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Effect of Thermomechanical Cyclic Loading Condition on Two-Way Strain in Ti-Ni-Cu Shape Memory Alloy

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This study describes the effect of thermomechanical cyclic condition on two-way strain in Ti-Ni-Cu shape memory alloy. The material used in this study is Ti-41.7Ni-8.5Cu(at%) shape memory alloy. The specimen shape is a wire with 1mm diameter and 70 mm gage length. The specimen was heat treated at 623K for 3.6ks. The process of the cyclic loading test in this study is loading-unloading-heating-unloading-cooling cycle. The specimen was loaded to given applied strain and subsequently unloaded. And then, the specimen was heated up to 373K or 423K and was kept at the temperature for 0.6ks under the constrained strain condition followed by unloading and cooling under free strain condition. Also, the number of cycles is 30 cycles. This study discussed the effects of heating temperature, applied strain and number of cycles on two-way strain in Ti-41.7Ni-8.5Cu(at%) shape memory alloy. The two-way strain slightly increases with increasing heating temperature. An increase in the maximum applied strain up to 7.5% increases the two-way strain. There is hardly effect of the number of cycles on the two-way strain.

Key words: two-way strain, Ti-Ni-Cu shape memory alloy, thermomechanical cycle, applied strain, heating temperature

1. INTRODUCTION

In recent years, shape memory alloys (SMAs) are being expected to be put to practical use in the micromechanics field since they have unique characters such as shape memory effect and superelasticity [1]. In particular, use of SMAs as an actuator attracts attention, because SMAs allow reduction in size and weight [2, 3].

SMA actuators usually employ a one-way shape memory effect. Therefore, SMA actuators require a bias force such as a sprig to return the SMA to its low-temperature shape. However, use of a two-way shape memory effect which memorizes both low-temperature shape and high-temperature shape requires no bias force so that further reduction in size and weight can be expected.

Ti-Ni-Cu alloys are one of promising materials for a component of a SMA actuator, because the recovery stress increases and the stress hysteresis and transformation temperature hysteresis decrease with increasing copper content in the alloys [4, 5].

This study carried out thermomechanical cycle tests using Ti-41.7Ni-8.5Cu alloy. Based on the results obtained, this study discussed the effect of applied strain, number of cycles and heating temperature on development of two-way strain.

2. EXPERIMENTAL PROCEDURES

The chemical composition of the alloy used in this study is Ti-41.7Ni-8.5Cu (at%). The specimen shape is a wire with 1 mm diameter and 70 mm gage length. The specimen was processed in the following manner; the Ti-Ni-Cu shape memory alloy ingot was made using a high frequency induction vacuum furnace, and then was hot forged and hot extruded followed by cold drawing and intermediate annealing. The cold working ratio (CW) of the specimen is 10%. Furthermore, the specimen was heat treated at the temperature of 623K for 3.6ks in air.

Martensite start temperature M_s, martensite finish temperature M_f, austenite start temperature A_s and austenite finish temperature A_f of the specimen measured by differential scanning calorimetry (DSC) are listed in Table I. Young's moduli of martensite phase E_M and parent phase E_A are also listed in Table I.

Table I Transformation temperatures and Young's moduli.

Transformation temperatures (K)				Young's moduli (GPa)	
M_f	M_s	A_s	A_f	E_M	E_A
331.5	332.4	332.4	346.8	12.8	63

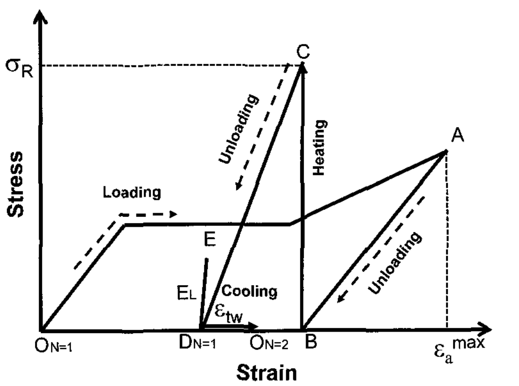

Fig.1 A schematic drawing of thermomechanical cyclic test.

