

# MICRO TUBE MANUFACTURING METHOD OF TUBE-SHAPED DILATATION MICROMANIPULATOR MADE OF SHAPE MEMORY POLYMER

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## 1 Introduction

There are shape-memory materials among advanced functional materials which have been developed recently. Above all, shape-memory alloys and a shape-memory polymer are proceeding toward practical utilization. A shape-memory polymer has low density compared to shape-memory alloys, and it is easy to deform as well as suitable for microminiaturization. A notable property of the shape-memory polymer is that its recovery distortion is more than 100 % while that of shape-memory alloys is only 6~8%[1]-[5]. This also indicates that a significant deformation of the shape-memory polymer is possible. The shape-memory polymer can be considered to be one of the most suitable materials for a micromanipulator, making use of the deformation property of materials.

This study presents a tube-shape dilatation micromanipulator made of a shape-memory polymer, which is suitable for microminiaturization. The manufacturing process of the tube and its heater is shown to explain the characteristics of the manipulator, as well as to point out its problems. Moreover, another new method to manufacture the tube of a uniform wall thickness is examined and presented to resolve the problems.

## 2 A proposal of a dilatation micromanipulator made of a shape-memory polymer

When a shape-memory polymer is heated and its temperature exceeds the glass transition temperature, it becomes as soft as rubber to be deformed significantly. After the temperature is lowered less than the glass transition temperature, the polymer becomes solid maintaining the changed shape. Moreover, it returns to its original shape when it is heated again and its temperature exceeds the glass transition temperature. The objective of this study is to develop a tube-shape dilatation micromanipulator 1mm in internal diameter and 100 mm long utilizing the properties of a shape-memory polymer mentioned above.

The manipulator proposed in this study is a tube of a shape-memory polymer to which a heater is attached as shown in Fig. 1. As shown in Fig. 2, when a part of the tube is heated with the heater and its temperature exceeds the glass transition temperature, it dilates due to the internal pressure, which causes the tube to bend. When the temperature is lowered, while maintaining the internal pressure, the changed shape is maintained. On the other hand, it restores its original shape when it is heated again, removing the internal pressure and its temperature exceeds the glass transition temperature.

The characteristic of this micromanipulator lies in that the large elastic deformation property of a shape-memory polymer is utilized in its deformation. This micromanipulator has a lot of advantages. It is easy to manufacture and assemble as well as suitable for microminiaturization because its shape is a simple tube. The arm section and end effector can be manufactured as a unit. It is actuated with its internal pressure without a built-in actuator, which makes microminiaturization possible. Moreover, it can be bent toward random positions or directions by devising a method of heating. Also, it can even be expanded and contracted.

## 3 Manufacturing of the tube

Casting, injection molding, and dip molding methods were tried and examined in manufacturing a shape-

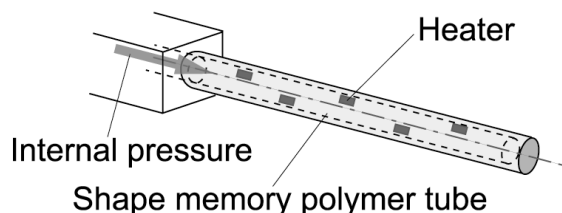


Fig. 1 Manipulator made of SMP

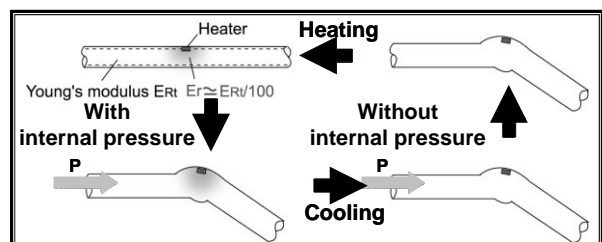


Fig. 2 Motion principle of SMP

memory tube as the body of the micromanipulator. By using the casting and injection molding methods, it was difficult to separate the tube from the moldings. Therefore, a dip molding method was adopted. The procedures are shown in Fig. 3. First, a wire was put through a Teflon tube, and a plummet was attached to the end of the wire to straighten the tube, which was dipped into a container filled with the shape-memory polymer. The tube was pulled up at a constant speed to be coated with the shape-memory polymer. After the tube was pulled out of the container, a solvent of the polymer on it was volatilized to make the polymer solid. When the polymer became solid enough, the Teflon tube inside was pulled out of it, which completed the process of making a shape-memory polymer tube. An external view and a section view of the tube 1 mm in internal diameter made using the dip molding method are shown in Fig. 4.

