Transactions of the Materials Research Society of Japan 32[3] 627-630 (2007)

Thermomechanical Behavior and Electric Characteristic of Ti-Ni-Cu Shape Memory Alloy

Y. Takeda*, T. Yamamoto**, A. Goto** and T. Sakuma**
*TAKE R&D, Shizuoka 426-0087
** Faculty of Engineering, Oita University, Oita 870-1192, sakuma@cc.oita-u.ac.jp

This paper describes thermomechanical behavior and electric characteristic of Ti-Ni-Cu shape memory alloy. The Materials used in this study are Ti-41.7Ni-8.5Cu (mol%) and Ti-42.6Ni-7Cu (mol%) alloys. Cold working ratio of the Ti-41.7Ni-8.5Cu (mol%) alloy wire was varied from 10% to 40%. Heating-cooling tests under the pre-strain was ranged from 1% to 3% were carried out using the T i-41.7Ni-8.5Cu (mol%) alloy wire at the isothermal temperature of 273K, for investigating the thermomechanical behavior of Ti-Ni-Cu alloy. Heating-cooling tests under the pre-strain was varied from 0% to 3% were also carried out using the Ti-41.7Ni-8.5Cu (mol%) alloy wire at room temperature, for examining electric characteristic of Ti-Ni-Cu alloy. The large pre-strain and high cold working ratio have efficacy for obtaining large recovery stress. An increase in the pre-strain has slightly increased the transformation temperature hysteresis (A_f'-M_s'). Also, the temperature responsive property has become lower with an increase in the pre-strain and cold working ratio. On the other hand, an increase in the pre-strain facilitates control of the SMA actuator because it decreases the electric resistivity hysteresis.

Key words: Ti-Ni-Cu alloy, shape memory alloy, actuator, pre-strain, cold working ratio

1. INRODUCTION

Shape memory alloys (SMAs) have unique functions such as super-elasticity and shape memory effect. Therefore, various fields have a high degree of expectations for SMAs. In particular, SMAs have been put to practical use in the industry field, the medical field, and so on [1-4].

SMAs under applied stress generate a recovery stress and strain due to heating of them. Developments of SMA actuators using this property are being carried out. SMAs allow reduction in size and weight, and construction simplification of actuators because SMA actuators require no sensor. Also, SMA actuators have the advantage of being high power even if they are light [5, 6].

Ti-Ni-Cu alloys are being expected to be used in SMA actuators, because, with increasing copper content in the alloys, the recovery stress increases and the stress hysteresis and transformation temperature hysteresis decrease [7, 8]. 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 [9-12].

This study carried out heating-cooling tests under constrained strain condition, for studying the thermomechanical behavior of Ti-Ni-Cu alloy. Furthermore, electric characteristic were also investigated.

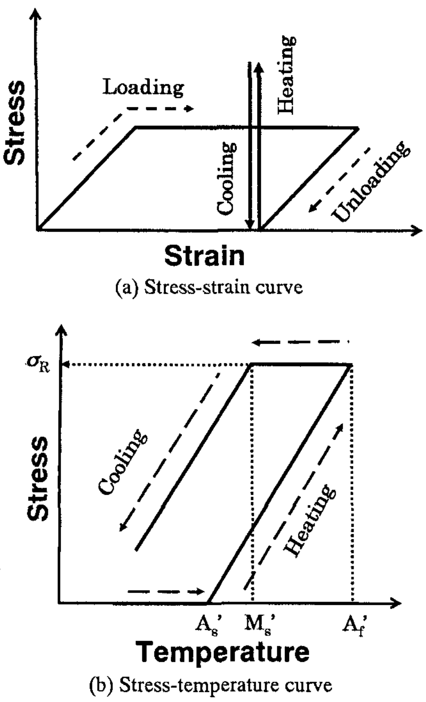
2. EXPERIMENTAL PROCEDURES

The chemical compositions of alloys are Ti-41.7Ni-8.5Cu and Ti-42.6Ni-7Cu (mol%). The specimen shape of Ti-41.7Ni-8.5Cu (mol%) alloy is a wire with 1 mm diameter and 70 mm gauge length, and that of Ti-42.6Ni-7Cu (mol%) alloy a wire with 0.3 mm diameter and 70 mm gauge length. Also, the Ti-42.6Ni-7Cu (mol%) alloy wire is Furukawa NT-H7-TTR. The Ti-Ni-Cu alloy wires were processed in the following manner; the Ti-Ni-Cu alloy ingots were made using a high frequency induction vacuum furnace, and then were hot forged and hot extruded followed by cold drawing and intermediate annealing. Cold working ratio of the Ti-41.7Ni-8.5Cu (mol%) alloy wire was varied from 10% to 40%. Furthermore, the wires were heat treated at 673K for 3.6ks in air. Martensite start temperature M_s, martensite finish temperature M_f, reverse transformation start temperature A_s and reverse transformation finish temperature A_f of the Ti-41.7Ni-8.5Cu (mol%) alloy wire measured by differential scanning calorimetry (DSC) are listed in Table I.

