Intelligent Shape Memory Actuators

Ryosuke Matsui, Kohei Takeda and Hisaaki Tobushi

Abstract The shape memory alloy has played an important role to develop the intelligent materials and structures. The shape memory polymer has also been used in practical applications. If the shape memory materials are applied into actuators, the novel intelligent shape memory actuators can be developed. In the present paper, the development of a functionally-graded shape memory alloy actuator, a functionally-graded shape memory polymer actuator and a shape memory composite actuator is discussed. The simple multi-way actuation can be developed by using the functionally-graded shape memory alloy wire and tape. The functionally-graded shape memory polymer board, showing a similar deformation property to a finger, can be applied to the elements coming into contact with body in the medical actuators. The three-way and three-dimensional actuators of simple mechanism can be developed by applying the shape memory composite with various kinds of shape-memory alloy and polymer.

Keywords Actuator • Shape memory alloy • Shape memory polymer • Functionally-graded material • Shape memory composite • Recovery stress

1 Introduction

In the intelligent materials, the development of shape memory alloy (SMA) has attracted high attention because the unique properties of the shape memory effect (SME) and superelasticity (SE) appear (Funakubo 1987; Duerig et al. 1990; Otsuka

---

R. Matsui (✉) · K. Takeda · H. Tobushi
Department of Mechanical Engineering, Aichi Institute of Technology,
1247 Yachigusa, Yakusa-cho, Toyota, Aichi, Japan
e-mail: r_matsui@aitech.ac.jp

K. Takeda
e-mail: k-takeda@aitech.ac.jp

H. Tobushi
e-mail: tobushi@aitech.ac.jp

Q. Sun et al. (eds.), *Advances in Shape Memory Materials*,
Advanced Structured Materials 73, DOI 10.1007/978-3-319-53306-3_10

and Wayman 1998; Tobushi et al. 2013a, b). If we use the SME and SE in practical applications, not only large recovery strain but also high recovery stress can be obtained. If we apply the recovery stress to the driving force, we can develop the novel SMA actuators. The main features of the SME and SE are induced due to the martensitic transformation (MT). In the shape memory materials, shape memory polymer (SMP) has also been developed (Hayashi 1993; Huang et al. 2012; Tobushi et al. 2013a, b). In SMP, large recovery strain of more than 100% can be obtained. The main features of SMP appear due to the glass transition. We can use not only the shape recovery and shape fixity but also recovery stress. We can therefore develop the novel SMP actuators by using the recovery stress.

Although elastic modulus and yield stress are large at high temperatures and small at low temperatures in SMAs, they are large at low temperatures and small at high temperature in SMPs. The dependence of rigidity and strength on temperature is therefore quite opposite between SMA and SMP elements. If the composite materials with SMA and SMP having different properties are developed, the new actuation properties of the material can be obtained (Murasawa et al. 2004, 2006; Tobushi 2006).

If the above-mentioned shape memory actuators are developed, the shape memory material works alone for measuring temperature and driving actuation. That is, sensors measuring temperature and motors or mechanical systems driving actuators are not necessary, and the simple mechanism can therefore be achieved.

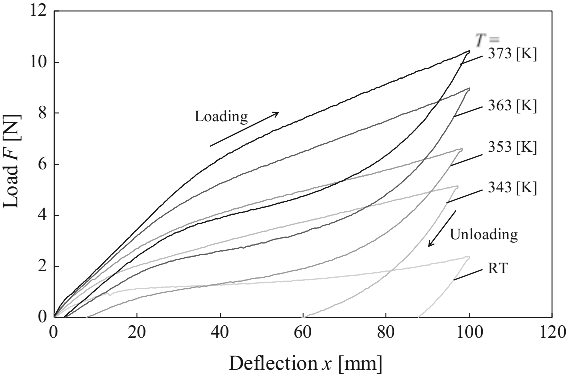
In the present paper, the development of the novel actuators using SMA and SMP will be investigated. First, based on the two-way SMA actuation, the multi-way SMA actuator and the functionally-graded SMA actuator will be discussed. Next, following the shape recovery SMP actuation, the functionally-graded SMP actuator will be considered. After that, based on the mechanical properties of SMA and SMP, the three-way actuation of the shape memory composite (SMC) will be developed and the new SMC actuator will be investigated. Finally, the subjects for development of shape memory actuators will be discussed.

