Application of Ultra-Precision Diamond Cutting for Fabrication of Cylindrical Micro Coil Line

Koichi OKUDA¹, Naoki FUJIWARA², Yuichiro SUMIYOSHI³ and Tadashi HATTORI⁴
¹ Graduate School of Engineering, University of Hyogo, Japan, okuda@eng.u-hyogo.ac.jp

² Dainippon Screen MFG Co.,

³ Japan Advanced Institute of Science and Technology

⁴ Labo. of Advanced Science and Technology for Industry, University of Hyogo

Abstract:

This paper describes an application of ultra-precision diamond cutting for a cylindrical micro coil line in a fabrication process by lithography. The coil lines fabricated by UV or X-ray lithography are electroplated by nickel and copper. The direct cutting of the resist and electroplating structure by diamond tool is attempted to finish the flat surface. The fluctuation of the resist thickness is reduced to 1 μ m or less by diamond cutting. By applying the diamond cutting operation in the conventional lithograph process, the micro coil with the line-and-space of 30 μ m is fabricated.

Keywords: diamond cutting, micro coil, lithography, photoresist, electroplating

1. Introduction

Micro machining technology is one of the most essential technologies in MEMS fields or the nano-technology fields. A semiconductor manufacturing process such as lithography and etching, and LIGA process have been applied to the fabrication of micro part or micro machine. Recently, the micro parts with 3-D or complicated structure are required.

For example, the fabrication of coil lines of micro size has been attempted for micro cylindrical solenoidal actuators [1-2]. It is hard to make 3-dimensional figures like the cylindrical micro coil line by the established 2-dimensional LIGA process. There are some problems to fabricate the micro coil. One of the problems is that the thickness of the photoresist coated on the surface of micro cylindrical bar is unevenness. The surfaces of the photoresist and the micro structures with a combination of resist and electroplating layer have to be finished smoothly. The flat surface is required to fabricate the complicated shape with laminated structure [3].

In the previous works [4-5], we applied the direct cutting of the resist layer and the nickel electroplating by diamond cutting tool in order to obtain the flat surface of 2-dimensional thick photoresist and nickel electroplating structure. In this study, we have continuously attempted to apply an ultra-precision diamond cutting technique for the fabrication of cylindrical micro coil line in UV lithography process.

PMMA and a negative type of epoxy resist are applied to a brass rod with a diameter of 3 mm and the micro lines were fabricated around the bar by UV and X-ray lithography. The workpiece is also electroplated by nickel and copper. The direct cutting of the resist and electroplating structure by diamond tool is attempted with an ultra-precision cutting machine and the surface finish of the resist and the electroplating layer and the uniformity of thickness of micro structure are discussed.

2. Fabrication process of micro coil lines by LIGA

Micro coils are mounted in electronic devices as inductors. As the devices are downsized, further reduction in size of the micro coils is also demanded. Then, the fabrication process of the micro coils with the LIGA process has been proposed [1]. Figure 1 shows the fabrication process with 3D-LIGA proposed by Hattori [2]. The procedure in detail is as follows.

(1) A positive type of photoresist (PMMA) is applied on a brass rod. Then, it is exposed with NewSUBARU (a synchrotron radiation facility at the University of Hyogo) through a line-and-space X-ray mask. After the brass rod is rotated by half a pitch and X-ray mask is moved, the other side of rod is exposed.

Figure 1: Fabrication process of micro coil line with 3D-LIGA[2].

(2) After development, the brass rod with PMMA coil pattern is used as a mold master. Then, Ni is electroformed on the rod.

(3) The brass rod is removed by etching and Ni micro mold is fabricated.

(4) Worm injection molding is performed using liquid crystal polymer (LCP) as molding resin. Then, the resin core is drawn out along the grooves of the coil while rotating the core.

(5) The LCP coil core is electroplated by copper.

(6) A part of Cu thin film is removed by isotropic etching and the micro coil line of Cu is created.

When the micro coil lines are applied to electromagnetic type of micro actuator, furthermore, aspect ratio of coil line must be increased for high quality factor.

In the LIGA process shown in Fig. 1, some problems occur in association with thick photoresist. For examples, a large swell is generated on the resist surface due to the baking treatment and the groove shape of Ni mold master is influenced by the swell (process (2) in Fig. 1). It is also difficult to remove the only disused Cu (process (6) in Fig. 1). In this study, the diamond cutting is applied in the process between (1) and (2), (5) and (6) in Fig. 1.

