PROCESSING AND SHAPE-SETTING OF SHAPE MEMORY ALLOYS

FOR SMALL SATELLITE ANTENNAS

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In this study, four different NiTi-based shape memory alloys (SMAs) compositions were processed, shape-set, and characterized to evaluate their effectiveness as SMA actuation component for satellite antennas. Three of the compositions were commercially available NiTi wires (90°C Flexinol® actuator NiTi wire and Confluent ADB SE508 NiTi wire), NiTi SM495 plates (ATI Specialty Alloys and Components) and the other composition was in house lab-produced NiTiCu plate. Different shape-setting techniques were performed such as pin and plate, fixtures and dies, and finally a sandwich fixture. The two most promising outcomes were the SE NiTi 508 wire and the NiTiCu plate. A SE NiTi 508 wire was first heat-treated at 550 °C for 3 hours and then it was shape-set at 450 °C for 30 min using a Cu tube which was previously deformed to the desired deployment curvature and fixed on a steel rig. The wire was kept inside the Cu tube during the shape-setting process to obtain the desired curvature. After shape-setting, the wire was thermally cycled multiple times. The results showed that the SE NiTi 508 wire was able to retain its deployment shape successfully after each thermal cycle. Furthermore, a NiTiCu plate was sandwiched between two steel sheets which were shaped into the desired full-deployment shape beforehand. The NiTiCu plate was shape-set at 450 °C for 30 min and then thermally cycled multiple times to test its effectiveness. The NiTiCu plate retained its full-deployment shape successfully after every thermal cycle.
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CHAPTER 1
INTRODUCTION

1.1 Motivation

Many different types of satellites have been developed over the years to explore space and, more recently, to improve human communication. These satellites have also improved in efficiency and in cost. One of the major challenges is reducing the size of the satellite and its components prior to deployment and then expanding them once in space with full functionality maintain. This challenge is especially important for antennas which are delivered into space in a small compact satellite but require a large surface area once deployed and in use. The large surface area of the antenna improves communication of information such as navigation systems, climate changes, and global issues in general [1] [2]. To address this issue of antenna size, we propose the use of smart materials, known as shape memory alloys (SMAs), which can provide a reliable and relatively simple solution to this problem.

1.2 Objectives

The goal of this research is to reduce the size of the components in the satellite prior to deployment and then allow them to expand once in space while maintaining full functionality. Also, the main objective is to provide a practical and reliable solution for efficiently compacting the satellite’s antenna using SMA actuators through processing, heat treating, shape-setting, and training.

1.3 Contribution of Thesis

The main contribution of this thesis is to report and compare commercially available NiTi-
based SMAs to non-commercial NiTiCu to provide a database of their mechanical behavior for
the aerospace field, specifically aerospace actuator applications. This was possible by testing
different SMA materials and compositions in various forms in order to evaluate their mechanical
and thermal behavior. The materials were processed, characterized, and shape-set, and their
thermomechanical effectiveness were tested to meet the specific requirements of making
actuator components for small satellites (NASA SBIR Project titled ShaMAn for Shape Memory
Alloy Membrane Antennas).
2.1 Shape Memory Alloys

SMAs are an exceptional group of materials which can memorize their original form when responding to a stimulus such as temperature or magnetic variations [3,4]. They are widely used in many different fields, such as biomedical, industrial, automotive, electronical and many others. One field that SMAs are raising attention in is the aerospace field [5,6]. Many aerospace applications use SMAs to fabricate their parts, such as actuators. SMAs can be made of metals, ceramics, polymers or even of a hybrid system that combines more than one class of a material [7]. Nonetheless, the metallic systems are the most desirable systems for the aerospace industry. The NiTi-based SMAs are the most commercially successful SMAs on the market, especially for actuation applications [5,6,8–11]. They have gained popularity over the years, due to their functionality and being commercially available.

These SMAs exhibit a low temperature phase (martensite) and a high temperature phase (austenite phase) [12], which result in a phase transformation when heating and cooling through these critical temperatures. This thermal hysteresis shape occurs as the SMA undergoes thermal cycling at a constant stress [13]. As the material is cycled, a loop is created where the original shape can be fully recovered after every cycle [4,14–16]. The transformation that occurs from the martensite phase to the austenite phase is called the martensitic transformation which is a diffusionless transformation. It influences the change in the material’s crystalline, shape and behavior when it responds to a stress or temperature change and the difference in Gibbs free energy [9,17]. The phase transformation can be tracked by the following temperatures $M_s$, $M_f$, $A_s$, $A_f$. 

...
As, and Af. Ms is the lowest transition temperature while Af is the highest transition temperature. Ms is the temperature that indicates the starting of the martensite phase while Mf indicates the completion temperature of the martensite phase where the phase is stable. On the other hand, As is the starting temperature of the austenite phase and Af signifies the end and the stableness of the austenite phase [9,17–20]. The martensite phase is known to have a lower symmetry than the austenite phase. It can experience the following variants of closed packed symmetrical structures orthorhombic, hexagonal closed pack (hcp) and monoclinic. Nonetheless, the austenite phase is high in symmetry and can be exhibited in either face centered cubic (fcc) or body centered cubic (bcc). The martensite shape variants are a result of an adaption mechanism that the structure takes in order to restore the shape change from the lattice distortion and phase transitions. This adaption mechanism is known as twinning, where the martensite does not break any bonds when applying stress. Instead, it creates multiple martensite crystallographic geometries. The detwinned martensite is formed when the material undergoes a recoverable stress below the As temperature, creating a twinned martensite. Then by heating up the SMA to the Af temperature, removing the stress and allowing the material to cool down to the martensite phase, the detwinned martensite is created. This phenomenon is known as the shape memory effect [3,6,12,14,16,17,21–24].

Pseudoelasticity is a phenomena in which the SMAs exhibit instant austenite phase recoverability without the need of applying heat to the SMA in the absence of stress. It occurs when the SMAs Af is below the functional temperature. When applying stress martensite phase is present and it is known as induced martensite (SIM). Martensite is only thermodynamically stable when stress is applied. By removing stress, the SMA reverts to austenite phase
immediately without the need of going through any thermal cycling. Pseudoelasticity can be tailored through heat-treatment which can be determined by phase diagram [25,26].

2.1.1 Types of SMAs

SMAs have different types such as one-way SMAs and two-way SMAs. One-way SMAs recover their initial shape by removing an applied external force on the low temperature phase and then heating the material above its high temperature phase. In one-way SMAs the material’s defined shape is set at the austenite phase. The material can only remember its shape in high temperature phase and that is due to the process of shape-setting. Therefore, the material is deformed in its martensite phase, and it recovers its shape upon heating up to the austenite phase. Nonetheless, two-way SMAs have the ability to retain their shapes in both martensite phase and austenite phase. The SMA can remember its martensite shape by constant thermomechanical training while it can remember its austenite shape by shape-setting [3,19,20,27–29].