2 Functionally-Graded SMA Actuator

2.1 Two-Way SMA Actuation

In order to understand the basic deformation properties of SMA, the force-deflection curves of the SMA helical spring obtained by the tension test at various temperatures T are shown in Fig. 1. The diameter of a TiNi SMA wire, the mean spring diameter, the number of active coils and the initial length of the coil were 0.7, 8.7, 6 and 4.2 mm, respectively. The loading rate was 4 mm/s and the maximum deflection was 100 mm. The reverse transformation finish temperature A_f obtained by the differential scanning calorimetry test was 360 K. As can be seen, the deformation resistance increases in proportion to temperature T. In the case of temperatures below A_f, the residual deflection appears after unloading. The residual

Fig. 1 Load-deflection curves of the SMA spring at various temperatures *T*

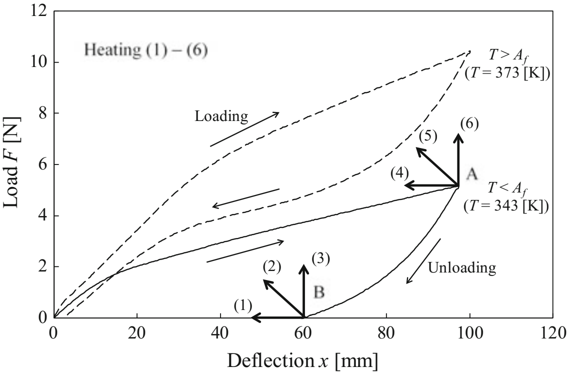


deflection disappears by heating under no-load, showing the SME. In the case of temperatures above A_f, the force-deflection curve draws a large hysteresis loop and the deflection disappears during unloading, showing the SE.

In order to understand the condition to use the driving force in the SMA actuators, the recovery force of the SMA spring which appears due to the reverse transformation by heating is shown on the force-deflection curves in Fig. 2. In Fig. 2, the various deformation behaviors (1)–(6) of the spring during heating from the maximum loading point A and the unloading finish point B at temperatures below the reverse transformation start temperature A_s are shown. The shape recovery under no-load (1) corresponds to the SME. The shape recovery under a constant force appears in the path (4). In the cases of perfect restriction of the deflection (3) and (6), the higher recovery forces appear than those in the cases (2) and (5) accompanying the shape recovery, respectively.

The typical two-way motion of the SMA spring is explained in Fig. 3. A dead weight *W* is hung on the spring at temperature $T < A_s$ and then the spring lengthens. If the spring is heated up to $T > A_f$ under the load *W*, the spring shrinks by a length *h*. The shrinking behavior corresponds to the shape recovery under a constant force in the path (4) shown in Fig. 2. Following the heating process, if the spring is

Fig. 2 Recovery forces of the SMA spring by heating subjected to various conditions (*1*)–(*6*)



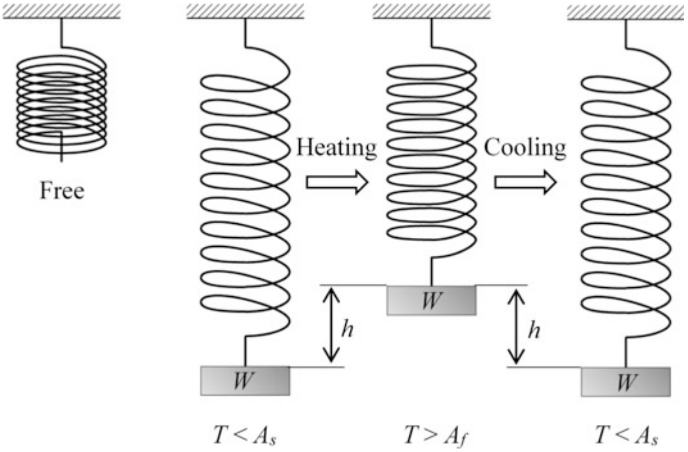


Fig. 3 Two-way motion of SMA coil

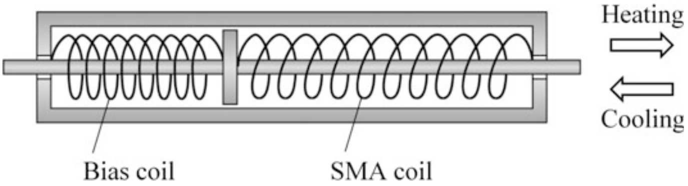


Fig. 4 Two-way actuation element using SMA coil and bias coil

cooled down to $T < A_s$, the spring lengthens by a deflection h. The two-way motion of the distance h is achieved during heating and cooling. The effective work Wh is obtained during the thermal cycling and it can be applied to the SMA heat engine as the driving source (Sakuma and Iwata 1998; Tobushi et al. 2010).

The two-way actuation element used in practical applications is shown in Fig. 4 (Funakubo 1987; Duerig et al. 1990). The SMA coil and a bias coil are arranged in series. The rigidity (spring constant) of the SMA coil is higher than that of the bias coil at $T > A_f$ and lower at $T < A_s$. The shaft in the element moves to the right during heating and to the left during cooling. The two-way motion x is therefore achieved during heating and cooling. The behavior of the SMA coil corresponds to the path (5) shown in Fig. 2.

