Cyclic Deformation of TiNi Shape Memory Alloy*

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The cyclic deformation properties of TiNi shape memory alloy wires and helical springs for the martensitic transformation and the R-phase transformation were investigated experimentally. The results are summarized as follows. For cyclic deformation associated with the martensitic transformation, the transformation stress decreases and the transformation temperature rises. The amount of variation in the transformation stress and the transformation temperature is large in the early number of cycles and is small after about the 20th cycle. For cyclic deformation associated with the R-phase transformation, the transformation stress and the transformation temperature vary little. For cyclic deformation of helical springs, the recovery deflection is very large in the R-phase transformation region. The recovery deflection and the recovery force of the helical spring under cyclic deformation vary slightly even in the martensitic transformation region.

Key Words: Inelastic Deformation, Nonferrous Metal, Titanium-Nickel Shape Memory Alloy, Cyclic Deformation, Martensitic Transformation, Rhombohedral Phase Transformation

1. Introduction

One of the advanced high-performance materials for which development and study for practical use have recently progressed is shape memory alloy (SMA)⁽¹⁾. SMAs are being used as industrial and medical materials^{(2),(3)}. In the applications to an actuator, robot and solid-state heat engine, SMA is used as a working element which performs cyclic motions. The working characteristics of the SMA element are specified by the beginning and completion temperatures of the motion, the working stroke and the working force. These characteristic values are determined by the transformation temperature, the transformation strain and the transformation stress⁽⁴⁾. The characteristic values associated with the trans-

formation vary through cyclic deformation, and fatigue is observed, which is the same as in normal metals^{(5),(6)}. Thus to design the SMA element, the behavior of the above-mentioned characteristic values subjected to thermomechanical cycles becomes crucial. Therefore we have investigated the basic properties of SMAs^{(7),(8)}, cyclic properties of the stress-strain-temperature relation⁽⁹⁾⁻⁽¹²⁾, and deformation of a helical spring⁽¹³⁾ and its properties under cyclic loading^{(14),(15)}.

In TiNi SMA, not only the martensitic transformation (MT) but also the rhombohedral phase transformation (RPT) occur⁽¹⁶⁾⁻⁽²⁰⁾. For RPT, because the response to heating and cooling is fast and fatigue strength is high, the applications of the material using RPT are drawing attention⁽²¹⁾.

In the current study, the properties of TiNi SMA subjected to the above-mentioned thermomechanical cycles are discussed. That is, the cyclic deformation properties associated with MT and RPT are discussed. Experiments with cyclic loading-unloading and experiments with thermal cycles on a wire and a helical spring were carried out. Based on experimental results, the design considerations for the SMA

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elements are discussed.

2. Experimental Method

2.1 Materials and specimen

The material was a Ti-55.3 wt%Ni SMA wire, 0.75 mm in diameter, which was produced by Furukawa Electric Co., Ltd. The specimens were given shape memory of a straight line and a helical spring through shape memory processing (SMP). This was done by holding the wire in the desired shape at the SMP temperature T_P for 20 min and cooling in the furnace. The pitch of the helical spring was 2.2 mm, the mean spring diameter 9 mm, the numbers of active coil turns 8~18. The reverse transformation completion temperature A_f was about 323 K for $T_P=673$ K.

2.2 Experimental apparatus

The experimental apparatus used for testing the wire was a shape memory property testing machine⁽¹⁸⁾. The experimental apparatus was composed of a tensile machine and a heating-cooling device. The specimen was heated by hot air or cooled by liquid carbon dioxide. The gauge length of an extensometer was 20 mm.

The experimental apparatus used for testing the helical spring was an offset crank SMA heat engine^{(22),(23)}. In the heat engine the SMA helical springs were mounted on the circumferences of a large disk and a small disk that were eccentric. The outside diameter of the large disk was 280 mm, that of the small disk 80 mm and the eccentricity between the centers of these disks 35 mm. The heating part was immersed in hot water and cooling part was in air.

