1 Introduction
The reinforcement of aluminum alloys with ceramic fibers has been proposed to improve the strength, rigidity, heat resistance and wear resistance of the alloys. However, there is a concern about a decrease in the machinability of the aluminum alloys by reinforcing with ceramics, because ceramics are generally difficult to machine. To develop a machinable aluminum alloy composite having a low thermal expansion rate, we focused on potassium titanate as the reinforcement because it has a low thermal expansion and hardness. Although a few investigations have been conducted on the aluminum alloy composites reinforced with potassium titanate whiskers [1-5], the whiskers are considered harmful to the respiratory organs [6]. The short potassium titanate fiber, having a greater diameter and length than the whisker, was developed to reduce this concern [7]. Based on these findings, we fabricated aluminum alloy composites reinforced with short potassium titanate fibers by squeeze casting, and clarified that the thermal expansion coefficient of the composite was lower than that of the unreinforced aluminum alloy [8]. In the present study, short potassium titanate fiber reinforced aluminum alloy composites were fabricated, and the effects of the fiber in the composite on the machinability were 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 potassium titanate fibers (TXAX, Kubota Co.), which have a different size and hardness, were used as the reinforcements (denoted as fibers A and B).

Potassium titanate whiskers and aluminum borate whiskers were also used to compare the machinability of the composites with the composites reinforced with fibers A and B. The composition and properties of the reinforcements [5, 7] are shown in Table 1. The Vickers hardness of the fibers is 250-300HV, which is considerably lower than that of the aluminum borate whisker and alumina (1500-2000 HV [9]). Fig. 1 shows SEM micrographs of the reinforcements.

The preforms were fabricated as follows. The reinforcements were dispersed using careful agitation in an aqueous medium containing polyvinyl alcohol (PVA) as the organic binder and Al2O3 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 Al2O3 binder. The preform had a 50 mm diameter and 20 mm thickness. The preforms contained 25 and 45 vol% of the reinforcement, respectively. Fig. 2 shows the appearance and SEM micrograph of a preform (short potassium titanate fiber A, $V_f = 25\, \text{vol}\%$). In the preform, the reinforcements were oriented in a random configuration.

The composite was fabricated by squeeze casting. As schematically shown in Fig. 3, the preform was horizontally placed in the permanent mold, and the aluminum alloy melt (1073 K) was poured into the mold (673 K). Pressure (40 MPa) was quickly applied and maintained until the solidification was complete. Fig. 4 shows the macrostructure of a
vertical section of a composite which is just after removal from the mold. This macrostructure indicates that the melt infiltration is perfectly accomplished with no observable defects. The height of the composite was approximately 20 mm, which is almost equal to that of the preform before the infiltration. This indicates that the infiltration was successful without any preform contraction or deformation.

The test piece with a 40 mm diameter was machined from the composite, clamped in a lathe, and then the machinability was examined by cutting the outside surface of the test piece with a cemented carbide cutting tool. The cutting conditions are shown in Table 2. The cutting resistances (cutting force) were measured by an elastic disc-type tool dynamometer, and roughness of the machined surface was measured by a surface profiler. The machined surface, cross section and chip forms of the specimens were observed. The width of the flank wear of the tool was measured by observing the flank of the tools after cutting the composite with a numerically-controlled lathe. Taking the practical finishing cut into consideration, the tool wear was measured for the cutting depth of 0.1 mm.

3 Results and Discussion

3.1 Microstructure and hardness of composites

Fig. 5 shows the optical micrographs of the parallel section of the composites. The reinforcements were observed as the dark phases in the micrographs. No agglomeration of the reinforcements or porosity is observed in the composite, indicating that the melt infiltration into the preform was perfectly accomplished. The reinforcements were in a random arrangement.

Table 3 shows the density of the composites, demonstrating that the density of the reinforcements directly affects that of the composites. Table 4 shows the Vickers hardness of the composites. It shows that the hardness increased as the fiber volume fraction (hereinafter $V_f$) increased. The hardness of composite BW was the highest due to the highest hardness of the reinforcement.

