BATCH FABRICATED FLAT WINDING SHAPE MEMORY ALLOY ACTUATOR FOR ACTIVE CATHETER

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ABSTRACT

Batch fabrication process of a shape memory alloy (SMA) sheet based on electrochemical pulsed etching with a sacrificial dummy metal layer has been studied and flat winding S-shape SMA actuators have been developed. The actuators are 38 μ m in thickness and generated forces from 40 to 95mN were obtained according to the width from 410 to 170 μ m. The flat winding SMA actuator could realize active catheter with small outer diameter and wide inner working channel. The batch fabrication process was also applied to micromachining of NiTi super elastic alloy (SEA) for biasing spring of the catheter.

INTRODUCTION

Active catheters with a function of controllable bending motion have been developed for interventional diagnosis and therapy in recent years [1-8]. In order to obtain large bending motion, 50%NiTi SMA coil actuators were used [1-5]. The catheters can be bent to multiple directions by three or four SMA actuators which are located at the space between an outer tube for protection and an inner tube for working channel. To satisfy the requirements for small outer diameter and wide inner working channel, thin actuators such as S-shape planar springs, for example made of bent SMA wire [8], are very effective. In order to obtain thin actuator with small width and large actuation stroke, fine pitch spring is needed.

In this work, batch fabrication process of NiTi SMA sheet based on electrochemical pulsed etching with sacrificial dummy metal layer has been studied. Flat winding SMA actuators have been developed by using the etching process. In comparison with chemical etching of SMA by using a solution based on hydrofluoric and nitric acid [9-10], the electrochemical etching is suitable method for deep etching because high etch rate can be obtained, side etching can be reduced and photoresist is usable for an etching mask [11,12]. Especially in the case of fabrication of complex microstructure, batch fabrication process is more favorable in mass-productivity than individual drawing methods such as laser cutting [13,14] and electro-discharge machining.

The batch fabrication process was also applied to micromachining of 51%NiTi super elastic alloy (SEA) sheet and a helical springs for biasing spring of catheter was made of a patterned SEA ribbon.

CONCEPT OF BATCH FABRICATION

Concept of the flat winding SMA and the application to an active catheter are shown in Figure 1. Flat shape memorized SMA sheet is used. Plural winding spring actuators are batch fabricated in the sheet. Each actuator is separated from the frame and attached to the active catheter under elongated condition. Another parts of the catheter such as ribbon cables for electrical interconnection can be also formed by planar batch process according to the need.

Helical coil rolled up from SEA ribbon is used for biasing spring. The helical coil has an advantage that it is stiff against compression, however, it is flexible for bending. Thin-walled polymer coating method on coil seems to be also available to the biasing spring to dispense with another inner tube [4]

