Transactions of the Materials Research Society of Japan 28 [3] 611-614 (2003)

Pseudoviscoelastic Behavior of TiNi Shape Memory Alloy in Subloop

Hisaaki Tobushi, Takenobu Ikawa and Ryosuke Matsui
Department of Mechanical Engineering, Aichi Institute of Technology,
Yagusa-cho, Toyota 470-0392, Japan
Fax: +81-565-48-4555, e-mail: tobushi@me.aitech.ac.jp

The superelastic behaviors of TiNi shape memory alloy under various subloop loadings were investigated. The results obtained can be summarized as follows. (1) In the case of subloop loading under strain controlled-conditions, the reloading curve passes through the unloading-start point. In the case of stress-controlled conditions, the return-point memory does not appear. (2) In the case of subloop loading under stress-controlled conditions, strain increases under constant stress in the loading process and decreases in the unloading process. (3) In the case of subloop loading under stress-controlled conditions, stress decreases under constant strain in the loading process and increases in the unloading process. (4) The above-mentioned behaviors about the return-point memory and the pseudoviscoelastic behaviors similar to creep and stress relaxation appear according to the martensitic transformation and the reverse transformation based on the variation in stress and temperature.
Key words: Shape memory alloy, Superelasticity, Subloop, Return-point memory, Creep, Stress relaxation, Titanium-nickel alloy, Stress control

1. INTRODUCTION

In shape memory alloys (SMAs), the shape memory effect and superelastic characteristics appear based on the martensitic transformation (MT) [1-7]. In practical applications of SMAs, SMA elements are subjected to various thermomechanical loadings. In order to design SMA elements, the thermomechanical properties of SMAs are important.

Recently it has been reported that the deformation behaviors under subloop loadings are different between the strain-controlled condition and the stress-controlled condition [8]. Although the return-point memory appears in the subloop loading under the strain-controlled condition, it does not appear under the stress-controlled condition. In the case of the stress-controlled condition, temperature increases due to the MT in the loading process and decreases due to the reverse transformation in the unloading process. Both stress and strain vary based on these variations in temperature, and therefore the return-point memory does not appear in the case of stress-controlled conditions [9]. Recently it has been also reported that creep deformation and stress relaxation appear in SMAs under the subloop loadings [10].

In the present study, the superelastic behaviors of TiNi SMAs under various loading conditions are investigated experimentally. The conditions to cause the return-point memory are discussed. The pseudoviscoelastic behaviors of creep deformation and stress relaxation under the subloop loadings with the stress-controlled condition are also discussed.

2. EXPERIMENTAL METHODS

2.1 Materials and specimens

The material tested was a rectilinear Ti-55.4wt%Ni SMA wire, 0.75 mm in diameter, produced by Furukawa Electric Co. Its straightness was shape-memorized through shape-memory processing. This was done by holding the wire rectilinear at 673 K for 60 min followed by cooling in the furnace. The reverse-transformation finish temperature A_f was about 323 K.

2.2 Experimental apparatus

The SMA testing machine was used. The machine was composed of the tensile machine and the heating-cooling device. Displacement was measured by an extensometer with gauge length of 20 mm. Temperature was measured by a thermocouple, 0.1 mm in diameter, which was pressed on the specimen at the central part of the gauge length.

2.3 Experimental procedure

In order to investigate the superelastic properties of the material, the following four kinds of thermomechanical tension tests under the various loading conditions were carried out by keeping the ambient temperature T=353 K above A_f constant. Stress and strain were treated in terms of nominal stress and nominal strain, respectively. Therefore the stress-controlled and strain-controlled conditions mean the load-controlled and displacement-controlled conditions, respectively. Before the four tests, the full-loop loading test was carried out. In the tension test, the full-loop loading and unloading were applied under constant strain rate $\dot{\varepsilon}$ and stress rate $\dot{\sigma}$. The MT completes in the loading process and the reverse transformation completes in the unloading process.

(1) Subloop loading under constant strain rate

Strain rate $\dot{\varepsilon}$ was kept constant during the loading and unloading processes. In the loading process, it was unloaded before the completion of the MT. In the unloading process, it was reloaded before the completion of the reverse transformation. The subloop-loading processes were repeated

(2) Subloop loading under constant stress rate

Stress rate $\dot{\sigma}$ was kept constant during the subloop-loading and unloading processes. The subloop-loading processes were repeated.

