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Constant-torque thermal cycling and two-way shape memory effect in $\text{Ni}_{50.3}\text{Ti}_{29.7}\text{Hf}_{20}$ torque tubes

O. Benafan^{a,*} and D.J. Gaydos^{b,a}

^aNASA Glenn Research Center, Materials and Structures Division, Cleveland, OH 44135, USA

^bOhio Aerospace Institute, Cleveland, OH 44142, USA

Abstract

Ni-rich $\text{Ni}_{50.3}\text{Ti}_{29.7}\text{Hf}_{20}$ (at.%) high-temperature shape memory alloy (SMA) tubes were thermomechanically cycled under constant torques. Four loading configurations were examined that consisted of a series of ascending stresses (low-to-high stress from 0 to 500 MPa outer fiber shear stress), a series of descending stresses (high-to-low stress from 500 to 0 MPa), and a series of thermal cycles at a constant stress of 500 MPa, all using an upper cycle temperature (UCT) of 300 °C. The last configuration consisted of another series of ascending stress levels using a lesser UCT of 250 °C. It was found that the descending series trial stabilized the material response in fewer cycles than the other loading paths. Similarly, cycling at a constant stress of 500 MPa for approximately 100 cycles reached near stabilization (<0.05% residual strain accumulation). Transformation shear strains were the highest and most stable when cycled from lower-to-higher stresses (ascending series), reaching 5.78% at 400 MPa. Cycling to lesser UCTs of 250 °C (vs. 300 °C) resulted in the highest two-way shape memory effect (TWSME), measuring over 3.25%. This was attributed to the effect of retained martensite and any transformation dislocations that served to stabilize the TWSME at the lower UCT. Results of this study suggest that different training paths might be used, depending on actuator performance requirements, whether the principal need is to maximize transformation strain, maximize the two-way shear strain, or stabilize the response in fewer cycles.

Keywords

two-way shape memory; torsion; NiTiHf; high-temperature shape memory alloys; SMA; torque tubes; constant-torque thermal cycling

1. Introduction

Shape memory alloy (SMA) torque tube actuators provide a potential technological advancement in the rotary actuator industry. Given the many benefits these alloys and actuators offer, such as adaptability and morphing as well as being lightweight and small form-factor, SMA torque tubes can be used in lieu of existing actuators or in areas where conventional technologies (e.g., hydraulic, pneumatic, or electric motors) are deemed

*Corresponding author: Tel.: +1 (216) 433 8538; fax: +1 (216) 977-7133. othmane.benafan@nasa.gov (O. Benafan).

unsuitable. As such, unexplored aircraft control surfaces, spacecraft mechanisms, oil drilling rigs, and other devices can be revisited and evaluated for enhanced benefits.

SMA in torque tube form are not a new idea. In fact, this form has been explored since the early 1990s for use in helicopters [1–4], aircraft [5–7], solar collectors [8], and other applications. An overview of these and other applications can be found in Ref. [9]. However, most of these applications lacked the proper alloy attributes; were comprised of low transformation temperatures that are not fit for most aircraft surfaces; exhibited unstable behavior, which does not warrant itself for an extended number of cycles; or required long training procedures that cost a lot of time and money, among other issues. More recently, some of these limitations have been extensively explored with some key contributions. New alloy formulations based on NiTiHf and NiTiZr have been shown to offer higher activation temperatures (above 100 °C) with a practical price tag as compared to costly alternatives such as NiTi-Pd, NiTi-Pt, or NiTi-Au [10, 11]. Ni-rich versions of these alloys have also been shown to possess superior thermal and dimensional stability when thermomechanically cycled through the phase transformation [11–13]. In addition, the latter also have much higher energy densities and work outputs, allowing for an even broader design space with larger strains and higher torque capabilities [14]. Key to most SMA actuator applications is the training of the alloy to perform repeatedly and with the desired actuation magnitudes. These training procedures have also been expanded from earlier work [15–17] to include a more systematic, and in some cases, a faster training routine [18, 19]. It has also been attempted to include training as part of the material processing phase, such as during wire or tube drawing or sheet rolling. In principle, by controlling the deformation rates and heat treatments imposed during such processing, it is possible to achieve an internal material state (i.e., internal stresses and textures) that promotes stability without any additional post-process training.