3. Experimental procedures

3.1 Experimental setup and cutting conditions

An ultra-precision cutting machine (Toshiba Machine Co., ULC-100A) was employed for the cutting experiment. The machine is equipped with a main spindle supported by ultra-precision cylindrical air bearings. Figure 2 shows the overview of the fixing situation of the workpiece and the cutting tool.

Figure 2: Overview of cutting test situation.

Table 1: Cutting conditions.

Tool material and geometry	Single crystal diamond Rake angle : 0° Relief angle : 8° Nose radius : 0.8 mm
Workpiece size	4 mm (diameter)
Spindle speed	1,000 rpm (2.1 m/s)
Feed rate	10 $\mu\text{m}/\text{rev}$
Depth of cut	10 μm

The workpiece with a rod shape is fixed by a scroll chuck via vacuum chuck and is turned by a diamond cutting tool. The brass rod with resist coating and the PMMA rod with Cu electroplating were prepared.

Table 1 shows the cutting conditions. The cutting tool is single crystal diamond and its geometry has the rake angle of 0°, the relief angle of 8° and the nose radius of 0.8 mm. The diameter of core rod (workpiece) is 4 mm. The cutting condition is constant of cutting speed 2.1 m/s, feed rate 10 $\mu\text{m}/\text{rev}$ and depth of cut 10 μm .

3.2 Cutting procedures

Figure 3 shows the cutting procedure for making micro structure with flat surface and the stage in the process with the cutting application. Two type of resists were used. The one is a positive type of photoresist (PMMA) and another is a negative type of epoxy resists (TGP-H developed by Toyo Gosei Co.).

The cutting operation is applied before and after a step of UV ray exposure. As shown in Fig. 3(a), the workpiece after baking treatment is firstly machined by a diamond cutting tool. The UV ray exposure and the development of the mask pattern are conducted to the finished surface.

In the procedures of Fig. 3(b), the UV ray exposure is firstly conducted. Next, the photoresist layer including latent image of mask pattern is cut. And then the development is processed.

In the procedures of Fig. 3(c), after the development or the formation of micro structure, the cutting is applied. However, in the case of PMMA coating, the cutting was performed only before the exposure (Fig. 3(a)) because a positive type of resist tends to go into liquid form by the exposure.

Figure 3: Cutting procedures and stage with cutting application.

4. Experimental results and discussions

4.1 Cutting of PMMA layer coated on brass rod

It is known that the roughness of substrate influences the coating thickness of photoresist and the asperity of

surface is desired to be uniform. Figure 4(a) shows the surface profile of originally commercial brass rod with the maximum height of approximately $2\mu\text{m}$. Then, the rod surface is finished by the diamond cutting before the resist coating (Fig. 4(b)).

PMMA is applied to the cut surface by the dipping method that the rod is dipped in liquid photoresist and is pulled out of the resist with its rotation. The rod is then dried in the air while being rotated before the baking process (200°C , 1 hour). In this method, the resist layer with the thickness of $30 - 50\mu\text{m}$ is able to be coated around the rod. The only PMMA layer is cut by the diamond tool after the baking treatment.

Figure 5 shows the profiles of originally PMMA coating and baking surface and PMMA cut surface. The overview of the brass rod after cutting of PMMA layer and the chip formation are also shown. The PMMA surface after the baking treatment is transparent and apparently smooth. However, it has the waviness or the swell due to the thermal contraction or the volume decrease in the baking process. This tends to take place growing of thickness. On the other hand, the profile of the cut surface shows the better roughness ($R_a=0.018\mu\text{m}$) than the roughness before cutting. The waviness is removed and the transparency is kept to be almost same. It is understood from the chip observation that the continuous chips are formed and the only PMMA layer is normally cut. By applying the cutting operation after the process (1) in Fig. 1, it is expected that the accuracy of the mold master is able to be improved.

Figure 6 shows the comparison with the resist thickness of before and after cutting. The measurement positions are at 4 points of a – d of some distance from the rod end. The measurement values are average at 4 places on the circumference of the rod. The dispersions of thickness are $6.8\mu\text{m}$ and $2.5\mu\text{m}$ before and after cutting, respectively. The uniformity of the resist layer thickness is improved by the cutting.