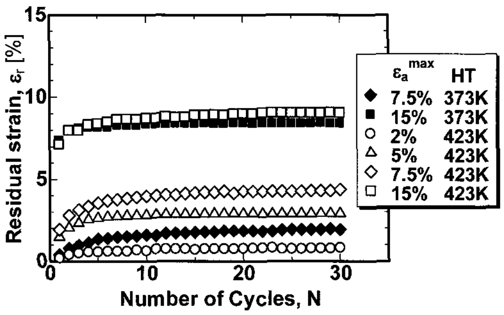

Fig.2 Variation of residual strain with number of cycles.

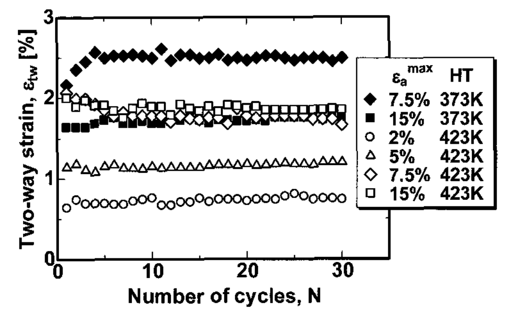

Fig.4 Variation of two-way strain with number of cycles.

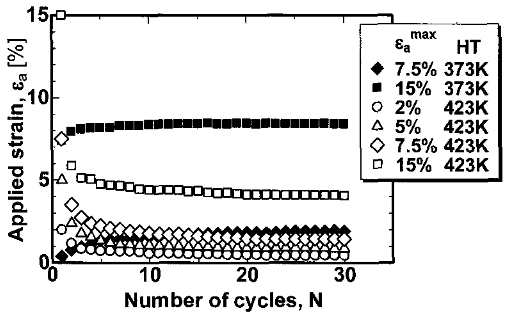

Fig.3 Variation of applied strain with number of cycles.

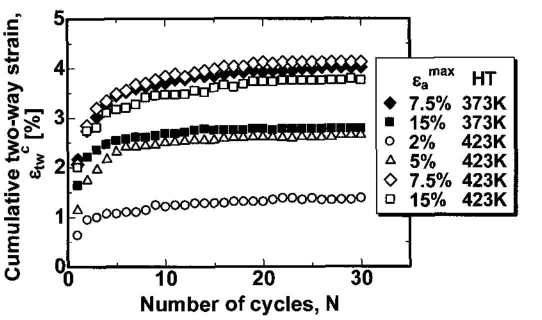

Fig.5 Variation of two-way strain with number of cycles.

To investigate the effect of thermomechanical cyclic loading condition on two-way strain in the Ti-Ni-Cu shape memory alloy, thermomechanical cyclic tests were carried out using the Ti-41.7Ni-8.5Cu (at%) alloy wire. Figure 1 shows a schematic drawing of thermomechanical cyclic test. The thermomechanical cyclic test was carried out in the following procedures;

(1) The specimen was loaded to given maximum applied strain ε_a^{max} ranged from 2% to 15% at the isothermal temperature of 263K lower than martensite transformation finish temperature M_f, and was subsequently unloaded ($O_{N=1}$→A→B).

(2) The specimen was heated up to 373K or 434K at 3K/min and was kept for 0.6ks under constrained strain condition (B→C). In this process, the recovery stress σ_R was obtained as shown in Fig.1. And then, it was unloaded (C→$D_{N=1}$).

(3) The specimen was loaded to the strain ranged from 0.3% to 0.4% which is elastic strain range, and was subsequently unloaded ($D_{N=1}$→C→$D_{N=1}$). The apparent Young's modulus E_L was evaluated from the incline of stress-strain relation obtained from this process.

(4) The specimen was cooled down to 263K at 5K/min under free strain condition. In this process, the two-way strain ε_{tw} ($D_{N=1}$→$O_{N=2}$) is caused by the appearance of the two-way shape memory effect.

