DESIGN AND ANALYSIS OF ENERGY HARVESTING
WITH SHAPE MEMORY ALLOY

A Thesis
Presented to
The Graduate Faculty of The University of Akron

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

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December, 2012
DESIGN AND ANALYSIS OF ENERGY HARVESTING
WITH SHAPE MEMORY ALLOY

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Thesis

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ABSTRACT

Shape memory alloys (SMAs) are metallic alloys made of Titanium & Nickel to retain a specific shape by undergoing a heating process. The shape memorization occurs via a temperature dependent phase transformation process between two crystal structures, austenite phase and martensite phase. Typical SMAs are thin wires and under the phase transformation they change shape. Specifically, under heat they shrink.

This research exploits this property of SMAs to create motion which can be transformed into mechanical energy and in turn convert into electrical energy via generations and store energy in the certain device. The goal of the thesis is to construct a device that encompasses SMA’s and a heat source (such as a wasted heat source from industries or from a machines) to generate periodic motions. Specifically, SMA is tied to a spring loaded shaft which expands is motion cyclically. We measured the change of temperature, position and voltage via a temperature sensor, a Hall Effect Sensor and oscilloscopes. The shaft was coupled to a motor which generates electricity. Electrical energy is stored in an energy storing device. For our analysis, this device is an ultra-capacitor. In addition, we investigated a theoretical approach along with simulations to calculate the total energy we could capture.
The accomplishments reported in this thesis represent a significant development in using shape memory alloy phase transformation to convert and capture the energy. It is anticipated that the results and methods in this work can be utilized in the practical shape memory alloy technologies and energy harvesting for commercial applications.
ACKNOWLEDGEMENTS

The work reported in this thesis was carried out in the Department of Electrical and Computer Engineering of The University of Akron between August 2011 and December 2012. First, and foremost, I extend the warmest and heartfelt thanks to my supervisor, Dr S. I. Hariharan, for his inspiration, keen insight and friendship. His encouragement and advice brought me successfully through this thesis. I would also like to express to another adviser, Dr. Erik D. Engeberg, who provided extensive help and guidance with the lab equipments and setup. Committee members, Dr. George Giakos and Dr. Kye Shin Lee who generously gave the gift of their times and support when needed, also deserve a big thank you.

I would also like to thank department chair Dr. Alex De Abreu Garcia and Gay Boden for their valuable suggestions and tremendous support during my stay in this department. Also, thank you to everyone who has provided valuable input that was critical for the success of this effort including all my friends who support me a lot.

Finally, an everlasting gratitude goes to my parents, for their consistent love, support and encouragement.
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CHAPTER 1

INTRODUCTION

There has been a continuing trend in technology towards the clean energy and energy harvesting. Following this trend, the factors such as new clean materials, cost and space constraints gain increased importance in the selection of suitable technologies. Shape memory alloys are generally considered a type of 'smart' materials because they have temperature sensing and multifunctional features.

This chapter will provide a brief introduction of energy harvesting and clean energy developed requires and the motivations behind our research. Then the research objectives of this thesis will be covered.

1.1 Energy Harvesting and Clean Energy

As we all know, the world faces a number of challenges in energy supply. While the main source of energy, the oil, is gradually running out, it is also an energy source that presents problems to the environment. The use of the oil, coal and other fossil energy sources are polluting the planet with greenhouse gas. The greenhouse gas causes air pollution and lead to environmental changes. Therefore, the global demand for a clean source of energy
is becoming an increasingly important area of research. These types of energy sources are commonly referred to as alternative energy sources and capturing energy from these sources are called energy harvesting. Thus, energy harvesting is motivated by dealing with the issues of climate change and global warming. At present, there are many sources of energy that are wasted and could be harvested and recycled for use in some other applications.

The history of energy harvesting dates back to the windmill and the waterwheel. Scientists have searched to store the energy from the vibrations and geo-potential for many decades [29]. Energy harvesting is the process by which energy is derived from other sources, like solar power, thermal energy, wind energy, salinity gradients, kinetic energy, captured and stored for some other devices, usually small such as wearable electronics and wireless sensor networks [30]. Generally speaking, energy harvesters provide a very small amount of power for low energy electronics. While the input fuel to some large-scale generations costs money (oil, coal, etc.), the energy source of energy harvesting is shown as common occurrences and usually it is free.

One motivation behind the search for the new energy harvesting design or devices is the desire to generate power without the cost of input power. Energy harvesting devices converting surrounding's energy into electrical energy have attracted much interest. The approach that is reported in this thesis is to generate mechanical energy through phase changes of shape memory alloy wires from temperature differentials. This mechanical energy then can be converted to electrical energy and stored for needed use.
1.2 Shape Memory Alloys

Shape memory alloys are also called smart materials, memory metals, and so on. It is a novel material which has the ability to return to an original or predetermined shape when the temperature raise up to transformation temperature. When it is cold or below its transformation temperature point, the shape memory alloys remain in the existing shape, and can be deformed very easily into any other new shape since it has very low yield strength. In most cases, the transformation temperature point of the shape memory alloy is chosen higher than room temperature, which dependents on the crystal structure of shape memory alloy. During this crystal transformation, shape memory alloy can generate extremely large forces if it encounters any resistance, and this process usually completes in a short time. They accomplish this shape transformation via a temperature dependent phase transformation process between two crystal structures: martensite phase in the lower temperature, and the austenite phase in the higher temperature. Martensite phase, the low-temperature, is soft and more malleable; whereas the austenite, the high-temperature phase, is relatively harder and has a much higher stiffness. When cool and in the martensite phase, the shape memory alloy can be easily stretched by applying a small external force. To recover its original length, the alloy is heated beyond a certain temperature (transformation temperature point), causing it to contract and transform into the austenite structure. Heating the shape memory alloy can be done via Joule heating or resistive heating using electric current.
The most common shape memory material is an alloy of nickel and titanium called Nitinol. This particular alloy has very good electrical and mechanical properties, long fatigue life, and high corrosion resistance. This work was a Nitinol wire.

1.3 Research Objectives and Approach

So far shape memory alloy commercial applications have been very limited, and in areas where they are applied, usage is often restricted to passive or on-off applications [7]. And most of them have generally been considered to be slow, inaccurate and difficult to control continuously [7]. The primary objective of this research is the construction and demonstration of a shape memory alloy energy harvesting device that collects electrical energy from the phase transformation of these special materials via the temperature change. The research can be accomplished via the design and implementation of practical, effective control systems and simulation.

The approach that has been adopted for this research initially involves investigating the response of shape memory alloy single and spring wire via Hall Effect Sensor. If small-signal responses can be detected, it means that this device can be induced, despite the existence of hysteresis and nonlinearities in the shape memory alloys practical applications. The aim of this experiment is to test and capture the mechanical energy via shape memory alloy phase changes. Modeling, simulations and experiments carried out to determine a simple shape memory alloy model that captures the mechanical energy overall behavior. This model relates the input heating power to output force response for
a single shape memory alloy wire, and it successfully demonstrates good comparison between simulation and experimental results.
CHAPTER II

SHAPE MEMORY ALLOYS

In this Chapter, background information of shape memory alloy research from the materials science view is presented. Section 2.1 explains an overview of the past and current work on development of SMA materials. Section 2.2 provides an overview on two different phases of shape memory alloys. We studied crystalline structure and stress-strain curves of two phases, martensite and austenite. A short introduction of annealing phase and hysteresis are presented in this section. Section 2.3 reviews and summarizes the character of shape memory effects. In this section, one way shape memory effect, two way shape memory effect and pseudoelasticity is covered. In section 2.4, a short description of stress-temperature analysis is shown. Also detwinned and twinned plot analysis, which is a standard tension test is presented.

2.1 Shape Memory Alloy Development Outline

According to Otsuka and Wayman (1998) [15], shape memory alloy was first noticed in 1930 via accomplishing shape memorization. Arne. Ölander, a physicist, discovered a "rubber-like" behavior in gold-cadmium alloy. Later he observed the pseudoelastic behavior of the Au-Cd alloy in 1932 [15]. And this is the first reported observation of
shape memory effect in history. However, the basic phenomenon of the memory effect governed by the thermoelastic behavior of the martensite phase was clearly described by Kurdjumov & Khandros (1949) [15, 31] and also by Chang & Read (1951) [15, 31]. And the similar effect was noticed in alloys of Cu-Zn, In-Tl and Cu-Al-Ni. These discoveries of shape memory alloys had captured the researchers' interests [7]. However, the practical and industrial applications of those alloys were not realized due to high costs, and the complexity of manufacturing technology [7]. The shape memory effect was discovered with the real phenomenological significance in Ni-Ti alloy, which is also known as Nitinol (Nickel-Titanium Naval Ordnance Laboratory) in the 1960s by William Buehler and his co-workers in the U.S [32]. Nitinol had better properties than other existing shape memory alloy material at that time. It was cheaper to produce, easier to composite and less dangerous [32]. In the 1980s, Nitinol became popular for medical application due to better biocompatible (means well tolerated by bone and other tissues) though more costly than stainless steel. It is also more attractive by providing a body temperature response [33]. It was only in 1990s that the research began for the robotic and actuator applications [7]. There also some non-alloy material displaying the shape memory effect, such as polymers, ceramics, biological systems which is shown in Table 2.1 [1].

