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Active Bending Catheter and Endoscope Using Shape Memory Alloy Actuators

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1. Introduction

Shape memory alloys (SMAs) are excellent materials for microactuators which can generate large force and large displacement. Shape memory alloy can recover its original shape after it is deformed over its elastic limit by external force. Several mechanisms with SMA micro-coil actuators, for example, bending, extension/contraction, torsional and stiffness control mechanisms have been developed. The principles underlying these mechanisms and the structure of each mechanism are detailed and medical applications, namely, catheters and endoscopes are presented.

2. SMA (Shape Memory Alloy)

2.1 Principle

Shape memory alloy (SMA) recovers previously memorized shape upon heating. The alloy has to be deformed in its Martensitic low temperature phase and subsequently heated to the Austenitic high temperature phase. The SMA generates a large deformation and large force during the phase transformation.

The response of SMA actuators tends to be slow due to the heat capacity of the actuator, resulting in lengthy heating and cooling. Because deformation of SMA is caused by a crystalline phase transformation which occurs without any diffusion of substances (Otsuka & Wayman, 1998), an SMA actuator can deform rapidly when it is miniaturized thus reducing its heat capacity.

The material of most bulk SMA is TiNi alloy. Because of the poor mechanical workability of TiNi alloy which results in high cost and defects in SMA, choice of shapes of bulk SMA is limited.

2.2 Fabrication and assembly of SMA microactuator

As a micromachining method for TiNi SMA, laser cutting is practical because it is fast and allows more complex patterns (Reynaerts et al., 1999). To prevent deterioration due to heat generation by the laser, appropriate laser power and cutting speed should be selected. A femtosecond laser is effective to prevent heat generation, but the cost of the system is relatively high.

Electrochemical etching is one of the most suitable methods to etch TiNi SMA with a high etch rate. Compared to conventional chemical etching, electrochemical etching has features including high etching rate, low side etching and a smooth etched surface. An etch factor (etched depth/under-cut) higher than 1.5 can be obtained. Another advantage of electrochemical etching is that normal photoresist can be easily used as an etching mask. Electrochemical etching can be carried out using a simple setup, as shown in Fig. 1 (Mineta et al., 2000; Mineta et al. 2002).

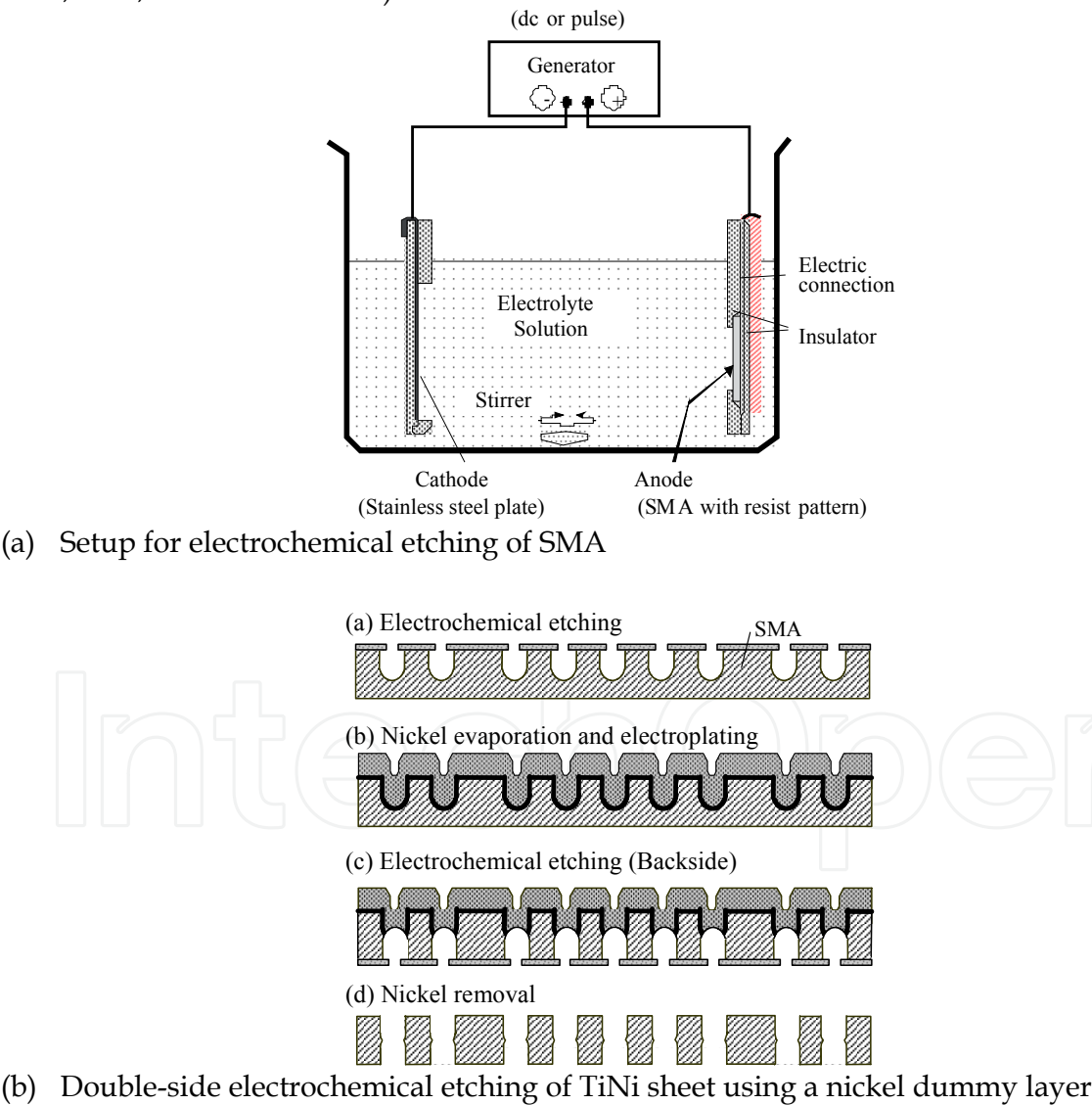
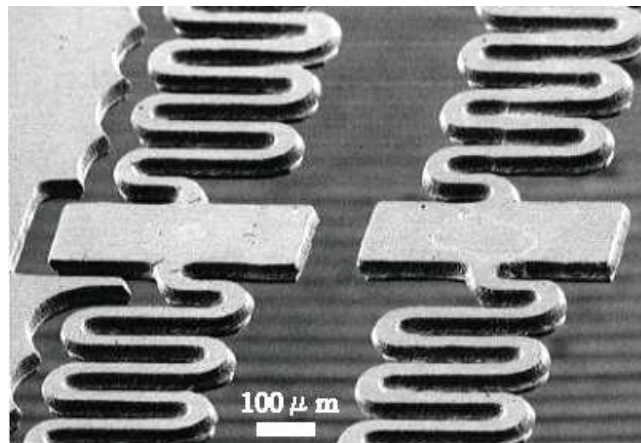


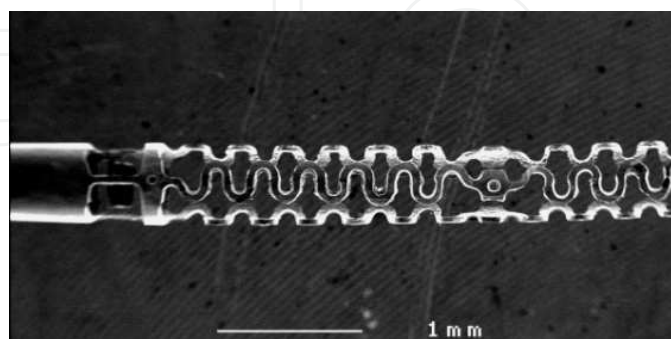
Fig. 1. Electrochemical etching of SMA sheet

Shape memory alloy coated with a photoresist is used as an anode. The anode and a counter cathode, for example a stainless-steel plate, were facing each other with a gap of several tens of millimeters in the electrolyte solution. A solution of 5 vol % (about 1 mol/L) H_2SO_4 -methanol has been used as an electrolyte for electrochemical etching of SMA (Allen & Chen, 1997) (Kohl et al., 1994). When a direct-current (DC) voltage, typically 8-10 V, is applied between the electrodes, the SMA anode is etched electrochemically. In addition to continuous voltage, pulse voltage is also useful for the electrochemical etching.

