Fabrication of Spiral Micro Coil Lines for Electromagnetic Actuators*

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Abstract
With the recent progress in downsizing and the sophistication of various industrial products, the need for more compact actuators is increasing. Actuators account for the larger percentage of volume and weight of a product compared with other parts and devices. We have proposed fabrication process of spiral micro coils that employs X-ray lithography. This process will be effective for fabricating coils of a high aspect ratio lines. Reducing the size of coil lines and increasing their aspect ratio are expected to reduce the size and increase the output of actuators. Using this process, we formed spiral coil lines that can be used in electromagnetic actuators. X-ray lithography was used to form a high aspect ratio helical structure on the surface of an acrylic resin pipe. As a measure to suppress void generation, which is one of the shortcomings of electroplating processes, the sputtering apparatus and plating equipment were improved, a pretreatment process was additionally provided, and the actual electroplating method was improved. As a result, a void-free metallic deposit could be formed on a thin coil line. At the final step of this research study, we etched the coil line to determine optimal etching conditions.

Key words: LIGA, X-Ray Lithography, Microcoil, Electroplating, Actuator

1. Introduction
Cameras, mobile phones, and many other industrial products have become smaller and/or more sophisticated in recent years, mainly because the progress of silicon microfabrication technology has accelerated the miniaturization and density growth of semiconductor devices. However, silicon microfabrication technology is reaching its physical limit and therefore continual progress of this technology can no longer be expected. Accordingly, size reduction and sophistication are required for the parts and devices to which no attention has been paid up to the present. In particular, market need for reducing the size of actuators is increasing. Actuators are widely used in many industrial products and account for the largest percentage of their volume and weight. Since the output of most actuators used in the industrial world increases in proportion to their volume, merely reducing their size with their original configuration left unchanged will result in output reduction. Miniaturization of actuators has made little progress since it requires microfabrication, processing, and other new technologies that are not compatible with traditional machining techniques.

We have proposed the application of the LIGA process for reducing the size of actuators. LIGA, which stands for Lithography (German: Lithographie), Electroforming (German: Galvanof ormung), and molding (German: Abformung), is a total process for
fabricating the master mold of microstructure parts using X-ray lithography, electroforming a micropattern mold, and molding plastic microstructure parts\(^1\). We intend to put the LIGA process into practice for fabricating and producing microactuators. We are focusing on the fabrication of electromagnetic microactuators that can be driven at a low voltage at a high efficiency\(^2\). Since electromagnetic actuators are more widely used in the industrial world than other types of actuators, miniaturized actuators will face little problem in practical use. Electromagnetic actuators will substantially decrease their output if they are miniaturized by merely reducing the size of the coil through miniaturization of the coil line. As a means of solving this problem, we have proposed fabrication process of spiral micro coils that uses X-ray lithography. X-ray lithography makes it possible to fabricate high aspect-ratio microstructures. If the width of the coil line is reduced by microfabrication, the number of coil turns can be increased. The high aspect-ratio coil line will increase its cross sectional area and therefore the allowable current limit will increase\(^3\). These measures will surely make it possible to fabricate small size, high power actuators.

In this paper, we discuss the fabrication of a micro coil comprising high aspect ratio lines.

2. Design of the Electromagnetic Actuator

Fabricating microactuators comprising a complicated mechanism is difficult to fabricate and impractical since the increased number of components and fabrication processes make them costly. Their construction should be as simple as possible. To meet these requirements, we designed a solenoid type actuator\(^4\). The external shape of actuator is shown in Fig 1. For this actuator, a coil is incorporated into a magnetic circuit consisting of a fixed iron core, plunger, and yoke. When an electric current is applied to the coil, the plunger moves toward the fixed iron core until they stick together. The coil is roughly illustrated in Fig 2. The coil should be hollow to allow the plunger to pass through. For this research study, an acrylic resin pipe with an outside diameter of 5 mm and inside diameter of 3 mm was used as the base material for coil line fabrication. The material of this pipe is PMMA (polymethylmethacrylate), which exhibits the property of a positive photoresist. Therefore, it could directly be exposed to X-ray lithography to form a high aspect ratio structure on the surface. The coil line was 30 µm wide and the distance between two adjacent line segments was 60 µm. This size of the coil line is difficult to fabricate machining. And a coil line of 225 turns could be fabricated in a 13.5 mm zone of the pipe.

![Figure 1 Solenoid model of actuator](image1)

![Figure 2 Design of coil part](image2)
3. Micro coil Fabrication Process

The coil line forming process is divided into three: an X-ray lithography process, uniform electroplating process, and uniform etching process. An outline of the coil line forming process is shown in Fig 3.

In the X-ray lithography process, an acrylic resin pipe was exposed to X-rays through an X-ray mask having a lattice-shaped pattern. During this process, the pipe was rotated and the mask was moved to transfer a spiral exposure pattern to the surface of the pipe. The pipe was then developed to form a spiral structure on the surface.