2.1.2 Shape-Setting

Shape-setting is the process in which the NiTi-based SMAs are reformed from their original shape to a preferred austenitic or remembered form. It is achieved by fixing the material in the final desired form then heat-treating at moderately high temperatures well above the transformation temperatures of the austenite phase followed by cooling back down into the low temperature martensite phase. Various techniques and methods can be used to shape-set SMAs including wrap around, pin and plate, straight annealed, sandwich fixture, over-straining, hot forming, fixtures and dies, and simple helix/spring [30].
2.1.3 Training

Oftentimes, training is also required for good structural and functional fatigue response [31] and to ensure the wire returns to its final set shape. Training involves thermal cycling, a process where the wire is thermally heated from the martensite phase to austenite phase and cooled back down to the martensite phase; thus, undergoing a phase transformation during each cycle [32]. Thermal cycling stabilizes the NiTi SMA wire, i.e. ensures that the phase transformation always occurs at the same temperatures and that the set shape is maintained accurately. Thermal cycling is oftentimes also performed at a fixed load, also known as isobaric testing, and is used to indicate the actuation stability of the SMA. Cycling may affect the SMAs function. With increasing the cycling numbers, the SMA functional properties may be compromised which is known as fatigue. SMAs thermomechanical response durability, such as their response to stress and utmost shape memory effect are controlled by the numbers of cycles that the SMA has gone through [31,33].

To achieve SMA stabilization while having great mechanical properties, the cycling should be conducted at the lowest temperature that the SMA would be utilized at. As the cycling continues at lower temperatures, the SMA elastic modulus tends to increase. On the contrary, the SMA elastic modulus decreases when cycling is conducted at higher temperatures. Also, it was observed that the martensitic transformation temperatures elevates when cycling is performed at higher temperatures [34].

2.2 NiTi Binary System

At room temperature, the elemental crystal structures for Ni and Ti are fcc and hcp, respectively; however, when combined as an SMA in the binary NiTi system, the crystal structures
appear in two forms. Its diffusionless phase transformation takes place between the parent phase austenite (B2 cubic crystal structure) and the derived form of the parent phase martensite (B19' orthorhombic crystal structure) [35]. Depending on the Ni and Ti compositions, the NiTi-based SMAs' properties change which leads to having different functional properties, due to the effect NiTi compositions have on the transformation temperatures and hysteresis. Having Ni-rich NiTi compositions in SMAs typically decrease the $M_s$ temperature which leads to lowering the transformation temperature [36,37], while also potentially narrowing the thermal hysteresis width [38]. On the other hand, Ti-rich NiTi SMA compositions tend to have higher transformation temperatures [39] and exhibit a larger hysteresis width, low thermal stability, and poor strength, typically due to the formation of stable oxides and precipitates. In comparison, Ni-rich NiTi compositions with the suitable aging heat-treatments show a higher strength and more stable transformation temperatures than Ti-rich NiTi compositions [40].

2.2.1 Alloying NiTi with Cu

NiTi-based SMA properties can be changed with the addition of another element such as Cu and Zr. Cu substitutes for the Ni atoms in the binary NiTi SMA system to form a NiTiCu SMA. Also, the addition of Cu enhances NiTi-based SMA fatigue life cycle; however, this addition of Cu also decreases the transformation temperatures and pseudoelastic hysteresis. This is not necessarily bad; it just narrows down its usage for some applications. Nonetheless, it is a suitable option for actuation applications since a narrower hysteresis translates to a lower amount of energy needed to induce the phase transformation and, thus, actuation of a device. NiTiCu alloys start to show brittleness and their ductility decreases upon adding more than 10.0 at. % Cu while using conventional melting techniques. This can be controlled, and the amount of Cu can be
increased by choosing a suitable melting technique [17,41–43].

Figure 2.1: Functional fatigue behavior of binary NiTi and ternary NiTiCu. Compilations of 20 DSC cycles are plotted for a) Ti₅₀Ni₅₀ and b) Ti₅₀Ni₃₅Cu₁₅ [32].

Figure 2.2: Functional fatigue behavior of binary NiTi and NiTiCu. Compilations of 500 thermal cycles are plotted for Ti₅₀Ni₅₀ and Ti₅₀Ni₃₅Cu₁₀ [45].
While binary NiTi SMAs can perform well after many thermal cycles, using a ternary NiTi-based SMA, such as NiTiCu, has been shown to have more thermal stability at the onset and after many thermal cycles [32]. This improved thermal stability is due to changes in the crystal lattice spacing as Cu substitutes for Ni, which can result a decrease in the crystal lattice mismatch between the martensite and austenite phases. Therefore, NiTiCu shows a smoother and more stable phase transformation during thermal cycling than NiTi [44]. Figure 2.2 compares the first 500 thermal cycles of NiTi and NiTi-10 at. % Cu. Increasing the number of thermos-mechanical cycles stabilizes the material and narrows the thermal hysteresis width/loop. The first cycle of NiTi shows how wide the thermal hysteresis is compared to the last cycle. Upon increasing the number of thermal cycles of NiTi, the transformation temperatures shift and the thermal hysteresis width decreases. On the other hand, the transformation temperatures and the hysteresis’ width in NiTi-10 at. % Cu stayed relatively about the same in the first 500 thermal cycles.

2.2.2 Heat Treatments

Heat treatments are used to alter the material’s thermo-mechanical properties through heating the material at a certain temperature, holding the material at that specific temperature for a particular amount of time and finally cooling down the material at a specific rate. Heat treatments change the mechanical properties by changing the material’s crystal structure. They are commonly done to enhance the material’s strength, ductility, toughness, hardness, machineability, surface properties, and wear-resistance properties. The property changes associated with heat treatments are most often the result of microstructural changes, such as finer grain size and precipitate formation. Furthermore, heat treatments can remove the internal
stresses that are caused by deformation from cold-working, and nonuniform cooling from elevated temperatures during the processes of melting and casting [46].

Transformation temperatures and thermomechanical properties of SMAs can be significantly affected by heat treatment and deformation processing the optimal heat-treatment temperature for SMAs can be determined by their phase transformation. Literature on optimal heat treatment temperatures for SMAs are limited since these optimizations are alloy specific [47].

2.2.3 Hot-Rolling

Rolling is a widely used metal-working process to shape the material to precise shape with a certain texture. It can be performed at low temperatures (cold rolling) and high temperatures (hot rolling). During the process, the metal is inserted between two rollers which create high compressive stress that results in a thickness reduction of the metal and thus a new shape. In hot-rolling, the material and/or the rollers can be preheated prior to and/or during the process of rolling. Rolling the material results in plastic deformation and creates new forms such as sheets from plates, and wires from rods.

NiTi-based SMAs can be both cold-rolled and hot-rolled. However, hot-rolling is preferred for NiTi SMA compositions because it has a weaker effect on the martensitic transformation. Cold-rolling NiTi-based SMAs retrains the transformation by generating random dislocations and amorphous regions [48]. When hot-rolling NiTi at a temperature of 800 °C, the predominate deformation mechanism is twinning which becomes more prevalent with increasing the amount of thickness reduction[49]Also, different NiTi textures and structures can be produced depending on the type of rolling performed [50].
2.3 Applications of SMAs

SMA biomaterials are manufactured SMA compositions that come in contact with tissues, blood, and fluids of a living creature without causing any harm to its organs or vital system. They can be used for implants, therapeutic operations, prosthesis, diagnosis, and many other applications without causing inflammation, pyrogenetic effects, carcinogenicity, or allergy [51]. NiTi-based implants are known to have great biocompatibility and corrosion resistivity. They are nontoxic materials that have high strength, great mechanical properties, and low specific weight which makes them desirable to be used as implants [52]. Furthermore, NiTi-based SMAs are used in making other biomedical applications such as stents, dental arch wire, heart valves, and medical tweezers [41–45].