Through-layer etching is important for the precise fabrication of micro actuators from an SMA sheet. During over-etching, the remaining SMA patterns tend to be etched non-uniformly due to imbalance of the electrolytic current distribution. The etching proceeds at the places where the current is concentrated, while it stops at other places. In order to overcome the problem of non-uniform sheet-through etching, a conductive dummy layer of Ni or Cu, which is formed on the back side of the SMA sheet previously, is very effective in maintaining a uniform current distribution during the over-etching. The dummy layers of Ni and Cu can be easily removed in concentrated nitric acid without damage to the SMA surface (Mineta et al., 2000). Meandering SMA micro actuators fabricated by electrochemical etching of 40 μm thick SMA sheet is shown in Fig. 2 (a).



(a) Electrochemical etching of SMA sheet (40 μm thick, Double-side etching)



(b) Tubular SMA actuator-unit electrochemically etched from a SMA tube (outer/inner dia.: 600/500 μm)

Fig. 2. Meandering SMA micro actuators fabricated using electrochemical etching

Electrochemical etching also can be used for fabrication of non-planar SMA structures. Fig. 2 (b) shows a tubular SMA actuator unit for an active catheter bending mechanism, in which meandering-shaped SMA actuators are formed. An SMA tube, covered with a photoresist pattern formed by non-planar photolithography, is electrochemically etched in a cylindrical vessel with a cylindrical cathode, resulting in the fabrication of a tubular SMA actuator-unit (Mineta et al., 2004).

2.3 Assembly of SMA microactuator

For purposes of mechanical fixation of SMA or parts with SMA, several assembly methods, for example, mechanical fixation, adhesion, welding and soldering are used.

The disadvantages of mechanical fixation are the requirement of large connection areas, impreciseness of length adjustment, low productivity because of the handmade process and fracture susceptibility in the fixation area because of local deformation and local stress of SMA.

A disadvantage of adhesion is that considerable time is necessary to make all connections when these connections have to be formed individually. Cyanoacrylates can be cured in a shorter time than epoxy resin but are relatively brittle. Adhesive tape (single sided or double sided) can be used for temporary fixation.

Regarding the heating process for heat-curable adhesive, soldering or welding, the temperature limit and heating time in the assembly should be considered to prevent deterioration of the shape memory effect. As SMA deformed from its memorized shape tends to be restored to its memorized shape during the heating process, a certain fixation method of the SMA is required to prevent the restoration.

Using polymer material for intermediate adhesion, not only a nonconductive adhesion part but also a conductive adhesion part using conductive resin is employed. As the nonconductive adhesive part, epoxy resin (Mineta et al., 2000) and UV curable resin (Ballandras et al., 1997) have been utilized. As the conductive adhesive part, epoxy resin containing silver powder (Mineta et al., 2000) or UV curable conductive epoxy resin have been utilized (Lim et al, 1996). Laser assisted deposition has been carried out for fixing an SMA coil to silicon parts for active bending catheters (Lim et al, 1996), vaporized polymer source material being selectively polymerized and deposited on the UV light-irradiated area. As considerable time is necessary to make all connections when these connections have to be formed individually, batch assembly method using nickel electroplating and acrylic resin electrodeposition has been developed (Haga et al., 2000). Fabrication is carried out as follows. The SMA coil and metal spring are coated with polymer and the polymer is partially removed by laser ablation for partial exposure of the SMA surface and metal surface. UV curable acrylic resin is locally deposited by electroplating between the exposed SMA surface and the exposed metal surface as shown in Fig. 3. Oxide film on the surface of TiNi alloy should be removed to achieve uniformity of electroplating.

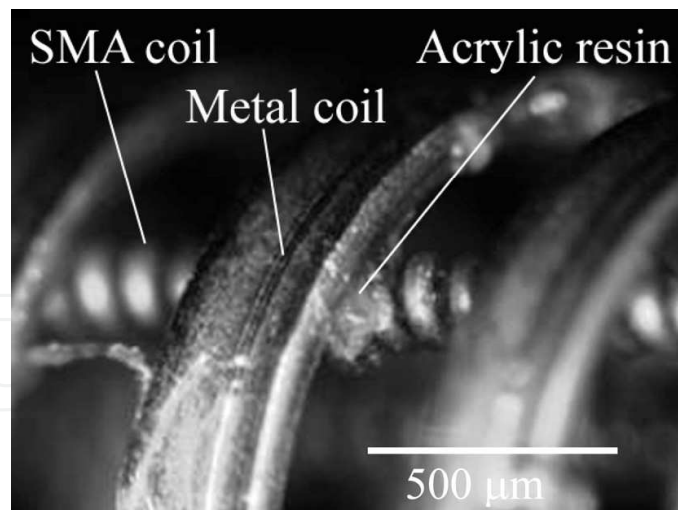


Fig. 3. Connection between SMA coil and metal coil formed by electrodeposition of acrylic resin

2.4 Actuation of SMA microactuator

Large scale bulk SMA actuators tend to have a slow response due to the large heat capacity of the actuator itself, which results in lengthy heating and cooling cycles. An SMA actuator can be rapidly deformed when it is miniaturized so as to reduce its heat capacity. An SMA micro actuator can be heated above its phase transformation temperature rapidly by small thermal energy and can be rapidly cooled down by ambient air without the addition of a cooling mechanism.

2.4.1 Direct heating

TiNi SMA can be actuated by Joule heat created by direct flow of an electrical current into the SMA when electrical resistance of the SMA is relatively high. The advantage of the actuation method is its simple structure without any heater or cooler. Disadvantages of direct heating are the requirement of high electrical resistance and electrical connections with low electrical resistance between the SMA and dissimilar conductive material.

Relatively high electrical resistance of SMA is required to avoid a high electrical current for actuating the SMA. Though the small or thin structure of SMA has high electrical resistance, it cannot generate high power. An array of small or thin SMA structures connected as a series circuit can solve this problem, but the structure is relatively complex.

Electrical connections with low electrical resistance between SMA and dissimilar conductive material, for example, copper as electrical lead wires, is required to avoid undesirable consumption of electrical current for heat generation at the connection.

2.4.2 Indirect heating

Indirect heating of an SMA actuator by additional heater lines with high resistance is advantageous for reducing the electric power needed for actuation. To realize indirect heating, it is necessary to select an appropriate mechanical design and fabrication processes of the heater and insulator so that they can deform without fracture during the SMA

actuation. For example, a thin Ni film (0.6 μm) on a Parylen-coated SMA coil is used as an indirect heater (Lim et al, 1996). The Parylene layer (1 μm thick) is an insulator between the Ni layer and the SMA surface. Parylene can be deposited uniformly in a vacuum on the entire surface of the SMA coil. A thin Ni heater layer is formed by electroless plating on the Parylene. No damage is observed in the Ni or Parylene films after 3000 cycles of prolonged experiments with applied power of 80 mW at 2 % strain of SMA coil.

