Fabrication and Three-way Bending Motion of Shape-memory Composite Belt*

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Abstract
The Shape Memory Composite (SMC) belt composed of two kinds of SMAs with different phase transformation temperatures and SMP was fabricated and the three-way (reciprocating) movement in bend actuation were investigated. The results obtained can be summarized as follows. (1) Two SMAs (showing shape memory effect and superelasticity) and three SMPs were used for fabrication. The shape-memorized round alloy tapes were arranged facing in the opposite direction and were sandwiched by one SMP tape in the central part and by two SMP tapes from upper and lower sides. The laminated SMC belt was fabricated without bubble and gap by using the appropriate factors. (2) The three-way bend movement was achieved during heating and cooling based on the characteristics of the SMA tapes and the SMP tape. (3) By the combination of the SMAs and the SMPs, the development and application of multi-functional SMCs with simple structure for three-dimensional actuators are highly expected.

Key words: Shape Memory Alloy, Shape Memory Polymer, Shape Memory Effect, Superelasticity, Composite, Three-Way, Bending

1. Introduction

The shape memory alloys (SMAs) are fascinating new functional materials as smart materials (1)-(3). The shape memory polymer (SMP) has been also practically used (4)-(6). In SMAs, the shape memory property appears based on the martensitic transformation (MT) in which the crystal structure varies depending on the variation in temperature and stress. In SMAs, the elastic modulus and the yield stress are low at temperatures below the reverse transformation start temperature \( A_s \) and high at temperatures above the reverse transformation finish temperature \( A_f \). If SMAs are deformed below \( A_f \), residual strain appears after unloading and the residual strain disappears by heating under no load, showing the shape memory effect (SME). If SMAs are deformed above \( A_f \), strain is recovered during unloading, showing the superelasticity (SE). Strain of 8% is recoverable and the high recovery stress can be used. The properties of energy storage and dissipation can be also used (7). Among the SMAs, the TiNi SMA shows excellent fatigue strength (8).

In SMPs, the elastic modulus and the yield stress are high at temperatures below the glass transition temperature \( T_g \) and low at temperatures above \( T_g \). If SMPs are deformed at temperatures above \( T_g \) and cooled down to temperatures below \( T_g \) by holding the deformed
shape constant, the deformed shape is fixed and SMPs can carry large load. This property is called the shape fixity (SF). If the shape-fixed SMP element is heated up to temperatures above \( T_g \) under no load, the original shape is recovered. This property is called the shape recovery (SR). The shape memory property appears based on the glass transition in which the characteristics of molecular motion vary depending on the variation in temperature. Among the SMPs, the polyurethane SMP with sheet, film, foam and other forms has been practically used and strain of several hundred percents is recoverable \(^9\).

In order to use new and higher functions by combining the excellent qualities of both the SMA and the SMP, the development of the shape memory composite (SMC) with the SMA and the SMP is expected \(^{10-13}\). If the SMP is used as the matrix in the SMC and the SMA as the fiber, the following properties can be obtained in the SMC. (1) The deformed shape is recovered at high temperature and (2) the deformed shape is held, (3) large load can be carried at low temperature and (4) the multi-way motion is achieved during heating and cooling. By combining the SMA and the SMP, the SMC element can be developed as demonstrated by Tobushi et al\(^{14,15}\).

In the present paper, the fabrication and mechanical properties of the SMC belt composed of two kinds of SMAs with different phase transformation temperatures and SMP which shows the three-way (reciprocating) motion depending on temperature variation are investigated. With respect to the characteristics of the SMC belt, the bend movement with the three-way property are discussed. The development and application of multi-functional SMC actuator with simple structure are also discussed.

2. Fabrication of SMC belt for three-way motion

2.1 Materials

With respect to the SMAs, two kinds of polycrystalline TiNi alloy tapes showing the SME and SE at room temperature were used. The SMA tape showing the SME was a TiNi alloy tape with a width of 5 mm and a thickness of 0.3 mm produced by Furukawa Techno Materials Co. The SEA tape showing the SE at room temperature was a TiNi alloy tape with a width of 2.5 mm and a thickness of 0.25 mm produced by Yoshimi Inc. In the shape memory processing, each alloy tape was set along the inside of a fixing ring with an inner diameter of 16 mm and was heat-treated to memorize the round shape with an outside diameter of 16 mm. The temperature \( A_f \) of the SMA tape was 342 K and that of the SEA tape was 309 K. The R-phase transformation finish temperature \( R_f \) of the SMA tape was 309 K. These phase transformation temperatures were obtained by the DSC test.