Many robotic applications use SMAs to address tasks and problems that are challenging and difficult for humans to solve. They are designed to function in dangerous and severe circumstances which can be hard for humans to survive in. For example, underwater robots use SMAs as ferromagnetic and thermal actuators [58]. In the automotive industry, SMAs actuators are being utilized as locking mechanisms, headlamps, rear-view mirror, tumble flaps and many other applications. This is because they have great functional density and high power output while maintaining a relatively low weight. Furthermore, SMAs can be stored in compact form and exhibit a smooth actuation motion which makes them suitable for automotive functions [59,60]. SMAs are used in the aerospace field to solve some of the aerospace engineering challenges, such as structural shape morphing using very compact SMA actuators. The unique properties of SMAs make them desirable in various manufacturing applications for different functions such as
hydraulic tubing coupling, low-shock release, thermal spacecraft actuators, and solar array hinges [61,62].
CHAPTER 3

EXPERIMENTAL METHODS

This section highlights the experimental methods which were performed for this research. The effects of adding Cu to the NiTi system was studied and compared thermo-mechanically.

3.1 Materials

Four different sets of material were used in this study; Dynalloy, Inc. 90°C Flexinol® actuator NiTi wire, Confluent ADB SE 508 NiTi wire (Ni_{50.8}Ti_{49.2}), commercially available SM 495 NiTi plates from ATI Specialty Alloys and Components, and an in house lab-produced Ni_{39.8}Ti_{50.2}Cu_{10} ingot.

Dynalloy, Inc. 90°C Flexinol® actuator NiTi wire with a diameter of 0.51 mm was used for this project, as shown in Figure 3.1 (a-b). The NiTi wire was sectioned into 15 cm lengths for the single element component. Confluent ADB SE508 NiTi wire with a diameter of 1.29 mm was used for this project, as shown in Figure 3.1 (c-d). The NiTi wire was sectioned into 15 cm lengths for the single element component.

Commercially available NiTi SM 495 thick plates (ATI Specialty Alloys and Components) were hot-rolled at 850 °C (30 min, each additional pass for 5 min) to get to the desired thickness. Then, the plates were sectioned using the diamond blade saw.

Ni_{39.8}Ti_{50.2}Cu_{10} ingot was melted in the lab by using vacuum arc-melting. First, the elements were placed on the water-cooled copper crucible. Then, the chamber was evacuated and filled with argon various of times to minimize the oxygen in the melting chamber. Before beginning the melting process, a Ti getter was melted before the alloy to further reduce any oxygen residue.
Figure 3.1: (a) Top and (b) side view of a spool of Dynalloy, Inc. 90°C Flexinol® actuator NiTi wire. (c) Top and (d) side view of a spool of Confluent ADB SE508 NiTi wire. (e) In house lab-produced 50 g of Ni$_{39.8}$Ti$_{50.2}$Cu$_{10}$ ingot. (f) NiTi SM 495 (ATI Specialty Alloys and Components).
During the process of melting, the ingot was flipped, and remelted an additional five times to ensure homogeneous mixing of the elements. Each sample weighted 50 g and was shaped into a cigar shape. After the melting process, the samples were homogenized at 1025 °C for 60 min. Finally, the samples were cut using the diamond blade saw. The NiTi-10 at.% Cu SMA was hot-rolled at 800 °C (30 min, each additional pass for 5 min) to get to a plate-shape and to get the desired thickness.

Figure 3.2: The four SMAs in this study plotted on the relationship of $M_s$ and $X_{(Ni)}$ of NiTi reported by Frenzel et al. [63].

Figure 3.2 illustrates the four materials used in this thesis plotted against the results of the relationship between $M_s$ and the concentration of Ni by Frenzel et al. [63]. Dynalloy NiTi wire,
ATI Specialty Alloys and Components SM 495 NiTi plate, and the in-house lab-produced Ni$_{39.8}$Ti$_{50.2}$Cu$_{10}$ ingot lay on the Ti-rich side. However, the Confluent ADB SE 508 NiTi wire (Ni$_{50.8}$Ti$_{49.2}$) lays on the Ni-rich side. The SE 508 NiTi wire is pseudoelastic at room temperature which is the functional temperature for this thesis. Therefore, heat-treatment is needed on the SE 508 NiTi wire to move up its transformation temperatures, which is possible since SE 508 NiTi wire is a Ni-rich composition and its transformation temperatures can be pushed up and its austenite phase can be stabilized through the formation of Ni$_4$Ti$_3$ precipitates by heat-treating it at a temperature and time such as 550 °C for 3 hours.

Figure 3.3: The in house lab-produced Ni$_{39.8}$Ti$_{50.2}$Cu$_{10}$ ingot (yellow dot) plotted on the relationship of Ms and X(Ni,Cu) of NiTi-10 at.% Cu reported by Frenzel et al. [44].

Figure 3.3 shows Frenzel et al. results of the relationship between M$_s$ and the concentration of Ni and Cu [44]. The yellow dot points out the in house lab-produced Ni$_{39.8}$Ti$_{50.2}$Cu$_{10}$ ingot composition on the graph. Cu was chosen to be added to NiTi because it hits
the application’s target transformation, narrows the hysteresis, increases ductility, improves the overall phase transformation, and improves the alloy’s strength [44,64–66].

The more Cu added to the matrix, the narrower the hysteresis becomes. However, as mentioned earlier in this thesis, upon adding more than 10 at. % Cu to NiTi, the alloy’s ductility decreases, and it starts to show brittleness. Figure 3.4 compares DSC results of NiTi-5 at. % Cu and NiTi-10 at. % Cu which were reported by Frenzel et al. [44]. The NiTi-10 at. % Cu has a narrower hysteresis than NiTi-5 at. % Cu. Having a narrow hysteresis is desirable for actuation applications, hence this thesis’ application.

Figure 3.4: DSC comparison of NiTi-10 at.% Cu and NiTi-5 at.% Cu reported by Frenzel et al. [44].

3.2 Material Characterization: Differential Scanning Calorimetry (DSC)

DSC measurements were performed on all four NiTi based-SMAs in different temperature ranges in 10 °C/min, according to ASTM standard F2004 – 17 [67], to determine their phase transformation temperatures.

Figure 3.5 shows the transformation temperatures of Dynalloy, Inc. 90°C Flexinol® actuator NiTi wire before shape-setting for three thermal cycles. It highlights the Ms, Mr, As, and
At of the NiTi wire for the first and last cycles. It is important to note that the transformation temperatures shifted with increasing the number of cycles. The first Ms was at approximately 54 °C which shifted down to approximately 46 °C in the third cycle. The Mf in the first cycle was about 47 °C and around 39 °C in the third cycle. Similarly, the Ar temperature changed with increasing the numbers of the cycles. In the first cycle was about 79 °C and in the third cycle it was approximately about 75 °C. The shift in three cycles of Ms temperatures was about 8 °C and also in Mf around 8 °C. Nonetheless, the shift in As temperatures was about 4 °C and in Ar around 3 °C.

Figure 3.5: Transformation temperatures of Dynalloy, Inc. 90°C Flexinol® actuator NiTi wire before shape-setting.

Figure 3.6 shows transformation temperatures of Confluent ADB SE 508 NiTi wire in the as drawn and after heat treatment conditions which were the previously reported by one of our lab colleagues, Zhang et al [68]. It highlights the Ms, Mf, As, and Ar of the Confluent ADB SE 508 NiTi wire in both cycles. Since the wire is pseudoelastic at room temperature which in this case the functional temperature for the actuator application, it needed to be heat-treated at 550 °C.
for 3 hours. This was done to remove the pseudoelastic effect by shifting the alloy from austenite to martensite at room temperature.

