Shape Memory Alloy Shape Training Tutorial

A Teacher's Guide
To Teaching SMA Shape Training

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1. Abstract

The following is a tutorial written for an instructor of a class that might discuss smart materials, namely shape memory alloys (SMAs). It provides fundamental information about SMAs, in-class shape-training exercises, and a longer take-home shape-training assignment. When we first commenced reading papers and running experiments to write this tutorial, we found most papers that describe the process of shape-training make it sound much simpler than it is. We have attempted in this tutorial to describe the pitfalls and the many lessons we learned through preparing to write this shape-training tutorial. We hope this tutorial gives classes of interested engineers and materials science students a more realistic and practical approach to understanding SMA shape-training.

2. Tutorial Purpose and Educational Outcomes

The purpose of this tutorial laboratory is to give hands-on experience to students new to shape memory alloys (SMAs). There are three sections to the tutorial, where each successive section is designed to build upon the previous section(s), augmenting the students' understanding so that each can confidently employ SMAs in a given design application. The three sections are described as follows:

1. A pre-lab reading assignment and a short lecture that describe the basic principles of the shape memory effect, the difference between superelasticity and shape memory, as well as shape training
2. An in-class tutorial providing initial hands-on experience with training wire and using the training process to control geometric and mechanical properties
3. A lab homework in which the students must employ their knowledge of SMAs to design an actuator with specific force/displacement characteristics

2.1. Educational Objectives

By the end of the tutorial, the student should:

1. understand the basic principles of shape training,
2. understand the difference between superelasticity and shape memory,
3. be able to train a wire into a desired shape,
4. be able to train a wire to have controlled properties (i.e. transformation temperature), and

5. be able to create a spring actuator with specific output forces and displacements using design equations.

3. Leader Guide

The following section covers the safety issues, material requirements, tutorial procedure, and grading methods. Instructors considering employing this lab should first examine the material requirements and procedures to ensure the tutorial costs, logistics, and times are feasible within their class structure.

3.1. Safety Issues

In this tutorial, instructors and students will be dealing with extremely high-temperature ovens (up to 550°C) or high current sources. Always use protective equipment such as tongs or high temperature gloves when handling hot items, and beware of electric shock. High temperatures will again be encountered when measuring transformation temperatures with a hot plate, so caution must be taken to prevent burns there as well. Also, the ceramic fixtures may break if dropped or if they encounter thermal shock. Students and instructors should be aware of possible jagged, sharp edges from broken fixtures.

3.2. Heating Methods

Shape-setting of SMA is a thermally-induced process that occurs when the alloy is heated to temperatures of approximately 500°C for 10 to 25 minutes. In most literature, shape-setting occurs in a furnace. When preparing the tutorial, our group made several attempts to shape-set in a furnace by placing the fixture in the chamber prior to turning on the oven, heating the oven to 500°C, dwelling at the temperature for 20 minutes, and allowing the oven to cool over several hours. Because this approach unavoidably holds the wire at high temperature for long periods of time, the result was a brittle wire that weakly exhibited the shape memory effect. We contacted Prof. John Shaw of the Aerospace department, and he advised us to put the fixture in the furnace once it reached temperature while using tongs, gloves, safety glasses, and caution, and to take the hot fixture out after about 10 to 25 minutes. We did not attempt this kind of heating due to the safety hazards involved, but we would expect improved shape memory of the wire if this technique were used.

In this lab, we suggest an alternative approach to shape-setting that involves resistive heating. Using high currents (3 - 5 A), the wire can be heated on ceramic fixtures. We have had some success in shape-setting with this method; when a wire that has been shape-set and straightened is heated above the transformation temperature, the location of the curves is evident although the exact shape that was set is not fully recovered. We suspect that the wire does not heat evenly as the ceramic fixture acts as a heat sink. The advantage of this process is that the shape training can be completed in class if power supplies are available and, if proper precautions are taken, the safety risk is much lower.

For future labs, we recommend further investigation into the safety and common practices of shape-setting in a furnace. Ideally, classes will have the option to shape-set in a furnace, but resistive heating can also be used if the wire cannot be safely heated otherwise.

3.3. Materials

The materials required for this tutorial lab are divided into two different sections: the in-class lab and the homework lab. Below is a list of materials for each tutorial and a description of their purpose.

3.3.1. In-class Lab

Pre-lab reading materials: This will consist of a paper for the students to read prior to participating in the lab that will give them basic information on how SMAs work. The suggested paper is "Taking the art out of smart! – Forming processes and durability issues for the application of NiTi shape memory alloys in medical devices" [3], and a copy of this paper can be found in the Appendix.

Lab instructions: Laboratory instructions can also be found in the Appendix. These will guide the students through each step of the tutorial, as well as alerting them to possible safety concerns and caveats.

Shape memory alloy wire (NiTi or NiTiNOL): For this lab, we used 70°C, 15 mil wire from Dynalloy, Inc. This wire can also be purchased from several on-line suppliers, such as Memry

Corporation (866-GO-MEMRY or Quotes@memry.com) and Johnson Mathey (408-727-2221 or metalinfo@jmusa.com). Ni compositions of around 50% are suggested.

Heat Source (High-temperature oven or electrical current): If oven heating will be used to set shapes in the prelab, the instructor will need access to an oven capable of generating temperatures of up to 550ºC. This cannot be accomplished in an ordinary kitchen oven. Note: controlling the properties of the SMA wire is dependent on how quickly the wire can be quenched in air after heating. If the oven is not capable of rapid heating, it will be necessary to first heat the oven and then place the fixture in the oven once it has reached the desired temperature. ***Use extreme caution if placing the fixture in the oven at high temperatures.*** If resistive heating will be used for shape-training in the pre-lab, a power source capable of at least 5 Amperes and 20 Volts will be necessary. ***Again, use extreme caution when operating the power supply at high currents.***

High temperature gloves/tongs: These should be used to protect the user when handling hot fixtures during removal from oven.

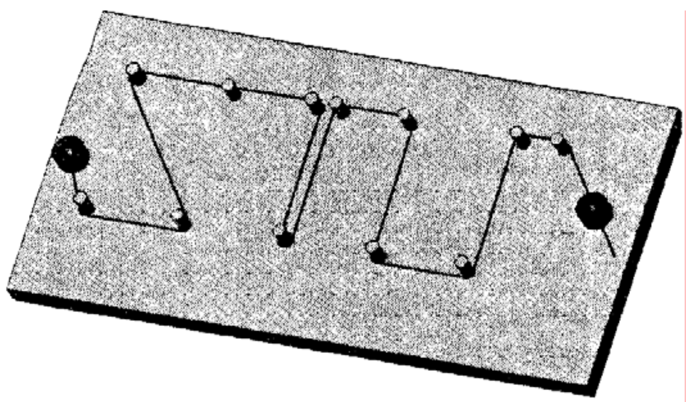

Figure 1: *Example of a pin and plate shape-setting holding fixture [1].*

Training fixtures: Ceramic training fixtures for this lab have been provided. Along with these fixtures, pegs that can be inserted and removed from holes in the fixtures have been included to give the student freedom in choosing the shape they want to create.

Bolts, washers, and nuts: Because SMA wires must be clamped down rather than tied in any way, bolts (less than ¼" diameter is advisable) will be used to clamp the ends of the wires, holding them in place. Accompanying hand tools, included pliers, wrenches, or screwdrivers, will be required.

Hot plate (magnetic spinner suggested), beaker of water, thermometer, tweezers, pliers, and ring stand: When measuring the transformation temperature of the sample each group makes in class, a hot plate with a beaker of water will be needed. Handle the wire with pliers or tweezers. The thermometer is required to continuously measure the temperature, and the magnetic spinner will ensure even heating throughout the volume of water. If no spinner is available, continuous stirring with a rod by hand should be sufficient.

3.3.2. Homework Lab

Previous materials: Many of the materials required for the in-class lab will be utilized again for the homework lab. These include the *NiTi wire*, the *high-temperature oven*, the *hotplate* with *beaker*, *thermometer*, and *ring stand*, and *high-temperature gloves or tongs*.

Reading materials: Further reading materials are recommended for the homework section of the tutorial. "Designing Shape Memory Alloy Springs for Linear Actuators" by C.G. Stevens can be found in the Appendix. The paper includes architecture descriptions for spring designs, as well as design equations and appropriate shape training graphs to follow.

Helical spring mandrels: As with the first experiment, fixtures are needed to set the shape of the SMA wire. However, in the homework lab, these will consist of different diameters of cylindrical mandrels around which the wires can be wrapped to provide the shapes of the helical springs.