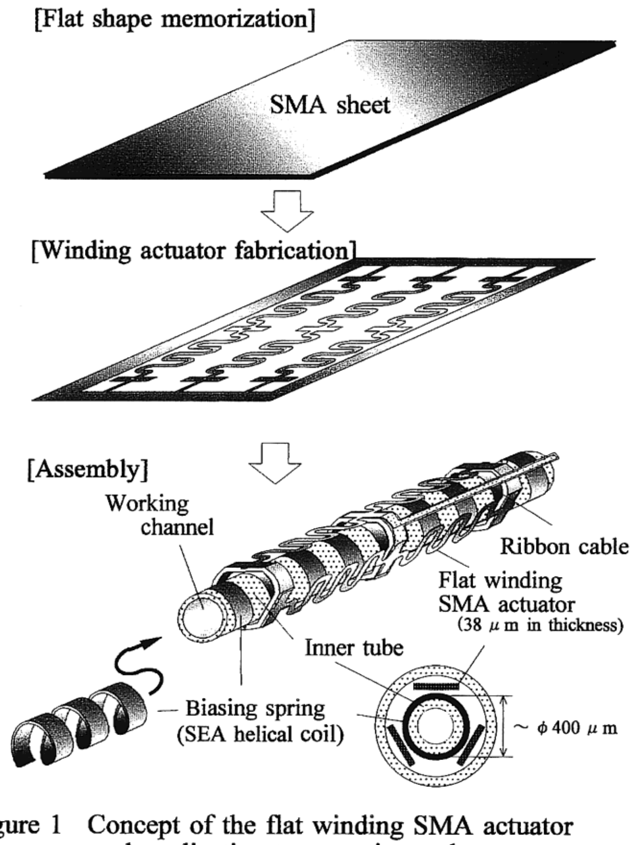


Figure 1 Concept of the flat winding SMA actuator and application to an active catheter.

FABRICATION PROCESS

Electrochemical etching was carried out in a rectangular glass vessel. The SMA sheet and a counter electrode of stainless steel plate ($50 \times 50mm^2$) were connected to a function generator. The etching vessel was sealed and dry N_2 was filled in it. The electrolyte of sulfuric acid in methanol was selected [11-13]. Fuming sulfuric acid ($10\%SO_3 \cdot H_2SO_4$) and dehydrated methanol were used to avoid an influence of water vapor contamination. Addition of 1vol% H_2O into the solution resulted in decrease of electrolytic current.

Potential of the SMA electrode vs. reference electrode of Ag/AgCl was measured. In the range of 0.55 to 5vol% sulfuric acid concentration, the potential of the SMA was constantly about 90% of the applied voltage because the counter electrode was large enough and hence the voltage drop at the counter electrode was negligible.

Preliminary experiments about a DC etching were carried out. After oxide film on the SMA surface was removed by hydrofluoric and nitric acid, the sheets of 38 μ m thick were electrochemically etched by about 20 μ m depth under various conditions as shown in Figure 2.

Negative photoresist (OMR83 Tokyo Ohka Kogyo Co., ltd.) was used for etching mask. Under high rate etching conditions such as high sulfuric acid concentration or high applied voltage, uniform and planarized etched were obtained but on the other hand worm-eaten shape tended to occur under the low etch rate conditions.

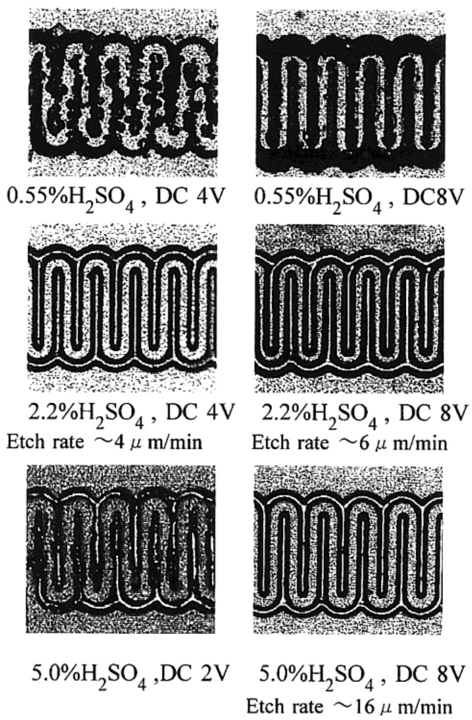


Figure 2 Etched shape under various conditions.

Dependence of etch rate and etch factor (= etching depth / side etching width) on width of mask space was evaluated under the high etch rate condition. The results are shown in Figure 3. The etch factor tends to be low at narrow mask space.

Similar evaluation was carried out about a pulsed etching as shown in Figure 4. Square pulsed voltage of 50% duty ratio was applied. The etch factor is not influenced by the mask space in the case of the pulsed etching.

