Shakedown Response of Conditioned Shape Memory Alloy Wire

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ABSTRACT
A series of experiments is presented examining the thermo-electro-mechanical response of commercially-available, conditioned, shape memory alloy (SMA) wires (Flexinol®, from Dynalloy, Corp.) during cyclic thermomechanical loading. A specialized experimental setup enables temperature control via a thermoelectric/heatsink in thermal contact with the wire specimen during various modes of testing. It allows simultaneous measurement of elongation, load, strain and resistivity in a selected gage length. It also allows full-field optical and infrared imaging to be performed during testing. A moderately high transition temperature NiTi-based shape memory wire (90°C Flexinol) is characterized first by differential scanning calorimetry and a series of isothermal experiments over a range of temperatures. Subsequent experiments examine the shakedown behavior over a range of dead loading temperature cycles. Results show a significant two-way shape memory effect, suggesting that both residual stresses and locked-in oriented Martensite are considerable in this commercial alloy. Repeatable behavior (little shakedown) is confirmed at relatively low stress levels, but significant evolution in the response (shakedown behavior) exists at higher stress levels during the first several temperature cycles.

Keywords: Shape Memory Alloy, SMA, Nickel Titanium, NiTi, Flexinol, Resistivity, Shakedown, Experimental Method, Two Way Effect

1. INTRODUCTION
Shape memory alloys (SMAs) are a unique group of metals that exhibits interesting and useful thermomechanical phenomena, notably the shape memory effect and superelasticity (or pseudoelasticity). The shape memory effect is the recovery of strain upon heating above a characteristic transition temperature, often near room temperature. Pseudoelasticity is the isothermal recovery of strain at temperatures somewhat above the material’s transition temperature. Both effects can be exploited to recover strains near 5 to 8% in polycrystalline NiTi SMA wires, arising from reversible martensitic (diffusionless) transformations between solid state phases, called Austenite and Martensite. The material response has many complexities and interesting aspects, leading to numerous experimental studies. The response is extremely nonlinear, temperature dependent, rate-dependent, hysteretic, and processing/form dependent. It may also have significant asymmetry in its tension vs. compression behavior and localization and propagation phenomena.

This paper presents initial results of a systematic study of the shakedown behavior of relatively high temperature, commercially-available, conditioned NiTi-based shape memory wire. Our aim is to provide experimental data suitable for thermo-electro-mechanical constitutive modeling that can then be used for performance and lifetime predictions in actuator applications. A new experimental setup was developed to measure stress, temperature, and electrical resistivity simultaneously during thermomechanical cycling. In this paper we focus on the dead loading response under temperature-controlled cycling. Similar previous studies exist on near equiatomic NiTi wires, but our scope of experiments, method, and starting condition of the material are different.

While “virgin”, unconditioned equiatomic NiTi wire is often used for scientific studies, it has complications that hinder its use in commercial applications. Often, its Austenite finish temperature (A_f) is between room temperature and 60 °C,
making it difficult to build robust actuators that are functional over a range of operating temperatures suitable for typical automotive and aerospace applications. Also, the response of “virgin” NiTi evolves rapidly with thermomechanical cycling in the first few tens to hundreds of cycles, making it problematic for repeatable actuation. Conditioned SMA wire, such as the Flexinol® alloys (available from Dynalloy Inc.), has relatively high transformation temperatures, has good fatigue life, and has been preconditioned to eliminate most shakedown effects at moderate tensile loads. The data presented herein is a work-in-progress as part of a larger experimental program to investigate shakedown on conditioned SMA wire for a variety of thermomechanical cycling modes, including superelastic (isothermal) shakedown and other thermomechanical loading paths.

