Recovery Stress Associated with R-Phase Transformation in TiNi Shape Memory Alloy*

(Properties under Constant Residual Strain)

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The recovery stress associated with the R-phase transformation in TiNi shape memory alloy was investigated experimentally with respect to constant residual strain. The results are summarized as follows. (1) The recovery stress in the heating process is larger than the R-phase transformation stress in the loading process at low temperature. (2) In the heating process, the recovery stress occurs at about 320 K and takes a maximum value at about 335 K. The recovery stress increases along the reverse transformation line on the stress-temperature plane. (3) The higher the shape memory processing temperature, the larger the recovery stress. (4) The larger the maximum strain at low temperature, the larger the recovery stress.

Key Words: Inelastic Deformation, Nonferrous Metal, Titanium-Nickel Shape Memory Alloy, Rhombohedral Phase Transformation, Stress-Strain-Temperature Relationship, Constitutive Equation

1. Introduction

In shape memory alloy (SMA), the nonlinear transformation strain remains after unloading at a certain temperature. The residual strain recovers upon heating, which is called the shape memory effect (SME). In many SMAs, SME appears due to martensitic transformation. In TiNi SMA, SME also occurs due to rhombohedral phase (R-phase) transformation⁽¹⁾⁻⁽⁹⁾.

In R-phase transformation, the crystalline lattice changes from a body-centered cubic lattice (parent phase) to a rhombohedral lattice (R-phase) with isotropic variation in three interaxial angles. The

characteristics of R-phase transformation are as follows. Transformation strain is smaller than 1% and thus fatigue strength is high⁽¹⁰⁾. Temperature hysteresis is small and thus response to heating and cooling is fast.

As an application for SME, recovery stress appears upon heating under constant nonlinear transformation strain which remains after unloading at low temperature. In many applications for SMA, the recovery stress is used. For example, many pipe couplings are used in airplanes. In order to design the SMA elements which use recovery stress, it is important for recovery stress to make the magnitude and conditions for progress clear. Little literature exists on the properties of recovery stress⁽¹¹⁾.

In the present study, with respect to recovery stress associated with the R-phase transformation under constant residual strain in TiNi SMA, we will investigate the magnitude and conditions for progress for the recovery stress by means of a heating test. That is, we will discuss the influence of shape memory processing (SMP) temperature and maximum strain on the magnitude of the recovery stress and conditions for progress.

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2. Experimental Method

2.1 Materials and specimen

The material was Ti-55.2 wt%Ni SMA wire, 0.75 mm in diameter, which was produced by Furukawa Electric Co. The wire was heat-treated at T_h for 1 hr before being cooled in the furnace so that it memorized a straight line as its shape. The values of T_h were 673 K, 698 K, 723 K and 773 K. The reverse transformation completion temperature A_f of the specimen depended little on T_h , and A_f measured by a differential scanning calorimeter was about 334 K⁽⁹⁾.

2.2 Experimental apparatus

The experimental apparatus was a shape memory

Fig. 1 Schematic stress-strain relationship in the heating test under constant residual strain

property testing machine which was composed of a tensile machine with a constant-temperature chamber and a temperature-control device⁽⁸⁾. The specimen was heated with a spray of compressed air heated by a heater. Temperature was measured with a thermocouple, 0.1 mm in diameter, on the surface of the specimen. Displacement of the specimen was measured with an extensometer of 20 mm gaugelength.

2.3 Experimental procedure

The schematic stress-strain relationship observed in the experiments is shown in Fig. 1. As seen in Fig. 1, first, the loading and unloading processes with maximum strain ϵ_m were performed at a constant temperature T_1 . Holding residual strain ϵ_p constant, the specimen was heated to temperature T_2 . Recovery stress, which appeared upon heating, was investigated. Strain rate in the loading and unloading processes was constant, 0.4%/min. Values of ϵ_m were 0.2, 0.4, 0.6, 0.8 and 1.0%. T_1 and T_2 were 303 K and 353 K, respectively. In the case of $T_h=773$ K, T_2 was 373 K. The heating rate was about 0.4 K/s.