Figure 3.6: Reported transformation temperatures of Confluent ADB SE 508 NiTi wire (Ni50.8Ti49.2) from Zhang et al. [68].

Figure 3.7 shows the transformation temperatures for the NiTi SM 495 plate before shape-setting for two thermal cycles. It is shown that the NiTi SM 495 has a very broad transformation. Also, the transformation temperatures of the second thermal cycle shifted over 20 °C from the first cycle during the heating cycle.

Figure 3.8 shows the transformation temperatures in house lab-produced Ni39.8Ti50.2Cu10 ingot before shape-setting for three thermal cycles. It highlights the Ms, Mf, As, and Ar of the NiTi-10 at.% Cu composition of the first and last cycle. It was noticed that the cycles showed a more stable behavior after the first cycle. The first Ms was at approximately 68 °C which which stayed the same around the third cycle. The Mf in the first cycle was about 57 °C and around 58 °C in the third cycle. However, Ar showed a temperature shifted in the third cycle from the first cycle. In
the first cycle was about 94 °C and in the third cycle it was approximately about 80 °C. There was no visible shift in three cycles of $M_s$ temperatures, but there was about 1 °C in the $M_f$. Nonetheless, there was a shift in $A_s$ temperatures which was about 5 °C and in $A_f$ around 14 °C.

Figure 3.7: Transformation temperatures NiTi SM 495 plate before shape-setting.

Figure 3.8: Transformation temperatures of NiTi-10 at.% Cu plate before shape-setting.
3.3 Shape-Setting Process

The NiTi-based samples were shape-set using various fixtures, which are described in the following text. The general shape-setting process follows the following steps. First, the NiTi-based sample is fixed on a custom-built rig which is designed to produce the desired austenite final shape. Then, the rig with the NiTi-based is placed in a furnace and heated up to 450°C and held for 30 minutes in air to allow for thermal homogenization and shape-setting. Next, the rig with the NiTi-based SMA is taken out of the furnace and allowed cool down in room temperature in air, where it returns to martensite. At this stage, the component can be deformed to any shape below plastic deformation and be fully recovered with heating.

In this study’s application, the NiTi-based SMA is deformed to be folded in a compact manner for storage before full deployment in space. To deploy the wire into its final austenite shape, the NiTi-based SMA is heated by either a heat gun for ease in the laboratory setting or an electric current for the actual space application. The thermal stability and the required training of the SMA was determined by the DSC data which was reported earlier in this thesis.
CHAPTER 4

RESULTS

The results of the process of hot-rolling, shape-setting and thermal cycling of NiTi and NiTi-10 at.% Cu. This section compares NiTi and NiTi-10 at.% Cu behaviors through thermal cycling.

4.1 Hot-Rolling of NiTi and NiTi-10 at.% Cu Plate

SM 495 NiTi plates were hot-rolled to reduce its thickness. First, the NiTi SM 495 plates were preheated to 850 °C before hot-rolling for 30 min. Then, they were heated for 5 min before each pass to ensure that the thickness is reduced without initiating any cracks. The first NiTi SM 495 plate thickness was reduced successfully. It took 65 passes to reduce its thickness by 87.6% from 6.0 mm to a 0.74 mm thick plate. However, Figure 4.1 shows results of hot-rolling NiTi plate with the following thickness of 5.7 mm to 0.99 mm which took 23 passes to be reduced by 83%. It was noticed that the NiTi plate thickness increased in the first pass by 3.1% from 5.7 mm to 5.8 mm and that is due to the oxidation layer that was formed during the preheating process which was 30 min. Therefore, the plate’s thickness reduction was counted from the second pass.

NiTi-10 at.% Cu

A small section of each melted sample was cut to hot-roll. First, the Ni\textsubscript{39.8}Ti\textsubscript{50.2}Cu\textsubscript{10} sample was preheated to 800 °C before hot-rolling for 30 min. Then, it was heated for 5 min before each pass to ensure that the material reduces its thickness without initiating any cracks. the Ni\textsubscript{39.8}Ti\textsubscript{50.2}Cu\textsubscript{10} sample thickness was reduced successfully. It took 34 passes to reduce its thickness by 88.3% from 7.88 mm to a 0.92 mm thick plate. Figure 4.2 shows hot-rolling data for another Ni\textsubscript{39.8}Ti\textsubscript{50.2}Cu\textsubscript{10} plate thickness in which it took 10 passes to reduce its thickness by 85%
from 7.08 mm to 1.02 mm. Unlike NiTi SM 495, Ni$_{39.8}$Ti$_{50.2}$Cu$_{10}$ did not build a thick oxidation layer and it successfully reduced its thickness from the first pass. Also, it took less passes to reduce its plate thickness than NiTi SM 495.

![NiTi SM 495 hot-rolling schedule](image1)

Figure 4.1: NiTi SM 495 hot-rolling schedule

![NiTi-10 hot-rolling schedule](image2)

Figure 4.2: NiTi-10 at.% Cu hot-rolling schedule
4.2 Shape-Setting and Thermal Cycling

Figure 4.3 (a-d) highlights the first attempts at shape-setting a NiTi SMA wire. Figure 4.3 (a) shows the steel plate or rig used for shape-setting the NiTi wire. The pins in the plate were positioned to match the desired curvature of the deploy satellite dish. Figure 4.3 (b) shows how the wire was clipped to the steel plate for shape-setting. Metal clips on the wire ends and steel washers on the pins were used to hold the wire flat to the plate during shape-setting. Figure 4.3 (c) shows how the wire looks in the rig after shape-setting at 450°C for 20 min. Figure 4.3 (d) shows the NiTi SMA wire after shape-setting at 450°C for 20 min. It is clear in Figure 4.3 (d) that the pins induce points of stress which do not follow the intended curvature. Although not shown here, this wire was thermally-cycled and showed excellent shape memory behavior.
To address the issue created by the pins, a small copper tube (K&S Precision Metals 5077 Bendable Copper Tube) with a diameter of 2.38 mm was used and deformed to the right curvature and then placed in the rig with the NiTi SMA wire inside, as shown in Figure 4.4 (a-c), which highlights the second attempts at shape-setting. Figure 4.4 (a) shows the rig with the small copper tube and the NiTi SMA wire before it was inserted into the tube for shape-setting (Figure 4.4 (b)). Two rulers were positioned vertically and horizontally to measure the right curvature points. Figure 4.4 (c) shows the NiTi SMA wire after shape-setting at 450°C for 20 min. It is clear that the wire curvature is continuous and no longer has induced stress points like those observed when using the pins alone (Figure 4.4 (d)).
Figure 4.4: (a) Rig with copper tube and NiTi SMA wire before shape-setting. (b) Rig with NiTi SMA wire inside copper tube before shape-setting. (c) NiTi SMA wire after shape-setting at 450°C for 20 min.

Figure 4.5 (a-d) highlights the thermal cycling behavior of the NiTi wire after shape-setting at 450°C for 20 min using the rig with the copper tube. Figure 4.5 (a) shows the NiTi SMA wire after shape-setting using the rig with a copper tube and before thermal cycling. The wire has been wrapped to mimic the shape before deployment. A metal weight was used to hold the wire in place during heating. Figure 4.5 (b) NiTi SMA wire after one thermal cycle. The metal weight failed to secure the wire during thermal heating; however, the wire has fully recovered the set shape for full deployment. Figure 4.5 (c) NiTi SMA wire rewrapped to again mimic the shape before full deployment. The wire was placed in a small piece of the copper tube to and taped to the paper to better secure the wire for thermal cycling. Figure 4.5 (d) NiTi SMA wire after twelve thermal cycles. The wire has mostly recovered the set shape for full deployment. During heating, the wire is fully recovered although once the heat is removed, some of the deformation from
wrapping the wire in its pre-deployment state is visible. The small piece of copper worked much better at securing the wire during thermal heating.