2. MATERIAL & EXPERIMENTAL SETUP

The material used in this study is 0.381 mm (0.015 in) diameter Flexinol wire that has a reported $A_f$ near 90 °C, so-called 90C Flexinol*. The material has been conditioned\(^1\) by the supplier and is provided in a prestrained state for the convenience of actuator construction. The experimental setup shown in Figure 1 was designed with the following goals: (1) precise temperature control; (2) accurate measurement of load, strain, temperature, and electrical resistivity; and (3) the ability to add full-field thermography and digital image correlation at a later date. The wire specimen was clamped at each end by hardened steel clamping plates (grips) with one grip attached to a rigid base and the other grip attached to a 100 N load cell and the moving crosshead of a testing machine (not shown). For isothermal, displacement-controlled experiments, the setup of Figure 1 was installed within an Instron electromechanical load frame (Model 5585). For dead-load, temperature-cycled experiments, a nearly identical setup was installed in an MTS servo-hydraulic load frame (Series 359).

A thermoelectric wafer and heat sink assembly were placed in thermal contact with the backside of the wire specimen. A thermally conductive grease (Omegatherm 201, thermal conductivity $k_g = 2.26 \text{ W/K-m}$) was used to ensure good thermal contact between the wire and the thermoelectric, while allowing the wire to slide as it was elongated (similar to an arrangement used previously\(^2\)). With this method, one side of the wire is still exposed to the air, making it available to full-field imaging methods. The temperature gradient across the wire diameter can be reasonably neglected since the Biot number is quite low ($Bi \equiv h d / k \approx 0.004$), where $h = 90 \text{ W/m}^2 \cdot \text{K}$ is an approximate film coefficient for stagnant air,\(^3\) $d = 0.000381 \text{ m}$

\(^*\)Certain commercial equipment, instruments, or materials are identified in this paper in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.

\(^1\)The precise details of the thermomechanical treatment during conditioning are unavailable, since it is proprietary to Dynalloy, Inc.
is the wire diameter, and \( k = 9 \text{ W/m-K} \) is the minimum thermal conductivity of NiTi (Martensite). Cartridge heaters were installed in the grips, which in combination with the thermoelectrical controller, allowed the specimen temperature to be controlled. Temperature was measured at two points, near the center and top of the wire specimen, by 0.381 mm exposed-junction K-type thermocouples immersed in the thermal grease connected to (Fluke 80 TK) thermocouple signal conditioning modules.

The initial free length of the wire specimen between the grips was about 60 mm. To eliminate grip effects, such as slippage and stress concentrations, the elongation and resistance were measured in a gage length of the wire within the uniform temperature region of the thermoelectric contact (away from the grips). Elongation in the gage length was measured by a laser extensometer (Electronic Instrument Research Ltd. model LE-05) according to the distance between two retro-reflective laser tags affixed to the specimen. The initial extensometer gage length, \( L_e \) (between 27 and 32 mm), is defined as the length measured at a high temperature (140 °C) sufficient to ensure full transformation to the Austenite phase (A), while imposing a minimal load (2 N, i.e. 13 MPa) to maintain a straight wire configuration.

Electrical resistance was measured with the four-point method, in which a moderate current (200 mA) was run through both the wire specimen/grip assembly and a calibrated shunt resistor (not shown) in a series circuit. The current was measured across the shunt resistor, and the resistance of the wire gage length was measured with a voltage probe attached by copper leads at the laser tags. Assuming a linear heat conduction law with a conservative thermal conductivity coefficient from thermal grease to NiTi wire of 2000W/m²-K, the temperature rise within the wire due to resistive heating should be only 0.15 °C. A challenging aspect of electrical resistance measurements was maintaining clean electrical contact with the wire during deformation to 8 % strain. The proximity of the thermoelectric device precluded any sort of mechanical clamp or crimp more than about 0.25 mm thick on one side. Consequently, a thin strip of 0.08 mm thick copper foil was crimped around the wire, with any gaps filled with flexible silver-filled electrically conductive epoxy (Cotronics 125). This method works well for strains under 5 % but produced a noisy signal at larger strains, so work is ongoing to improve this aspect. Electrical resistivity was derived, correcting for the dimension changes in the wire assuming isochoric deformation, using the approximation \( \rho_e = R_e A_0 (1 - 0.5 \varepsilon)^2 / L_e (1 + \varepsilon) \approx (1 - 2 \varepsilon) R_e A_0 / L_e \), where \( \varepsilon = \delta_e / L_e \) is the measured average strain in the gage section.