2.3 Experimental procedure

To investigate the cyclic properties of deformation, the following five experiments were carried out.

2.3.1 Cyclic deformation test for MT

(1) Exp. MPE: cyclic properties of PE

Several-percent strains induced by MT in the loading process recover in the unloading process at temperatures above A_f , the property of which is called pseudoelasticity (PE). In the experiment MPE, the cyclic properties of PE were investigated by tensile tests of the wire. That is, the loading and unloading processes were repeated at temperature T above A_f for the maximum strain ϵ_m ⁽⁹⁾. The strain rate in the loading and unloading processes was 2%/min.

(2) Exp. MRD: cyclic properties of RD

In the experiment MRD, the cyclic properties of recovery deformation (RD) were examined by the tensile tests of the wire⁽¹⁰⁾. That is, at first, the initial strain with the corresponding stress was given at the low temperature T_1 below A_s . Following this process and maintaining the same axial force, i.e., constant nominal stress σ_0 , the process of heating to the high

Table 1 Maximum and minimum elongations and shear strain of helical spring

n	$l_{\max}$ %	$l_{\min}$ %	$\gamma_{\max}$ %	$\gamma_{\min}$ %
8	563	195	4.69	1.62
10	436	138	3.60	1.14
12	334	93	2.84	0.79
14	271	65	2.30	0.55
16	236	49	1.94	0.41
18	196	32	1.62	0.26

(1) Elongation $l=(L-L_0)/L_0$

where L =axial length of coils

L_0 =initial length of coils

(2) Shear strain $\gamma=d(L-L_0)/\pi D n$

where d =wire diameter

D =mean coil diameter

n =number of active coils

temperature T_2 above A_f followed by cooling to T_1 was repeated. The rate of heating and cooling was about 1.5 K/s.

2.3.2 Cyclic deformation test for RPT

(1) Exp. RPE: cyclic properties of PE

In the experiment RPE, similarly as in Exp. MPE, the cyclic properties of PE were examined by cyclic loading and unloading at constant temperature T for the wire. The maximum strain ϵ_m was smaller than 1%, the strain rate was 0.4%/min and $T=333$ K.

(2) Exp. RRD: cyclic properties of RD

In the experiment RRD, similarly as in Exp. MRD, the cyclic properties of RD were examined by cyclic heating and cooling under constant stress for the wire. The initial strain ϵ_0 was 1%.

2.3.3 Cyclic deformation test for the helical spring (Exp. SPR) The SMA helical spring connected each point on the circumferences of the large and small disks in the offset crank engine that were divided into six equal parts⁽¹⁵⁾. The maximum and minimum elongations for each number of coil turns of the SMA coils are shown in Table 1. The maximum and minimum shear strains on the surface of the coils are also shown in Table 1. The experiments were performed with no load and the rotational speed was about 65 rpm. By detaching the SMA coils from the heat engine at the prescribed number of cycles, the deflection of the coil with no load and the axial force under the maximum deflection were measured in hot water and in air. The temperature of the hot water was 353 K.

3. Experimental Results and Discussion

3.1 Cyclic deformation associated with MT

3.1.1 Stress-strain relation with loading-unloading As an example of the results of Exp. MPE with the loading-unloading cycles, the stress-strain curves are shown in Fig. 1. The curves are

parametrized by the number of cycles N . As seen in Fig. 1, the nonlinear strain induced by MT in the loading process diminishes due to its reverse transformation in the unloading process, resulting in the hysteresis loop of the stress-strain curve. The MT stress σ_M and its reverse transformation stress σ_A decrease with an increase in N . While the amount of decrease in σ_M from $N=1$ is about 100 MPa to $N=2$ and about 300 MPa to $N=100$, that in σ_A is about 50 MPa to $N=2$ and about 100 MPa to $N=100$. The residual strain ε_p appears after unloading increases with N . The value of ε_p is about 0.3% in $N=1$ and about 2.2% in $N=100$. Due to the increase in ε_p , the transformation strain decreases with N . The reason why the transformation stress and transformation strain vary with N may be considered as follows.

