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Effect of Heat Treatment on Temperature Response and Recovery Stress of Ti-Ni-Cu Shape Memory Alloy after Pre-Deforming

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This work describes the effect of heat treatment on temperature response and recovery stress of Ti-Ni-Cu shape memory alloy. The materials used in this study are Ti-41.7Ni-8.5Cu (at%) alloys which have different cold working ratio (10, 40%). Heat treatment temperatures of wire specimen are varied from 623 K to 773 K. Heating-cooling tests after pre-strain ranged from 1% to 3% at the isothermal temperature of 263K, are carried out to investigate the thermomechanical behavior of Ti-Ni-Cu alloy. The temperature response is decreased with increasing pre-strain and decreasing heat treatment temperature. However, the recovery stress becomes larger with increasing pre-strain and decreasing heat treatment temperature. On the other hand, there is little effect of heat treatment temperature, cold working ratio and pre-strain on transformation temperature hysteresis.
Key words: Ti-Ni-Cu alloy, shape memory alloy, actuator, pre-strain, heat treatment temperature

1. INTRODUCTION

The shape memory alloy (SMA) is better known as a functional material, since it has unique characters which are shape memory effect and superelastic behavior [1]. Ti-Ni SMAs have been already put to practical use in the fields of industry and medical because they have not only superior shape memory characteristic, but also ductility, toughness, fatigue resistance, corrosion resistance, abrasion resistance [2-4]. For example, Ti-Ni SMAs are used as a pipe coupling, an antenna of a mobile telephone, auto parts, an actuator and spring in the field of industry [5, 6]. They are also used as a stent in the chest surgery field and an orthodontic wire in the dentistry field [7, 8]. Furthermore, SMAs are being expected to be used as on actuator in the micromechanics field, since SMAs allow reduction in size and weight and can also generate recovery stress and strain [9, 10].

The response of SMA actuators is dependent on its temperature, and the generative force of them is determined by the recovery stress of SMAs. Ti-Ni-Cu alloys are one of promising materials for a component of SMA actuators, because the recovery stress increases and the stress hysteresis and transformation temperature hysteresis decrease with increasing copper content in the alloys [11, 12]. However, it is reported that the recovery stress and transformation temperature of SMAs are influenced by manufacturing processes such as processing rate and heat treatment [13-16].

This work carried out heating-cooling tests under constrained strain condition using the Ti-41.7Ni-8.5Cu (at%) alloy, for studying the effect of heat treatment on temperature response and recovery stress of Ti-Ni-Cu shape memory alloy after pre-deforming.

2. EXPERIMENTAL PROCEDURES

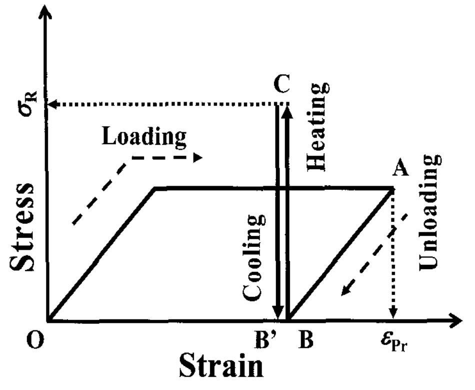
The chemical composition of the alloy used in this study is Ti-41.7Ni-8.5Cu (at%). The specimen shape is a wire with 1 mm diameter and 70 mm gage length. The specimen was processed in the following manner; the Ti-Ni-Cu shape memory alloy ingot was made using a high frequency induction vacuum furnace, and then was hot forged and hot extruded followed by cold drawing and intermediate annealing. Cold working ratio (CW) of the specimen was varied from 10% and 40%. Furthermore, the specimen was heat treated at the temperature range from 623 K to 773 K 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.

To investigate the effect of heat treatment on the temperature response and recovery stress of the Ti-Ni-Cu shape memory alloy, heating-cooling tests under constrained strain condition were carried out using the Ti-41.7Ni-8.5Cu (at%) alloy wire.