3. BASELINE CHARACTERIZATION

To begin our study, differential scanning calorimetry (DSC) and a series of isothermal mechanical experiments were performed. These responses together are a common way of characterizing SMA wire, at least initially, and are presented here for a baseline characterization of this particular variety of wire.
### 3.1 Differential Scanning Calorimetry

Figure 2 shows two respective DSC thermograms, obtained by a Perkin-Elmer Pyris 1 Differential Scanning Calorimeter, on two varieties of as-received, stress-free Flexinol wire: 70C Flexinol and 90C Flexinol. The DSC machine measured the heat power input \((\dot{Q} = \frac{dQ}{dT})\) on material samples (near 50 mg) as the temperature was scanned at 10 °C/min. This has been converted to \(\frac{\dot{Q}}{\dot{T}} \) vs. \(T\) in the Figure to give specific heat-like units on the vertical axes. While shakedown experiment are presented below only on the 90C Flexinol, Figure 2(a) is included for comparison, since it is characteristic of typical Nitinol. The plots show both latent heats of transformation as well as stress-free transformation temperatures. Figure 2(a) shows three latent heat peaks: one endothermic peak during heating separating thermal Martensite \((M)\) and Austenite \((A)\), and two exothermic peaks during cooling separating Austenite \((A)\), the Rhombohedral R-phase \((R)\), and thermal Martensite \((M)\). The R-phase, while less well-known than the other two phases and a relatively minor player in the mechanical response, plays an important role in resistivity measurements as discussed later.

Figure 2(b), by contrast, shows only two latent heat peaks, one for heating and one for cooling, and they are shifted to the right in temperature. During cooling, the material transforms from \(A\) to \(R\) and then to \(M\), all within overlapping peaks that have their minimum (peak temperature) at \(M_p = 50.1\) °C. During heating, the transformation is reversed, proceeding as \(M \rightarrow R \rightarrow A\) in a peak with maximum at \(A_p = 76.6\) °C and ending near \(A_f = 77.5\) °C, according the conventional construction line (dotted) along the steepest slope of the thermogram. The latent heat of transformation, \(20.8 \text{ J/g}\), is measured as the area under this \(M \rightarrow R \rightarrow A\) peak.

Compared to Figure 2(a), the \(M\) peak in Figure 2(b) occurs at higher temperatures, such that it overlaps the \(R\) peak, and the widths of the peaks are noticeably narrower and taller (note the change in vertical scales between the two plots, and that the top of the \(M \rightarrow A\) in Figure 2(b) has been cropped). The temperature width of the 90C Flexinol Austenite peak is about 10 °C, while the temperature width of the 70C Flexinol Austenite peak is over 20 °C and is more typical of “virgin” NiTi. The 90C Flexinol peak is typical for a transformation from oriented Martensite to Austenite, rather from thermal Martensite to Austenite. The temperature hysteresis in Figure 2(a) between the peak temperature of \(90^\circ\)C Flexinol, are typically seen when the Martensite microstructure has changed from relatively randomly-oriented Martensite to a highly oriented Martensite microstructure.

### 3.2 Isothermal Experiments

A series of isothermal experiments (see Figure 3) shows how the mechanical response changes with temperature. Each experiment was performed under grip-displacement control at a rate of \(\dot{\delta}/L = 7 \times 10^{-4} \text{ s}^{-1}\) and was performed with a different wire specimen from the same batch in thermal contact with a thermoelectric/heat sink as described in Section 2. Each experiment began by increasing the temperature to above 130 °C at a dead load of 2 N (13 MPa), just enough to maintain the wire straight, recovering the prestrain induced by the supplier (about 4.5 %) and establishing a consistent zero strain reference. The temperature was sufficient to ensure the wire had changed entirely to Austenite, and the free length (between the grips) under these conditions is considered the reference length \((L)\). The temperature was then reduced to the required level and held constant for the remainder of the experiment.

