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Recovery Stress and Transformation Temperature Behavior of Partial Shape-Recovered Shape Memory Alloy

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In many cases that a shape memory alloy is applied to the engineering and medical field, and so on, the shape is constrained after partial shape recovery, and the recovery stress at that time is used. It is reported that transformation temperatures are changed by pre-strain and constrained strain condition. Therefore, it is important to investigate the relationship between the partial recovery strain and the deformation and transformation characteristics such as recovery stress and transformation temperatures, and so on. The purpose of this work is to clarify the influence of partial recovery strain on recovery stress and transformation temperatures in Ti-Ni alloy. The specimens are Ti-50at%Ni alloys, annealed at 1103 K for 60s. The variation of recovery stress and transformation temperatures with partial recovery strain ratio is investigated experimentally. Results show that pre-strain of 9% is suitable for partial shape recovery use.

Key words: Ti-Ni alloy, shape memory alloy, recovery stress, partial recovery strain

1. INTRODUCTION

Shape memory alloys are receiving attention as functional materials in various fields such as engineering and medicine, and their applications are being studied [1-3]. Especially, Ti-Ni based alloy is practically used because its superior mechanical properties and corrosive resistance, and so on. In many cases that shape memory alloys are applied to the engineering and the medical field, their shapes are constrained after partial shape recovery, and the recovery stress generated at that time is used. It is reported that transformation temperatures are changed by pre-deformation and constrained strain conditions [4-7]. Therefore, it is important to investigate the relationship between the partial recovery strain and the deformation and transformation characteristics such as recovery stress and transformation temperatures.

Authors have reported that the degradation of some functions in Ti-Ni alloys was caused by the residual martensite subjected to slip deformation and the residual martensitic volume fraction is capable of representing the degradation of functions [8- 10].

In this paper, the deformation and transformation characteristics during the reverse transformation process after pre-deforming are investigated and the effect of pre-deformation on them will be discussed in relation to the slip-deformed martensitic volume fraction.

2. EXPERIMENTAL PROCEDURE

Ti-Ni alloy ingot was made using a high frequency induction vacuum furnace. The composition of alloy was Ti-50at%Ni. The specimen was a wire with 1.0 mm in diameter and 70 mm in length, annealed at 1103 K for 60s. The transformation temperatures were measured by DSC and the elastic modulus E_M of martensitic phase and E_A of parent phase were obtained by isothermal tensile tests at temperatures of A_s-20 K and above A_f, respectively. The transformation temperatures and elastic moduli are listed in Table I.

In order to investigate the variation of recovery stress and transformation temperatures with pre-strain and partial recovery strain, the tensile and heating/cooling tests were carried out by following method. Figure 1 shows the schematic drawing of stress-strain curve. The specimens were completely transformed to a martensitic phase by cooling down to M_f-30 K. The specimen was elongated to a given pre-strain ε_{pr} (O-A) at a given temperature T_C (=A_s-20 K), and then it was unloading to stress free (A-B). At point B, the specimen was heated up to a temperature T_H (>A_f) and the strain was constrained at a partial recovery strain of $\Delta\varepsilon_a$ (B-C-D), and then it was cooled down (D-C'). Based on these test results, the recovery stress and the transformation temperatures of A_f', A_s' and M_s' for pre-deformed specimens were obtained by stress-temperature curves. The elastic modulus E_L was obtained by unloading curve (D-E) at T_H.

Table I Transformation temperatures and elastic moduli.

Transformation temperatures (K)				Young's moduli (GPa)	
M_f	M_s	A_s	A_f	E_M	E_A
314.5	329.5	343.1	362.3	21.4	47.2

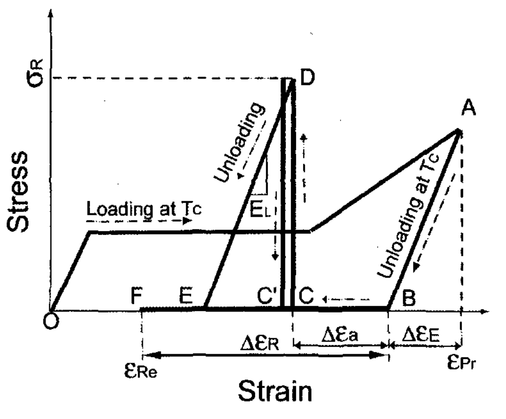

Fig.1 Schematic drawing of stress-strain curve of heating / cooling tests.

