Shape memory alloy actuators and their reliability

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ABSTRACT

We have developed two types of shape memory alloy (SMA) actuator and estimated the long-term reliability of SMA microcoils. A tube type tip articulator consists of 4 sets of SMA microcoil (wire diameter: 0.125 mm, coil diameter: 0.5 mm) for driving source and super elastic alloy (SEA) microcoils (wire diameter: 0.1 mm, coil diameter: 0.5 mm) for bias springs, support plates and flexible outer tube. The tube type tip articulator was bent approximately 90 degrees in any directions when a 200 mA current was applied. The joint mechanism consists of base plate, universal joint, reflection plate (diameter: 170 mm), SMA microcoil springs (wire diameter: 0.1 mm, coil diameter: 0.9 mm) and bias spring. The joint mechanism showed good response for control values with maximum tilt angle of 3.2 degrees. We also estimated the thermal cycling behavior of SMA microcoil actuators with the resistance monitoring method. SMA microcoil actuators (wire diameter: 0.1 mm, coil diameter: 0.5 mm) were given 3.0% shear stress and heated by current. For 10,000 cycles, the force of SMA microcoil actuators was approximately constant and showed good long-term reliability. Since the results show good characteristics and reliability, SMA microcoil actuators can be used in a wide range of industrial and medical applications.

Keywords: shape memory alloy, micro actuator, micro coil, tip articulator, thermal cycling behavior

1. INTRODUCTION

When a micromachine works in narrow spaces inside tubules and equipment, micro actuators with large stroke and output power are required. SMA coil spring actuators are well suited to this purpose because of their large displacement compared with conventional actuators. In addition, because of their large output power per unit cross section and reduction of heat capacity due to micronization, response is improved. As a flexible actuator that performs expansion-contraction operation by heating and cooling, this device will be suitable for micro mechanisms.

In the fabrication of SMA coil springs, we examined fabrication conditions such as the tension and pitch of the SMA wire. As a result, we have successfully fabricated coil springs with a minimum outer diameter of 76 µm. SMA wire of 25 µm diameter and stainless steel wire of 30 µm diameter were used. As an application using SMA actuators, we developed an electrically and optically driven tip articulation mechanism for microfactories in our previous works. To put the SMA actuators to practical use, the heat cycling behavior may be important. Especially, R-phase of Ti-Ni alloy has very small hysteresis between the martensite-phase and austenite-phase. In R-phase transformation, we can monitor the state of the transformation of SMA from electric resistance because the electric resistance of SMA is proportional to temperature. Also, Ti-Ni is suited for electrical driving because of its comparatively high electric resistance. Therefore, it is very important to know the heat cycling behavior when the actuator is driven by an electric current.

In this paper, we present the design and characteristics of two types of SMA microcoil actuator: the tube type tip articulator and the joint mechanism. We also discuss the long-term reliability of SMA microcoil actuators with reference to thermal cycling behavior up to 10,000 heat cycles.

2. TIP ARTICULATION MECHANISM

In our previous works, we developed a tip articulation mechanism that consists of a tip articulator and SMA coil spring actuator. The actuator has two kinds of SMA coil spring: helical compressive springs used in the tip articulator
and close wound coil springs used in the SMA coil spring actuator. The schematic diagram of the tip articulation mechanism is shown in Fig. 1. The close wound coil springs are stretched, one end being fixed to the support plates, and the other edge fixed to the wires. The helical compressive springs are compressed between support plates. The principle of the mechanism is as follows: At room temperature, the two kinds of SMA coil spring are balanced and apply no force to the pull wire. When one SMA close wound coil spring on the actuator is heated with the backside SMA compressive coil springs on the tip articulator to restore their original shape, the displacement of the wire and force of the compressive coil springs bend the tip articulator. The same occurs in the opposite direction. As a result, the tip articulation mechanism was bent approximately 60 degrees and returned to the straight position when a current was applied to each of the SMA coil springs. But the part of the SMA coil spring actuator was comparatively long and rigid; for applying the mechanism to flexible devices, it was necessary to avoid making rigid parts.

3 FIBER-OPTIC ACTUATOR FOR TIP ARTICULATION

A fiberscope tip articulator is necessary to move the tip to the observation point. Although we have been developing a tip articulator using a shape memory alloy (SMA) coil spring, electric current drove it. For observing in humidity atmosphere and EMI immunity, it was necessary to improve the heating method.

