THE EFFECT OF UNIAXIAL CYCLIC DEFORMATION ON THE EVOLUTION OF PHASE TRANSFORMATION FRONTS IN PSEUDOELASTIC NITI WIRE.

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ABSTRACT
Experiments are presented of the response of pseudoelastic NiTi wires subjected to displacement controlled cycles. A custom built thermo-mechanical testing apparatus is used to control the background temperature field of the wire specimen while allowing the evolution of transformation fronts to be tracked by full field infrared imaging. Two experiments under similar end-displacement histories, but at temperatures \( \geq 8^\circ C \) apart, are shown to give remarkably different cyclic responses. The mechanical response for the lower temperature experiment continued to soften but retained its shape through 43 partial transformation cycles, and the pattern of transformation fronts seemed to reach a steady state. The response for the higher temperature experiment showed a change in shape of the mechanical response and distinct changes in transformation front patterns over 31 partial transformation cycles.

INTRODUCTION
Shape Memory Alloys (SMAs), such as NiTi, exhibit two remarkable properties, the shape memory effect and pseudoelasticity. The shape memory effect is the material’s ability to erase large mechanically-induced strains (up to 8%) by moderate increases in temperature. Pseudoelasticity refers to the ability of the material in a somewhat higher temperature regime to accommodate strains of this magnitude during loading and then recover upon unloading (via a hysteresis loop). The underlying mechanism is a reversible martensitic transformation between solid-state phases, often occurring near room temperature. The transformation can be induced by changes in temperature or by changes in stress due to the strong thermo-mechanical coupling in the material behavior. NiTi’s remarkable behavior arises from the interplay of two phases, a high temperature phase (austenite), having a cubic lattice structure, and a low temperature phase (martensite), having a monoclinic structure (Otsuka et al., 1971). Due to its low degree of symmetry, the martensite phase exists either as a randomly twinned structure (low temperature, low stress state) or a stress-induced detwinned structure that can accommodate relatively large, reversible strains.

It is now well known that unstable mechanical behavior can occur during stress-induced transformation in uniaxial loaded SMAs (see Shaw & Kyriakides (1995) and Liu et al. (1998)). The transformation from austenite \((A)\) to martensite \((M)\) and back again during the pseudoelastic response of virgin polycrystalline NiTi occurs through the nucleation and propagation of phase transformation fronts. These events lead to distinctly non-uniform deformation and temperature fields. Local to each transformation front is the generation or absorption of latent heat which can cause self-heating or self-cooling of the material. A feedback loop between the material’s inherent temperature sensitivity of the transformation stress, the internal heating/cooling, and the heat exchanges with the ambient media is responsible for the material’s rate and environmental sensitivities. Nearly isothermal conditions tend to produce few transformation fronts and distinct plateaus in the mechanical response. Nearly adiabatic conditions tend to produce numerous transformation fronts and more stable looking force–displacement responses. The

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number of nucleation events (and therefore the number of transformation fronts) was shown to be related to the size of the nucleation peak compared to the non-uniform temperature field in the specimen (Shaw & Kyriakides, 1997), and this correlation has been confirmed by quantitative finite element simulations (Shaw, 2000).

The ability of SMAs, especially NiTi, to generate large stresses and deformations compared to other so-called “smart” materials, makes it a promising candidate for novel structural applications (see Funakubo (Ed.) (1987), Duerig et al. (1990), and Otsuka & Wayman (Ed.) (1998)), such as actuators and passive energy absorption devices. These require devices to be reliable and the response of the material to be predictable over its lifetime. In many applications some improvement in the predictability of the material has been accomplished through cycling prior to use, which is often referred to as “training”. Such cycling has also been used to induce a two-way shape memory effect where some strain change occurs on cooling in addition to heating. Training and fatigue have been investigated through thermal cycling (Edo (1989), Hebda & White (1995), and Lagoudas et al. (2000)), mechanical cycling (Miyazaki et al. (1986), Tobushi et al. (1998), and Miyazaki et al. (1999), Sehitoglu et al. (2001)), and combined thermal-mechanical cycling (Tanaka et al. (1995)). Fundamental work on the effect of cycling on the stress induced martensite transformation is reported in Melton & Mercier (1979), Sade et al. (1985)(for CuZnAl), and Miyazaki et al. (1986). This work shows that: (1) the reorientation of martensite under stress leads to gradual defect accumulation at martensite-martensite interfaces; (2) crystal dislocation defects may act as obstacles to martensite transformation; and (3) permanent strain is a consequence of a combination of slip and residual martensite that still exists after unloading. Additionally, the permanent strain shows a strong dependence on the stress applied during cycling. Accordingly, the residual stress field caused by defect accumulation in the microstructure results in features in the cycle response, permanent set, and the two-way shape memory effect seen at the macroscopic scale.