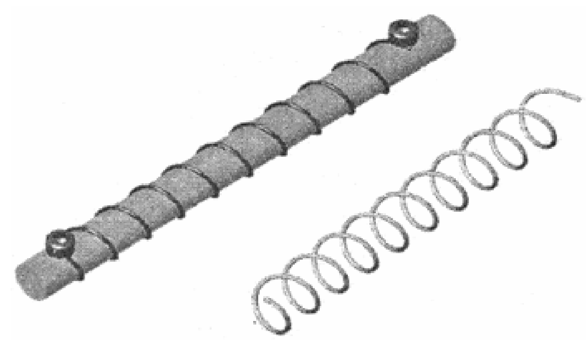

Figure 2: *Example of a cylindrical mandrel – a shape-setting holding fixture to create helical springs [1].*

Power supply: This will be used to heat the spring actuators during the weight-moving tests.

3.4. Procedure

Groups of 3 to 4 students are recommended to allow all students to participate in the design process while maintaining reasonable workloads.

3.4.1. In-Class Workshop

In the course of this tutorial, the students will learn how to set a shape into SMA wire. Peg boards are provided so that the students may create their own custom shapes. Using their knowledge of the heat-treating process, they will attempt to achieve specific transformation temperatures decided upon by the class.

3.4.1.1 Walk-through Example

Introduce the topic by doing a walk-through example. Following the procedure listed below, train a wire in front of the class for 10 minutes at a relatively high current (for 15 mil, 70°C Flexinol wire, 3.25 A works well). See Section 3.4.1.3 for the equation for maximum temperature as a function of current and wire diameter. Use this time to explain other details of the tutorial. Refer to the **Talking Points** (Section 3.4.1.4) below if you need further material. When finished, you do not need to find the transformation temperature. Simply demonstrate the shape memory effect by running a low current (about 1.5 - 2 A) through the wire.

3.4.1.2 Fixturing

To load the wire in the fixture, have the students perform the following steps:

1. To begin, have each team select one of the fixtures. Tell them to BE CAREFUL with the fixtures as they are ceramic and might have sharp edges.
2. For those selecting a peg board, provide pegs for them to place into a desired arrangement.
3. Clamping
    a. Have them clamp the wire down by running it between washers on a bolt and tightening down on a nut. See the Figure 3 below for an example.
    b. Be sure only to pinch/grasp the wire. Knot-tying and coiling will yield poor results.

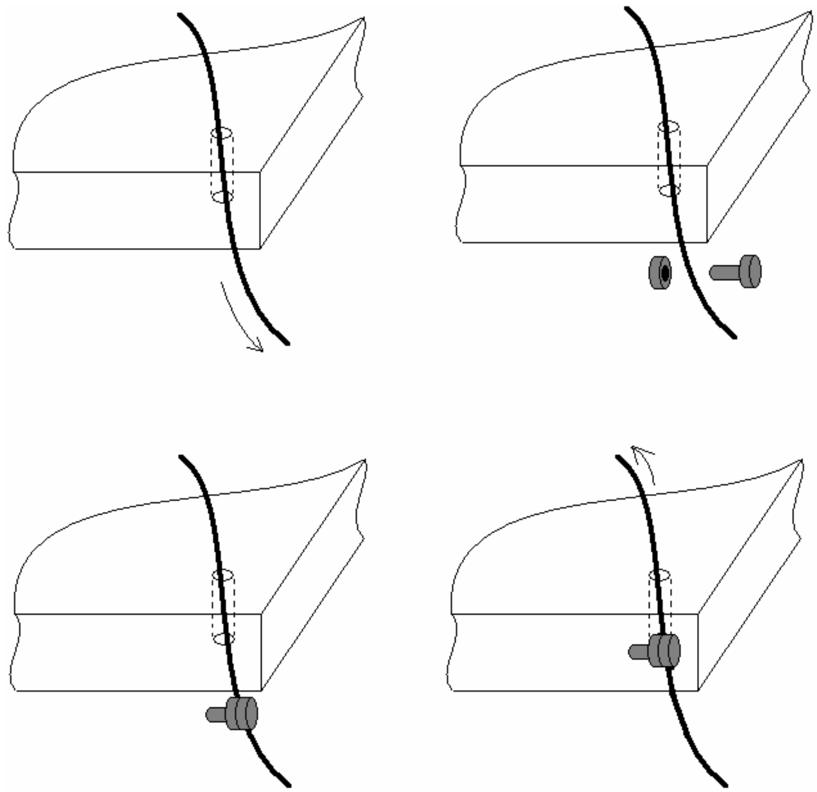

Figure 3: *Fixture fastening scheme*

4. Have them use the fixture to configure the wire into some shape (i.e., wrap it around the pegs or sandwich it between the plates). Adjust the pin locations and route the wire until it is in a somewhat taut configuration. The application of heat will cause the wire to contract and tighten around the pegs.

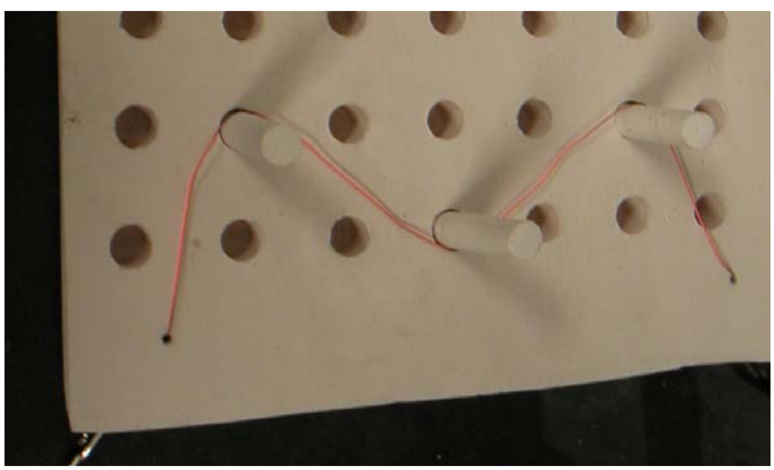

Figure 4: *Example of wire being shape-trained via electric heating.*

5. Have the students take digital photographs of the shapes they set.

3.4.1.3 Heat Treatment

Rather than seeking specific transformation temperatures, explain to the students that they will be collectively performing an experimental study. Explain that while some information is available in the literature to predict the effects of annealing temperature and time, one must often determine these relationships again for particular wires and geometry. Further, electrical heating does not provide the constant temperature profiles attained during oven heating, again affecting the outcome. Therefore, by having each group experiment with different wire temperatures and times, they will be working to provide a "transformation temperature versus time and annealing temperature" plot for your particular heating method and wire alloy.

Before the in-class tutorial, the instructor should create a table of experiments to be run, and then divide these up among the groups. Try to create a matrix that matches your number of groups. For example, if you have five groups and time for each group to train two wires, then you can run ten experiments. The experiments could consist of three different times and three different temperatures, yielding nine unique experimental data points. The tenth experiment should be a redundant backup of one of the other nine. An example of such a matrix is shown below for using a 15 mil, 70°C Flexinol wire.

Current (amps)	3.25	3.5	3.75
Calculated T (°C)	430	487	547
Time 1 (minutes)	10	10	10
Time 2 (minutes)	15	15	15
Time 3 (minutes)	20	20	20

To create such a matrix, you need to estimate the wire temperature as a function of current and wire diameter, using the following formula:

$$T_{\max} = 16.383\frac{I}{d} + 3.987\left(\frac{I}{d}\right)^2$$

T – annealing temp (°C)
I – current (amps)
d – wire diameter (mm)

Now that the wire has been clamped into the fixture, have the students perform the following steps:

1. If using a current-controlled power source, have the students set the current to the desired value and turn the supply on. Each group should monitor the time, heating the wire for the specified duration. Note that the wire may or may not glow bright orange or red. No one should touch the wire, the leads, or the fixture while the current source is on to avoid risks of burns and electric shock. Ideally, thermocouples or a non-contact temperature sensor can be used to record the actual annealing temperature.
2. Once cool, encourage the students to play and experiment with the wire to see if the properties have changed. However, they should be careful not to overstrain the wire. If the wire is strained past 8%, its shape memory effect is reduced.
3. As performed in the walkthrough example, reheat with a lower current to assess shape memory. This step is not to collect data, but to demonstrate the shape memory effect and make sure the training worked. Add notes to log. Take a digital picture of the resulting shape.
4. In addition, pass the wire over the flame of a Bunsen burner or cigarette lighter while holding the wire with tweezers or pliers. Observe to what degree the wire recovers its trained shape. If the recovered shape is greatly different from that in the previous step, have the students take another digital picture.
5. Identify the wire with a labeled piece of tape.

