SHAPE MEMORY ALLOY FRACTURE AS A DEPLOYMENT ACTUATOR

By

DARRICK MATTHEW BUBAN

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As members of the Dissertation Committee, we certify that we have read the dissertation prepared by Darrick Matthew Buban entitled Shape Memory Alloy Fracture as a Deployment Actuator and recommend that it be accepted as fulfilling the dissertation requirement for the Degree of Doctor of Philosophy

_____
Dr. George Frantziskonis Date: _____

_____
Dr. Donald Uhlmann Date: _____

_____
Dr. Robert Fleischman Date: _____

_____
Dr. Krishna Muralidharan Date: _____

Final approval and acceptance of this dissertation is contingent upon the candidate's submission of the final copies of the dissertation to the Graduate College. I hereby certify that I have read this dissertation prepared under my direction and recommend that it be accepted as fulfilling the dissertation requirement.

_____
Dr. George Frantziskonis Date: _____

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ABSTRACT

Many applications require deployable structures to meet operational objectives such as satellites that unfurl antenna arrays. Typically, most deployment efforts involve the use of explosive and non-explosive actuators (EAs and NEAs respectively) that have implementation drawbacks such as the expense associated with special handling and the bulk encountered with mounting the devices.

To mitigate EA and NEA drawbacks, the integration of shape memory alloys (SMA) as a deployment actuator was investigated. SMA specimens were heated and pulled to failure developing an environmental and structural operating envelope for application as deployment mechanisms. A Finite Element Model (FEM) was also created to model the response behavior induced during specimen testing so that modeled performance could be used in lieu of testing when integrating SMA actuators into deployment systems.

Experimental results verified that SMAs can be implemented as deployment actuators. Recorded data showed that SMA fracture is possible over a wide range of temperatures and strains, filling a material performance gap not found in the literature. The obtained information allows design engineers to appropriately size SMAs given design requirements achieving the desired deployment effects. The Finite Element Model was partially successful, capable of emulating strained ambient material behavior up to

approximately 6.1%. The limited response is due to lack of experimentally derived large stress and strain available for model emulation.

CHAPTER 1: INTRODUCTION

Humans have produced many technological advances spanning complexity from the wheel to satellite radio. Yet utilization or implementation of certain technologies can typically be broken down into the interaction of much simpler subsystems and components. In the case of satellite radio for example, an antenna (Figure 1) must be unfurled in space after launch with a spring loaded articulating arm, being deployed through the initiation of an actuator system.

Figure 1. Harris antenna shown in stowed and unfurled configurations (1)

1.1 Actuator System Types

1.1.1 Explosive Actuators (EAs)

These actuators are electrically-detonated explosive devices (Figure 2) that when activated allow a secondary function to be performed.

Figure 2. Industrial explosive actuators (2)

EAs range in size from that of an AA battery to small fire extinguisher. Examples include (2):

- Explosive bolts and nuts: release and separate bolted connections on command
- Gas generators: inflation of many types of products or devices
- Pyrotechnic electrical disconnects: high speed, severing or termination of electrical circuits
- Cable cutters: severing of electrical cables, structural cables, tubing, cord, etc.
- Fire suppression systems: deployment and dispersion of liquid, solid or gaseous suppressants
- Pin pullers and pin pushers: rapid actuation or movement of latches, locks, mechanisms
- Propelling cartridges: eject or launch projectiles using pyrotechnic energy or using pyrotechnics to release a propelling mechanism

The form of EA that most people are familiar with are those that initiate automobile air bag deployment. When a sensor (e.g. accelerometer) within the automobile senses a rapid deceleration of the vehicle the control algorithm commands the EA to fire. Specifically, the “sensors send an electric signal to the canister that contains...sodium azide and the electric signal detonates a small amount of an igniter compound. The heat from this ignition starts the decomposition of the sodium azide and the generation of nitrogen gas to fill the air bag...From the time the sensor detects the collision to the time the air bag is fully inflated is only 30 milliseconds. Some 50 milliseconds after an accident, the car’s occupant hits the air bag and its deflation absorbs the forward-moving energy of the occupant.” (3)

1.1.2 Non-Explosive Actuators (NEAs)

These devices incorporate electromechanical actuations that perform the same function as EAs (Figure 3).

Figure 3. Non-explosive actuator examples (4)

They tend to occupy larger volumes compared to EAs as they lack the pyrotechnic capability to perform action. Examples include (4):

- Frangibolts: a Shape Memory Alloy (SMA) cylinder elongates to fracture a bolt element thereby achieving separation of two or more components.
- Pinpullers: a SMA actuated pinpuller releases stored energy from a compression spring used to secure and release numerous spacecraft deployables.
- Ejector release mechanisms: a bolt is threaded into the coupler section of the Actuator and used to secure a spacecraft deployable. On command the coupler section is released by powering the Actuator.

1.2 EA and NEA Drawbacks

A critical review of implementing EAs and NEAs found several drawbacks:

1. Expensive. Special precautions must be taken when dealing with EAs given the explosive nature of their actuation. Tailored design, assembly, packaging, handling, transportation, storage, and training are required to regulate the risks which add to the cost of the devices.
2. Dangerous. Both types of actuators are capable of severely damaging the overall system and/or maiming personnel with the possibility of death both from accidental release of the stored energy within device or through an explosive discharge.
3. Bulky. Both types of actuators must occupy a particular volume within or adjacent to the deployable structure. Typically they are rigidly mounted and

accompanied by redundant fail-safe initiating mechanisms, wiring, and command and control electronics. Specifically, when used inside a deployable missile cover the volume required to house the actuator is significant and can shift the center of gravity (CG) of the missile requiring ballasting to counteract the effects.

Ballasting has the drawback of increasing missile weight with the deleterious effects of reduced missile range and/or maneuverability.

4. Risky. Although both types of actuators must be fully qualified to MIL-DTL-23659, General Design Specification for Electric Initiators, several electronic, mechanical, and/or chemical interactions must occur before actuation. Their reliability is thus the product of the reliability of the cumulative systems and the components.

More interactions = more risk

Given this, redundant systems are often utilized to minimize the risk of faulty hardware.

5. Undesired effects. When used in space applications, actuators have the potential to impart dynamic disturbances into the structure which are difficult and sometimes impossible to dampen in the vacuum of space; rendering the craft unusable. Also, if components of the actuator break away post actuation the potential exist for collision with the host and adjacent systems leaving them nonfunctional.

1.3 EA and NEA Drawback Mitigation: Shape Memory Alloy Actuator (SMAA)

Lyman and Koehler proposed (5) an alternative method to EAs and NEAs for achieving actuation. Their patent states that a pre-strained and restrained piece of SMA could be fractured almost instantaneously upon the application of heat to the specimen. The patent does not provide the specific material type, geometry, temperature, stress, or strain required to achieve SMA fracture.