The martensitic phase (M-phase) grows in the loading process and diminishes in the unloading process. According to cyclic loading and unloading, the interface between the M-phase and the parent phase (P-phase) shifts repeatedly. With cyclic movement of the interface, the dislocations accumulate around the infinitesimal defects in the interface. Based on the increase in the dislocation density, residual strain appears and internal stress occurs. Because the internal stress causes the M-phase to grow, MT progresses even if the externally applied stress is low^{(4),(5)}. The reason why the amount of decrease in σ_M is larger than that in σ_A may be considered as follows. In the loading process, strain increases due to MT under high stress. Thus a large amount of dislocations accumulates, yielding high internal stress and large decrease in σ_M .

As seen in Fig. 1, the stress-strain curves vary significantly in the early cycles, but the rate of these variations decreases at $N \geq 20$. Thus in the application of the SMA element, if training is applied before practical use, the constant shape memory property may be obtained.

The detailed influences of T_p , ε_m and T on the

Fig. 1 Stress-strain curves in Exp. MPE with loading-unloading cycles at constant temperature ($T_p=673$ K, $\varepsilon_m=8\%$, $T=373$ K)

cyclic properties of the stress-strain curves are found in Ref. (9). The area surrounded by the stress-strain curve and the area below the unloading curve represent the dissipated strain energy and the recoverable strain energy per unit volume, respectively. The amounts of these strain energies are somewhat larger than that for normal metal in the range of recoverable deformation. Thus the function of TiNi SMA as a high damping material and an energy storage material is excellent. These detailed characteristics of PE are found in Refs. (9)-(11).

3.1.2 Strain-temperature relation with heating-cooling

As an example of the results of Exp. MRD with the heating-cooling cycles, the strain-temperature curves are shown in Fig. 2. The curves are parametrized by the number of cycles N . As seen in Fig. 2, strain decreases due to the reverse transformation in the heating process and increases due to MT in the cooling process, resulting in the hysteresis loop of the strain-temperature curve. Both the MT temperature T_M and its reverse transformation temperature T_A rise with an increase in N . While the amount of rise in T_M from $N=1$ is about 10 K in $N=2$ and about 40 K in $N=100$, that in T_A is about 5 K in $N=2$ and about 15 K in $N=100$. The irrecoverable strain ε_p appearing after heating at $T_2=393$ K increases with N . The amount of increase in ε_p from $N=1$ is about 0.2% in $N=2$ and about 2% in $N=100$. The amount of increase in strain with N at T_2 is larger than that at T_1 . In this case, because σ_0 is higher than MT stress σ_M at T_1 of 280 MPa, the reverse transformation completion temperature T_{Af} under σ_0 is higher than A_f (see section 3.3). Because T_{Af} rises with cyclic heating-cooling, the reverse transformation is not completed if the high temperature T_2 is not high enough, and thus ε_p at T_2 increases significantly.

As mentioned above, T_M and T_A rise with N . The amount of increase in T_M is larger than that in T_A . The reason may be explained similarly as for the case of cyclic loading-unloading in section 3.1.1. In the

Fig. 2 Strain-temperature curves in Exp. MRD with heating-cooling cycles under constant stress ($T_p=673$ K, $T_1=293$ K, $T_2=393$ K, $\varepsilon_0=6\%$, $\sigma_0=400$ MPa)

cooling process, because strain increases due to MT, more dislocations accumulate and higher internal stress occurs, yielding higher rise in T_M .

As seen in Fig. 2, variation in the strain-temperature curves is significant in the early cycles and slight after about the 20th cycle. This cyclic property is the same as the cyclic property of PE discussed in section 3.1.1.

The detailed influences of ε_0 and T_2 on the cyclic properties of the strain-temperature curves are found in Ref. (10).