3.4.1.4 Talking Points

While the wire is annealing, describe other elements of the shape training process, including the following:

- Discuss the differences between oven and electrical heating as described in Section 3.2 (Heating Methods).
    - Oven heating is preferable (point out heat sinks)
    - Resistance heating makes in-class project easier and more interesting (quicker, train more wires per class period – "quick & dirty").
- Discuss and show charts for predicted transformation temperature: Figures 5, 6, and 7. Talk about the differences in these charts. For example, Figure 7 looks much different that the other, which is possibly because of different material composition and/or its much longer annealing time.
- Explain the purpose of collecting data and the charts you will create.
- Explain the process for the homework lab and how it differs from the in-class lab.

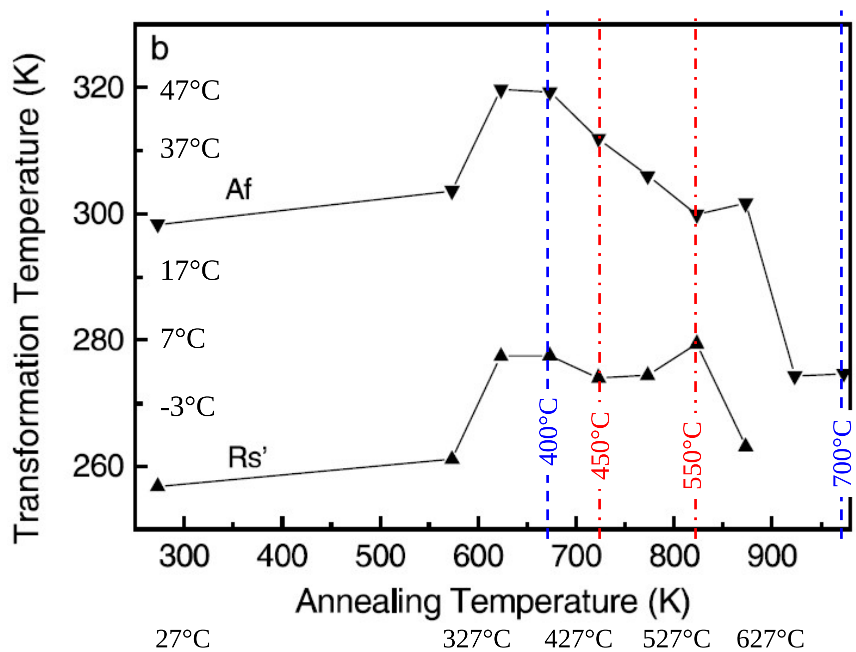

Figure 5: *Transformation Temperature (Af) of Ti-50.85 Ni (at.%) alloy as a function of annealing temperature [2]. The annealing time is 30 minutes followed by air cooling. The dotted red lines indicate the temperature range used in Figure 6. The dotted blue lines indicate the temperature range from Figure 7.*

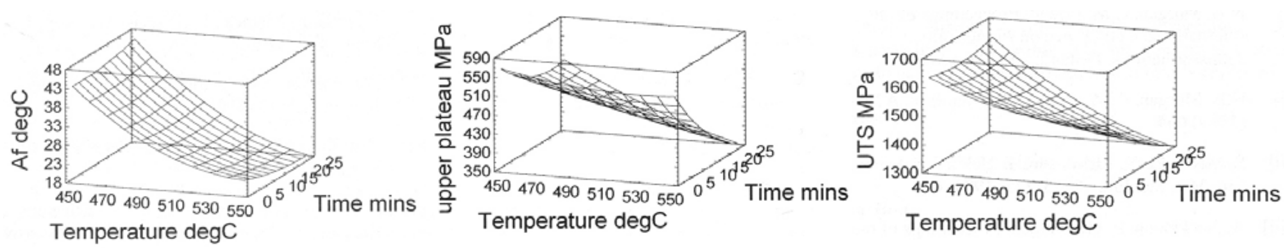

Figure 6: *Temperature, Upper Plateau Stress, and Strength as functions of Annealing Process Parameters [3]. The material is a nickel rich, superelastic alloy in the as drawn condition on production tooling.*

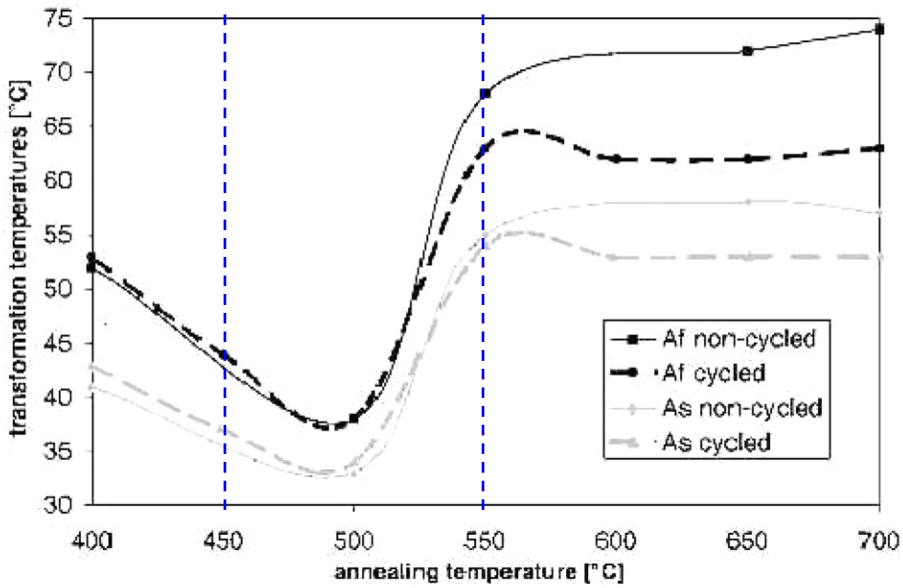

Figure 7: *Transformation Temperature (Af) of Ti-50.1 Ni (at.%) alloy as a function of annealing temperature [4]. The specimen is 25% cold-worked ribbon. The annealing time is 60 minutes. The dashed blue lines indicate the temperature range from Figure 6.*

3.4.2. Transformation Temperature

The students need to determine the actual transformation temperature of the SMA and compare it to their predictions. Again, the students should be sure not to physically overstrain the wire. Have the students perform the following steps:

1. Bend the wire into a shape other than the set shape (a straight line is preferable). Place the wire in a beaker full of water at room temperature. Note that you may want to keep another source of very hot water nearby, so that you can add it to the beaker to speed up the process.
2. Use a hot plate and magnetic spinner to uniformly and slowly heat the water. (Alternatively, use a gas flame and a stirring rod. If so, have them indicate the exact method used.)
3. Tracking the water temperature with a thermometer, slowly increase the temperature until the wire changes back to its trained shape.
4. Since the shape change may be hard to detect, remove the wire every few degrees and re-straighten it. This will make the onset of the shape memory effect more obvious.

5. If possible, note the temperatures at which shape change begins and ends. If necessary, repeat the test at a slower heating rate to improve accuracy.
6. After the shape change is complete, photograph the final shape. Compare it to the original shape that had been set in the fixture and to the shape attained from the other heating methods.
7. Finally, clean up the work areas and return all the fixtures, pegs, and wire, sorting them into boxes.

3.4.3. Homework Lab

In this assignment, students will be introduced to SMA spring actuators by requiring them to design and fabricate an SMA compression spring that pushes a weight a desired distance. The instructor should assign a set of reasonable force and displacement requirements on the order of Newtons and centimeters, respectively, to each group of students. Groups should be given approximately two weeks to complete this lab.

For this assignment, it should be noted that only the linear portion of the stress-strain curve will be used. This allows for a simpler design procedure but also constrains the maximum spring stress to be less than the martensitic yield strength (70 to 140 MPa). This assumption is also convenient because the material can be considered to be linearly elastic with the Young's modulus as a temperature-dependent parameter.

Refer the students to the article "Designing Shape Memory Alloy Springs for Linear Actuators," by Christopher G. Stevens. The article, found in the appendix, uses standard design equations for springs from *Mechanical Engineering Design* (J.E. Shigley) with the stiffness properties of SMA in the martensitic and austenitic state to compose a spreadsheet that can be used as a tool in SMA spring design. Advise the students to compose their own spreadsheets as discussed in the article to use as a tool for designing their springs.

In the article, the author makes an incomplete conclusion that wires with diameters less than 1 mm have unacceptably high shear stresses and should be avoided (most commercially available wires are less than 0.5 mm). The shear stresses are high because the wire that the author is referring to is required to exert a relatively high force (4.5 kgf, 10 lb) for this type of spring actuator. It is important to make the students aware that this conclusion only applies for a specific set of loading and displacement requirements and will not apply to their individual problems.