3. Active Catheter

3.1 Catheter and motion control mechanism

To inject contrast medium or medicine into the blood vessel or to measure blood pressure locally, a catheter, which is a hollow flexible small tube, is used. Catheter-based procedures (catheterization) enable doctors to access almost every diseased site which needs to be checked and treated via a blood vessel. Doctors control the tip of the catheter by moving its proximal part from outside of the body. Depending on blood vessel size, the catheters are approximately 0.3-3.0 mm in diameter and 1.5 m in length. As doctors must control the tip of the catheter from outside the body, operations with catheters require considerable skill, particularly when the blood vessel has a loop or complex configuration. Thus, there is a demand for an active catheter which moves like a snake in the blood vessel. Precise and safe manipulation of the catheter is realized if doctors can control the motion of the catheter from outside the body. As back-and-forth operation of the catheter from outside the body is relatively easy, a self-propelling mechanism is not necessarily demanded. Consequently, almost all controllable steering mechanisms are installed near the tip of the catheter. Active catheters which have micro-actuators at the tip have been developed for use in every part of the body. The tip can be controlled from outside the body and moves like a snake if many micro-actuators are distributed and properly controlled. Not only bending motion, but also torsional and precise back-and-forth motion is useful for manipulation of the tip of the catheter.

3.2 Active bending mechanism using SMA microactuator

An active catheter which has a bending mechanism realized by thin TiNi SMA plates has been developed (McCoy, 1985) (Kaneko, 1995). One of the SMA plates fixed along the side of the catheter bends when the plate is heated by application of a current to restore its memorized shape. To realize precise control of bending motion by feedback control using temperature monitoring, a component which has heaters, temperature sensors and circuits on a flexible polyimide film substrate has been fabricated using MEMS technology (S. Kaneko, 1995). The film components are fixed on the TiNi SMA plates placed on the sides of the catheter. To realize multi-directional bending, pairs of film components and SMA plates are fixed serially on alternating sides of the catheter. The external diameter of such a fabricated multi-joint catheter is 1 mm. The SMA plates utilized for this catheter are two directionally memorized SMAs, the shape of which is restored by cooling. A bending mechanism with a diameter of 15 mm has been developed for gastrointestinal application (Reynaerts et al., 1999). This mechanism consists of a stack of elements with an SMA plate at the center of each element. When the SMA plates are actuated by the application of current, the whole structure bends in two directions like a vertebra of the human body.

Shape memory alloy wires are also utilized for active catheters (Fukuda et al., 1994) (Takizawa et al., 1999) (Lim et al., 1999). When the SMA wires are embedded in the catheter eccentrically and heated above a certain transformation temperature by direct application of an electrical current to the SMA wire, the wire actuator bends the catheter by contraction of its length. The contraction length of the SMA wire, however, is relatively short and SMA wires fixed to the opposite side tend to restrict bending motion since the wires have to bend and stretch passively. Consequently, it is difficult to realize bending with a small radius of curvature.

Shape memory alloy micro-coil actuators are used to obtain a large bending motion and to realize multi-joint actuation as shown in Fig. 4. Shape memory alloy coils enable multi-directional bending with a large bending angle because the SMA coil actuators fixed at the opposite side can be passively extended. Shape memory alloy coil actuators can also be actuated by direct application of current when the wire diameter of the coil is small. Three SMA coil actuators, which are extended (from their memorized shapes) and fixed in the catheter, contract and bend in several directions. Multi-joint and multi-directional active catheters using silicon-glass link structures have been fabricated. Three SMA coil actuators are fixed between two silicon-glass link structures at intervals of 120 degrees. Many joints are serially connected and each joint can bend in any direction. The external diameter of the fabricated catheter is 2.7 mm (Lim et al., 1996).

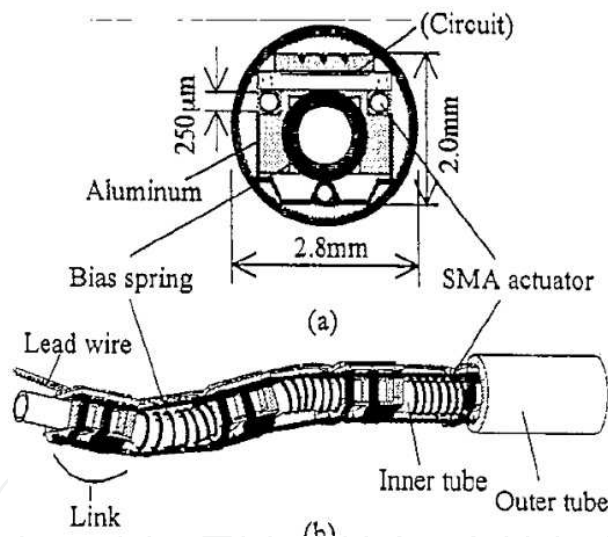


Fig. 4. Active bending catheter using SMA coils

By locating SMA coil actuators inside the liner coil and fixing them to the liner coil directly, link structures can be eliminated and the liner coil can be used as a skeleton and a bias spring (Fig. 5). Furthermore, every part works as a joint and hence bends more flexibly than that with links (Haga et al., 1998). As the catheters for use in blood vessels are disposable to avoid blood infection, active catheters need to be fabricated at low cost. To solve this problem, batch assembly methods have been developed. One is silicon wafer-level batch fabrication with a silicon joint structure (Mineta et al., 1999) and the other is fabrication using nickel electroplating and acrylic resin electrodeposition (Haga et al., 2000). Fabrication

using electroplating and deposition is carried out as follows. The SMA coil and metal spring are coated with polymer and the polymer is partially removed by laser ablation for partial exposure of the SMA surface and metal surface. UV curable acrylic resin is locally deposited by electroplating between the exposed SMA surface and the exposed metal surface. This novel method enables low cost batch assembly and a small external diameter.

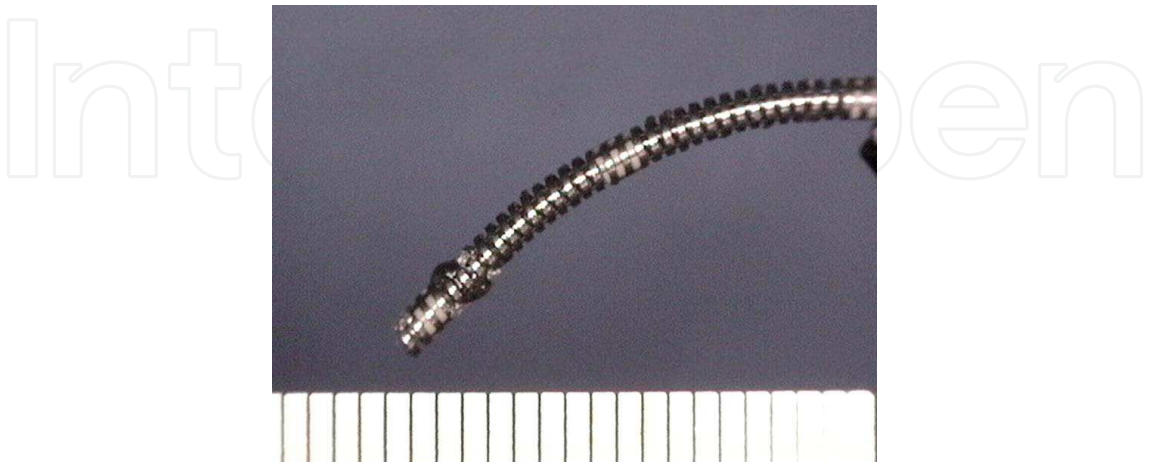


Fig. 5. Active bending catheter fabricated using electrodeposition (external diameter, 1.6 mm)

Instead of a coil shape, flat meandering-shaped SMA actuators are also used for active catheters. The flat shape meets both demands of small external diameter and large working channel by realizing a thin wall (Lim & Lee, 1999). A batch fabrication method for flat meandering SMA actuators from an SMA (TiNi) sheet has been developed using electrochemical pulsed etching for active catheters (Mineta et. al, 2000). Furthermore, to simplify the assembly process of the SMA actuators, three meandering actuators are formed in an SMA pipe using electrochemical etching mentioned above.