3. Experimental Results and Discussion

3.1 Stress-strain relationship

The stress-strain curves obtained in the experiments are shown for each SMP temperature T_h and maximum strain ϵ_m , in Fig. 2.

As seen in Fig. 2, on the whole, recovery stress is

Fig. 2 Stress-strain curves

large in proportion to ϵ_m . Because R-phase transformation progresses in proportion to ϵ_m , the amount of recovery due to reverse transformation in the heating process after unloading may be large for large ϵ_m , resulting in large recovery stress. Compared with the R-phase transformation stress in the loading process, the recovery stress is very large in the case of large ϵ_m . This inclination of recovery stress appears significantly in the case of high T_h . With respect to the ratio of recovery stress to transformation stress in the loading process, the ratio of recovery stress due to R-phase transformation is larger than that due to martensitic transformation^{(12),(13)}.

As seen in Fig. 2, in the case of high T_h , recovery stress is large for small ϵ_m . In the case of $T_h=773$ K, though the R-phase transformation region (horizontal yield stage) does not clearly appear in the loading process, large recovery stress is obtained in the heating process after unloading. In the case of high T_h , because the R-phase transformation is completed under a small strain in the loading process, the amount of recovery (the amount of variation in the volume fraction of the R-phase) due to reverse transformation in the heating process is large even if ϵ_m is small, resulting in large recovery stress.

As seen in Fig. 2, in the case of small ϵ_m and low T_h , even if R-phase transformation is induced in the loading process, recovery stress σ_r does not appear. It may be assumed from the behavior of σ_r that, though it is not clear on the stress-strain curve, reverse transformation appears in the unloading process.

3.2 Stress-temperature relationship

The stress-strain curves shown in Fig. 2 and the corresponding stress-temperature curves are simultaneously shown for maximum strain ϵ_m of 0.8% and SMP temperature T_h of 723 K and 773 K in Fig. 3. As seen from the stress-temperature curves in Fig. 3, in the heating process under constant residual strain from the temperature T_i at which loading and unloading were performed, stress varies slightly in the early stage of heating, increases significantly above a certain temperature and varies little above a certain other temperature.

In order to investigate the behavior of stress in the heating process in more detail, the stress-temperature curves shown in Fig. 3 are enlarged in Fig. 4. The starting line σ'_{As} and completion line σ'_{Af} of reverse transformation⁽⁹⁾, which were obtained by the tensile test at a constant temperature, are shown by the dashed lines in Fig. 4. As seen in Fig. 4, with a rise in temperature, stress increases significantly from about 320 K and stops increasing at about 335 K. Comparing the behavior of recovery stress in the heating process with the transformation lines shown by dashed lines, it

is ascertained that recovery stress begins increasing at the reverse transformation starting line and stops increasing at the reverse transformation completion line. This behavior of recovery stress is the same as the behavior of recovery stress associated with martensitic transformation^{(12),(13)}.

In the case of $T_h=773$ K and $\epsilon_m=0.8\%$, recovery stress increases again at temperatures above about 360 K. The reason why recovery stress increases again may be explained as follows. In the case of high SMP

Fig. 3 Stress-strain curves and stress-temperature curves ($\epsilon_m=0.8\%$)

Fig. 4 Stress-temperature curves ($\epsilon_m=0.8\%$)

temperature, the martensitic transformation start stress decreases and approaches the R-phase transformation stress⁽¹⁴⁾. Therefore, though the two transformation regions associated with R-phase transformation and martensitic transformation (two horizontal yield stages) are not clearly observed on the stress-strain curves in Fig. 2, it may be assumed that martensitic transformation is induced after completion of R-phase transformation in the loading process. The reverse transformation starting line of martensitic transformation is located on the higher-temperature side of the reverse transformation completion line of R-phase transformation⁽⁸⁾. Thus it may be considered that the recovery stress appears due to reverse transformation of martensitic transformation above about 360 K in the heating process after reverse transformation completion of R-phase transformation. Detailed investigation of the recovery stress associated with both transformations will be a future problem.