The current work studies the effect of cycling deformation on the evolution of inhomogeneous phase transformation in pseudoelastic polycrystalline NiTi wire. Since the nature of transformation fronts has important implications on the rate and ambient medium sensitivity of the material behavior, it is likely to be a significant player in the cycling performance. The kinetics of phase transformation fronts are measured with a special experimental setup during the cycling history by exploiting the non-uniform temperature fields that arise due to latent heat changes.

**EXPERIMENTAL PROCEDURE AND MATERIAL**

An experimental arrangement to effectively control the ambient temperature field and still allow access to the front of the specimen for full field monitoring was shown to produce high quality experimental data in Iadicola & Shaw (2000). A similar arrangement is used here. The SMA wire specimen is tested in an uniaxial testing machine and is in contact with a thermal conduction block (behind it). Displacement controlled tension tests are conducted while monitoring the load. The specimen is instrumented with fine thermocouples that have been calibrated to ASTM certified thermometers at two calibration temperatures (for the range of the experiment). A digital infrared imaging system (Inframetrics, now FLIR, ThermaCam SC1000 with a PtSi 256 x 256 detector array) monitors the evolution of temperature of the front side of the specimen. The accuracy of the temperature measurement from the infrared imaging system depends on knowledge of the emissivity of the specimen, which is calibrated by comparing the reported temperatures from the system to the thermocouple readings (in our case, ε=0.82 to 0.85). The resolution of the temperature measurement is ±0.03°C.

Fig. 1 shows the temperature control apparatus. An aluminum block is placed behind the specimen and hardened steel grips on the top and bottom. A copper pipe circulates fluid (usually water) through the aluminum block and the grips to a temperature-controlled circulating bath, creating an ambient environment for the wire specimen. A thermally conductive paste is used to ensure good thermal contact with the specimen. The wire is gripped between the two hardened steel plates at each end of the specimen. Thermoelectric modules are placed between the specimen and the aluminum thermal block.

![Figure 1. Thermal control apparatus.](image-url)
These allow precise control of the specimen temperature relative to the ambient environment provided by the fluid circulating system. The modules use the Peltier effect to heat or cool depending on the direction of DC electrical current (see Fraden (1997)). One 40 x 40 mm thermoelectric module (inner) is placed between two 6 x 6 mm thermoelectric modules (outer) along the specimen length. The outer and inner thermoelectric modules are controlled by separate power supplies to allow different temperature fields to be induced (although this capability is not used in the experiments herein). Since the transformation stresses are a strongly increasing function of temperature (8.6MPa/°C), raising or lowering the thermoelectric module temperature relative to the grip temperature creates the effect of changing the apparent cross-sectional area distribution of the specimen. In this way a “dogbone” specimen can be simulated during the onset of the $A \rightarrow M$ transformation, thereby forcing the nucleation of stress induced martensite to occur away from the ends of the specimen.