An extensive literature review was conducted to consolidate design guidelines for incorporating the aforementioned actuation. The literature focuses heavily on characterizing the fatigue behavior of superelastic SMA (6-18) and the propagation of fatigue induced defects within the material leading to fracture (Figure 4).

Figure 4. Thermo-mechanically induced defect (19)

The reason for the focus is that the superelastic SMA variant is used heavily in the medical industry “for nonvascular and vascular stents” (19) which encounter thousands of cyclical stress cycles within the human body. Understanding the propagation behavior of defects within the superelastic SMA allows design engineers “to predict the fatigue failure life” (20) of SMA devices potentially preventing life threatening situations from occurring.

Other investigations (21-26) focus on utilizing the inherent ability of SMAs to perform repeatable actuations like opening and closing latches while maintaining structural integrity.

The aforementioned efforts differ from this work in that fracture is desired and the SMA will be actuated in an “as manufactured” condition for one cycle and not fatigue loaded prior to use.

SMAs instituted in lieu of EAs and NEAs potentially affords the following benefits to be realized:

1. Cost savings. The SMA design would be simple, consisting of mechanical or bonded fixturing, a SMA specimen with predetermined geometry to facilitate failure, and a resistive heating element to fracture the specimen. The design would still need to be fully qualified but not to the extent outlined in MIL-DTL-23659

because of pyrotechnic actuation elimination and decreased amount of components. This has the direct impact of reducing per unit cost.

2. Increased safety. The possibility of maiming or killing personnel is reduced as explosive discharges are eliminated resulting in less stringent handling and training requirements and potential cost savings.
3. Decreased bulk. The simplified SMA design will occupy less overall volume. Although still rigidly mounted (mechanically or bonded), complicated fail-safe initiating mechanisms, wiring, and command and control electronics will be reduced. Specifically, when used inside a deployable missile cover the volume required to house the SMA will decrease significantly resulting in less center of gravity shifting and ballasting to counteract the effects. Less ballasting translates into decreased missile weight and increased range and/or maneuverability.
4. Increased reliability. The SMA will consist of essentially three components: the SMA specimen, the resistive element, and the initiator for the element. The simplified design and elimination of pyrotechnics and electromechanical mechanisms has the potential to dramatically increase the reliability of the system because it directly correlates to the reliability of the cumulative system and the component interaction.

Less interactions = less risk

If redundant systems were still required, the added cost would be less compared to the current methods given the simplicity of the actuation.

5. Decreased undesired effects. When used in space applications, SMAs will not impart explosive impulses into the system thus dynamic disturbances are less likely to occur. Additionally, there are no components to break away post actuation thus they cannot cause damage.

1.4 Shape Memory Alloy: Unique Characteristic

Shape memory alloys are metallic material compositions that when deformed plastically will return to original form after being heated. “The shape memory effect can be used to generate motion and/or force... This phenomenon results from a crystalline phase change known as ‘thermoelastic martensitic transformation.’” (24) Turner investigated the thermomechanical response of SMAs as part of his dissertation effort involving hybrid composite systems. In that work he captured that “shape memory alloys are a class of materials that exhibit a diffusionless martensitic transformation when cooled from the higher-temperature austenitic state... A SMA can be easily deformed in the low temperature martensitic condition and can be returned to its original configuration by heating through the reverse transformation temperature range. This type of (shape memory effect) is termed free recovery. Conversely, in a constrained recovery configuration, the SMA element is prevented from recovering the initial strain and a large tensile stress (recovery stress) is induced. A situation in which the actuator performs work (deforms under load) is called restrained recovery.” (27) Succinctly, when a SMA is strained, restrained, and then heated, it performs actuation.

Common alloys include copper aluminum beryllium (CuAlBe), copper aluminum nickel (CuAlNi), and nickel titanium commonly referred to as Nitinol (Nickel Titanium Naval Ordnance Laboratory). Nitinol SM495 was used in this study and is composed of “nearly equiatomic compositions of nickel and titanium by weight. Nitinol is considered to be the shape memory alloy with the most potential for engineering applications because its ductility at low temperature, high degree of shape-recovery capability, large pseudoelastic hysteresis, corrosion and fatigue resistance, biomedical compatibility, and relatively high electrical resistance.” (27) Nitinol Devices and Components, Inc. (NDC) provided a free 10 foot section of SM495 rectangular cross-section wire for testing.

Figure 5 shows structurally the shape memory behavior of Nitinol when stressed and heated. “At high temperatures, Nitinol is stable in the austenitic phase with properties that are similar to many titanium alloys (top station in triangle). When Nitinol is sufficiently cooled, it adopts a new crystal structure called ‘twinned martensite’ (lower right of triangle) with dramatically different properties, more like those of lead or tin. When twinned martensite is deformed, it does not deform through conventional mechanisms, but by moving and eliminating twin boundaries—a kind of ‘unfolding’ in a sense. When the deformed martensite (lower left) is sufficiently heated, it returns to the original austenite structure. All martensite (whether deformed or not) reverts to the same austenitic structure upon heating, and thus the original structure and shape is recovered.” (28)

Figure 5. The basic "shape memory triangle" (28)

1.5 SMA Compared to Conventional Metals

SMA was intentionally chosen as the deployment actuation method for study as compared to conventional metals (e.g. stainless steel) due to its uniquely inherent physical properties. When a SMA specimen is loaded at ambient conditions (e.g. room temperature) it will have a martensitic structure and follow stress-strain curve “A” shown in Figure 6. If restrained and heated as indicated, the structure will change to that of less ductile austenite, and fracture will occur if the specimen strain in the martensite condition cannot be accommodated by the less ductile austenite.

Figure 6. Visual representation of SMA fracture through the application of heat and based on (25)

The instantaneous structural change from martensite to austenite through the application of heat is not found in traditional metals and therefore cannot be used for fracture deployment. It is also understood by the author that “the transformation temperatures increase with increasing operating stress” (25) (Figure 7) thus a fundamental key in utilizing this unique characteristic is being able to quantify the temperature-strain relationship required to induce the phase change and achieve reliable actuation.

Figure 7. Influence of applied stress on SMA transformation temperatures (25)

CHAPTER 2: EXPERIMENTAL PROCESS

2.1 Methodology

The main purpose of this effort was to conduct original research and provide previously unavailable temperature dependent performance data of tensioned SMA specimens. With this data, design guidelines for implementing SMAs as deployment actuators can be developed. A unique characteristic of SMAs is that “all properties change significantly at the transformation temperatures M_s , M_f , A_s and A_f ” (22) meaning the transformation temperatures of the material must be known in order to draw meaningful correlations between the structure of the material and its fracture when heat is applied. For this purpose, Dr. Scott Robertson at NDC, Inc. provided the DSC plot (Figure 8) based on 28.3 mg from the provided 10 foot section of SM495.