In the uniform electroplating process, which was used to preliminarily treat the pipe before it was subjected to the uniform etching process, copper (Cu) was thinly deposited on the pipe surface by spattering. The thin Cu layer was used as an electrode in the electroplating process. During electroplating, the pipe was rotated in the plating solution so that a flat and smooth plated layer could be formed on the pipe surface. The electroplating was continued until the spiral structure groove on the pipe surface was completely covered with the plating film.

In the uniform etching process, which is the final process, the plating layer on the pipe surface was dissolved to form a coil line by leaving only the deposit in the structure groove that had been formed by X-ray lithography. In this process, the pipe was also rotated in the etchant so that the plating layer would be etched uniformly. The following sections give a detailed description of each process.

4. X-ray Lithography Process

For the X-ray lithography, X-rays radiated from BL-11 installed in New SUBARU were used. New SUBARU is a synchrotron radiation facility attached to the University of Hyogo. The electron storage ring of the New SUBARU stores electrons at 1.0 to 1.5 GeV to emit a high-intensity radiant light in a range from vacuum ultraviolet to soft X-rays. The BL-11 is a beam line especially designed for X-ray lithography in the LIGA process. The exposure chamber is equipped with a multi-axial exposure stage to facilitate 3-D X-ray lithography. This exposure stage makes it possible to independently maneuver an X-ray mask and sample. Since the X-ray mask and sample can be moved relative to each other, X-ray lithography can form a 3-D structure to any desired configuration.

We used this multi-axial exposure stage to expose the acrylic resin pipe. During the exposure, the pipe was rotated and the X-ray mask was moved at a rate of 1/60 pitch per 6° rotation angle of the pipe. Thus the mask was displaced by one pitch per one turn of the pipe, and thereby the exposure pattern was spirally transferred onto the pipe surface. A pulse motor was used to rotate the pipe and a PZT stage was used for moving the X-ray...
mask. A lattice-pattern mask having a 30 µm wide line was used as the X-ray mask. With the above setup, a structure containing a 30 µm wide groove spiraled at a pitch of 60 µm was successfully fabricated. A photograph of spiral structures after development is shown in Fig 4. This process is currently available for fabricating a structure with an aspect ratio of 1 to 5 by properly controlling the light exposure and developing time. In our research study, an acrylic resin pipe containing a structure of an aspect ratio 2 was plated for each series of plating experiments.

Figure 4 SEM image of spiral structures

5. Seed Layer Formation by Sputtering

Since an acrylic resin pipe is nonconductive, forming a conductive seed layer on the pipe surface was required for electroplating. We formed a seed layer on the pipe surface using an Electron Cyclotron Resonance (ECR) ion beam sputtering system. Since the ECR system was provided only a stage for silicon substrates, it could not mount the acrylic resin pipe. For the sputtering, a pipe mounting jig consisting of pipe rotating and positioning mechanisms was prepared. With these mechanisms, the ECR system could rotate and position the pipe in the exposure chamber to form a uniform seed layer on the pipe surface. We had expected that rotating the pipe during the sputtering might change the seed layer deposition rate from that for silicon substrates. To verify this, we first measured the seed layer deposition rate. In this test, the seed layer thickness was measured at 30, 60, and 120 minutes after start of the sputtering with the pipe rotation speed fixed at 3 rpm. The seed layer deposition rates for a silicon substrate and acrylic resin pipe are shown in Fig 5. As seen in this figure, the seed layer deposition rate for the acrylic resin pipe was approximately one half of the rate for the silicon substrates. To verify this, we first measured the seed layer deposition rate. In this test, the seed layer thickness was measured at 30, 60, and 120 minutes after start of the sputtering with the pipe rotation speed fixed at 3 rpm. The seed layer deposition rates for a silicon substrate and acrylic resin pipe are shown in Fig 5. As seen in this figure, the seed layer deposition rate for the acrylic resin pipe was approximately one half of the rate for the silicon substrates. In the case of silicon substrates, a seed layer with a thickness of around 0.2 µm was enough for electroplating. For the acrylic resin pipe, we conducted sputtering for 60 minutes to deposit a 0.2 µm or more thick seed layer on the surface. After the test, we found that the seed layer had been formed defectively at both ends of the seed layer because of high electrical resistance value. And we considered the possibility that the structure formed on the pipe surface disturbed the seed layer deposition, as illustrated in Fig 6. We solved this problem by moving the pipe along its axis during the sputtering. In practice, the pipe was subjected to sputtering at three positions: the center and two points 15 mm distant from the center on both sides. As a result, a fully conductive seed layer was deposited on both pipe ends.
6. Uniform Copper Electroplating

Following the seed layer deposition by sputtering, we immersed the acrylic resin pipe in a copper sulfate solution to uniform electro copper plating. In this electroplating, high phosphorous copper was used as the anode and the seed layer deposited on the pipe surface as the cathode. A plating film was formed as an electric current was applied to the seed layer. To make the plating film grow uniformly over the entire pipe surface, the pipe was connected to the mixer to rotate the pipe in the plating solution. In addition, four anodes were arranged around the pipe. An image of the copper plating system is shown in Fig 7. The first plating test was conducted using the above plating equipment. After the plating,
the pipe was etched. The result showed the lines had become partially hollowed as shown in Fig 8. The cause of such a defect was assumed to be due to voids that had generated inside the plated layer, which would be used for a coil line, during plating. To confirm this, the pipe was cut and the cross section was observed. A photograph of the cross section of the line containing voids is shown in Fig 9. As shown in this photograph, voids were produced in the center of the line.