A laser extensometer (Electronic Instrument Research Ltd. model LE-05) is used to measure the elongation in a central region of the specimen. The extensometer is designed to measure the distance between the bottom edges of two retro-reflective targets. These targets are glued to the specimen near the ends as shown in Fig. 2. The figure shows the definition of reference lengths between the grips ($L_G$), the reflective targets ($L_E$), and the overall length of the thermoelectrics ($L_T$). The lower grip is held fixed and the displacement ($\delta_G$) is applied at the upper grip. A small air gap exists between the grip and the outer thermoelectrics at each end of the specimen. In the experiments to follow, the grips are held at a higher temperature than the center section of the wire (thermoelectric region) so conduction from the grips minimizes the effects of these air gaps. Global elongation of the specimen between the grips is defined as $\delta_G/L_G$. Elongation within the central region of the specimen (in contact with the thermoelectrics and as measured by the extensometer) is defined as the change in distance between the reflective targets ($\delta_E$) divided by the reference spacing of the targets ($L_E$). This regional elongation is used along with the global elongation to determine the extent of grip slippage and deformation beyond the central region of the specimen.

The material used in the experiments is nearly equi-atomic NiTi wire that was heat-treated straight by the manufacturer, Memry Corporation (Guide-BB-30). Specimens are cut to length, between 135 and 139 mm (5.33-5.47 in.). The average wire diameter is 0.765 mm (0.0301 in.) with an uncertainty less than ± 0.00127 mm (± 0.0005 in., the resolution of our measuring device). Each experiment used a wire specimen that was in its virgin state from the manufacturer. A plot of the differential scanning calorimetry for the virgin material is shown in Fig. 3. The material is pseudoelastic at temperatures above the austenite finish of 12°C.

The experiments are performed in displacement control. During the first cycle, the material in contact with the thermoelectric modules is fully transformed ($A \rightarrow M$), and then is completely unloaded ($M \rightarrow A$). This first cycle serves as a baseline from which all subsequent cycles are compared. Subsequent cycles are performed at intermediate displacements such that only a portion of the specimen is transformed. During the experiments, transformation front locations are determined by tracking local points of self-heating and self-cooling using the infrared imaging system. Images are taken at one second intervals to observe the evolving thermal behavior. Preliminary experiments showed that the thermoelectric modules were quite efficient in the control of the specimen temperature as compared to other methods of tem-

![Figure 2. Sketch of specimen with retro-reflective targets for use with the laser extensometer.](image)

![Figure 3. Differential scanning calorimetry for virgin NiTi sample (95mg) having transition temperatures: $A_s = -28^\circ C$, $A_f = 12^\circ C$, $R_s = 13^\circ C$, $R_f = -29^\circ C$, $M_s = -76^\circ C$, and $M_f = -118^\circ C$.](image)
perature control, such as air environmental chambers or liquid bath arrangements. A displacement rate of \( \dot{\delta} = 10^{-3} \text{s}^{-1} \) was found to produce measurable but small latent heat effects in the specimen, therefore this rate is used for all experiments shown here.

**EXPERIMENTAL RESULTS**

Two experiments at pseudoelastic temperatures are presented below: the first is performed with the temperature of the thermoelectrics \((T_T)\) set to 16.5°C and a grip temperature \((T_G)\) of 46.1°C; the second is performed with a thermoelectric temperature of 24.6°C and a grip temperature of 58.3°C.

**Experiment 1**

Figure 4 shows the mechanical response through 43 cycles for the first experiment \((T_T=16.5°C)\). Selected cycles shown in black are discussed later in some detail. In Fig. 4a, the nominal stress (load, \(P\), over initial area, \(A_0\)) is plotted versus the global elongation, whereas in Fig. 4b nominal stress is plotted versus the elongation within the central region of the specimen (laser extensometer). For inhomogeneous transformations such as this one the responses as measured by the grip displacement and laser extensometer may differ depending on where transformation has occurred in the specimen. The elongation (normalized) reported in the center region (Fig. 4b) is slightly greater than the global elongation (Fig. 4a). The difference is due to the fact that the fraction of transformation along the length that has occurred between the grips \((L_G)\) is different than that which has occurred within the laser extensometer region \((L_E)\). The nucleation event \((A \rightarrow M)\) for the first cycle \((N=1)\) occurs at about \(\delta_E/L_E=1.1\%\), and the stresses of nucleation and propagation are 465 MPa and 401 MPa, respectively. During this cycle, the central region of the specimen is fully transformed. As the transformation enters the warmer regions near the edge of the thermoelectrics a higher propagation stress is required. This is seen as a rise in the load displacement response near the end of the loading plateau. During unloading the specimen is fully transformed back to austenite along a propagation stress of 154 MPa. No nucleation is seen since transformation fronts already exist and they simply reverse direction. After full \(M \rightarrow A\) transformation, the specimen unloads along nearly the same elastic slope as during initial loading.