Figure 4.5: (a) NiTi SMA wire after shape-setting using the rig with a copper tube and before thermal cycling. The wire has been wrapped to mimic the shape before deployment. (b) NiTi SMA wire after one thermal cycle. The wire has fully recovered the set shape for full deployment. (c) NiTi SMA wire rewrapped to again mimic the shape before full deployment. (d) NiTi SMA wire after twelve thermal cycles. The wire has mostly recovered the set shape for full deployment.

Figure 4.6 (a-h) highlights the results of shape-setting wire B and C using a Cu tube. The same rig and Cu tube that were used previously to shape-set the NiTi SMA wire A were also used here. Furthermore, the same method was followed except the wires were shape-set in the furnace for additional 10 min, to further ensure homogeneous shape-setting. A different thermal gun was used for both wire B and C. It resulted in the wire returning to their set shape faster because the new thermal gun has a higher thermal energy. Figure 4.6 (a-d) shows wire B after shape-setting and in various states of thermal cycling. Figure 4.6 (a) shows the NiTi SMA wire B after shape-setting and before any thermal cycling. The sample was deformed to its pre-
deployment shape. Figure 4.6 also shows the NiTi SMA wire B Figure 4.6 (b) after one thermal cycle and in its austenite shape, Figure 4.6 (c) before the third thermal cycle and in its pre-deployment shape, and Figure 4.6 (d) after the third thermal cycle and in its deployment shape. The wire moved during its third cycling which resulted in some parts of the wire to not heat uniformly; however, it did fully transform to its austenite shape. Figure 4.6 (e-h) shows wire C after shape-setting using a Cu tube for 30 min and Figure 4.6 (e) before its first thermal cycle and in its pre-deployment shape, (f) after one thermal cycle and in its austenite shape, Figure 4.6 (g) before the third thermal cycle and in its pre-deployment shape, and Figure 4.6 (h) after the third thermal cycle and in its deployment shape. The wires behaved better when they were shape-set in the furnace for 10 additional min. This was shown during thermal cycling as they transformed to their austenite shape easily and were able to retain their shape better.
Figure 4.6: (a) NiTi SMA wire B after shape-setting using the rig with a copper tube and before thermal cycling. The wire has been wrapped to its pre-deployment shape. (b) NiTi B wire after one thermal cycle. (c) NiTi SMA wire B rewrapped to pits pre-deployment shape again. (d) NiTi SMA wire B after three thermal cycles. (e) NiTi SMA wire C after shape-setting using the rig with a copper tube and before thermal cycling. The wire was set to its pre-deployment shape. (f) NiTi SMA wire C after its first thermal cycle and in its full deployment shape. (g) NiTi SMA wire C in its pre-deployment shape before its third cycle. (h) NiTi SMA wire C after its third thermal cycle. The wires have mostly recovered the set shape for full deployment.

Figure 4.7 (a-l) highlights the results of shape-setting of a 1.29 mm thick SE 508 NiTi wire. The wire was pseudoelastic at room-temperature and hard to shape. Therefore, it was heat-treated at 550 °C for 3 hours to push up its transformation temperatures by forming Ni₄Ti₃ Precipitates. Figure 4.7 (a) shows the SE 508 NiTi wire as drawn and before conducting any heat-treatment while (b) represents the SE 508 NiTi wire after the three hours heat-treatment. Figure 4.7 (c) shows the SE 508 NiTi wire inside a Cu tube fixed on the rig before shape-setting it and Figure 4.7 (d) shows the SE 508 NiTi wire after shape-setting on a grided paper. The wire was thermally cycled for nine more times. However, the first four cycles are documented and
reported below. Figure 4.7 (e) shows the SE 508 NiTi wire before any thermal cycling and in its
pre-deployment shape. Figure 4.7 (f) shows the SE 508 NiTi wire after its first thermal cycling and
in its full-deployment shape. The second thermal cycling are represented in Figure 4.7 (g) and (h).
Figure 4.7 (g) shows the SE 508 NiTi wire in its prior to deployment shape while Figure 4.7 (h)
shows the SE 508 NiTi wire in its fully-deployed status. Figure 4.7 (i) and (j) shows the SE 508 NiTi
wire before and after its third thermal cycle, respectively. Finally, Figure 4.7 (k) represents the SE
508 NiTi wire in its pre-deployment shape and before its fourth thermal cycling while (l) shows
the SE 508 NiTi wire after its fourth thermal cycling and in its full deployment shape. The wire
retained its full-deployment shape successfully.
Figure 4.7: (a) Ni$_{50.8}$Ti$_{49.2}$ wire as drawn. (b) Ni$_{50.8}$Ti$_{49.2}$ wire after the heat-treatment. (c) Ni$_{50.8}$Ti$_{49.2}$ wire inside a Cu tube fixed on the rig before shape-setting. (d) Ni$_{50.8}$Ti$_{49.2}$ wire after shape-setting. (e) Ni$_{50.8}$Ti$_{49.2}$ wire before its first thermal cycling and in its pre-deployment shape. (f) Ni$_{50.8}$Ti$_{49.2}$ wire after its first thermal cycling and in its deployment shape. (g) and (h) Ni$_{50.8}$Ti$_{49.2}$ wire before and after its second thermal cycling, respectively. (i) and (j) Ni$_{50.8}$Ti$_{49.2}$ wire before and after its third thermal cycling, respectively. (k) and (l) Ni$_{50.8}$Ti$_{49.2}$ wire before and after the fourth thermal cycle, respectively.