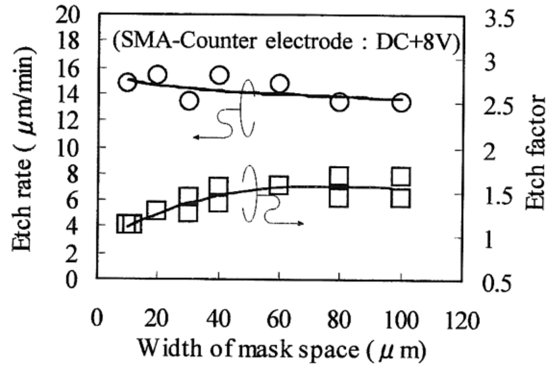


Figure 3 Etch rate and etch factor dependence on width of mask space. (DC etching)

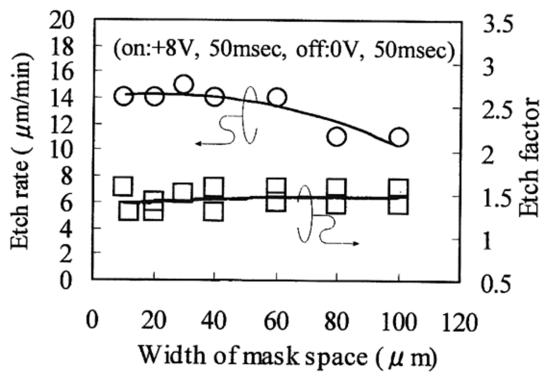
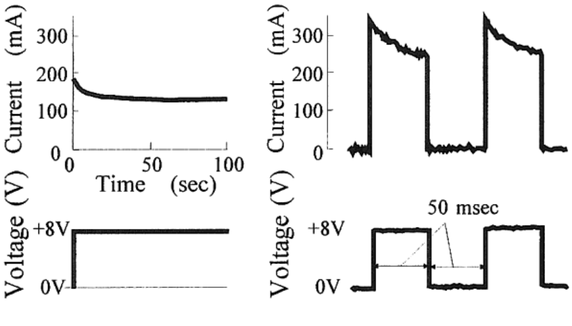


Figure 4 Etch rate and etch factor dependence on width of mask space. (Pulsed etching)

We chose the pulsed etching instead of DC etching because it seems to be suitable to the etching of narrow mask space. The pulsed etching had additional merits to obtain smooth etched surface and uniform depth. Etch rate of the pulsed etching was as high as the rate of DC etching.

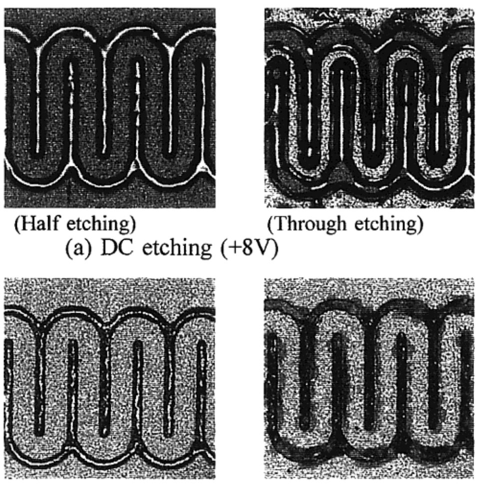
Electrolytic current during the etching is shown in Figure 5. The electrolytic current in the case of pulsed etching is about twice as large as that of DC etching. In the case of the DC etching, electrolytic current decreased during the etching because diffusion of reaction products was a rate-limiting step. Although the current slightly decreased during the voltage was turned on, reaction products can be replaced with fresh solution during the voltage was turned off.



(a) DC etching (b) Pulsed etching

Figure 5 Electrolytic currents during SMA etching.

In the case of complex patterns such as winding actuators, etching through the SMA sheet was difficult. After the sheet was etched through, remained SMA lines were etched like worm-eaten shape as shown in Figure 6(right) because uniform electric field distribution seemed to be lost. The backsides of the SMA sheet were covered by photoresist. The etching proceeded with high rate at the place where electric field was concentrated but on the other hand etch rate became low at another place. The worm-eaten shape was finer in the case of the pulsed etching than that of the DC etching.