Generally speaking, NiTi-based alloys, Cu-based alloys and Fe-based alloys are active mainly in the field of scientific research [7]. The properties of these alloys are shown in the Table 2.2. At present, Ni-Ti and Cu-Zn-Al are still considered as the most useful shape memory alloys. Other alloys are unsuitable for industrial manufacturing, since the constituent elements are expensive or cannot be used unless it is in the single crystal form, as shown in Table 2.2. (Funakubo 1987 & Liang 1990).
Table 2.1 Category list of with shape memory properties.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metals</td>
<td>NiTi-based; Cu-based; Fe-based</td>
</tr>
<tr>
<td>Polymers</td>
<td>PTFE (polytetrafluoroethylene)</td>
</tr>
<tr>
<td>Ceramics</td>
<td>ZrO2 (Zr: Zirconium)</td>
</tr>
<tr>
<td>Biological Systems</td>
<td>Bacteriophages</td>
</tr>
</tbody>
</table>

Table 2.2 Shape memory alloys materials (from Liang 1990) [34]

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Composition %</th>
<th>Transformations range (Austenite start) °C</th>
<th>Note</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>AgCd</td>
<td>Cd: 44 - 49, at</td>
<td>-190 - 50</td>
<td>at: atomic percentage</td>
<td>Ag: Silver; Cd: Cadmium</td>
</tr>
<tr>
<td>AuCd</td>
<td>Cd: 46.5 - 50, at</td>
<td>30 - 100</td>
<td></td>
<td>Au: Gold</td>
</tr>
<tr>
<td>CuAlNi</td>
<td>Au: 14 - 14.5, wt Ni: 3 - 4.5, wt</td>
<td>-140 - 100</td>
<td>wt: weight percentage</td>
<td>Cu: Copper; Al: Aluminium Ni: Nickel</td>
</tr>
<tr>
<td>CuZn</td>
<td>Zn: 38.5 - 41.5, wt</td>
<td>-180 - 200</td>
<td></td>
<td>Zn: Zinc</td>
</tr>
<tr>
<td>CuZnX</td>
<td>X: small, wt</td>
<td>-180 - 200</td>
<td>X=Si, Sn, Al</td>
<td>Si: Silicon; Sn: Tin</td>
</tr>
<tr>
<td>InTl</td>
<td>Tl: 18 - 23, at</td>
<td>60 - 100</td>
<td></td>
<td>In: Indium; Tl: Thallium</td>
</tr>
<tr>
<td>NiAl</td>
<td>Al: 36 - 38, at</td>
<td>-180 - 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NiTi</td>
<td>Ti: 46.2 - 51, at</td>
<td>-50 - 110</td>
<td>Ti: Titanium</td>
<td></td>
</tr>
<tr>
<td>TiNiX</td>
<td>Ni+X: 5-50, at X: 5-50, at</td>
<td>-200 - 700</td>
<td>X=Pd, Pt</td>
<td>Pd: Palladium Pt: Platinum</td>
</tr>
<tr>
<td>TiNiCu</td>
<td>Cu: 0-15, at</td>
<td>-150 - 100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiNiNb</td>
<td>Nb: 0-15, at</td>
<td>-200 - 50</td>
<td></td>
<td>Nb: Niobium</td>
</tr>
<tr>
<td>TiNiAu</td>
<td>Ni+Au: 50, at</td>
<td>20 - 610</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiPdX</td>
<td>Pd+X: 50, at</td>
<td>0 - 600</td>
<td>X=Cr, Fe</td>
<td>Cr: Chromium</td>
</tr>
<tr>
<td>MnCu</td>
<td>Cu: 5-35, at</td>
<td>-250 - 180</td>
<td></td>
<td>Mn: Manganese</td>
</tr>
</tbody>
</table>
The property of Ni-Ti and Cu-Zn-Al are completely different due to their different microstructures. Ni-Ti alloys have proven to be considered as the better materials in engineering applications, since they have much higher strength, larger recoverable strain, better corrosion resistance and most importantly higher reliability than Cu-Zn-Al. This is shown in Table 2.3 [35].

Table 2.3 Comparison of Ni-Ti and Cu-Zn-Al Alloys (Funakubo 1987) [35]

<table>
<thead>
<tr>
<th></th>
<th>Ni-Ti</th>
<th>Cu-Zn-Al</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recovery strain</td>
<td>max 8%</td>
<td>max 4%</td>
</tr>
<tr>
<td>Recovery stress</td>
<td>max 400 MPa</td>
<td>max 200 MPa</td>
</tr>
<tr>
<td>Corrosion resistance</td>
<td>good</td>
<td>stress corrosion cracking</td>
</tr>
<tr>
<td>Workability</td>
<td>poor</td>
<td>fair</td>
</tr>
<tr>
<td>Processing</td>
<td>comparatively easy</td>
<td>fairly difficult</td>
</tr>
</tbody>
</table>

Shape memory alloys are commonly used in the form of single wires or helical springs. In our research, the shape memory alloys which are commercially produced Ni-Ti, has been used in wire and spring forms for all modeling and experiments.
2.2 The Phases of Shape Memory Alloy

In the practical applications, a Ni-Ti shape memory alloy can exist in different temperatures which depend on the crystal structures or phases: primarily martensite and austenite. And also stress-induced martensite is noted by [2]. In this thesis, we are restricted on martensite phase and austenite phase.

At low temperature or room temperature, the alloy is in the martensite phase which is weaker, soft and can be easily stretched. Once heated up to the high temperature (over the transformation point), the alloy contracts and reverts to the austenite phase and becomes stronger and more rigid [32]. Its transformation and reverse transformation are lattice transformations involving a deformation which results from atomic movements.

Martensite and austenite phase show several different properties.

2.2.1 Martensite Phase

Crystalline Structure

In the martensite phase (low temperature), Ni-Ti has a monoclinic structure which is shown in Figure 2.1 with $a = 0.2889 \text{ nm}$, $b = 0.4120 \text{ nm}$, $c = 0.4622 \text{ nm}$ and $\beta = 96.8^\circ$ (Nenno, 1982; Funakubo, 1987).
The crystal structure of the martensite phase is aligned. The alloy can be bent or formed easily. The required deformation pressure is 10,000 to 20,000 psi [3]. Bending deforms the crystalline structure of the alloy producing internal stress.

As we can see, there are two martensite variants between martensite phase transformations which are called martensite re-orientation. This process is always related by stress and is associated with the conversion between variants. As the stress increases, one group of conversions takes place until the specimen consists of only one variant until a large macroscopic strain is produced. This process is called detwinning. Corresponding to this concept, the initial martensite phase is called twinned martensite (TM, right). It is called detwinned martensite (DM, left) after this process which is shown as Figure 2.2.
Stress-Strain Curves

Stress-strain curves are unique for each material, and are found by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress). The relationship between the stress and strain that a particular material displays is known as that material's Stress-Strain curve [5].

Strain is defined as "deformation of a solid due to stress" and can be expressed as

\[ \varepsilon = \frac{\Delta L (\text{in})}{L (\text{in})} \]  \hspace{1cm} (2.1)

where \( \Delta L \) is the difference of length and \( L \) is initial length [5].

Stress is the ratio of applied force \( F \) and cross section \( A \), defined as "force per area", and can be expressed as

\[ \sigma (\text{psi}) = \frac{F (N)}{A (\text{in}^2)} \]  \hspace{1cm} (2.2)

where \( F \) is normal component force and \( A \) is area [5].

Young's Modulus is \( D = \text{stress} / \text{strain} \) [5].

The stress-strain curves of martensite phase, are depicted in Figure 2.3 [7].
When an external stress is applied to the alloy that is fully martensitic, the alloy deforms elastically (Figure 2.3, stage 1). If the stress exceeds the martensite yield strength, a large non-elastic deformation will occur, which allows a large strain in the material with a small increase in external stress. The martensite is strain recoverable up until this stage 2. However, further increase in stress causes the material to again behave elastically up to the point where the external stress begins to break the atomic bonds between the martensite layers in stage 3 and 4 shown in the Figure 2.3 [7].

The strain at which this permanent deformation occurs in Ni-Ti material is 8%. Most applications will restrict strains to 4% or lower [6,7].
2.2.2 Austenite Phase

Crystalline Structure

In the austenite phase, Ni-Ti alloy shows body-centered cubic lattice with $a_0=0.3015\text{nm}$, shown in Figure 2.4.

![Figure 2.4](image1.png)

Figure 2.4 The crystal structure of austenite phase (Nenno, 1982; Funakubo, 1987).

The movement is generated in this phase when the temperature is above transition temperature. The exact transition temperature varies depending upon the composition of the shape memory alloy which is shown in Table 2.2. The yield strength with which the material tries to return to its original shape is 35,000 to 70,000 psi which is much higher than the martensite phase which is shown in Figure 2.5.

![Figure 2.5](image2.png)

Figure 2.5 Crystalline structure of austenite phase [4].
Stress-Strain Curves

![Stress-Strain Curves Diagram]

Figure 2.6 The stress and strain curve of austenite phase [7].

The austenite phase has a higher yield strength compared to martensite phase. Initially, the alloy will behave elastically which is shown in the stage 1 in Figure 2.6 until the stress exceeds its yield strength. From this point, plastic deformation will ensue causing unrecoverable stretching upon unloading shown in stage 2 and 3 of Figure 2.6 [6, 7].

2.2.3 Annealing Phase

The high temperature phase in a annealing phase. The alloy will reorient its crystalline structure to "remember" its present (original) shape. The annealing phase for the Nitinol wire we are working with is approximately 540°C.

2.2.4 Martensite Transformation and Hysteresis

The shape memory mechanism is based on a reversible, solid-state phase transformation between martensite phase (low temperature or present phase) and austenite phase (high temperature) on atomic scale, which is known as martensite transformation [15]. Of course, if the Ni-Ti alloys haven't been deformed or stressed in the martensite phase, the
crystalline structure changes still occur from martensite transformation, but do not result in any movement.

Figure 2.7 Microscopy for martensite transformation [7]

Shape memory effect shown microscopically: martensite without undergoing a shape change, is deformed by moving twin boundaries. Heating state will return the original austenitic structure and shape. Once austenite is cooled, it becomes martensite [11].