Figure 4.8 (a-l) highlights the results of shape-setting another SE 508 NiTi wire with the same thickness of 1.29 mm. The same process for this SE 508 NiTi wire in Figure 4.8 was also followed here in preparing the Ni$_{50.8}$Ti$_{49.2}$ wire. The wire was heat-treated at 550 °C for 3 hours to form Ni$_4$Ti$_3$ precipitates and push up the transformation temperatures. Figure 4.8 (a) shows the Ni$_{50.8}$Ti$_{49.2}$ wire as drawn and before performing any heat-treatment on the wire while Figure 4.8 (b) shows the Ni$_{50.8}$Ti$_{49.2}$ wire after the three hours heat-treatment. Figure 4.8 (c) shows the Ni$_{50.8}$Ti$_{49.2}$ wire in a Cu tube fixed on the rig before shape-setting while Figure 4.8 (d) shows the Ni$_{50.8}$Ti$_{49.2}$ wire after shape-setting. The wire was thermally cycled for four times only. Nonetheless, the first four cycles are documented and shown below. Figure 4.8 (e) shows the Ni$_{50.8}$Ti$_{49.2}$ wire before any thermal cycling while Figure 4.8 (f) shows the Ni$_{50.8}$Ti$_{49.2}$ wire after its first thermal cycling and in its full-deployment shape. The second thermal cycling results are
shown in Figure 4.8 (g and h). Figure 4.8 (g) shows the Ni$_{50.8}$Ti$_{49.2}$ wire in before its second thermal cycle while Figure 4.8 (h) shows the Ni$_{50.8}$Ti$_{49.2}$ wire after its second thermal cycle and in its full deployment shape. Figure 4.8 (i and j) show the Ni$_{50.8}$Ti$_{49.2}$ wire before and after its third thermal cycle, respectively. Finally, Figure 4.8 (k) shows the Ni$_{50.8}$Ti$_{49.2}$ wire before its fourth thermal cycle while Figure 4.8 (l) shows the Ni$_{50.8}$Ti$_{49.2}$ wire after its fourth thermal cycling and in its fully-deployed status. The Ni$_{50.8}$Ti$_{49.2}$ wire was able to retain its full-deployment shape successfully in each cycle. This improvement in shape memory response was due to less plastic deformation in the pre-deployment state. This is shown in Figure 4.8 (m) as the first thermal cycle one and fourth thermal cycle results are aligned on top of each other to show that the Ni$_{50.8}$Ti$_{49.2}$ wire was able to retain its full-deployment shape after four thermal cycles. The faded and the upper plate represents the Ni$_{50.8}$Ti$_{49.2}$ wire after its first thermal cycle while the bottom plate represents the Ni$_{50.8}$Ti$_{49.2}$ wire after its fourth cycle.
Figure 4.8: (a) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire as drawn. (b) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire after the heat-treatment. (c) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire inside a Cu tube fixed on the rig before shape-setting. (d) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire after shape-setting. (e) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire before its first thermal cycling. (f) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire after its first thermal cycling and in its deployment shape. (g) and (h) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire before and after its second thermal cycling, respectively. (i) and (j) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire before and after its third thermal cycling, respectively. (k) and (l) Ni\textsubscript{50.8}Ti\textsubscript{49.2} wire before and after the fourth thermal cycle, respectively. (m) Thermal cycle 1 and thermal cycle 4 on top of each other.
Figure 4.9 (a-k) highlights the results of shape-setting a 0.92 mm thick NiTi-10 at.% Cu plate. Figure 4.9 (a) shows the NiTi-10 at.% Cu plate before shape-setting while Figure 4.9 (b) illustrates how the NiTi-10 at.% Cu plate was fixed on the rig to obtain the desired curvature before shape-setting it in the furnace at 450 °C. The screws on the rig ensured that the NiTi-10 at.% Cu plate stay in place during the shape-setting process as it formed the desired curvature. The rig and the attached NiTi-10 at.% Cu plate, were held in the furnace at 450 °C for 30 min. Figure 4.9 (c) shows the NiTi-10 at.% Cu plate after shape-setting and in its full deployment shape. The curvature of the plate appears abrupt rather than a more continuous bend like previous cases. This abruptness in curvature was due to the fact that the increased thickness of the plate, as compared to previous sheets and wires, made bending more difficult. Figure 4.9 (d) presents the NiTi-10 at.% Cu plate in a curved shape before any thermal cycling. Figure 4.9 (e) shows the NiTi-10 at.% Cu plate after thermally cycling it for the first time. The NiTi-10 at.% Cu plate was able to retain its shape successfully. Furthermore, nine more thermal cycles were performed on the NiTi-10 at.% Cu plate. Nonetheless, this project focuses on the material’s first four cycles behavior. Figure 4.9 (f) shows the NiTi-10 at.% Cu plate before its second thermal cycle while Figure 4.9 (g) highlights the NiTi-10 at.% Cu plate after its second thermal cycle and in its full deployment curve. Figure 4.9 (h-i) shows the NiTi-10 at.% Cu plate before and after its third thermal cycling, respectively. Finally, Figure 4.9 (j) shows the NiTi-10 at.% Cu plate before its fourth thermal cycle while Figure 4.9 (k) shows the NiTi-10 at.% Cu plate after its fourth thermal cycle and in its full-deployment shape. The NiTi-10 at.% Cu plate behaved better than the NiTi sheet. The ternary NiTi-10 at.% Cu plate exhibited a better stability than the binary NiTi sheet.
Figure 4.9: (a) NiTi-10 at.\% Cu plate before shape-setting. (b) NiTi-10 at.\% Cu plate fixed on the rig before shape-setting. (c) NiTi-10 at.\% Cu plate after shape-setting. (d) NiTi-10 at.\% Cu plate before its first thermal cycling. (e) NiTi-10 at.\% Cu plate after its first thermal cycling. (f) and (g) NiTi-10 at.\% Cu plate before and after the second thermal cycle, respectively. (h) and (i) NiTi-10 at.\% Cu plate before and after the third thermal cycle, respectively. (j) and (k) NiTi-10 at.\% Cu plate before and after the fourth thermal cycle, respectively.

Figure 4.10 (a-k) illustrates shape-setting a NiTi-10 at.\% Cu plate using two steel sheets. Using only the screws on the rig to shape-set the NiTi-10 at.\% Cu plate did not result in the right and desired curvature. It resulted in a sharp curvature. Therefore, another NiTi-10 at.\% Cu plate was shape-set using steel sheets. The NiTi-10 at.\% Cu plate was sandwiched between two steel sheets and was kept fixed by using two paper clips to ensure that the NiTi-10 at.\% Cu plate stays in place during the shape-setting process. The steel sheets were used to get a softer and less sharp curvature. Figure 4.10 (a) shows the NiTi-10 at.\% Cu plate on a paper before shape-setting it. Figure 4.10 (b) shows the NiTi-10 at.\% Cu sheet sandwiched between two steel sheets on the rig before shape-setting. The steel sheets’ curvatures were measured on the previously used rig to maintain the same curvature points. Figure 4.10 (c) shows the NiTi-10 at.\% Cu plate sandwiched between two steel sheets on a grided paper before putting them in the furnace at 450 °C for 30 min to shape-set it. Then, the NiTi-10 at.\% Cu plate was thermally cycled for 10
times. However, the first four cycles were documented. Figure 4.10 (d) shows the NiTi-10 at.% Cu plate before its first thermal cycle while (e) shows the NiTi-10 at.% Cu sheet after its first thermal cycle. Figure 4.10 (f) and (g) shows the NiTi-10 at.% Cu plate’s behavior before and after its second thermal cycle, respectively. Furthermore, Figure 4.10 (h) shows the NiTi-10 at.% Cu sheet before its third thermal cycling while (i) shows the the NiTi-10 at.% Cu plate after its third thermal cycling and in its full-deployment shape. Finally, Figure 4.10 (j) and (k) NiTi-10 at.% Cu plate before and after the fourth thermal cycle, respectively. The NiTi-10 at.% Cu plate did recover its shape. However, the results were not documented well.
Figure 4.10: (a) NiTi-10 at.% Cu plate before shape-setting. (b) NiTi-10 at.% Cu plate sandwiched between two steel sheets on the rig before shape-setting. (c) NiTi-10 at.% Cu plate sandwiched between two steel sheets on a grided paper before shape-setting. (d) NiTi-10 at.% Cu plate before its first thermal cycling. (e) NiTi-10 at.% Cu plate after its first thermal cycling. (f) and (g) NiTi-10 at.% Cu plate before and after its second thermal cycling, respectively. (h) and (i) NiTi-10 at.% Cu plate before and after its third thermal cycling, respectively. (j) and (k) NiTi-10 at.% Cu plate before and after the fourth thermal cycle, respectively.