With respect to the SMP, a polyurethane SMP sheet (MM6520) produced by SMP Technologies Inc. was used. The thickness was 0.25 mm and the glass transition temperature \( T_g \) was 338 K. The SMP tape with a width of 10 mm was used for the SMC belt.

2.2 Structure and movement properties of SMC belt

The SMC belt with a length of 60 mm, a width of 10 mm and a thickness of 1.03 mm was fabricated by using two kinds of alloy tapes and three SMP tapes. In the laminated SMC belt, the SMP tapes were used as a matrix and the alloy tapes as a fiber. The length of the SMA tape and the SEA tape was 50 mm. The SMA tape and the SEA tape were located in the central part of the SMC belt.

The structure of the SMC belt is shown in Fig. 1. As can be seen, the SMA tape and the SEA tape were laminated inside the SMC belt and arranged facing in the opposite directions for the shape-memorized round shape. The principle of the three-way (reciprocating) bend movement in the SMC belt during heating and cooling is shown in Fig. 2. As can be seen in Fig. 2, the SMC belt bends to convex downward (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 upward (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.

2.3 Fabrication of SMC belt

At first, two incisions were given to one SMP tape and the SMA tape was passed through these incisions. In this process, the SMA tape and SEA tape were arranged facing in the opposite directions for the memorized round shape as shown in Fig. 3. In order to keep the proper positions of both alloy tapes and to protect the projection of the edge by the recovery force of the SMA tape, both edges of the alloy tapes were connected by a thin steel clamp. The SMP tape passed through 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 the SMC belt.

The upper and lower molds were fastened through the bolts by a compressive stress of 7.46 MPa as shown in Fig. 4. The mold was held in the furnace at 448 K for 60 min followed by cooling in air. The laminated SMC belt without bubbles and gaps among the materials could be fabricated under these appropriate conditions: the number of SMP tapes, the fastening force, the heat-treating temperature and time.

![Fig. 1 Structure of SMC belt laminated with SMA tape, SEA tape and SMP tape](image)

![Fig. 2 Principle of three-way bend behavior in SMC belt during heating and cooling](image)
3. Three-way bend movement of SMC belt

3.1 Three-way bend behavior

The photographs of the three-way (reciprocating) bend motion of the fabricated SMC belt during heating and cooling are shown in Fig. 5. The heating and cooling were carried out between 293 K and 365 K. In Fig. 5, the symbols \(A_{f,SEA}, A_{f,SMA}, R_f,SMA\) and \(T_g\) represent the reverse-transformation finish temperatures of the SEA tape and the SMA tape, the R-phase transformation finish temperature of the SMA tape and the glass transition temperature of the SMP tape, respectively. At 293 K \(\text{①}\), the internal bending moment induced in the SEA tape is high, and therefore the SMC belt bends in the direction of the shape-memorized round shape of the SEA tape. If the SMC belt is heated \(\text{①} \rightarrow \text{②}\), the SMP belt...
becomes soft and the SMC belt bends further to convex downward (in the same direction at 293 K) at temperatures around \( T_g \). If the SMC belt is heated up above \( T_g \) and \( A_f,\text{SEA} \) and therefore the SMC belt bends in the direction of the shape-memorized round shape of the SMA tape. If the SMC belt is cooled thereafter, the recovery force in the SMA tape decreases and the recovery force in the SEA tape becomes higher. Therefore, the SMC belt bends again to its original shape. This three-way bend motion can be repeated by the cyclic heating and cooling.