(3) Subloop loading under constant stress

Stress was kept constant during the MT in the loading process and during the reverse transformation in the unloading process for a certain duration. Variation in strain was observed under constant stress.

(4) Subloop loading under constant strain
Strain was kept constant during the MT in the loading process and during the reverse transformation in the unloading process for a certain duration. Variation in stress was observed under constant strain.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Subloop superelastic behavior under strain-controlled condition

The stress-strain curves obtained by the subloop loading test under constant strain rate $\dot{\varepsilon}$ =1 %/min are shown in Fig.1. In the test, the process (A_i, B_i and C_i) corresponds to unloading and the process (C_i, D_i and A_{i+1}) to reloading. The process (A_i, B_i) and the process (C_i, D_i) are elastic. The reverse transformation appears in the process (B_i, C_i) and the MT appears in the process (D_i, A_{i+1}). The MT stress decreases under cyclic deformation [11]. Therefore the MT stress plateau during the reloading process (D_i, A_{i+1}) decreases with an increase in the number of cycles N. The reloading curve (C_i, D_i and A_{i+1}) passes through the unloading-start point A_i. Therefore the return-point memory is observed in the case of the strain-controlled condition.

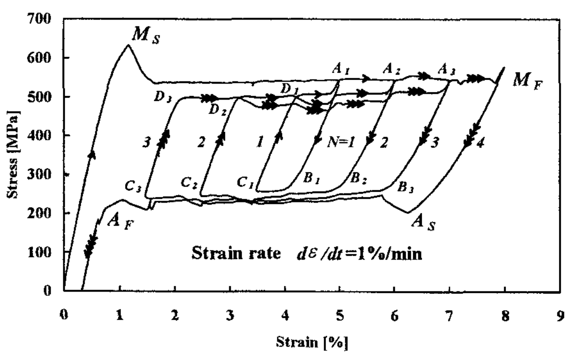


Fig.1 Stress-strain curves for subloop loading under constant strain rate $\dot{\varepsilon}$

3.2 Subloop superelastic behavior under stress-controlled condition

(1) Stress-strain curve

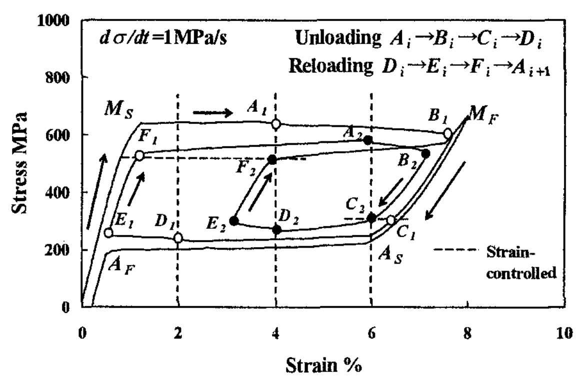
The stress-strain curves obtained by the subloop loading test under constant stress rate $\dot{\sigma}$ are shown in Fig.2. As can be seen, strain increases in the early stage of unloading (A_i, B_i) and decreases in the early stage of reloading (D_i, E_i). The variation in strain is lager under low-stress rate. These strain behaviors are quite different from those under constant strain rate observed in Fig.1. In the reloading process, the stress-strain curve does not pass through the unloading-start point A_i. Therefore the return-point memory which is observed under the strain-controlled condition does not appear under the stress-controlled condition.