2.2 Temperature-Dependent Continuous SMA Actuation

The rigidity (spring constant) of the SMA coil increases and the recovery force appears due to the reverse transformation during heating up to $T > A_f$. Based on this

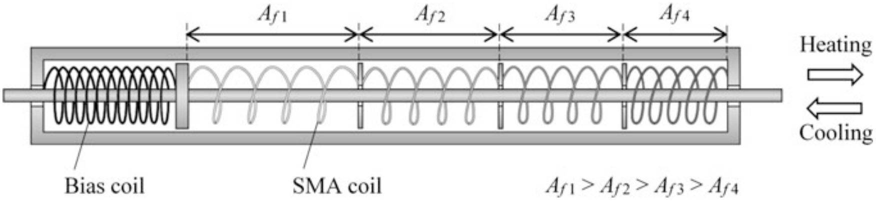


Fig. 5 Four-stepwise two-way actuation element using SMA coils with different reverse transformation temperatures and bias coil

property, the two-way stepwise actuation is obtained by the element shown in Fig. 4. If the SMA coils having different reverse transformation temperatures A_{f1}, A_{f2}, A_{f3}, A_{f4} and a bias coil are arranged in series as shown in Fig. 5, four-stepwise motion to the right can be achieved during heating up above A_f of each SMA coil. The shape recovery or recovery force appears at lower temperature during heating in the SMA coil having lower A_f. The continuous two-way motion can therefore be obtained by using the SMA coils having various transformation temperatures during heating and cooling.

2.3 Multi-way SMA Actuation

In SMA elements, the designated shape is memorized by the shape memory heat treatment (Funakubo 1987; Duerig et al. 1990; Otsuka and Wayman 1998). The memorized shape is recovered by heating after deformation due to the SME. The multi-way actuation of the SMA actuator is shown in Fig. 6. In the actuator, the SMA tape and the superelastic alloy (SEA) tape are laminated. The SMA tape is composed of six SMA elements having different transformation temperatures $A_{f1} - A_{f6}$ in which the various bent forms are shape-memorized. The flat form is

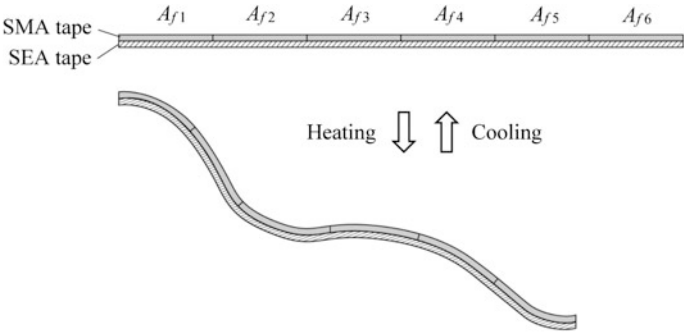


Fig. 6 Multi-way actuation of SMA actuator with SMA tape and SEA tape

shape-memorized for the SEA tape. The bending rigidity of the SEA tape is higher than that of the SMA elements at room temperature and the flat form is therefore obtained. The bending rigidity of the SMA elements becomes higher than that of the SEA tape during heating up to above A_f in each SMA element. The various memorized-shapes of SMA elements are recovered during heating. The flat form is regained during cooling. The multi-way motion is therefore obtained during heating and cooling.

2.4 *Functionally-Graded SMA Actuation*

As an example of the functionally-graded shape memory alloy (FGSMA), we developed a new fabrication process that combines powder metallurgy and hot extrusion as shown in Fig. 7 to obtain the FGSMA wire in which the transformation temperature varies from high to low along the wire axis (Matsui et al. 2012). First, a multilayered TiNi green compact in which the Ti–Ni compositions varied layer by layer was sintered using a spark plasma sintering process and then the compact was hot extruded into a wire. We used a characteristic that the phase transformation temperature of TiNi SMA changes depending on the composition of Ti and Ni (Funakubo 1987; Duerig et al. 1990; Otsuka and Wayman 1998).

Figure 8 shows the stress–local strain curves at three points of the hot extruded wire (Matsui et al. 2012). The wire shows the SE at the position that correspond to a Ni content of 51.0 at.% and the SME at the position of 50.4 at.% Ni. These differences appear to be based on the different MT temperatures at each position.

If the FGSMA wire or tape is developed, the temperature-dependent continuous actuation shown in Fig. 5 or the multi-way actuation shown in Fig. 6 can be obtained by using only one SMA coil or tape, respectively.

If the FGSMA tape is applied to a rotary driving element by using the torsional deformation of the tape, the FGSMA rotary actuator with a small and simple mechanism can be developed (Tobushi et al. 2013a, b).