If the external stress causes $M_s$, the martensite start temperature to increase beyond the current temperature, martensite will form. This makes the alloy malleable under small increase in stress. Once the stress is removed, the transition temperatures decreases and the alloy returns to the austenite phase.
There are also other transformations associated with shape memory, such as rhombohedral (R-) and bainitic transformations [7]. We are focusing on martensite transformation between martensite and austenite in this thesis.

Stress-Strain Figure Via Austenite and Twinned, Detwinned Martensite.

Figure 2.8 Stress-strain figure via austenite and twinned, detwinned martensite [3].

This is the simplest type of loading, one dimensional extension of a uniform test [3]. A plot from this test is shown in Fig.2.8. Consider a SMA wire containing a mixture of austenite and twinned martensite. Put this wire into a standard tension testing machine and carry out a tension test [3].

During loading from stage a to stage b, the behavior is mainly elastic although some transformation may happen, as indicated by a small amount of nonlinearity in the curve.
If the stress goes over a certain critical stress, whose magnitude depends on the temperature of the specimen, suddenly a large transformation-induced strain occurs from stage b to stage c. In this process, the transformations are martensitic transformation and martensite re-orientation. After the martensitic transformation has almost been completed, from stage c to stage d, the martensite re-orientation (detwinning) dominates [3].

During unloading, after a period of pure elastic recovery, a small portion of the detwinned martensite may transform back to twinned martensite accompanied with some reverse martensitic transformation, which is shown from stage d to stage e. If the temperature of the specimen is not too high, further unloading will lead to more reverse transformation (from stage e to stage f). The only way of fully recovering the original shape is by heating the wire above a certain temperature under zero stress. Shape memory effect [3], which will discuss in section 2.3.

Hysteresis

The temperature range for the martensite-to-austenite transformation that takes place upon heating is higher than that for the reverse transformation upon cooling (Figure 2.7) [7]. The difference between the transition temperatures upon heating and cooling is called hysteresis. Hysteresis is generally defined as the difference between the temperatures at which the material is in 50% transformed to austenite upon heating and in 50% transformed to martensite upon cooling. This difference can be up to 20–30°C [BUHEL E R et al., 1967].
Figure 2.9 The curve of martensite-to-austenite transformation [7].

The martensitic phase transformations of the alloy can be defined by four transformation temperatures:

\[ A_s, \] the temperature at which austenite phenomenon start,

\[ A_f, \] the temperature at which austenite phenomenon finish,

\[ M_s, \] the temperature at which martensite phenomenon start,

\[ M_f, \] the temperature at which martensite phenomenon finish.

[BUEHL E R et al., 1967].

The shape memory alloy consists only of the martensite phase when the temperature is less than \( M_f \), which is from left of the curve shown in Figure 2.9. As the temperature is increased over \( A_s \), austenite phase starts to form in the alloy and when the temperature exceeds \( A_f \), the alloy is fully in the austenite phase. As the shape memory alloy cools
down, martensite phase begins to form when the temperature drops below $M_s$, and when the temperature reaches $M_f$, the alloy is again in the martensite phase [7].

As can be seen in Figure 2.9, this transition between the austenite and martensite phases can be formed by a wide thermal hysteresis loop. The hysteresis varies according to the alloy system. For NiTi alloys, the temperature hysteresis is generally between 30-50°C [7].

During the martensite phase transformation, in the range where both martensite and austenite co-exist, the stress-strain response of shape memory alloys are nonlinear and prominently hysteretic [7, 8]. They are influenced by material composition, processing, temperature and the number and sequence of activated thermo-mechanical loading cycles [8].

During phase transitions between martensite and austenite, most of the properties of shape memory vary. These include Young’s Modulus, electrical resistance and thermal conductivity and so on. Parts of them are shown in the following tables.

<table>
<thead>
<tr>
<th>Properties of Ni-Ti under different phase</th>
<th>Transformation Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transformation Temperature</td>
<td>-210 to 110°C</td>
</tr>
<tr>
<td>Hysteresis</td>
<td>30 to 50°C</td>
</tr>
</tbody>
</table>
### Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Melting Point</td>
<td>1300 °C</td>
</tr>
<tr>
<td>Density</td>
<td>6.45 g/cm³</td>
</tr>
<tr>
<td>Thermal Conductivity</td>
<td></td>
</tr>
<tr>
<td>Austenite</td>
<td>0.18 W·cm⁻¹·°C⁻¹</td>
</tr>
<tr>
<td>Martensite</td>
<td>0.086 cm⁻¹·°C⁻¹</td>
</tr>
</tbody>
</table>

### Electrical and Magnetic Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistivity (austenite)</td>
<td>approx. 100 µΩ·cm⁻¹</td>
</tr>
<tr>
<td>Resistivity (martensite)</td>
<td>approx. 80 µΩ·cm⁻¹</td>
</tr>
<tr>
<td>Magnetic Permeability</td>
<td>&lt; 1.002 H/m</td>
</tr>
<tr>
<td>Magnetic Susceptibility</td>
<td>3.0x10⁻⁹ emu g⁻¹</td>
</tr>
</tbody>
</table>

### Mechanical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Young's Modulus (austenite)</td>
<td>approx. 83 GPa</td>
</tr>
<tr>
<td>Young's Modulus (martensite)</td>
<td>28-41 GPa</td>
</tr>
<tr>
<td>Yield Strength (austenite)</td>
<td>195 to 690 MPa</td>
</tr>
<tr>
<td>Yield Strength (martensite)</td>
<td>70 to 140 MPa</td>
</tr>
<tr>
<td>Poisson's Ratio</td>
<td>0.33</td>
</tr>
</tbody>
</table>

#### 2.3 Shape Memory Effect

Shape Memory Effect (SME) is the ability to remember a predetermined shape even after several deformations in shape memory materials. In addition to common shape change
effects such as elastic and plastic deformations, as well as thermal expansion and contraction, shape memory alloys also show three key effects depending on the temperature variation that are mainly attributed to martensite phase transformation, which are One Way Shape Memory Effect, Two Way Shape Memory Effect and pseudoelasticity.

1) One Way Shape Memory Effect.

After the removal of an external force, the material shows permanent deformation. It can recover its original shape upon heating. Subsequent cooling does not change the shape unless it is stressed again.

2) Two Way Shape Memory Effect.

In addition to the one way effect, shape change occurs upon cooling and without the applying of external stress.

3) Pseudoelasticity

Mechanical loading at temperatures beyond $A_f$ stretches the alloy and upon unloading, it reverts to its initial shape. No thermal process is involved.

The characteristics associated with these three behaviors are presented below, and the various strain mechanisms behind these effects are demonstrated using simplified 2-dimensional crystal structure models and stress-strain-temperature curves.
2.3.1 One Way Shape Memory Effect

One Way Shape Memory Effect (OWSME) is the basis form of SME. The shape recovery and the high forces are enables in the phase transformation, which is shown in Figure 2.10.

![Diagram of One Way Shape Memory Effect](image)

Figure 2.10 One Way Shape Memory Effect: (a) Martensite, (b) Loaded and deformed in martensite phase, (c) Heated above $A_s$, (d) Cooling to martensite[11, 29].

The One Way Shape Memory Effect of shape memory alloy is depicted in Figure 2.10 and Figure 2.11.
Based on the 2D model of Figure 2.10, it can be seen that as the temperature of the austenite decreases, martensite begins to form. Note that no shape change occurs during cooling (also depicted as stage 4 both in Figure 2.11 and Figure 2.12). The martensite in
this form is said to be `twinned' with each layer separated by a twinning boundary [4]. Loading external stress to the martensite will result in stage 1 in both Figure 2.11 and Figure 2.12. Martensite in this state is said to be `detwinned'. Martensite in this state is highly malleable and has a very low elastic limit to easy change the shape.[7]

Further stressing causes unrecoverable strain up to fracture [7]. With relaxation in the recoverable strain range, depicted as stage 2 in Figure 2.11 and Figure 2.12, the alloy maintains the deformed shape.

By heating the deformed martensite beyond A$_s$, the austenite start temperature, austenite begins to form and the material begins to contract in the stage 3 shown in Figure 2.12. Full shape recovery can be achieved by heating above A$_f$, where the alloy is completely in the austenite phase again. As this shape recovery only occurs in one direction, it is referred to as the OWSME. This effect can be repeated over many cycles following the process in Figure 2.10. It can also be observed that a large hysteresis loop exists in this phenomenon [7][10].

2.3.2 Two Way Shape Memory Effect

The mechanism of SME described above, only the shape of the austenitic phase is remembered. However, it is possible to remember the shape of the martensite phase under certain condition. This behavior is a common property of shape memory alloy; it is called Two Way Shape Memory Effect (TWSME), in contrast to the OWSME [12].
Two Way Shape Memory Effect is not intrinsic property (as the OWSME) to shape memory alloy, but it can be exhibited after specifically thermo-mechanical treatments known as training, so it is also called reversible shape change [7]. The TWSME refers to the reversible shape change of materials with thermal cycling both heating and cooling without requiring any external load. The first report of TWSME is due to Delay, then to Wang and Buehler for a Ni-Ti alloy [29]. A schematic representation of the macroscopic observed behavior is reported in Figure 2.14 and Figure 2.15 [7][29].
The TWSME is less pronounced than the one way effect and usually requires training. This results in the direct transformations between austenite and detwinned martensite is in Figure 2.15. It can also be described using the curves located only in the strain-
temperature plane, as shown in Figure 2.15. Hysteresis is also prominent in the TWSME. Shape memory alloys can be trained to exhibit the TWSME using two methods, which are spontaneous and external load-assisted induction [10]. However, the shape change obtained is in practice less than that of the one way effect.