As seen from stress-strain curves in Fig. 2, after completion of reverse transformation (after recovery stress takes a maximum value) in the heating process, recovery stress tends to decrease slightly. This decrease in stress appears significantly in the case of small maximum strain, that is, if the heating process starts during the R-phase transformation. The reason why the decrease in stress appears when heating temperature becomes higher than the reverse transformation completion temperature may be considered as follows. In the present study, the specimen is heated under constant residual strain ϵ_p , and thus thermal stress due to thermal expansion occurs if temperature rises. The thermal stress that is induced due to heating under constant strain is compressive stress, but the recovery stress due to reverse transformation of R-phase transformation considered in the present study is tensile stress. Therefore the thermal stress acts in the opposite direction of the recovery stress, yielding decrease in the recovery stress.

3.3 Relationship between recovery stress and SMP temperature

The relationship between recovery stress σ_r and SMP temperature T_h obtained in the experiments is shown for each maximum strain ϵ_m in Fig. 5. In Fig. 5, the recovery stress σ_r represents the stress that was induced by heating at temperature T_2 , as shown in Fig. 1.

As seen in Fig. 5, for every ϵ_m , the higher the SMP temperature T_h , the larger the recovery stress σ_r . The reason why σ_r is large in proportion to T_h may be considered as follows. In cold working, by which wire is produced, dislocations with high density are induced. If T_h is high, many dislocations are removed, and thus deformation resistance in the R-phase trans-

formation and reverse transformation decreases⁽¹⁵⁾. As observed in the previous paper⁽⁹⁾, in the case of low T_h , because reverse transformation appears due to partial pseudoelasticity in the unloading process, the amount of recovery (the amount of variation in the volume fraction of R-phase) due to reverse transformation in the heating process is small, and thus the recovery stress is small.

3.4 Relationship between recovery stress and maximum strain

The relationship between the recovery stress σ_r and maximum strain ϵ_m is shown for each SMP temperature T_h in Fig. 6. In Fig. 6, σ_r represents stress at temperature T_2 .

As seen in Fig. 6, for every T_h , the larger the maximum strain ϵ_m , the larger the recovery stress σ_r . The reason why σ_r is large in proportion to ϵ_m may be considered as follows. Because R-phase transformation progresses in proportion to ϵ_m in the loading process, the amount of recovery (the amount of variation in the volume fraction of the R-phase) due to reverse transformation in the heating process after unloading is large in the case of large ϵ_m . As observed in Fig. 4, the recovery stress increases along the reverse transformation zone. If the volume fraction of R-phase is small, the recovery stress reaches the reverse transformation completion line rapidly (at low temperature), as in the case of martensitic transformation^{(12),(16)}. Therefore the recovery stress is small in the case of small ϵ_m .

Fig. 5 Dependence of recovery stress σ_r on SMP temperature T_h

Fig. 6 Dependence of recovery stress σ_r on maximum strain ϵ_m

4. Conclusions

The heating test under constant residual strain for TiNi SMA was carried out, and the magnitude and conditions for progress for the recovery stress associated with R-phase transformation were discussed. The results obtained are summarized as follows.

(1) Compared with the R-phase transformation stress induced in the loading process at low temperature, the recovery stress that appears in the heating process is very large.

(2) The recovery stress begins increasing at about 320 K and takes a maximum value at about 335 K. The recovery stress in the heating process increases along the transformation lines on the stress-temperature plane.

(3) The higher the SMP temperature, the larger the recovery stress.

(4) The larger the maximum strain induced at low temperature, the larger the recovery stress.

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