### 3.2 Evaluation of motion based on internal bending moment

The three-way bend motion due to variation in temperature appears based on the variation in the internal bending moment induced in the SEA tape, the SMA tape and the SMP tape in the SMC belt. The internal bending moment can be evaluated as follows. The maximum bending strains of all elements in the three-way movement are calculated by using the radius of curvature and the thickness of each element. The maximum bending strains of the SMA tape, SEA tape and SMP tape were 0.8 %, 0.6 % and 2.7 %, respectively. These strains are in the elastic region of each material and therefore the internal bending moment of all elements can be evaluated by the theory of elasticity. The internal bending moment \( M \) is proportional to the bending rigidity \( EI \) and inversely proportional to the radius of curvature \( r \) of each element: \( M = EI/r \). The dependence of the internal bending moment on temperature can be evaluated as follows. The bending rigidity of the strip is expressed by \( EI \) where \( E \) denotes the elastic modulus and \( I \) the second moment of area. The internal bending moment of the SMC belt \( M_c \) is given by a sum of the internal bending moment in each element as follows

\[
M_c = \frac{E_c I_c}{r_c} + \frac{E_{\text{SEA}} I_{\text{SEA}}}{r_{\text{SEA}}} + \frac{E_{\text{SMA}} I_{\text{SMA}}}{r_{\text{SMA}}} + \frac{E_P I_P}{r_P} \tag{1}
\]

where \( E_c, E_{\text{SEA}}, E_{\text{SMA}} \) and \( E_P \) denote the elastic modulus of the SMC belt, the SEA tape, the SMA tape and the SMP tape, respectively. \( I_c, I_{\text{SEA}}, I_{\text{SMA}} \) and \( I_P \) represent the second moment of area of the SMC belt, the SEA tape, the SMA tape and the SMP tape, respectively. \( r_c, r_{\text{SEA}}, r_{\text{SMA}} \) and \( r_P \) denote the radius of curvature of the SMC belt, the SEA tape, the SMA tape and the SMP tape.
and the SMP tape, respectively. There is a following relation for the second moment of area

\[ I_c = I_{SEA} + I_{SMA} + I_p \]  

(2)

It should be noticed that the neutral axes of the SMC belt and each element do not coincide. The internal bending moment of the SMC belt is given by the sum of the internal bending moment of each element as expressed by Eq. (1). However, in the case of the phase transformation by heating and cooling under no load, the internal bending moment of the SEA element and that of the SMA element act to bend the SMC belt in the opposite direction to which the round shape of each element was shape-memorized. The internal bending moment in the SMP element acts to bend the SMC belt in the direction of shape-memorized flat shape.

With respect to evaluation of the second moment of area obtained from Eq. (2), since the central SMP tape sandwiched between the SEA tape and the SMA tape melts during holding the pressed state at 448 K in the heat-treating process and therefore becomes thin, it can be assumed that the neutral axis of the cross-section in the SMC belt which passes through its centroid coincides with the boundary face between the SEA tape and the SMA tape. Therefore, the neutral axis of the cross-section in each alloy element is located from the centroid of the cross-section by a distance of \( h/2 \) and the second moment of area of the alloy element with the width \( b \) and height \( h \) is 

\[ I = bh^3/12 + A \cdot (h/2)^2 = bh^3/3 \]

where the area of the cross-section \( A = bh \).

The elastic modulus of the TiNi alloy tape is 70 GPa at temperatures \( T > A_f \) and 20 GPa at \( T < R_f \). Therefore, the internal bending moment of the SEA tape \( E_{SEA}A_{SEA}/r_{SEA} \) is 118 mN·m at temperatures above 293 K for \( r_{SEA} = 7.9 \) mm. \( E_{SMA}A_{SMA}/r_{SMA} \) of the SMA tape is 114 mN·m at 293 K and 399 mN·m at 365 K for \( r_{SMA} = 7.9 \) mm. The elastic modulus of the SMP tape is 1 GPa at \( T < T_g \) and 10 MPa at \( T > T_g \). Therefore, the internal bending moment of the SMP tape \( E_pA_p/r_p \) is 34.8 mN·m at 293 K for \( r_p = 24.5 \) mm and 0.249 mN·m at 365 K for \( r_p = 34.3 \) mm. Based on the temperature dependence of the internal bending moment, the SMC belt moves as follows. At 293 K, the fabricated SMC belt is taken out from the mold, and the SMC belt bends in the direction of the shape-memorized round shape of the SEA tape where the internal bending moment of this element is largest. At 333K around \( T_g \), since the bending rigidity of the SMP tape decreases, that of the SEA tape becomes correspondingly large and therefore the SMC belt bends further in the shape-memorized direction of the SEA tape. At 365 K, the SMC belt bends in the direction of the shape-memorized round shape of the SMA tape where the internal bending moment of this element is largest.