Figure 4.11 (a-l) shows the results of reshape-setting the 0.92 mm thick NiTi-10 at.% Cu plate that was shape-set in Figure 4.10 by following the same process that was done in shape-setting the NiTi-10 at.% Cu plate in Figure 4.10 except this time the correct measurements were taken to deform the steel sheets. The NiTi-10 at.% Cu plate was sandwiched between two steel sheets and was fixed by using two paper clips to secure the NiTi-10 at.% Cu plate between the steel sheets during the process of shape-setting. Figure 4.11 (a) shows the NiTi-10 at.% Cu plate sandwiched between two steel sheets before shape-setting. The NiTi-10 at.% Cu plate and steel sheets were held on the furnace at 450 °C for 30 min to shape-set the plate. Figure 4.11 (b) shows the NiTi-10 at.% Cu plate after shape-setting and on a grided paper. The NiTi-10 at.% Cu plate was thermally cycled for four times.
Figure 4.11: (a) NiTi-10 at.% Cu plate sandwiched between two steel sheets before shape-setting. (b) NiTi-10 at.% Cu plate after shape-setting. (c) NiTi-10 at.% Cu plate after shape-setting before any thermal cycles. (d) NiTi-10 at.% Cu plate before its first thermal cycling. (e) NiTi-10 at.% Cu plate after its first thermal cycling. (f) and (g) NiTi-10 at.% Cu plate before and after the second thermal cycle, respectively. (h) and (i) NiTi-10 at.% Cu plate before and after the third thermal cycle, respectively. (j) and (k) NiTi-10 at.% Cu plate before and after the fourth thermal cycle, respectively. (l) thermal cycle 1 and thermal cycle 4 on top of each other.

Figure 4.11 (c) shows the NiTi-10 at.% Cu plate before any thermal cycling while Figure 4.11 (d) shows the NiTi-10 at.% Cu plate after its first thermal cycle. Figure 4.11 (e) shows the NiTi-10 at.% Cu plate before its second thermal cycling while Figure 4.11 (f) shows the NiTi-10 at.% Cu plate after its second thermal cycling and in its full deployment shape. Figure 4.11 (g-h) shows the NiTi-10 at.% Cu plate before and after its third thermal cycling, respectively. Finally, Figure 4.11 (j) shows the NiTi-10 at.% Cu plate before its fourth thermal cycling while Figure 4.11 (k) shows the NiTi-10 at.% Cu plate after its fourth thermal cycling and in its full-deployment shape. The NiTi-10 at.% Cu plate exhibited a better behavior after reshaping-setting it. It was able to retain its full-deployment curvature successfully. This improvement in shape memory response was due to less plastic deformation in the pre-deployment state. This improvement is shown Figure 4.11 (l) as the first thermal cycle and fourth thermal cycle results were aligned on top of each other to show that the NiTi-10 at.% Cu plate retained its deployment shape fully after four thermal cycles. The faded and the upper plate represents the NiTi-10 at.% Cu plate after its first thermal cycle while the bottom plate represents the NiTi-10 at.% Cu plate after its fourth cycle.
4.3 Thermo-Mechanical Cycling of NiTi SM 495 and NiTi-10 at.% Cu Plates

A rig was designed and built to perform isobaric thermal cycling of NiTi-based plates which is shown Figure 4.12. The plates were pinned down during the process so they would stay fixed. The plates are attached to a stainless-steel wire to attach the weights on the other end of the rig. A measuring grid is used against the plates to measure the difference.

Figure 4.13 shows both NiTi SM 495 plate and NiTi-10 at.% Cu plate were thermally cycled to evaluate their thermomechanical behavior. Different weights were used to determine the most durable weight during the process of thermal cycling. The cycling was done using a rig that was designed specifically to train NiTi-based components for this study. After hot-rolling and machining the components, they were shape-set to be straight at 450°C for 30 min by weighting them down using steel blocks to ensure that the plates stay fixed during the process of shape-setting. Both plates followed the same thermal cycling process in which different weights were tested in the same order. One plate was thermally cycled at each time, starting with the NiTi SM 495 plate. It was fixed on one end on the rig and the other end was wrapped around a steel wire which was attached to the applied weights.

In the first two cycles, the applied weight to the NiTi SM 495 plate was 1150 g. The NiTi SM 495 plate was not able to retrieve its straight shape when thermal heat was applied because the weight was too heavy. When the 1150 g weight was removed, the NiTi SM 495 plate was able to gain some of its shape back without applying heat and then it gained most of its shape back when thermal heat was applied. Finally, the NiTi SM 495 plate was allowed to air-cool to room temperature. It was noticed that on the second cycle that the plate bent further than the first cycle when the 1150 g weight was applied. Similarly, in NiTi-10 at.% Cu plate, the applied weight
to the NiTi-10 at.% Cu plate was 1150 g in the first two cycles. The NiTi-10 at.% Cu plate was not able to retrieve its full straight shape when thermal heat was applied because the weight was too heavy. When the 1150 g weight was removed, the NiTi-10 at.% Cu plate was able to retrain almost all of its shape back when thermal heat was applied. Unlike NiTi SM 495, the NiTi-10 at.% Cu plate did not bend further when the same weight was applied in the second thermal cycle. Finally, the NiTi-10 at.% Cu plate was allowed to air-cool to room temperature.

In the third cycle, the same process was followed on the plates except that the applied weight was changed to 1000 g. It was noticed that the 1000 g weight created the same curvature as the previous cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. When the 1000 g was removed, the plates retrieved some of their shape and then with applying heat, the plates retrained most of their shape. Finally, the plates were allowed to air-cool to room temperature.

In the fourth cycle, the weight was lowered to 900 g and the same process was followed. The 900 g weight created the same curvature as the previous cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. When the 900 g weight was removed, the plates gained some of their shape back and then heat was applied to the plates to retain their full austenite shape. Finally, the plates were allowed to air-cool to room temperature.

In the fifth cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the previous cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. Then, the 900 g was removed, and a 50 g weight was applied to the plate. Thermal heat was applied to the plate while still having the
50 g weight attached to the plate. The Plate was able to gain most of its shape while having the 50 g on. After that, the 50 g was removed, and thermal heat was applied to the plate. The plates gained the remaining of their shape back, but it was a minor difference. Finally, both plates were allowed to air-cool to room temperature.

In the sixth cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the pervious cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. After that, the 900 g was removed, and a 100 g weight was applied to the plates. Thermal heat was applied to the plate while still having the 100 g weight attached to the plate. The Plate was able to gain most of its shape while having the 100 g attached. Then, the 100 g was removed, and thermal heat was applied to the plate. The plates gained the remaining of their shape back which was a minor difference. Finally, the plate was allowed to air-cool to room temperature.

In the seventh cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the pervious cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. Then, the 900 g was removed, and a 150 g weight was applied to the plate. Thermal heat was applied to the plate while still having the 150 g weight attached to the plates. The Plates was able to gain most of their shape while having the 150 g on. After that, the 150 g was removed, and thermal heat was applied to the plates. The plates gained the remaining of their shape back, but it was a minor difference. Finally, the plates was allowed to air-cool to room temperature.

In the eighth cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the pervious cycles for the NiTi SM 495 while it was noticed
that it created less curvature for the NiTi-10 at.% Cu plate. After that, the 900 g was removed, and a 120 g weight was applied to the plate. Thermal heat was applied to the plate while still having the 120 g weight attached to the plate. The Plates were able to gain most of their shape while having the 120 g attached. Then, the 120 g was removed, and thermal heat was applied to the plates. The plates gained the remaining of their shape back which was a minor difference. Finally, the plates were allowed to air-cool to room temperature.