3.5. Grading

The following section provides guidelines for grading this tutorial. The instructor may want to modify the questions or grade percentages as they deem appropriate for the focus of their class.

3.5.1. Grading the Basics

To evaluate that the first two educational objectives (i.e. understand the basic principles of shape training, and learn the difference between superelasticity and shape memory effect) have been met, a few short answer questions can be used to verify learning once the pre-lab article has been read. Those questions could be the following:

1. In shape training a shape memory alloy with a given composition, how is the transformation temperature set? By what can it be affected?
   Answer: The transformation temperature is set primarily by the shape training temperature. It can also be very slightly affected by length of time spent at the shape training temperature. Apart from shape training, transformation temperatures can be greatly affected by composition such as variation in nickel content (i.e., 0.1% increase in nickel content can raise the transformation temperature by 10°C).
2. What is the difference between shape memory and superelasticity? On a macroscopic level? On a microscopic level?
   Answer: Shape memory is strain recovery across a transformation temperature – a temperature-induced transformation. Superelasticity is immediate shape recovery from release of stress above the transformation temperature – a stress-induced transformation. On a microscopic level, shape memory and superelasticity are both possible due to a twinned crystal structure.

These questions should be worth 5% of the overall grade.

3.5.2. Grading the In-class Lab

To evaluate the educational objective associated with the in-class lab (i.e., be able to train wire into a desirable shape), several measures should be used. First, once the students have loaded their wire onto the training fixture, they should sketch the wire shape or take a digital image. After the wire has gone through shape training, it should be cooled, deformed, and then heated above its transformation temperature to return to its set shape. This shape should be compared to the pre-training drawing or photograph. If the shapes are different, the students should consider why this could have happened. Additionally, for each wire they shape train during class, the students should report the transformation temperature within ±2 °C. And finally, short-answer questions focusing on transformation temperatures should be given:

1. For what applications could a wire with the following temperatures be used? Be creative.
    a. 15°C
    b. 37°C
    c. 100°C

    Answers:

    a. arbitrary cool temperature which allows SMA to be superelastic at room temperature (e.g. eyeglass frames)

    b. body temperature – any implantable medical devices (e.g. vascular stents, Harrington rods, orthodontic wire)

    c. temperature of boiling water (e.g. temperature sensor, any actuator that would be activated above room temperature)

This section is worth 25% of the overall grade.

3.5.3. Grading the Homework Lab

To evaluate that the educational objectives of the homework lab have been met (i.e., be able to train a wire to have controlled properties and be able to create a spring actuator with specific output forces and displacements using the design equations), a thorough review of the design process and outcomes should be done. First, basic error analysis of the design targets (force and displacement) should be performed (i.e. (target-actual)/target). A team should be within 20% of both targets. This part is worth 25% of the total grade. However, if they are not within 20%, it is still valid to give full credit for this task if the team documented their progress and decisions well and they made several attempts to meet the specifications. Otherwise, if a team is not within 20% of the targets and does not well document their process, points should be deducted based on the size of the error and the quality of their reporting. Because documentation becomes a big part of grading this section (30% of the total grade), all teams should submit their design calculations and a description of the decisions they made.

In addition to the above, several open-ended questions should be posed to verify a thorough understanding of the project that was just completed. Those questions could be similar to those listed below. The first four questions should be worth 10% with the last being worth 5%.

1. If the design needs more force than the original specification, what should be changed in the spring design?
   Answer: Wire thickness can be increased, coil diameter can be decreased, and number of coils can be decreased.
2. If there were more coils than what was originally designed for, what could that change?
   Answer: Deflection could be increased.
3. If the wire diameter were smaller or larger, how would that affect the design specifications?
   Answer: *If all else is the same, force could be increased with larger diameter wire and vice versa.*
4. If the transformation temperature needed to be higher or lower, what would need to change about the shape-training process?
   Answer: *If the transformation temperature needed to be higher, the shape training temperature should be increased. If only a few degrees increase in transformation temperature was necessary, the shape training time could be increased instead.*
5. For what creative application might one use the spring actuator as designed?

The homework lab is worth a total of 70% of the overall grade.

4. Validation

The validation for the tutorial has come from the Fall 2004 Smart Materials and Structures class. The class took a slightly modified version of the in-class tutorial laboratory, and four short questions were asked of each student to highlight good points and areas where improvement was needed.

What was the purpose of this lab?

This question was asked to determine if the background of the lab was thoroughly explained, in both the pre-lab reading, and in the short talk given during wire heating. Some typical responses to this question were:

- "To learn about the functions and applications of SMA as well as the difficulties with them"
- "The purpose was to explore the effect of annealing temperature and time on the retraining of austenite finish temperature on shape memory alloy."
- To "Learn the basics of SMA shaping through practice"
- To "Shape train SMAs (using heating) to ready them for any application"

While each of these is correct, we felt that no one understood that the lab was meant to show the difficulties with SMA, while simultaneously giving experience using SMA so that they could use it themselves with more confidence and understanding.

What did you learn during that lab?

This question was meant to determine what material was emphasized during the talk given while shape training, as well as to find how well the entire process taught the students about shape training. Some typical responses were:

- "Learned how to train SMAs, the fact that we shouldn't heat the wires too high. (The wires that we used seemed burnt out)"
- "How to shape SMA by using power supply and ceramic accessories (posts, bare plates)"
- "The shape changes don't work great, and the theoretical model is probably not going to be met."
- "SMA is very temperamental and electrical heating to specific temperatures is tough."

The answers to these questions showed an understanding that SMAs can be hard to work with, especially at first during the learning process. This goes for our group as well, because the difficulty of working with SMAs in this lab was increased by our own lack of experience. Furthermore, trouble with determining the temperature of the wire without a thermocouple made transformation temperatures and required electrical amperages difficult to predict.

What were the highlights of the lab?

This question was meant to show what went well from a "coolness" point of view. Some answers to this were:

- "Shape training, memory recovery"
- "Our wires didn't work so well, so the heating was the highlight."
- "Seeing the wire return to its set shape was really neat."
- "The hands-on experiment was a very good idea, especially seeing them tighten so quickly. I really expected it to be gradual."

From this information, it is clear that the groups had varying success training the wire. We could have had better success if we could measure the wire temperature, forcing a guess based on current and wire diameter.

Please suggest specific ways that the lab can be improved:

- "Some more about SMA sensitivity to its composition"
- "Demonstrate something other than just a simple shape. Maybe have a premade design that has a practical function to show its real world use along with its novelty."
- "Thermocoupling, heating in furnace"

These answers again point to the need for more precise measurement during resistance heating such as a thermocouple. Also, only the shape memory process was emphasized; showing the strength and usefulness of the material may have been valuable as well.

5. Conclusions

Overall, we were very pleased with the results of the tutorial. Students gained hands-on experience with SMA as desired. Reviewing the answers to the four questions also shows that they now have a greater understanding of the caveats of working with SMA and are better equipped to set up an SMA fixture for their own projects. The suggestions from the evaluations, as well as the understandings we have gained about the tutorial setup, have been incorporated back into the procedure so that future tutorials will be better able to accomplish the goal of teachings students the basics of shape training.

6. References

1. Smith, S.A., Hodgson, D.E., "Shape Setting Nitinol." Proceedings from the Materials & Processes for Medical Devices Conference. 8-10 Sept 2003.
2. Moorleghem, W.V. and Otte, D., "The Use of Shape Memory Alloys for Fire Protection." Duerig, T.W. et al (Eds.). Engineering Aspects of Shape Memory Alloys. Butterworth-Heinemann Ltd., London, 1990.
3. Morgan, N.B., Broadley, M., "Taking the art out of smart! – Forming processes and durability issues for the application of NiTi shape memory alloys in medical devices." Proceedings from the Materials & Processes for Medical Devices Conference. 8-10 Sept 2003.
4. Brailovski, V., Terriault, P., Prokoshkin, S., "Influence of the Post-Deformation Annealing Heat Treatment on the Low-Cycle Fatigue of NiTi Shape Memory Alloys." Jour. of Materials Eng. And Perf. 11(6): 614-621. 2002.
5. Stevens, C.G., "Designing Shape Memory Alloy Springs for Linear Actuators." Springs. Winter 1999, 24-35.

7. Appendix

- Pre-lab Reading
- Pre-lab questionnaire (per individual student)
- In-Class Workshop Instructions and Questions (per group)
- Homework Lab Instructions and Questions (per group)
- Grade Sheet (per group)
- Survey
- Supplemental Figures

7.1. Pre-lab Reading

Proceedings from the Materials & Processes for Medical Devices Conference, 8-10 Sept 2003. Anaheim, Calif., ASM International, 2004

Taking the art out of smart! - Forming processes and durability issues for the application of NiTi shape memory alloys in medical devices

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Abstract

Despite the fact that shape memory effects and superelasticity are now well understood there still exist many myths and misinterpretations that can lead to frustration and failure of prototype projects. This paper will seek to take some of the 'art' out of using the shape memory effect.