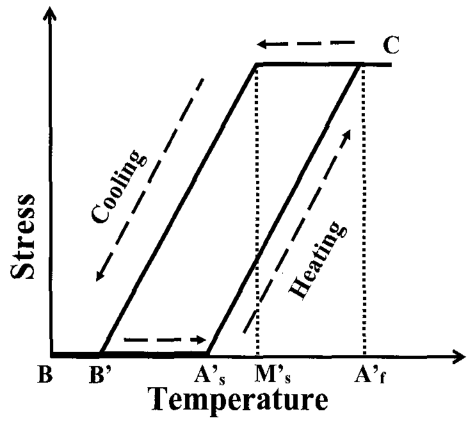
Figure 1 (a) shows a schematic diagram of the experiment to obtain the stress-strain curve in the heating-cooling test under constrained strain condition. The specimen was loaded to given pre-strains ranged from 1% to 3% at the isothermal temperature of 263 K lower than martensite transformation finish temperature

Table I Transformation temperatures of Ti-41.7Ni-8.5Cu (at%) alloy measured by DSC

T_{HT} (K)	Transformation temperatures (K)							
	M_f		M_s		A_s		A_f	
	CW10	CW40	CW10	CW40	CW10	CW40	CW10	CW40
623	313.7	274.7	336.1	323.5	333.9	292.7	351.5	336.2
673	311.5	291.6	332.4	318.5	332.4	309.7	346.8	335.4
723	315.4	306.2	336.4	320	333.9	324.9	350.3	339.7
773	318.1	320.4	330	333.7	336.1	338.2	347.5	350.6



(a) Stress-strain curve



(b)Stress-temperature curve

Fig.1 Schematic drawing of experimental procedure.

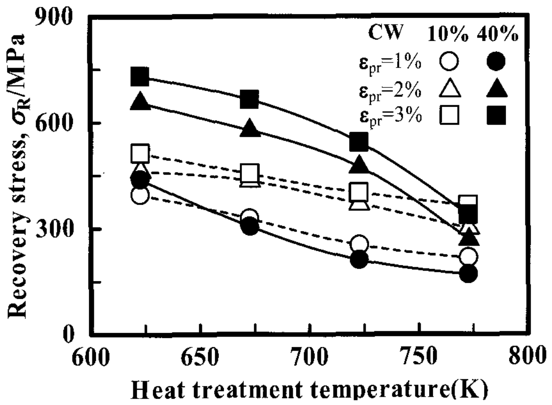


Fig.2 Variation of recovery stress σ_R with heat treatment temperature.

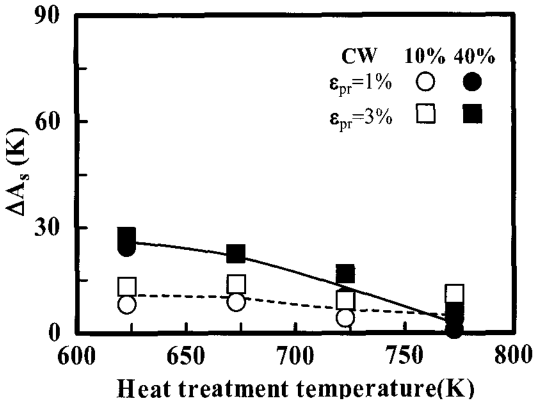


Fig.3 Variation of ΔA_s (=A_s'-A_s) with heat treatment temperature.

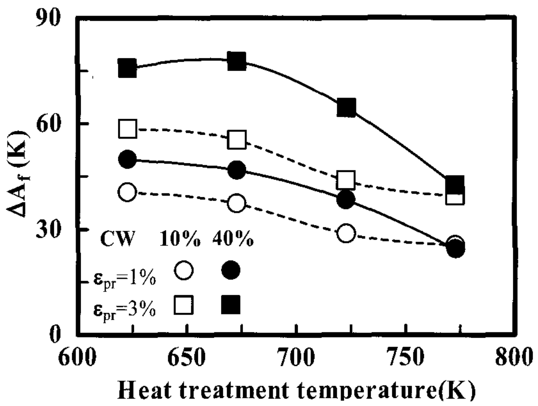


Fig.4 Variation of ΔA_f (=A_f'-A_f) with heat treatment temperature.

and was subsequently unloaded (O→A→B). And then, the specimen was heated at 3 K/min (B→C) and cooled at 5 K/min (C→B') under constrained strain condition. From the stress-strain curve and the stress-temperature relation during heating-cooling progress (B→C→B') shown in Fig.1 (b), the recovery stress σ_R, martensite start temperature M_s', reverse transformation start temperature A_s' and reverse transformation finish temperature A_f' after the pre-strain were obtained, respectively.