4.2 Cutting of epoxy resist layer coated on brass rod

The cutting operations were applied to the brass rod coated with negative type of epoxy resist (TGP) as shown in Fig. 3. In this case, the simple pattern was actually created by UV ray exposure and development. The UV ray exposure was processed for 300 sec ($2,790\text{ mJ/cm}^2$). The development was processed in a special TG-P developer for 30 min and then the workpiece was rinsed for 30 min.

Figure 7 shows the profiles of the resist surface after the development and SEM photographs of the resist structure. Three cases are compared. Figure 7(a) is the case that the resist structure is created by ordinary lithograph process without cutting. Figure 7(b) and 7(c) are corresponding to the process of Fig. 3(b) and 3(c), respectively. In the process of Fig. 3(a), the surface integrity finished by cutting was much deteriorated. The viscosity or the hardness of the photoresist (TGP) changes drastically before and after UV ray exposure [3]. The viscosity is very high after the baking treatment or before the UV ray exposure.

The arithmetic average roughness R_a of the non-cut

Figure 4: Surface profiles of brass rod.

Figure 5: Profiles of originally PMMA coating surface and PMMA cut surface.

Figure 6: Step between brass rod surface and PMMA resist surface.

surface indicates the least value of $0.007\mu\text{m}$. However, the fluctuation of thickness among each resist patterns is large as mentioned later. The resist layer at the cutting in Fig. 7(b) consists of the hardened layer by UV ray exposure and the viscous layer. That means the resist layer including the latent image is cut. The result of Fig. 7(c) is the same as the cutting result of the workpiece in Fig. 7(a). The remarkable difference between the profiles of Fig. 7(b) and (c) is not recognized. The feed marks are observed in the both profile as well as the metal-cut surface. The difference in the visual appearance is not much observed

Figure 7: Surface profiles and observation of epoxy resist (TGP).

in the photographs of three workpieces, although it has been expected that the burr is generated at the edge of resist in Fig. 7(c).

Table 2 shows the comparison with the resist thickness after the development shown in Fig. 7. The measurement positions are at 4 points of a – d of some distance from the rod end (same as Fig. 6). The measurement values are average at 4 places on the circumference of the rod. The fluctuations of thickness in Fig.7(a), (b) and (c) are 13.0μm, 0.7μm and 1.2μm, respectively. The uniformity of the resist layer thickness is greatly improved by the cutting.

Table 2: Step between brass rod surface and resist.

	Step (μm)			
Position	a	b	c	d
Non cut surface	30.0	38.0	39.5	43.0
After exposure	18.3	17.8	18.0	18.5
After development	20.5	19.8	19.5	19.3

4.3 Cutting of resist and Ni electroplating structure

In the previous sections, the cutting performance of the resist layer and the uniformity of the resist thickness were examined. In this section, the cutting tests of the complex structure with the combination of the resist and the metal electroplating were carried out.

Figure 8 shows the overviews of the brass rod electroplated with Ni and the surface profiles at the Ni electroplating before and after cutting. The workpiece in Fig. 8(a) is comparable to the workpiece in Fig. 7(a) with Ni electroplating. The thickness of Ni layer (30 – 50 μm)

is almost equal to that of the resist layer (TGP). The surface roughness of Ni before cutting is 0.37μm Ra and the appearance is not much metallic shiny surface. However, the roughness of the cut surface is 0.048μm Ra and it looks like mirror surface.

Figure 9 shows SEM photographs of vicinity of Ni and the resist before and after cutting (corresponding to Fig. 8) in addition with the surface profile after cutting and the chip formation of Ni. The Ni electroplating before cutting looks a patterned indented surface with no orientation and grows overhanging to the resist. As shown in Fig. 9(b), by the cutting, the border lines of Ni and the resist appear clearly and smooth surface of Ni is finished without asperities. However, the complex structure of Ni and the resist have not perfectly flat. The steps of approximately 0.2μm are generated at the interface between Ni and the resist. These steps seem to be caused by a slip at the

(a) Ni electroplating surface (b) Cut surface of Ni electroplating

Figure 8: Ni electroplating on brass rod and resist

interface between Ni and the resist or the difference between the elastic recovery of Ni and the resist. The continuous type chips of Ni are formed just with the chips of the resist shown in Fig. 5.