A case study approach will be employed to demonstrate all the stages in the production cycle, from alloy selection and melting to wire drawing and shape setting treatments. A review of recent research will be used to discuss and explore some of the durability issues associated with NiTi products including fatigue life and biocompatibility.

Ultimately it is hoped that this case study will demonstrate how pitfalls can be avoided and how defined processes can result in successful medical applications that utilize the unique properties of NiTi alloys.

Introduction

This paper seeks to answer some of the most common questions that arise during a shape memory product development cycle. Each section is preceded by a question that the authors are commonly asked by those wishing to work with shape memory alloys. Although many of these concepts are common to all shape memory alloys this paper will concentrate upon nitinol as it is this alloy that has found wide spread application in the medical market.

To facilitate a case study approach this paper uses the manufacture of a nitinol 'star' as the example product. The first question from the customer is therefore:

Question 1: ***We want to set a star shape in nitinol. We need two different versions, one that displays very high elasticity and flexibility at body temperature (37°C) and one that can be deformed but will recover at a temperature just above body temperature but not greater than 50°C. Is this possible?***

Answer 1: Yes, the term nitinol actually encompasses a family of nickel titanium alloys that depending upon the exact composition (based upon a small compositional window of approximately 50.0:50.0 NiTi to 51.5:48.5 NiTi) will display either superelasticity (spontaneously recoverable strains up to 8.0%) or shape memory (heat recoverable strain up to 8.0%).

The Origin of Shape Memory Effects

Question 2: ***Is nitinol simply a very elastic metal?***

Answer 2: No, not really. For metals the term elastic is generally associated with deformation up until a point when the atoms in the crystals are permanently moved out of position, i.e. 'slip'.

The strain effects associated with nitinol have their origin in a particular type of phase transformation (change in internal crystal structure) which produces a microstructural constituent known as martensite. A martensitic transformation is displacive, occurring through a shearing of the crystal structure from the so-called parent-phase, to that of the martensite. This is illustrated schematically in the two dimensional analogue shown in Fig. 1.

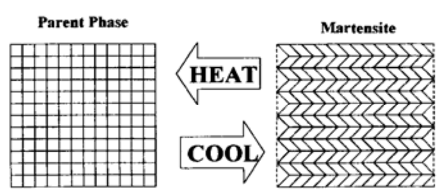

Figure 1: Two dimensional/two variant analogue of a thermoelastic martensitic transformation.

A feature of all martensitic transformations is that there are a number of crystallographically equivalent shear directions through which the martensite can form. In this analogue the two opposite shears maintain the macroscopic shape of the crystal block (represented by the dotted line). Such a microstructure, where the shear of one variant is accommodated or "cancelled" by that of the other is known as a self-accommodating structure. Imagine this self-accommodation in three dimensions and you have the basic crystallographic process behind both thermal shape memory effects and superelasticity.

The boundaries between the martensite variants are glissile (mobile) and their positions can be influenced by external variables; perhaps most importantly by applied stress. This is illustrated in Fig. 2 where the orientation of the martensite crystals change under the influence of stress creating a balance of variants whose shears best accommodate the direction of the resulting strain. It is the ability to re-orientate martensite variants under stress which forms the basis of the large recoverable strains that are associated with shape memory and superelasticity.

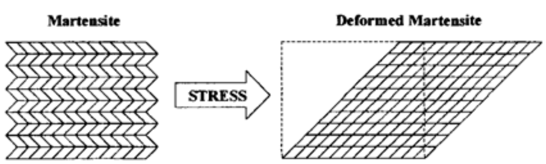

Figure 2: Variant reorientation in thermoelastic martensites.

Question 3: ***So how does this result in the thermal shape memory and superelasticity effects?***

Answer 3: One-Way Shape-Memory: The phase transformation that takes place may either occur athermally (i.e. upon a change in temperature) or by the application of stress which results in 'stress-induced' martensite. The temperatures which are used to define the stages in the phase transformation are known as:

- M_s for the start of the martensite transformation on cooling
- M_f for the finish of the martensite transformation on cooling
- A_s for the start of the parent phase transformation on heating
- A_f for the finish of the parent phase transformation on heating

Figure 3 schematically illustrates the macroscopic response of a one-way shape memory alloy. If such an alloy is deformed in the fully martensitic state (i.e. below M_f) and subsequently unloaded, then an apparently permanent strain will remain. This is a result of the martensite microstructure being re-oriented as shown in Fig. 2. If the alloy is now reheated above the A_f transformation temperature range (i.e. transformed into the parent phase) then this apparently permanent strain will fully recover, returning the original macroscopic shape. This is the so-called one-way memory effect.

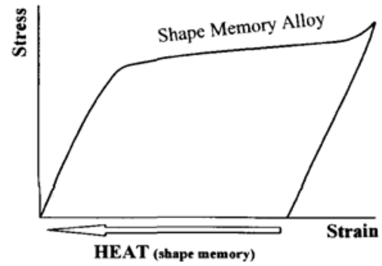

Figure 3: Stress-strain behavior during the one-way memory effect.

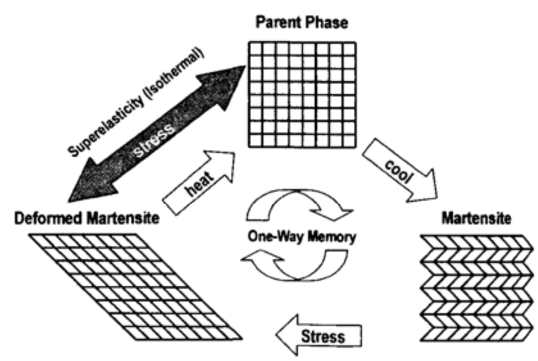

Figure 4: Microstructural changes during thermal memory and superelastic phenomena.

The internal structural changes that take place during this process can be visualized by referring to Fig. 4. Deformation takes place in the self-accommodated martensite condition. During loading this structure becomes deformed resulting in a net macroscopic shape-change. When the alloy is unloaded this deformed structure remains resulting in the apparent permanent strain. However, if the alloy is now re-heated to a temperature above A_f the original parent-phase microstructure and macroscopic shape is restored. When the alloy is subsequently cooled to below the M_f a self-accommodating martensite microstructure is formed once more and the original shape before deformation is retained. Thus a one-way Shape-Memory is achieved. The maximum strain that may be recovered is approximately 8% for nitinol alloys.

Pseudoelasticity or the Superelastic Effect: When a nitinol alloy is deformed isothermally at a temperature above A_f, the martensite transformation can be induced mechanically. The martensite formed in this way is known as stress-induced martensite (SIM) and is only stable under the application of stress. Upon unloading the decreasing stress and surrounding elastic forces generated during transformation cause the martensite to shrink back to the original parent-phase. Figure 5 shows the mechanical behavior of such a transformation and compares it to that of a stainless steel. Again, the maximum strain that may be recovered in this way is approximately 8% for nitinol alloys. It can be seen in Fig. 5 that superelastic deformation displays a hysteresis, the upper plateau occurring during stress-induced martensite transformation and the lower during reversion on unloading. It is both the large recoverable strain and constant stress plateaus that can be utilized in superelastic medical applications.

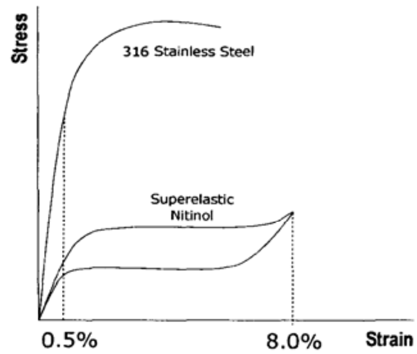

Figure 5: Comparison of the stress-strain curves of conventional and superelastic alloys.

Figure 4 can also be used to explain the microstructural origin of the superelastic effect. A nitinol alloy will display superelasticity when it is above the A_f temperature, i.e. when it is in the parent phase. This time the martensite is induced purely by the application of stress. The application of the stress essentially prevents self-accommodation and instead results in preferentially orientated martensite concurrent with the direction of applied stress and results in a macroscopic shape strain. When the stress is removed the martensite becomes thermodynamically unstable and the martensite variants shrink back to the parent phase thus restoring the original shape of the alloy.