Figure 8. SM495 DSC plot provided by Nitinol Devices and Components, Inc. (29)

The values in red are as defined (29):

- M = Martensite phase
- R = Rhomohedral phase
- A = Austenite phase
- f = Finish temperature
- p = Peak temperature
- s = Start temperature

The Rhombohedral phase shown on the DSC plot is “a ‘pre-martensite’ phase that often shows up and is due to processing variables.” (29) This phase was eliminated to only deal with the martensite and austenite phases during testing by soaking the test specimens at 28.6°F (-1.9°C) for nine hours.

2.2 SMA Specimen Geometry

A dual notch configuration was selected for the test specimens (Figure 9).

Figure 9. Modeled dual notch specimen

This geometry was selected for five reasons:

1. A notched region concentrates failure loads in defined location and reduces the possibility of specimen fracture at the grips
2. The symmetric distribution of notches about the centerline of the specimen allows for a quarter symmetry solid model to be used (if needed) when

conducting finite element analyses; reducing solution computation time while achieving intended results

3. The equations detailing the calculation of the stress concentration K_t are readily available
4. Several fabrication houses confirmed that the semi-circular notches would be easier to create than sharp notches
5. The maximum calculated failure load of 43 pounds provides greater than a 5x safety factor for the 250 pound load cell used during the tensile testing

Roark's Formulas for Stress and Strain (30) provided geometry guidelines for designing a rectangular dual notch specimen (Figure 10) as defined by the following equations:

$$K_t = C_1 + C_2 \left(\frac{2h}{D}\right) + C_3 \left(\frac{2h}{D}\right)^2 + C_4 \left(\frac{2h}{D}\right)^3 \quad (1)$$

$$0.1 \leq h/r \leq 2.0 \quad (2)$$

$$C_1 = 0.850 + 2.628\sqrt{h/r} - 0.413 h/r \quad (3)$$

$$C_2 = -1.119 - 4.826\sqrt{h/r} + 2.575 h/r \quad (4)$$

$$C_3 = 3.563 - 0.514\sqrt{h/r} - 2.402 h/r \quad (5)$$

$$C_4 = -2.294 + 2.713\sqrt{h/r} + 2.575 h/r \quad (6)$$

Appropriate geometric dimensions and tolerances were also applied based on a tolerance analysis (Figure 12) ensuring adherence to the Roark specified h/r requirement $0.1 \leq h/r \leq 2.0$.

Nominal			MMC - Smallest Notch			LMC - Largest Notch		
h =	0.007	in	h =	0.004	in	h =	0.010	in
r =	0.0100	in	r =	0.0070	in	r =	0.013	in
D =	0.030	in	D =	0.030	in	D =	0.030	in
h/r =	0.700	dim less	h/r =	0.571	dim less	h/r =	0.769	dim less
C ₁ =	2.760	dim less	C ₁ =	2.601	dim less	C ₁ =	2.837	dim less
C ₂ =	-3.354	dim less	C ₂ =	-3.296	dim less	C ₂ =	-3.371	dim less
C ₃ =	1.452	dim less	C ₃ =	1.802	dim less	C ₃ =	1.264	dim less
C ₄ =	0.144	dim less	C ₄ =	-0.106	dim less	C ₄ =	0.270	dim less
K _t =	1.525	dim less	K _t =	1.848	dim less	K _t =	1.232	dim less

Figure 12. Specimen geometry tolerance analysis

2.3 SMA Specimen Fabrication

The SMA wire was machined into specimens (Figure 13a and 13b) per the geometry specified in Figure 11 and Appendix A; the specimen length was 2.000 ± 0.015 inches.

Figure 13 (a) top: typical SMA specimen; (b) as produced SMA specimen notch geometry

The machining was performed by Proto Tech located in Tucson, Arizona. The shop utilized wire electrical discharge machining (EDM) to create the features followed by aluminum oxide finishing, reducing heat affected zones imparted by the EDM process.

2.4 Tensile Test Station

A TestResources 200R (Figure 14) “digital DC servo-controlled electromechanical test system for universal mechanical testing applications” was used to generate and record structural material property data about the SMA specimens. “(T)he system features a mechanical load frame and a load cell sized to produce loads to the users test requirements.” (31)

Figure 14. TestResources 200R (31)

A conversation with Petroula Hansen (32) helped verify that the 250 pound load cell was calibrated correctly. A 31.66 N force (7.12 lbf) was suspended from the load cell three

separate instances. The readings per the TestResources software were 31.8 N, 31.8 N and 31.9 N respectively. The maximum .76% deviation demonstrated both accuracy and repeatability errors less than the ASTM E4 requirement of “ $\pm 1.0\%$.” (33)

2.5 SMA Specimen Alignment

The 200R uses knurled compression grips to hold specimens in place. To repeatedly position the specimens within the grips and in line with the pull axis of the 200R, the fixture in Figure 15 was built (see Appendix B for additional alignment fixture details).

Figure 15. Alignment fixture

The fixture also rigidly secured the specimens in place limiting specimen deformation while the grips were torqued to 10 ft-lb (13.6 Nm) (Figure 16).

Figure 16. Fixture placing specimen between grips

2.6 Heater Design and Assembly

Applying heat to the SMA to achieve actuation can be achieved in a myriad of ways. In keeping with the idea that implementing SMA for actuation should be simple and cost effective, imparting heat via simple resistive heating was selected.

The heater was designed to accommodate the:

1. Defined specimen geometry
2. SMA transformation temperatures
3. Orientation of the specimens while being secured in the test station

The DSC plot (Figure 8) showed that the heater needed to operate at temperatures from ambient room temperature 73°F (23°C) up to 151°F (66°C). Real time temperature control and feedback was also implemented to achieve precise temperature control in a timely manner.

Omega Engineering Inc. in Stamford, Connecticut was selected as the supplier for the heater components due to cost and item availability. The items listed in Table 1 were selected as their assembly produced an easily controllable and self-regulating temperature system.

Item	Description	Part Number
1	225 W Heating Element	STRI-1248/120V
2	1/16 Din Controller	CN7823
3	Solid State Relay	SSRL240DC10
4	Finned Heat Sink	FHS-1
5	K-Type Thermocouple	5TC-GG-K-20-36
6	Power Cord	POWER CORD-SE

Table 1. Heater bill of materials

The numerically identified items in Table 1 were integrated as an assembly as shown in Figure 17.

Figure 17. Heater assembly with Table 2 items identified

2.7 Tensile Test – SMA Specimen Material Properties Characterization

Suppliers typically provide material data sheets listing average and/or conservative material properties. Unfortunately then, the available data does not offer the fidelity required to accurately model and predict potential material behavior. In order to develop an accurate Finite Element Model as described in Chapter 3, five SMA specimens were

pulled to failure at 74.3°F (23.5°C) while logging stress and strain data (Appendix C).

