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Effect of Cold Working on Deformation and Transformation Behavior of Partial Shape-Recovered Shape Memory Alloy

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To understand correctly the effects of composition, heat-treatment temperature and cold working on the deformation and transformation characteristics of Ti-Ni shape memory alloys make it possible to control transformation temperature and recovery stress. The purpose of this work is to clarify the effect of cold working on the deformation and transformation characteristics of the partial shape-recovered shape memory alloy. The specimens are Ti-50at%Ni alloys, annealed at 627K for 3.6ks. The variation of recovery stress and transformation temperatures with partial recovery strain ratio is investigated experimentally. The variation of volume fraction of slip-deformed martensite, recovery stress and reverse transformation temperature difference is discussed in relation to cold working ratio and partial recovery strain ratio.
Key word: Ti-Ni alloy, shape memory alloy, recovery stress, partial shape recovery, cold working

1. INTRODUCTION

Shape memory alloy (SMA) is already used as a functional material in an industrial field and a medical field because it is superior in mechanical properties, corrosive resistance, and so on [1-4]. The recovery stress and the recovery deformation caused by the shape memory effect are practically used in many applications. For example, in applying SMA as a joint of a pipe, the recovery deformation is carried out until it constrains a pipe, and the recovery stress is generated when it strains pipe. Therefore, it is important to investigate the relationship between the partial recovery strain and the deformation and transformation behavior. It is well known that the deformation and transformation characteristics of SMA will change with composition, cold working and heat treatment conditions. It is also reported that transformation temperatures are changed by pre-deformation [5-8].

The purpose of this work is to clarify the effect of cold working ratio on the recovery stress and transformation temperatures in partial shape-recovered shape memory alloy.

2. EXPERIMENTAL PROCEDURE

Ti-Ni alloy ingots were made using a high frequency induction vacuum furnace. The composition of alloy was Ti-50at%Ni. The ingots were hot-forged and hot-extruded followed by cold drawing and intermediate annealing to make wires with a diameter of 1.0 mm. The wires were cold-drawn with the reduction of 10%, 20% and 30%. The wire specimens were annealed at 1103K-60s and 627 K-3.6ks. The transformation temperatures of the specimens measured by DSC and elastic moduli of martensitic phase E_M and parent phase E_A obtained by tensile tests are listed in Table1.

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

Table 1 Transformation temperatures and elastic moduli of Ti-Ni alloy.

Cold working ratio (%)	Transformation temperatures (K)				Yong's moduli (GPa)	
	M_f	M_s	A_s	A_f	E_M	E_A
Solution treatment	316	328	346	363	21.4	47.2
10	310	327	347	359		
20	279	325	335	357		
30	247	298	328	349		

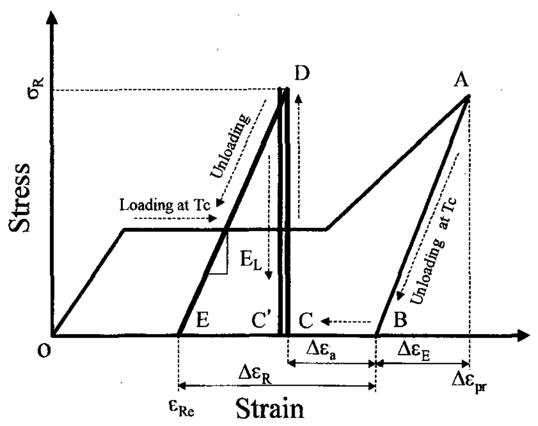

Fig.1 Schematic drawing of experimental procedure.

3. RESULTS AND DISCUSSION

3.1 Deformation behavior

Figure 2 shows the effect of cold working ratio (CW) on the recoverable strain $\Delta\varepsilon_R$ (stress free condition) and the recovery stress σ_R (constrained strain condition) and the elastic recovery strain $\Delta\varepsilon_E$ at pre-strain ε_{pr} of 9%. The recovery stresses have a strong sensitivity to the cold working ratio, and they increase linearly with increasing cold working ratio. However, the recovery strain and the elastic recovery strain are insensitive to cold working ratio above 10%.

Change in deformation characteristics is caused by slip deformation. It is 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 is capable of representing the degradation of functions [9, 10].

Figure 3 shows the variation of volume fraction of slip-deformed martensite ξ with cold working ratio under both the conditions of stress free and constrained strain at pre-strain of 9%. The volume fraction of slip-deformed martensite was calculated by following equation [9,10].