(Half etching) (Through etching)
(a) DC etching (+8V)

(Half etching) (Through etching)
(b) Pulsed etching (+8V, 50/50msec)

Figure 6 Worm-eaten shape ocurrence.

In order to realize more uniform etching, sacrificial conductive dummy layer was used on the backside of the SMA so that constant etching can be maintained after the SMA layer is etched through. The thick dummy layer has to be deposited and can be removed selectively after the SMA etching.

Ni was most suitable material because thick film could be deposited by using electroplating and removed by using concentrated nitric acid at the rate of about 0.2 μ m/min. Adhesion of the electroplated Ni was improved by using evaporated Ni film as an insert layer. Although electroplated Cu had a similar feature to Ni, the Cu film was not adhesive enough.

Preliminary experiments using testing pattern revealed that etch rate and etch factor did not depend on the rolling direction of the SMA sheet. Stretching direction of the actuator was aligned perpendicularly to the rolling direction of the sheet.

SMA actuator was fabricated by dual side etching so as to reduce the side etching as shown in Figure 7.

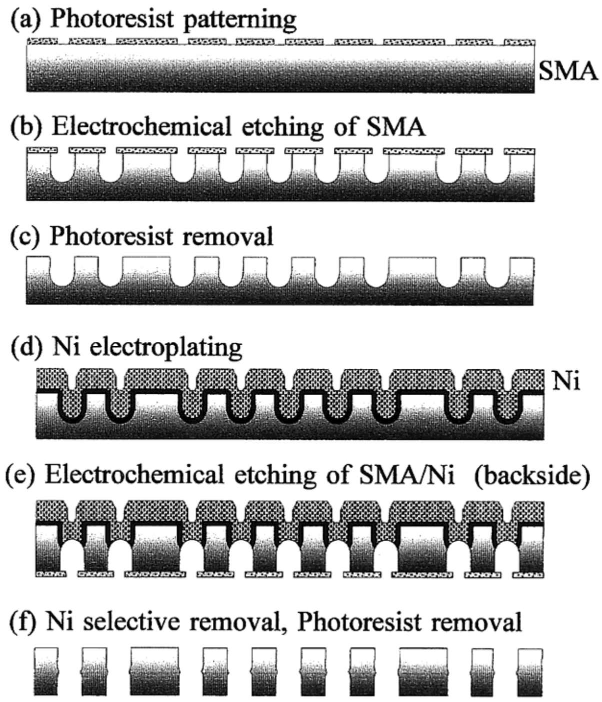


Figure 7 Process flow of SMA fabrication

(a) Flat shape memorized NiTi SMA sheet of 38 μ m in thickness was used. Negative photoresist pattern baked at 80℃ was used for the etching mask.

(b) The SMA was electrochemically etched by pulsed etching (+8V, on/off =50/50 msec). Etched depth was 25 μ m.

(c) Ni film of 0.1 μ m in thickness was evaporated as an insert layer.

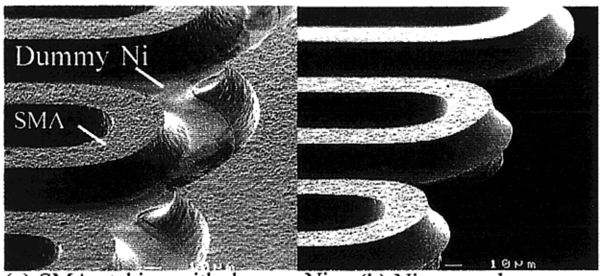
(d) Ni was electroplated thicker than 5 μ m.

(e) The SMA was electrochemically etched from backside through the SMA to the Ni layer.

(f) Ni layer was selectively removed by using concentrated nitric acid.

By using this fabrication process, the winding SMA actuator could be fabricated uniformly as shown in Figure 8. There was no damage on the SMA surface after Ni dummy layer removal.