At temperatures above 85 °C the responses followed typical superelastic loops, each progressing between low strain Austenite \((A)\) and tensile-oriented, stress-induced Martensite \((M^+)\) along two stress plateaus. At lower temperatures (see 55 °C and below), the wire reverts to the high-strain, oriented-Martensite \((M^+)\) phase rather than randomly-oriented, thermal Martensite \((M^+/M^-)\) as would be common in unconditioned Nitinol. This is known commonly as the two-way shape memory effect (TWSME) and is behavior typical of highly-conditioned SMA wires;\textsuperscript{28,29} it will be explored further in section 4.1. A quasi-phase diagram (see Figure 4) was then constructed by plotting the available loading (red dots) and unloading (blue dots) plateau stresses against temperature\textsuperscript{3}. These stresses were fit with straight lines, resulting slopes of 8.2 MPa/°C and 7.9 MPa/°C for loading and unloading, respectively. The intermediate dotted line represents a hypothetical “phase equilibrium” line, which has a zero stress intercept at a “reference transformation temperature” \(T_R = 73\) °C, a characteristic temperature for the material that is useful for modeling. The agreement between the construction lines and

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\textsuperscript{3}We recognize that further \(A \rightarrow M^+\) transformation occurs at strain and stress levels taken beyond these plateau stresses and that this is accompanied by progressively larger amounts of plasticity (slip) and consequent residual stresses, but for simplicity we associate plateau stresses with “transformation stresses.”
the measured plateau stresses is remarkably good, except for the unloading plateau stresses above about 125 °C where the plateaus in Figure 3 are relatively indistinct and significant residual strain remains at zero load (indicating significant residual internal stress, plasticity, and locked-in Martensite).

### 3.3 NiTi Resistivity and the R-phase

Studies of NiTi SMA resistivity are numerous but are by no means exhaustive. Modeling efforts have for the most part neglected this property in favor of purely thermomechanical properties. Nevertheless, when building NiTi-based actuators, a good knowledge of how resistivity evolves is critical to predicting actuator power and actuator performance.
At zero load, a NiTi crystal can take one, or a mixture, of three phases: a low-symmetry (monoclinic) Martensite phase (in various microstructural arrangements) at low temperatures, a high-symmetry (cubic) Austenite phase at high temperatures, and an R-phase (rhombohedral) at intermediate temperatures. The R-phase appears most prominently upon cooling from Austenite, and its effect is an initial nonlinear knee in the mechanical response during the first 0.5 to 1.5 % strain, or so. While it is often ignored in constitutive models and experiments, it does however make a large contribution to the resistivity and thus cannot be ignored if an accurate resistivity model is to be developed. Previous studies involving resistivity measurements have been done for a single load, single temperature cycle, but with no temperature measurement, and single load, single temperature cycle with temperature measurement, many temperature cycles, but limited data resolution and temperature control, several loads, but under 80 MPa, with no temperature cycling, and some interesting recent experiments performed to identify the R-phase using in situ neutron diffraction and electrical resistivity measurements.

Figure 5 shows a dead-load experiment at a small stress (13 MPa) as the temperature was increased and decreased between room temperature and about 120 °C (solid lines – heating, dotted lines – cooling). The strain response (δ/Le, black line) shows a hysteretic loop with low strains at high temperature (A) and strains near 3.8 % at low temperature (M'). It shows a large TWSME, arising from the conditioning of the material done by the supplier. The resistivity response (ρ, blue line) shows an unusual (for NiTi) hysteresis loop with local maxima occurring during both heating and cooling. We suspect this behavior is due to locked-in R, and intend to confirm this in future work. Also, overlaid on the plot is the DSC thermogram with vertical construction lines (red) showing the peak temperatures, Mp and Ap, for reference. The temperature A, during heating corresponds well with the temperature at which both the strain and resistivity drop sharply. The temperature Mp, during cooling (increasing strain) coincides exactly with the onset of the drop in resistivity. The blue construction lines indicate temperatures where the resistivity has a local extremum. During heating, the resistivity has a peak that occurs as the strain (near 3.5 %) begins to decrease more dramatically and the DSC thermogram begins its upturn into the Austenite peak. During cooling, the minimum resistivity occurs as the strain (near 0.2 %) begins increasing and where the DSC thermogram begins decreasing towards the Martensite peak. The maximum resistivity line during cooling is associated with the sudden plateau in the resistivity, which seems to be where the DSC thermogram enters the Martensite peak more sharply. It is also associated with a strain of 2 %, seeming to indicate the exhaustion of transformation to R-phase.