The process from (1) to (4) mentioned above was defined as one cycle. The point $O_{N=i}$ was set as the start point of N=i cycle, and the repeated cycles of the process was 30 cycles. In this study, the residual strain ε_r was defined as the range from $O_{N=1}$ to $D_{N=i}$, the applied strain in each cycle ε_a the range from $O_{N=i}$ to A, the two-way strain in each cycle ε_{tw} the range from $D_{N=i}$ to $O_{N=i+1}$ and the cumulative two-way strain ε_{tw}^c the range from $D_{N=1}$ to $O_{N=i+1}$, respectively.

3. RESULTS AND DISCUSSIONS

3.1 Effect of thermomechanical cycle loading condition on two-way strain

Figures 2 and 3 show the variation of the residual strain ε_r with the number of cycles and the variation of the applied strain ε_a with the number of cycles. The ε_a decreases with increasing ε_r. On the other hand, an increment of the ε_r decreases with decreasing ε_a. As a result, the ε_r increases and the ε_a rapidly decreases during the first few cycles, and the variation of them with the number of cycles become small after these cycles.

Figures 4 and 5 show the variation of the two-way strain ε_{tw} with the number of cycles and the variation of the cumulative two-way strain ε_{tw}^c with the number of cycles. In the case of the maximum applied strain ε_a^{max} =7.5%, the ε_{tw} slightly decreases in the early cycles. However, there is hardly effect of the number of cycles on the ε_{tw}. On the other hand, the number of cycles affects the ε_{tw}^c. The ε_{tw}^c increases with the number of cycles up to approximately 15 cycles but become almost constant after these cycles. This is the reason why the ε_{tw}^c includes the inclement of the residual strain ε_r.

Figure 6 shows the relationship between the two-way strain and the maximum applied strain ε_a^{max}. The reason for the appearance of two-way strain may be considered due to the internal stress occurring at the interface

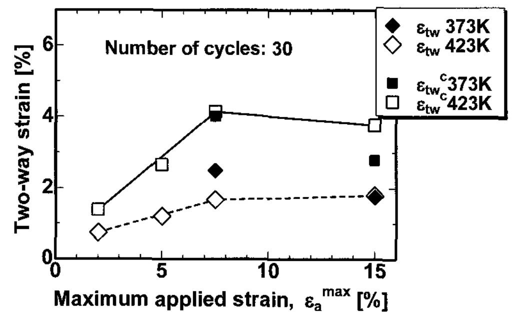

Fig.6 Relation ship between two-way strain and maximum applied strain.

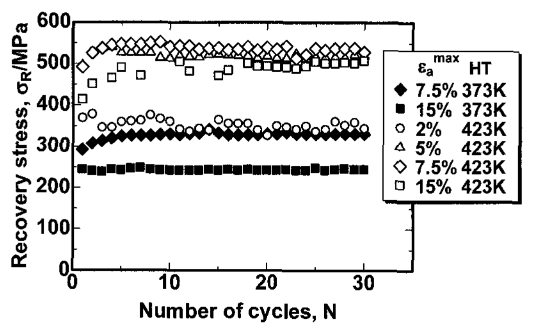

Fig.7 Variation of recovery stress with number of cycles.

between the recoverable martensite phase and the damaged irrecoverable martensite phase [6]. The two-way strain ε_{tw} and cumulative two-way strain ε_{tw}^c increase with increasing ε_a^{max} up to 7.5%. However, the further increase in the ε_a^{max} tends to decrease the ε_{tw} and ε_{tw}^c. The reason is considered as follows. An increase in the ε_a^{max} up to 7.5% increases both the recovery strain and the residual strain so that the internal stress increases. And then the further increase in ε_a^{max} decreases the recovery strain because of the increase of residual strain caused by slip, thus, the internal stress decreases. Additionally, the ε_{tw} slightly increases with increasing heating temperature at the ε_a^{max}=7.5%.