2.3.3 Pseudoelasticity

When a closed loop originates from a stress-induced transformation upon loading and the reverse transformation upon unloading, it is called super-elasticity. With a contrast, if it occurs by the reversible movement of twin boundaries in the martensitic state, it is called rubber-like behavior [15].

Stress makes martensite form if the alloy is in the austenite phase and an external stress is applied [7]. If the stress is removed, the material reverts back into austenite. This effect is known as pseudoelasticity (SE) [7].

Figure 2.16 and Figure 2.17 presents the 2D model curve of and the stress-strain-temperature in pseudoelasticity of shape memory alloys.
There is no temperature change required for pseudoelastic behavior. The strain characteristic can be described using only the stress-strain plane of Figure 2.17. By applying external stress above $A_f$, the austenite initially behaves in an elastic manner followed by a plateau in which highly nonlinear deformation occurs up to a virtual yield.
limit. Upon unloading, the curve returns via the lower hysteresis loop for complete strain recovery [7][14].

2.3.4 Summary

From the description above, the characteristic of shape memory effect is showing in the Table 2.5. It is easy to change the shape in one way shape memory effect and two way shape memory effect while it is very rigid in the pseudoelasticity. And there is no shape change from heating statement to cooling statement in the OWSME and pseudoelasticity.

Table 2.5 Summary of SME in the different situations.

<table>
<thead>
<tr>
<th></th>
<th>Original</th>
<th>Loading</th>
<th>Unloading</th>
<th>Heating</th>
<th>Cooling</th>
</tr>
</thead>
<tbody>
<tr>
<td>One way shape memory effect</td>
<td></td>
<td>▲</td>
<td>▲</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two way shape memory effect</td>
<td></td>
<td></td>
<td></td>
<td>▲</td>
<td>▲</td>
</tr>
<tr>
<td>Pseudoelasticity</td>
<td></td>
<td></td>
<td>▲</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

2.4 Stress and Temperature

In addition, we can find the stress and the temperature are linear in the shape memory alloy both in martensite phase and austenite phase which is shown in Figure 2.18.
Shape Memory Alloys Stress-Temperature Phase Schematic Diagram:

The plateau region is a result of the formation of stress-induced martensite from austenite. External stress on the material increases the phase transformation temperatures [13]. This relationship is fairly linear, as can be seen in Figure 2.18, although \( A_s \) and \( A_f \) behave nonlinearly at low stress levels.

This stress dependence of the four transformation temperatures can be approximately represented as:

\[
\frac{d\sigma}{dT} = \frac{1}{c_m} \\
T(\sigma) = c_m \sigma + T_0
\]  \hspace{1cm} (2.3) \hspace{1cm} (2.4)

where \( 1/cm \) is the stress rate; \( T(\sigma) \) is the stress dependent transformation temperature; \( T_0 \) is the zero stress transformation temperature [13].
Stress-Temperature Schematic Diagram In SME and Pseudoelasticity:

![Schematic Diagram](image)

Figure 2.19 Schematic diagram representing SME and SE in temperature–stress [30].

It can be noted the critical stress for the case of a high critical stress (red line) and low critical stress (blue line) [30].
CHAPTER III

LITERATURE OVERVIEW OF EXISTING
APPLICATION AND MODELING

In this Chapter, the literature review reveals the history of shape memory alloy in application and modeling. In section 3.1, an overview of the application areas for shape memory alloy are presented. Section 3.2 presents the application in biomedical fields, actuator design and aerospace. In section 3.3 we introduce some typical models, especially Kuribayashi's model, Tanaka thermo-mechanical law, and Liang's model. Finally we summarize the advantage and limitations of the shape memory alloy's character in the practical applications.

3.1 Overview

The discovery history of shape memory has been demonstrated fully in the section 2.1. According to [7] and [10], the applications of shape memory alloys include the following major areas:

1) Medical applications, which include endovascular medical applications and orthodontic applications, medical stents, implants and arterial clips [16, 18, 19].
Although more costly than stainless steel, Ni-Ti alloys, which is biocompatible and can be manufactured to provide body temperature response and shape changes, proves to be more attractive for medical applications [16].

2) Thermo-mechanical. Simple applications involving shape memory change, such as thermo mechanical couplings and sealing [18].

3) Aerospace application. The construction of space device platforms and self-unfolding devices used by rapid development of astronautics in the USSR and USA [10].

4) Temperature-sensitive and dynamic applications.

5) Dynamic applications of shape memory alloys as actuators which is still active and growing since there are many advantages in the research stage [19,20,21,22,23].

Actuator applications of shape memory alloy include linear actuators, micro-switches, micro-valves, robotic grippers, vibration control and active damping of structures, medical endoscopes and micro-electro-mechanical systems (MEMS) according to [7].

3.2 Shape Memory Alloy Application Design Review

3.2.1 Medical Applications of Shape Memory Alloys

The main objectives of biomedical engineering are design, development and use of materials, devices, equipment and techniques for diagnosis, treatment and rehabilitation of the patients, among these, the shape memory alloys have a good applicability. In particular, due to good biocompatibility, cardiovascular applications in Figure 3.1,
orthopedic applications in Figure 3.2 and other surgical applications. These two biomedical fields in which Nitinol shape memory alloy have employed extensively and successfully in surgical applications.

Figure 3.1 Shape memory self-expanding stents in cardiovascular applications [40].

Figure 3.2 Shape memory alloy rod in orthopedic applications [39].
3.2.2 Actuator Designs

Researchers started to use shape memory alloy actuators for robotic and control applications steadily in the 1980s. Most of the actuator applications involve the use of long, straight shape memory alloy wires, including those reported in [41, 42] (Likhachev et al. 1994); others use shape memory alloy coils or springs in their research to achieve larger displacements compared to shape memory alloy wires [43, 44] (Bergamasco et al. 1989).

![Shape memory alloy hinge](image)

Figure 3.3 Shape memory alloy hinge.

Linear motion actuator shown in Figure 3.3 is a shape memory alloy hinge. From the transport position, intermediate potion to final position, shape memory alloy make the hinge change the position via temperature change (from Likhachev et al. 1994).
Another example in Figure 3.4, based on Bergamasco et al. (from Bergamasco et al. 1989), shows a direct-drive robotic actuator. The joint can rotate back and forth by heating two Nitinol springs alternately. A cooling liquid was used to improve the limited bandwidth of shape memory alloys, and similar concepts have been used in many other actuators [7].

3.2.3 Aerospace Applications

In the 1960's, Nitinol sheets and rods had been considered to unfurl satellite antennas upon exposure to solar heating, see Figure 3.5 and Figure 3.6.
Figure 3.5 Shape memory alloy satellite antenna (from Gandhi and Thompson 1992).

Figure 3.6 SMA satellite antenna.

Figure 3.6 shows another simple shape memory alloy satellite antenna made of Nitinol wire, which was designed and tested in China (from Yang et al. 1985).
3.2.4 Energy Harvesting Device

In a recent patent application, it has been proposed to use shape memory alloy to deform mechanical components so that the work caused by the deformation can be harvested and used for other purposes [45][50][51][52]. However, this patent application neglects the use of shape memory alloy for creating electrical potential energy.

Another patent application has proposed the use of shape memory alloy to drive mechanical beams with attached piezoelectric elements. The stress and strain of the shape memory alloy creates motion of the beam which is converted to electrical energy through an electro-active generator. The electric energy is then stored in batteries for later use [46].

Here we propose and demonstrate that wasted heat energy can be converted to mechanical energy using shape memory alloys and then store them as electrical energy for future use.

3.3 Modeling Review

In order to simulate these behaviors, there are many constitutive models that have been proposed to describe and explain the thermo-mechanical behavior and the hysteresis effects of shape memory alloys.

<table>
<thead>
<tr>
<th>Constitutive model</th>
<th>Author</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenomenological models based on</td>
<td>Kuribayashi [24]</td>
<td>1986</td>
</tr>
<tr>
<td>Description</td>
<td>Author(s)</td>
<td>Year</td>
</tr>
<tr>
<td>----------------------------------------------------------------------------</td>
<td>-----------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td></td>
<td>Liang and Rogers [26]</td>
<td>1990</td>
</tr>
<tr>
<td></td>
<td>Brinson [27]</td>
<td>1993</td>
</tr>
<tr>
<td>A theory of non-equilibrium thermostatics</td>
<td>Cory and McNichol [31]</td>
<td>1985</td>
</tr>
<tr>
<td>Models derived from a special free energy formulation</td>
<td>Richter, Frank; Kastner, Oliver; Eggeler, Gunther (Achenbach-Müller) [32]</td>
<td>1985</td>
</tr>
<tr>
<td></td>
<td>Leclercq and Lexcellent [33]</td>
<td>1996</td>
</tr>
<tr>
<td>Models based on thermodynamic laws</td>
<td>Ortin and Planes [34]</td>
<td>1991</td>
</tr>
<tr>
<td></td>
<td>Moumniand Nguyen</td>
<td>1996</td>
</tr>
<tr>
<td>Constitutive laws based on a model for hysteresis</td>
<td>E.g. Preisach model [35]</td>
<td>1938</td>
</tr>
<tr>
<td></td>
<td>Bhattacharya and James [38]</td>
<td>1996</td>
</tr>
<tr>
<td>Models derived from the deformation of crystal structure during phase transformation</td>
<td>Falk</td>
<td>1989</td>
</tr>
<tr>
<td></td>
<td>Fischer and Tanaka</td>
<td>1992</td>
</tr>
</tbody>
</table>
So far, most of these models are phenomenological models which are based on the input-output relationship of shape memory alloys. They are explained by martensite transformation, strain and temperature. Phenomenological models are widely used because they avoid parameters that are difficult to measure, such as free energy, and they use clearly defined engineering material constants.