Actuators of three types were fabricated in a SMA sheet as shown in Figure 9. The widths of the actuators were changed as shown in Figure 10. As a result of 15 μ m side etching, the width of the top surface of the SMA lines were about 30 μ m when photoresist pattern of 60 μ m in width was used.



(a) SMA etching with dummy Ni (b) Ni removal

Figure 8 SEM photographs of winding SMA fabricated with Ni dummy layer.

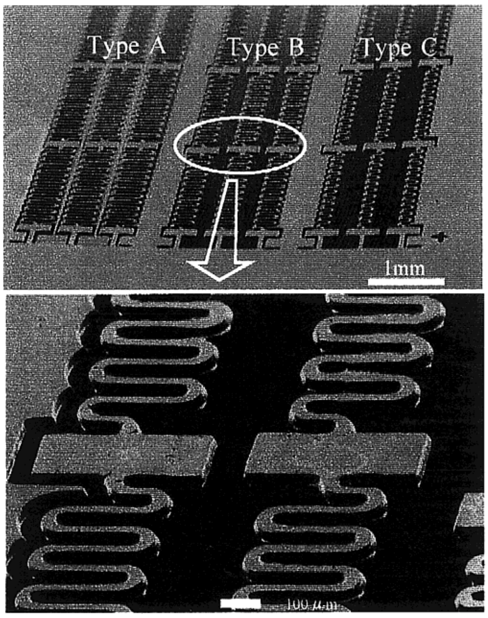


Figure 9 SEM photographs of the fabricated SMA actuators.

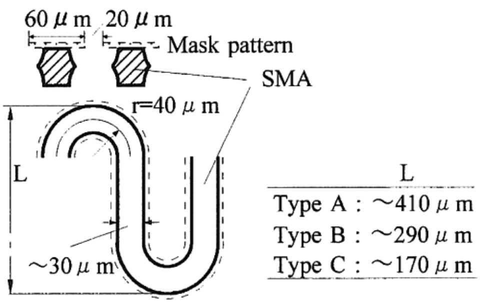


Figure 10 Dimensions of the fabricated actuators.

CHARACTERISTICS OF THE ACTUATOR

Elongation characteristics of the SMA actuators were evaluated as shown in Figure 11. The SMA actuators were clamped and elongated as long as about 90, 70 and 35% of their initial lengths in the case of type A, B and C, respectively. Each S-shape unit could be deformed uniformly and out of plane deformation was less than 20 μ m.

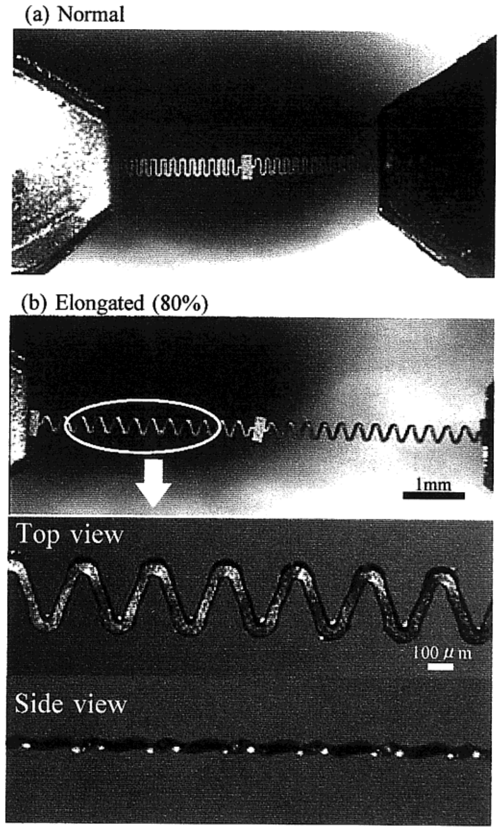


Figure 11 Photographs of the elongated SMA actuator (Type B).