#### 4 Heating experiment at a joint part of the manipulator

As shown in Fig. 5(a), a type of energized heater, which makes the joint section of the manipulator, was experimentally manufactured by soldering a copper wire on a Nichrome foil 1-mm square and 20 $\mu$ m thick in order to examine the heating method. The heater was glued to the polymer tube mentioned above, and an actuating experiment was conducted. The relationship between the passed current and the temperature at the experiment is shown in Fig. 5(b). As a consequence, a film of the polymer tube ruptured at the end of the portion where the heater was glued.

It is conceivable that it was because a stress concentration arose in the area where hard Nichrome was glued to soft polymer, which caused an inadequate heat distribution, and the wall thickness of the tube was not uniform.

#### 5 Problems in manufacturing a polymer tube

In manufacturing polymer tubes using the dip molding method, there were problems. Knots were sometimes generated against the axial direction of the tubes as shown in Fig. 6(a). Even if knots were not generated, the wall thickness of some tubes was not uniform and their cross sections were eccentric. It is conceivable that this could be due to the viscosity of the polymer and pulling-up speed. Also, the humidity in the manufacturing environment is considered to have an influence on the tube. As shown in Fig. 6, a whitish part was generated on some polymer tubes, which could be due to the humidity while being manufactured.

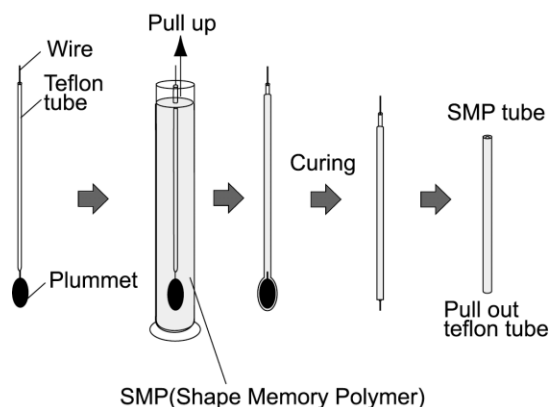
Therefore, it was decided that the viscosity of polymer, pulling-up rate, temperature and humidity should be controlled in manufacturing the tubes to resolve the problems mentioned above.

#### 6 Dip molding equipment

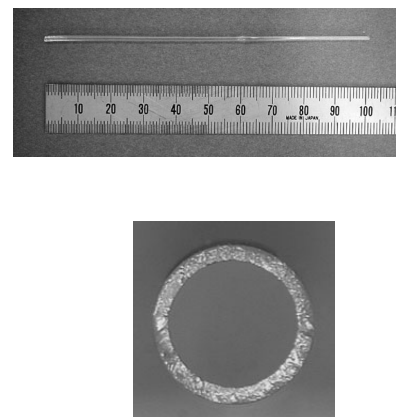
A diagrammatic sketch of the new dip molding equipment is shown in Fig. 7. The equipment consists of the pulling-up segment and the environmental controlling segment.

**Pulling-up segment:** A wire sticking out of a Teflon tube dipped in the shape-memory polymer is attached to a ball screw on the mobile part of the equipment. The tube is pulled up with the ball screw actuated by a stepping motor. The tube can be pulled up at a speed between 0.001 mm/s and 1 mm/s.

**Environmental controlling segment:** A container with the shape-memory polymer in it was placed in a thermostatic chamber made of an acrylic case covered with an insulator, in which the tube was dipped and then pulled up. A heater was set in the thermostatic chamber to control the temperature inside by turning on or off the current through the heater with a thermo-comparator. Also, a fan was set to make the temperature inside the chamber



**Fig. 3** Manufacturing method of tube



**Fig. 4** Trial manufactured tube

uniform. The temperature inside the chamber can be controlled between the room temperature and 80°C. Moreover, it was confirmed that the humidity inside the chamber can be controlled below 10% by sending nitrogen into it.

The new dip molding equipment manufactured experimentally is shown in Fig. 7. The left part of the figure shows the pulling-up segment (the upper part of the equipment) while the right part shows the thermostatic chamber as the environmental controlling segment (the bottom part of the equipment), in which the container with the shape-memory polymer is placed.

The pulling-up speed,  $V$  [mm/s] and the viscosity of shape-memory polymer,  $\mu$  [Pa·s] were used as parameters in manufacturing the tubes because they exert an influence on the wall thickness of the tubes. By varying these parameters, the tubes were manufactured as shown in Fig. 8, and their wall thickness was measured.