For heating SMA coil spring, we have developed step-etched fiber (see Fig.2). The fiber irradiates light in direction of not only straight but also axis. The step-etched fiber is fabricated by chemical etching of hydrofluoric acid. Schematic diagram of fiber-optic actuator for tip articulation is shown in Fig.3. Laser diode (wavelength: 810nm, 1W) was used as light source. For the transmitting source, a laser fiber 400/500µm (core/clad) in
diameter was used. The light from step-etched fiber can heat SMA actuator more than Af. Using the optically driven SMA actuator, we have developed tip articulator for bending the tip of the environmental recognition device. Fig.4 shows that optically driven tip articulator was bent approximately 60 degrees and returned to the straight position when laser light was turned off.

4. LATCH MECHANISM AND FIBER-OPTIC SENSOR FOR MICROSCOPIC OBSERVATION

Latch mechanism wants holding rigid state a tip-articulator to measuring the dimensions of microparts. Heating all SMA close round coil springs and pulling all wires locks the tip-articulator (See Fig.5). Using the latch mechanism, we have developed microscopic observation system for fiberscope. Also a tactile sensor was developed for microscopic observation and measurement system. A fiber-optic tactile microsensor was attached to the tip of the latch mechanism. A cross-sectional view of the tactile sensor we designed is shown in Fig.6. The tactile sensor consists of optical fiber, rubber and steel ball/rod arranged in a SUS pipe of 0.6/0.36 mm outer diameter. The light through the optical fiber is reflected at the steel ball/rod surface. If the steel ball/rod contacts the object, the optical reflection intensity is modulated by displacement of the steel ball/rod7. The 0.1 mm thick polyurethane rubber was formed by KrF excimer laser ablation. The performance of the sensor is shown in Fig. 7. Resolution of touch sensing is less than 10mN. The results demonstrate that easy and safe tactile measurement is possible in narrow spaces. Three tactile sensors were assembled in this microscopic observation system. The systems consist of the tactile sensor, an ordinary fiberscope and a contact scope. Fig.8 is a cross-sectional view of the microscopic observation and measurement system. The contact scope does not have a focal lens on the tip of the image-guide fiber. Thus, if there is any distance between the image-guide fiber and target, the contact scope cannot obtain the image. However, when the tip of the image-guide fiber touches the surface of the target using latch mechanism, the microscopic image can be determined from the image-guide fiber.
An ordinary fiberscope obtains the far field image to direct the systems to the observation area. The contact scope obtains the near field image and can observe small structure even less than outer diameter of the contact scope.

5. TUBE TYPE TIP ARTICULATOR

A novel tube type tip articulator consists of 4 sets of SMA microcoil (wire diameter: 0.125 mm, coil diameter: 0.5 mm) as the driving source and super elastic alloy (SEA) microcoils (wire diameter: 0.1 mm, coil diameter: 0.5 mm) for the bias springs, support plates and flexible outer tube. A schematic diagram of the tube type tip articulator is shown in Fig.9. The SMA close wound coils are driven by electric current, so the support plates must be made of insulated material. Support plates made of polyamideimide were fabricated by excimer laser machining. The wavelength of machining beam was 248nm of KrF. A photograph of the support plate of 4mm outer diameter is shown in Fig.10. The flexible outer tube consists of stainless steel coil (wire diameter: 50 µm, coil diameter: 4.0 mm) and polyparaxylene thin film (thickness: 20 µm) was formed by thermal evaporation. A photograph of the flexible outer tube is shown in Fig.11.

Because the SMA coil springs are built into bending part of the tip articulator with SEA bias springs, there is no rigid part compared with our previous work shown in Fig.1. The fully flexible structure of the tip articulator allows it to be used for a very wide range of applications such as medical and industrial scopes. The tube type tip articulator was bent approximately 90 degrees in any direction when a 200 mA current was applied. Bending motion of the tip articulator is shown in Fig.12. Although the amplitude of the current was relatively large, it is thought that the current can be reduced. The SMA coil springs were controlled by the electric resistance feedback method. Thus, the tip articulator could be bent at any angle in any direction.
6. JOINT MECHANISM

We also applied the SMA microcoil actuator to a joint mechanism. Conventional joint mechanisms for robots used to be driven by motors and wires, but such mechanisms occupy a rather large volume and generate much noise. Application of the SMA microcoil actuator to the mechanism may make it significantly quieter, smaller and lighter compared with the conventional one. The joint mechanism that we have developed consists of a base plate, universal joint, reflection plate (diameter: 170 mm), SMA microcoil springs (wire diameter: 0.1 mm, coil diameter: 0.9 mm) and bias spring. Two laser position meters were attached to the base plate to measure the tilt angle of the reflection plate. A schematic diagram and photograph of the joint mechanism are shown in Fig.13 and Fig.14, respectively.