3.2 Machinability of composites

Fig. 6 shows the variation in the cutting force $F_c$ during the cutting of the unreinforced AC8A alloy and composites. The width of the serrations (variation in $F_c$) at the feed rate $f$ of 0.2 mm/rev was greater than that of 0.1 mm/rev for every specimen. The occasional significant change in the width can be seen during cutting the AC8A alloy (Fig. 6(a)), while the widths of the composites are relatively stable (Fig. 6(b)-(e)). This figure also indicates that the average $F_c$ of the composite is lower than that of the AC8A alloy.

Fig. 7 shows the effect of $V_f$, the feed rate $f$, and the cutting speed $v$ on the cutting force $F_c$ of the AC8A alloy and composites. As shown in Fig. 6, the variation in $F_c$ can be seen. Therefore, hereafter, we used the average values of the width in the vicinity of 2.0 m of the cutting distance as the $F_c$ values. At every cutting speed and feed rate, the $F_c$ values of the composites were lower than that of AC8A alloy ($F_c = 0$ vol%); reinforcement with the fiber or whisker decreased the $F_c$. Furthermore, the $F_c$ values of composites A and B were lower than those of whisker-reinforced composites (composites TW and BW). It is considered that the reinforcement in the composite has opposite roles; the role to facilitate the shear deformation by generating a high stress concentration as an inclusion and the role as an inclusion to inhibit the shear deformation [10, 11]. The decrease in $F_c$ by the reinforcement is probably due to the former role; the existence of the fibers or whiskers facilitates the shear deformation of the chips during the cutting. It should be noted, however, that the $F_c$ of the composites with a 45 vol% reinforcement is similar to that of the composites with a 25 vol% reinforcement. This is probably due to the offset of the former and the latter roles. At every cutting speed, the $F_c$ increased as $f$ increased. This is due to the increase in the cutting area by increasing the feed rate. The $F_c$ of every specimen little changed even if $v$ increased.

Fig. 8 shows the effect of $V_f$ and feed rate $f$ on the surface roughness (maximum height) $R_z$ of the AC8A alloy and composites ($v = 50$ m/min). For every cutting condition, the $R_z$ values of the composites were significantly lower than those of the AC8A alloy. The $R_z$ values of the fiber-reinforced composites (composites A and B) were slightly higher than those of the whisker-reinforced
composites (composites TW and BW). A comparison between Figs. 8(a) and (b) shows that $R_z$ increased as $f$ increased for every specimen. The theoretical roughness can be geometrically obtained from the nose radius of the cutting tool and feed rate [12]. It can be written as

$$R_{th} = \frac{f^2}{8r} \quad (1)$$

where $R_{th}$ is the theoretical roughness and $r$ is the nose radius. The values of $R_{th}$ calculated using eq.(1) are shown in Fig. 8 with the experimental values. It shows that the $R_z$ values approached the $R_{th}$ values due to the reinforcement under every cutting condition.

Fig. 9 shows SEM micrographs of the machined surfaces of the AC8A alloy and composites with 45 vol% reinforcements ($v = 50$ m/min, $f = 0.2$ mm/rev). On the machined surfaces of the AC8A alloy (Fig. 9(a)), plastic flow is pronounced. In contrast, the machined surfaces of the composites (Fig. 9(b)-(d)) are smoother than that of the AC8A alloy. An enlarged view of the machined surface of composite A is shown in Fig. 10. The surface is smooth, indicating that the fibers facilitated the shear deformation during the cutting.

The cutting force and the surface roughness have a relationship with the formation of the built-up-edge [12]. Therefore, we investigated the formation of the built-up-edge when the AC8A alloy and composites were machined. Fig. 11 shows the scanning electron images and cross-sectional optical micrographs of the AC8A alloy and composites 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 observed (Arrows in Fig. 11((a) and (d)). 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. 11(b) and (e)) and that in the composite BW was negligible (Fig. 11(c) and (f)). The machined surface and the chip surface in contact with the tool were smoother than that of the AC8A alloy, and serrated chips were formed.