Figure 18 shows a typical load vs. displacement curve for the five specimens. Specimen D was chosen as the curve to show as it exhibited the most representative performance of the group according to the AVERAGE values calculated in Table 2.

Figure 18. Specimen D providing a typical force versus displacement curve for the studied SMA specimens

Specimen	Ultimate Force		Ultimate Displacement		Ultimate Stress		Ultimate Strain
	(lb)	(N)	(in)	(mm)	(PSI)	(MPa)	(%)
A	35.2	156.6	0.10	2.57	204,193	1,408	10.1%
B	32.7	145.4	0.09	2.40	197,506	1,362	9.4%
C	31.6	140.6	0.10	2.62	198,219	1,367	10.3%
D	32.6	145.0	0.09	2.30	196,502	1,355	9.0%
E	31.3	139.2	0.07	1.72	184,360	1,271	6.8%
AVERAGE	32.7	145.4	0.09	2.32	196,156	1,352	9.1%
STD DEV	1.5	6.8	0.01	0.36	7245	50	1.4%

Table 2. Ambient material properties of five specimens pulled to failure

Once the ambient tests were complete, satisfying the needs of the FEM, two sets of thermal performance experiments were conducted:

- The initial being that specimens were heated then pulled to failure to assess the effects of stress-induced martensite formation on fracture
- The second being that the specimens were pulled to failure while being heated from ambient lab conditions to assess fracture strength vs. heat energy input

CHAPTER 3: FINITE ELEMENT ANALYSIS

Engineers typically develop working design models prior to fabrication and implementation in order to predict behaviors when the design is subjected to environmental stresses. Doing so allows the engineer to make necessary modifications before any chips are cut with a direct correlation to reduced costs. Designs also typically involve well characterized materials (e.g. aluminum) with well-defined material properties and predictable behavior.

SMAs however do not fit into the typical linear-elastic material category. The material properties vary as a function of temperature and stress and “conventional inelastic models do not provide an adequate framework for representing the unusual macrobehavior.” (35) Given the “dearth of computational tools to support the design process of shape-memory-alloy devices” (35) efforts outlined in the literature focus on developing custom algorithms (20) (36) and “User-defined Material Subroutine(s)” (37) modeling the “isothermal” (38041) fatigue behavior of the Superelastic (different from shape memory) form of the material.

Evident from the literature, development of an algorithm or User Material Subroutine (UMAT) addressing large displacement and thermomechanical behavior of SMAs is in itself an area of research beyond the scope of this effort. Thus, commercially available

computational analysis tools were used in an attempt to create a Finite Element Model (FEM) that closely modeled Nitinol response when restrained and strained to failure.

3.1 Select Multi-physics Modeler – ANSYS Workbench

ANSYS Workbench Release 12.1 was chosen as the multi-physics program due to its “project schematic view (that) ties together the entire simulation process, guiding the user through...complex multiphysics analyses with drag-and-drop simplicity.” (42) Given the experimentally derived behavior of the material, it was modeled as nonlinear with large displacement.

3.2 Select Analysis System

ANSYS offers many different analysis systems to aid the designer in predicting concept behavior. It is anticipated that the SMA will be instituted in a pre-strained static condition with heat being applied while in that static condition. Thus, the Static Structural analysis system was selected for developing the SMA finite element model.

3.3 Determine Analysis Material Properties

Nitinol is not available in the martensitic shape memory form as a standard material preloaded in ANSYS and so was created. Material characteristics required to accurately model nonlinear material behavior include:

1. Poisson's Ratio, ν
2. Young's Modulus of Elasticity, E

3. Stress and plastic strain “seed values” (42) from experimentation used to accurately model specimen isotropic hardening; “behavior of the material after the yield point” (43)

Available Poisson’s Ratio values ranged from .30 (45) to .33 (46) (47) with .33 being used in this analysis. Table 2 showed that Specimen D exhibited the most representative material behavior of the sample average parameters and as such was used as the source of supplied nonlinear stress-strain seed values detailed in Chapter 3.4.

3.4 Stress-Strain Seed Values

16,525 stress-strain data points were recorded during the Specimen D tensile test and plotted in Figure 19.

Figure 19. Specimen D stress-strain curve

The data set was reduced to 55 points as the quantity was sufficient to emulate the experimental material behavior and the elastic strain was removed from the experimental strain via Equation 7 as only plastic strain is required as an input for a nonlinear ANSYS FEM:

$$\epsilon_{plastic} = \epsilon_{experimental} - \frac{\sigma_{experimental}}{E_{calculated}} \quad (7)$$

$E_{calculated}$ was established by determining the slope produced by the second experimental stress-strain points ($E = 62 \text{ psi}/0.00297\% = 2,087,542 \text{ psi}$) then multiplying by 10 to

produce an arbitrarily stiff modulus of 20,875,421 psi to establish a clear linear portion of the stress-strain curve. Having such a stiff curve within the first two points of the stress-strain curve had a negligible impact on the remaining calculations given the small stress and strain.

Further consideration of the FEA seed values identified that the notched specimen geometry prohibited direct use of the calculated plastic strain seed values. Strain is a local quantity and tensile tests typically involve using dog bone shaped specimens (Figure 20) where the entire gauge length, G , is being strained equally allowing direct incorporation of strain output into FEMs.

Figure 20. Standard tensile test dog bone geometry (51)

The notched geometry of the specimens utilized in this effort concentrates loads and deformations in the notched region. The recorded ultimate strain from tensile testing Specimen D is actually a global average value as a majority of the deformation would have occurred in the notched region. This fact requires that the globally derived input

deformation values be adjusted by correction factor α to account for the stress concentrations. Assuming uniform stress and strain distribution in the thinnest cross section of the specimen (width of 0.0166 inches, Figure 21), and considering that the Specimen D geometry is similar to that shown in Figure 22, the relation between the local notch strain, ϵ_{local} (at the thinnest cross section) and ϵ_{global} (defined as the average or overall strain over the specimen length) was determined.

Figure 21. Measured specimen geometry

Figure 22. Detailed view of notched specimen

The calculations assume strain and stress uniformity in the thinnest cross section and that the notched geometry can be simplified to piece-wise rectangular specimen geometry.

We have that by definition for the normal strain, ϵ and for δ denoting the displacement of a specimen of length L ($L = 1$ inch here)

$$\epsilon = \frac{\text{Deformation}}{\text{Unit Length}} = \frac{\delta}{L} \quad (8)$$

and that

$$\epsilon_{global} = \epsilon_{average} = \frac{\delta}{L}, \text{ with } L = 1 \quad (9)$$

$$\epsilon_{local} = \alpha \epsilon_{average} \quad (10)$$

From (8)-(10) it follows that

$$\epsilon_{local} = \alpha \delta \quad (11)$$

Thus, the recorded Specimen D displacement values need only be multiplied by α prior to input as strain seed values.

