Influence of reduction surface defects by a triple-facet tool in ultra-precision cutting of Al-Mg alloys

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Abstract. In this study, we investigated the ultra-precision cutting technology of aluminum alloys for polygon mirrors made of Al-Mg Alloys. It is necessary to improve the geometric surface roughness achieved in the mirror cutting of Al-Mg alloys and to remove the tear-out marks and scratch marks that occur during the cutting process. We investigated the cutting edge shape using a straight diamond tool to reduce the surface defects produced during the ultra-precision cutting of Al-Mg alloy. We developed two triple-facet tools to reduce the surface defects in the ultra-precision cutting of Al-Mg alloys and investigated influence of surface defects. The use of a triple facet tool could achieve good machined surface roughness without surface defects at a feed rate 200 μm/rev. This feed rate is 4 times higher than of normal operation, resulting in a 4-fold improvement in efficiency.

Introduction

Recently, high efficiency and high performance have become essential requirements of information equipment such as laser printers [1,2]. As a result, optical scanning parts that reduce optical aberration, scatter, and diffraction in laser printers are in considerable demand [3,4]. Figure 1 shows examples of microphotographs and surface roughness profiles of machined surfaces [5]. In this study, we shortened the manufacturing process to improve the productivity and ultra-precision cutting technology of polygon mirrors made of aluminum alloys. It is necessary to improve the geometric surface roughness achieved during the mirror cutting of Al-Mg alloys and to remove the tear-out marks and scratch marks that occur during the cutting process. Therefore, we investigated the shape of the cutting edge using a diamond tool to reduce surface defects during the ultra-precision cutting of Al-Mg alloys.

Fig. 1 Photographs and surface roughness profiles of machined surfaces

(a) Feed marks
(b) Tear-out marks
(c) Scratch marks
Experiment result and consideration

The cutting conditions are summarized in Table 1, and the experimental setup is shown in Fig. 2. The machined surface damage due to entwining chips was restrained using the minimum quantity of lubrication (MQL) required and a chip collector.

Table 1 Experimental equipment and conditions

<table>
<thead>
<tr>
<th>Machine tool</th>
<th>NC ultra-precision turning machine ULG100C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting tool</td>
<td>Diamond tool (single crystal diamond)</td>
</tr>
<tr>
<td>Work piece</td>
<td>A5186 OD 130mm ID 40mm</td>
</tr>
</tbody>
</table>
| Cutting conditions| Cutting speed \( V = 193 \sim 628 \text{ m/min} \)  
                   | Feed rate \( F = 50 \sim 200 \text{ μm/rev} \)  
                   | Depth of cut \( t = 30 \text{ μm} \)  
                   | Tool setting angle \( \theta = 0^\circ \sim 0.05^\circ \) |
| Lubricating system| MQL                                        |
| Cutting fluid     | UP-2A                                       |
| Chip collector    | GSB-10537exP                               |
| Dynamometer       | Type9251A KISTLER                          |

Results from prior experimentation

Figure 3 shows the surface generation model for a straight tool. With a positive tool setting angle, the surface roughness increases, because tear-out marks occur on the side cutting edge. With a negative tool setting angle, we achieved a good machined surface without tear-out marks. The reason for this is that the tear-out marks were removed by the end cutting edge. However, these methods cannot support a high feed rate, since wear is a time-consuming process. A straight tool was used to produce a good machined surface without tear-out marks in a narrow range of tool setting angles \( \theta \) from \(-0.015^\circ \) to \(-0.008^\circ \) [9,10,11]. We produced a double-facet tool to expand the range of the tool setting angle. Figure 4 shows the surface generation model for a double-facet tool. In addition, it is difficult to give a direct micro-facet. Therefore, we developed a double-facet tool that has a side rake angle on the rake face to produce a pseudo-facet. The use of the double-facet tool results in a 10 fold increase in the range of the tool setting angle. This produces a good machined surface without tear-out marks. However, when the feed rate was over 100 μm/rev, there were tear-out marks and scratch marks on the processing face. The use of a double-facet tool cannot remove scratch marks [12]. The feed force of the cutting conditions of Table 1 is less than 0.2 N, and since the tool displacement of feed direction is 10 nm or less, it is considered not to influence change of a tool setting angle.