Fig. 12 shows the chip forms of the AC8A alloy and composites ($v = 100$ m/min, $f = 0.1$ mm/rev). Continuous chips were formed after cutting the AC8A alloy (Fig. 12(d)), while serrated chips were formed after cutting the composites. In addition, the chips were shorter when $V_t$ was high.

The tendencies observed in Figs. 8-12 were also observed at every cutting speed and feed rate.

Generally, the formation of the built-up-edge decreases the cutting force and the tool wear, while it increases the variation in the cutting force and the surface roughness [12]. Some findings obtained in the present study are consistent with these general findings; the build-up-edge, the variation in cutting force and the surface roughness of the AC8A alloy were greater than those of the composites. As shown in Fig. 8, the surface roughness values of the AC8A were significantly higher than $R_{th}$ because the formation of the built-up edge and the accretions formed on the rake face of the tool roughened the machined surface. The decrease in $R_z$ by the reinforcement shown in the present study is probably due to the fact that the fibers or whiskers 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 in Fig. 7, 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 [10, 11]. 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.

Fig. 13 shows the appearance of the front edge of the tools after cutting the AC8A alloy and composites.
The flank wear of the tool after cutting the AC8A alloy for 300 minutes could not be observed, and the tool edge was covered with the accretion (Fig. 13(a)). From Figs. 11(a) and (d), it can be stated that this accretion is the built-up-edge. In contrast, the flank wear was observed after cutting the composite. The accretion of the composites on the tool seems to be less than that of the AC8A alloy (Fig. 13(b) and (c)).

Fig. 14 shows the effect of the cutting time $t$ on the width of the flank wear ($VB$) after cutting the AC8A alloy and composite B ($V_f = 25$ vol%, $f=0.1$ mm/rev). $VB$ increases as $v$ increases because the cutting distance increases along with $v$. Even if after cutting for 300 minutes at 150 m/min, however, $VB$ was approximately 0.12 mm; this is lower than 0.2 mm, which is the tool life value for the finishing cut of nonferrous metals established in JIS. This result suggests that the composite can be machined for a long time without changing the tool. From the viewpoint of industrial applications, replacement of the carbide tool by the PCD tool would reduce the tool wear. The $VB$ was zero even if after cutting the AC8A alloy for 300 minutes. As shown in Figs. 11(a), (d) and Fig. 13(a), the formation of the built-up edge decreases the tool wear. Moreover, the hardness of the AC8A is lower than those of the composites. We believe that these results lead to the inhibition of the tool wear.

4 Conclusions

1. Reinforcement with fibers or whiskers decreased the cutting force of the AC8A aluminum alloy. The cutting force of the short potassium titanate fiber-reinforced composite was lower than those of the whisker-reinforced composites.
2. The machined surfaces of the composites were smoother than that of the AC8A alloy. The machined surface and 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.
3. The fiber-reinforced composite can be consecutively machined for more than 300 minutes at 150 m/min without changing the carbide tool. Although the built-up-edge was formed in the machined AC8A alloy, it was only slightly formed or negligible in the machined composites.

5 Acknowledgement

The financial support of the MEXT-supported program for the strategic Research Foundation at Private Universities (2012-2014) is gratefully acknowledged.

References

Table 1 Properties of reinforcements [5,7].

<table>
<thead>
<tr>
<th></th>
<th>Short potassium titanate fiber A</th>
<th>Short potassium titanate fiber B</th>
<th>Potassium titanate whisker (TW)</th>
<th>Aluminum borate whisker (BW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition</td>
<td>$K_2Ti_6O_{13}$</td>
<td>$K_2Ti_8O_{17}$</td>
<td>$9Al_2O_3\cdot2B_2O_3$</td>
<td></td>
</tr>
<tr>
<td>Melting point [K]</td>
<td>1583</td>
<td>1573</td>
<td>1693</td>
<td></td>
</tr>
<tr>
<td>Density [Mg/m$^3$]</td>
<td>3.5</td>
<td>3.3</td>
<td>2.9</td>
<td></td>
</tr>
<tr>
<td>Average length [μm]</td>
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<td>45</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>Average diameter[μm]</td>
<td>13</td>
<td>10</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Hardness [HV]</td>
<td>250</td>
<td>300</td>
<td>350</td>
<td>1000</td>
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</table>

Fig. 1 SEM micrographs of reinforcements.