Beginning with the second cycle \((N=2)\) and continuing for all of the remaining cycles, the specimen is partially transformed through deformation between \(\delta_G/L_G\) of 1.3% and 4.7% for a total of 43 cycles. During each cycle as the global elongation \((\delta_G/L_G)\) approaches 4.7%, the stress tends to increase and approach the stress for the previous cycle at that same value of global elongation. As the global elongation approaches 1.3%, the stress tends to decrease below the stress of the previous cycle at that same global elongation. The reduction of propagation stresses with cycles for both \(A \rightarrow M\) and \(M \rightarrow A\) transformations is a general trend in the experiment (Fig. 5). Figure 6 is a plot of hysteresis stress (hysteresis load, \(P_{hys} = P_{A \rightarrow M} - P_{M \rightarrow A}\), over initial area) versus cycle. Although the slopes in Figs. 5 and 6 for \(N>35\) are less than earlier cycles, a slight negative slope still
exists. This suggests that the material has not reached but is approaching a limit cycle response. In Fig. 4, the general reduction of the $A \rightarrow M$ transformation stress is temporarily interrupted by a small (18MPa) undulation in the plateau stress starting in Cycle 12 and decaying away through Cycle 32. This will be discussed below. During unloading at the end of the last cycle the remainder of the central region is transformed ($M \rightarrow A$) followed by elastic unloading. Note that the slope of the elastic unloading (53GPa) after Cycle 43 is less than initial loading slope (76GPa) for Cycle 1, but greater than initial unloading (30GPa) for Cycle 1. A residual deformation of approximately $\delta_E/L_E=0.30\%$ remains after full unloading.

Temperature profiles of the specimen are processed from images taken with the infrared imaging system. Figure 7a shows three of the temperature profiles selected at distinct stages of transformation, during the first loading cycle. Figure 7b is an intensity plot of the entire series of infrared images (taken at one second intervals) for the first cycle. A “V” and reference number are shown in Fig. 7b at the time of each profile shown in Fig. 7a. During loading, the nucleation and propagation of stress-induced martensite results in the local self-heating of the wire. Just after nucleation two peaks are seen in profile (1) at a position between $x/L_T=0.1$ and 0.2. These peaks approximately locate the transformation fronts. The left peak is quickly arrested as the right peak propagates toward the other end of the specimen ($x/L_T=1$), as shown in Fig. 7b. During unloading, the propagation of the reverse transformation front results in local self-cooling of the wire. This is seen in profile (2) at approximately $x/L_T=0.37$ and 0.6. Profile (3) is the temperature distribution after the specimen is completely unloaded.

To aid in the determination of the location and intensity of local heating or cooling, it is useful to subtract a reference temperature profile from the current temperature profile. This produces a profile of the change in temperature ($\Delta T$) along the specimen by eliminating the background temperature distribution. Profile (3) in Fig. 7a is used for this purpose.

Figure 8 shows the $\Delta T$ images and associated nominal stress values for selected cycles during the experiment. Each cycle is indicated by its cycle number ($N$) and is shown on a consistent scale of time, where $t=0$ at the start of each cycle. The selected cycles correspond to those shown in black in Fig. 4. The exothermic $A \rightarrow M$ transformation upon loading is seen as a 2 to 3°C peak propagating across the specimen, and the endothermic $M \rightarrow A$ transformation upon unloading is seen as a -1 to -2°C depression propagating part way across the specimen. The large temperature shift above $x/L_T=0.97$ is due to the motion of the laser extensometer target during loading and unloading (see the sketch next to Fig. 8a). (The emissivity for the system was set based upon the wire specimen and is not appropriate for the reflective targets, therefore infrared readings in these regions are not representative of the actual temperature.)