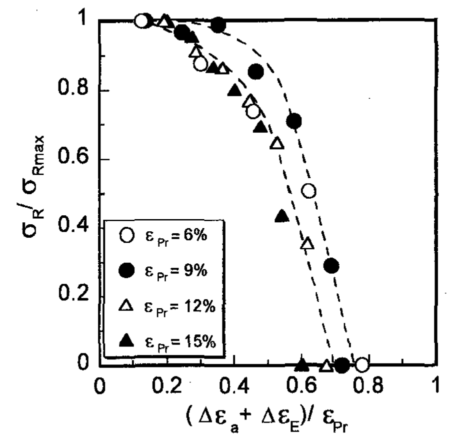

Fig.3 Variation of recovery stress rate σ_R/σ_{Rmax} with recovery ratio $(\Delta\varepsilon_a + \Delta\varepsilon_E) / \varepsilon_{Pr}$.

3. RESULTS AND DISCUSSION

Figure 2 shows the variation of the recoverable strain $\Delta\varepsilon_R$, the elastic recovery strain $\Delta\varepsilon_E$ and the maximum recovery stress σ_{Rmax} with the pre-strain ε_{Pr}. The elastic recovery strain increases with increasing pre-strain. On the other hand, the recoverable strain shows the tendency to saturate when the pre-strain is exceeding about 12%. The recovery stress increases with increasing pre-strain until pre-strain is under about 9%, and then it decreases with increasing pre-strain when pre-strain is exceeding about 9-12%.

The amount of slip deformation in specimen increases with increasing pre-strain and martensites subjected to slip deformation remain even after being heated up above A_f. Therefore, it is assumed that the recoverable strain decreases with increasing pre-strain. Furthermore, in the reverse transformation process, the amount of slip deformation in the specimen becomes larger and the recoverable strain becomes smaller than those of stress free conditions because of the recovery stress. Thus, the recovery stress decreases in the high pre-strain range.

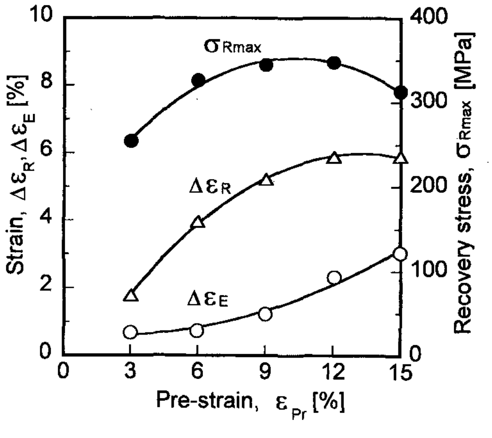

Fig.2 Variation of shape recovery strain $\Delta\varepsilon_R$ and elastic recovery $\Delta\varepsilon_E$ strain and recovery stress σ_R with pre-strain ε_{Pr}.

Figure 3 shows the effect of the partial recovery strain on the recovery stress. The values are normalized against the maximum recovery stress and plotted as a function of the partial recovery strain ratio $(\Delta\varepsilon_a+\Delta\varepsilon_E)/\varepsilon_{Pr}$ for various pre-strain. The recovery stress decreases with increasing recovery strain ratio for every pre-strain. Moreover, it is found that, the recovery stress ratio of ε_{Pr} =9% is lager than those of other pre-strain and keeps higher value against the varying of partial recovery strain.

Martensites subjected to slip deformation do not transform to parent phase even though they are heated up above A_f. Authors have been reported that the volume fraction of slip-deformed martensite corresponds to the density of dislocations [8,9]. Relationship between the residual strain ε_{Re} and the volume fraction of slip-deformed martensite is shown in Fig. 4. The volume fraction ξ of slip-deformed martensite is calculated by following equation [9,10].

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

Residual strain increases with increasing the volume fraction of slip-deformed martensite, and it does not depend on pre-strain and recovery strain ratio. Residual strain is corresponding to the density of dislocation of alloy. Therefore, it can be said that the volume fraction of slip-deformed martensite is corresponds to the density of dislocations and does not depend on the amount of pre-strain and recovery strain ratio.

Figure 5 shows the variation of the volume fraction of slip-deformed martensite ξ with the recovery strain ratio $(\Delta\varepsilon_a+\Delta\varepsilon_E)/\varepsilon_{Pr}$. It is found that the volume fraction of slip-deformed martensite increases with increasing the pre-strain, and it decreases with increasing the recovery strain ratio.

When the specimen is heated under constrained strain conditions, the recovery stress is generated. Furthermore, in this heating process, the specimen consists of the martensitic and parent phases. The critical stress for slip for the parent phase is several times larger than that of martensitic phase. Therefore, the slip deformations introduced into martensitic phase of the specimen is lager than those of stress free condition. Figure 6 shows the relationship between the increase of volume fraction of slip-deformed martensite $\Delta\xi$ $(=\xi-\xi_f)$ and the recovery stress σ_R. Where, ξ_f is the volume fraction of slip-deformed martensite at stress free conditions.