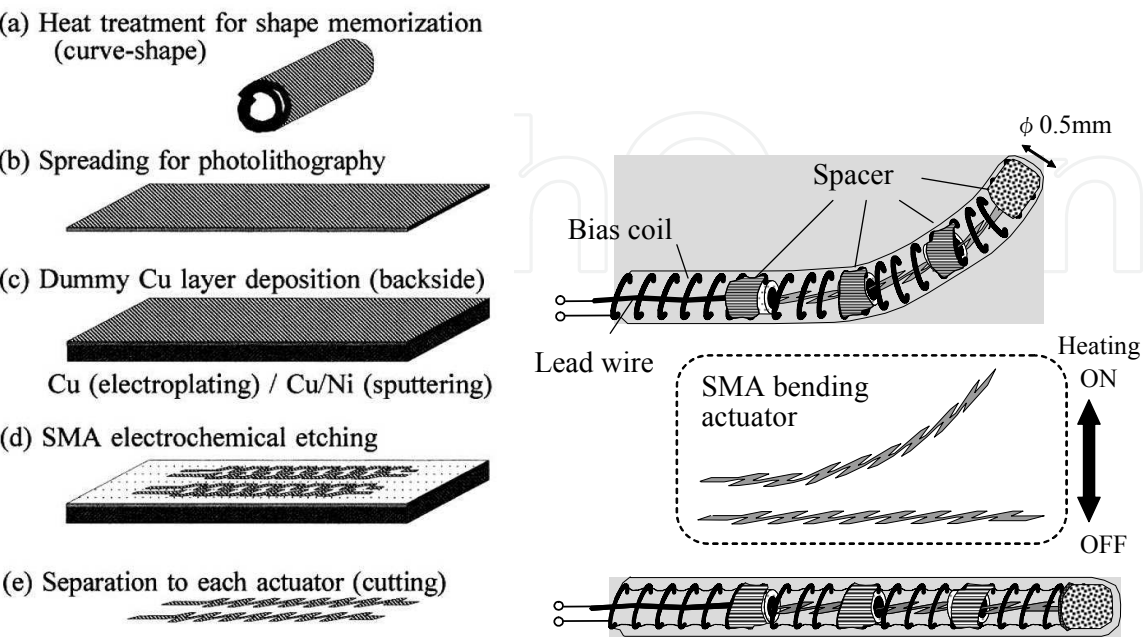


Fig. 6. Active guide wire using an SMA bending actuator

Guide wires are wires which have a relatively flexible tip and are used for guidance of the catheter. An active bending guide wire has been fabricated using a flat meandering actuator (Fig. 6). The guide wire is bent by an electrical current supplied to the actuator because the actuator has a memorized curved shape (Mineta et. al, 2002).

3.3 Other motion mechanisms

By changing the deformation shape of the SMA and the configuration of the mechanism, several motions can be realized, not only bending motion, but also torsional and extension motions (Fig. 7).

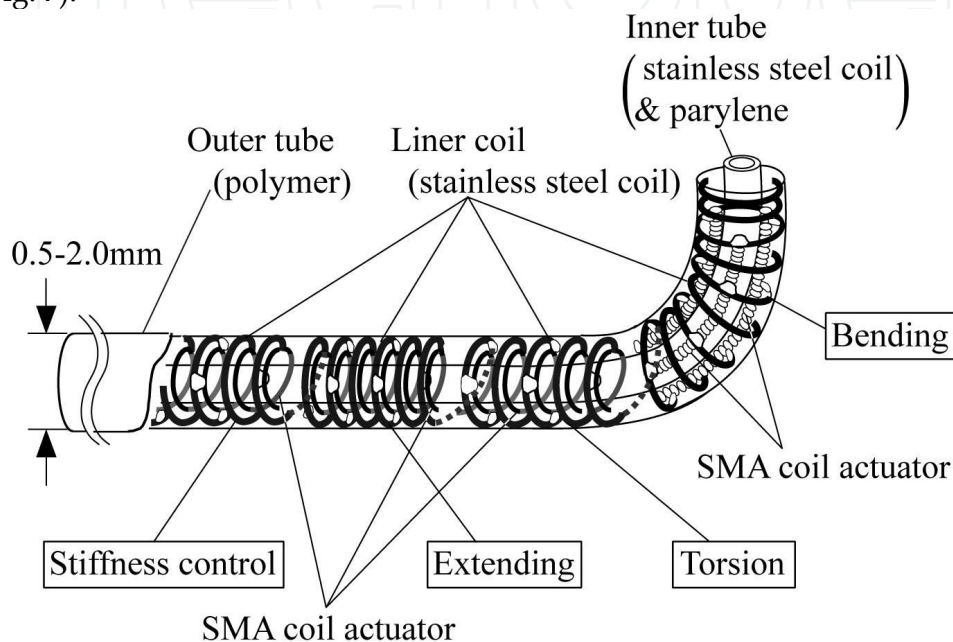


Fig. 7. Bending, torsional and extending active catheter using SMA coil actuators

3.3.1 Torsional mechanism

A torsional mechanism has been developed for medical application. For conventional manipulation of catheters through branches of blood vessels, a J-shaped tip of the catheter or guide wire, which is used for guidance of the catheter, is torsionally rotated from outside the body. However, the torque cannot be transmitted with good control when a blood vessel has a loop or complex configuration. This problem can be solved by installing an active torsional mechanism at the tip of the catheter or the guide wire. The structure of the torsional mechanism using the SMA micro-coil actuator consists of a metal spring coil and a twisted SMA coil fixed coaxially inside the metal coil. The metal coil plays the roles of a bias spring and a lead wire. When the SMA coil is heated above a certain transition temperature by an electrical current, the SMA coil is untwisted. Conversely, the metal coil twists (turns back) the catheter when the electrical current is turned off. The external diameter of the fabricated torsional mechanism is 1.3 mm without an outer tube and its length is 7 mm (Fig. 8). A torsional rotation of 70 degrees can be obtained with a current of 80 mA (Haga et al., 2000). Fabrication is carried out using electrodeposition of acrylic resin.

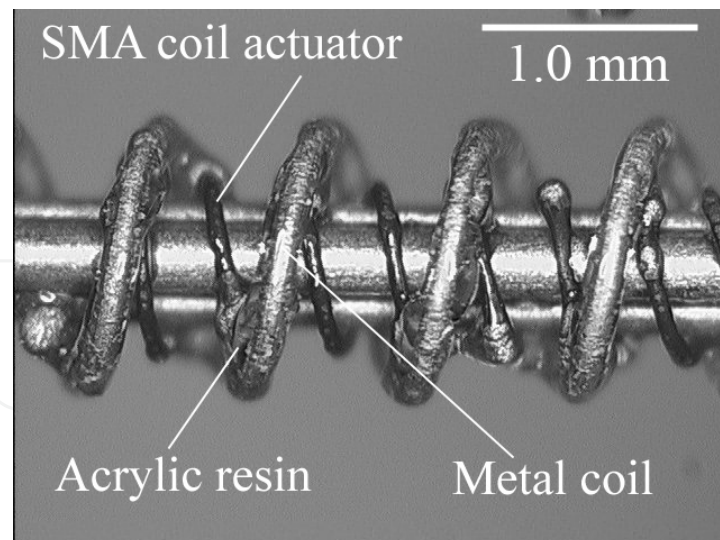


Fig. 8. Torsional mechanism fabricated using electrodeposition of acrylic resin (external diameter, 1.3 mm)

3.3.2 Extension/contraction mechanism

An extension/contraction mechanism has been developed for back-and-forth motion for precise manipulation of catheters, endoscopes and guide wires. This mechanism has also been employed for a dynamic pin display for the visually impaired or sightless.