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

The volume fraction of slip-deformed martensite decreases linearly with increasing cold working ratio regardless of constrained strain or stress free conditions. It is apt to be thought that the density of dislocation will be high with increasing of the cold working ratio. The volume fraction of slip-deformed martensite under constrained strain condition is larger than that of stress free condition because the recovery stress is generated under constrained strain condition.

Figure 4 shows the relationship between the increase of volume fraction of slip-deformed martensite $\Delta\xi$ ($=\xi-\xi_f$) and the partial recovery strain ratio ($\Delta\varepsilon_a/\Delta\varepsilon_R$). Where, ξ_f is the volume fraction of slip-deformed martensite at stress free condition. The $\Delta\xi$ decreases

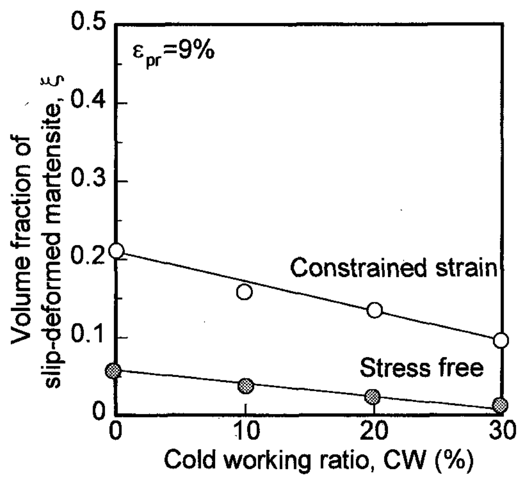

Fig.3 Variation of volume fraction of slip-deformed martensite ξ with cold working ratio.

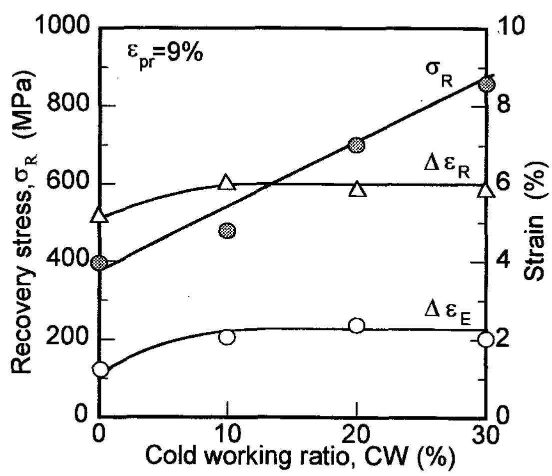

Fig.2 Variation of recoverable strain $\Delta\varepsilon_R$, elastic recovery strain $\Delta\varepsilon_E$ strain and recovery stress σ_R with cold working ratio.

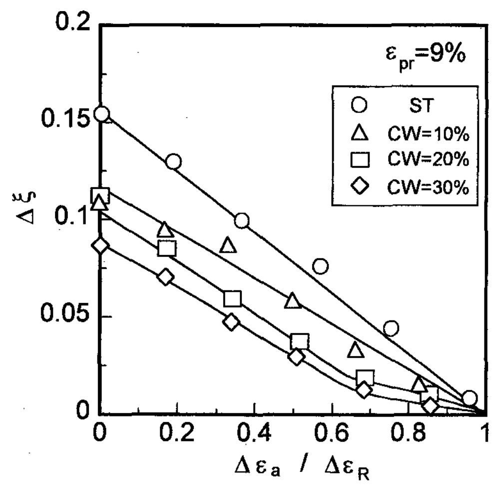

Fig.4 Relationship between the increase of volume fraction of slip-deformed martensite $\Delta\xi$ and the partial recovery strain ratio ($\Delta\varepsilon_a/\Delta\varepsilon_R$).

linearly with increasing the partial recovery strain ratio ($\Delta\varepsilon_a/\Delta\varepsilon_R$).

Figure 5 shows the relationship between the recovery stress σ_R and the increase of volume fraction of slip-deformed martensite $\Delta\xi$ for various cold working ratio. It is found that the changes in recovery stress against the $\Delta\xi$ increase with increasing the cold working ratio. As shown in Fig.4, the variation of $\Delta\xi$ is corresponding to that of the partial recovery strain. Therefore, the larger the cold working ratio, the larger the change of recovery stress becomes against that of partial recovery strain. Thus the recovery stress is insensitive to the partial recovery strain for solution treatment (ST), and sensitive for the cold working

3.2 Transformation temperature behavior

Figure 6 shows the variation of ΔA_s'(=A_s'-A_s), ΔA_f' (=A_f'-A_f) and ΔM_s' (=M_s'-M_s) with cold working ratio. The values of constrained strain condition are those of partial recovery strain $\Delta\varepsilon_a$ of 0.