Alloy Selection and manufacture

Question 4: **What controls whether the nitinol displays superelasticity or thermal shape memory and which should we choose for our 'star' wire forms?**

Answer 4: As described earlier in this paper the compositional range of nitinol is quite small. Essentially it is the composition that controls whether the component will be superelastic or whether it will display a thermal one way memory. A compositional difference of just 0.1% may result in a change to the transformation temperatures of 10ºC. Essentially the higher the nickel content the lower the transformation temperatures, therefore the superelastic star will be made from a nitinol wire that is slightly higher in nickel. The exact transformation temperatures may be finely tuned using heat treatment; this will be explained in a later section.

As well as intentional changes to composition, impurities within the alloy may also affect the transformation temperatures. Impurities such as carbon and oxygen may combine with the titanium resulting in a depletion of titanium in the bulk alloy and therefore a decrease in the transformation temperatures.

Question 5: ***If the transformation properties of the alloy are so sensitive to composition and impurities then how are they made?***

Answer 5: High purity raw materials and a melting method that ensures a homogeneous final product is required.

Commercial nitinol alloys tend to be produced using one of two methods: vacuum arc remelting (VAR) or vacuum induction melting (VIM).

VAR involves compacting the nickel and titanium into a large ingot which is subsequently used as an electrode to strike an arc between it and the bottom of a large crucible. Gradually the NiTi compact is consumed forming a molten alloy in the bottom of the crucible. The whole process is carried out under vacuum and results in an alloy of very high purity.

VIM involves melting the nickel and titanium in a crucible (often graphite) which is heated by electrical induction. The induction effect stirs the molten alloy resulting in a more homogenous structure than that produced by VAR. As with VAR the whole process is carried out under vacuum. The drawback of VIM is that it tends to result in a higher level of carbon impurities because of the graphite crucible used during manufacture.

Both VAR and VIM are capable of producing very high quality nitinol ingots suitable for medical applications.

Question 6: ***So how should we specify the alloys for our star application?***

Answer 6: To some extent this depends upon which properties are most important for the final application. For instance, in a stent application using superelastic wire a range within which the upper plateau stress must lie may be specified. In addition a temperature range for the A_f may also be specified.

For the superelastic star three specified properties would be appropriate: -

1. The upper plateau stress
2. The ultimate tensile stress
3. A temperature range for the A_f far enough below body temperature to ensure superelastic behavior

These properties are dependent upon one another and therefore some experimentation will be necessary to achieve an optimized solution.

For the thermal shape recovery star the following specified properties would be appropriate: -

1. Ultimate tensile stress
2. An A_f temperature range above body temperature (37°C) and below 50°C (as specified)

It should be kept in mind that there are other factors that influence the final measured properties and performance of the nitinol product. The shape of the final product is 'set' using heat. Typically the heat treatment is carried out at a temperature between 450°C and 550°C. This heat treatment causes a change to the microstructure of the nitinol and correspondingly a change to the mechanical properties and transformation temperatures. With appropriate experimentation the heat treatment may be employed to 'fine tune' the desired properties.

The starting condition of the alloy will also have a strong influence on the final properties. Commonly the nitinol may be purchased in either the 'straight annealed condition' or in the 'as-drawn condition'. *Straight annealed* means that the wire has essentially been shape set into a straight length as it leaves the drawing bench. To achieve this, the wire travels through a continuous strand straightening furnace before being coiled onto the spool. *As drawn* means that the wire is coiled directly from the last drawing step.

Shape Setting the Nitinol Product

The following information is the mechanical and transformation property requirements chosen by the customer for the nitinol stars: -

Superelastic star specification
The upper plateau stress should be between 450 and 500MPa when tested at a temperature between 20°C and 25°C
The ultimate tensile stress should be above 1300MPa
The temperature range for the A_f is between 25°C and 30°C

Thermal shape recovery star
The ultimate tensile stress should be above 1000MPa
An A_f temperature range should be between 45°C and 50°C

<u>Question 7:</u> ***How can the nitinol wire be shape set to achieve these properties?***

<u>Answer 7:</u> The most common way of shape setting nitinol is to clamp it in a tooling fixture during the heat treatment. Fig. 6 shows the tooling used to shape set the nitinol stars. The wire is clamped at one end and subsequently wrapped around the pegs to create a series of star shapes. The end is then clamped off to hold the wire in place during heat treatment. The tooling is made from stainless steel to facilitate repeated use without significant oxide build up. Figure 6 also demonstrates a problem with using small pins in tooling. Notice how some of the pins have become bent from the forces put on them by the nitinol during heat setting. This tool has produced approximately 500 parts.

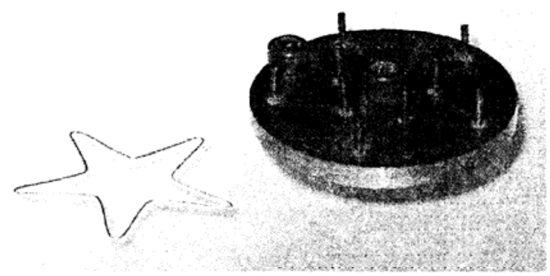

Figure 6: The tooling (right) and finished product (left) for the superelastic star.

To establish the exact heat treatment temperature and time a factorial experimental design may be performed to create a surface response for each of the specified properties. This can be used to specify an optimum heat treatment for a particular tool design.

To determine a heat treatment temperature for the superelastic star a factorial experiment is carried out on a nickel rich, superelastic alloy in the as drawn condition on the production tooling.

The temperature/time factorial matrix design is shown below in Table 1.

Table 1: Time and temperature parameters for heat treatment determination

450°C	475°C	500°C	525°C	550°C
5mins	5mins	5mins	5mins	5mins
10mins	10mins	10mins	10mins	10mins
15mins	15mins	15mins	15mins	15mins
20mins	20mins	20mins	20mins	20mins
25mins	25mins	25mins	25mins	25mins

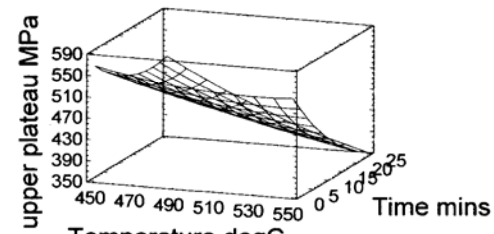

Figure 7: Surface response of upper plateau stress.

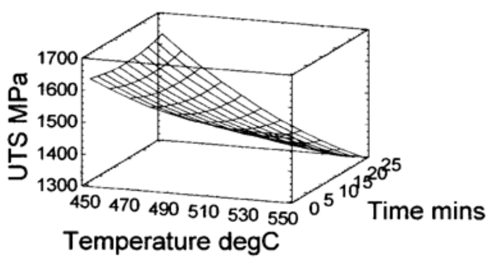

Figure 8: Surface response for ultimate tensile stress.

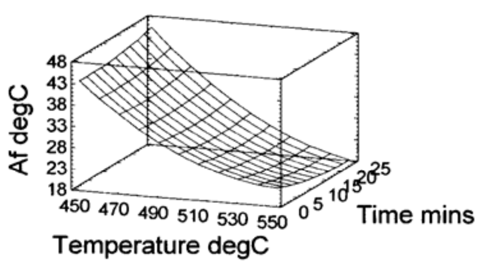

Figure 9: Surface response for A_f temperature.

The results indicate that a heat treatment carried out at 500ºC for 10 minutes will yield the following properties: -

Upper plateau – 480MPa
Ultimate tensile stress – 1500MPa
A_f temperature – 27ºC

This heat treatment procedure yields properties in the middle of the specification range and is therefore suitable for the superelastic star.

A similar experimental design could be carried out for the thermal recovery star to establish a suitable heat treatment for the specified properties.

A finished superelastic star product is shown in Fig. 6.

Fatigue and Biocompatibility

Question 8: ***The human body is an aggressive environment for any material. How does nitinol behave in terms of fatigue and biocompatibility?***

Answer 8: Fatigue Life: The non-linear nature of the superelastic phase transformation in NiTi means that conventional fatigue life theory is difficult to apply [i]. The volume fraction of martensite/parent phase and its role in the fatigue mechanism is still not clearly understood. Fatigue life remains one the most discussed yet least understood aspects of NiTi alloys. The FDA requirement of a fatigue life exceeding 400 million cycles for intravascular stents means that a better understanding of the factors affecting fatigue life and the mechanism of crack initiation and growth is essential [ii].