There are mainly two ways for realizing an extension/contraction mechanism with SMA micro-coil actuators. When a compressed SMA micro-coil actuator is heated by an electrical current, the SMA extends, causing an extending motion. Conversely, an extended SMA micro-coil actuator contracts, causing contracting motion, when the SMA is heated by an electrical current.

3.3.3 Stiffness control mechanism and laser machining of TiNi SMA tube

Application of a stiffness control mechanism is expected to improve manipulation of medical instruments (endoscopes, catheters or guide wires) by changing the stiffness of the shaft of the instrument. A hard shaft is preferable during passage through a relatively safe site, while a soft, flexible shaft is preferable during passage in a relatively dangerous site, for example, a curved area or narrow passage. The stiffness control mechanism is also expected to be useful during the therapeutic operation of intravascular occlusion (recanalization) with guide wires. Chronic total occlusion of a blood vessel is treated by pushing a hard-tipped guide wire through the occlusion. Presently, several shape and stiffness guide wires have to be selected and used for precise and safe intravascular treatment. A guide wire whose shape and pushability can be controlled would be useful for such purposes.

Stiffness can be changed when the shaft of a medical instrument is equipped with an SMA micro-coil actuator in the state of its memorized shape. When the SMA is heated by an electrical current, its stiffness changes due to the shape memory effect.

For this purpose, a spring-shaped SMA micro-coil with a square cross section is preferable. Such an SMA micro-coil has been fabricated by spiral cutting of a TiNi SMA tube with a femtosecond laser. The conventional method of fabricating an SMA micro-coil is coiling of SMA wire. This method however, is not suitable for making a spring-shaped SMA micro-coil with a square cross section. Use of a femtosecond laser enables micromachining of the memorized SMA without deterioration of the shape memory effect because its pulse width is very short (10^{-15} sec) and heat generation is sufficiently reduced during laser machining. The external diameter of the fabricated TiNi SMA micro-coil actuator is 0.9 mm and the size of its wire is 0.07×0.25 mm. The pitch of the turns of the micro-coil is 0.4 mm. Stiffness change of the 10-mm-long SMA coil was evaluated by pushing it in the longitudinal direction with a force gauge until flexion occurred. A change of 20 mN was measured by a flowing electrical current of 150 mA.

3.4 Communication and control circuit

A major problem with active catheters which has many joints and functions is the necessity of too many lead wires to control each SMA actuator. To minimize the number of lead wires, flexible polyimide-based integrated complementary metal oxide semiconductor (CMOS) interface circuits for communication and control (C&C) have been developed and utilized in active catheters. To reduce the system size and simplify the assembly work, the C&C integrated circuit (IC) and three lead wires are fabricated on the same substrate using a CMOS-compatible polyimide-based process (Fig. 9). The outer diameter of the fabricated active catheter without an outer tube is approximately 2.0 mm (Park et al., 1996).

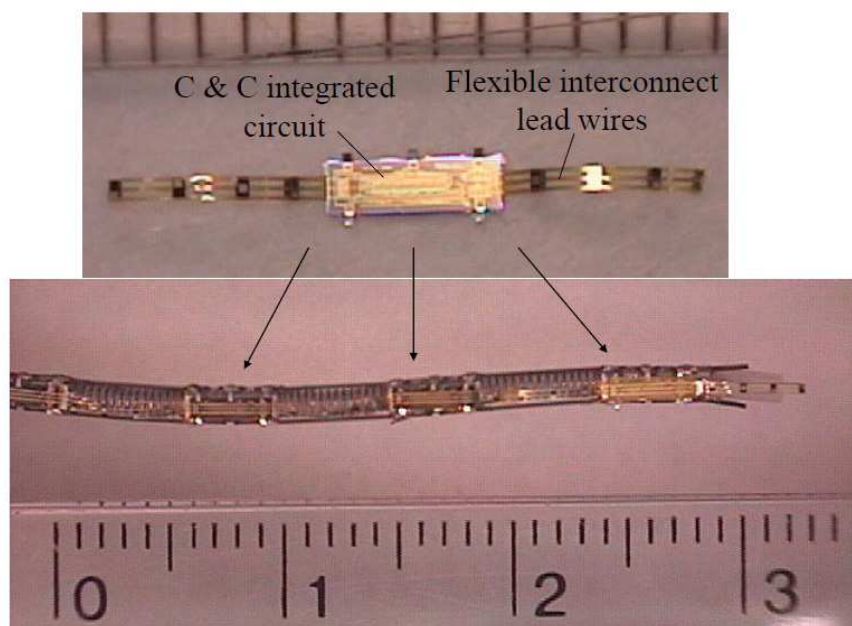


Fig. 9. Torsional mechanism fabricated using electrodeposition of acrylic resin (external diameter, 1.3 mm)

4. Active Bending Intestinal Tube

Intestinal obstruction (ileus) is a serious passage disorder in the intestines which causes acute pain. There are two methods for treatment of ileus. One is abdominal surgery and the other relatively minor method is nonoperative treatment by insertion of a long intestinal tube (LIT) made of silicone rubber to the intestine and depressurization by continuous suction from outside the body. Half of the patients are cured with the latter treatment in Japan. As shown, a doctor inserts the LIT into the patient's nasal cavity and pushes it forward from outside the body, while monitoring its position using X-ray fluoroscopy. In insertion of the tube, it is difficult to pass the lower opening of the stomach (pylorus) because of its narrowness. Fig. 10 shows the pylorus and the tip of the LIT. The external diameter of the tip is 6 mm. Doctors must be skilful and sufficiently experienced to successfully manipulate and insert the tube into the intestine (Hachisuka et al., 1991).

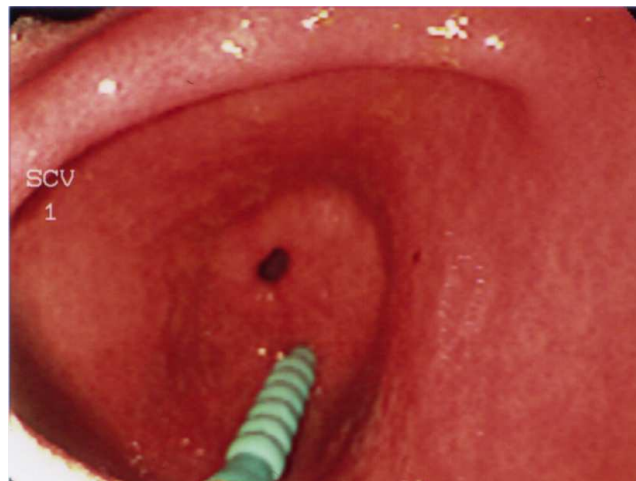


Fig. 10. Pylorus and long intestinal tube

An LIT that has stainless steel weights at the tip is most widely used. This tube utilizes gravity to facilitate manipulation of the tip. However, a patient must endure pain when he or she changes position. Furthermore, accuracy of positioning of the tip is insufficient. In the endoscopic procedure, doctors can control the motion of the tip of the endoscope by manipulating wires in the shaft of the endoscope from outside the body. However, this method cannot be applied to control the tip of the LIT because of its length (over 3 m) and buckling of the silicone rubber shaft due to its softness. For precise manipulation of the tip of the LIT, an active bending LIT incorporating an SMA micro-coil actuator has been developed for easy passage of the pylorus (Mizushima et al., 2004).