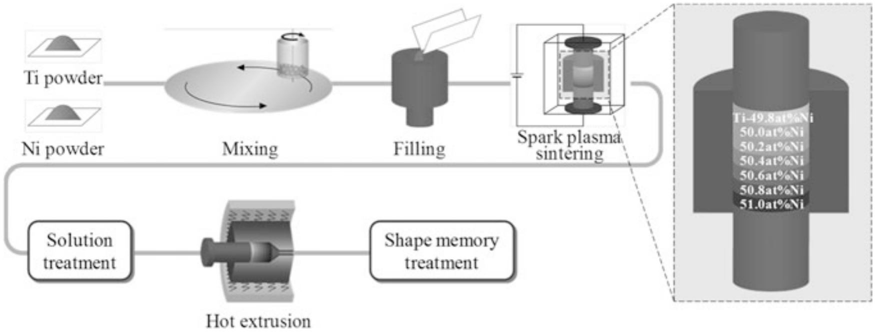


Fig. 7 Fabrication process and structure of FGSMA wire

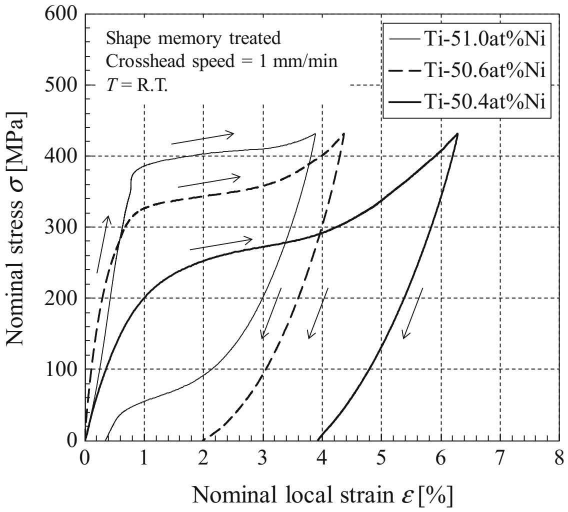


Fig. 8 Stress-local strain curves of the FGSMA wire at various Ni content positions

3 Functionally-Graded SMP Actuator

3.1 Shape Recovery SMP Actuation

In order to understand the basic deformation properties of SMP, the shape recovery actuation of SMP foam in compression is shown in Fig. 9. The corresponding stress-strain curves and stress-temperature curves of the polyurethane SMP under various strain rates dε/dt are shown in Fig. 10 (Tobushi et al. 2003). In the process (1), the SMP foam is compressed at temperature T_h above the glass transition temperature T_g. The lower the strain rate, the larger the maximum compressive strain is. In the case of low strain rate, the foam becomes dense under slow compression for a long time in the loading process (1), resulting in large compressive strain. In the cooling process down to temperature T_l below T_g (2), the deformed shape is held constant. The thermal contraction occurs and the compressive stress therefore decreases during cooling. The deformed shape is held under the stress-free condition at T_l. This property is called the shape fixity. If the deformed foam is heated up to temperature above T_g under the stress-free condition (3), the original

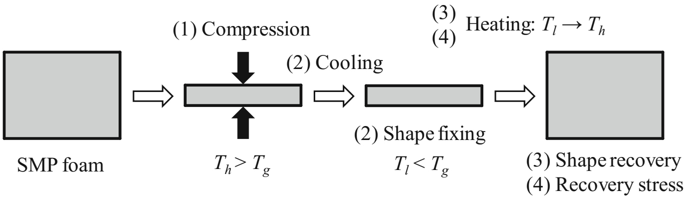


Fig. 9 Shape fixity, shape recovery and recovery stress of SMP foam in compression

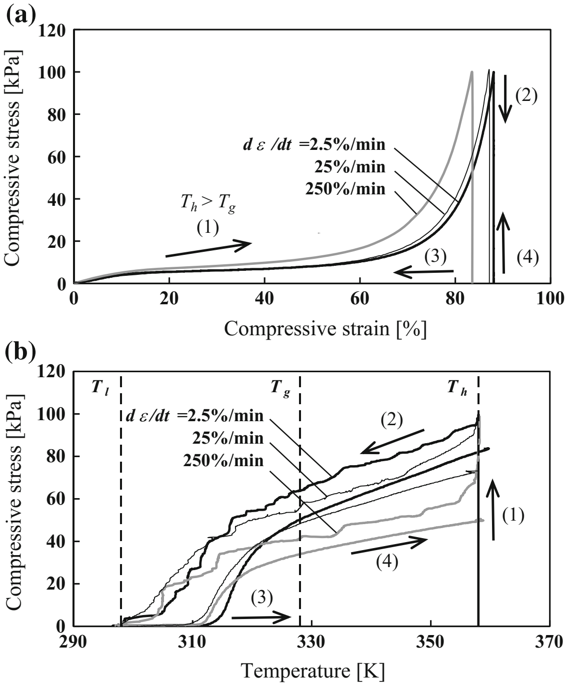


Fig. 10 **a** Stress-strain curves and **b** stress-temperature curves of SMP foam in compression under various strain rates dε/dt