\[ \Delta : \text{Depth of tear-out} \quad \theta : \text{Tool setting angle} \quad \beta : \text{Micro-facet angle} \quad f : \text{Feed rate} \]
\[ d : \text{Inclination of front cutting edge} \quad Hth : \text{Theoretical surface roughness} \]
\[ n : \text{Undefomed chip thickness with micro-facet} \]

Therefore, we investigated the formation of scratch marks. The mechanism of scratch formation is shown in Fig. 5. Depth of cut with micro-facet \( n \) of Fig. 5 and undeformed chip thickness with micro-facet \( n \) are the same values. We found that the tool crashed against the bumps formed by
crystallization, producing small pieces. Then, these pieces attached to the end cutting edge and acted as micro cutting edges. As a result, these small pieces caused the scratch marks. Based on the mechanism of scratch mark generation, the ductility-mode processing of a crystallization can be expected if the depth of the cut with micro-facet \( n \) is small. We developed triple-facet tool with a double-facet at the end cutting edge to remove scratch marks and investigated the influence of surface defects.

![Fig. 5 Schematic of scratch mark formation with cutting edge of micro-facet](image)

**Comparison between the Triple-Facet Tools (A) and (B)**

We developed four triple-facet tools and selected two triple-facet tools, which are denoted as triple-facet tool (A) and triple-facet tool (B). Figure 6 shows the cutting edge shapes of triple facet tool. The triple-facet tool has two micro-facets at the end cutting edge and can perform micro-cuts. In addition, in the triple-facet tool, micro-facet \( \beta_2 \) removes tear-out marks, and micro-facet \( \beta_1 \) removes scratch marks. The removal of tear-out marks and scratch marks separately by the each micro-facet produces a good machined surface. Figure 7 shows enlarged views of the end cutting edges of triple-facet tools (A) and (B). The dashed line indicates the ideal cutting edge shape. In triple-facet tool (A), there was a curved portion on the end cutting edge and micro-facet \( \beta_1 \). This curved portion is marked as a red line. We defined the cutting edge with a length of 570 \( \mu m \) as the end cutting edge. The angle of the cutting edge for the end cutting edge. In contrast, the measured cutting edge shape of triple-facet tool (B) has an ideal cutting edge shape. We investigated the influence of surface defects using triple-facet tools (A) and (B).

![Fig. 6 Cutting edge shape of triple-facet tool](image)

**Cutting Characteristic of the Triple-Facet Tool (A).** We investigated the influence of surface defects when the feed rate was from 100 to 200 \( \mu m/rev \). The experimental results showed that we achieved a good machined surface without tear-out or scratch marks using tool setting angle \( \theta \) from...
0.01° to 0.05° at tool feed rates of 100 and 150 μm/rev. Next, we investigated the influence of surface defects when the feed rate is 200 μm/rev. Figure 8 shows the relationship between the tool setting angle $\theta$ and the surface roughness $R_z$ at tool feed rate of 200 μm/rev. Figure 8 shows that we achieved a good machined surface roughness with a tool setting angle in the range of 0.01° to 0.05°. In addition, when the tool setting angle was between 0.04° and 0.05°, there were tear-out marks on the machined surface. When the tool setting angle was between 0.01° and 0.03°, we could produce a good machined surface without tear-out or scratch marks. Figure 9 shows the photographs of the surface with oblique illumination and differential interference microscope when the tool setting angle was 0.02°.