Fig. 11 shows the structure and principle of this LIT. Although it has a one-directional bending mechanism, doctors can control the bending direction by rotating the shaft from outside the body. The active bending element consists of a silicone inner tube, polymer links, a TiNi SMA micro-coil actuator placed along the inner tube and a silicone outer tube. The external diameter of the employed TiNi SMA micro-coil actuator is 0.3 mm and the diameter of its wire is 0.07 mm. The SMA actuator is electrically connected to the controller by two electrical lead wires in the small lumen of the shaft.

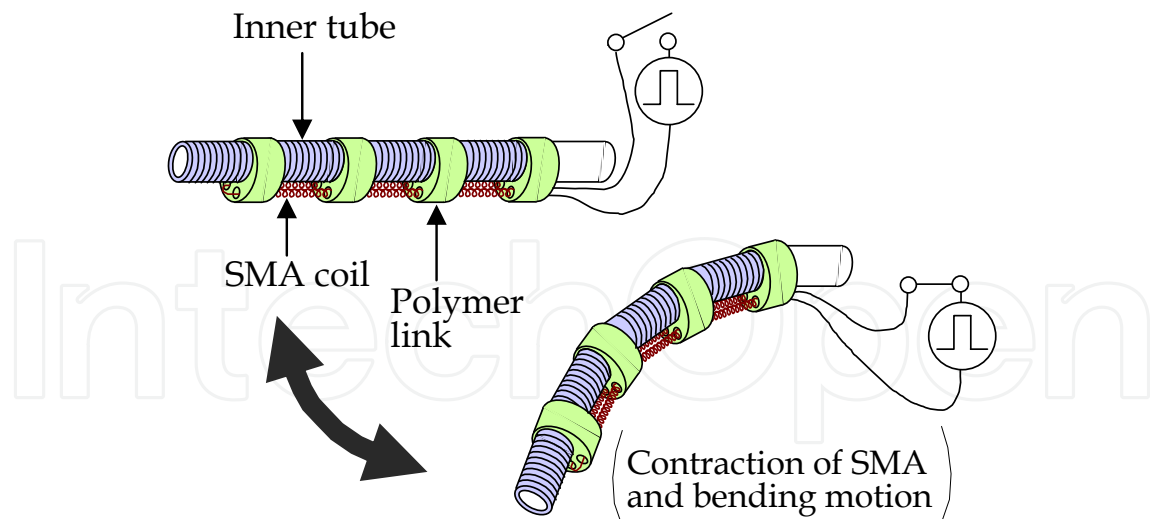


Fig. 11. Structure of active bending element of long intestinal tube

Fig. 12 shows the tip of the fabricated active bending LIT. The active bending LIT system consists of a one-directional 40-mm-long active bending tip with an external diameter of 6 mm, a 3-m-long main silicone tube with an external diameter of 5 mm and a battery powered controller for controlling the bending motion of the tip. The active bending tip is surrounded by a silicone rubber tube with six ring weights made of stainless steel for the conventional manipulation function using gravity, in addition to the active bending mechanism. Its bending angle is controlled by changing the duty ratio by pulse width modulation (PWM). Doctors can easily control the bending motion of the tip of the tube with a stick-type controller. The tube has a through hole as a working channel for insertion of a guide wire or injection of fluids (medicine or contrast medium). The active bending tip bends within 1 sec in 25°C air and maintains its bent shape by the flow of an electrical driving current. The maximum bending angle of the tip is 110 degrees and the radius of curvature is about 20 mm. The bending tip is flexible even if an electrical driving current is supplied and bends because of softness of the SMA micro-coil. A soft tip is preferable for safety operation in the human body. Stiffness of the tip can be evaluated by pushing in the longitudinal direction with a force gauge until flexion occurs. The measured force of a commercialized LIT was found to be 55.2 gf and that of the fabricated active bending LIT was 23.7 gf.

It is desirable that the surface temperature of any medical instrument used in the human body be 41°C or less. The surface temperature of the tip during active bending motion was measured under conditions of 38°C and 95% humidity simulating those in the stomach and the intestine. It takes 45 seconds for the surface temperature to rise over 41°C when the bending angle is maintained at 30 degrees.

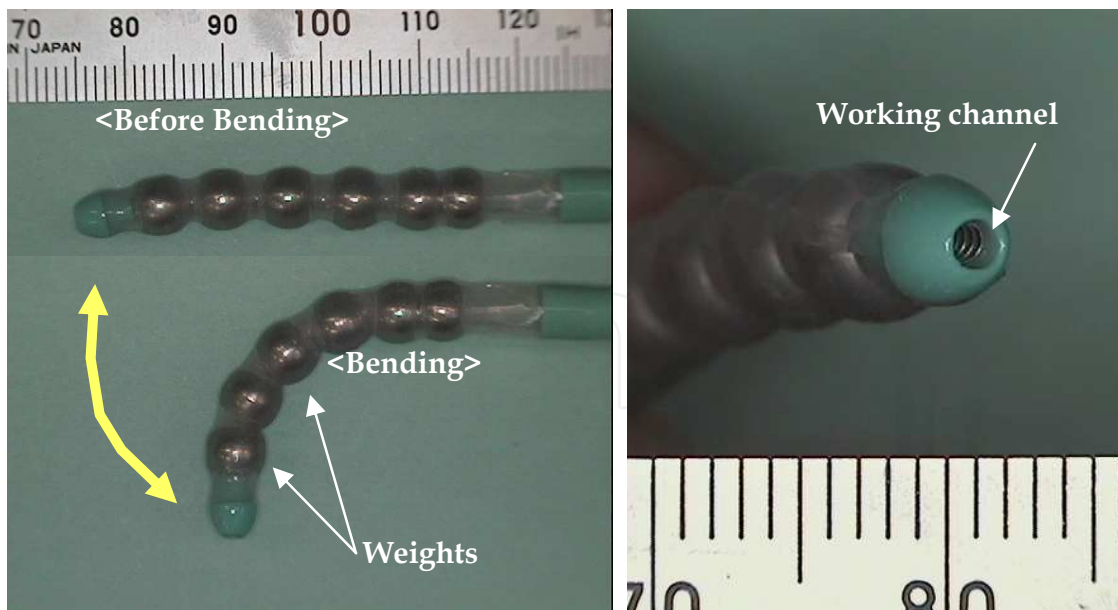


Fig. 12. Active bending tip of long intestinal tube (LIT)

5. Active Bending Electric Endoscope

Several flexible endoscopes are used in the esophagus, stomach, duodenum (gastrointestinal endoscopy), colon (colonoscopy), and ureter and kidney (ureteropyeloscopy). These endoscopes can be bent (deflected) by manipulation of wires from outside the human body. The tip of a conventional endoscope has a bending mechanism using wire traction from outside the body of a patient. The shaft of an endoscope should be relatively hard to avoid buckling by wire traction. Therefore, precise operation of the endoscope is difficult in complex shaped areas such as the intestine which has a complex structure and makes it difficult to manipulate the endoscope accurately.

One of the purposes of active bending endoscopes is insertion deep into the digestive tract, for example small intestine. The other purpose of active bending endoscopes is inspection deep area of the human body where conventional endoscopes which have relatively hard shaft is difficult to achieve.

A capsule endoscope can achieve inspection deep area of the human body but the capsule endoscope cannot be precisely controlled in position, especially in wide areas and the double-balloon endoscopes cannot be thin enough and be inserted from nasal cavity.

For colonoscopy, active steerable endoscopes which diameter is relatively big have been developed. To pass through the colon, which meanders with a small radius, a steerable endoscope with a diameter of 13 mm and incorporating SMA coil actuators has been developed. The SMA coil actuator contracts when heated by the application of an electrical current from outside the body. Consequently, contraction of the SMA coil bends the endoscope. The external diameter of the utilized SMA coil actuator is 1.0 mm and the diameter of its wire is 0.2 mm. Five bending segments are serially connected and controlled synchronously with an external servomotor which moves the endoscope back and forth

from outside the body (Ikuta et al., 1998). Unfortunately the bending mechanism doesn't have any imager. A steerable tip with a CMOS (Complementary Metal Oxide Semiconductor) imager has also been developed using SMA coil actuators. The external diameter of the utilized SMA coil actuator is 0.7 mm and the diameter of its wire is 0.22 mm (Menciassi et al., 2002).