It was confirmed that these voids produced inside the coil line had prevented the formation of a satisfactory coil line.

The following were estimated as the causes of void generation.
(a) Electric current concentration at the corners of the structure.
(b) Air bubbles remaining in the groove of the structure due to surface tension.
(c) Decrease of plating solution density in the groove of the structure.

We removed these causes by improving the plating equipment and method. When a complexly shaped object is plated, the electric current concentrates at the corners, accelerating the growth of plating film at the corners in contrast to portions. As plating time passes, the plating film that has grown at the corners begins to cover the groove and prevents the plating film from growing inside the groove, thus preventing the plating film from growing evenly in the groove.

A leveling agent was added to the copper sulfate solution to prevent electric current from concentrating. This agent has a property to preferentially adhere to a part being exposed to a higher electric current, and therefore suppresses the growth of plating film at the portions where this agent has accumulated. It was expected that this agent would adhere densely to the corners of an object having a complex surface thereby ensuring uniform plating growth over the entire surface. This plating solution was used for the second plating test.

Since a high aspect ratio structure had been formed on the pipe surface to be plated, it was estimated that air bubbles would remain inside the groove due to surface tension when the pipe is dipped in the plating solution. Growth of the plating film would be disturbed in those areas where air bubbles remain, resulting in void generation. As a measure for ensuring a uniform plating film formation by clearing air bubbles from the structure groove,
a vacuum defoaming process was introduced before the start of the plating process. In the vacuum defoaming process, the pipe, following immersion in pure water was placed in a vacuum chamber and underwent decompression. It was supposed that the groove would allow air bubbles to form again if the structure surface was dried after the bubbles were once removed. To avoid such an unfavorable condition, the pipe was kept immersed in pure water after the vacuum defoaming and was then brought into the plating equipment. Immediately after being taken out of the pure water vessel, the pipe was dipped in the plating solution.

The plating solution was stirred during the pipe plating. However, it was anticipated that the plating solution would not be sufficiently circulated in the groove of the microstructure. Therefore, copper ion concentration of the plating solution would decrease in the groove section as the plating progresses and hence the copper deposition rate would decrease at some portions of the groove. This would cause the plating film to cover the upper part of the structure before the groove is fully filled with the metallic deposit, resulting in void generation. To eliminate such an abnormal condition, the pipe was moved up and down during the plating. The plating solution inside the groove was discharged when the pipe was moved up, while fresh solution entered the groove when the pipe was moved down. The plating solution in the groove was circulated in this manner.

After improving the plating conditions as described above, we confirmed that a void-free plating film could be formed as shown in Fig 10.

![Figure 10 Image of a cross section of the pipe after electroplating](image)

7. Uniform Etching

After the plating film was formed on the pipe surface, the pipe was subjected to a uniform etching process. In this process, the pipe rotation mechanism that had been used during the plating process was also used to rotate the pipe in the etchant to ensure uniform pipe surface etching. As a result, we could form a coil line as shown in Fig 11, though limited. However, the line was completely formed by etching at some portions, while the plating film remained even after the etching, resulting in incomplete coil line formation. We concluded that the reason for the defective etching was that the plating film thickness and etching rate had varied along the pipe in the longitudinal direction. These variations were considered to be due to insufficient stirring of the plating solution and etchant in their surface zones since they were only stirred from the bottom of the baths, thereby lowering both the plating and etching rates. Another possible cause was that the pipe ends did not simultaneously leave the plating solution when the pipe was moved up in the plating process. Failure to achieve successful formation of the coil line was considered to be due to the use of two consecutive wet processes of plating and etching, which usually tends to create non-uniformity. To overcome these difficulties, we are currently investigating the formation of coil lines by machining instead of etching.
8. Conclusions

We applied X-ray lithography, electroplating, and etching processes for fabricating coils for use in electromagnetic actuators. A spiral structure with an aspect ratio of 2, which consists of a 30 µm wide line and groove, was formed on the surface of an acrylic resin pipe. For electroplating, a seed layer was formed on the pipe surface by spattering. After improving the plating method and equipment, we succeeded in forming an air-bubble free plating film on the structure with an aspect ratio of 2. However, we could not satisfactorily etch the coil line in the etching process. We are currently in the process of forming coil lines by machining in place of etching.

The objective of this research study is to successfully fabricate coil lines. In addition, we will make coil lines having different aspect ratios, line widths, and pitches on an experimental basis. And after successful completion of the coil lines, we will assemble them into actuators, measure their output, and further inquire into the coil line configuration that can produce a higher output.

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References