3.2 Cyclic deformation associated with RPT

3.2.1 Stress-strain relation with loading-unloading As an example of the results of Exp. RPE with the loading-unloading cycles, the stress-strain curves at each T_p are shown in Fig. 3. The curves are parametrized by the number of cycles N . As seen in Fig. 3, the nonlinear strain induced due to RPT in the loading process diminishes due to its reverse transformation in the unloading process, resulting in the hysteresis loop of the stress-strain curve. The RPT

(a) $T_p = 648$ K,

(b) $T_p = 673$ K,

(c) $T_p = 723$ K

Fig. 3 Stress-strain curves in Exp. RPE with loading-unloading cycles at constant temperature ($T = 333$ K)

completion strain is about 0.6~0.8% which is about one-tenth of the MT completion strain of about 7% observed in Fig. 1. The width of the hysteresis loop is very narrow and the difference in stress between the loading curve and the unloading curve is smaller than 20 MPa. The difference between the RPT yield stresses of 20 MPa is smaller than one-tenth of the difference between the MT yield stresses of 200~400 MPa observed in Fig. 1.

As seen in Fig. 3, the stress-strain curves vary little in $N=1\sim 20$. Thus it is ascertained that the property of PE associated with RPT is stable for cyclic deformation. This is quite different from the phenomenon observed in Fig. 1 that the stress-strain curves due to MT vary significantly in the early cycles. Because the stress-strain curves vary little at every T_p , the influence of T_p on the cyclic deformation properties associated with RPT may be small.

For the stress-strain curves in Fig. 3, the slope of the curves in the RPT region is large at low T_p . Because the width between the loading curve and unloading curve is narrow and the slope of the curves is large in the transformation region, the RPT starting stress σ_{MS}' is lower than its reverse transformation starting stress σ_{AS}' . Thus the RPT transformation strip overlaps with its reverse transformation strips on the stress-temperature plane (see section 3.3).

3.2.2 Strain-temperature relation with heating-cooling

As an example of the results of Exp. RRD with the heating-cooling cycles, the strain-temperature curves are shown in Fig. 4. The curves are parametrized by the number of cycles N . As seen in Fig. 4, strain decreases due to the reverse transformation in the heating process and increases due to RPT in the cooling process, resulting in the hysteresis loop of the strain-temperature curve. The variation in the strain-temperature curves with cycling is as follows. The irrecoverable strain ε_p at the high temperature T_2 increases about 0.1% from $N=1$ to $N=2$, and after that, up to $N=100$, the strain-temperature curves

Fig. 4 Strain-temperature curves in Exp. RRD with heating-cooling cycles under constant stress ($T_p = 673$ K, $T_1 = 293$ K, $T_2 = 378$ K, $\varepsilon_0 = 1\%$, $\sigma_0 = 200$ MPa)

move upward about 0.1%, keeping almost the same form. This means that, except for the relation at $N=1$, the deformation property due to RPT varies slightly with cycling. That is, the RPT temperature T_M' and its reverse transformation temperature T_A' vary little with cycling. The difference in strain of about 0.6% between the high temperature T_2 and the low temperature T_1 , which specifies the working stroke of a SMA element with heating-cooling, varies little with cycling except at $N=1$.

Comparing with the strain-temperature curves for MT in Fig. 2, the width between the heating curve and cooling curve is very narrow. Thus the RPT starting temperature T_{Ms}' is higher than its reverse transformation starting temperature T_{As}' . The detailed dependence of the transformation temperature on T_p is found in Ref. (20).

3.3 Design considerations for SMA element

3.3.1 Transformation line and transformation strip In order to design a SMA element, the relationship between the transformation stress and the transformation temperature of the material, which specify the working force and the working temperature of the element, is important. We have proposed a simple theory that describes the complex deformation behavior of SMA^{(7),(8)}. In the theory, the progress of the transformation is governed by the transformation kinetics. The relationships between stress σ and temperature T that describe the starting and completion conditions of MT are

$$\sigma = c_M(T - M_s) \quad (1)$$

$$\sigma = c_M(T - M_s) - 2 \ln 10 / b_M, \quad (2)$$

and the starting and completion conditions of its reverse transformation are

$$\sigma = c_A(T - A_s) \quad (3)$$

$$\sigma = c_A(T - A_s) - 2 \ln 10 / b_A, \quad (4)$$

respectively. In these equations, c_M and c_A represent the slopes of the transformation lines, b_M and b_A specify the widths of the transformation strips, and M_s and A_s are the temperatures at which MT and its reverse transformation begin under stress-free conditions, respectively.