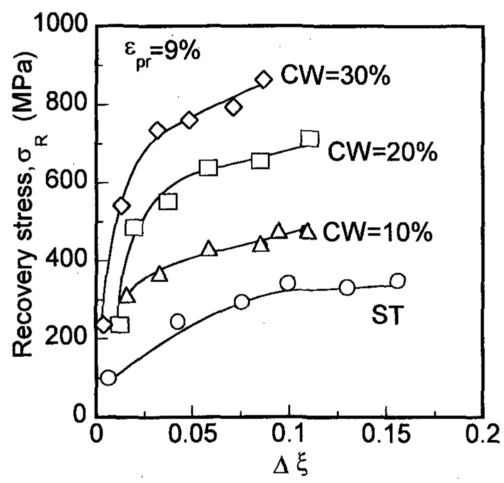

Fig.5 Relationship between the recovery stress σ_R and the increase of volume fraction of slip-deformed martensite $\Delta\xi$ for various cold working ratio.

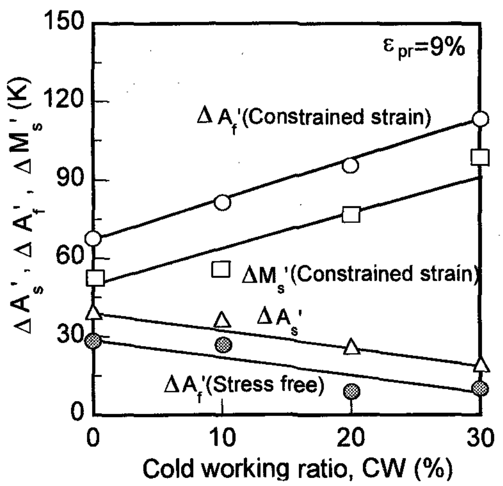

Fig.6 Variation of ΔA_s', ΔA_f' and ΔM_s' with cold working ratio.

It is reported that the elastic strain energy stored during martensitic transformation is concerned with the variation of transformation temperature [8]. 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. When the cold working ratio increases, the density of dislocation of material increases and the elastic strain energy can not be relaxed easily. As a result, the value of ΔA_s' decreases linearly with increasing cold working ratio. The value of ΔA_f' of stress free condition also decreases linearly with increasing cold working ratio. However, the value of ΔA_f' of constrained strain condition increases linearly with cold working ratio. The recovery stress, which resists the reverse transformation, is generated under the constrained strain condition and increases with increasing cold working ratio. Therefore, the driving force to transform to the parent phase becomes large and ΔA_f' of constrained strain condition is larger than that of stress free condition.

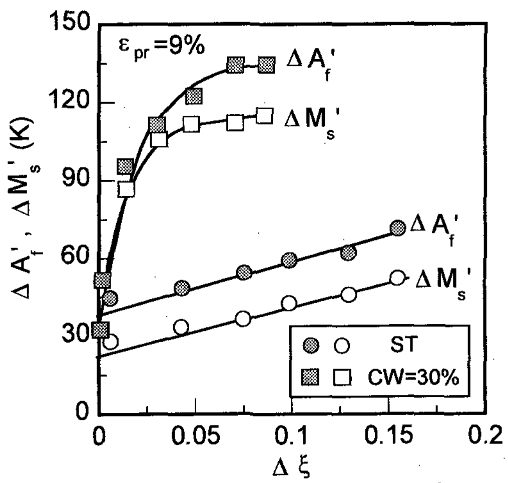

Fig.7 Relationship between the ΔM_s' and ΔA_f' and the $\Delta\xi$.

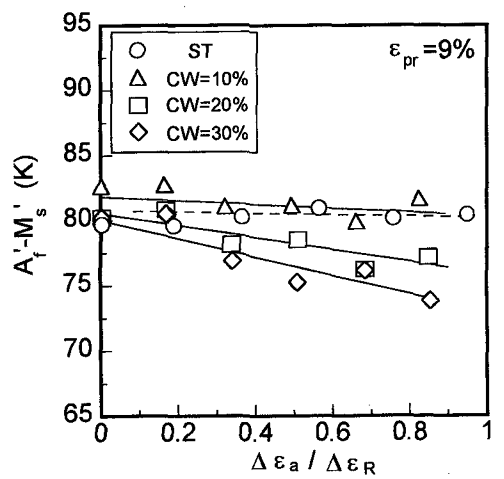

Fig.8 Relationship between temperature hysteresis (A_f'-M_s') and partial recovery strain ratio ($\Delta\varepsilon_a/\Delta\varepsilon_R$).