(2) Condition for progress of phase transformation

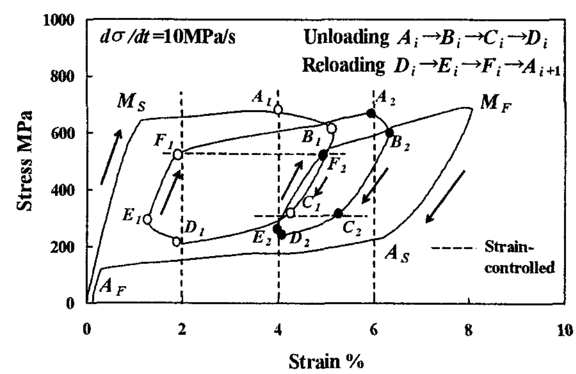
The condition for the progress of the MT and the reverse transformation is governed by the kinetics of the phase transformation [12, 13]. The condition for the progress of the phase transformation under subloop loadings is shown on the stress-temperature phase diagram in Fig.3 [9]. The conditions for the start and finish of the MT and the reverse transformation are expressed by the transformation lines M_S, M_F, A_S and A_F, respectively. Each transformation progresses in the transformation strip between the start line and the finish line. As can be seen, the MT progresses if the state of stress and temperature varies to the directions ① and ② in which the volume fraction ξ of the M-phase increases. The reverse transformation progresses if the state varies to the directions ④ and ⑤ in which ξ decreases. Based on this consideration, the MT must progress in the early stage of unloading (A_i, B_i) under constant $\dot{\sigma}$ and strain increases as observed in Fig.2. The reverse transformation must progress in the early stage of reloading (D_i, E_i) and strain decreases as observed in Fig.2.

3.3 Strain behavior under constant stress

The stress-strain curve obtained by the subloop loading test under constant stress is shown in Fig.4. In the loading process (O, A) and the unloading process (B, C), stress rate was 1 MPa/s. Stress was kept constant during the process (A, M_F) following the point A and during the process (C, A_F) following the point C. The condition of constant stress will correspond to the condition under very low stress rate. Therefore, as observed in Figs.2 and 4, the MT progresses under low stress rate or constant stress due to decrease in temperature, resulting in increase in strain. The reverse transformation also progresses under constant stress due to increase in temperature, resulting in decrease in strain. The increase in strain under constant stress is similar to creep deformation and the decrease in strain under constant stress is similar to creep recovery after unloading which appear in the viscoelastic material. These creep and creep

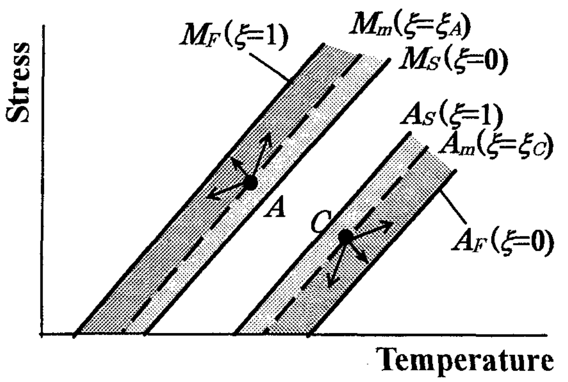


(a) $\dot{\sigma}$ =1 MPa/s

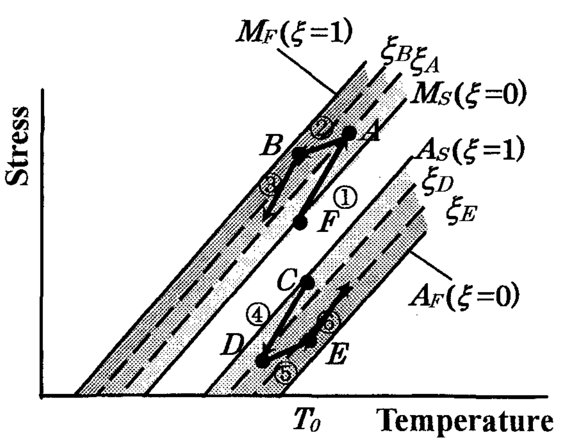


(b) $\dot{\sigma}$ =10 MPa/s

Fig.2 Stress-strain curves for subloop loading under constant stress rate $\dot{\sigma}$



(a) Path for progress of phase transformation



(b) Paths for progress and stop of phase transformation

Fig.3 Conditions for progress of MT and the reverse transformation under subloop loadings

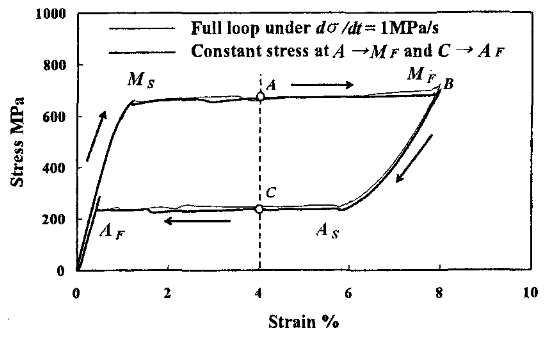


Fig.4 Stress-strain curves for subloop loading under constant stress during loading and unloading