The calculated Modulus of Elasticity, E , needed to be modified by α as well given that the displacement of the global specimen is an average value, making the calculated E a global and/or average value also not representative of what's occurring in the notched region.

By definition, with σ denoting normal stress, given that

$$E_{global} = E_{average} = \frac{\sigma}{\epsilon_{average}} \quad (12)$$

and with A_n denoting the cross-sectional area of the specimen at the thinnest cross section, A the area outside the notch, and P the force applied on the specimen, we have that

$$E_{average} = \frac{P/A}{\delta/L} = \frac{PL}{\delta A} \quad (13)$$

and

$$E_{local} = \frac{P/A_n}{\epsilon_{local}} \quad (14)$$

From (9), (13) and (14) it follows that

$$E_{local} = \frac{1}{\alpha} \frac{A}{A_n} E_{global} \quad (15)$$

Based on Figure 21, $A/A_n = 0.0295/0.0166 = 1.777$.

Once it was determined that both the deflection values and Young's Modulus needed to be multiplied by the same α to account for the geometric discontinuity, a parametric spreadsheet was set up such that the new modulus and strain seed values, modified by α , could be inputted into the FEM. A value of α approximately equal to 0.65 was found to yield the optimum results (Chapter 4.2.2) in capturing the experimentally observed

response of the specimens with the FEM. The fact that α is less than unity can be attributed to the non-uniform stress and strain distribution over the thinnest cross-sectional area of the tested specimens, which, under the assumptions herein is assumed uniform. This furthermore implies that data for large strains are not available (beyond a strain of $0.65 \times \text{maximum strain in experiments}$) unless the experimentally observed curves are extrapolated. Since there is no rational basis for extrapolation, the maximum strain in FEM is limited, and thus the extent (strain) of prediction of the experiments with FEM.

3.5 Create the Material – Engineering Data

Nitinol SMA exhibits large displacement when loaded along with plastic deformation and as such was created as a nonlinear material in ANSYS through the Engineering Data interface. The aforementioned values of E and ν were inputted into the Engineering Data section of the Static Structural model and the plastic seed values, modified by α and plotted in Figure 23, were added to the multilinear isotropic hardening curve table which is the portion “of the stress-strain curve after the linear portion; yield point onward.” (48)

Figure 23. Plotted nonlinear seed values in ANSYS

3.6 Import Specimens for Analyses

Two finite element analyses were conducted for this work, linear and nonlinear, both of which used different specimen geometry, analysis settings and goals. Each was imported from ProE into the ANSYS model as .igs files. The reason that the specimens were not created in ANSYS was that the principal investigator was more familiar with the dimensional controls available with ProE.

3.6.1 Linear Analysis and Specimen

A linear static structural analysis using a frictionless support and user defined displacement was conducted to verify that the FEM was set up correctly and produced results as anticipated by hand calculations. The analysis used the rectangular cross-section specimen shown in Figure 24 based on the measured fabricated dimensions of Specimen D. The length of the specimen was one inch.

Figure 24. Cross-section of linear FEA specimen

3.6.2 Nonlinear Analysis and Specimen

A nonlinear large displacement static structural analysis using a fixed support and user defined displacement was conducted in an effort to emulate the observed behavior of the tested specimens. The analysis used the notched cross-section specimen shown in Figure 21 based on the measured fabricated dimensions of Specimen D. The specimen length was one inch, simulating the amount of specimen between the grips during experimentation.

3.7 Assign Material to Model

The default material assigned to the specimen by ANSYS was generic structural steel.

The material was changed to the created Nitinol for both the linear and nonlinear analyses.

3.8 Refine Mesh

ANSYS fits a default mesh onto the imported specimen solid model as shown in Figure 25.

Figure 25. ANSYS default mesh

The default mesh for the linear specimen (not shown) and notched specimen was too coarse for ANSYS to converge on a solution thus a mesh refinement study was conducted where all the mesh parameters were varied to assess the impact of the changes relating to

result fidelity. Figure 26 shows a distinct knee in the curve indicating that after 5,036 nodes the incremental fidelity gained through adding more nodes does not return a significantly better result.

Figure 26. Fidelity results.

Table 3 defines the ANSYS mesh control parameters that were modified to create the meshed non-linear model shown in Figure 27. The same parameters were also used on the linear model.

Parameter	From	To
Relevance Center	Coarse	Fine
Span Angle Center	Coarse	Fine
Transition	Fast	Slow

Table 3. Mesh parameters

Figure 27. Refined mesh model

3.9 Apply Supports and Loads

- Fixed support. A fixed support was placed on one end of the specimen model (Figure 28) as it's anticipated that it will be mounted in this manner when installed on the host assembly
- Displacement. A displacement based on the ultimate strain from the tensile testing was placed on the specimen face opposite the fixed support and normal to the face (Figure 29)

Figure 28. Fixed static support applied to specimen

Figure 29. Displacement applied to specimen

3.10 Refine Analysis Settings

ANSYS offers many setting options to tune analysis results. Settings used in this effort are as follows:

- Nonlinear Effects: set to *No* for the linear FEA and *Yes* for the nonlinear FEA
- Auto Time Stepping: set to *On* as this “ease(s) convergence” (53)
- Substeps: *Initial*, *Minimum*, and *Maximum Substeps* were initially set to 25, 10, and 50 respectively to “enhance convergence” (54) but were all later changed to 100, 100, and 1000 as the fidelity of the analysis output increased with only an associated two minute increase in computation time
- Large Deflection: set to *On* as the deflection on the Nitinol causes “strains beyond (the) elastic limit” of the material when compared to standard FEA materials (55)

3.11 Select Desired Output Results

- Total Deformation and Maximum Stress were the chosen outputs for the linear analysis as a means for comparing resultant to calculated values
- Total Deformation and Force Reaction Maximum stress were the chosen outputs for the nonlinear analysis as a means of comparing analysis to experimental results

3.12 Run Analyses

Once all of the parameters were established, the analyses were run and reviewed. See Chapter 4 for details.

CHAPTER 4: RESULTS

4.1 Testing Results

SMA mechanical behavior is dependent on both the temperature and load applied to the material. Elevating the temperature causes the material structure to change phase from martensite to austenite and loading the material reverses the structural change even at elevated temperatures unless the material temperature is above the Martensite Deformation (M_d) temperature, a point at which the heat energy required to change the structure from martensite to austenite is equivalent to the austenitic plastic deformation energy. In other words, loading material when the temperature is above M_d doesn't cause a structural change; the stress-strain curve follows that of the austenitic stress-strain curve shown in Figure 6.

Given the synergistic performance relationship of specimen temperature and load, obtaining a set of stress-strain performance curves based on SMA temperature was paramount in deriving design requirements. 17 SMA specimens were heated then loaded to failure to obtain the aforementioned data.