3.3.1 Kuribayashi’s Model

Kuribayashi observed a linear relationship between very small variations in the force and strain of a shape memory alloy wire in his experiments. Under constant strain, the relationship between the force and supplied voltage was also observed to be approximately linear [24].

Hence, the following static mathematical model can be obtained by considering the small variations of force, voltage and strain as Δf, Δu and Δx respectively:

$$\Delta f = \alpha_0 \Delta u + \beta_0 \Delta x$$

where $\alpha_0$ and $\beta_0$ are gain constants.

Equation 3.1 can be regarded as the steady state of a dynamic system. Kuribayashi presented a dynamic model by adding first order terms $G(s)$ and $H(s)$ in the Laplace domain as follows:

$$\Delta f(s) = \alpha_0 G(s) \Delta u(s) + \beta_0 H(s) \Delta x(s)$$

(3.2)
The above force model resulted in a summation of two first-order terms with different time constants, and Kuribayashi extended it to a position model by considering the shape memory alloy plant as a mass-damper system [7].

3.3.2 Tanaka Thermo-mechanical Law

Tanaka (1985) [25] proposed a thermo-mechanical law that governs the stress-strain behavior of the shape memory alloys. He assumed that the thermo-mechanical behavior of shape memory alloy can be fully described by three state variables: strain, temperature and martensite fraction. And he proposed the following governing constitutive relation in the rate form:

\[ \dot{\sigma} = D \dot{\epsilon} + \Theta \dot{T} + \Omega \dot{\xi} \]  

(3.3)

where \( \sigma \) is the Piola-Kirchhoff stress, \( \epsilon \) is the Green strain, \( T \) is the temperature, and \( \xi \) the martensite ratio. The material parameters \( D \) is the Young's modulus, \( \Theta \) is the coefficient of thermal expansion and \( \Omega \) is metallurgical quantity. In general, \( D \), \( \Theta \) and \( \Omega \) are functions of \( \epsilon \), \( T \) and \( \xi \), but Tanaka assumed them to be constant. According to [47], the phase transformation kinetics law is the most critical part of the model as it defines the hysteresis behavior of the material. Tanaka proposed the following exponential functions relating martensite ratio to stress and temperature to describe the transformation kinetics.

The martensite ratio \( \xi \) is an internal variable used to account for the phase change of shape memory alloys, and is dependent on the applied stress and temperature. It is the ratio of martensite to austenite varying from complete martensite, \( \xi = 1 \), to complete austenite, \( \xi = 0 \). During the heating process,
\[ \xi_{M \rightarrow A} = e^{[A_s(T-A_s)+B_s\sigma]} \] (3.4)

And for the cooling process,

\[ \xi_{A \rightarrow M} = 1 - e^{[A_m(T-M_f)+B_m\sigma]} \] (3.5)

where \( A_s, A_m, B_s \) and \( B_m \) are material constants in terms of transition temperatures, \( A_s, A_f, M_s \) and \( M_f \).

As is typically in metallurgy, a transformation is regarded as complete when \( \xi_M \) or \( \xi_A \) are 0.99. Substituting this value and its corresponding temperature into Equation 3.4 and Equation 3.5, the constants \( A_m \) and \( A_a \) can be expressed as

\[ A_m = -2\ln10/(M_s-M_f) \] (3.6)

\[ A_a = -2\ln10/(A_f-A_s) \] (3.7)

The constants \( B_m \) and \( B_a \) can be expressed as

\[ B_m = \frac{A_m}{C_m} \] (3.8)
\[ B_u = \frac{A_u}{C_u} \]  \hspace{1cm} (3.9)

where \( C_a \) and \( C_m \) represent the slopes defined in Figure 3.7, i.e.

\[ C_m = \tan \alpha \]  \hspace{1cm} (3.10)

\[ C_a = \tan \beta \]  \hspace{1cm} (3.11)

Tanaka's model is simple and based on material parameters that can be measured easily. Such as temperature and martensite ratio. It has been used in a variety of studies (Tanaka et al. 1995).

3.3.3 Liang's Model

Liang and Rogers [26], Brinson [27] and Elahinia [28] improved upon Tanaka's model using different transformation kinetic equations relating the martensite fraction to the stress and temperature.

Liang (1990) assumed \( D, \Theta \) and \( \Omega \) to be constants. Hence Equation 3.3 can be integrated to give

\[ \sigma - \sigma_0 = D(\varepsilon - \varepsilon_0) + \Theta(T - T_0) + \Omega(\xi^M - \xi^M_0) \]  \hspace{1cm} (3.12)

where \((\sigma_0, \varepsilon_0, T_0 \text{ and } \xi_0)\) represent the initial states of the material.

Liang assumed \( \xi^M \) to be a cosine function, and hence the transformation from austenite to martensite could be described by

\[ \xi^{A \rightarrow M} = \frac{1 - \xi_0}{2} \cos[A_m(T - M_f^0 - \frac{\sigma}{C_m})] + \frac{1 + \xi_0}{2} \]  \hspace{1cm} (3.13)

where
\[ C_m (T - M_s^0) < \sigma < C_m (T - M_f^0) \]  

(3.14)

While the reverse transformation is described by

\[ \xi^{M \rightarrow A} = \frac{\xi_0}{2} \cos[A_a (T - A_f^0 - \frac{\sigma}{C_a})] + \frac{\xi_0}{2} \]  

(3.15)

where

\[ C_a (T - A_f^0) < \sigma < C_a (T - A_f^0) \]  

(3.16)

where \( A_m \) and \( A_a \) are given by

\[ A_m = \frac{\pi}{(M_s^0 - M_f^0)} \]  

(3.17)

\[ A_a = \frac{\pi}{(A_f^0 - A_f^0)} \]  

(3.18)

and \( C_m \) and \( C_a \) are the same as in Tanaka’s model (\( C_m = \tan \alpha \) & \( C_a = \tan \beta \)).

3.4 Advantages and Limits

3.4.1 Advantages

According to [7], the advantages of using shape memory alloys are:

1. Clean and silent operation, since shape memory alloys do not require friction mechanisms [7], so it avoids the dust particles, sparks and noise which make shape memory alloys very suitable for a clean energy harvesting material.

2. High power-to-weight ratio. Ikuta [49] pointed out that shape memory alloy give the highest power to weight ratio compared to different types of other material technologies.
This property makes shape memory alloy highly attractive for many different miniature applications.

3. Mechanical simplicity. A shape memory alloy only uses the shape recovery of the alloy and it can be shape changed directly via Joule heating and electrical current [7].

3.4.2 Limitations

Despite the above advantages, shape memory alloys materials are not free from limitations and drawbacks [7].

1. Low energy efficiency. The maximum theoretical efficiency of SMAs is of the order of 10% based on the Carnot cycle, according to [50]. In reality, the efficiency is often less than 1%, this means that the conversion of heat into mechanical work is very inefficient.

2. Low repeatability. The reliability of shape memory material depends on a couple of factors which are maximum temperature, stress, strain and so on. So care should be taken to prevent overheating and overstressing of the Ni-Ti alloys for long durations.

3. Slowly speed. Shape memory alloys have generally been considered to have slow response due to restrictions in heating and cooling, and also due to the inherent thermal hysteresis.
CHAPTER IV

PHENOMENOLOGICAL MODEL

Kuribayashi's, Tanaka's and Liang's models have been introduced in Chapter 3 as the typically phenomenological model. During the report of this thesis, an approach was developed which uses the same state variables as Liang's model which includes thermal expansion, strain components and constitutive equation. And finally, Graesser's and Cozzarelli's Model was simulated.

4.1 Thermal Expansion

From the thermo-mechanical law proposed by Tanaka [25] that governs the stress-strain behavior of the shape memory alloys as following,

\[ \dot{\sigma} = D\dot{\varepsilon} + \Theta \dot{T} + \Omega \dot{\xi} \]  

(4.1)

where \( \sigma \) is the stress, \( \varepsilon \) is the strain, \( T \) is the temperature, and \( \xi \) is the martensite ratio. It is the ratio of martensite to austenite varying from complete martensite, \( \xi = 1 \), to complete austenite, \( \xi = 0 \). The parameter \( D \) is the Young's modulus, \( \Theta \) is the coefficient of thermal expansion and \( \Omega \) is metallurgical quantity.
In general, $D$, $\Theta$ and $\Omega$ are functions of $\varepsilon$, $T$ and $\xi$, but here we assumed they constant (from Tanaka) \cite{25}.

4.2 Strain Components

We consider the total strain

$$\varepsilon = \varepsilon^e + \varepsilon^t$$ \hspace{1cm} (4.2)

where $\varepsilon^e$ is the elastic strain and $\varepsilon^t$ is the transformation strain.

From the definition of Young’s Modulus $D$,

$$\varepsilon^e = \frac{\sigma}{D}$$ \hspace{1cm} (4.3)

Also,

$$\varepsilon^t = \varepsilon_{max}^t \times \xi$$ \hspace{1cm} (4.4)

where $\varepsilon_{max}^t$ is the maximum transformation strain.