Some aspects of nitinol fatigue do appear to have some *conventionality* about them. Surface condition, inclusions and plastic deformation do appear to influence stage 1 crack growth [iii]. The crack growth stage of fatigue (Stage 2) is where the most confusion arises, a number of factors have to be considered when studying fatigue crack growth in nitinol medical applications. In vitro fatigue testing of nitinol usually involves cyclic loading in either strain control (where the amount of deformation for each cycle is controlled) or stress control loading (where the level of load applied for each cycle is controlled). In comparison to other alloys nitinol shows excellent fatigue properties at high strain levels. One of the complications of using laboratory test data for assessing the fatigue life of real applications is that the actual loading conditions in vivo are likely to be complicated combinations of varying mean strain (i.e. the average strain of the loading cycle), mean stress and the compliance of the surrounding tissue [iv].

A common way of assessing the fatigue life of alloys with regards to alternating strain amplitude and the mean strain on the samples is to construct a Goodman diagram. Classically Goodman relationships are linear and the greater the mean strain the lower the alternating strain required for fatigue failure. Interestingly nitinol appears to show a non-linear Goodman relationship [iv].

Other unusual fatigue behavior that appears to be related to the mean strain is an apparent increase of fatigue life with increasing mean strain [iii]. Analysis of fracture surfaces and microstructure implies that these unusual aspects of nitinol fatigue behavior are associated with domains of high dislocation densities, internal stresses, stabilized martensite and micro-fissures [i] [iii] [v]. Other data also supports the importance of microstructure [vi] and volume fraction of martensite/parent phase for the fatigue life of nitinol [vii] [viii].

Stage 3 final fast fracture of nitinol is typically characterized by micro-void coalescence leading to ductile overload [iii].

Bioperformance: It is well known that titanium is not toxic when used in the human body; however, nickel is extremely toxic. Nickel is carcinogenic and is implicated in various other reactions including allergic response and degeneration of muscle tissue. Fortunately however, nitinol forms a passive titanium oxide layer (TiO_2 - the same as that which forms on titanium alloys) that acts as both a physical barrier to nickel oxidation and protects the bulk material from corrosion.

One of the most important considerations as far as the biocompatibility of nitinol is concerned is that of cytotoxicity. Cytotoxicity concerns the damage that the material may incur on cells and is usually measured by in vitro experimentation. It has been shown that the cytotoxicity of nitinol is comparable with other implantable alloys [ix]. These findings are supported by another study that showed no cytotoxic, allergic or genotoxic response to the nitinol during short term in vitro testing [x]. Surface processing has been shown to have a significant effect on cytotoxicity [xi].

In vivo testing has also yielded positive results for nitinol. Some studies have shown that nitinol has no toxic effects on tissue [xii], or that it is at least comparable to stainless steel and Ti6Al4V titanium alloy [xiii].

Contradictory evidence on the bioperformance of nitinol does exist. A study by *G. Riepe et al* on explanted AAA endovascular graft stents found large areas of pitting corrosion and fractures in nitinol wire. The authors concluded the mechanism of the observed corrosion was due to cell-induced electrochemical corrosion and active cellular destruction of the surfaces [xiv].

Summary and Conclusion

Nitinol offers unique capabilities for the medical device industry, in particular for interventional radiology. Whilst the processing and forming of nitinol is unusual in many respects this paper has shown that basic principles can be employed to produce working products.

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7.2. Pre-Lab Questionnaire

Name ___________________________

To be completed after reading "Taking the art out of smart! – Forming processes and durability issues for the application of NiTi shape memory alloys in medical devices" (Morgan, N.B. and Broadley, M., 2004):

1. In shape training a shape memory alloy, how is the transformation temperature set? By what can it be affected?

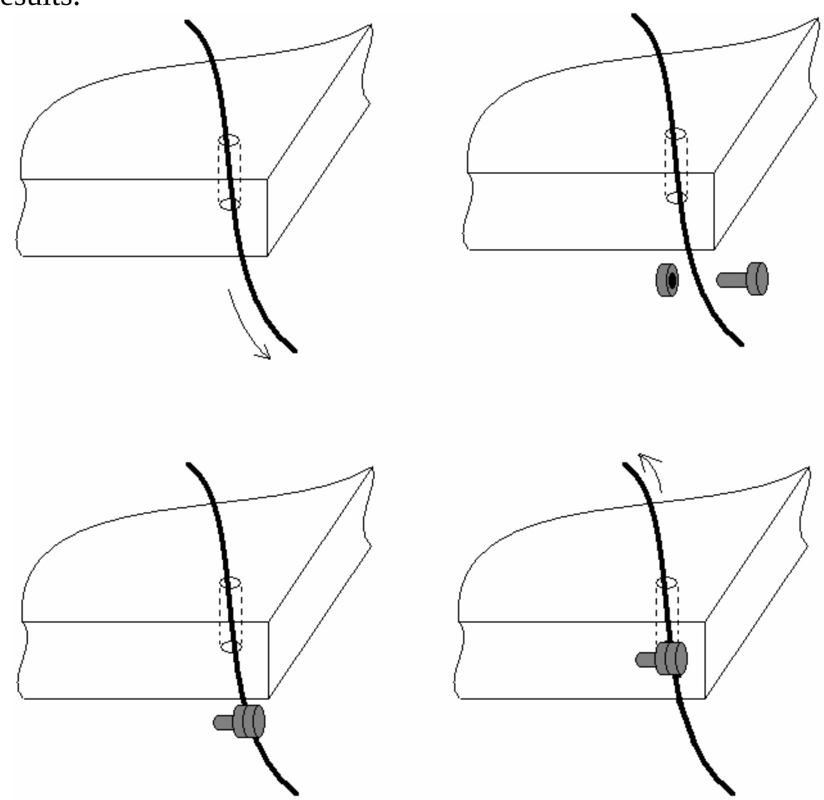
2. What is the difference between shape memory and superelasticity? On a macroscopic level? On a microscopic level?

7.3. In-Class Workshop Instructions

In the course of this tutorial, you will learn how to train a shape into Nitinol SMA wire. Peg boards are provided so that you may create your own custom shapes. Using your knowledge of the heat-treating process, you will attempt to achieve specific transformation temperatures decided between yourselves and the TA.

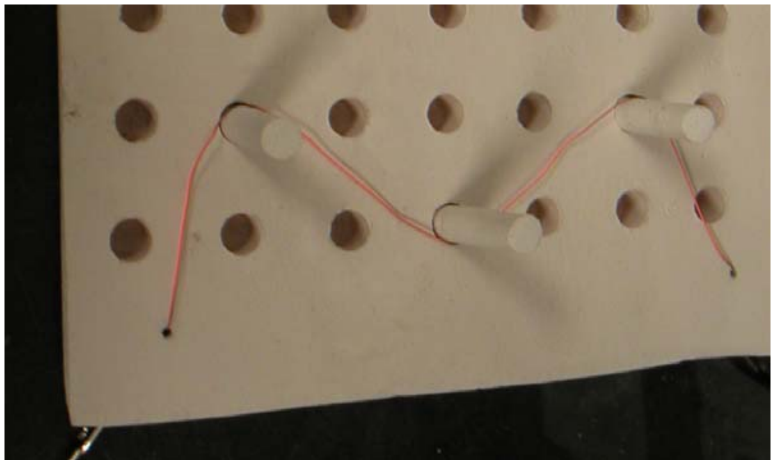
Fixturing

1. To begin, select one of the fixtures provided by the TA. BE CAREFUL with the fixtures, as they are ceramic and might have sharp edges.
2. If you have selected a peg board, place the pegs into a desired arrangement.
3. Use the fixture to shape the wire into a unique shape. (i.e. wrap it around the pegs or sandwich it between the plates.)
4. Clamping
    a. Clamp the wire down by running it between washers on a bolt and tightening down on a nut. See the the figure below for an example.
    b. Be sure only to pinch/grasp the wire. Knot-tying and coiling will yield poor results.



Fixture fastening scheme

5. Use the fixture to configure the wire into some shape (i.e., wrap it around the pegs or sandwich it between the plates). Adjust the pin locations and route the wire until it is in a somewhat taut configuration. The application of heat will cause the wire to contract and tighten around the pegs. Note that even after the wire contraction, it only needs to be somewhat taut around the pegs.



Example of wire being shape-trained via electric heating.

6. Take a digital photograph of the shape you set.

Heat Treatment

Specific heating times and temperatures have been chosen by your GSI. Each group will perform heating training with one or two specific combinations of heat and time, found in the table below. To see how these conditions may correlate to the resulting transformation temperatures, refer to the tables on the Supplemental Information page.

GSI, Modify this table ahead of time. Remove this bubble before printing.