Additionally, significant work was recently completed on numerous NiTiHf high-temperature SMA tubes with varying geometries and stress states [9]. This work reported on the torque and twist angle capacity of NiTi-20Hf torque tubes subjected to thermomechanical cycling. Two-way shape memory effect (TWSME) was also examined in the context of magnitudes and evolution with preapplied stresses. To date, most actuator training is based on thermomechanical cycling under a constant load and torque. While this approach yields acceptable results, extensive time and resources required for this approach can be discouraging. Other potential approaches, such as combined loading paths [20, 21] or multiaxial loading, may lead to a faster and better training approach.

In this work, NiTiHf torque tubes are further examined by applying different loading configurations and assessing the ensuing effect on transformation shear strains, stability, and TWSME. Constant-torque thermal cycling experiments were investigated, which consisted of a series of ascending stress levels, a series of descending stresses, and an extended series of thermal cycles at a constant stress and variable upper cycle temperatures (UCTs). Implications to training and stability are discussed here.

2. Experimental Procedures

2.1 Material and Sample Geometry

The material used was an Ni-rich $\text{Ni}_{50.3}\text{Ti}_{29.7}\text{Hf}_{20}$ (at.%) alloy produced by vacuum induction skull melting with a melt size of ~27 kg (60 lb), designated as FS#5. The molten metal was first cast into 3.048-cm-diameter steel molds, then vacuum homogenized at 1050 °C for 72 h, and finally furnace cooled. The ingots were then extruded at 900 °C through an area reduction ratio of 7:1. Tubes were machined from the extruded rods with an outer diameter of 9.525 mm and a total length of 88.9 mm. Inner diameters were gun drilled and honed to 6.985 mm for tubes 1, 3, and 4, and 5.715 mm for tube 2 (Table 1). Eighteen splines were machined on each end with a 12.7 mm length, yielding an effective gage length of 63.5 mm. Finally, each tube was double-wrapped in tantalum foil, subjected to an aging treatment of 3 h at 550 °C, and then air-cooled.

2.2 Thermomechanical Testing

An MTS axial-torsional servohydraulic test frame was used to test the tubes. The test frame was equipped with a 250-N•m torque cell, custom hot-grips, a 10-kW Ameritherm[®] induction heating system, an air compressor for cooling, and a GOM ARAMIS digital image correlation (DIC) optical metrology system for strain measurements. Once the tubes were installed, torque was applied at a rate of 0.226 N•m/s, while the axial load was maintained at a constant 53 N to retain the splines in the grip. Induction coils around the sample and the grips were used to maintain a uniform temperature across the tube length. Heating was controlled at a rate of 25 °C/min, while cooling was performed by forcing air inside of the tubes. The temperature was monitored with Type-K thermocouples that were spot welded directly to the tubes. For strain measurements, images with a virtual gage length of 17 mm (facet size = 32–40, facet step = 16–20) with black and white speckle patterns were captured using a 5-megapixel Titanar-100 stereo camera system. Figure 1 shows a schematic of the test setup.

Constant-torque thermal cycling experiments consisted of applying a torque, holding that torque constant, and thermally cycling between an upper and lower cycle temperature (LCT). Four different loading configurations were investigated in this work in order to assess the impact on stability, training, and the TWSME. The torques used are listed in Table 1 and the loading sequences are graphically shown in Figure 2. In all tubes, the experiments were conducted with a series of applied torque on the same sample where each tube was loaded, unloaded, and reloaded as shown in Figure 2. Experiments consisted of a series of ascending stress levels from 0 to 500 MPa (Tube 1, Fig. 2(a)), a series of repeated thermal cycles at 500 MPa (Tube 2, Fig. 2(b)), a series of descending stress levels from 500 to 0 MPa (Tube 3, Fig. 2(c)), and finally a similar series of ascending stress levels from 0 to 500 MPa, but using a lower UCT of 250 °C (Tube 4, Fig. 2(d)). At each stress level, the tubes were thermomechanically cycled 20 times, and thermally cycled twice after each unloaded condition to 0 MPa.

Shear stresses and strains were calculated using the conventional elastic pure torsion theory, where shear stresses refer to the maximum stress at the outer radius, and the shear strains are

calculated on the outer surface of the sample. All shear strains reported in this work are the measured strains from the DIC analysis, not strains calculated from the crosshead rotation of the test frame. However, all the reported angles of twist were measured using the crosshead angular transducer.