4. CONSTANT LOAD SHAKEDOWN

The following are two dead-load shakedown experiments, presented in detail, as part of a larger series of experiments. The first is at the lowest load (13 MPa) that still maintains a straight wire. The second is at a moderately high load of 351 MPa, twice the manufacturer’s recommended load for millions of cycle life. This section ends with an overview of all six dead-load shakedown experiments, spanning dead loads from 13 MPa to 439 MPa.

4.1 Experiment 1: 13 MPa (2 N Load)

Figure 6(a) shows the time (t) histories of temperature (T, red line), strain (δ/Le, black line), and resistivity (ρ, blue line) during the first three temperature cycles. In this and all other shakedown experiments the first temperature cycle was performed quickly to 140 °C at a dead load of 13 MPa to establish the Austenite reference length (L) before beginning shakedown temperature cycles at the selected dead-load. Note that during cycle 1 cooling from 140 °C to room temperature 20 °C the resistivity response is non-monotonic with a rapid decrease, increase then decrease again. The resistivity reaches a local minimum when the temperature is about 99 °C, and the local maximum occurs when the temperature reaches about 52 °C. Figure 6(a) shows again the TWSME starting at a strain near 3.8 % at the start of cycle 2. As the temperature rises, the resistivity increases while the strain remains relatively static (slight decrease). The resistivity start to decrease again when the temperature reaches about 65 °C and levels off when the temperature is about 84 °C, at which point the strain has decreased to 0.55 %. These characteristics are then repeated as the temperature is cycled.

Figures 6(b)–(c) shows the evolution of δ/Le and ρ as the temperature is cycled between 20 and 120 °C. Only cycles 2 and 20 are shown, for clarity. As was mentioned in section 3.3, Figure 6(b) shows a large TWSME. Surprisingly, by the 20th cycle, the maximum and minimum values of δ/Le have both reduced somewhat, resulting in a shorter wire than the as-received wire. The effect is small, but is still measurable, with a final strain of δ/Le = −0.035 %. In fact, both the maximum and minimum lengths are actually lower after cycling. We suspect that this is due to a slight reversal of the effects of conditioning.
The maximum resistivity, $9.45 \times 10^{-7} \, \Omega \cdot \text{m}$, in Figure 6(c) occurs during cooling at 52 °C. Due to experimental limitations, the specimen does not reach a sufficiently low temperature to complete whatever transformation (likely $R \rightarrow M^+ / M^-$) is causing the subsequent drop in $\rho_e$. Upon heating, $\rho_e$ rises again, peaking at a temperature of 65 °C at a local maximum of $9.35 \times 10^{-7} \, \Omega \cdot \text{m}$. In contrast, this heating peak is absent for typical “virgin” wire under stress-free conditions, and it is typically only associated with wire being cycled under load.\textsuperscript{25} Between cycles 2 and 20, there is no measurable change in $\rho_e$ at the temperature extremes, while it does tend to decrease slightly at intermediate regions of the curve.

Of particular relevance to actuators and sensors is the relationship between strain and resistivity shown in Figure 6(d). During the portion of decreasing strain associated with heating in the transformation regime, there is a nearly linear relationship between the two. During the cooling transformation regime (increasing strain), the nonlinearity is another manifestation of the asynchronous action of $\rho_e$ and $\delta_e / L_e$ shown previously in Figure 5. At high strains (low temperatures), the steep “tail” represents the change in resistivity while the strain remains relatively constant.