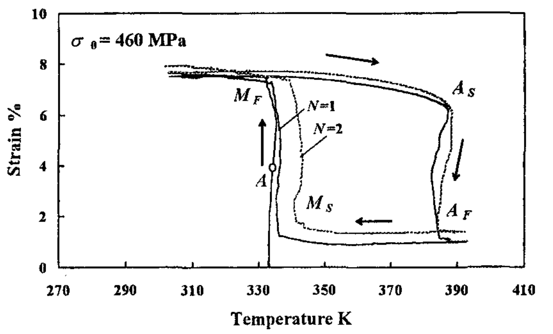


Fig.5 Variation in strain during heating and cooling under constant stress σ_0

recovery in SMA must appear owing to the MT and the reverse transformation, respectively, based on the variation in temperature.

As observed above, temperature varies due to the phase transformation during loading and unloading, and temperature returns to the ambient temperature with lapse of time under constant stress, resulting in variation in strain. In order to confirm the strain behavior during variation in temperature under constant stress, the heating-cooling test under constant stress was carried out. The relationship between strain and temperature obtained by the test is shown in Fig.5. In the test, at first, strain ε_0= 4 % at the point A was applied at temperature T_0=333 K. Following the loading to the point A and keeping stress σ_0=460 MPa at the point A constant, the specimen was cooled down to T_l=303 K which was followed by heating up to T_h=393 K. The heating and cooling under constant stress were repeated twice. As can be seen in Fig.5, strain decreases due to the reverse transformation between A_S and A_F in the heating process. In the cooling process, strain increases due to the MT between M_S and M_F. Therefore, it is important to note that, even if the ambient temperature is constant in applications of SMAs, creep and creep recovery must appear if temperature varies based on the phase transformation in the subloop loadings.

3.4 Stress behavior under constant strain

The stress-strain curve obtained by the subloop loading test under constant strain is shown in Fig.6. In the loading and unloading processes, stress rate was 30 MPa/s. Strain was kept constant for 10 min during the loading process (A_i, B_i) and during the unloading process (C_i, D_i). As can be seen in Fig.6, stress decreases under constant strain during (A_i, B_i) and increases during (C_i, D_i). The decrease in stress and the increase in stress stop on the upper stress plateau and on the lower stress plateau of the stress-strain curve under low strain rate, respectively.

The variations in stress and temperature during first step of the subloop loading (O, M_S, A_1 and B_1) are shown in Fig.7. In the test, stress rate was constant during loading (O, M_S and A_1) and strain was kept constant during (A_1, B_1). As can be seen in Fig.7, temperature increases due to the MT during loading (M_S, A_1). Both stress and temperature decrease markedly just after keeping the strain constant at the point A_1 and hold constant thereafter till the point B_1. Although temperature varies due to the MT in the early stage under constant strain, temperature approaches the ambient temperature after the early stage. The decrease in stress under constant strain is similar to stress relaxation and the increase in stress under constant strain is similar to stress recovery after unloading which appear in the viscoelastic material. These stress relaxation and stress recovery must appear owing to the MT and the reverse transformation, respectively, based on the variation in temperature.

In the experiments of the present study, temperature was controlled to keep the ambient temperature constant. Therefore the variation in temperature of the material depends on the heating and cooling conditions. This means that the variations in stress and strain which appear based on the MT due to the variation in temperature depend on the size of the SMA elements and the conditions of heat transfer between the SMA elements and atmosphere. Therefore, in order to design the SMA elements, these pseudoviscoelastic behaviors must be taken into account in the case of the stress-controlled subloop loadings.

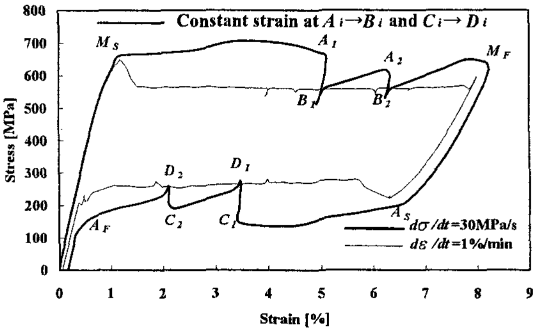


Fig.6 Stress-strain curves for subloop loading under constant strain during loading and unloading

