107 Study on Surface Integrity of Magnesium Alloys in Ultra-Precision Diamond Cutting

K. Okuda¹, T. Tanaka² and M. Nunobiki³

¹ Himeji Institute of Technology, 2167 Shosha, Himeji, Hyogo, Japan, okuda@mie.eng.himeji-tech.ac.jp
² Hitachi-Kiden, 3-4-1 Shimosakabe, Amagasaki, Hyogo, Japan, tsutomu_tanaka@hitachi-kiden.co.jp
³ Himeji Institute of Technology, 2167 Shosha, Himeji, Hyogo, Japan, nunobiki@mie.eng.himeji-tech.ac.jp

Summary
This paper deals with an experimental study of ultra-precision diamond cutting of magnesium alloys. In order to investigate the cutting performance on the surface integrity and understand the problems on the generation of the good mirror surface in a micro cutting, the experiments on the diamond cutting of magnesium alloys and pure magnesium with an ultra-precision turning machine has been carried out. The surface integrity of finished surface of magnesium alloys was mainly examined and discussed the effect of inclusion and intermetallic compound in the micro structure. It was found that the inclusions (Al-Mn compounds) in the work material (AZ31, AZ61) caused to generate the scratches on the finished surface and influenced the integrity of mirror surface. The scratches were not observed on the finished surface of pure magnesium and AZ91 (cast plate).

Keywords: Diamond cutting, Magnesium alloys, Surface integrity, Mirror surface, Inclusions

1. Introduction
The demand for the magnesium alloy increases in parts such as the household electronic equipment product, the camera, the cellular phone, the personal computer case, and the car in the recent year. The expansion of the usage as precise machine parts and micro parts is expected in the future. Then, the establishment of machining technology especially, precision cutting technology becomes important, while molding process such as casting and injection is dominant at the present time.

It is recognized that the machinability of the magnesium alloys in the conventional cutting is more excellent than that of aluminum or carbon steel (1)(3). It is also thought that there are few problems in the machining process except the point in the safety management concerning the burning of chip. Therefore, a systematic examination of the machinability is not so done even in the conventional cutting of the magnesium alloy, and the machinability data in the much more, ultra-precision cutting is hardly reported (4).

However, in the micro cutting with extremely small depth of cut like an ultra-precision cutting with a diamond tool, a peculiar machinability to the micro cutting is expected to appear. For instance, it is well known that a remarkable effect of the size occurs because of the factors such as the inclusions, the voids, the grain boundary in the micro structure and the roundness of cutting tool (5).

Therefore, in the present study, the experiments on the diamond cutting of magnesium alloys with an ultra-precision turning machine were carried out in order to investigate the cutting performance on the surface integrity and understand the problems on the generation of the good mirror surface in a micro cutting. The surface integrity of finished surface of magnesium alloys was mainly examined and discussed the effect of inclusion and intermetallic compound in the micro structure.

2. Experimental procedures
The ultra-precision cutting machine (Toshiba Machine Co., ULC-100A) was employed for the experiment. The machine is equipped with a main spindle supported by ultra-precision cylindrical air bearings. Figure 1 shows the main part of the experimental equipment. The workpiece with a shape of a quarter-circular plate is fixed to the face of vacuum chuck. The cutting tool of single crystal diamond is fixed to the tool holder attached to the tool post. Three components of the cutting force are measured with a piezoelectric type dynamometer (Kistler, 9251A) installed in the tool holder (6).

The cutting tests were carried out under the conditions summarized in Table 1. Commercial magnesium alloys of AZ31 (rolled and extruded plate), AZ61 (extruded plate), AZ91 (cast plate) and pure magnesium were used as the
cutting specimen. The commercial pure aluminum (A1070), which is a typical material for a mirror surface by a diamond cutting, was also used as a comparative material. Figure 2 shows the photographs of the micro structure of AZ31(rolled plate), AZ91 and pure magnesium. The micro structure of AZ31 consists of the grains from several to tens of μm and the inclusions (Al-Mn compounds) from several μm to 20 μm. AZ61 has a micro structure same as AZ31, though the grain size of AZ61 is from tens of to hundreds of μm. AZ91 shows a typical cast micro structure (dendrite) and the precipitation of Mg17Al12. The inclusions are not observed in a micro structure of pure magnesium.