Nine SMA microcoils were electrically connected in series and mechanically connected in parallel (ξ-array). Both ends of each SMA microcoil were bound to a sleeve that was fabricated by YAG laser processing (wavelength: 1.06 μm). SMA actuators having high electric resistance and high power can be achieved by using the ξ-array. SMA microcoil units were attached to the joint mechanism of 42mm in length. The recovery force of the SMA microcoil unit was 2.6N. A schematic diagram of the SMA microcoil units is shown in Fig.15. Stainless steel springs (wire diameter: 0.7 mm, coil diameter: 6.4 mm) for the bias springs were also attached to the joint mechanism with SMA actuator units. Four sets of SMA actuator unit and bias spring make it possible to drive the joint mechanism in any direction. The bending
angle of the joint mechanism was controlled by the distance between the reflection and base plates from two laser position meters.

The SMA microcoil actuators were driven by a sine wave (T: 25-60s). The reflection plate circulated according to the period and magnitude of the applied sine wave. The laser position meter detected displacement between the reflection plate and base plate, and the SMA microcoil actuators were controlled based on the displacement. The motion of the reflection plate is shown in Fig.16. The motion of the reflection plate followed the sine-wave driving current at low frequencies, but to drive at a high frequency, it is necessary to improve the method of cooling the SMA actuators. As a result, the joint mechanism showed good response for control values with maximum tilt angle of 3.2 degrees.

7. THERMAL CYCLING BEHAVIOR OF SMA

To apply SMA microcoil actuators in practice, the cyclic behavior of SMA microcoil actuators is very important. H. Tobushi et al. 9) investigated the cyclic properties of SMA helical springs by applying heat cycles using hot water and air. But our applications mentioned above are driven by electric current and controlled electric resistance feedback. To estimate the thermal cyclic behavior of SMA microcoil actuators, it is necessary to apply the heat cycle by electric current. For this purpose, we developed a thermal cyclic test by electric resistance monitoring. A schematic diagram of the test equipment is shown in Fig.17.

The specimen was a Ti-Ni SMA microcoil, 0.1mm in wire diameter and 0.5mm in coil outer diameter. The number of windings of the coil was 150. The microcoil was heat-treated at 623 and 723 K for 1 hour in a furnace. After that, the specimens were attached to the heat cycle test equipment with 3.0% shear stress. Details of the specimens are shown in Table 1.

<table>
<thead>
<tr>
<th>No.</th>
<th>Composition (at%)</th>
<th>Heat Treatment Temp. (K)</th>
<th>Transformation Temperature (K)</th>
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<tr>
<td></td>
<td>Ni</td>
<td>Ti</td>
<td>Af</td>
</tr>
<tr>
<td>(1)</td>
<td>50.03</td>
<td>49.97</td>
<td>623</td>
</tr>
<tr>
<td>(2)</td>
<td>50.03</td>
<td>49.97</td>
<td>723</td>
</tr>
<tr>
<td>(3)</td>
<td>50.95</td>
<td>49.05</td>
<td>623</td>
</tr>
<tr>
<td>(4)</td>
<td>723</td>
<td>315.6</td>
<td>299.1</td>
</tr>
</tbody>
</table>

The SMA microcoils were heated by electric current while monitoring the electric resistance of the coils, then after heating, the SMA microcoils were cooled spontaneously. The thermal cycle was repeated up to 10,000 cycles. The change of generated force of the SMA microcoil is shown in Fig.18. Samples except for No.3 showed good reliability. Also, samples of Ti-49.95at%Ni SMA show better characteristics than samples of Ti-49.03at%Ni SMA. It is obvious from Fig.18 that the long-term reliability is closely related with the composition of Ti-Ni alloy and temperature of heat treatment. Figure 19 shows the relationship between electric resistance and force of the SMA microcoil. There is no difference between the initial state and after repeated thermal cycles. It is clear from Figs.18 and 19 that Ti-49.95at%Ni SMA shows excellent characteristics both in terms of generated force and electric resistance, hence it can be used in a wide range of applications for highly reliable actuators.
8. CONCLUSIONS

We have developed two types of shape memory alloy (SMA) actuator and estimated the long-term reliability of SMA microcoils. A tube type tip articulator was bent approximately 90 degrees in any direction when a 200 mA current was applied. The joint mechanism showed good response for control values with maximum tilt angle of 3.2 degrees. We also estimated the thermal cycling behavior of SMA microcoil actuators with the resistance monitoring method. For 10,000 cycles, the force of the SMA microcoil actuators was approximately constant and showed good long-term reliability. Since the results show good characteristics and reliability, SMA microcoil actuators can be used in a wide range of industrial and medical applications such as microfactories, powerplant maintenance and minimally invasive surgery.

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