4.3 Constitutive Equation

Integrated by equation 4.1, could get

$$\sigma - \sigma_0 = D(\varepsilon - \varepsilon_0) + \Theta(T - T_0) + \Omega(\xi - \xi_0)$$ \hspace{1cm} (4.5)

where ($\sigma_0, \varepsilon_0, T_0$ and $\xi_0$) represent the initial states of the shape memory alloys. $D$, $\Theta$ and $\Omega$ are assuming to be constant. And we assume that shape memory alloy are heated to the high temperature and cooled down under zero stress, so initial conditions to be zeros, $\sigma_0 = \varepsilon_0 = T_0 = \xi_0 = 0$. Equation 4.5 becomes

$$\sigma = D\varepsilon + \Theta T + \Omega \xi$$ \hspace{1cm} (4.6)
During the test, $\sigma$ is increased until the full detwinned martensite $\xi = 1$, and the Young's modulus $D = 28\text{GPa}$ in martensite phase from Table2.4. And the thermal expansion coefficient $\Theta$ is $6.6\times10^{-6}/\degree\text{C}$ in martensite phase [53], $\varepsilon$ is 4% to 8%. We obtain

$$\sigma = 28 \times 10^3 \times 4\% + 6.6 \times 10^{-6}T + \Omega$$

(4.7)

According to [49], if we pick $\varepsilon = 6.7\%$, the result of $\Omega$ is -1.893GPa.

4.4 Graesser and Cozzarelli's Model [51]

This model is based on the modified plasticity models. The one dimensional stress and strain are related by the following rate equation which contains a potential hardening:

$$\dot{\sigma} = E \left[ \dot{\varepsilon} - |\dot{\varepsilon}| \left( \frac{\sigma - \beta}{Y - kf_r} \right) \right]$$

(4.8)

where

$$\beta = E \alpha \left[ \varepsilon - \frac{\sigma}{E} + f_r \right] \text{erf} (a\varepsilon)$$

(4.9)

is the one-dimensional backstress and $(Y-kf_r)$ is the critical stress.

The error function is

$$\text{erf} (x) = \frac{2}{\sqrt{\pi}} \int_0^x e^{-t^2} \, dt$$

(4.10)

All other symbols represent parameters that are material constants. We use one set of material constants given in Graesser and Cozzarclli, and one set of corresponding strain

$$\varepsilon = 0.016 \sin t$$

(4.11)
and other constants [52] are

\[
E = 196\text{GPa} \\
Y = 207\text{MPa} \\
\alpha = 0.0197 \\
k = 3.84\text{GPa} \\
n = 3 \\
a = 2500 \\
c = 0.001 \\
f_r = 0.04
\]

The stress-strain relationship appears linear at small strains which are shown in Figure 4.1, and the stress-time curve is shown in Figure 4.2.

![Stress-strain curve](image)

**Figure 4.1** The curve of stress-strain in Graesser and Cozzarelli’s Model ($\varepsilon = 0.016\sin t$)
Figure 4.2 The curve of stress-time in Graesser and Cozzarelli's Model ($\varepsilon = 0.016 \sin t$)

But under very small strains, this model does not reproduce a linear stress-strain relationship. For example, when the prescribed strain is $\varepsilon = 0.0015 \sin t$, the stress-strain relationship exhibits hysteresis as shown in Figure 4.3 and the stress-time curve is shown in Figure 4.4.
Figure 4.3 The curve exhibits hysteresis in Graesser and Cozzarelli's Model

Figure 4.4 The curve of stress-time with small strain in Graesser and Cozzarelli's Model
In this Chapter, we will investigate the possibility of shape memory alloy having efficiency and detectable responses when subjected to cyclic heating and cooling, especially the process of heating. In section 5.1, the introduction shows the general idea of the energy harvesting device. The experimental setup is described in section 5.2. The data collection of position, temperature and voltage will be investigated in section 5.3. At the end of this section, the open loop control system analysis will be provided.

5.1 Introduction

There have been some discussions over the years as to whether shape memory alloys can respond very efficiently to temperature [49] [50] [51]. As noted in the literature review of Chapter 2, researchers have attempted to improve upon the controllable property of SMA applications. Some of the results are quite significant, especially in the small or micro-actuator scale.
The investigation involves resistively heating Ni-Ti alloy SMA wires using a heat gun to make the temperature increase. The mechanical response is detected by connecting the SMA wire to a generator and measuring the captured energy.

In the following section, the experimental setup as well as the experimental procedures will be described. The results of the experiments, both single wire and spring wire, are presented in Chapter 6.

5.2 Experimental Setup

The objective is to design an experiment that distinguishes between the shape memory effect and normal thermal expansion. There are mainly two parts for this design: mechanical part and electrical. The left of the design in the following Figure 5.1, is the mechanical which shows the shape memory alloy wire which is placed inside of the housing. A heat gun blows hot air through the hole on the bottom support. One side of the SMA wire is attached on the shaft which goes though the housing using a bearing, while the other side is attached on the top of the inner housing. Next, the SMA wire material is tightened around the shaft. We use the coupling connecting the shaft and the motor which is shown in Figure 5.1.
Figure 5.1 The device setup for the energy harvesting.

Figure 5.2 Details inside of the housing.
From Figure 5.2 and Figure 5.3 we could see more details of the inner housing and the devices for detecting the position of the variable length of the shape memory alloy. We use the Hall Effect Sensor to detect the rotation of the shaft during the thermal process. It is shown in the Figure 5.2 and Figure 5.5.

![Figure 5.3 The device used in the experiment.](image)

5.3 Data Collection

5.3.1 Position

1 Hall Effect Sensor

Hall Effect Sensors can be used to detect magnetic flux density and are applied in both movement and position sensing. This transducer varies its output voltage in response to a magnetic field. The output voltage is proportional to the magnetic flux. The greater the magnetic flux density, the higher the voltage output will be. In this thesis, an A1321 Hall Effect Sensor is used (Figure 5.4).
In this experiment, the magnet is fixed to a certain place on one side of the shaft (Figure 5.5). When the shaft rotates during the thermal process, the magnet gets close to the Hall Effect Sensor. This is interpreted as a position change from the output voltage indicated by the Hall Effect Sensor.
2 RC Low Pass Filter

A low pass filter was added after the output of the Hall Effect Sensor in order to block the high frequency components, such as the 60 Hz noise. A passive low pass filter is used in the experiment since no power supply is needed. The values of resistance (R) and capacitance (C) are determined from the cutoff frequency. 10Hz cutoff frequency ($f_{\text{cutoff}}$) is needed in this experiment. The low pass filter transfer function is:

$$H(s) = \frac{V_{\text{out}}(s)}{V_{\text{in}}(s)} = \frac{1}{CR} = \frac{1}{RCs + 1}$$

(5.1)

$$f_{\text{cutoff}} = \frac{1}{2\pi RC}$$

(5.2)

Choice of $R = 1k\Omega$, so yields $C = 15\mu F$. Note the reduction in noise from the input signal ($V_{\text{in}}$) compared to the output signal ($V_{\text{out}}$), Figure 5.6.

Figure 5.6 Testing for RC low pass filter, the top signal is the original signal ($V_{\text{in}}$), and bottom one is the signal after the low pass filter ($V_{\text{out}}$).
3 Operational-Amplifiers

The response of the harvesting devices in the experiment is not high; that requires amplifying the signal for easy detecting.

Figure 5.7 LM324 chip (Left) used in the inverting amplifier design (Right).

LM324 operational amplifier consists of four independent high-gain frequency compensated amplifiers that are designed specifically to operate from a single supply over a wide range of voltages. (Figure 5.7, right). The gain of an inverting op-amp (Figure 5.7, right) is given by

\[
gain = \frac{V_{out}}{V_{in}} = \frac{R_f}{R}
\]

(5.3)

where \(R_f = 20 \text{ K}\Omega\), the gain is 10 which is shown in the following Figure 5.9.

The effect of two different values of gain (2 and 10) can be seen in Figure 5.8. Note that the output voltage is the lower signal which is greater in amplitude than the input voltage (top signal) in each case.
Figure 5.8 Test for amplifier with gain is 2 (left) and gain is 10 (right).

Figure 5.9 The circuit for the position detection.
The signal of position detection was captured by Hall Effect Sensor. Then the signal was passed through two passive low pass filters with cutoff frequency 10Hz. Then the amplifiers was designed in the circuit with a gain of 10, which is shown in Figure 5.9. The Figure 5.10 shows the physical implementation of circuit used in the experiment.

5.3.2 Temperature Detection

1 Non-Contact IR Temperature Sensor

Using infrared technology in the experiment, non-contact sensors was used for temperature measurement of the SMA housing, shown in Figure 5.11. The IR temperature sensor was mounted within a Lexan support that was placed atop the SMA housing to measure the temperature increase imparted by the heat gun.
Figure 5.11 Temperature sensor powered via PC is used in the experiment.

2 Heat Gun

A heat gun (Figure 5.12) was used to emit a stream of hot air instead at temperatures between 0°C to 150°C. This was used to heat the SMA to cause rotation of the shaft connected to the generator.

Figure 5.12 Heat gun.

5.3.3 Voltage Measurement of the Generator

1 Generator

The generator used in this experiment was a DC motor (Figure 5.13). When the SMA was heated to spin the motor, electricity was generated through the back-electromotive force.
2 Open loop System Analysis of SMA Energy Harvesting System

A representation of the energy harvesting system (Figure 5.14) shows that when a heat source is applied, the SMA, which is wound around the shaft, contracts. This causes the shaft to rotate which spins the generator. The electric current created from this rotation then yields a voltage that can be harvested ($V_o$).

![Figure 5.14 Schematic diagram of the energy harvesting system.](image)
3. Transfer function of the Electro-mechanical System

For the mechanical part of the energy harvesting system, we can get the relationship between the angle $\Theta(t)$ and the generator's back-electromotive voltage $e_a(t)$:

$$e_a(t) = k_e \dot{\Theta}(t)$$  \hspace{1cm} (5.4)

where $k_e$ is a constant.