We have developed an active bending electric endoscope using SMA coil microactuators with a CCD (Charge Coupled Device) imager. The external diameter of the fabricated endoscope is 5.5 mm, the external diameter of the utilized SMA coil actuator is 0.3 mm and the diameter of its wire is 0.075 mm (Makishi et al., 2000). Three SMA coil actuators, which are extended (from their memorized shapes) and fixed in the endoscope, contract and bend in several directions. Bending angle and direction is controlled using joystick controller. The fabricated bending mechanism makes the shaft of the endoscope soft and thin (external diameter 5.5 mm), because SMA coil actuators are soft and traction wire is not used.

For more thin and short rigid area of the active bending endoscope a FPC (Flexible Circuit Board) like spiral cut cylindrical substrate for thin endoscope has been fabricated using laser processing on cylindrical substrates (Fig. 13). The fabricated cylindrical substrate consists of a spiral flexible part as a lead wire and a polymer spring of bending mechanism and circuit pattern for mounting CCD imager related parts. Fabrication process is shown in Fig. 14 (a). Metallization and patterning have been performed on a polyimide tube with 2 mm external diameter using maskless lithography techniques with a laser exposure/ablation system as shown in Fig. 14 (b). Cu layer is formed as a seed layer and a thick copper layer is electroplated after exposure and development of the resist. Fig. 15 shows a mounted CCD imager and electric components at a tip of the substrate. White LEDs for light guide are mounted at the tip of endoscope. As shown in Fig. 15 (b) the fabricated endoscope has a working channel at the side wall. The external diameter and length of the CCD imager part are 3.9 mm and 15 mm respectively. An inner diameter of working channel which is located on a side is 1.5mm. Bending motion and inspection using mounted CCD is demonstrated in a colon model as shown in Fig. 16. The maximum bending angle of the fabricated endoscope is 98 degrees (Curvature radius is 19.3 mm at 120 mA).

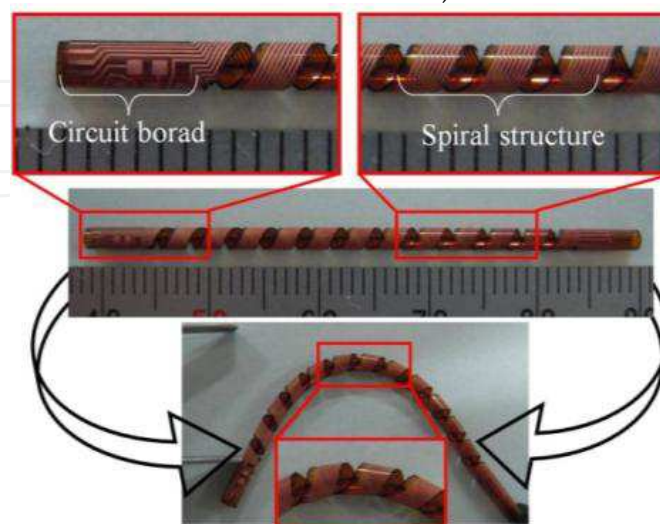
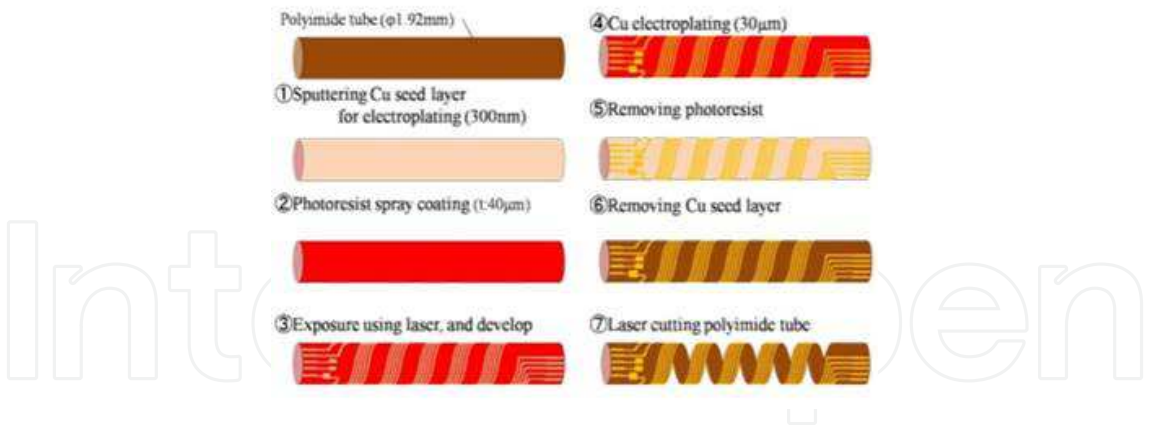
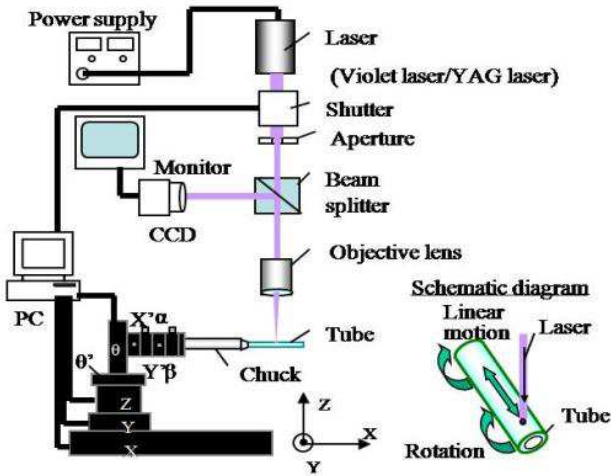


Fig. 13. Fabricated spiral polyimide substrate



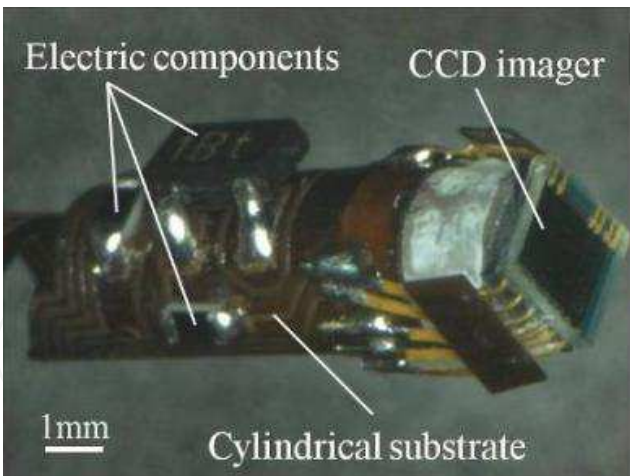
(a) Fabrication process of spiral substrate