Table 1 Experimental conditions

<table>
<thead>
<tr>
<th>Tool material and geometry</th>
<th>Single crystal diamond, Rake angle 0 deg., Relief angle 8 deg., Nose radius 0.8 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Workpiece</td>
<td>Magnesium alloy (AZ31, AZ61, AZ91) Pure magnesium, aluminum (A1070)</td>
</tr>
<tr>
<td>Spindle speed</td>
<td>1,000 (rpm)</td>
</tr>
<tr>
<td>Cutting speed</td>
<td>2.6 - 4.7 (m/sec)</td>
</tr>
<tr>
<td>Feed rate</td>
<td>5 - 40 (μm/rev)</td>
</tr>
<tr>
<td>Depth of cut</td>
<td>10 (μm)</td>
</tr>
<tr>
<td>Cutting fluids</td>
<td>Kerosene</td>
</tr>
</tbody>
</table>

3. Experimental results and discussion

3.1 Surface roughness

As for magnesium alloys, it is known that the transcript of the cutting tool to its finished surface is excellent and the glossy surface is generated in a conventional cutting. However, as shown in Fig. 3, many scratches are observed on the surface finished by diamond cutting of AZ31, while a good mirror surface is generated in the diamond cutting of aluminum under the same condition.

Figure 4 shows the examples of profiles of finished surface obtained under the condition of feed rate of 5 and 40 μm/rev. The scratches are observed in the surface profile of AZ31 at feed rate of 5 μm/rev and are caused to deteriorate the surface integrity. In contrast, a good mirror surface is finished in cutting of

![Surface profiles of AZ31 and aluminum finished under feed rate of 5 and 40 μm/rev](image)
aluminum under the same condition. The surface profiles obtained at feed rate of 40 μm/rev show the wave patterns or the cutter marks with regular cycle corresponding to the feed rate. This indicates that the edge profile of diamond tool is copied on the workpiece surface along the relative movement of the tool and the workpiece. Although the roughness Ry of both materials are at the same level, the profile of AZ31 has the trace of scratches at the bottom of valley or the tip of cutting edge.

Figure 5 shows the surface roughness (maximum height Ry) of AZ31 and aluminum measured in the range from 5 to 40 μm/rev of feed rate with a theoretical roughness curve. Rys of AZ31 were measured on the finished area without the scratches. The surface roughness of AZ31 and aluminum is almost at the same level in the condition of 20 μm/rev or more, while the roughness of AZ31 becomes larger than that of aluminum in the condition of low feed rate. The mirror surface with Ry of around 0.1 μm is partly obtained in the finished surface of AZ31. However, the scratches are observed over whole finished surface and then the surface visually expresses the clouded mirror, while the scratches are hardly observed on the finished surface of aluminum.

The generation of scratches in diamond cutting of AZ31 is a big problem to be solved for the improvement of the surface integrity. Especially under the condition of low feed rate, the depth of scratch becomes a dominant factor.

3.2 Generation of scratch

As shown in the previous section, the dull surface was partly obtained in the wet cutting of AZ31, while good mirror surface was finished in aluminum. In dry cutting, the whole finished surface of AZ31 became cloudy and the surface of aluminum was also deteriorated with a lot of scratches.

The photographs of finished surface in dry and wet cutting of AZ31 are shown in Fig. 6. In addition to the scratches extended to the cutting direction, a lot of inclusions or voids are observed on the finished surface in both photographs. In dry cutting, two kinds of scratches are generated. One is a long scratch over the cutting length of workpiece and another is a short scratch which starts from the edge of inclusion or void. The long scratches, which are observed in the dry cutting of AZ31 and aluminum, can be removed by applying the cutting fluids (kerosene). However, the short scratches remain on the finished surface by the wet cutting. It is expected that these two kinds of scratches have been generated by different causes. The long scratches are generated due to the adhesion of work material to the cutting edge or the micro built-up edge. As a result, the long scratches are not almost generated by the anti-adhesive effect of cutting fluids. The short scratches are caused by the abrasive action of the inclusions. Al-Mn compounds are distributed in the micro structure of AZ31.

Figure 7 shows example of observation of the inclusions on the finished surface of AZ31. It is recognized in the figure that the inclusions remain on the surface and fracture to two pieces by cutting. In addition to this photograph, some are crushed to segments and others are fallen away. In most case, the scratches occur from the inclusions or voids, though they are not formed along all cutter paths. From these facts, it is thought that the short scratches are formed by micro abrasive grains or hard particles of intermetallic compound when the inclusions are fractured and ploughed. Therefore, these scratches can not
be removed by applying the cutting fluids.

In order to examine the effect of Al-Mn compounds on the generation of scratches, the cutting experiments of pure magnesium have been carried out. As shown in the micro structure (Fig. 2-c), the inclusions basically do not exist in the micro structure of pure magnesium. Figure 8 shows the finished surface of pure magnesium in dry and wet cutting and the profiles shown in Fig. 9 are corresponding to the photographs.