The variation of the recovery stress σ_R with the number of cycles is shown in Fig.7. Slight increase of the σ_R in the early cycles is found in some cases but there is hardy effect of the number of cycles on the σ_R. Also, an increase in the ε_a^{max} up to 7.5% increases the σ_R but the further increase in the ε_a^{max} decreases the σ_R. This indicates that an increase in the ε_a^{max} more than 7.5 % decreases the recoverable martensite phase because of the increase of the damaged irrecoverable martensite phase caused by slip.

3.2 Evaluation of two-way strain by volume fraction of slip-deformed martensite

The slip-deformed martensite phase does not transfer to the parent phase by heating, and remains locally in the parent phase [7]. Authors have defined the remained fraction of martensite phase in the parent phase as the volume fraction of slip-deformed martensite ξ, and have

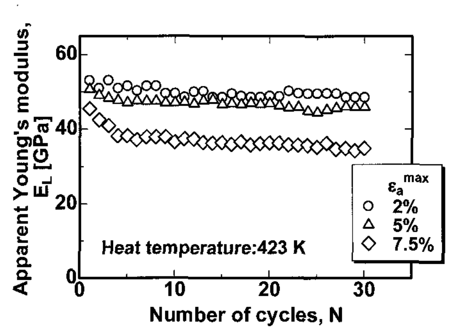

Fig.8 Variation of apparent Young's modulus with number of cycles.

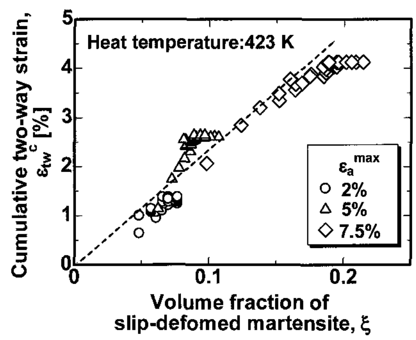

Fig.9 Relationship between cumulative two-way strain and volume fraction of slip-deformed martensite.

clarified that the volume of ξ can be used as a criterion of applied strain induced dislocation [8-10].

In the thermomechanical cyclic test of this study, the internal damage in material occurs in the process of (1) and (2). In the process of (1), the internal damage in material is induced by the applied strain. In the process of (2), the recovery stress is generated by the reverse transformation with an increase in temperature. Since there are both the parent phase and martensite phase in the material during the process of the reverse transformation, the slip deformation occurs in the martensite phase having the lower critical stress for slip by the recovery stress [7]. In addition, the variation of the fraction of slip-deformed martensite emerges as the variation of the apparent Young's modulus E_L.

The variation of the apparent Young's modulus E_L with the number of cycles is shown in Fig.8. The E_L decreases with increasing the number of cycles in the early cycles and then become almost constant after these cycles. This result is believed that the slip-deformed martensite phase increases with increasing number of cycles in the early cycles and then hardly increases after these cycles. Also, an increase in the ε_a^{max} decreases the E_L. This indicates that an increase in the ε_a^{max} increases the slip-deformed martensite phase.

The volume fraction of slip-deformation martensite ξ is defined as the following equation [8,9], where, E_A and E_M are Young's moduli of parent phase and martensite phase, respectively.

$$\xi = \frac{E_M(E_A - E_L)}{E_L(E_A - E_M)} \quad (1)$$

Figure 9 shows the relationship between the cumulative two-way strain ε_{tw}^c and volume fraction of slip-deformed martensite ξ. The ε_{tw}^c lineally increases with increasing ξ. This result shows that the ξ can be used as a criterion of ε_{tw}^c.

4. CONCLUSIONS

Thermomechanical cyclic tests were carried out using the Ti-41.7Ni-8.5Cu (at%) alloy in order to studying effect of thermomechanical cycle loading condition on two-way strain in Ti-Ni-Cu shape memory alloy. The obtained results are summarized as follows;

(1) An increase in the maximum applied strain up to 7.5% has increased the two-way strain.

(2) There has been hardly effect of the number of cycles on the two-way strain.

(3) The two-way strain slightly has increased with increasing heating temperature at the maximum applied strain of 7.5%.

(4) The volume fraction of slip-deformation martensite can be used as a criterion of cumulative two-way strain.

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