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

Cold working ratio (%)	Transformation temperatures (K)			
	M_s	M_f	A_s	A_f
10	331.5	312.2	333	345.7
20	326.4	307.8	329	342.5
30	319.8	302.7	322.4	337.2
40	317	300.6	322.9	336.7

To investigate the thermomechanical behavior of Ti-Ni-Cu alloy, heating-cooling tests under constrained strain condition were carried out using the T i-41.7Ni-8.5Cu (mol%) alloy wire. Figure 1 (a) shows a schematic diagram of the experiment to obtain the stress-strain curve in the heating-cooling test under



(a) Stress-strain curve

(b) Stress-temperature curve

Fig.1 Schematic drawing of experimental procedure.

constrained strain condition. The specimen was loaded to given pre-strains ranged from 1% to 3% at the isothermal temperature of 273K lower than martensite start temperature M_s and was subsequently unloaded. And then, the specimen was heated at 3K/min and cooled at 4K/min under constrained strain condition. From the stress-strain curve and the stress-temperature relation during heating-cooling progress 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 loading-unloading were obtained, respectively.

Heating-cooling tests under constrained strain condition were also carried out using the Ti-41.7Ni-8.5Cu (mol%) alloy wire, for examining electric characteristic of Ti-Ni-Cu alloy. The variation of electric resistivity during heating at 3K/min and cooling at 4K/min progress was measured after the specimen was loaded to given pre-strain varied from 0% to 3% at room temperature followed by unloading.

3. RESULTS AND DISCUSSION

3.1 Effect of cold working ratio and pre-strain on recovery stress

Figure 2 shows the variation of the recovery stress with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy. The recovery stress increases with increasing cold working ratio. The recovery strain increases with increasing cold working ratio since the extra damage introduced into the specimen decreases with increasing cold working ratio. Therefore, an increase in the cold working ratio increases the recovery stress because there is an approximate linear relationship between the recovery stress and the recovery strain. An increase in

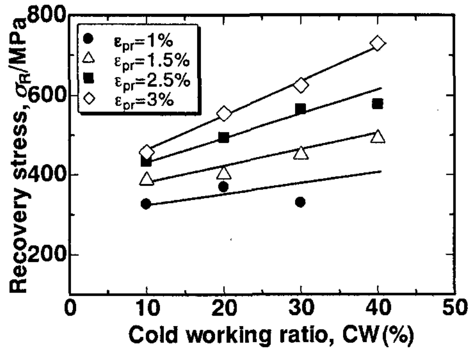


Fig.2 Variation of recovery stress with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy.

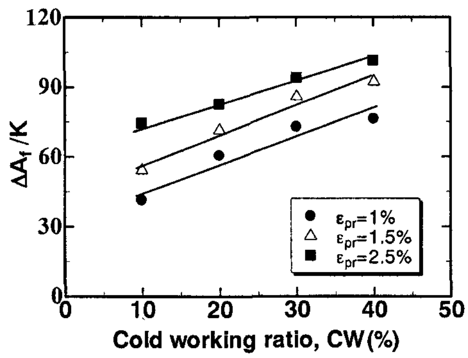


Fig.3 The variation of ΔA_f (=A_f'-A_f) with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy

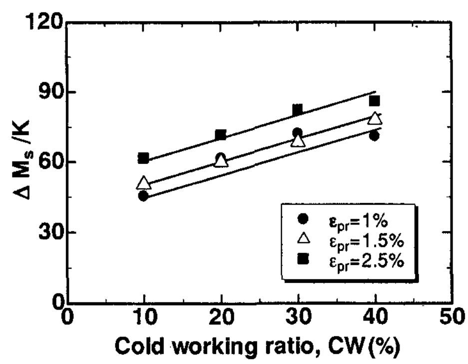


Fig.4 The variation of ΔM_s (=M_s'-M_s) with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy.

the pre-strain also increases the recovery stress because it increases the recovery strain. These results show that the high cold working ratio and large pre-strain have efficacy for obtaining large recovery stress from the Ti-41.7Ni-8.5Cu (mol%) alloy.