In dry cutting, the remarkable scratches are observed on the finished surface and the profile. The cutting edge was also observed by SEM. It was confirmed that the work material adhered to the rake face and the flank face of cutting tool and the adhesion was not observed in the wet cutting. The long scratches in the dry cutting are obviously due to the adhesion of work material on the cutting tool. It is also understood that magnesium is easy to adhere on the diamond tool and the cutting fluids have an operation to prevent the adhesion.

On the other hand, the scratches are not observed on the finished surface in the wet cutting. The photograph (Fig. 8-b) and the profile (Fig. 9-b) show only the cutter marks with a regular cycle corresponding to the feed of 20 μm. A good mirror surface was obtained. The defects such voids are observed at the crystal grain boundary on the finished surface. However, those defects do not take part in the generation of scratches. The integrity of mirror surface of magnesium alloys strongly depend on the hard particle in the micro structure such Al-Mn inclusion.

### 3.3 Effect of micro structure

In this section, the effect of AZ-metal's micro structure on the surface integrity is examined and discussed. Figure 10 shows the photographs of finished surface of AZ31 and AZ61 workpieces cut from the extruded plate. The grain size of the extruded AZ31 is a little larger than that of the rolled AZ31. AZ61 contains about twice of Al element (5.5 - 7.2 wt. %) and about a half of Mn element (0.15 - 0.4 wt. %) comparing with AZ31. Al-Mn compounds are distributed in the micro structure of these materials. A remarkable difference is not seen in the size and the distribution. As shown in the photographs, it is understood that the scratches are generated on the
finished surface as well as the rolled AZ31. The overviews of whole finished surface in three kinds of AZ materials look similar all.

In contrast, a good mirror surface was obtained in the wet cutting of AZ91 (cast alloy). Fig. 11 shows the overview of finished surface. The surface looks no scratches in the appearance. The micro structure of AZ91 consists of mainly Mg solid solution and Mg₃Ga₂ precipitation phase. Al-Mn compounds which cause to make scratches in AZ31 and AZ61 are hardly included in AZ91.

Fig. 12 shows the photographs taken with differential interference microscope and the profiles of finished surface of AZ91. The scratches are not observed excepting for the cutting marks. A lot of dots are scattered about the grain boundary. These dots are estimated not to be Al-Mn compounds but Mg₃Ga₂ phase. Mg₃Ga₂ phase in the cast structure is not thought to act as the hard particles or the abrasives.

The surface roughness (maximum height Ry) of extruded AZ31, AZ61 and cast AZ91 are summarized in Fig. 13 with a theoretical roughness curve including that of rolled AZ31 and aluminum. The plots are the average values of some points of finished surface without the scratches. As to the Ry at mirror surface without scratches, a significant difference among magnesium alloys is not recognized, though the overview of other alloys than AZ91 looks like dull. The mirror surfaces of AZ91 and aluminum look same quality in the appearance. However, Ry of AZ91 and other alloys is larger than that of aluminum. The defects such voids, inclusions and Mg₃Ga₂ precipitation phase in the micro structure of alloys, which are mainly distributed at the grain boundary, are thought to deteriorate the surface roughness.

The solution treatment for AZ91 was carried out in order to examine the effect of the compound in the micro structure on the generation of scratches and the surface integrity. By the solution treatment, the precipitation of Mg₃Ga₂ phase does not occur easily and in return the supersaturated solid solution is obtained. Fig. 14 shows the photographs of micro structure in cast and solution treatment of AZ91. Instead of Mg₃Ga₂ phase, the structure of the solid solution is formed and the compounds caused by natural aging are observed.

Fig. 15 shows a photograph of the finished surface of solution-treated AZ91. The scratches are observed as well as the finished surface of AZ31 and AZ61. It is expected that the compounds generated in process of natural aging play a role as the hard particles and thus cause the scratches on the surface.
4. Conclusions

The experiments on the diamond cutting of magnesium alloys (AZ31, AZ61 and AZ91), pure magnesium and aluminum with an ultra-precision turning machine were carried out in order to investigate the surface integrity in micro cutting. The results are summarized as follows:

The scratches are generated on the finished surface of magnesium alloys such AZ31, AZ61 and thus deteriorate the integrity of mirror surface. In dry cutting, the scratches occur due to the adhesion on the rake face and the flank face of cutting tool and Al-Mn compounds in the micro structure. The scratches due to the adhesion, which generate in all workpieces in use, can be removed by using the cutting fluids, while the scratches due to the compounds remain.

In the wet cutting of AZ91 and pure magnesium, good mirror surface without scratches was obtained as well as aluminum, because the compounds or the inclusions which may act as the abrasives are hardly included in the micro structure. However, as the defects such voids and Mg17Al12 precipitation phase in the micro structure of alloys are mainly distributed at the grain boundary, the surface roughness becomes larger than aluminum.

References