As shown by Eqs. (1)~(4), the starting and completion conditions of MT and its reverse transformation are expressed by linear functions of σ and T . These functions represent the straight lines on a stress-temperature plane, which are called the transformation lines. The transformation progresses in the region located between the starting line and the completion line of each transformation.

Concerning RPT, each transformation line is also represented by a straight line⁽¹⁸⁾⁻⁽²⁰⁾. The width of the RPT strip and its reverse transformation strip is very narrow, and these transformation strips are located

between the MT strip and its reverse transformation strip. Because the RPT starting stress is lower than its reverse transformation starting stress as noted in section 3.2.1, the RPT strip almost overlaps its reverse transformation strip.

As ascertained from discussions in sections 3.1 and 3.2, concerning MT, the yield stress decreases and the transformation temperature rises with cyclic deformation. This means that the MT line and its reverse transformation line move downward and to the right with cycles. The detailed behavior of each transformation line for cyclic deformation subjected to various thermomechanical paths is found in Ref. (24). On the other hand, for RPT, because the yield stress and the transformation temperature vary slightly with cycles, each transformation line moves little.

3.3.2 Design considerations for SMA element subject to cyclic deformation Based on the behaviors of the transformation lines that were discussed in the preceding sections, let us discuss the design considerations for a SMA element using a wire subjected to cyclic deformation in practical application.

The cyclic behavior of the transformation lines on the stress-temperature plane discussed in section 3.3.1 is schematically shown in Fig. 5. In Fig. 5, σ_{Ms} , σ_{Mf} , σ_{As} and σ_{Af} denote the starting line and the completion line of MT and its reverse transformations and σ_{Ms}' , σ_{Mf}' , σ_{As}' and σ_{Af}' the corresponding lines of RPT and its reverse transformations, respectively. Transformation lines in the first cycle and N -th cycle are represented by a solid line and a dashed line, respectively.

Let us first consider the cyclic properties concerning MT. In the state at point A obtained through loading to point B followed by unloading at temperature T_A shown in Fig. 5, the residual strain due to MT appears. The residual strain diminishes upon reverse transformation if heated at a temperature above A_f without stress. This phenomenon is called the shape

Fig. 5 Schematic starting lines and completion lines of MT and RPT in first cycle and N -th cycle.

memory effect. In the application for a SMA element subject to cyclic deformation under these loading-unloading and heating-cooling paths, if the SMA element is not heated at a temperature above the intersection of $\sigma_{Af}(N)$ and the horizontal axis, the element does not recover its original form. At the temperature $T_c(>A_f)$, strain is caused due to MT by loading to point D, and the strain recovers due to reverse transformation upon unloading in the state at point C. This phenomenon is called PE. This characteristic is important for elements in which the properties of high damping and energy storage are necessary⁽²⁶⁾⁻⁽²⁷⁾. In the application of a SMA element subjected to cyclic deformation under these loading-unloading paths, if the intersection of $\sigma_{Af}(N)$ and the horizontal axis is higher than T_c , only a part of the transformed strain recovers due to the partial PE, even if $T_c > A_f$. Furthermore, if the intersection of $\sigma_{As}(N)$ and the horizontal axis becomes higher than T_c , the transformed strain does not recover upon unloading.