3. Results and Discussion

3.1 Constant Torque Thermal Cycling

Shear strain-temperature responses corresponding to the 20th cycle are shown in Figure 3. All curves were shifted to 0% strain at the UCT to better visualize the effect on transformation strains and temperatures as a function of shear stress. For tube-1 (Fig. 3(a)) where stresses were serially augmented, the characteristic transformation temperatures are shown to shift higher with increasing stresses, particularly more so for the austenite finish (A_f) and martensite start (M_s) temperatures. The temperature spans $A_f - A_s$ (or $M_s - M_f$) also broaden as a function of the increase in stresses from 100 to 400 MPa. Such behavior is commensurate with the classical ClausiusClapeyron relationship, as has been previously described [9]. It is noted that the tube fractured on loading to 500 MPa and no data was collected for that case. Tube-2 (Fig. 3(b)) was tested cyclically between 500 and 0 MPa and no major evolution in transformation temperatures can be observed. However, there was a notable change in the hysteresis width from the initial (labeled 500 MPa-1) to the final cycles (labeled 500 MPa-5) at 500 MPa, where the hysteresis reduced by an approximate factor of two, from ~31 to ~16 °C. In this tube, the initial cycle (labeled 500 MPa-1) belongs to the 2nd overall cycle and not the 20th, following the stress-cycle graph of Figure 2(b).

Tube-3 (Fig. 3(c)) was tested in reverse, starting with 500 MPa and descending to 100 MPa. Overall, the shifts in transformation temperatures and widening of the temperature spans are comparable to tube-1, but the hysteresis width appears to be more narrow than tube-1 and tube-2 at 500 MPa. Finally, tube-4 was thermomechanically cycled, ascending from 100 to 500 MPa with a lesser UCT of 250 °C (versus 300 °C that was used for tubes 1–3). While the responses at stresses from 100 to 300 MPa are very comparable to tube-1, it is clearly shown that transformation loops are incomplete at higher stresses, especially at 500 MPa.

The residual strains, measured at the LCTs, are shown in Figure 4 for each tube loading configuration. These residual strains are an indication of dimensional stability (or lack thereof) and are ideally close to zero for beneficial use in actuator applications requiring more than one cycle. It is expected that residual strains accumulate in untrained materials, even more so at higher stresses, as contributions from mechanisms other than reversible phase transitions such as plasticity, retained martensite, ageing, etc., become significant. Nevertheless, stability can be reached after some number of cycles or induced by using some other training routines. Tube-1 (Fig. 4(a)) shows the accumulation of residual strains is minimal, approaching ~0.15% by the 20th cycle for the 100 and 200 MPa stress, followed by a significant increase at higher stresses, approaching 0.79% at 400 MPa. Tube-2 (Fig. 4(b)) shows a decrease in residual strains with additional cycles and reaches near stabilization (i.e., no change from cycle to cycle) by the end of the test at ~120 cycles. Tube-3 (Fig. 4(c)), starting at 500 MPa, had a high initial buildup of residual strains (up to 1.2%), but the buildup diminished and the material stabilized much faster when the stresses

were lowered. This is beneficial from a material training standpoint because higher stresses can quickly stabilize the material response for applicable stresses below that point. Finally, tube-4 (Fig. 4(d)), using 250 °C for a UCT, exhibited less strain accumulation when compared to the same loading scenario of tube-1, but with a higher UCT.

While residual strains are a key parameter to an actuator application, the transformation (or actuation) strains are equally important as they define the range of motion (in this case, angle of twist) available for use. The transformation shear strains as a function of cycle number for each loading configuration are shown in Figure 5. The gaps between each stress cycle correspond to the 0 MPa data (i.e., TWSME) and will be presented later. For each stress level shown, the plotted data displays both the transformation strain magnitudes and the strain stability up to the tested 20th cycle. Tube-1 (Fig. 5(a)) shows a gradual increase in strain response with mostly stable magnitudes up to 300 MPa stress (i.e., constant strain at a given stress). At 400 MPa the strain magnitude increases, but the response is less stable as the strains drop with increasing cycles. In tube-2, the overall transformation strain magnitude decreases with increasing cycles and the response is less stable at this higher cycling stress. For tube-3 (Fig. 5(c)), the magnitudes are slightly lower when starting with 500 MPa compared to tube-2, but the responses appear to be more stable as the stress was lowered. This is concomitant with the low residual strains reported for this case in Figure 4(c), suggesting the use of an enhanced loading configuration for attaining quick stabilization (i.e., faster training). Finally, tube-4, using a lesser UCT of 250 °C (Fig. 5(d)), showed analogous behavior compared to the higher cycling temperature of tube-1 with a similar loading configuration. However, due to the incomplete phase transformation at higher stresses of 500 MPa, the magnitudes and stability declined drastically with cycling. This is expected since retained (or untransformed) martensite is no longer contributing to the strain generation and hence, results in lower shear strains and a much inferior stability.