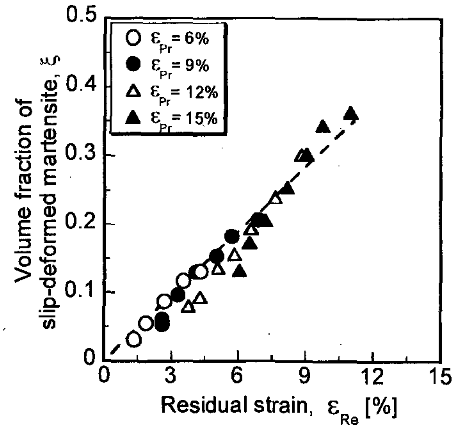

Fig.4 Relationship between volume fraction of slip-deformed martensite ξ and residual strain ε_{Re}.

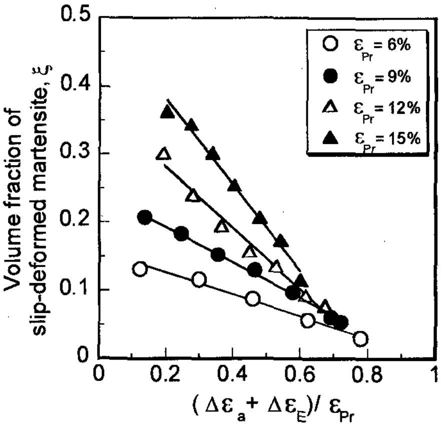

Fig.5 Variation of volume fraction of slip-deformed martensite ξ with recovery ratio $(\Delta\varepsilon_a+\Delta\varepsilon_E)/\varepsilon_{Pr}$.

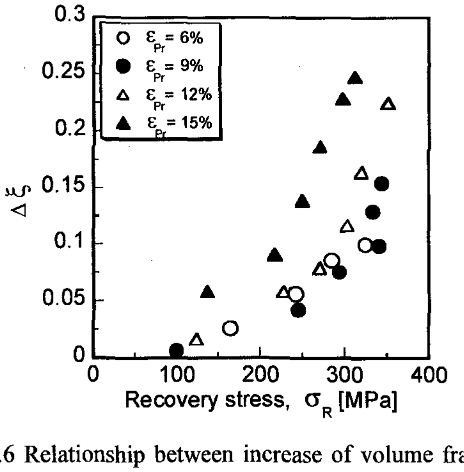

Fig.6 Relationship between increase of volume fraction of slip-deformed martensite $\Delta\xi$ and recovery stress σ_R.

It is found that the volume fraction of slip-deformed martensite increases with increasing recovery stress for all pre-strain. At ε_{Pr}=9%, although the recovery stress are higher than other pre-strain, the damage of the specimen is relatively small. When the pre-strain is exceeding 9%, the damage of the specimen becomes larger. Therefore, it can be said that the pre-strain ε_{Pr} of 9% is a suitable amount of pre-strain from the viewpoint of recovery stress and the resistance for slip deformation.

Figure 7 shows the variation of the increase of reverse transformation start temperature ΔA_s $(=A_s'-A_s)$, finish temperature ΔA_f $(=A_f'-A_f)$ and martensitic transformation start temperature ΔM_s $(=M_s'-M_s)$ with pre-strain at stress free and completely constrained strain conditions. It is reported that the elastic strain energy stored during martensitic transformation is concerned with the variation of transformation temperature [7]. The stored elastic strain energy resists transformation and assists reverse transformation. Therefore, if the stored elastic strain energy is relaxed by slip, the martensitic and reverse transformation temperatures will be raised. As shown in Fig.7, the reverse transformation temperatures increase with increasing pre-strain for both conditions. The values of ΔM_s increase with increasing pre-strain. However, when the pre-strain is exceeding about 6%, the values of ΔM_s decreases slightly with increasing pre-strain. Therefore, it is thought that, by the applying pre-strain, the stored elastic strain energy is relaxed. The ΔA_f of constrained strain condition is larger than that of stress free condition. The recovery stress is generated in constrained strain condition, and it resists reverse transformation. Therefore, the driving force to transform completely to the parent phase becomes large, and ΔA_f is larger than that of stress free condition.

Figure 8 shows the variation of ΔM_s with the recovery strain ratio for various pre-strain above 6%. ΔM_s decreases with increasing the recovery strain ratio for every pre-strain. As shown in Fig. 7, ΔM_s does not almost change when the pre-strain is exceeding about 6%.