3.2 Effect of cold working ratio and pre-strain on transformation temperature hysteresis

Figure 3 shows the variation of ΔA_f (=A_f'-A_f) with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy. ΔA_f increases with increasing cold working ratio. As shown in Fig.2, the recovery stress increases with increasing cold working ratio. The recovery stress acts as the resistance to the reverse martensitic transformation since it acts as the reverse force against

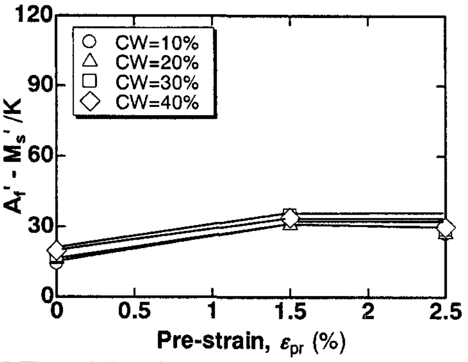


Fig.5 The variation of transformation temperature hysteresis A_f' -M_s' with pre-strain in the Ti-41.7Ni-8.5Cu (mol%) alloy.

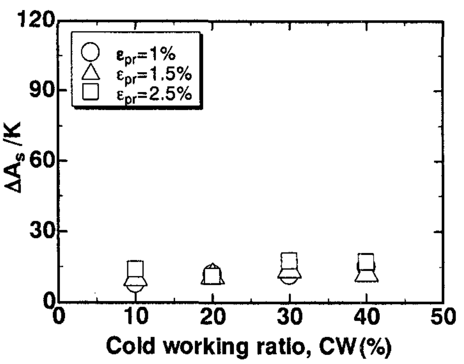


Fig.6 The variation ΔA_s (=A'$_s$-A_s) with pre-strain in the Ti-41.7Ni-8.5Cu (mol%) alloy.

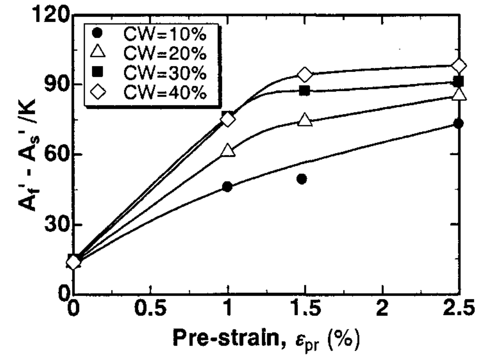


Fig.7 The variation of reverse transformation temperature difference A_f'-A_s' with pre-strain in the Ti-41.7Ni-8.5Cu (mol%) alloy.

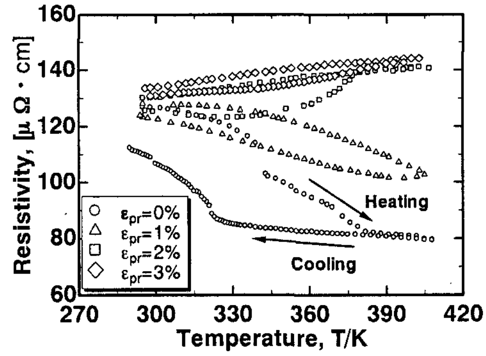


Fig.8 The variation of electric resistivity with temperature in Ti-42.6Ni-7Cu (mol%) alloy.

the shape recovery of the specimen. Therefore, an increase in the recovery stress increases a driving force needed to finish the reverse martensitic transformation. This is presumably the reason why ΔA_f increases with increasing cold working ratio. ΔA_f also increases with increasing pre-strain. This result suggests that the elastic strain energy stored in material is released by loading of pre-strain.

Figure 4 shows the variation of ΔM_s (=M_s'-M_s) with cold working ratio in the Ti-41.7Ni-8.5Cu (mol%) alloy. Since M_s raises up with the raising of A_f, there is an increase in ΔM_s with increasing cold working ratio and pre-strain. An increase in ΔM_s with increasing cold working ratio and pre-strain is a little smaller than that in ΔA_f.

Figure 5 shows the variation of transformation temperature hysteresis (A_f'-M_s') with pre-strain in the Ti-41.7Ni-8.5Cu (mol%) alloy. The transformation temperature hysteresis gently increased with increasing pre-strain up to 1.5%. However, the pre-strain more than 1.5% did not give further increase in the transformation temperature hysteresis (A_f'-M_s'). It is clear that an increase in the pre-strain slightly increases the transformation temperature hysteresis (A_f'-M_s') because an increase in ΔM_s with increasing cold working ratio is a little smaller than that in ΔA_f as shown in Figs. 3 and 4. In addition, the transformation temperature hysteresis (A_f'-M_s') is little affected by cold working ratio.

