigated the formation of the built-up edge when the AC8A alloy and composites were machined. Figure 3 shows the cross-sectional optical micrographs of the AC8A alloy and composite B in the vicinity of the cutting part where they had contacted the tool edge. These photos were taken after the machining was quickly stopped and the tool was removed. For the AC8A alloy, the built-up edge was obviously observed (Arrow in Fig. 3(a)). The Vickers hardness of the built-up edge was approximately 140 HV, while that of the chip area was approximately 105 HV and that of the unmachined area was 90 HV. In addition, the machined surface and the chip surface in contact with the built-up edge were rough and seemed to be plucked by the machining. In contrast, the built-up edge in composite B was slight (Fig. 3(b)), and the machined surface and the chip surface in contact with the tool were smoother than that of the AC8A alloy.

Figure 4 shows the chip forms of the AC8A alloy and composites obtained when the feed rate \( f \) is 0.1 mm/rev. For every cutting speed, continuous chips were formed after cutting the AC8A alloy, whereas the sheared or serrated chips were formed after cutting the composites. The difference in the chip morphology between two composites was hardly observed. This tendency was also observed when \( f \) is 0.2 mm/rev. These results indicate that the fibers are fractured by the shear stress during the machining process which facilitated the shear deformation and division of the chips.

Generally, the formation of the built-up edge decreases the cutting force and the tool wear, while it increases the surface roughness \[9\]. Some findings obtained in the present study are consistent with these general findings; the build-up edge and the surface roughness of the AC8A alloy were greater than those of the composites. The decrease in surface roughness by the reinforcement is probably due to the fact that the fibers suppressed the formation of the built-up edge and the accretions on the rake face. However, for the cutting force, the data in the present study conflict with the general findings; the cutting force of the composites was lower than that of AC8A alloy in the present study. As stated, it is reported that dispersing the hard phases in the aluminum alloy facilitates the shear deformation of the alloy due to the stress concentration in the hard phase during the cutting \[7\]. The results that obtained in the present study can be expressed by the same mechanism; the fibers in the composite facilitate the shear deformation and division of the chips because the fibers are easily sheared by the cutting.

Flank wear was not observed when the AC8A alloy was machined under these cutting conditions.
The machinability rating of a material is often used to quantify the machinability of various materials. Machinability rating can be expressed by the ratio in percent of the speed of cutting the work piece giving 60 min tool life to the speed of cutting the standard metal. In the present study, JIS-SUM23L, one of the free-cutting steel, was used as the standard metal, and the tool life value was defined as the time when the flank wear of the tool reached 0.2 mm. Since the flank wear after cutting the unreinforced alloy could not be observed under the cutting conditions in the present study, only the machinability rating of the composites was measured. Machinability rating of the composite A and B were 67% and 27%, respectively. This result indicates that the hardness of the fiber has a strong effect to decrease the machinability rating of the composite.

For the composites, it can be concluded that the hardness of the alumina fiber does not affect the surface roughness and chip morphology but the cutting force and tool life.

![Figure 4: Chip forms of the AC8A alloy and composites (t = 1.0 mm, f = 0.1 mm/rev).](image)

![Figure 5: Effect of cutting distance on width of flank wear after cutting the composites (t = 0.1 mm, f = 0.1mm/rev).](image)
4 CONCLUSIONS

(1) The cutting force of the AC8A alloy decreased due to the fiber reinforcement for every cutting condition. The cutting force of composite A was lower than that of composite B, because the hardness of the fiber in composite A is lower than that in composite B.

(2) The surface roughness decreased due to the fiber reinforcement. The surface roughness of composites A and B were similar, and this shows that the difference in hardness of the fibers hardly affects the surface roughness.

(3) Although the built-up edge was obviously formed when the AC8A alloy was machined, it was only slightly formed when the composites were machined. These results revealed that the fiber-reinforcement suppress the formation of the built-up edge and decrease the surface roughness.

(4) The observation of chip forms indicated that the fibers in the composite facilitated the shear deformation of the chips because the fibers were easily sheared by the cutting.

(5) The machinability rating of the composite decreased as the hardness of the fiber increased.

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REFERENCES