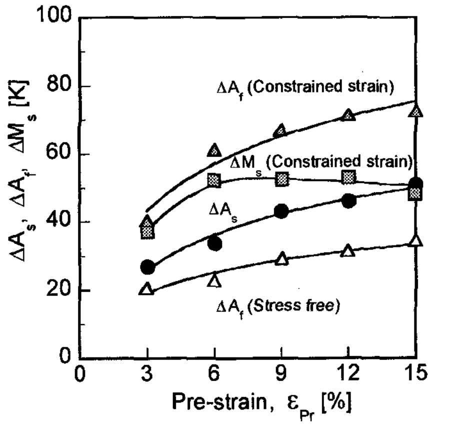

Fig.7 Variation of ΔA_s, ΔA_f, ΔM_s with pre-strain ε_{Pr}.

Therefore, there is no difference between each pre-strain.

Figure 9 shows the relationship between temperature hysteresis (A_f'-M_s') and the recovery strain ratio $(\Delta\varepsilon_a+\Delta\varepsilon_E)/\varepsilon_{Pr}$. It is found that temperature hysteresis is almost constant for each pre-strain, and it does not depend on partial recovery strain ratio. Therefore, it can be said that the driving force to transform to martensitic phase from parent phase depends on the pre-strain and does not depend on the partial recovery strain ratio.

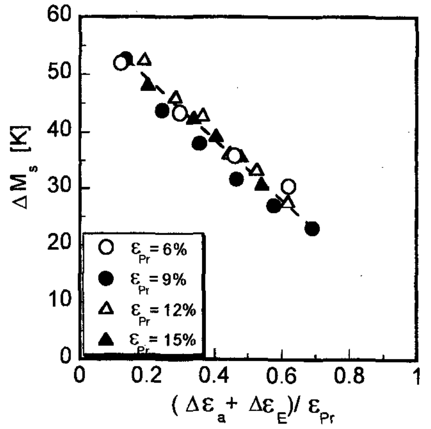

Fig.8 Variation of ΔM_s with partial recovery strain ratio $(\Delta\varepsilon_a + \Delta\varepsilon_E) / \varepsilon_{Pr}$.

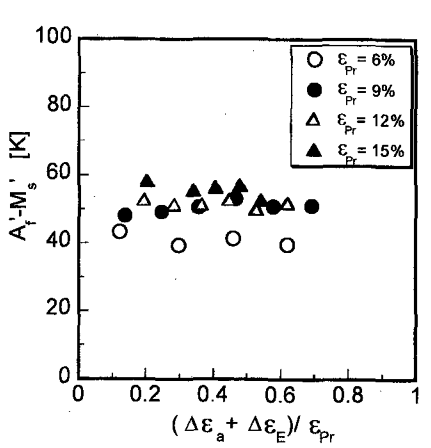

Fig.9 Variation of temperature hysteresis (A_f'-M_s') with partial recovery strain ratio $(\Delta\varepsilon_a + \Delta\varepsilon_E) / \varepsilon_{Pr}$.

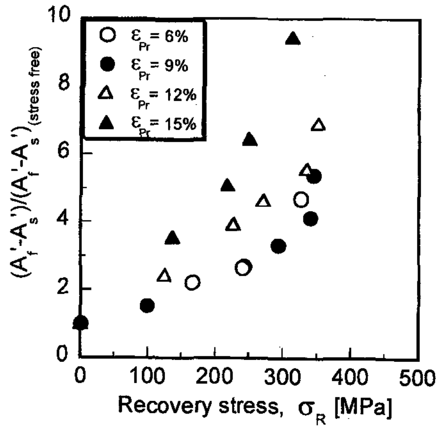

Fig.10 Variation of (A_f'-A_s')/ (A_f'-A_s')$_{stress\ free}$ with recovery stress σ_R.

Figure 10 shows the relationship between the increase rate of the difference of temperatures from reverse transformation start to finish (A_f'-A_s')/ (A_f'-A_s')$_{stress\ free}$ with recovery stress. When the strain is constrained during reverse transformation, the recovery stress is generated. Then it resists reverse transformation, and the temperature required to finish reverse transformation becomes large. As shown in this figure, the increase rate of (A_f'-A_s') increases with increasing recovery stress. And at ε_{Pr}=9%, its increasing rate to recovery stress is relatively smaller than other pre-strain. Therefore, at pre-strain of 9%, it can generate the high recovery stress keeping the small (A_f'-A_s') temperature.

4. CONCLUSION

The effects of partial recovery strain and pre-strain on the recovery stress and transformation temperatures in Ti-Ni alloys were investigated. The results obtained are summarized as follows.

(1) Recovery stress and recovery strain have the maximum values when the pre-strain is about 9-12%.

(2) Recovery stress keeps higher value during partial recovery at pre-strain of 9% than those of other pre-strain.

(3) The difference of temperature from the reverse transformation start to finish increases with increasing recovery stress. When pre-strain is 9%, the increasing rate of temperature difference can be kept small in spite of higher recovery stress.

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