### 4.2 Experiment 2: 351 MPa (40 N Load)

The previous experiment is now compared to a similar one at a higher dead-load of 351 MPa (40 N load). At this load level (see Figure 7(a)), the temperature cycles between 40 °C and 175 °C, reflecting the higher temperatures needed to transform between $M^+$ and $A$. The strain cycles between larger strain extremes, 0.8 % and 5.6 %. Some noise exists in the electrical resistance signal, affecting the measurement of $\rho_e$ at these larger strains due factors discussed in section 2. The $\delta_e / L_e$ curve in Figure 7(b) shakes down significantly in the first few cycles. The recoverable strain is larger than in Experiment 1, now 5.2 % during cycle 2. By the 3\textsuperscript{rd} cycle, the maximum $\delta_e / L_e$ increased from 6 % to 6.35 %, and by the 20\textsuperscript{th} it grows to 6.91 %.
Figure 7. Shakedown Experiment 2 (351 MPa dead load) showing: (a) temperature ($T$), strain ($\delta_e/L_e$), and resistivity ($\rho_e$) histories during the first three temperature cycles; cycles 2 and 20 (b) strain response; (c) resistivity ($\rho_e$) response; (d) resistivity vs. strain ($\delta_e/L_e$).

Figure 7(b) shows the resistivity response for the 2nd and 20th cycles. The jaggedness should be disregarded, but some general trends can still be noted. First, within each cycle the maximum resistivity is nearly the same on both heating and cooling, $10 \times 10^{-7} \text{ } \Omega \cdot \text{m}$ in the 2nd cycle and $9.7 \times 10^{-7} \text{ } \Omega \cdot \text{m}$ in the 20th cycle. Second, the resistivity shakes down to an interesting pattern. At the extreme low temperature, the change is minimal, progressing from 9.7 to $9.6 \times 10^{-7} \text{ } \Omega \cdot \text{m}$, but at the highest temperature, the difference is three times greater, progressing from 9.1 to $8.8 \times 10^{-7} \text{ } \Omega \cdot \text{m}$. Overall, the general trend is for the resistivity and temperature hysteresis to decrease somewhat with cycling. One might expect resistivity to increase as the material is further “conditioned” due to additional generation of crystal defects and residual stresses, but this does not appear to be the case. It appears that the amount of residual, locked-in, Martensite, which generally has a lower resistivity than Austenite or R-phase, is the dominant consideration.

During the previous experiment (13 MPa), strain and resistivity did not change at the same time during cooling. This effect is less pronounced at this higher load as shown in Figure 7(d). In this case, a large, nearly linear regime exists between the two with minimal strain hysteresis during transformation on heating and cooling, but a nonlinear portion still exists, confined to the extreme temperatures where strain was relatively unchanging.

4.3 Overview of Shakedown Experiments

A total of six shakedown experiments taken to 20 cycles were performed at the load levels 13 MPa, 88 MPa, 175 MPa, 263 MPa, 351 MPa, and 439 MPa. Figure 8(a) and 8(b) show cycles 2 and 20, respectively, for all six experiments. The three experiments at the lowest loads show little shakedown behavior. In fact, the 175 MPa shows almost no shakedown in the strain extremes with a small reduction in temperature hysteresis. Both the 13 MPa and 88 MPa experiments show small
Figure 8. Strain responses ($\delta_e/L_e$) for six dead-load experiments: (a) cycle 2, (b) cycle 20.