The remainder of the discussion for Experiment 1 will detail the behavior observed in Fig. 8. The second cycle ($N=2$) has an elastic region that may be seen in the plot of nominal stress (Fig. 8b) which corresponds to a series of $\Delta T$ images (Fig. 8a) during which no temperature change is observed. Although the images straddle the precise moment of nucleation, it is clear that nucleation occurred near $x/L_T \approx 0.28$. The corresponding time
in the plot of stress shows the characteristic drop in stress followed by a plateau. At \( t=30 \text{s} \), the plateau rises slightly. The images show that the two fronts propagate as the stress initially plateaus, and that the rise in the stress plateau coincides with the lower front stopping and the upper front propagating at a faster rate. This is consistent with the findings of Shaw & Kyriakides (1997). In general, one front in motion results in a higher propagation stress \( A \rightarrow M \) (due to the somewhat more intense self-heating) than the propagation stress \( A \rightarrow M \) when two fronts are in motion. Unloading begins with an elastic region seen again in the images as a brief region with no change in the temperature of the specimen gage section. No reverse nucleation is seen since the transformation fronts already exist and simply reverse direction. As these fronts begin to move the depressions in the \( \Delta T \) images are seen to propagate from the ends toward the center of the specimen.

The infrared images for Cycles 3 through 6 are quite similar to that shown for Cycle 7. The location of the fronts at the start of Cycle 7 are shifted up slightly in the gage section (between \( x/L_T \) of 0.39 and 0.60) from their location at the end of Cycle 2. During loading, the fronts begin to move in the \( \Delta T \) images and a minor dip is seen in the stress response. The propagation stress is reduced compared to the earlier cycles, but rises near the end of the loading segment as the front approaches the less cycled region near \( x/L_T \approx 0.89 \). Note: the intensity of the temperature peak is greater in this region.

Starting with Cycle 12 and lasting until Cycle 32, a small undulation occurs in the stress response at the beginning of the \( A \rightarrow M \) transformation. In each cycle, as the upper front begins propagating, the lower front does not move and the stress rises. Later, the motion of the lower front coincides with the drop in stress. (This is the reverse sequence of the behavior that is seen during \( A \rightarrow M \) propagation in Cycle 2.) During each Cycle 12 through 32, a successively lower propagation stress \( (A \rightarrow M) \) is observed, as noted earlier. At the end of the loading segment the stress rises to \( \approx 382 \text{MPa} \) in each cycle as the fronts approach the less cycled region at the ends of the transformation region (\( x/L_T < 0.10 \) and \( x/L_T > 0.85 \)). In Cycles 17 through 22, the rise is a result of the combined effects of only one front being in motion and that front approaching a less cycled region. The reverse transformation \( (M \rightarrow A) \) in Cycles 12 through 32 is at a stress \( \approx 133 \text{MPa} \) somewhat lower than previous cycles, but otherwise events are repetitive.

In Cycles 37 through 42, minimal changes are seen in the propagation stresses \( (A \rightarrow M \) and \( M \rightarrow A) \) and the maximum stress (at the end of loading). The stress plateau remains relatively flat. The \( \Delta T \) images also show little change from cycle to cycle.
Figure 8. Experiment 1: temperature and nominal stress histories of SMA wire for selected cycles \( (N) \): (a) infrared images of the change in temperature along the length of the specimen and (b) corresponding nominal stress histories.
**Experiment 2**

The mechanical response through 31 cycles for Experiment 2 is shown in Fig. 9. Again, selected cycles shown in black are discussed in detail later.