shape is recovered. This property is called the shape recovery. If the foam is heated up to temperature above T_g by keeping the deformed shape (4), recovery stress increases during heating. The recovery stress is about 80% of the applied stress. The recovery stress is used as the driving force in the SMP actuator. Since large change in volume can be obtained for SMP foam elements, they can be applied to the easily portable energy sources to obtain the driving force. In the case of the SMP sheet and film in tension, the recovery stress obtained by holding the residual strain constant during heating is about 50% of the applied stress. In the case of SMP sheet and film in tension, the recovery stress also appears during cooling under the constant maximum strain due to the deformation resistance to thermal contraction and is about twice as large as the applied stress (Tobushi et al. 1997).

3.2 Functionally-Graded SMP Actuation

As an example of the functionally-graded shape memory polymer (FGSMP), the SMP foam elements having four glass transition temperatures T_{g1}, T_{g2}, T_{g3} and T_{g4} are laminated as shown in Fig. 11. The SMP foam having the low T_g is easily deformed. In the FGSMP foam, the element having lower T_g is highly deformed in compression (1). The deformed shape is fixed during cooling (2). If the shape-fixed

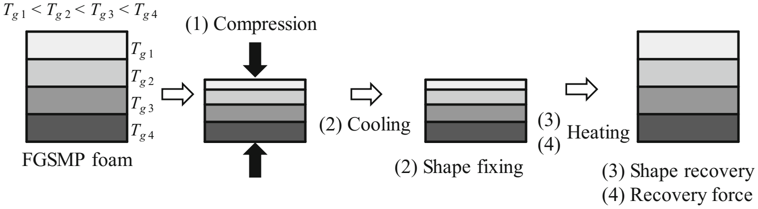


Fig. 11 Four-stepwise shape recovery and recovery force of FGSMP foam having various glass transition temperatures

foam is heated, four-stepwise shape recovery motion (3) or four-stepwise recovery force (4) can be obtained during heating. Since the SMP foam element having lower T_g is easily deformed, the shape recovery or recovery force appears at lower temperature during heating. The continuous shape recovery motion can therefore be obtained by using the FGSMP foam having various glass transition temperatures during heating and cooling. We note that the deformation properties of the SMP foam in compression depend not only on T_g but also on expansion ratio and cell structure (Gibson and Ashby 1999).

The polyurethane SMP foam and sheet having different glass transition temperatures T_g were laminated and the FGSMP board was fabricated. The photograph and structure of the SMP board are shown in Fig. 12. Two SMP foams of thickness 5 mm with $T_g = 298$ K and two SMP sheets of thickness 2 mm with $T_g = 308$ and 328 K were laminated. The indentation test was carried out for the FGSMP board. The relationship between force and depth obtained by the test for a maximum force of 5 N in five cycles is shown in Fig. 13. In Fig. 13, the result for a finger of a young man is also shown. As can be seen, with respect to the finger, force increases till a depth of 3 mm and the slop of the curve becomes gradually steep thereafter during loading. Force decreases in the unloading process accompanying a large hysteresis loop of the force-displacement curve in the loading and unloading processes. The relationship of the FGSMP board is similar to that of the finger. The deformation properties of the body differ depending on the region. The FGSMP board corresponding to each region can be developed by the combination of the sheet and foam with appropriate thickness, glass transition temperature and their arrangement. The FGSMP board can therefore be applied to the elements coming into contact with body in the medical actuators.

Fig. 12 **a** structure and **b** Photograph of FGSMP board

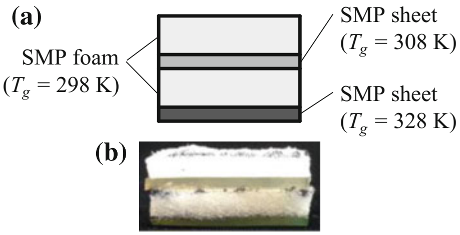
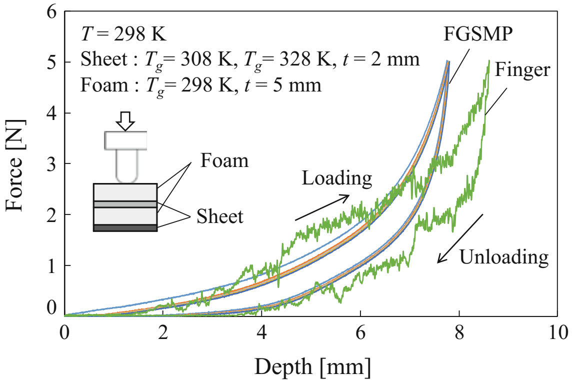