In the case that, after loading to the stress σ_b at the point B at T_A in which MT appears, a SMA element is heated with σ_b constant, if the temperature is raised above $\sigma_{Af}(1)$, for example, heated at the point G, the transformed strain recovers by reverse transformation. Following this process and cooling under constant σ_b , if the temperature falls below $\sigma_{Ms}(1)$, strain increases by MT. In the application of a SMA element, these processes are observed in a working element subjected to heating-cooling under a constant load. In the case that the heating-cooling process is repeated with constant σ_b , if $\sigma_{Mf}(N)$ and $\sigma_{As}(N)$ move to the right, the transformed strain does not recover upon heating at the point G. Then, to recover the transformed strain, it is necessary to raise the temperature at point H. On the other hand, MT is completed at T_A in the cooling process.

In the application of the SMA elements, in order to obtain large recovery force or high strain energy density, the elements can be operated in the range of high stress, large strain and high temperature. Here it should be noted that irrecoverable strain appears rapidly with cyclic deformation. It must also be taken into account that the number of cycles to failure decreases with increase in the stress amplitude or the strain amplitude, similarly as in fatigue of a normal metal^{(5),(6)}.

On the other hand, as shown in Fig. 5, the RPT transformation lines, whose width is narrow, are located between the MT transformation lines, and move little with thermomechanical cycles. For RPT, the shape memory effect and PE appear, similarly as in the case for MT mentioned above. In the case that

a SMA element is operated under constant σ_b , although it is necessary for MT to heat and cool the element between points B and G, it is sufficient, for achieving RPT, to operate the element between points E and F. From this finding, it is ascertained that, because the difference in temperature to cause deformation associated with RPT is small, the response of the element with heating-cooling is fast. Thus it may be concluded that, for the element in which excellent cyclic property and fast response are important, RPT should be used. In this case, it should be taken into account that the RPT strain is smaller than 1%, which is smaller than one-tenth the MT strain.

Considering the response speed of a SMA element from the viewpoint of heat transfer, the element should be thin. In order to obtain a large working stroke through a simple SMA element, extension of a helical spring or bending of a thin belt can be adopted.

3.4 Cyclic deformation of helical spring

3.4.1 Recovery deflection As an example of the results of Exp. SPR, the relationship between the recovery deflection of the SMA coil l_r and the maximum shear strain on the surface of the coil $\gamma_{\max}$ is shown in Fig. 6. The recovery deflection l_r , which denotes the ratio of the deflection recovered by heating and the maximum deflection, is represented by

$$l_r = (L_{\max} - L_N) / (L_{\max} - L_0), \quad (5)$$

where $L_{\max}$ denotes the maximum length of the coil, and L_0 and L_N denote the lengths in initial and N -th cycles without a load in hot water, respectively. The initial length L_0 is the length of the coil subject to the training of 100 cycles prior to the experiment. As shown in Table 1, $\gamma_{\max}$ is related to the number of coil turns. In Fig. 6, l_r in the prescribed number of cycles N for each specimen is plotted and the points with the same N are connected by a solid curve.

As observed in Fig. 6, l_r with the same N decreases with an increase in $\gamma_{\max}$. The variation in l_r with $\gamma_{\max}$ increases for $\gamma_{\max} \geq 2.5\%$ in the case of low

Fig. 6 Relationship between recovery deflection and maximum shear strain for helical spring in Exp. SPR ($T_p=673$ K)

N and increases for $\gamma_{\max} \geq 1.5\%$ in the case of high N . The reason why l_r depends on $\gamma_{\max}$ may be explained as follows. In comparing deformation of a SMA helical spring with elastic deformation of the normal metals, Hooke's law does not hold and the stress distribution is different. In the cross section of the wire of the SMA spring, MT and RPT occur only in the surface area, and the state of the central part remains elastic⁽¹³⁾. As observed for uniaxial tension in sections 3.1 and 3.2, the RPT completion strain is about 0.8% and the MT starting strain about 1%. For deformation of the helical spring, as mentioned above, the wire is mainly subjected to torsion. It is assumed that both transformations start and finish at a certain equivalent strain ϵ_e . That is, we assume that, for torsion, RPT completes at $\epsilon_e = \gamma/\sqrt{3} = 0.8\%$ and MT starts at $\epsilon_e = \gamma/\sqrt{3} = 1\%$. From this assumption, on the surface of the wire of the SMA helical spring, RPT completes at $\gamma_{\max} = 1.4\%$ and MT starts at $\gamma_{\max} = 1.7\%$. Thus, for $\gamma_{\max} \leq 1.5\%$, elastic deformation and RPT occur in the cross section of the wire, and l_r takes a very large value even at high N . For $\gamma_{\max} \geq 2.5\%$, MT appears in the surface area of the wire, and becomes small with low N .