3. RESULTS AND DISCUSSION

3.1 Effect of heat treatment on recovery stress

Figure 2 shows the variation of the recovery stress with heat treatment temperature. The recovery stress decreases with increasing heat treatment temperature and with decreasing pre-strain. In addition, the recovery stress after pre-strains of 2% and 3% below the heat treatment temperature of 723 K increases with increasing CW. However, there is little effect of CW on the recovery stress after pre-strain of 1% and that after pre-strains of 2% and 3% at the heat treatment temperature of 773 K. It is reported that the critical stress for slip increases since the cold working increases the dislocation density within the material [17]. Therefore, the recovery stress increases with increasing CW since the extra damage introduced into the material due to pre-strain decreased with increasing CW. On the other hand, the recovery stress decreases with increasing heat treatment temperature, because an increase of heat treatment temperature causes the rearrangement and annihilation of dislocations [18] so that the dislocation density within the material decreases.

3.2 Effect of heat treatment on transformation temperature

Figure 3 shows the variation of ΔA_s (=A_s'-A_s) with heat treatment temperature. The A_s' and A_s show the reverse transformation start temperature after pre-strain

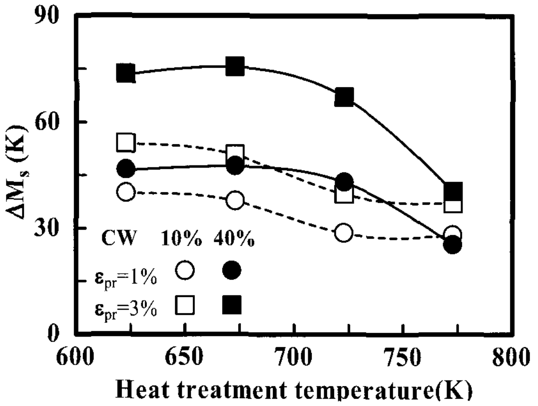


Fig. 5 Variation of ΔM_s (=M_s'-M_s) with heat treatment temperature.

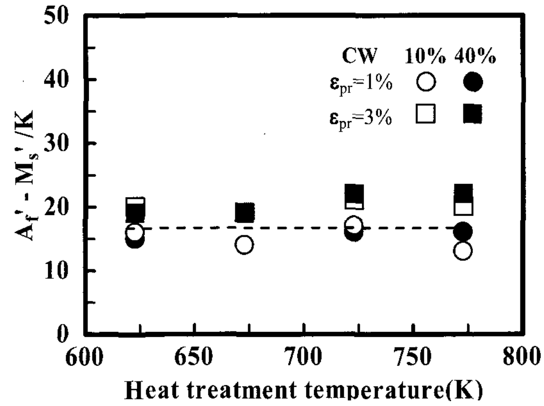


Fig. 7 Variation of A_s'-M_s' with heat treatment temperature.

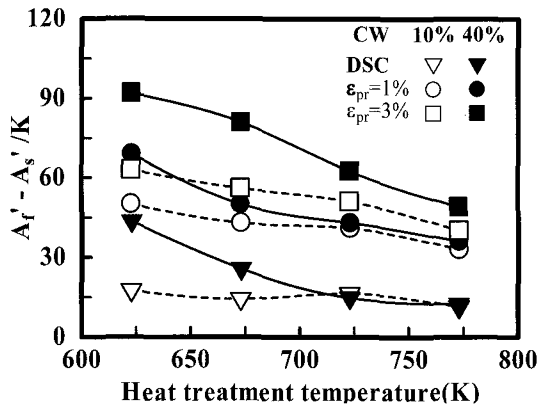


Fig. 6 Variation of A_f'-A_s' with heat treatment temperature.

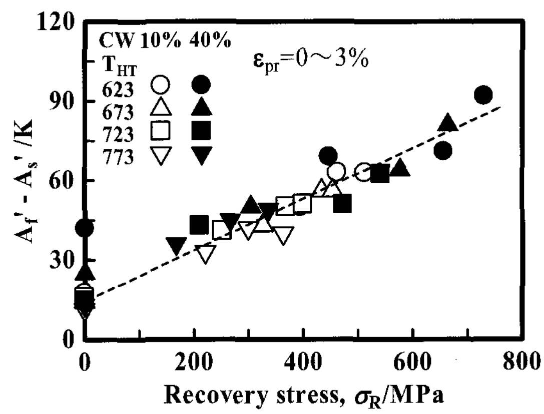


Fig. 8 Relationship between A_f'-A_s' and recovery stress σ_R.