Fig. 13 Indentation curves of FGSMP board and finger



4 Shape Memory Composite Actuator

4.1 *Characteristics of Shape Memory Composite with SMA and SMP*

In order to discuss the characteristics of shape memory composite (SMC) with SMA and SMP, the dependence of elastic modulus of SMA, SMP and steel on temperature and that of yield stress are shown in Figs. 14 and 15, respectively. The symbols σ_M and σ_A represent the MT stress and reverse transformation stress, respectively. Elastic modulus and σ_M are small at temperatures below A_s and large above A_f in SMAs. The stress σ_A appears above A_f. Both σ_M and σ_A increase in proportion to temperature (Funakubo 1987; Duerig et al. 1990; Otsuka and Wayman 1998; Tobushi et al. 2013a, b). If steel is used as a bias element in combination with SMA element in the temperature region above and below A_f, the two-way shape memory effect (TWSME) can be achieved by heating and cooling as discussed in Sect. 2.1.

On the other hand, elastic modulus and yield stress are large at temperatures below T_g and small above T_g in SMPs. The dependence of rigidity and strength on

Fig. 14 Dependence of elastic modulus on temperature for SMA, SMP and steel

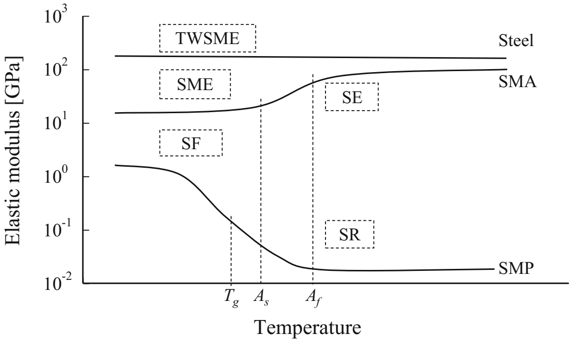
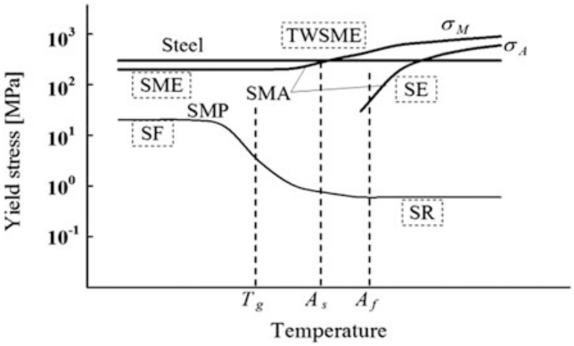


Fig. 15 Dependence of yield stress on temperature for SMA, SMP and steel

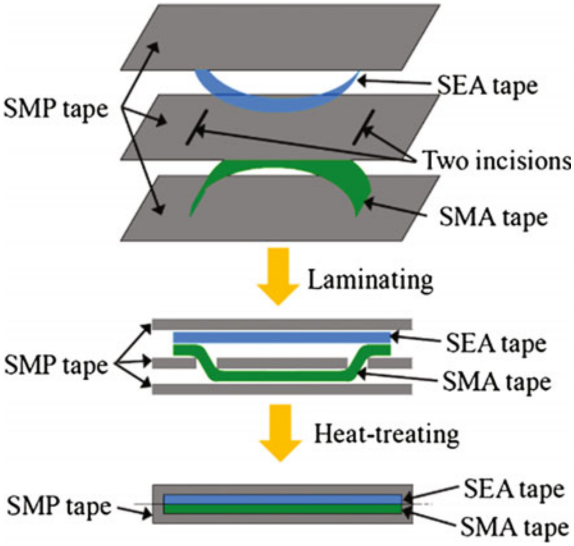


temperature is therefore quite opposite between SMA and SMP elements. If the composite materials with SMA and SMP having different properties are developed, the new actuation properties of the material can be developed.

4.2 *Three-Way Shape Memory Composite Actuation*

The SMC belt was fabricated by using two kinds of shape memory alloy tapes and three SMP tapes (Tobushi et al. 2011). The glass transition temperature of the SMP tape was between the phase transformation temperatures of the SMA tape and SEA tape. The SMA tape and SEA tape were arranged facing in the opposite directions for the memorized round shape as shown in Fig. 16. The SMP tape passed through

Fig. 16 Arrangement of SMA, SEA and SMP tapes for laminating and heat-treating SMC belt



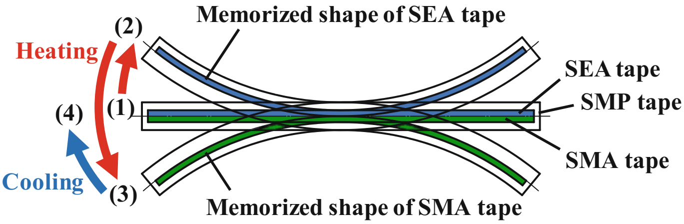


Fig. 17 Principle of three-way bending behavior in SMC belt during heating and cooling

the SMA tape and the SEA tape were sandwiched between two SMP tapes from upper and lower sides. The laminated material was set in the mold for heat-treating of the SMC belt.