### 7 Examination of the wall thickness of new tubes according to the pulling-up speed and viscosity of polymer

Remarkable variations of the wall thickness in the axial direction among the measurement results are investigated. In the results, the horizontal axis indicates the distance between the top end of a polymer tube and a position of each cross section of the tube examined in the experiment. Each value is the measured wall thickness.

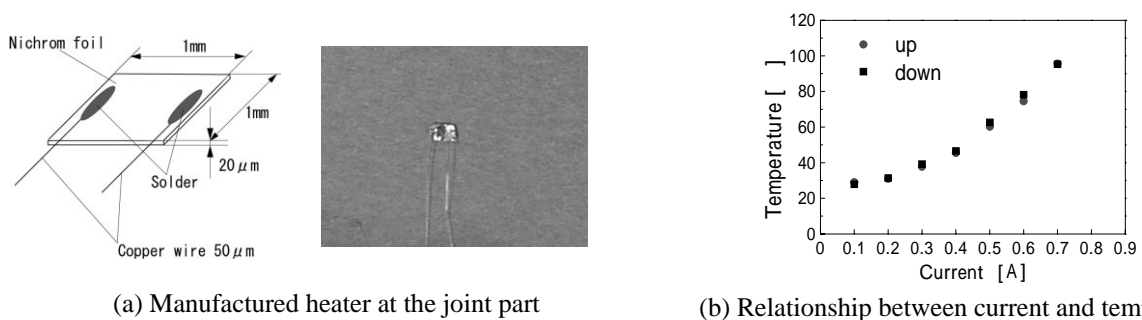


Fig. 5 Trial manufacturing of heater

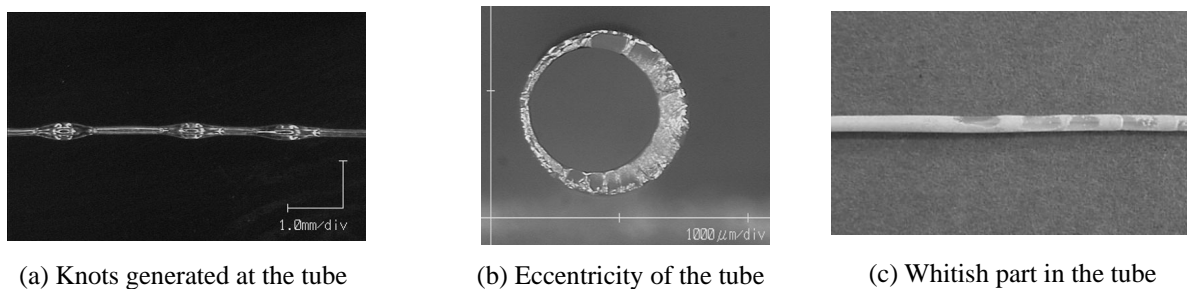


Fig. 6 Manufactured failure tube

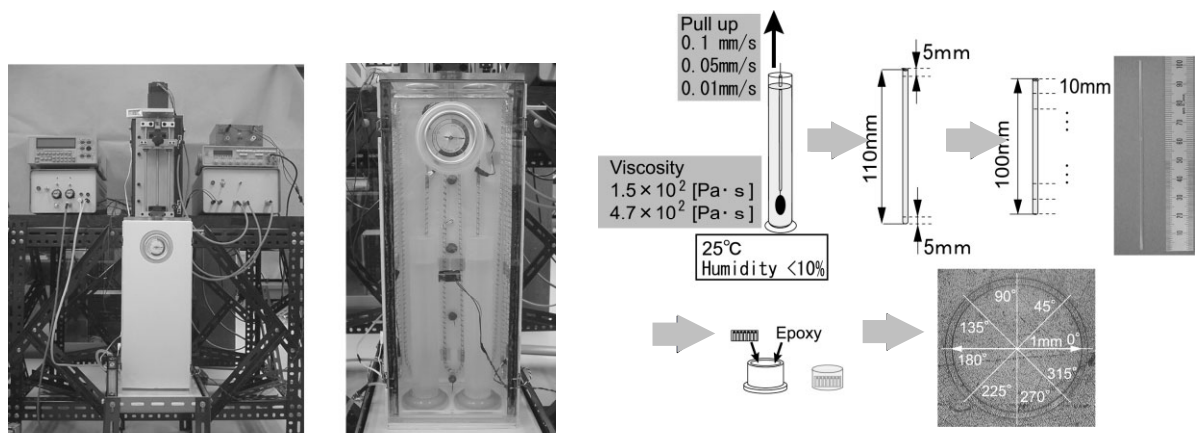


Fig. 7 Manufacturing machine of the new tube

Fig. 8 New tube manufacturing method and manufactured tube

When the viscosity of the polymer is high and the pulling-up speed is fast, specifically, the viscosity is  $4.7 \times 10^2$  Pa·s, and the speed is 0.1 mm/s, the wall thickness of tubes increases toward the bottom of the tube and its deviation increases from the top toward the bottom. On the other hand, the wall thickness and its deviation are constant when the viscosity is low and the pulling-up speed is slow, specifically, the viscosity is  $1.5 \times 10^2$  Pa·s, and the speed is 0.01 mm/s.

