Machinability of Short Alumina Fiber Reinforced Al-Si-Cu-Ni-Mg Alloy Composite

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Aluminum alloys have been used in many industrial applications as the lightweight material instead of steel or cast iron, because it is lightweight and its strength can be improved by alloying or heat treatment. However, their use in parts that require heat resistance or wear resistance is still limited because their high temperature strength and wear resistance are insufficient. In order to improve these properties, the reinforcement of the aluminum alloy with ceramic fibers has been presented. The alumina fiber would be most suitable for improving the properties of the aluminum alloy, because its high temperature strength and hardness are superior. The alumina fiber-reinforced aluminum alloy composites have not only been fundamentally studied but also made in trials or put into practical use. From the viewpoint of the practical use of such composites, it is very important to clarify their machinability. There is a concern about a decrease in machinability of the aluminum alloy by reinforcing with alumina fibers, because alumina is generally difficult to machine. Although Saga et al. reported the machinability of an alumina fiber-reinforced aluminum alloy composite, the machinability of the composite has not yet been sufficiently clarified. In addition, there are many chemical compositions and crystal structures of alumina fibers, and the properties of the fiber strongly depend on its composition or structure. However, there are no reports regarding the effect of the properties of alumina fibers on the machinability of a composite.

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.

1. Introduction

2. Experimental Procedure

The Al-Si-Cu-Ni-Mg cast alloy (JIS-AC8A alloy) with its chemical composition shown in Table 1 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 2 lists the chemical composition and properties of the fibers, 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. Figure 1 shows SEM micrographs of the fibers. As a result of measuring the average fiber diameter based on 10 micrographs, the average diameter of both fibers was 4 µm. 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 (diameter of SiO₂; 12 nm) as the inorganic binder. Dewatering was
conducted by press forming, followed by drying at 373 K for 3 h 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 h to burn off the PVA and generate the strength due to the presence of the SiO$_2$ binder. The preform was 50 mm diameter and 30 mm thick. The fiber volume fraction in the preform was 15 vol%. Figure 2 shows a SEM micrograph of the preform (fiber A). In the preform, the fibers were oriented in a random planar configuration.

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 with a diamond cutting tool. Figure 3 shows the appearance of a test piece clamped in a lathe. The cutting conditions are shown in Table 3. The cutting resistances (cutting force and feed 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.

3. Results and Discussion

3.1 Microstructure and hardness of composites

Figure 4 is an optical micrograph of the parallel section of composite A. 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 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.

Table 4 shows the Vickers hardness of the AC8A alloy and composites. It shows that the hardness increased by the fiber reinforcement. The hardness of composite A is greater than that of composite B due to the fact that fiber A is harder than fiber B.
3.2 Machinability of composites

Figure 5 shows the variation in the cutting force, $F_c$, during the cutting of the AC8A alloy. When the cutting speed $v$ was 50 m/min, the range 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 (Fig. 5(a)). A similar tendency was recognized when the cutting speed was 150 m/min (Fig. 5(b)). Figure 6 shows the variation in $F_c$ during the cutting of composite A. The range of the serrations (variation in $F_c$) increased as $f$ increased as well as for the AC8A alloy. Under the same cutting conditions, however, the mean values of $F_c$ of the composite were lower than those of the AC8A alloy. The range of the serrations for the composite was almost same as that for the AC8A alloy. When $v$ was 50 m/min (Fig. 6(a)), the variation in $F_c$ was more fractional than for the AC8A alloy. Figure 7 shows the variation in $F_c$ during the cutting of composite B. The range of the serrations was greater than that of the AC8A alloy (Fig. 5) or composite A (Fig. 6), especially when $f$ was 0.2 mm/rev. This is probably due to the fact that both the increase in $F_c$ and the following decrease in $F_c$ by the fiber fracture during the shear processing of the chips are pronounced by dispersing the hard fibers.