3.3 Effect of cold working ratio and pre-strain on temperature responsive

Figure 6 shows the variation ΔA_s (=A'$_s$-A_s) with pre-strain in the Ti-41:7Ni-8.5Cu (mol%) alloy. ΔA_s is small compared to ΔA_f and ΔM_s. Also, there is little effect of cold working ratio and pre-strain on ΔA_s.

In case of using the shape recovery and the recovery stress of SMAs, the smaller the heating quantity needed for finishing the reverse transformation is, the more the temperature responsive property increases. Figure 7 shows the variation of the reverse transformation temperature difference (A_f'-A_s') with pre-strain in the Ti-41.7Ni-8.5Cu (mol%) alloy. There is an increase in the reverse transformation temperature difference (A_f'-A_s') with increasing pre-strain. The increase in cold working ratio also gives an increase in the reverse transformation temperature difference (A_f'-A_s'). This fact means that the temperature responsive property becomes lower with an increase in the pre-strain and cold working ratio.

3.4 Effect of temperature and pre-strain on electric characteristic

Figure 8 shows the variation of the electric resistivity with temperature in Ti-42.6Ni-7Cu (mol%) alloy. The variation of electric resistivity with temperature under the pre-strain of 0% and 1% shows negative resistance characteristics. However, the positive resistance characteristics are found under the pre-strain of 2% and 3% because the electric resistivity increases with increasing temperature. Also, an increase in the pre-strain increases the electric resistivity and decreases the electric resistivity hysteresis. Consequently, an increase in the pre-strain will facilitate the position control of the SMA actuator because it decreases the electric resistivity hysteresis.

4. CONCLUSIONS

Heating-cooling tests under the pre-strain was ranged from 1% to 3% were carried out using the T i-41.7Ni-8.5Cu (mol%) alloy wire at the isothermal temperature of 273K, for investigating the thermomechanical behavior of Ti-Ni-Cu alloy. Heating-cooling tests under the pre-strain was varied from 0% to 3% were also carried out using the Ti-41.7Ni-8.5Cu (mol%) alloy wire at room temperature, for examining electric characteristic of Ti-Ni-Cu alloy. The obtained results are summarized as follows;

(1) The recovery stress has increased with increasing cold working ratio and pre-strain. Therefore, the high cold working ratio and large pre-strain have efficacy for obtaining large recovery stress.

(2) An increase in the pre-strain has slightly increased the transformation temperature hysteresis (A_f'-M_s')

(3) The reverse transformation temperature difference (A_f'-A_s') has increased with increasing cold working ratio and pre-strain. Therefore, the temperature responsive property becomes lower with an increase in the pre-strain and cold working ratio.

(4) The increase in the pre-strain will facilitate the position control of the SMA actuator because it decreases the electric resistivity hysteresis.

REFERENCES

[1] S. Miyazaki, T. Sakuma and T. Shibuya, "Properties and Application Development of Shape Memory Alloy", CMC, Japan (2001), pp.233-260.

[2] T. Honma, *J. Jpn. Soc. Mech. Eng.*, **87**, 517-522 (1984).

[3] K. Yamauchi, *Jpn. Inst. Met.*, **7**, 495-499 (1993).

[4] M. Miyazaki, *Jpn. Inst. Met.*, **24,** 69-74 (1985).

[5] D. Homma, *Journal of the Robotics Society of Japan*, **8-4**, 107-109 (1990)

[6] D. Homma, *J. Jpn. Inst. Met.*, 77-84 (1989).

[7] S. Miyazaki, K. Mizukoshi, T. Ueki, T. Sakuma and Y. Liu, *Mater. Sci. and Eng.*, **A273-275**, 658-63 (1999).

[8] T. Sakuma, U. Iwata, H.Takaku, N. Kriya, Y. Ochi, and T. Matsumura, *Trans. Japan Soc. Mech. Eng.*, **A66-664**, 748-54(2000).

[9] T. Saburi, *Metals and Technology*, 59, 11-18 (1989).

[10] S. Miyazaki and H. Sakamoto, *Jpn. Inst. Met.*, **24,** 33-44 (1985).

[11] T. Todoroki and H. Tamaura, *J. Jpn. Inst. Met.*, **50,** 538-545 (1986).

[12] T. Sakuma, Y. Mihara, H. Toyama, Y. Ochi and K.i Yamauchi, *Jpn. Inst. Met.*, **47**, 787-791 (2006).

(Received January 20, 2007;Accepted May 10, 2007)