The principle of the three-way (reciprocating) bending actuation in the SMC belt during heating and cooling is shown in Fig. 17. The SMC belt bends to convex downwards (in the direction of the memorized round shape of the SEA tape) by the recovery force of the SEA tape during heating (1)–(2). It bends to convex upwards (in the direction of the memorized round shape of the SMA tape) by the higher recovery force of the SMA tape at higher temperature (2)–(3). It regains its original shape during cooling (3)–(4).

The photographs of the bending motion of the fabricated SMC belt during heating and cooling are shown in Fig. 18. As can be seen, the three-way (reciprocating) bending actuation can be obtained by a simple SMC structure.

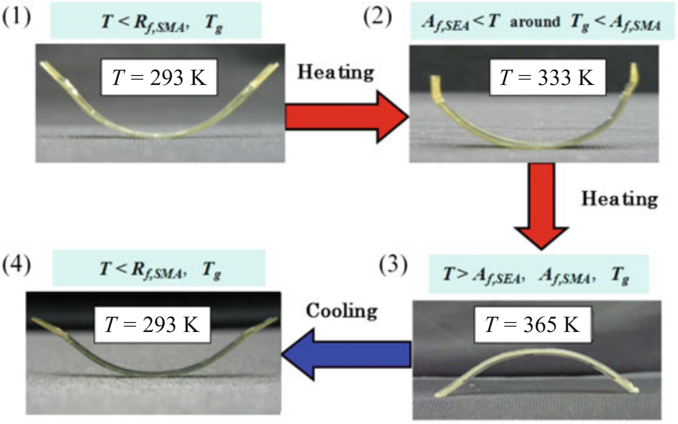


Fig. 18 Photographs of three-way bending motion of SMC belt during heating and cooling

4.3 Three-Dimensional Shape Memory Composite Actuation

The actuation properties of the SMC belt vary depending on the combination of the SMA and SMP elements with various phase transformation temperatures, volume fractions, structural compositions and heating-cooling rates. Various kinds of multi-way actuators can therefore be developed by using these combinations. The cyclic deformation properties and strength of the interfaces between alloy and polymer are important for development of SMC actuators. They are the future subjects.

The three-way bending actuation of the SMC belt observed in Fig. 18 exists in a certain plane. The axes of the SMA and SEA tapes in the SMC belt are in the same plane. If the axes of the SMA wires or tapes in the SMC sheet are arranged in various directions, the SMC sheet bends in the various planes. That is, the three-dimensional actuations can be achieved by using these combinations.

The development and application of multi-functional SMC actuators with simple structure for the three-dimensional actuation are therefore highly expected.

5 Subjects for Development of Shape Memory Actuators

In order to develop the proposed shape memory actuators, the main subjects to be solved are as follows.

5.1 Cyclic Deformation and Fatigue Properties

Actuators work repeatedly in practical applications. The constant deformation properties are requested under cycling. The conditions to use the stable deformation properties are therefore necessary to be clarified. With respect to actuators used for a long time, the fatigue property is very important in all actuators. The high-fatigue strength SMA and SMP are necessary to be developed.

5.2 Interface Properties

In FGSMA, FGSMP and SMC actuators, there exist interfaces among SMA, SMP and other materials with different properties. In general, the micro-structure of the interface between two materials is different from each element and the stress concentration therefore occurs under deformation, resulting in reduction of strength.

It is important to develop the fabrication method to increase strength of the interface between various elements in each actuator.

5.3 Multi-axial Deformation Properties

The deformation properties of shape memory materials are complex since the functional properties appear due to the phase transformation and they depend on the thermomechanical hysteresis. In particular, the deformation properties under multi-axial stress are very complex (Nishimura et al. 2000; Tokuda et al. 1998). Although they are complex, we can use them to novel actuators. One possible application is as follows. By using one SMA shaft, both axial and rotational motions can be achieved simultaneously during heating and cooling. That is, we can develop actuators with very simple structure. It is necessary to clarify the deformation properties of SMA and SMP under multi-axial stress for the development of these actuators.

6 Conclusions

If the shape memory alloy and shape memory polymer are applied into actuators, the novel intelligent shape memory actuators can be developed. In the present paper, the development of a functionally-graded shape memory alloy actuator, a functionally-graded shape memory polymer actuator and a shape memory composite actuator was discussed. The main points confirmed are as follows.