Figure 9: SEM photographs of non-cut and cut surface

4.4 Cutting of Cu electroplating in micro coil lines

It has been demonstrated that the smooth surface with the roughness of sub-micrometer order can be obtained for the resist layer, Ni electroplating and their complex structure by the application of the diamond cutting. In this final section, the cutting performance of the micro coil lines is demonstrated.

Figure 10 shows the photographs and the surface profiles of Cu electroplating on acrylate pipe. The Cu electroplating surface is observed to be grained due to granular crystal growth and then the roughness is

Figure 10: Surface profiles and observation of epoxy resis

comparatively large ($0.34\mu\text{m}$ Ra). On the other hand, the Cu electroplating surface after cutting is apparently finished in mirror and its roughness reaches to $0.008\mu\text{m}$ Ra.

Figure 11(a) shows SEM photograph of the line-and-space structure made around the acrylate pipe by X-ray lithography and Fig. 11(b) shows SEM photograph of Cu electroplated pipe. It is observed in the photograph that the line-and-space with an interval of $30\mu\text{m}$ and a depth of $70\mu\text{m}$ is created. Copper is spattered on the acrylate pipe with the line-and-space structure in order to form the seed layer before Cu electroplating. The electroplating layer has convex outer surface with a regular interval because of the electroplating overflow and the inhomogeneous distribution of current density.

Figure 12 shows the overviews, the surface profiles and SEM photographs of Cu electroplated acrylate pipe before and after cutting. The cutting of copper layer was performed so that the line part of acrylate pipe appeared on the surface. The lines (acrylate) and space (copper) is not observed on the workpiece before cutting, because copper is electroplated around the whole surface of the pipe due to the overflow of copper. The surface profile

Figure 11: SEM photographs of micro coil lines

Figure 12: Cut surface of micro coil lines

shows a large roughness with periodic asperities. By the cutting, the asperities are removed and its roughness is improved to 0.09 μm Ra. The line-and-space with an interval of 30 μm is clearly observed in SEM photograph.

5. Conclusions

The diamond cutting technology was applied in the conventional lithography process. The ultra-precision diamond cutting of the photoresist, the metal electroplating and their complex structure was attempted in order to fabricate the micro coil lines. The results are summarized as follows.

- (1) When the photoresist layer (30-50 μm) on the brass rod is finished by diamond tool with a depth of cut of 10 μm , the normal cutting operation with a continuous chip formation can be performed and the surface roughness of 0.02 μm Ra is obtained.
- (2) The fluctuation of the resist thickness coated around the brass rod is reduced to 1 μm or less by diamond cutting, while the thickness of the resist before cutting is varied in the range of 10 μm or more.
- (3) The electroplating layer of Ni and Cu can be finished by diamond cutting in a similar manner of the ordinary cutting operation. It is also possible to cut the complex structure of the resist and the metal

electroplating. By applying the diamond cutting operation in the conventional lithograph process, the micro coil with the line-and-space of 30 μm is fabricated.

References

- [1] Yamashita, S., Kusumi, S., Shimada, O., Okuda, K., Noda, D. and Hattori, T., 2006, Proceedings of 10th International Conference on New Actuator, pp.701-704.
- [2] Yamashita, S., Matsumoto, Y., Idei, K., Okuda, K., Noda, D. and Hattori, T., 2006, Proceedings of International Symposium on Micro-Nanomechatronics and Human Science (IEEE), pp.497-502.
- [3] Kim, J., Yamagata, Y., Morita, S., Moriyasu, S., Ohmori, H. and Higuchi, T., 2005, Proceedings of The 3rd Manufacturing & Machine Tool Conference, p.225-226 (in Japanese).
- [4] Okuda, K., Nakagawa, S., Fujiwara, N., Utsumi, Y., Sakai, N. and Hattori, T., 2005, Proceedings of the 3rd International Conference on Leading Edge Manufacturing in 21st Century, pp.1041-1046.
- [5] Okuda, K., Fujiwara, N. and Hattori, T., 2006, Proceedings of the 6th euspen International Conference, Vol.2, pp.340-343.