Cutting Characteristic of the Triple-Facet Tool (B). We investigated the influence of surface defects when the feed rate was from 100 to 200 μm/rev. At feed rate of 100 μm/rev, we achieved a good machined surface roughness. However, there were scratch marks when the tool setting angle $\theta$ was from 0° to 0.05° and tear-out marks when the tool setting angle was from 0.03° to 0.05°. Next, we investigated the influence of surface defects when the feed rate was 200 μm/rev. Figure 10 shows the relationship between the tool setting angle $\theta$ and the surface roughness $R_z$ at a feed rate of 200 μm/rev. Figure 10 shows that we achieved a good machined surface roughness with a tool setting angle in the range of 0° to 0.05°. When the tool setting angle was from 0.02° to 0.05°, there were tear-out marks on the machined surface. In addition, when the tool setting angle was from 0° to 0.05°, there were scratch marks on the machined surface. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect. Using triple-facet tool (B), we could not achieve a good machined surface without any surface defect.
Influence of Scratch Marks on Undeformed Chip Thickness. The presence of scratch marks on a machined surface depends on the sharpness of the diamond tool’s cutting edge and machining conditions. Figure 12 shows the relationship between the tool setting angle and the undeformed chip thickness for triple-facet tools (A) and (B). In Fig. 12, symbol “○” shows a good machined surface without scratch marks, symbol “◇” shows generation of scratch marks, and symbol “△” shows generation of scratch marks and tear-out marks. Also, Fig. 13 shows photographs of the surface with differential interference microscope of each symbol. We calculated the undeformed chip thickness \( n \) of both triple-facet tool (A) and (B) using Eqs. 1 and 2. In Eqs. 1 and 2, “\( F \)” is feed rate, “\( \beta_0 \)” is micro-facet of triple-facet tool (A), “\( \beta_1 \)” is micro-facet of triple-facet tool (B), and “\( \theta \)” is tool setting angle.

\[
\begin{align*}
  n &= F \times \sin (\beta_0 - \theta), \ (0^\circ \leq \theta < 0.036^\circ). \\
  n &= F \times \sin (\beta_1 - \theta), \ (0^\circ \leq \theta < 0.071^\circ). 
\end{align*}
\]

Figure 12 shows that using triple-facet tool (A), could achieve a good machined surface roughness without tear-out marks or scratch marks when the undeformed chip thickness was less than 100 nm. The use of triple-facet tool (A) enables cutting at a feed rate 200 \( \mu \)m/rev. The feed rate is 4 times higher than of normal operation, resulting in a 4-fold improvement in efficiency. On the other hand, there were scratch marks with triple-facet tool (B), when the undeformed chip thickness was less than 100 nm at a feed rates of 100 and 200 \( \mu \)m/rev. Therefore, we assume that only micro-facet \( \beta_1 \) had not functioned well enough to remove the scratch marks. With triple-facet tool (A), since the micro-facet \( \beta_0 \) functioned to remove the scratch marks, we could achieve a good machined surface without surface defects when the undeformed chip thickness was less than 100 nm. In future, we plan to produce some
multi-facet tools to evaluate the cutting edge of triple-facet tool (A). In addition, we will investigate the influence of surface defects on the cutting edge of each tool and evaluate the cutting performance of micro-facet $\beta_0$.

**Conclusions**

In this study, we investigated the cutting edge shape using two triple-facet tool (A) and (B) to reduce surface defects. We obtained the following results:

1. Triple-facet tool (A) that there was a curved portion on the end cutting edge
   The use of triple-facet tool (A) achieves good machined surface roughness without tear-out marks or scratch marks at feed rates ranging from 100 to 200 $\mu$m/rev. We believe that micro-facet $\beta_0$ functioned to remove the scratch marks.

2. Triple-facet tool (B) that the measured cutting edge shape has an ideal cutting edge shape
   The use of the triple-facet tool (B) achieves good machined surface roughness at feed rates of 100 and 200 $\mu$m/rev. However, there are tear-out marks and scratch marks on the machined surface.

**References**