The three-way movement property of the SMC belt depends on the composition and fraction of the SMA and SMP elements and the rate of heating and cooling processes. For example, if the SMC is cooled rapidly, the SMP element located on the surface is cooled at first and the rigidity of the SMP increases, and therefore the polymer layer becomes hard to deform and the shape at high temperature is fixed. Therefore, in this case, the large recovery movement during cooling can’t be obtained by the internal bending moment which appears in the SEA element located inside of the SMC. In order to develop the high-functional SMC actuator, it is necessary to clarify these properties.

3.3 Observation of three-way movement through displacement at the center of SMC belt

The three-way movement was observed through the displacement at the center of the SMC belt. At first, the initial bent-form SMC belt was set on the supports of the three-point bending device in the chamber of the shape-memory characteristics testing machine. After setting the SMC belt, the point of the punch contacted slightly the center of the SMC belt.
Keeping the slight contact condition under the contact load lower than 0.1N, the SMC belt was heated and cooled, and the displacement at the center of the SMC belt was measured. The average heating and cooling rates were ±0.02 K/s. The temperature of 365 K was kept constant for 60 min at the end of heating process ③.

The relationship between the displacement at the center of the SMC belt and temperature obtained by the test is shown in Fig. 6. The symbols $A_{f,SEA}, A_{f,SMA}, R_{f,SMA}, R_{S,SMA}$ and $T_g$ shown in Fig. 6 represent the reverse-transformation finish temperatures of the SEA tape and the SMA tape, the R-phase transformation start and finish temperatures of the SMA tape, and the glass transition temperature of the SMP tape, respectively. The symbols ①～④ correspond to the deformed states ①～④ shown in Figs. 2 and 5. It should be noticed that if the deflection of the SMC belt increases, the center of the SMC belt moves downward and the displacement decreases to the negative side. In the heating process ① ～ ②, the displacement at the center of the SMC belt increases, since the SMP exists in the glass transition region ② and the SMP becomes soft. In the heating process ② ～ ③, the displacement of the SMC belt increases, since the internal bending moment of the SMA tape increases at temperatures above $A_{f,SMA}$ due to the reverse transformation of the SMA tape. In the cooling process ③ ～ ④, the displacement of the SMC belt decreases rapidly at temperatures between $R_{f,SMA}$ and $R_{S,SMA}$ since the internal bending moment of the SMA tape decreases and that of the SEA tape becomes higher than that of other elements.

4. Development of multi-functional SMC actuator

The SMC belt fabricated in the present paper shows the three-way bend properties during heating and cooling. The SMC belt was composed of two kinds of SMAs with different phase transformation temperatures and SMP. The glass transition temperature of the SMP was between the phase transformation temperatures of the SMAs. The thermomechanical properties of SMC vary depending on the combination of the SMA and the SMP with various phase transformation temperatures, volume fractions, structural
compositions and heating-cooling rates. Therefore, various kinds of multi-way actuators can be developed by using these combinations. The cyclic deformation properties and strength of the interfaces between the alloy and the polymer are important for development of SMC actuators. They are the future subjects.

The three-way bend behavior observed in the SMC belt was in the same plane. The axes of the SMA tapes with different phase transformation temperatures were in the same direction in the SMC belt. If the axes of the SMA 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 obtained by using these compositions.

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

5. Conclusions

The SMC belt composed of two kinds of SMAs with different phase transformation temperatures and SMP was fabricated and the three-way bend movement and recovery force were investigated. The results obtained can be summarized as follows.

1. Two kinds of TiNi alloy tapes showing the SME and SE were heat-treated to memorize the round shape, respectively. The shape-memorized round alloy tapes were arranged facing in the opposite direction and were sandwiched by one SMP tape in the central part and by two SMP tapes from upper and lower sides. The laminated SMC belt was fabricated without bubble and gap by using the appropriate factors: the number of SMP tapes, the fastening force, the heat-treating temperature and time.

2. The three-way bend movement was achieved during heating and cooling based on the characteristics of the alloy tapes and the SMP tape.

3. The development and application of multi-functional SMCs with simple structure for three-dimensional actuators are highly expected by the combination of the SMAs and the SMPs with various kinds of phase transformation temperatures, volume fractions, compositions and heating-cooling rates.

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7. References