The Laplace transformation of Equation 5.4 is,

$$E_a(s) = k_e s \theta(s)$$  \hspace{1cm} (5.5)

And for the electrical part of the energy harvesting system, the output voltage of this circuit is the capacitor voltage $V_o$, so

$$v_o(t) = v_c(t) = \frac{1}{C} \int i_c(t) dt$$  \hspace{1cm} (5.6)

The Laplace transform of Equation 5.6 leads to

$$V_o(s) = \frac{I_o(s)}{Cs}$$  \hspace{1cm} (5.7)

According the Kirchhoff's laws, we could get

$$L \frac{di}{dt} + Ri(t) + \frac{1}{C} \int idt = e_a(t)$$  \hspace{1cm} (5.8)

R, C, L are resistance, capacitance and inductance, respectively.

The Laplace transform of Equation 5.8 leads to

$$I_o(s)[Ls + R + \frac{1}{Cs}] = E_a(s)$$  \hspace{1cm} (5.9)

Substituting 5.7 into 5.9 yields

$$CsV_o(s)[Ls + R + \frac{1}{Cs}] = E_a(s)$$  \hspace{1cm} (5.10)
and
\[
\frac{V_o(s)}{E_a(s)} = \frac{1}{CLs^2 + Rs + 1}
\] (5.7)

If we treat \( \theta(t) \) as the input and \( V_o(t) \) as output, we could get the transfer function from equation (5.5) and equation (5.11),
\[
\frac{V_o(s)}{\theta(s)} = k_c \frac{s}{CLs^2 + Rs + 1}
\] (5.8)

4. Analysis of second-order system response [52]

The open loop transfer function of the system shown in Figure 5.1 is
\[
\frac{V_o(s)}{\theta(s)} = \frac{k_c s}{CL} \frac{1}{s^2 + \frac{R}{CL} s + \frac{1}{CL}}
\] (5.9)

\[
= \frac{k_c s}{LC} \frac{1}{\left(s + \frac{R}{2CL} \sqrt{\left(\frac{R}{2CL}\right)^2 - \frac{1}{CL}}\right) \left(s + \frac{R}{2CL} \sqrt{\left(\frac{R}{2CL}\right)^2 + \frac{1}{CL}}\right)}
\] (5.10)

For the transient-response analysis, it is convenient to write
\[
\omega_n^2 = \frac{1}{CL}
\] (5.11)
\[
\sigma = \zeta \omega_n = \frac{R}{2CL}
\] (5.12)
\[
\zeta = \frac{R}{R_c}
\] (5.13)
\[
R_c = 2\sqrt{CL}
\] (5.14)

where \( \sigma \) is the attenuation, \( \omega_n \), the undamped natural frequency, and \( \zeta \) is the damping ratio of the system, which is the ratio of the actual damping \( R \) to the critical damping \( R_c \).
In terms of $\zeta$ and $\omega_n$, the system shown in Figure 5.14 can be written

$$\frac{V_o(s)}{\theta(s)} = \frac{k_c \omega_n^2 s}{s^2 + 2\zeta \omega_n s + \omega_n^2} \quad (5.15)$$

Thus, the dynamic behavior of the second-order system can be described in terms of two system parameters $\zeta$ and $\omega_n$. We shall consider three different cases: the underdamped, critically damped, and overdamped cases.

From Equation 5.12, is clear that there is one zero at the origin (a differentiator). There are two poles in this system as well.

Zeros: $s = 0$

Poles: $s = \frac{-RC \pm \sqrt{(RC)^2 - 4CL}}{2LC}$

1) Underdamped Case ($0 < \zeta < 1$)

$$\Delta = (RC)^2 - 4CL < 0 \quad (5.20)$$

$$\frac{V_o(s)}{\theta(s)} = \frac{k_c \omega_n^2 s}{(s + \zeta \omega_n)(s + \zeta \omega_n - j\omega_d)} \quad (5.16)$$

where $\omega_d = \omega_n \sqrt{1-\zeta^2}$ is the damped natural frequency.

In this case, the response is fast but it is also has ringing. This system will be stable, and it has some overshoot.

2) Critically damped Case ($\zeta = 1$)

$$\Delta = (RC)^2 - 4CL = 0 \quad (5.17)$$

If the two poles of transfer function are equal, the system is said to be critically damped.

In this case, the pole is $-\frac{R}{2L}$, as the pole is in the left half plane, the system is stable.
Depending on the criteria of the system settling time, we can choose the value of \( -\frac{R}{2L} \) as a fastest response without oscillations.

(3) Overdamped Case \((\zeta > 1)\)

\[
\Delta = (RC)^2 - 4CL > 0 \quad (5.18)
\]

In this case, the two poles of transfer function are real and unequal. The poles are still in the left plane for any values for C, L and R, but it will have a slow response.

Above all, case (2) is the best case; however, the physical system response will resemble an overdamped case.
In section 6.1 and 6.2, two different SMA samples will be used to perform experiments.

The first sample is the shape memory alloy single wire which shows one way shape memory effect and the second sample is the shape memory alloy spring wire which shows two way shape memory effect.

In the section 6.3, two potential recycling energy harvesting ideas will be shown.

In the section 6.4, the shape memory alloy energy harvesting application will be covered.

6.1 The Shape Memory Alloy in Single Wire

The diameter of this single SMA sample is 0.0297 inches (Figure 6.1).

Figure 6.1 SMA single wire.
Figure 6.2 shows the temperature, position and voltage during the thermal process. The temperature range of the SMA housing is from room temperature (24°C) to 60°C which changed within 80 seconds. The position ranges 0 to 0.6 radian, and reaches the peak value at the 60 seconds, with corresponding temperature 52°C. The peak value 0.08V was mostly generated during the first 25 seconds. That means during the temperature range of 24°C - 40°C in this sample, the SMA device could generate the energy, however, beyond that range, very little energy was generated.

Figure 6.2 The voltage generated via shape memory alloy single wire in the experiment.

6.2 Shape Memory Alloy in Spring Wire

For the spring wire sample (Figure 6.3), the SMA housing temperature was changed from room temperature to 34°C. This caused the shaft to rotate 0.98 rad. More energy could be
generated during this process in less time, the absolute value of the voltage reach 0.2 V (Figure 6.4).

Figure 6.3 SMA spring wire.

Figure 6.4 The energy captured via shape memory alloy spring wire in the experiment.

6.3 Potential Recycling Energy Harvesting Ideas

We investigated the property of shape memory alloy in Chapter 2, which shows that of SMA can change with different temperatures via shape memory effect. Heat source is applied to the two way shape memory alloy materials in this experiment.
First notice that the angle of the shaft changed with the temperature shift from 30°C to 40°C. When the temperature increased, the shaft rotated clockwise; otherwise it tends to turn back counterclockwise due to the torsional spring attached to the shaft. Second, the repeatable process could be accomplished in a short time, five times within 80 seconds as shown in Figure 6.5.

With this result, we report two potential ideas of effective energy harvesting devices.

Figure 6.5 Result of experiment via repeatable heat source.

Figure 6.6 The recycling energy harvesting envisage with sustainable heat source.
A closed wire of shape memory alloy could be used as shown on the left of Figure 6.6. When the heat source increase, the temperature in the housing increases. At the same time, the shaft rotates, since the shape memory alloy in the housing contracts. Obviously, the temperature of the housing is lower than the inside. The structure of shape memory wire is expanded via their phase change which was discussed in Chapter 2. In this situation, keeping the temperature difference is required during the experiment to capture sustainable energy.

![Diagram of recycling energy harvesting envisage with repeatable source.](image)

**Figure 6.7** The recycling energy harvesting envisage with repeatable source.

In another embodiment of the energy harvesting devices, the heat source is not continuous in the work interval time span. The temperature could be controlled to go up and down repetitively. As the temperature increases, the shaft rotates in a clockwise direction. However, when the temperature decreases, the shaft rotates in the counterclockwise direction. Because of the torsion spring which creates return motion. It is easy to rotate back in the martensite phase. However, energy would be creating during both directions of processes. Since the polarity of the generated voltage is opposite for
each direction of motion, a diode would be needed to properly store the energy in the future work. With this method, the sustainable energy also could be implemented.

6.4 Results and Discussions

Energy harvesting results have been observed to occur in the phase transformation temperature range of the SMA. This effect is found to be sensitive to thermal processes, and we could capture the energy via conversion from mechanical energy to electrical energy by SMA wire.

From the two different samples, we can detect the amount of energy created by the phase transformation of SMA in the device. The functional temperature range is just from 25 - 40°C roughly. It is not high efficient at present, but there was still some energy captured during the experiment. The amount of the captured energy depends the length of SMA and the different Ni-Ti combinations of the SMA.
In this Chapter, the simulation of the energy harvesting device based on shape memory alloy wire is presented. This simulation is based on the same concept as the design in section 5.2 and section 5.3, but it is designed to avoid the practical difficulties that had been encountered when testing the single wire SMA and spring wire SMA in the Chapter 6.

7.1 Temperature Simulation

From the experiment in section 6.1 and section 6.2, we obtained the plots for the temperature and position. The curve of the temperature is approximately linear, and the range of the temperature and time are 28°C - 58°C and, 5s - 75s, which is shown in Figure 6.2. This was simulated a in Figure 7.1

The slope of this linear line is

\[
k = \frac{\Delta T}{\Delta t} = \frac{30}{70} = 0.43
\]  

(7.1)

Then choose a random point (5, 28) and put into

\[
T - T_0 = k(t - t_0)
\]  

(7.2)
which leads to

\[ T = 0.43t + 25.86 \]  

(7.3)

The temperature range is changed is from a heat up to cooling down cycle (Figure 7.2). And it was assumed that the heating time is shorter than the cooling down time for simulating the real application as shown in Figure 7.2 (a). In this simulation, we just performed the heating up part as shown in Figure 7.2 (b).

Figure 7.1 The temperature simulation for heating up and cooling down.