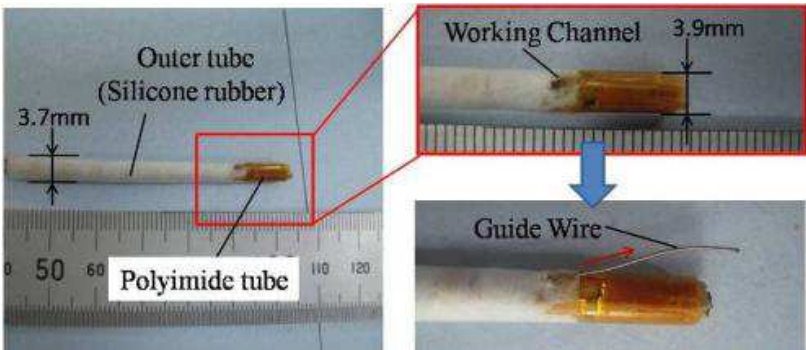
(b) Laser exposure system

Fig. 14. Fabrication process and exposure system

CMOS (Complementary Metal Oxide Semiconductor) imagers have become cheaper and have higher resolution by improvement of the semiconductor processing technology. For colonoscopy, active bending colonoscope with CMOS imager has been fabricated. Circular printed circuit boards were stacked for assembly imaging parts and LEDs as shown in Fig. 17. Fabricated active bending colonoscope is shown in Fig. 17. The external diameter and length of the bending part are 5 mm and 60 mm respectively. The external diameter and thickness of the CMOS imager part are 9 mm and 5 mm. Bending motion is controlled using controller as shown in Fig. 18. The maximum bending angle of the fabricated endoscope is 90 degrees (Curvature radius is 38 mm at 150 mA). Bending motion and inspection using CMOS imager were demonstrated in digestive tract model.



(a) Mounted CCD imager and electric components at a tip of substrate



(b) Fabricated endoscope with working channel and insertion of guide wire

Fig. 15. Fabricated small diameter active bending endoscope

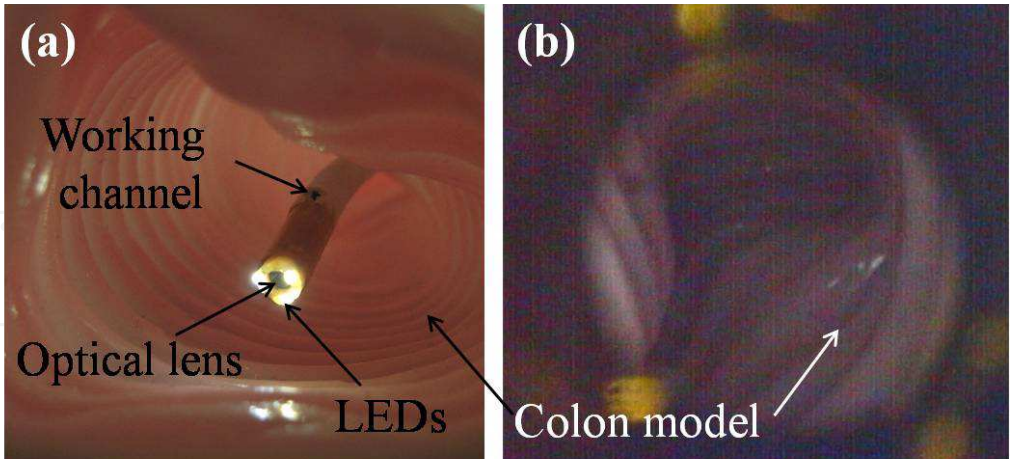


Fig. 16. Motion and inspection in digestive tract model

- (a) Inserted endoscope into a digestive tract model
- (b) Photograph of digestive tract model using CCD imager

Structure of a bending mechanism using SMA actuator is more simple than that using wires traction. Low cost disposable gastroscopes and colonoscopes can be realized using active steerable mechanism using SMA micro actuators.

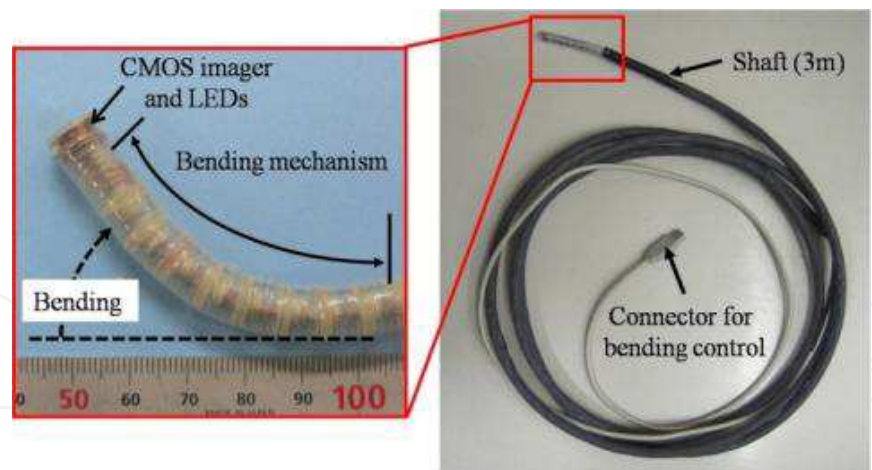


Fig. 17. Fabricated active bending colonoscope (external diameter, 10 mm)

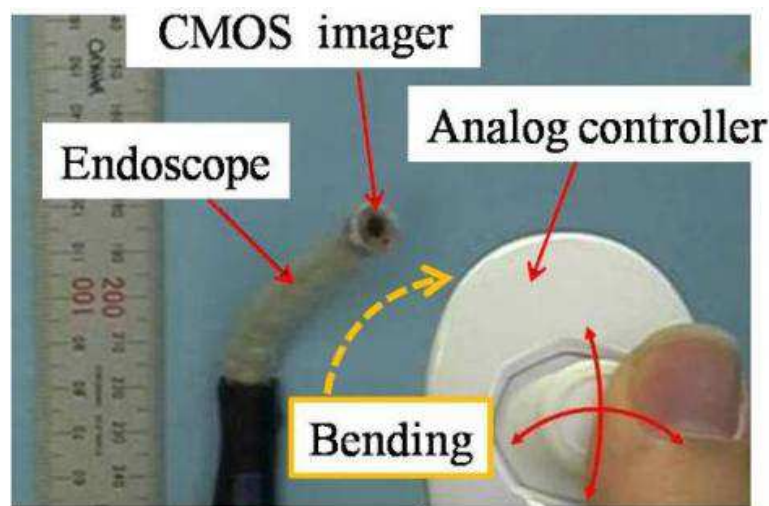


Fig. 18. Controller and bending actuation

6. Conclusion

SMA materials, particularly TiNi-based alloys, have excellent mechanical properties for actuators, such as large force generation and large deformation. Technical progress has resulted in the development of many SMA micro devices.

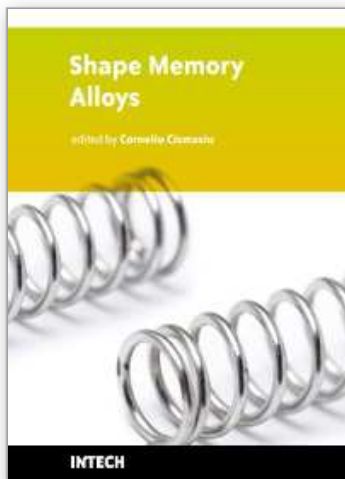
Medical applications of SMA micro actuator, namely, catheters and endoscopes are mentioned. Active catheters which have a bending mechanism using SMA wires, plates, spiral coil and meandering coil were described. And an active torsional, stiffness control mechanism and a bending mechanism for an active guide wire were described. Active bending endoscopes which have imager at the tip of bending mechanism were also mentioned.

SMA micro actuators have some disadvantages such as low displacement controllability and heat generation. However, thin, soft and low cost medical steering mechanism will effective for realization of active catheters and active endoscopes which enable easy insertion, inspection and precise treatment in the human body.

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In the last decades, the Shape Memory Alloys, with their peculiar thermo-mechanical properties, high corrosion and extraordinary fatigue resistance, have become more popular in research and engineering applications. This book contains a number of relevant international contributions related to their properties, constitutive models and numerical simulation, medical and civil engineering applications, as well as aspects related to their processing.

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