![Figure 9](image)

**Figure 9.** Mechanical response of SMA wire for Experiment 2 \((T_f=24.6^\circ C)\) through 31 cycles: nominal stress versus (a) global elongation based upon end displacement and (b) regional elongation based upon laser extensometer.

![Figure 10](image)

**Figure 10.** Change in propagation stress \((\Delta P/A_0)\) from Cycle 1 measured at \(\delta_E/L_E=2.5\%\) for loading \((A \rightarrow M)\) and \(\delta_E/L_E=2\%\) for unloading \((M \rightarrow A)\), during Experiment 2.

![Figure 11](image)

**Figure 11.** Magnitude of stress hysteresis for Experiment 2 measured at the same values of elongation as used in Fig. 10.

In Fig. 9a, the nominal stress is plotted versus the global elongation, whereas in Fig. 9b nominal stress is plotted versus the elongation within the central region (laser extensometer) of the specimen. The nucleation event for the first cycle \((N=1)\) occurs at about 1.0% strain, and the stresses of nucleation and propagation are 549 MPa and 471 MPa, respectively. These stresses are larger than the nucleation and propagation stresses in Experiment 1, due to the strong stress-temperature (Clausius-Clapeyron) dependence in the material. As for Experiment 2, the stress of propagation tends to decrease with increasing cycles for
both forward and reverse transformations (Fig. 10). This general trend is temporarily interrupted during loading starting at Cycle 6 through Cycle 12, where the plateau is no longer smooth. This is similar to the Experiment 1, but occurs earlier in this experiment. The change in stress hysteresis (Fig. 11) occurs earlier in the cycle history than in the Experiment 1. Additionally, the slopes in Figs. 10 and 11 near Cycle 31 are almost zero. This suggests that the material is approaching a limit cycle response. Overall, the drop in hysteresis stress for this experiment is larger than that of Experiment 1 and the shape of the hysteresis in the final cycle (Fig. 9) is different than the final cycle in Experiment 1 (Fig. 4).

The transition from the elastic behavior to transformation behavior is smoother, and the slope during transformation is distinctly positive. One might be tempted to interpret this positive slope as being associated with a uniform transformation, but as will be seen, this is not the case.

In Fig. 9b, the elongation limits of the partial transformation cycles begin to shift starting with Cycle 12. This shift combined the large difference in residual deformation between Figs. 9a and 9b suggests that grip slippage and/or deformation outside of the central region occurs. At the end of the last cycle in Fig. 9 no further transformation occurs and the specimen elastically unloads. The slope of the elastic unloading (31 GPA) as measured by the laser extensometer (Fig. 9b) is less than both the initial slope (81 GPA) during austenite loading and the initial slope of the martensite elastic unloading (38 GPA). After full unloading, a residual deformation of $\delta_E/L_E=0.22\%$ occurs. Possible reasons for this response are discussed below.

Figure 12 shows the $\Delta T$ images and associated nominal stress histories for selected cycles during Experiment 2, in a similar format to Fig. 8 for Experiment 1. The second cycle begins with an elastic loading seen in the stress response and in the $\Delta T$ images as an unchanging temperature distribution. Nucleation results in a sudden drop in stress followed by a plateau. In the $\Delta T$ images, the drop in stress correlates to the temperature rise near $x/L_T=0.68$. During the stress plateau, two transformation fronts propagate toward the grips. At $t=35s$, the upper front stops moving and the lower front accelerates. At the same time, a slight rise occurs in the stress plateau (similar to behavior seen in Experiment 1). During unloading ($M \rightarrow A$), the existing fronts propagate simultaneously from the ends of the specimen toward the center of the specimen.

In Cycle 4, the existing fronts (Fig. 12) begin to propagate as soon as the plateau stress (slightly below the plateau of the earlier cycles) is reached. Both fronts move simultaneously from the middle to the ends of the specimen. The upper front stops prior to the lower front and a slight rise occurs in the stress plateau, followed by the sharp rise at the end of the plateau. The latter rise is due to the lower front approaching a less cycled portion of the specimen near $x/L_T=0.15$. The reverse transformation proceeds similar to Cycle 2, but more of the specimen is transformed ($M \rightarrow A$) than in earlier cycles.