(a)
Figure 7.2 (a) The temperature changed in the simulation for the future work. (b) The simulation for heating up in the experiment.

7.2 The Position Simulation

There are two ways to simulate the position, which is using Matlab polyfit function and approximating with the exponential equation.

1. Matlab Function

First we are going to use the Matlab function p = polyfit(x,y,n) to find the coefficients of the polynomial p(x) of degree n that can fits this data (Table 7.1).

Choosing n = 4, leads to

\[ pos(t) \approx -0.006t^2 + 0.025t + 0.1167 \]  \tag{7.4}
2. Exponential approximation

\[
\frac{\theta}{T} \approx \frac{1}{\tau s + 1} \quad (7.5)
\]

Assuming the input signal is step signal

\[
T = \frac{1}{s} \quad (7.6)
\]

results in

\[
\theta = \frac{1}{s} \left[ \frac{1}{\tau s + 1} \right] \quad (7.7)
\]

\[
\theta = \frac{1}{s} - \frac{1}{s + \frac{1}{\tau}} \quad (7.8)
\]

\[
\theta(t) = 1 - e^{-\frac{t}{\tau}}. \quad (7.9)
\]

Thus,

\[
\theta(\tau) \approx 1 - e^{-1} = 0.632 \quad (7.10)
\]

Equation 7.9 yields a step response as shown in Figure 7.4. In comparison to the experimental data shown in Figure 7.5, this is clearly a reasonable approximation.

Table 7.1 The data of time and position in the process of experiment.

<table>
<thead>
<tr>
<th>Time(s)</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Position(rad)</td>
<td>0.238</td>
<td>0.312</td>
<td>0.385</td>
<td>0.426</td>
<td>0.460</td>
<td>0.498</td>
<td>0.506</td>
</tr>
<tr>
<td>Time(s)</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>55</td>
<td>60</td>
<td>65</td>
<td>70</td>
</tr>
<tr>
<td>Position(rad)</td>
<td>0.513</td>
<td>0.536</td>
<td>0.538</td>
<td>0.535</td>
<td>0.550</td>
<td>0.550</td>
<td>0.550</td>
</tr>
</tbody>
</table>
Figure 7.3 Position from the workspace in the Simulink.

Figure 7.4 The approximation of position in Matlab.

Figure 7.3 The result from the scope 9 in Figure 7.3.
7.3 The Voltage Captured Simulation.

For small signal detection, errors should be considered in the simulation. To avoid errors and obtain high accuracy simulation results, we select the data from workspace (Figure 7.3) as input position data instead of the approximate position data. Also several low pass filters were used in the simulation for filtering the noise (Figure 7.4). The output of the simulated voltage is depicted in Figure 7.5.

Figure 7.4 The simulation for the voltage capture after several low pass filters in Simulink.

Figure 7.5 The voltage simulation result of scope 2 from Figure 7.4.
7.4 Simulation and Experiment Result Comparison

In this section we will compare the temperature, position and voltage from experiment which are shown in Figure 7.6 and simulation which is shown in Figure 7.7.

![Figure 7.6 The result of temperature, position and voltage could capture from the experiment.](image1)

(a)

(b)
Figure 7.7 The result of temperature, position and voltage could capture from the simulation. (a) Temperature (b) Position (c) Voltage.

A side by side comparison of the voltage predicted by the model to the voltage measured during the experiment shows a very close similarity (Figure 7.7).

Figure 7.8 The voltage contrast from experiment (up) and simulation (down).

From Figure 7.8, it is clear that the model fits the data very well. The error between the simulation and the experimental results is low, on the order of 0.08V which is within the same range of magnitude as the noise in the system. To better understand the error made in the simulation, we analysis the system by calculating the errors with

\[
\text{Error} = \text{Average of } |\text{Voltage from experiment} - \text{Voltage from simulation}|
\]

which is shown in Figure 7.9.
The error calculation is affected by many elements, such as white noise, time delays, 60HZ noise, etc.

7.5 The Energy Capture

The total electric potential energy stored in a capacitor is given by

$$E = \int_0^t pdt = \int_0^t vdt = \int_0^t \frac{dv}{dt} dt = C \int_0^v dv = \frac{1}{2} CV^2$$

(7.10)

where E is the stored energy. This energy is simulated as in Figure 7.10.

Figure 7.10 The simulation for the energy could capture.
From this simulation, we could know the energy we could get from the energy harvesting device via shape memory alloy simulation is $5.5 \times 10^{-5}$ J. This is dependent upon the size of the capacitor, which could be made larger to increase the efficiency of the device.
8.1 Summary of Contributions

In this thesis, the research on energy harvesting via phase transformation of shape memory alloy and the obtained results are documented and discussed. In many energy harvesting applications, weight and sizes can be an issue, shape memory alloy presents a potential solution with their high force-to-weight ratio, mechanical compactness, as well as their clean and silent operation.

Investigation of the response of shape memory alloy single wire and spring wire yielded some interesting results. It was observed that mechanical response of spring wire can be induced even in the 23°C-35°C temperature range. The experimental evidence showed that this is due to the shape memory effect. The results opened the door for the possibility of implementing control systems, which may be able to improve the system response even in the presence of external load inertia. Thus, a large generator could be explored in future work that is controlled either with the application of hot and cold fluids.
To sum up, the research presented in this thesis represents a significant step forward for practical shape memory alloy energy harvesting design.

8.2 Future Work

Even though this work has resulted in practical experiments that can improve the method of clean energy harvesting immensely, there are several future research directions that can be followed.

The force and position model proposed in this thesis is relevant and integral in the design and simulation. Another thing is the underestimation of the shape memory alloy cooling process, which in turn increases the predicted average forces. Further work could be done to obtain better approximations of the shape memory alloy stress or strain under cooling conditions.

All of these have been accomplished with free convection cooling and not in a temperature controlled condition. A closed loop control system could be use in a rapid heating and cooling mechanism.

As mentioned in Chapter 6, both wires we used in the experiments are in a narrow range of wire diameters. It would be interesting to investigate the response behavior of a large range of wire diameters as well as other types of shape memory alloy wires, to see how their responses will compare with the result in this thesis.
REFERENCES


APPENDIX

THE MATLAB CODE FOR GRAESSER AND COZZARELLI'S MODEL

IN STRAIN $\varepsilon = 0.016\sin t$ AND $\varepsilon = 0.0015\sin t$

%% Graesser's and Cozzarella's model main code first part

clc

clear all

% initial conditions and time period

y0=280;

tspan = 0:0.001:10;

% solve ode for sigma_dot

[T,sigma_dot] = ode45(@vdp,tspan,y0,odeset('reltol',1e-6));

% strain at each time step

strain = 0.016*sin(tspan);

% plot the strain vs stress for each time step

figure(1)

plot(strain,sigma_dot,'r')

xlabel('strain')

ylabel('stress')

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% plot the time vs stress for each time step

figure(2)

plot(T,sigma_dot)

xlabel('Time')

ylabel('Stress')

%
Graesser's and Cozzarelli's model code second part

function sigma_dot = vdp(t,sigma)

% syms sigma

% constant values

E=196e9; Y=207e6; f=0.04; sigma_c = Y - k*f; n =3 ; a=2500;
alpha=0.0197; c = 0.001 ;

% time period

% for t=1:10;

strain = 0.016*sin(t);

strain_dot = 0.016*cos(t);

% error function for each x

X=a.*strain;

Error = erf(X);

% one dimensional backstress at each time step

% beta(t) = E*alpha*(strain - sigma/E + f*(abs(strain)^c)).*Error);

% sigma_dot(t) = E.*(strain_dot-abs(strain_dot).*((sigma-beta(t))/sigma_c)^(n-1))*/(sigma-beta(t))/sigma_c);

beta = E*alpha*(strain - sigma/E + f*(abs(strain)^c)).*Error);
\[
\sigma_{\dot{}} = E.*(\text{strain}_{\dot{}}-\text{abs}(\text{strain}_{\dot{}})\times(\text{abs}((\sigma-\beta)/\sigma_c)^{(n-1)})\times((\sigma-\beta)/\sigma_c));
\]

% end

return

%%% Graesser's and Cozzarelli's model main code first part

clear all

% initial conditions and time period

y0=280;
tspan = 0:0.001:10;

% solve ode for \( \sigma_{\dot{}} \)

[T,sigma_dot] = ode45(@vdp,tspan,y0,odeset('reltol',1e-6));

% strain at each time step

strain = 0.0015*sin(tspan);

% plot the strain vs stress for each time step

figure(1)

plot(strain,sigma_dot,'r')

xlabel('strain')
ylabel('stress')

% plot the time vs stress for each time step

figure(2)

plot(T,sigma_dot)

xlabel('Time')
ylabel('Stress')

%% Graesser's and Cozzarelli's model code second part

function sigma_dot = vdp(t,sigma)

% syms sigma

% constant values

E=196e9; Y=207e6; k=3.84e9; f=0.04; sigma_c = Y - k*f; n =3 ; a=2500;
alpha=0.0197; c = 0.001 ;

% time period

% for t=1:10;

strain = 0.0015*sin(t);

strain_dot = 0.0015*cos(t);

% error function for each x

X=a.*strain;

Error = erf(X);

% one dimensional backstress at each time step

% beta(t) = E*alpha*(strain - sigma/E + f*(abs(strain)^c).*Error);

% sigma_dot(t) = E.*(strain_dot-abs(strain_dot).*((sigma-betta(t))/sigma_c)^(n-1))*(sigma-betta(t))/sigma_c);

beta = E*alpha*(strain - sigma/E + f*(abs(strain)^c).*Error);

sigma_dot = E.*(strain_dot-abs(strain_dot).*((sigma-betta)/sigma_c)^(n-1))*(sigma-betta)/sigma_c);

% end

return