A summary of the transformation shear strains as a function of applied stress and the transformation twist angles as a function of applied torque corresponding to the 20th cycle is shown in Figures 6(a) and (b), respectively. These charts provide a comparison between all loading configurations and the methods that yield the highest magnitudes. From an engineering design standpoint, the angle versus torque data of Figure 6(b) serves as a meaningful way of providing a sense of the loads and angles expected for the current tube geometry as would be the case in an actual application (i.e., strains are typically not measured on an actuator system but angles are). Overall, it is shown that tubes-1 and -4 perform similarly up to 300 MPa irrespective of the UCT, but a clear demarcation is observed at higher stresses as retained or untransformed martensite effects become more dominant. Tube-3 exhibited lower strains in general, while tube-4 seemed to approach a shear strain of ~4.8% after the 120 cycles.

3.2 Two-Way Shape Memory Effect

Implications on the TWSME for each loading configuration are shown in Figure 7. These data were taken from the 2nd cycle at zero shear stress measured after the listed preapplied shear stress (Fig. 7(a)) or torque (Fig. 7(b)). For tubes 1, 2, and 4, the TWSME is shown to increase with increasing stress and/or cycles reaching 3.2% for tube 4, while exhibiting an

upward trend for potentially more strain capability. However, tube-3, which was tested at higher stresses first, exhibited a TWSME of 2.4% and remained nearly constant as the stresses were reduced. It is apparent that internal stresses imposed by thermomechanical cycling at higher external stress served to lock-in the two-way effect throughout the stress cycle profile. The corresponding twoway angles of twist as a function of preapplied torque are also reported in Figure 7(b) and a similar conclusion can be drawn.

When using a lower UCT (Fig. 7b), this condition provided the highest TWSME of 3.2% compared to < 3% at a UCT of 300 °C. It is known from prior work that the TWSME is stabilized by the formation of internal stress fields that induce the same martensite variants during transformation as are generated during training, but without the need for external stress. These internal stresses can be created by mechanisms such as dislocation arrays generated during thermomechanical training [22] or retained martensite [23], among other mechanisms [24, 25]. In this condition, it is clear that retained martensite is present, which contributed to this effect, and it is expected that transformation dislocations remain and help stabilize it at this lower UCT. When increasing the cycling temperature to 300 °C, more of the retained martensite is transformed and some dislocation structures can potentially be annihilated, resulting in a diminishing TWSME.

Depending on the application, whether the actuator is using TWSME, constant stress, variable torque, or some combination thereof, each loading configuration presents a method for obtaining a set of properties that can be tuned for the anticipated goals. The precipitation strengthening in these NiTiHf alloys provides the added advantage of stable response at lower stresses without any training. However, some form of training is still required, although it is considerably less time-consuming when compared to conventional alloys like binary NiTi to fine tune the material response to the desired actuator use. For example, to maximize transformation strain, an ascending series of shear stresses might be employed during thermal cycling. If the objective is maximizing the two-way shear strain, a lower UCT might be employed. Similarly, to develop and stabilize a TWSME more quickly, a descending series of shear stresses might be employed. It should be noted that only 20 cycles per stress level were used in this work to show the trends and benefits. For a given application with known loads, more cycles according to the loading configuration of choice may be necessary to fully stabilize and train the material in an actuator form.