Figure 9. Summary of strain responses during cycling: (a) ($\delta_e/L_e$)$_{\text{max}}$ (closed boxes) and ($\delta_e/L_e$)$_{\text{min}}$ (open boxes) $\delta_e/L_e$, (b) recoverable strains $\Delta\delta_e/L_e = (\delta_e/L_e)_{\text{max}} - (\delta_e/L_e)_{\text{min}}$. 
reductions in the strain extremes. The most repeatable behavior is seen in the 175 MPa experiment, which is consistent with the manufacturer’s maximum recommended load (20 N). Shakedown progresses in a more dramatic fashion for the highest three dead-loads studied. Figure 8(a) shows that the loops do not close for the highest two load levels, and Figure 8(b) shows that they do not quite close for the highest load level even after 20 cycles. A summary of maximum and minimum strains for each cycle within each experiment is shown in Figure 9(a), and the differences between the maximum and minimum strains, i.e. recoverable strains, are shown accordingly in Figure 9(b). Note that for \( P/A_0 \) of 13 and 88 MPa in Figure 9(a), the maximum strains actually decreases over 20 cycles, the opposite of what intuition would suggest. At 175 MPa and above, the trend is for both strains to increase faster with increasing \( P/A_0 \). The recoverable strain in Figure 9(b) decreases slightly for 13 MPa and 88 MPa, remains relatively constant for 175 MPa, decreases slightly for 263 MPa, and decreases dramatically for 351 MPa and 439 MPa, so much that they cross the curves at the lower loads. This underscores the need to avoid overloading the wire in actuator applications, as the recoverable stroke may become degraded. For all experiments except 175 MPa, the recoverable strain decreased as cycles increased, but for two different reasons: for \( P/A_0 < 175 \) MPa, the maximum strain decreased faster than the minimum; the opposite is true for \( P/A_0 > 175 \) MPa.

Following each shakedown experiment, the load and temperature were brought to \( P = 2 \) N (13 MPa) and \( T = 150 \) °C for another measurement of the stress-free (mostly Austenite) length in order to measure the residual strain \( \varepsilon_r \). Figure 10 shows this permanent deformation on the vertical axis, plotted against \( P/A_0 \). It shows that at the minimum load, the residual is -0.035 %, so some stretching caused by wire conditioning must have been recovered. At 175 MPa the residual strain is minimal, but positive, and then residual strain increases with higher loads to a maximum of about 3 %.

Due to the TWSME, our stress-free results do not match that of typical NiTi.²⁷ Our experiments at slightly higher loads, within the range of the linear strain-resistivity relationship, agree with previous findings where the load levels were kept relatively low (below 80 MPa).²⁶ Lastly, Figure 11 shows a summary of resistivity vs. strain responses (cycle 2) for four of the six shakedown experiments (the two not shown were excessively noisy). It shows a reduction in hysteresis as the load level is increased, consistent with the elimination of the appearance of the R-phase. It shows that the linear portions of the responses tend toward a common line, although the extent is shifted along the strain axis.

### 5. SUMMARY & CONCLUSIONS

A systematic experimental study was performed on commercially-available, conditioned SMA wires (90C Flexinol from Dynalloy, Inc.) to quantify the shakedown behavior of the material under thermomechanical cyclic loading over a large range of stresses. The experiments are the beginning of a broad experimental effort to understand and quantify the thermo-mechanical behavior and its evolution during its lifetime in thermal actuator applications. The relationships between phase
fraction, stress, strain, temperature, and electrical resistivity, as well as their evolution through multiple dead-load thermal cycles were investigated using a new experimental setup.

A baseline characterization of 90C Flexinol was performed by differential scanning calorimetry (DSC) and isothermal mechanical experiments over a broad temperature range. This material is different from typical unconditioned Nitinol in several aspects, including higher transformation temperature, the significantly reduced hysteresis seen in the DSC response, and the large two-way shape memory effect seen in the mechanical responses. The resistivity responses for 90C Flexinol also exhibit some interesting new nonlinear effects, compared to Nitinol, that remain to be explored.

The shakedown response exhibited by 90C Flexinol was similar to Nitinol under overload conditions (above the supplier’s recommended maximum stress level), but was relatively stable/repeatable for moderate stress levels. At low stress level, a small, but detectable, reverse strain shakedown effect was noted where shakedown causes a reduction in both maximum and minimum strains during temperature cycling.

Work is ongoing to improve the resistivity measurements through improved attachment methods. Other experimental improvements are also underway to allow a broader range of temperature, an increased number of temperature cycles, and more complex thermomechanical paths during shakedown. Microscopy of tested specimens before and after different shakedown regimens is planned for the future to better connect the observed macroscopic phenomena to changes in the underlying microstructure.

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