On the other hand, as seen in Fig. 6, $l_r > 99\%$ for $N = 10^4$ at $\gamma_{\max} = 2.5\%$, and $l_r > 99\%$ for $N = 5 \times 10^5$ at $\gamma_{\max} = 1.5\%$. Thus it is ascertained that, for the helical spring subjected to cyclic deformation, the recovery deflection is very large and an almost constant working stroke may be obtained in the application of the SMA elements.

3.4.2 Recovery force Figure 7 shows the relationship between the axial force F_h at high temperature of the SMA coil subjected to the maximum deflection in hot water and $\gamma_{\max}$. The relationship

Fig. 7 Dependence of axial force at high temperature and effective recovery force on maximum shear strain in first cycle and 10^4 th cycle for Exp. SPR ($T_p = 673$ K)

between the effective recovery force of the SMA coil $F_r = F_h - F_l$, which is determined by the difference between the axial force in hot water and the axial force in the air under the maximum deflection, and $\gamma_{\max}$ is also shown in Fig. 7. In the application for the SMA coil, F_h could be used as the recovery force at high temperature, and F_r as the effective recovery force under the thermal cycles with heating-cooling. In Fig. 7, the solid curves are the results in the first cycle, and the dashed curves those in the 10^4 th cycle.

As shown in Fig. 7, the variations in F_h and F_r with $\gamma_{\max}$ decrease when $\gamma_{\max}$ becomes large. This inclination of the curves $F_h - \gamma_{\max}$ and $F_r - \gamma_{\max}$ is the same as that of the load-deflection curve of the SMA coil subject to tension under constant temperature⁽¹³⁾. For the curves in Fig. 7, the clear yielding point which was observed in Figs. 1 and 3 does not appear. For $\gamma_{\max} \geq 2.5\%$, F_h and F_r decrease with N . This phenomenon may be caused by the fact that the MT region in the cross section of the wire expands into the center if $\gamma_{\max}$ is large⁽¹³⁾ and that the yield stress of MT decreases under cyclic deformation. Nevertheless, the amount of decrease in F_h and F_r at $N = 10^4$ is somewhat smaller than that in σ_M observed in Fig. 1. From these considerations, the following points may be concluded. For the SMA coils subject to cyclic deformation, the axial force does not vary in the RPT region. Even in the MT region, the interior of the wire still consists of the elastic region and the R-phase-transformed region, yielding very little decrease in the axial force. Thus, in the application of the SMA coils subject to cyclic deformation, an almost constant recovery force is obtained.

The detailed influences of the number of cycles, training and T_p on l_r and F_h and the fatigue property are found in Refs. (14) and (15).

4. Conclusions

The cyclic deformation properties of TiNi SMA wires and helical springs for MT and RPT were investigated experimentally, and the cyclic properties of the stress-strain-temperature relationship and the design considerations for a SMA element were discussed. The results are summarized as follows.

For cyclic deformation associated with MT, the transformation stress decreases and the transformation temperature rises. The amounts of variation in the transformation stress and the transformation temperature are large in the early number of cycles and is small after about the 20th cycle. On the other hand, for cyclic deformation associated with RPT, the transformation stress and the transformation temperature vary little. In order to design a SMA element, it is important to consider the cyclic properties of the

transformation stress and the transformation temperature that specify the working characteristics of the element. For cyclic deformation of a helical spring, the recovery deflection is very large in the RPT region. The recovery deflection and the recovery force of the helical spring under cyclic deformation vary slightly even in the MT region.

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