4. Conclusions

Ni-rich NiTi-20Hf torque tubes were subjected to constant-torque thermal cycling under different loading configurations. Torque tubes with an outer diameter of 9.525 mm and an effective length of 63.5 mm were thermally cycled at a series of ascending, descending, and constant torques ranging from 0–73.8 N•m (maximum outer fiber shear stresses from 0–500 MPa) and two different upper cycle temperatures (UCTs). The ensuing transformation shear strains, stability, and two-way shape memory effect (TWSME) were evaluated, and the following conclusions can be drawn:

- Thermomechanical cycling from higher-to-lower stresses (descending series) versus lower-to-higher stresses (ascending series) proved to be a better loading path to quickly stabilize the material response.
- Cycling at higher stresses of 500 MPa for an extended number of cycles resulted in a notable reduction in the hysteresis width by an approximate factor of two (from ~ 31 °C in cycle one to ~ 16 °C in cycle 120).
- Transformation shear strains were the highest and most stable for the tube cycled from lower-to-higher stresses (ascending series), reaching 5.78% at 400 MPa. At lower stresses, contributions from permanent deformations are the lowest, which allows more preferential alignment of martensite plates to generate more strain. However, when starting at higher stresses, the permanent deformations are more prevalent, which limits some of the martensite reorientation process, resulting in lesser strains.
- Cycling to lesser UCTs of 250 °C (versus 300 °C) resulted in much lower transformation shear strains at stresses above 300 MPa. This is apparent from the strain-temperature responses indicating incomplete reverse transformation at higher stresses. This retained or untransformed martensite limits the shear strain generation. Conversely, TWSME was highest, measuring over 3.25%, when cycling with the lowest UCT. It appears that the presence and associated microstructural interactions of retained or untransformed martensite along with any dislocation structures served to promote a better internal state for TWSME development.
- For the case of higher-to-lower stresses (descending series), TWSME saturated at $\sim 2.5\%$ strain, while extended cycling at constant high stresses promoted additional two-way strain with added cycles.

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Figure 1. Schematic of torsional test setup showing sample grips, induction coils, and camera system used for strain measurements.

Figure 2.

Stress-cycle profile corresponding to constant-torque thermal cycling experiments for (a) series of ascending stress levels from 0 to 500 MPa, (b) series of repeated 500 MPa cycles, (c) series of descending stress levels from 500 to 0 MPa, and (d) series of ascending stress levels from 0 to 500 MPa using lower upper cycle temperature (UCT) of 250 °C.

Figure 3. Shear strain-temperature response corresponding to 20th cycle for (a) tube 1, (b) tube 2, (c) tube 3, and (d) tube 4. For each stress level, data were shifted to 0% strain at upper cycle temperature (UCT) for comparison purposes.

Fig. 4

Figure 4.

Cumulative residual strains measured at lower cycle temperatures (LCTs) for (a) tube 1, (b) tube 2, (c) tube 3, and (d) tube 4.

Fig. 5

Figure 5.

Transformation shear strains as function of cycle number for 20 constant-torque thermal cycles at each stress level for (a) tube 1, (b) tube 2, (c) tube 3, and (d) tube 4.

Figure 6.
 (a) Summary of transformation shear strains as function of applied stress and (b)
 transformation shear angles as function of applied torque corresponding to 20th cycle.

Figure 7.

(a) Two-way shear strains as function of preapplied stress and (b) two-way shear angles as a function of preapplied torque corresponding to 2nd cycle.

Table 1.

Torque tube geometries and applied torques

Tube no.	Sample ID	Outer diameter, mm (in)	Inner diameter, mm (in)	Wall thickness, mm (in)	Effective length, mm (in)	Applied torque N·m (lbf·in)					Cycling temperature °C (°F)	
						100 MPa	200 MPa	300 MPa	400 MPa	500 MPa	LCT ^a	UCT ^b
1	AT-013	9.525 (0.375)	6.985 (0.275)	1.27 (0.050)	63.5 (2.5)	12.1 (106.7)	24.1 (213.5)	36.2 (320.2)	48.2 (426.9)	-----	35 (95)	300 (572)
2	AT-022	9.525 (0.375)	5.715 (0.225)	1.905 (0.075)	63.5 (2.5)	-----	-----	-----	-----	73.8 (653.5)	35 (95)	300 (572)
3	AT-023	9.525 (0.375)	6.985 (0.275)	1.27 (0.050)	63.5 (2.5)	12.1 (106.7)	24.1 (213.5)	36.2 (320.2)	48.2 (426.9)	60.3 (533.7)	35 (95)	300 (572)
4	AT-025	9.525 (0.375)	6.985 (0.275)	1.27 (0.050)	63.5 (2.5)	12.1 (106.7)	24.1 (213.5)	36.2 (320.2)	48.2 (426.9)	60.3 (533.7)	35 (95)	250 (482)

^a Lower cycle temperature^b Upper cycle temperature