and that measured by DSC, respectively. In the case of CW=40%, the ΔA_s decreases with increasing heat treatment temperature, because an increase of heat treatment temperature relax the elastic strain energy stored during cold working so that the A_s becomes a large as shown in Table I. In the case of CW=10%, the heat treatment temperature hardly affect the A_s since the release of elastic strain energy is saturated. Therefore, the ΔA_s of CW=10% is maintained nearly-constant. Furthermore, the ΔA_s decreases with increasing CW and with decreasing pre-strain. It is reported that the A_s is raised by the deformation in M phase because the elastic strain energy stored during martensite transformation is relaxed by slip [19]. The dislocation density increases with increasing CW. And also, the further slip decreases with decreasing pre-strain. Consequently, it is believed that the A_s' becomes a small since the stored elastic strain energy is hardly relaxed with increasing CW and with decreasing pre-strain.

The variation of ΔA_f (=A_f'-A_f) with heat treatment temperature is shown in Fig.4. The A_f' and A_f show the reverse transformation finish temperature after pre-strain and that measured by DSC, respectively. The ΔA_f decreases with increasing heat treatment temperature. As shown in Fig.2, the recovery stress decreases with increasing heat treatment temperature. Thus, it is presumed that the ΔA_f becomes a small because a decrease of the recovery stress decreases a driving force needed to finish the reverse transformation. In contrast, the ΔA_f increases with increasing CW and with increasing pre-strain due to the increase of a driving force needed to finish the reverse transformation, because the recovery stress increases with increasing CW and pre-strain as shown in Fig.2.

The variation of ΔM_s (=M_s'-M_s) with heat treatment temperature is shown in Fig.5. The M_s' and M_s show the transformation start temperature after pre-strain and that measured by DSC, respectively. M_s decreases with the decrease of A_f. Therefore, the ΔM_s decreases with increasing heat treatment temperature and with decreasing CW and pre-strain.

Figure 6 shows the variation of the reverse transformation temperature difference (A_f'-A_s') with heat treatment temperature. The (A_f'-A_s') decreases with increasing heat treatment temperature and with decreasing CW and pre-strain. The temperature response increases with the decrease of the (A_f'-A_s') since a SMA can recover its shape by the small temperature change if the reverse transformation temperature difference is small. Therefore, this result means that the temperature response increases with increasing heat treatment temperature and with decreasing CW and pre-strain.

The variation of transformation temperature hysteresis (A_f'-M_s') with heat treatment temperature is shown in Fig.7. There is little effect of the heat treatment temperature on the (A_f'-M_s'). Additionally, the variation of (A_f'-M_s') with CW is within 5 K.

3.3 Relationship between reverse transformation temperature difference and recovery stress

Figure 8 shows the relationship between the transformation temperature difference (A_f'-A_s') and the recovery stress. The recovery stress decreases with increasing heat treatment temperature as shown in Fig.2. The (A_f'-A_s') also decreases with increasing heat treatment temperature as shown in Fig.6. As a result, the (A_f'-A_s') increases almost linearly with increasing recovery stress. The decrease of the (A_f'-A_s') increases the temperature response. Thus, this result indicates that the temperature response increases with decreasing recovery stress.

4. CONCLUSIONS

Heating-cooling tests under constrained strain condition were carried out using the Ti-41.7Ni-8.5Cu (at%) alloy, for studying effect of heat treatment on temperature response and recovery stress of Ti-Ni-Cu shape memory alloy after pre-deforming. The obtained results are summarized as follows;

(1) The recovery stress has decreased with increasing heat treatment temperature and with decreasing CW and pre-strain.

(2) The ΔA_s has decreased with increasing heat treatment temperature. The ΔA_f has also decreased with increasing heat treatment temperature.

(3) The reverse transformation temperature difference (A_f'-A_s') decreases with increasing heat treatment temperature and with decreasing CW and pre-strain. Therefore, the temperature response increases with increasing heat treatment temperature and with decreasing CW and pre-strain.

(4) There has been little effect of the heat treatment temperature on the transformation temperature hysteresis (A_f'-M_s').

(5) The reverse transformation temperature difference (A_f'-A_s') has increased with increasing recovery stress. This result shows that the temperature response increases with decreasing recovery stress.

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