(1) With respect to the shape memory alloy actuators, based on the two-way shape memory effect, the temperature-dependent continuous and multi-way actuations can be obtained by using various shape memory alloys with different phase transformation temperatures. The simple multi-way actuator can be developed by using the functionally-graded shape memory alloy wire and tape.
(2) With respect to the shape memory polymer actuators, based on the shape recovery and recovery stress, the temperature-dependent continuous actuation can be obtained by using various shape memory polymers with different glass transition temperatures. The functionally-graded shape memory polymer board, showing a similar deformation property to a finger, can be applied to the elements coming into contact with body in the medical actuators.
(3) With respect to the shape memory composite actuators, by the combination of various kinds of shape-memory alloy and polymer, the three-way actuation and three-dimensional actuation can be obtained.
(4) If the functionally-graded shape memory alloy and polymer actuators and the shape memory composite actuator are developed, the shape memory materials

work alone for measuring temperature and driving actuation. The simple mechanism without sensors measuring temperature and motors or mechanical systems driving actuators can therefore be achieved.

(5) The subjects for development of the shape memory actuators are to develop high-fatigue strength shape memory alloy and polymer and to find the fabrication method to increase strength of the interface among shape memory alloy, polymer and other materials.

Acknowledgements The experimental work for this study was carried out with the assistance of students in Aichi Institute of Technology, to whom the authors wish to express their gratitude. The authors also wish to extend thanks to the administration of Scientific Research (C) in Grant-in-Aid for Scientific Research by the Japan Society for Promotion of Science for financial support.

References

Duerig TW, Melton KN, Stockel D, Wayman CM (1990) Engineering aspects of shape memory alloys. Butterworth-Heinemann, London

Funakubo H (ed) (1987) Shape memory alloys. Gordon and Breach Science Publishers, New York

Gibson LJ, Ashby MF (1999) Cellular solids structure and properties, 2nd edn. Cambridge University Press, Cambridge

Hayashi S (1993) Properties and applications of polyurethane series shape memory polymer. Int Prog Urethanes 6:90–115

Huang WM, Yang B, Fu YQ (2012) Polyurethane shape memory polymers. CRC Press, Boca Raton

Nishimura F, Watanabe N, Tanaka K (2000) Evolution of martensite start condition in general thermomechanical loads of Fe-based shape memory alloy. Int J Mech Sci 42:347–365

Matsui R, Osumi T, Shintani K, Kyogoku H, Yoshida F (2012) Fabrication of a functionally graded TiNi shape memory alloy wire by powder metallurgy and plastic working (2nd Report, functionally graded properties of extruded wire). Trans Japan Soc Mech Eng Ser A 78:1189–1197 (in Japanese)

Murasawa G, Tohgo K, Ishi H (2004) Deformation behavior of NiTi/polymer shape memory alloy composites—experimental verification. J Compos Mater 38:399–416

Murasawa G, Tohgo K, Ishi H (2006) The effect of fiber volume fraction and aspect ratio on the creation of internal stress in the matrix and deformation for short-fiber shape memory alloy composite. Smart Mater Struct 15:33–40

Otsuka K, Wayman CM (eds) (1998) Shape memory materials. Cambridge University Press, Cambridge

Sakuma T, Iwata U (1998) Working characteristics of s reciprocating-type heat engine using shape memory alloys. JSME Int J Ser B 41:344–350

Tobushi H, Date K, Miyamoto K (2010) Characteristics and development of shape-memory alloy heat engine. J Solid Mech Mater Eng 4:1094–1102

Tobushi H, Hashimoto T, Hayashi S, Yamada E (1997) Thermomechanical constitutive modeling in shape memory polymer of polyurethane series. J Intell Mater Syst Struct 8:711–718

Tobushi H, Hayashi S, Hoshio K, Makino Y, Miwa N (2006) Bending actuation characteristics of shape memory composite with SMA and SMP. J Intell Mater Syst Struct 17:1075–1081

Tobushi H, Hayashi S, Pieczyska EA, Date K, Nishimura Y (2011) Three-way actuation of shape memory composite. Arch Mech 63:443–457

Tobushi H, Matsui R, Takeda K, Pieczyska EA (2013a) Mechanical properties of shape memory materials. Nova Science Publishers, New York

Tobushi H, Pieczyska EA, Miyamoto K, Mitsui K (2013b) Torsional deformation characteristics of TiNi SMA tape and application to rotary actuator. J Alloys Compd 577S:S745–S748

Tobushi H, Shimada D, Hayashi S, Endo M (2003) Shape fixity and shape recovery of polyurethane shape-memory polymer foams. Proc Inst Mech Eng 217, Part L: J Mater: Des Appl 135–143

Tokuda M, Ye M, Takakura M, Sittner S (1998) Calculation of mechanical behaviors of shape memory alloy under multi-axial loading conditions. Int J Mech Sci 40:227–235