Figure 8 shows the effect of the cutting speed $v$ on the $F_c$ of the AC8A alloy and composites. As shown in Figs. 5, 6 and 7, since the serrations (variation in $F_c$) were observed during the cutting, the mean values of $F_c$ were shown in Fig. 8. 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. 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. A comparison between Figs. 8(a) and (b) shows that $F_c$ increased as the feed rate increased for every specimen. This is due to the increase in the cutting area by increasing the feed rate. However, the $F_c$ of every specimen little changed or only slightly decreased even if the cutting speed increased.

Figure 9 shows the effect of the cutting speed $v$ on the surface roughness ($R_z$) of the AC8A alloy and composites. For all specimens, the $F_c$ value was lower than the $F_c$ value (Fig. 8) for each condition. The variation in the $F_c$ values due to the variation in the cutting conditions was similar to that of the $F_c$ values.

Figure 10 shows the effect of the cutting speed $v$ on the surface roughness ($R_z$) of the AC8A alloy and composites. For every cutting condition, the $R_z$ values of composites were lower than those of the AC8A alloy. Furthermore, the $R_z$ values of composite A were slightly lower than those of composite B. Although the $R_z$ of the AC8A alloy little changed even if $v$ increased, that of the composites decreased as $v$ increased. A comparison between Figs. 10(a) and (b) shows that the $R_z$ increased as the feed rate $f$ increased for every specimen.

The theoretical roughness can be geometrically obtained from the nose radius of the cutting tool and feed rate. It can be written as
where $R_{th}$ is the theoretical roughness and $r$ is the nose radius. The $R_{th}$ values calculated using eq. (1) are shown in Fig. 10. Under every cutting condition, the $R_z$ values approached the $R_{th}$ values due to the fiber reinforcement. This tendency was pronounced as the feed rate $f$ and cutting speed $v$ increased, and the $R_z$ values of the composites were almost equal to the $R_{th}$ values when $v$ and $f$ were, respectively, 150 m/min and 0.2 mm/rev. During the machining of the aluminum alloy, a built-up edge was sometimes formed by contacting of the chip flow with the rake face which lead to the deposition.11) The decrease in $R_z$ by the fiber reinforcement shown in the present study is probably due to the fact that the fibers suppressed the formation of the built-up edge.

Figure 11 shows SEM micrographs of the machined surfaces of the AC8A alloy and composites ($v = 50$ m/min). On the machined surfaces of the AC8A alloy, plastic flow is pronounced as the feed rate $f$ increased. In contrast, the machined surfaces of composites are smoother than that of the AC8A alloy and the (fiber-matrix) interfacial exfoliation by the cutting is not observed. This tendency was also recognized when $v$ was 100 and 150 m/min.

Figure 12 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.

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.

Although the machinability of the composites was clarified in the present study, the tool wear by machining would also have to be clarified. We plan to examine the effects of the fibers in the composite on the tool wear.

4. Conclusions

The machinability and the cutting mechanisms of the short alumina fiber reinforced AC8A aluminum alloy composites were investigated. The following conclusions were obtained.

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R_{th} = \frac{f^2}{8r} \quad (1)
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The mean values of the cutting force, $F_c$, of the AC8A alloy decreased by the fiber reinforcement. The mean values of $F_c$ of composite A were lower than that of composite B for every cutting condition, because the hardness of the fiber in composite A is lower than that in composite B. The range of the variation in $F_c$ during the cutting of composite A was almost the same as that of the AC8A alloy. The range for composite B was greater than that for the AC8A alloy or composite A.

(2) $R_z$ decreased due to the fiber reinforcement for every cutting condition, and $R_z$ of the composites was almost the same as the theoretical roughness especially when the cutting speed and feed rate were high. This result indicates that the fibers in the composite suppress the formation of the built-up edge.

(3) The machined surfaces 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.

(4) These results lead to the conclusion that the machinability of the composites, especially composite A, is superior to that of the AC8A alloy.

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REFERENCES