A distinct change in front kinetics occurs in Cycle 7. During loading ($A \rightarrow M$), the upper front propagates while the lower front does not ($x/L_T=0.55$). Fronts not in motion are not actively transforming material, thus they do not appear in the infrared images. Knowledge of the location of a stationary front is based upon its last known location (the last time it was in motion, in an earlier cycle). A sudden drop in stress occurs as a nucleation occurs at $x/L_T=0.17$. Four fronts are now present in the specimen. Two from the previous cycle (one in motion near the top of the specimen and the other stationary near the middle of the specimen) and two diverging fronts at the new nucleation location. At the nucleation, the bottom front almost immediately stops near $x/L_T=0.16$ as the upper front begins to move. At $t \approx 20s$, the upper front stops and a rise is seen in the propagation stress (only one front is in motion). At the maximum extension, the middle two fronts (one stationary from the previous cycle and the other being the only moving front) coalesce at $x/L_T=0.5$ and the lower front begins to move into the less cycled area at the lower end of the specimen. During unloading ($M \rightarrow A$), the fronts propagate from the ends toward the middle of the gage section. The upper front stops before the lower front and a drop in propagation stress is seen. This is similar to the behavior in the $A \rightarrow M$ transformation, but instead of a rise in stress due to less fronts being present a drop in stress occurs due to the endothermic nature of the $M \rightarrow A$ transformation.

The $A \rightarrow M$ transformation in Cycle 9 is similar to Cycle 7, but the nucleation occurs slightly earlier in the loading history and the plateau stress is decreased. Again when the upper front stops the middle front (created during the nucleation event) increases speed and a slight rise is seen in the plateau stress. As this front enters a region that has been subjected to fewer cycles a rise occurs in the stress until the end of loading. During unloading ($M \rightarrow A$), the upper front begins to propagate first followed soon after by the lower front. As an austenite nucleation occurs at $x/L_T=0.45$ the stress has a sudden rise (four fronts are present momentarily in the specimen). After the coalescence of two of the fronts $t=72s$, the stress decreases back to its value at $t=65s$.

Cycles 10 through 12 show similar behavior. During loading, nucleation $A \rightarrow M$ occurs at the same point along the specimen as coalescence occurred in the previous cycle ($x/L_T=0.39$ and 0.35 for Cycles 10 and 12 respectively), and corresponds to a small drop in stress. Until 14.4s, there are three moving fronts. After 14.7s, only one front is in motion (near the middle of the specimen), the self-heating intensifies, and the stress level rises. During unloading ($M \rightarrow A$), the outer two fronts propagate first and a nucleation of austenite occurs at $x/L_T=0.45$ and is accompanied by a rise in stress. This is the same nucleation site as in Cycle 9, but in these cycles the nucleation occurs at an earlier time.
Figure 12. Experiment 2: temperature and nominal stress histories of SMA wire for selected cycles (N): (a) infrared images of the change in temperature along the length of the specimen and (b) corresponding nominal stress histories.
During Cycles 18 thru 30, nucleation events are no longer accompanied by distinct drop in stress and the intensities of the $\Delta T$ peaks are decreased. The loading plateau now resembles a hardening curve (relatively smooth and positive slope). The continuous rise in stress is due to the propagating front traversing material that has experienced fewer cycles (the center region of the gage section). The unloading behavior for Cycle 18 and beyond is similar to Cycle 12, but no changes in stress are seen coincident with nucleation or coalescence events. Note that in Cycles 18 through 30 the entire center region of the specimen is involved with transformation fronts ($A \rightarrow M$).