Each specimen was installed in the tensile grips and a multi-axis optical slide was used to position the heating element in line with the notched portion of the specimen. It was anticipated that the line contact between the element and the specimen would not be conducive for heat transfer between the two items. Omegatherm 201, thermally

conductive paste (TCP) produced by Omega Engineering Inc., was placed on the specimen in the region where contact with the element occurred. The thermocouple controlling the element temperature was also placed in this region as shown in Figure 30.

Figure 30. Assembly for heat application to specimen using TCP

The principle investigator determined that it was best to consult SMA expert Dr. Scott Robertson on how to best convey the test data and provide a meaningful contribution to the field. In a personal communication (34), Robertson suggested plotting temperature on the x-axis, and the following variables on the y-axis:

1. Initial loading modulus
2. Plateau stress (measured at a constant strain value; e.g. the stress associated with 3% strain since the plateau region of the specimens isn't flat)

3. Second loading modulus
4. Ultimate strain
5. Ultimate stress

Robertson's data conveyance suggestions are displayed graphically in Figure 31.

Figure 31. Graphical representation of tensile test results conveyance

Table 3 was created to tabulate the testing results and provide the foundation information for the plots suggested by Robertson.

Specimen	Ave Failure Temp	Initial Loading Modulus, .2% Offset	Plateau Stress, 3% Strain	Second Loading Modulus	Ultimate Strain	Ultimate Stress
(#)	(°F)	(PSI)	(PSI)	(PSI)	(%)	(PSI)
1	86	5,374,645	65,429	3,100,000	9.0%	197,207
2	96	4,855,952	64,994	2,864,865	8.9%	193,353
3	103	4,869,203	55,726	3,466,667	9.2%	195,245
4	114	3,743,528	44,063	3,000,000	8.7%	172,297
5	121	4,633,785	55,307	2,933,333	9.1%	179,866
6	130	4,449,097	53,245	2,816,901	9.4%	184,201
7	143	4,106,426	53,581	3,164,557	9.5%	189,865
8	158	4,833,053	58,072	2,745,098	9.2%	177,446
9	185	6,242,897	59,171	1,640,000	9.1%	165,057
10	210	6,156,239	75,182	2,133,333	8.1%	157,198
11	243	5,788,229	76,228	2,333,333	7.3%	159,211
12	267	5,013,077	77,654	2,666,667	6.8%	135,716
13	287	5,575,783	92,182	2,600,000	5.1%	136,674
14	313	6,133,055	101,451	3,333,333	5.9%	152,515
15	331	6,758,389	108,329	4,000,000	4.7%	148,071
16	344	5,863,364	100,423	3,750,000	4.9%	142,850
17	427	7,596,966	115,741	4,473,684	3.9%	136,847

Table 4. Tabulated heated tensile test results

The general trend of the data shown in Figure 32 through Figure 36 is that the material becomes less ductile with an increase in temperature as evidenced by the increase in the Initial Loading Modulus and Plateau Stress at 3% strain with the associated decreases in ultimate strain and stress.

Figure 32. Initial Loading Modulus vs. Average Failure Temperature

Figure 33. Plateau Stress at 3% Strain, vs. Average Failure Temperature

Figure 34. Second Loading Modulus vs. Average Failure Temperature

Figure 35. Ultimate Strain vs. Average Failure Temperature

Figure 36. Ultimate Stress vs. Average Failure Temperature

The recorded trends also support the literature that as the material approaches the Martensite Deformation (M_d) temperature ($\sim 200^\circ\text{F}$ above A_f ; $\sim 360^\circ\text{F}$ in this case), the temperature at which the phase transformation from martensite to austenite cannot be stress induced, the stress-strain curve morphs toward that of typical linear-elastic materials (e.g. aluminum) with an appreciable decrease in ultimate stress and strain (Figure 37).

Figure 37. SMA stress-strain curve transition from martensitic structure to austenitic

Figure 32 through Figure 37 provide data that is not currently available in the literature. The plots presented allow design engineers to assess anticipated SMA performance when operated in particular temperature regimes.

For example, Figure 37 identifies that at ambient conditions, the ultimate strength and strain of a SMA specimen with the defined geometry is approximately 195 ksi and 9% respectively. If that specimen was loaded to 100 ksi and ~6% strain in a deployment actuator configuration, fracture is anticipated to occur at temperatures above 427°F. Utilizing the SMA in this manner allows for almost a 2x safety margin in terms of stress and strain.

To assess the aforementioned hypothesized failure conditions, a second SMA testing effort was conducted where 12 specimens were prestrained to approximately 4%, 5%, and 6%, restrained, and then heated to failure, the details of which are captured in Table 5.

Specimen	Initial Strain	Initial Temp	Failure Temp	Ultimate Stress	Heat Start Time	Specimen Failure Time	Ramp Rate
(#)	(%)	(°F)	(°F)	(psi)	(min)	(min)	(°F/min)
20	4.01%	82	784	86,137	4.07	6.66	271
21	4.01%	82	734	95,646	4.02	6.06	320
22	4.01%	82	815	86,236	4.04	6.50	297
23	5.01%	82	608	116,107	5.03	6.52	353
24	5.01%	82	667	120,678	5.16	6.78	361
25	5.02%	82	694	104,432	5.03	6.86	335
26	6.01%	82	495	138,072	6.06	7.21	358
27	6.01%	82	624	125,106	6.08	7.62	352
28	6.01%	82	606	126,100	6.04	7.54	349
29	7.00%	82	518	126,775	7.08	8.30	357
30	7.01%	82	550	129,695	7.01	8.35	349

Table 5. Specimen failure data based on prestrained condition

Figure 38 (based on Table 5) shows that lower initial strains required more heat energy (failure temperature) to achieve fracture when compared to higher initial strains which was anticipated based on Figure 37.

Figure 38. Failure temperature decreases as initial strain increases

However, taking 6% strain for example, two of the three samples require that they be heated to almost 650°F before failure; approximately 1.5 times the predicted amount based on Figure 37. The reason for the apparent discrepancy is thought to be related to a combination of the preset strain and the heating element ramp rate. It is beyond the goals of the present work to study the effects of ramp rate. The results are based on relatively constant ramp rate for all the performed experiments.

When comparing Figures 39 through 42, the amount of specimen necking prior to failure generally decreases as both the strain and ramp rate increase, trending toward a more instantaneous fracture. For example, Specimen 20 (Figure 39) takes almost 45 seconds to fail (4% strain, ramp rate = 271°F/min) once it reaches the ultimate stress whereas Specimen 29 (Figure 42) fails in 10 seconds (7% strain, ramp rate = 357°F/min). If the

thermal ramp rate had been quicker, the structure change from martensite to austenite would have been almost instantaneous eliminating the gradual failures.