As a next attempt, the SMA actuators were heated by electrical current under various conditions of elongation. The forces of the actuators were measured under the various elongation conditions at constant current under ambient temperature of 25℃. Before current condition was changed, the actuator was heated electrically without clamping in order to restore its initial shape. The initial electrical resistances at ambient temperature of type A, B, and C were 15, 11, 9 Ω, respectively.

Results of current-force relationships are shown in Figure 12. The forces at 0mA correspond to an elastic tension and the differences from the tension correspond to generated forces of the SMA actuators. The maximum generated force of the actuator of type A, B and C were about 40mN, 75mN, and 95mN, respectively. The wide winding actuator such as type A is rather suitable to an application of large actuation stroke, while the narrow winding actuator such as type C is rather suitable to an application of large actuation force. In the cases of coil spring type SMA actuators whose outer diameters are in the range of 150 to 250 μ m, the generated forces were from 35 to 50mN and tensions at low temperature were about 40mN, respectively [2,5]. The developed flat winding SMA actuators seem to be usable for active catheter bending.

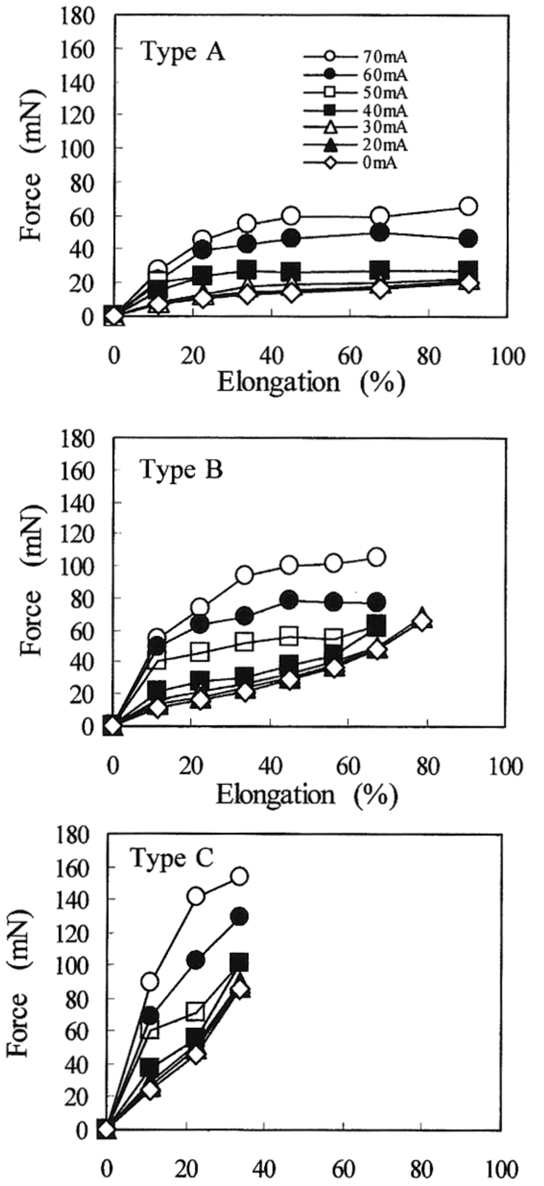


Figure 12 Elongation-force relationships of the SMA actuators.

APPLICATION TO SEA FABRICATION

The developed batch fabrication process for 50%NiTi SMA was also applicable to 51%NiTi SEA because the etch rate and the etch factor were not different from SMA etching. SEA ribbons were fabricated in a sheet as shown in Figure 13. Each ribbon was separated and rolled up around a rod of 0.4mm diameter individually. After heat treatment for shape memorization, helical coils for biasing spring of active catheter could be fabricated as shown in Figure 14. Using this method, complex patterned SEA parts can be built in the helical coil. Active catheter smaller than 1mm in outer diameter could be fabricated using the helical coil and three flat winding SMA actuators of type B (Figure 15).