Fig. 2 Appearance and SEM micrograph of a preform (short potassium titanate fiber A, $V_f = 25$ vol%).

Fig. 3 Schematic illustration of squeeze casting.

Table 2 Cutting conditions.

<table>
<thead>
<tr>
<th></th>
<th>Carbide (H1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rake angle</td>
<td>$5^\circ$</td>
</tr>
<tr>
<td>End cutting edge angle</td>
<td>$15^\circ$</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>0.10, 0.20</td>
</tr>
<tr>
<td>Cutting fluid</td>
<td>None</td>
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</table>
**Table 3** Density of composites [Mg/m$^3$].

<table>
<thead>
<tr>
<th>Composite</th>
<th>$V_f$ (vol%)</th>
<th>A</th>
<th>B</th>
<th>TW</th>
<th>BW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>2.88</td>
<td>2.89</td>
<td>2.84</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>3.05</td>
<td>3.05</td>
<td>2.97</td>
<td>2.79</td>
</tr>
</tbody>
</table>

Density of AC8A alloy is 2.69 Mg/m$^3$. Composite BW with 25 vol% whisker was not fabricated.

**Table 4** Hardness of composites [HV].

<table>
<thead>
<tr>
<th>Composite</th>
<th>$V_f$ (vol%)</th>
<th>A</th>
<th>B</th>
<th>TW</th>
<th>BW</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25</td>
<td>123</td>
<td>147</td>
<td>170</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>45</td>
<td>191</td>
<td>192</td>
<td>208</td>
<td>292</td>
</tr>
</tbody>
</table>

Hardness of AC8A alloy is 90 HV.

**Fig. 5** Microstructure in parallel section of composites. $V_f$ represents the fiber volume fraction in composite.

**Fig. 6** Variation in cutting force during cutting of AC8A alloy and composites ($V_f$=45vol%) at the cutting speed of 50 m/min. $f$ in the figure represents the feed rate.
Fig. 7  Effect of fiber volume fraction $V_f$, feed rate $f$, and cutting speed $v$ on cutting force $F_c$ of AC8A alloy and composites.

Fig. 8  Effect of fiber volume fraction $V_f$, feed rate $f$ on surface roughness $R_z$ of AC8A alloy and composites at the cutting speed of 50 m/min.

Fig. 9  SEM micrographs of machined surfaces of AC8A alloy and composites ($V_f=45\text{vol}\%$) ($v = 50$ m/min, $f = 0.2$ mm/rev).

Fig. 10  Enlarged view of machined surfaces of composite A ($V_f=45\text{vol}\%$, $v = 50$ m/min, $f = 0.2$ mm/rev).
Fig. 11 Features of chip formation of AC8A alloy and composites ($V_f = 45$ vol%, $v = 50$ m/min, $f = 0.2$ mm/rev). Arrows in the figure indicate built-up-edge.

Fig. 12 Chip forms of AC8A alloy and composites ($v = 100$ m/min, $f = 0.1$ mm/rev).
Fig. 13 Appearance of the front edge of the tools after cutting the AC8A alloy and composite B ($V_f = 25\, \text{vol}\%, \, t = 0.1\, \text{mm}, \, f = 0.1\, \text{mm/rev}, \, v = 150\, \text{m/s}$).

Fig. 14 Effect of cutting time $t$ on width of flank wear $V_B$ after cutting AC8A and composite B ($V_f = 25\, \text{vol}\%$, $f = 0.1\, \text{mm/rev}$).