The value of ΔM_s' increases with increasing cold working ratio. Because the value of ΔA_f' increases, the value of ΔM_s' also increases together.

Figure 7 shows the relationship between the ΔM_s' and ΔA_f' and the $\Delta\xi$ and also shows the effect of the partial recovery strain. In case of solution treatment, the values of ΔM_s' and ΔA_f' increase linearly with increasing the $\Delta\xi$ and decrease with increasing partial recovery strain. However, in case of cold working ratio of 30%, the variation of these values with the $\Delta\xi$ (or partial recovery strain) becomes large because the variation of recovery stress with the $\Delta\xi$ becomes large as shown in Fig.5.

When we use the shape memory effect, the transformation temperature hysteresis is desired to be small. Figure 8 shows the relationship between temperature hysteresis (A_f'-M_s') and the recovery strain ratio. The temperature hysteresis does not almost change with the recovery strain ratio for solution treatment. However, in case of cold working, the temperature hysteresis decreases slightly with increasing the partial recovery strain and as the cold working ratio increases, the temperature hysteresis becomes small.

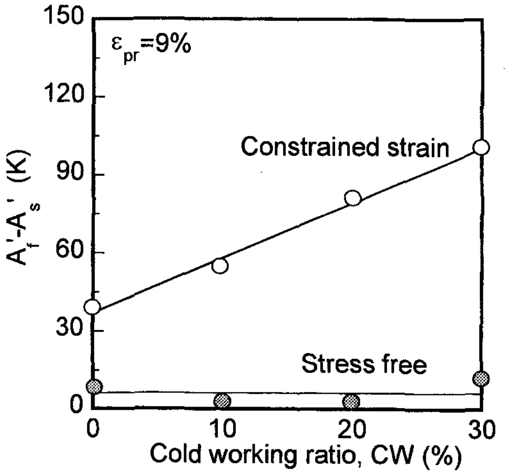

Fig.9 Variation of (A_f'-A_s') with cold working ration.

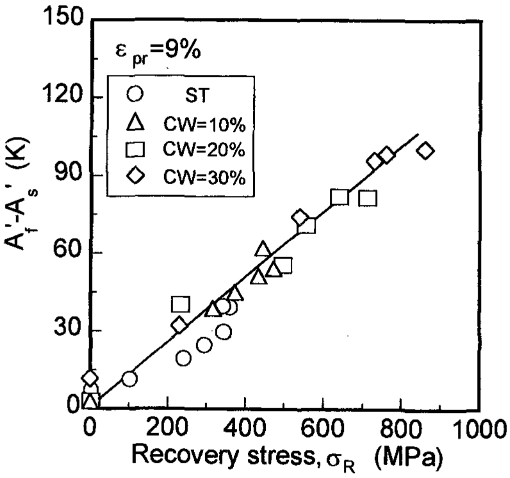

Fig.10 Relationship between (A_f'-A_s') and recovery stress σ_R for various cold working ratio.

As the temperature difference (A_f'-A_s') decreases, the response to temperature changes is improving and the recovery stress can be used in small temperature changes. Figure 9 shows the variation of (A_f'-A_s') with cold working ratio. In stress free, the values of A_f'-A_s' are insensitive to cold working ratio. However, in constrained strain, they increase linearly with cold working ratio. Therefore, improving the temperature response, the solution treatment is effective for samples.

Figure 10 shows the variation of the (A_f'-A_s') with the recovery stress σ_R and also shows the effect of the partial recovery strain. The values of (A_f'-A_s') increase almost linearly with increasing recovery stress. Furthermore, they do not depend on the cold working ratio and the partial recovery strain.

4. CONCLUSION

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

(1) The variation of recovery stress with partial recovery strain becomes large according to the increase of cold working ratio.

(2) The transformation temperature hysteresis with the partial recovery strain does not change for the solution treatment and decreases slightly with increasing cold working ratio.

(3) The temperature difference (A_f'-A_s') increases linearly with increasing cold working ratio and recovery stress.

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