The electrochemical etching of NiTi alloy is, of course, usable to non-planar fabrication. Figure 16 shows a helical coil fabricated from a SEA pipe whose outer and inner diameters were 1.0mm and 0.8 mm, respectively. Dip coated Photoresist on the surface of the SEA pipe was patterned by photolithography with a rolled up masking tape.

The developed micromachining technique of the NiTi sheet seems to be applicable not only for the catheter but also for another MEMS in wide fields such as cardiovascular stents and micro actuators of various shapes.

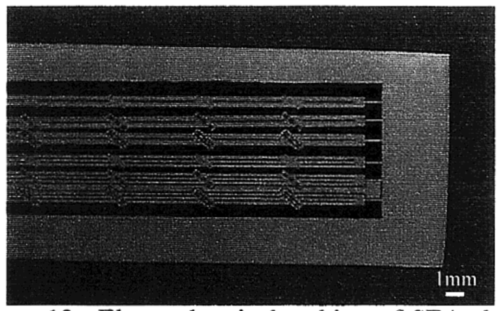


Figure 13 Electrochemical etching of SEA sheet. (30 μ m thick, etched from one side)

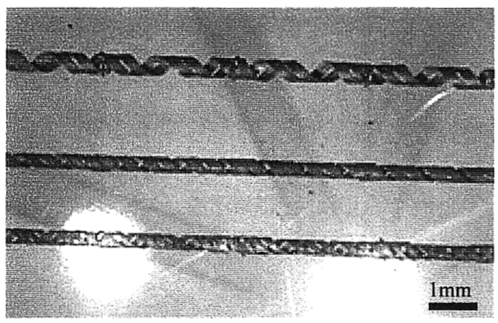


Figure 14 Helical coils made of rolled SEA ribbons.

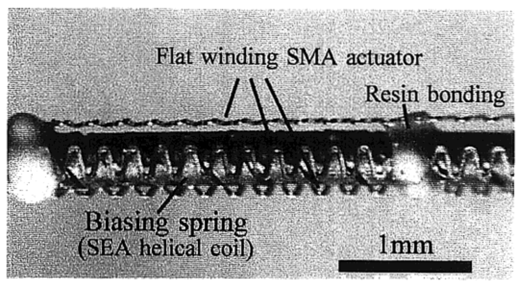
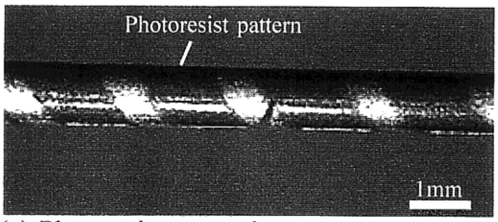
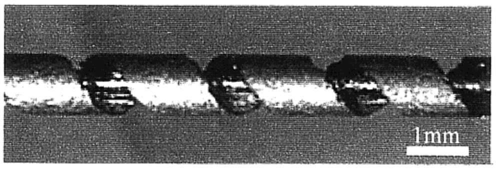


Figure 15 Active catheter consists of the SMA actuators and the SEA biasing spring.



(a) Photoresist patterning



(b) Electrochemical etching

Figure 16 Helical coil made of etched SEA pipe.

CONCLUSIONS

Flat winding S-shape SMA actuator has been developed by using batch fabrication process based on electrochemical pulsed etching of SMA sheet with sacrificial dummy Ni layer. The flat SMA actuator can realize active catheter with small outer diameter and wide inner working channel. The sheet fabrication process can realize additional capabilities that another parts of the catheter such as ribbon cables can also be fabricated on the sheet. The fabrication process was also applied to micromachining of SEA sheet for biasing spring of the catheter. The micromachining technique of NiTi seems to be useful not only for actuator of catheter but also for another MEMS in wide fields.

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