**Summary of Experimental Observations**

The two experiments shown were performed on wire taken from the same batch of material, and tested under similar conditions with the exception of a change in the ambient temperature by $\approx 8^\circ$C. Some behaviors were common to both experiments. In both experiments, the propagation stress for $A \rightarrow M$ and $M \rightarrow A$ generally decreased with cycle number. An increase in the number of fronts caused a drop in stress during $A \rightarrow M$ transformation, and a decrease in the number of fronts caused a rise in stress. During the $M \rightarrow A$ transformation, an increase in the number of fronts caused a rise in propagation stress and a decrease in the number of fronts resulted in a drop in stress. The intensity of the $\Delta T$ peaks and depressions in Figs. 8 and 12 appear to decrease with increased cycle number. This was most apparent in the Experiment 2. The intensity change in $\Delta T$ peaks indicate a reduction in the latent heat release/absorption. It appears that less material is transforming (and less of a strain jump occurs) across transformation fronts that have traversed the same regions multiple times. Comparing the final cycles for the two experiments shown in Figs 4 and 9, the final stress hysteresis was larger in Experiment 1 than in the Experiment 2, and the change in shape of the hysteresis loop was more dramatic in Experiment 2. Additionally, Experiment 2 seemed to approach a limit cycle faster than in Experiment 1.

Although many similarities exist in the experiments, the progression of the transformation (Figs. 8 and 12) was different. In Experiment 1, minor shifting of the region of transformation and a generally consistent pattern of front motion occurred. In Experiment 2, the extent of the transformation region continuously increased with a varied pattern of front motion until transformation involved the entire specimen length. Unlike the Experiment 1, Experiment 2 had multiple nucleations during cycling. It is interesting to note the location of the nucleations in Experiment 2. The $A \rightarrow M$ nucleation in Cycle 7 occurred near the nucleation in Cycle 1 (not shown). The $M \rightarrow A$ nucleation in Cycle 9 was near the location where the fronts stopped in the first six cycles, and a coalescence occurred during loading in Cycle 7. The location of this nucleation remains a nucleation site in all of the remaining cycles. $A \rightarrow M$ nucleation sites for the remaining cycles followed the coalescence locations of the previous cycle.

Both experiments presented were performed under a fixed end displacement interval. If the actual transformation strain was the same for repeated cycles, then only the same percentage of material may be transformed during each cycle. Experiment 1 appears to behave in this manner, but Experiment 2 does not. In Experiment 2, more material was transformed with every successive cycle, this would require a local reduction the transformation strain recovery with the increase in local cycle number. This is likely the result of residual deformation as shown by (Miyazaki et al., 1986). The existence of residual martensite may explain the changes in the slope of the elastic unloading during the final cycle in Figs. 4b versus 9b, and the decrease in the energy to nucleate martensite in Fig. 12 for Cycles 18 through 30.

**CONCLUSIONS**

Two experiments were presented at two pseudoelastic temperatures ($\approx 8^\circ$C apart) for commercially available NiTi Shape Memory Alloy wire. Evolution of transformation fronts were monitored through a special experimental arrangement incorporating infrared imaging of temperature profile changes due to the latent heat of transformation. In both experiments a significant drop in both the $A \rightarrow M$ and $M \rightarrow A$ transformation stresses were observed with deformation induced cycles. The drop in $A \rightarrow M$ transformation stress was more significant than the drop in the $M \rightarrow A$ transformation stress. Additionally, these drops were larger for the higher temperature experiment. This is likely due to the higher stresses involved for the experiment at the higher temperature. In the lower temperature experiment, the mechanical response was still evolving after 43 cycles, but the transformation front kinetics seemed to reach a steady state. In the higher temperature experiment, the mechanical response seemed to be close to a limit cycle after 30 cycles, and the transformation occurred through various front patterns.

In the lower temperature experiment, the shape of the load displacement response and evolution of transformation fronts did not change much during cycling. However, both the shape of the load displacement response and motion of transformation fronts changed dramatically for the higher temperature experiment. Consequently, even relatively small changes in temperature (and therefore transformation stress) can have a strong effect on the cyclic material response. We suspect that the stresses in this experiment were high enough that the competing deformation mechanism of micro-plasticity plays a role. One would expect that such damage could lead to performance problems and eventual fatigue of the material.

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