Figure 39. Stress vs. time plot for specimens prestrained to 4% then heated to failure

Figure 40. Stress vs. time plot for specimens prestrained to 5% then heated to failure

Figure 41. Stress vs. time plot for specimens prestrained to 6% then heated to failure

Figure 42. Stress vs. time plot for specimens prestrained to 7% then heated to failure

Plotting Figure 37 again but this time with strained, restrained, and heated specimens (Figure 43), the ultimate strength of all specimens stays well below the ultimate strength of Specimen D that was pulled to failure at room temperature, indicating that rapid temperature increase of the specimens does induce the desired fracture effect well within the material's maximum capabilities. It seems likely that a designer would be willing to trade short duration, 1.5x increase in total applied heat energy, to achieve fracture and gain strength and strain design margin in return.

Figure 43. Relative performance of strained, restrained, and heated specimens vs. room temperature strain to failure and preheated strain to failure

4.2 Finite Element Analysis Results

4.2.1 Linear Analysis

Hand calculations were conducted to assess the function of the FEM:

$$E = 5,288,542 \text{ psi (experimentally derived value)}$$

$$\delta L = 0.01 \text{ inches (elongation within initial elastic zone of SMA specimen)}$$

$$L = 1.00 \text{ inches (specimen gauge length)}$$

$$\sigma = E \frac{\delta L}{L} = 52,885 \text{ psi} \quad (16)$$

The analysis settings detailed in Chapter 3, combined with the displacement of 0.01 inches selected above, created a FEM that returned an Equivalent Maximum Stress of 52,885 psi (Figure 44). This demonstrates a 100% correlation with the calculated 52,885 psi indicating that the FEM is set up correctly.

Figure 44. Linear FEA stress result

4.2.2 Nonlinear Analysis

Figure 45 shows that using $\alpha = 0.65$ produces FEA results that best mirrors the experimental data. Due to the value of α , the FEA cannot reach the strain attained by the experiments unless the experimentally observed stress-strain response is extrapolated. Since there is no basis to robustly perform such an extrapolation, it was not attempted.

Figure 45. Alpha influenced stress-strain plot

CHAPTER 5: CONCLUSIONS

The information obtained through investigating the use of SMA fracture as a deployment actuator indicates that it is possible to create a device that capitalizes on the material's distinctive performance where instantaneous fracture can be achieved through straining, restraining, and heating the material. This investigation provides material performance data that is presently unavailable in the literature promoting the use of SMAs as deployment actuators. The test data indicates that SMA actuators can be loaded to predetermined ultimate strength or strain levels while maintaining adequate design margin.

Designs implementing materials other than SMAs for actuation will be met with potentially prohibitive results. For example, Wood's metal has "a melting point (not fracture) of approximately 158°F" (57) yet the relatively low "5,990 psi" (58) tensile strength necessitates a comparable actuator with almost 33 times (196 ksi/5.9 ksi, Table 2) the tensile area of Nitinol; a prohibitive value in terms of weight (composed of dense bismuth, lead, and tin (58)), size (bulk), and most likely cost, particularly in sensitive tactical and proprietary applications.

Other considerations might involve using commonly available titanium as a deployment actuator. Ti-6Al-4V is the typical form of Titanium alloy used in a majority of Aerospace applications with the ambient longitudinal ultimate tensile strength reaching "135 ksi in

annealed bar with diameter <0.500 inches” (59), approximately 69% the strength of Specimen D (135/196 ksi, Table 2). For failure, the Titanium would need to be heated to “2919-3020°F” (60) to melt – not instantaneously fracture, requiring approximately 7 times (3000°F/427°F) more heat energy to induce failure than with Specimen 17; a potentially prohibitive value in terms of capacity if the main craft cannot supply the required power and/or cost if the supply adds unacceptable weight and complexity.

The Finite Element Model was partially successful, capable of emulating strained ambient material behavior up to approximately 6.1%. The limited response is due to lack of experimentally derived large stress and strain available for model emulation.

Not having additional strain data necessitates a design of experiments to characterize SMA material prior to integration.

The details contained herein are being shared with the community through a two part journal submission (61) (62) to Materials Science and Engineering.

APPENDIX A

APPENDIX B

APPENDIX C

Peak Load	35.22 LB
Peak Stress	204193 psi
Minimum Load	0.00530 LB
Modulus of Elasticity	4351489 psi
Yield @ 0.20% Offset	39975 psi
Yield @ 0.00% Offset	10285 psi
Yield @ 0.20% Offset	6.896 LB
Yield @ 0.00% Offset	1.774 LB
Yield @ 0.50% Extension-EUL	21930 psi
Yield @ 0.00% Extension-EUL	1771 psi
Yield @ 0.00% Extension-EUL	1771 psi
Yield @ 0.50% Extension-EUL	3.783 LB
Yield @ 0.00% Extension-EUL	0.306 LB
Yield @ 0.00% Extension-EUL	0.306 LB
Auto Elong. @ Break	10.10 %
Man. Elong. @ Break	9.431 %
Reduction of Area	-579610 %
E646 exp. n: 0.012-0.100 (e)	0.902
E646 coef. K: 0.012-0.100 (e)	1416055 psi
Energy @ 70.00% Droop	1.572 LBin
C273 Shear Stress	2028 psi
C273 Shear Modulus	429.1 psi
C273 Shear Area	0.0174 sq in
Poisson's Ratio	0
Yield-Halt of Force	28998 psi
UYS	NA
LYS	NA
YPE	NA
Strain Ratio	NA

Figure 46. Specimen A tensile test results summary

Figure 47. Specimen A tensile test results plots

Peak Load	32.69 LB
Peak Stress	197506 psi
Minimum Load	0.00662 LB
Modulus of Elasticity	5233042 psi
Yield @ 0.20% Offset	46158 psi
Yield @ 0.00% Offset	11124 psi
Yield @ 0.20% Offset	7.639 LB
Yield @ 0.00% Offset	1.841 LB
Yield @ 0.50% Extension-EUL	26386 psi
Yield @ 0.00% Extension-EUL	2773 psi
Yield @ 0.00% Extension-EUL	----
Yield @ 0.50% Extension-EUL	
Yield @ 0.00% Extension-EUL	
Yield @ 0.00% Extension-EUL	
Auto Elong. @ Break	
Man. Elong. @ Break	
Reduction of Area	
E646 exp. n: 0.014-0.094 (e)	
E646 coef. K: 0.014-0.094 (e)	
Energy @ 70.00% Droop	
C273 Shear Stress	196.1 psi
C273 Shear Modulus	516.1 psi
C273 Shear Area	0.0167 sq in
Poisson's Ratio	0
Yield-Halt of Force	43936 psi
UYS	NA
LYS	NA
YPE	NA
Strain Ratio	NA