In order to compare the wall thickness of the tubes according to the different length of internal diameter, 300- $\mu$ m-internal diameter-polymer tubes 30 mm long were manufactured under the same manufacturing conditions as the 1-mm-internal diameter-tubes and their wall thickness were measured. The mean value and the deviation of the wall thickness are shown in Fig. 9 along with the results of the 1-mm-internal diameter-tubes. The results of the 300- $\mu$ m-internal diameter-tubes are shown in a dark color while those of the 1-mm-internal diameter-tubes are in a light color.

Polymer tubes manufactured when the viscosity was  $1.5 \times 10^2$  Pa·s and the pulling-up speed was 0.01 mm/s were too thin to measure their wall thickness. They deformed when they were dipped in epoxy resin. It was shown that the deviation was smaller as the internal diameter was shorter. Especially, when viscosity was  $4.7 \times 10^2$  Pa·s, the deviation of 1-mm-internal diameter tubes became large at a speed of under 0.05 mm/s while the deviation of 300- $\mu$ m-internal diameter-tubes was small. The average wall thickness of 300- $\mu$ m-internal diameter-tubes was thinner than that of the 1- mm-internal diameter-tubes. Moreover, the 100- $\mu$ m-internal diameter-tubes were experimentally manufactured under the same conditions as the 1-mm-internal diameter-tubes. Finally, a 100- $\mu$ m-internal diameter-tube was experimentally manufactured when the pulling-up speed was 0.01 mm/s and the viscosity was  $4.7 \times 10^2$  Pa·s. Its wall thickness was 11  $\mu$ m.

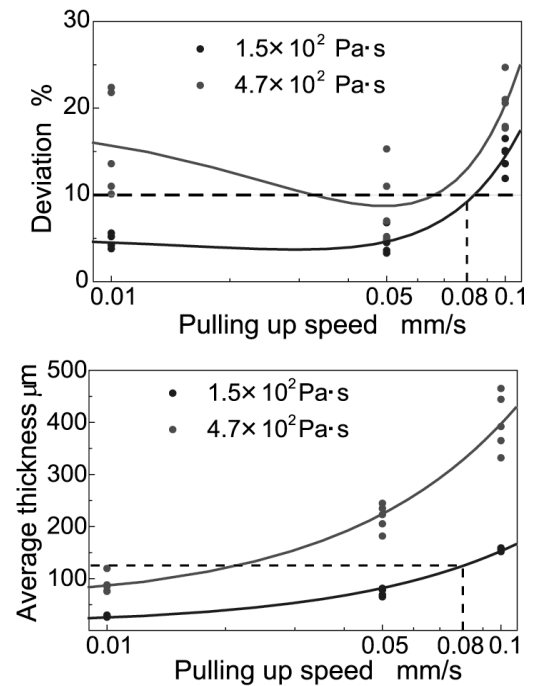
## 8 Conclusions

We have proposed and discussed the tube-shape dilatation micromanipulator made of the shape-memory polymer and the new tube manufacturing method to obtain the constant thickness tube. In the results, we have the following conclusions.

- (1) This study presented a dip molding method as a method of manufacturing shape-memory polymer tubes aiming at microminiaturization and pointed out the problem of their non-uniform wall thickness.
- (2) Dip molding equipment was experimentally manufactured, while taking account of the pulling-up speed, viscosity of the polymer, temperature and humidity in the manufacturing environment.
- (3) The relationship of the viscosity of the polymer and pulling-up speed with the wall thickness of tubes in manufacturing polymer tubes 1 mm in internal diameter and 100mm long was explained, and the manufacturing conditions to keep the deviation of the wall thickness below 10% were shown in this study. Under these conditions, the wall thickness was between 30  $\mu$ m and 120  $\mu$ m.
- (4) This study indicated that manufacturing polymer tubes 300 $\mu$ m and 100 $\mu$ m in internal diameter was possible under the same conditions as manufacturing 1- mm-internal diameter-polymer tubes.

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**Fig. 9** Average thickness and its deviation vs. pulling up speed of the tube