In the ninth cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the pervious cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. After that, the 900 g was removed, and a 100 g weight was applied to the plate. Thermal heat was applied to the plate while still having the 100 g weight attached to the plate. The Plate was able to gain most of its shape while having the 100 g attached. Then, the 100 g was removed, and thermal heat was applied to the plate. The plates gained the remaining of their shape back which was a minor difference. Finally, the plate was cooled with a cooling dryer to room temperature.

In the tenth cycle, two different weights were applied. First, the 900 g weight was applied which created the same curvature as the pervious cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. After that, the 900 g was removed, and a 200 g weight was applied to the plate. Thermal heat was applied to the plate while still having the 200 g weight attached to the plate. The Plate was able to gain most of its shape while having the 200 g attached. Then, the 200 g was removed, and thermal heat was applied to the plate. The plates gained the remaining of their shape back which was a minor difference. Finally, the plates were cooled with a cooling dryer to room temperature.
In cycle 11, 12, and 13, a 300 g weight was attached to the plates which created the same curvature as the previous cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. Thermal heat was applied to the plate while still having the 300 g weight attached to the plate. Then, the plates were cooled with a cooling dryer to room temperature.

In the last three cycles (14, 15 and 16), a 400 g weight was attached to the plate which created the same curvature as the previous cycles for the NiTi SM 495 while it was noticed that it created less curvature for the NiTi-10 at.% Cu plate. Thermal heat was applied to the plate while still having the 400 g weight attached to the plate. Then, the plate was cooled with a cooling dryer to room temperature. It was noticed that both plates had the ability to retain the same amount of plasticity while having the 400 g weight attached to them. Therefore, it was decided to compare the results of the last three cycles for both materials.

When comparing SM 495 NiTi plate cycle 1 (1150 g) and cycle 16 (400 g) which were shown in Figure 4.14, it was noticed that lower loads resulted in less actuation. Furthermore, cycle 14 (400 g) and cycle 16 (400 g) were compared in Figure 4.15 it was noticed that increased number of cycles resulted in slightly more overall actuation for the SM 495 NiTi plate. On the other hand, when comparing NiTi-10 at.% Cu plate cycle 1 (1150 g) and cycle 16 (400 g) which are shown in Figure 4.16, it was noticed that lower loads resulted in less actuation. In addition, cycle 14 (400 g) and cycle 16 (400 g) were compared in Figure 4.17 it was noticed that increased number of cycles resulted in less overall actuation for the NiTi-10 at.% Cu plate. NiTi-10 at.% Cu SMA was supposed to show a more stable behavior than the NiTi SMA during thermo-mechanical cycling; however, due to the inconsistent set-up, the results were not as expected. The rig and
the camera need to be fixed during the cycling process. During the process of switching the weights and the plates, the set-up was unintentionally moved. Even though, the rig and the camera placement were marked on the table. A fixed set-up would help improve the results. Another parameter that affected the results was the stainless-steel wire. Using a thermally-insulated wire would be a better suited option than using stainless-steel wire. Since the stainless-steel wire can potentially deform elastoplastically, absorb some of the applied heat, and cause friction along the rig. Lastly, the plates dimensions need to be identical so that the load is identical too. Having slightly different dimensions affect the plates performance against the applied load. Controlling these variables is believed to result in NiTi-10 at. % Cu having a better thermo-mechanical performance than the SM 495 NiTi plate.
Figure 4.14: (a) SM 495 NiTi plate cycle 1 (1150 g) and cycle 16 (400 g) with applied weights (b) SM 495 NiTi plate cycle 1 (1150 g) and cycle 16 (400 g) after actuation shape.

Figure 4.15: (a) SM 495 NiTi plate cycle 14 (400 g) and cycle 16 (400 g) with applied weights (b) SM 495 NiTi plate cycle 14 (400 g) and cycle 16 (400 g) after actuation shape.

Figure 4.16: (a) NiTi-10 at. % Cu plate cycle 1 (1150 g) and cycle 16 (400 g) with applied weights (b) NiTi-10 at. % Cu plate cycle 1 (1150 g) and cycle 16 (400 g) after actuation shape.
Figure 4.17: (a) NiTi-10 at. % Cu plate cycle 14 (400 g) and cycle 16 (400 g) with applied weights (b) NiTi-10 at. % Cu plate cycle 14 (400 g) and cycle 16 (400 g) after actuation shape.
CHAPTER 5
CONCLUSIONS

5.1 Summary

In conclusion, having a small compact form of an antenna is needed to deliver satellites into space and then once in space the antenna needs to be fully deployed with a significantly larger surface area. Therefore, using SMAs provides a solution to this problem since SMAs can revert back their original shape after deformation through a thermal or electrical stimulus. In this thesis, four NiTi-based SMA compositions were investigated and are as follows, two commercially available NiTi wires (90°C Flexinol® actuator NiTi wire and Confluent ADB SE508 NiTi wire), commercially available NiTi SM495 plates (ATI Specialty Alloys and Components), and an in house lab-produced NiTiCu plate. First, the materials were processed and shape-set. Then, they were characterized to evaluate their thermomechanical behavior and effectiveness as SMA aerospace actuators. Various shape-setting techniques such as pin and plate, fixtures and dies, and sandwich fixture were performed to obtain the desired final austenite shape.

SE NiTi 508 wire and the NiTiCu plate were the most promising components for the desired application. The SE NiTi 508 wire underwent a heat-treatment at 550 °C for 3 hours, followed by shape-setting at 450 °C for 30 min using a Cu tube. The wire was kept fixed inside the Cu tube during the shape-setting process to obtain the desired curvature. After the shape-setting process, the SE NiTi 508 wire underwent four thermal cycles. The SE NiTi 508 wire was able to retrieve its full deployment form successfully after all four thermal cycles. In addition, a NiTiCu plate was shape-set using by sandwiching it between two steel sheets which were deformed to the desired full-deployment shape previously. The NiTiCu plate was shape-set at
450 °C for 30 min. After that, it was thermally cycled for four times to evaluate its effectiveness. The NiTiCu plate regained its full-deployment curvature shape successfully after all the four thermal cycles.

Furthermore, hot-rolling data and thermal cycling behaviors for both the NiTi SM495 and NiTiCu plates were compared. The NiTiCu SMA was able to reduce its thickness in a fewer number of passes than the NiTi SM 495 SMA. Also, the NiTiCu plate showed a faster recoverability, i.e. a faster shape memory response due to a narrower thermal hysteresis, during the process of thermal cycling than the NiTi SM 495 plate.

Additionally, hot-rolling data and thermal cycling behaviors of the NiTi SM 495 and NiTi-10 at.% Cu plates were compared. The thickness of the NiTi-10 at.% Cu SMA was able to be reduced in a few number of passes than that of the NiTi SM 495 SMA. Also, NiTi-10 at.% Cu plate showed a more stable behavior in thermal cycling than NiTi SM 495 plate.

5.2 Future Research

Future research should include a fixed set-up for the rig and the camera. Also, a thermal wire should be used instead of stainless-steel wire. Making the plates dimension identical should make the applied load identical resulting in a more accurate experimental results. Furthermore, adding Zr as another element to the NiTiCu composition can increase the transformation temperatures and further stabilize the fatigue response through better phase compatibility. Also, the process and the parameters of making NiTiCuZr with different compositions should be explored. This exploration can be achieved by (1) melting the composition, then (2) determining the optimal temperature range for hot-rolling and optimal processing routes, (3) identifying the suitable machining technique for each composition, (4) determining the right annealing
temperatures and heat-treatments, and finally (5) studying the thermomechanical behaviors of each SMA and comparing them to the already reported compositions in this thesis.
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