Figure 48. Specimen B tensile test results summary

No Image
Available

Figure 49. Specimen B tensile test results plots – file corrupted

Peak Load	31.64 LB
Peak Stress	198219 psi
Minimum Load	-0.778 LB
Modulus of Elasticity	4690567 psi
Yield @ 0.20% Offset	37377 psi
Yield @ 0.00% Offset	9669 psi
Yield @ 0.20% Offset	5.965 LB
Yield @ 0.00% Offset	1.543 LB
Yield @ 0.50% Extension-EUL	23103 psi
Yield @ 0.00% Extension-EUL	280.0 psi
Yield @ 0.00% Extension-EUL	280.0 psi
Yield @ 0.50% Extension-EUL	3.687 LB
Yield @ 0.00% Extension-EUL	0.0447 LB
Yield @ 0.00% Extension-EUL	0.0447 LB
Auto Elong. @ Break	10.37 %
Man. Elong. @ Break	0 %
Reduction of Area	-626466 %
E646 exp. n: 0.010-0.103 (e)	0.807
E646 coef. K: 0.010-0.103 (e)	1053095 psi
Energy @ 70.00% Droop	1.480 LBin
C273 Shear Stress	1875 psi
C273 Shear Modulus	419.5 psi
C273 Shear Area	0.0169 sq in
Poisson's Ratio	0
Yield-Halt of Force	9911 psi
UYS	NA
LYS	NA
YPE	NA
Strain Ratio	NA

Figure 50. Specimen C tensile test results summary

Figure 51. Specimen C tensile test results plots

Peak Load	32.62 LB
Peak Stress	196502 psi
Minimum Load	0.00795 LB
Modulus of Elasticity	5288542 psi
Yield @ 0.20% Offset	44500 psi
Yield @ 0.00% Offset	10738 psi
Yield @ 0.20% Offset	7.387 LB
Yield @ 0.00% Offset	1.783 LB
Yield @ 0.50% Extension-EUL	26506 psi
Yield @ 0.00% Extension-EUL	2080 psi
Yield @ 0.00% Extension-EUL	2080 psi
Yield @ 0.50% Extension-EUL	4.400 LB
Yield @ 0.00% Extension-EUL	0.345 LB
Yield @ 0.00% Extension-EUL	0.345 LB
Auto Elong. @ Break	9.055 %
Man. Elong. @ Break	8.381 %
Reduction of Area	-602310 %
E646 exp. n: 0.011-0.090 (e)	0.790
E646 coef. K: 0.011-0.090 (e)	1154796 psi
Energy @ 70.00% Droop	1.397 LBin
C273 Shear Stress	1951 psi
C273 Shear Modulus	521.5 psi
C273 Shear Area	0.0167 sq in
Poisson's Ratio	0
Yield-Halt of Force	45301 psi
UYS	NA
LYS	NA
YPE	NA
Strain Ratio	NA

Figure 52. Specimen D tensile test results summary

Figure 53. Specimen D tensile test results plots

Peak Load	31.34 LB
Peak Stress	184360 psi
Minimum Load	0.0103 LB
Modulus of Elasticity	5025478 psi
Yield @ 0.20% Offset	43482 psi
Yield @ 0.00% Offset	10437 psi
Yield @ 0.20% Offset	7.392 LB
Yield @ 0.00% Offset	1.774 LB
Yield @ 0.50% Extension-EUL	24961 psi
Yield @ 0.00% Extension-EUL	2164 psi
Yield @ 0.00% Extension-EUL	2164 psi
Yield @ 0.50% Extension-EUL	4.243 LB
Yield @ 0.00% Extension-EUL	0.368 LB
Yield @ 0.00% Extension-EUL	0.368 LB
Auto Elong. @ Break	6.819 %
Man. Elong. @ Break	6.136 %
Reduction of Area	-588135 %
E646 exp. n: 0.011-0.067 (e)	0.927
E646 coef. K: 0.011-0.067 (e)	2203187 psi
Energy @ 70.00% Droop	1.061 LBin
C273 Shear Stress	1831 psi
C273 Shear Modulus	495.6 psi
C273 Shear Area	0.0171 sq in
Poisson's Ratio	0
Yield-Halt of Force	24188 psi
UYS	NA
LYS	NA
YPE	NA
Strain Ratio	NA

Figure 54. Specimen E tensile test results summary

Figure 55. Specimen E tensile test results plots

APPENDIX D

Figure 56. Test Specimen #1

Figure 57. Test Specimen #2

Figure 58. Test Specimen #3

Figure 59. Test Specimen #4

Figure 60. Test Specimen #5

Figure 61. Test Specimen #6

Figure 62. Test Specimen #7

Figure 63. Test Specimen #8

Figure 64. Test Specimen #9

Figure 65. Test Specimen #10

Figure 66. Test Specimen #11

Figure 67. Test Specimen #12

Figure 68. Test Specimen #13

Figure 69. Test Specimen #14

Figure 70. Test Specimen #15

Figure 71. Test Specimen #16

Figure 72. Test Specimen #17

APPENDIX E

Max stress = 204 ksi
Distance between grips = 1"

Figure 73. SMA Load vs. Position curve zones defined (34)

Explanation of Zones & Slope Changes

While the magnitude of the forces and strains will vary depending on the phase present, the general shape of the stress-strain relationship will look the same. An explanation of the microstructure changes is below:

	Condition 1: $T < M_f$ (i.e. 22°C)	Condition 2: $A_f < T < M_d$ (i.e. 100°C)	
Zone 1	Elastic deformation of twinned martensite.	Elastic deformation of austenite.	
Slope Change 1	Enough force applied to detwin the martensite	Enough force has been applied to transform that austenite into martensite. The martensite forms in twins, but is immediately (i.e. speed of sound) detwinned.	
Zone 2	Martensite is being detwinned. If the test were stopped and load removed, the material would remain deformed. However, heating it would return it to its original twinned martensite form and shape.	Transformation of grains from austenite to martensite. If the test were stopped and the load removed, the material would automatically spring back to shape by reversing the phase transformation.	
Slope Change 2	All of the martensite grains have been detwinned. The change in slope is because the detwinned grains are being elastically deformed in Zone 3.	All of the grains have been transformed from austenite to detwinned martensite.	
Zone 3	Elastic deformation of detwinned martensite. Again, because only detwinning and elasticity have occurred, you could release the load and apply heat to return the sample to its original shape.	The detwinned martensite grains are now being elastically deformed. Again, since only phase changes and elasticity has occurred, you can release the load and the material will spring back to its original shape via a phase transformation back to austenite.	
Slope Change 3	Onset of plasticity (true yield).	Onset of plasticity (true yield).	
Zone 4	Plasticity of the detwinned martensite. Note: for $T < M_f$, the material will never become austenitic	Plasticity of the detwinned martensite. Note: fracture occurs with the material in a martensitic phase.	

Figure 74. SMA Load vs. Position curve zones explained (34)

Explanation of Zones & Slope Changes

The mechanical behavior of the material at $T > M_d$ is very different. In this condition, the material behaves like a "normal" metal. It has a yield $<1\%$ and remains austenite throughout the test.

Figure 75. SMA Load vs. Position curve zone clarification (34)

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