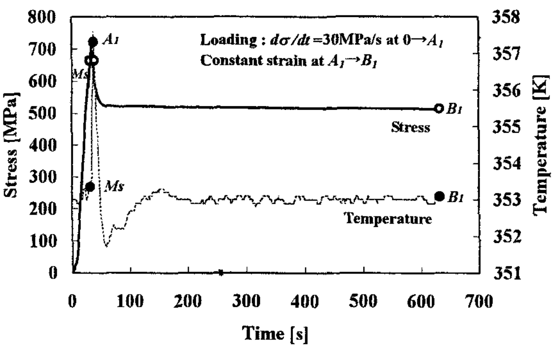


Fig.7 Variations in stress and temperature during subloop loading (O, Ms, A_1, B_1) with constant strain (A_1, B_1)

4. CONCLUSIONS

The superelastic behaviors of TiNi SMA under various subloop loadings were investigated. The results obtained can be summarized as follows.

(1) In the case of subloop loading under strain-controlled conditions, the reloading curve passeses through the unloading-start point. In the case of stress-controlled conditions, the return-point memory does not appear.

(2) In the case of subloop loading under stress-controlled conditions, strain increases under constant stress in the loading process and decreases in the unloading process.

(3) In the case of subloop loading under stress-controlled conditions, stress decreases under constant strain in the loading process and increases in the unloading process.

(4) The above-mentioned behaviors concerning the return-point memory and the pseudoviscoelastic behaviors similar to creep and stress relaxation appear according to the MT and the reverse transformation based on the variation in stress and temperature.

ACKNOWLEDGEMENTS

The experimental work of this study was carried out with the assistance of the students in Aichi Institute of Technology, to whom the authors with to express their gratitude. The authors are also grateful to the Scientific Research (C) in Grants-in-Aid for Scientific Research by the Japan Society for Promotion of Science for financial support.

REFERENCES

[1] H. FUNAKUBO [Ed.], *Shape memory alloys*, Gordon and Breach Science Pub., 1987.
[2] T. W. DUERIG, K. N. MELTON, D. STOCKEL and C. M. WAYMAN [Eds.], *Engineering aspects of shape memory alloys*, Butterworth-Heinemann, 1990.
[3] K. OTUKA and C. M. WAYMAN [Eds.], *Shape memory materials*, Cambridge University Press, 1998.
[4] T. SABURI [Ed.], *Shape memory materials*, Trans Tech Pub., 2000.
[5] Archives of Mechanics, **51**, 6, 1999.
[6] Y. Y. CHU and L. C. ZHAO [Eds.], *Shape memory materials and its applications*, Trans Tech Pub., 2002.
[7] Q. P. SUN [Ed.], *IUTAM Symposium on mechanics of martensitic phase transformation in solids*, Kluwer Academic Pub., 2002.
[8] G. SOCHA, B. RANIECKI and S. MIYAZAKI, *Influence of control parameters on inhomgenity and the deformation behavior of Ti-51.0at%Ni SMA undergoing martensitic phase transformation at pure tension*, 33rd Solid Mechanics Conference, 369-370, 2000.
[9] H. TOBUSHI, K. OKUMURA, M. ENDO and K. TANAKA, *Deformation behavior of TiNi shape-memory alloy under strain- or stress-controlled conditions*, Arch. Mech. **54**, 1, 75-91, 2002.
[10] D. HELM and P. HAUPT, *Termomechanical behavior of Shape memory alloys*, Smart structures and materials 2001, Proc. of SPIE, **4333**, 302-313, 2001.
[11] H. TOBUSHI, S. YAMADA, T. HACHISUKA, A. IKAI and K. TANAKA, Thermomechanical properties due to martensitic and R-phase transformation of TiNi shape memory alloy subjected to cyclic loadings, Smart Mater. Struct., **5**, 788-795, 1996.
[12] K. TANAKA, S. KOBAYASHI and Y. SATO, *Thermomechanics of transformation pseudoelasticity and shape memory effect in alloys*, Inter. J. Plasticity, **2**, 59-72, 1986.
[13] K. TANAKA, A thermomechanical sketch of shape memory effets: one-dimensional tensile behavior, Res Mechanica, **18**, 251-263, 1986.

(Received December 21, 2002; Accepted March 10, 2003)