Current (amps)	3.25	3.5	3.75
Calculated T (°C)	430	487	547
Time 1 (minutes)	10	10	10
Time 2 (minutes)	15	15	15
Time 3 (minutes)	20	20	20

The wire temperatures in the above matrix were estimated as a function of current and wire diameter, using the following formula:

$$T_{\max} = 16.383\frac{I}{d} + 3.987\left(\frac{I}{d}\right)^2$$

where T = annealing temp (°C), I = current (amps), d = wire diameter (mm)

1. Each group will receive specific heating times and temperatures from the GSI.
2. If using a current-controlled power source, set the current to the desired value and turn the supply on. Monitor the time, heating the wire for the specified duration. Note that the wire may or may not glow bright orange or red. No one should touch the wire, the leads, or the fixture while the current source is on to avoid risks of burns and electric shock. Ideally, thermocouples or a non-contact temperature sensor can be used to record the actual annealing temperature.
3. Once cool, play and experiment with the wire to see if the properties have changed. However, be careful not to overstrain the wire. If the wire is strained past 8%, its shape memory effect is reduced.
4. As demonstrated by the GSI, reheat with a lower current to assess shape memory. This step is not to collect data, but to demonstrate the shape memory effect and make sure the training worked. Add notes to your log. Take a digital picture of the resulting shape.
5. In addition, pass the wire over the flame of a Bunsen burner or cigarette lighter while holding the wire with tweezers or pliers. Observe to what degree the wire recovers its trained shape. If the recovered shape is greatly different from that in the previous step, take another digital picture.
6. Identify the wire with a labeled piece of tape.

Transformation Temperature

Determine the actual transformation temperature of the SMA and compare it to your prediction. Again, be sure not to physically overstrain the wire.

1. Bend the wire into a shape other than the set shape (a straight line is preferable.)
2. Place the wire in a beaker full of water at room temperature. Note that you may want to keep another source of very hot water nearby, so that you can add it to the beaker to speed up the process.
3. Use a hot plate and magnetic spinner to uniformly and slowly heat the water. (Alternatively, use a gas flame and a stirring rod. If so, indicate the exact method used.)
4. Tracking the water temperature with a thermometer, slowly increase the temperature until the wire changes back to its trained shape.
5. Since the shape change may be hard to detect, remove the wire every few degrees and re-straighten it. This will make the onset of the shape memory effect more obvious.
6. If possible, note the temperatures at which shape change begins and ends. If necessary, repeat the test at a slower heating rate to improve accuracy.
7. After the shape change is complete, photograph the final shape. Compare it to the original shape that had been set in the fixture and to the shape attained from the other heating methods. The entire shape will not likely be recovered exactly, but try to observe if the major bends are recovered.
8. Finally, clean up the work areas and return all the fixtures, pegs, and wire, sorting them into boxes.

7.4. In-Class Workshop Supplemental Information

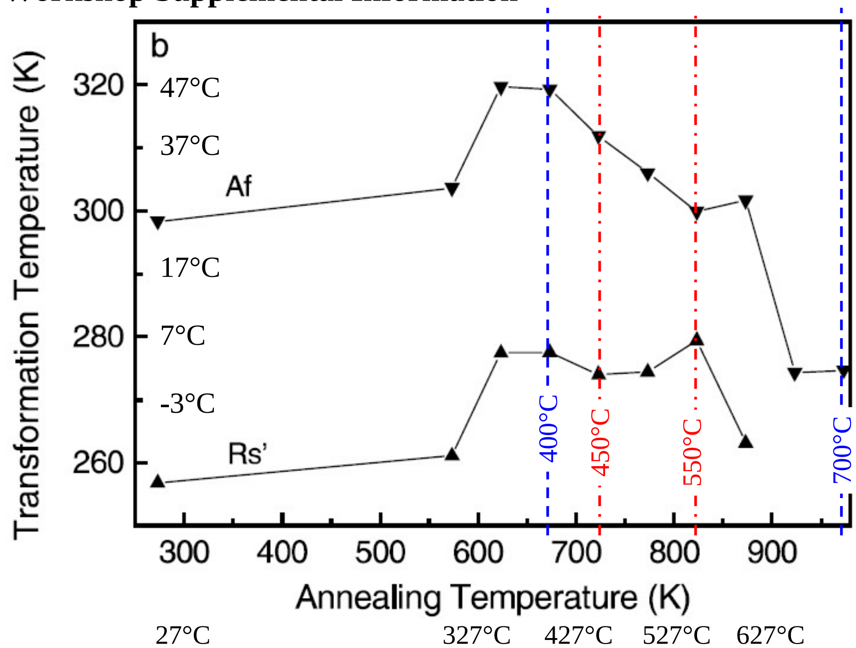


Figure A: *Transformation Temperature (Af) of Ti-50.85 Ni (at.%) alloy as a function of annealing temperature [2] The annealing time is 30 minutes followed by air cooling. The dotted red lines indicate the temperature range used in Figure B. The dotted blue lines indicate the temperature range from Figure C.*

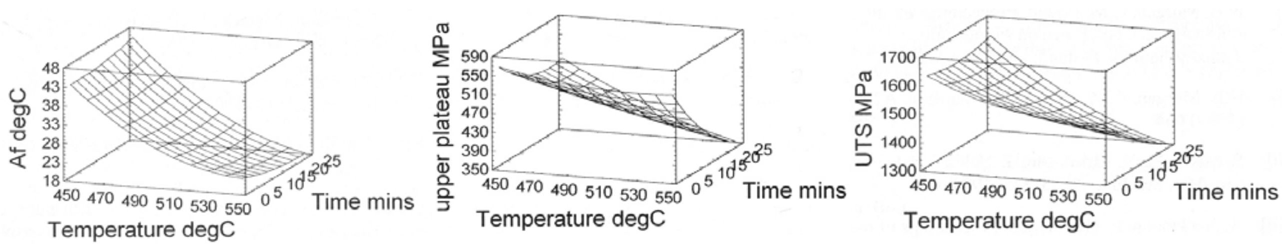


Figure B: *Temperature, Upper Plateau Stress, and Strength as functions of Annealing Process Parameters [3]. The material is a nickel rich, superelastic alloy in the as drawn condition on production tooling.*

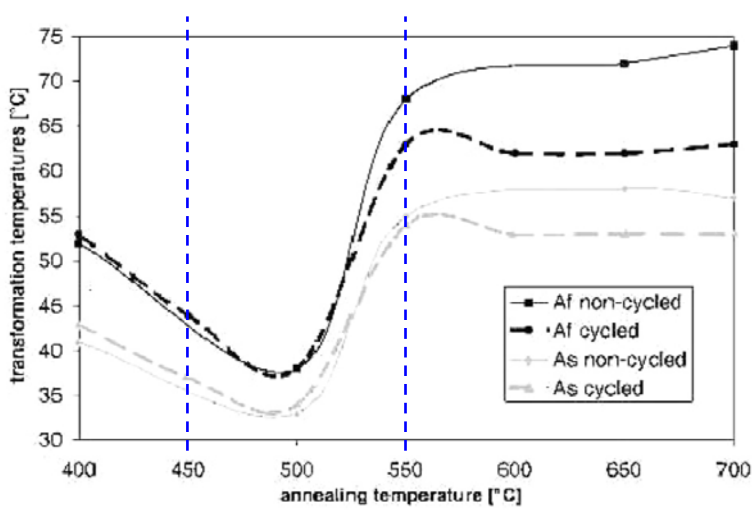


Figure C: *Transformation Temperature (Af) of Ti-50.1 Ni (at.%) alloy as a function of annealing temperature [4]. The specimen is 25% cold-worked ribbon. The annealing time is 60 minutes. The dashed blue lines indicate the temperature range from Figure B.*

7.5. In-Class Workshop Questions

Team Members: ____

To answer and turn in upon completion of the in-class workshop:

Transformation Temperature

Determine and report transformation temperatures within ±2 °C for all wires your team trained:

Wire 1 ________

Wire 2 ________

Wire 3 ________

Shape

Attach a picture or sketch of the wire shape in the fixture prior to heating and after heating once it has been recovered above the transformation temperature. Comment on why these two shapes are different from one another, if at all.

Short-Answer Questions

1. For what applications could a wire with the following temperatures be used? Be creative.
    a. 15°C

    b. 37°C

    c. 100°C

7.6. Homework Lab Instructions

DESIGNING SHAPE MEMORY ALLOY SPRINGS FOR LINEAR ACTUATORS

This report discusses the various engineering calculations necessary to design shape memory alloy (SMA) springs for linear actuators. It also provides a brief background on SMAs and their mechanical properties, focusing on Nitinol wire, a shape memory metal made from nickel and titanium.

This analysis uses a linear extrapolation of published Nitinol wire force vs. wire diameter data to derive data for larger, more useful wire diameters up to 5,000μm. Although several exponential relationships for the published data were evaluated, the linear model provided the most reasonable prediction of the forces available at large wire diameters.

Engineering analysis of the Nitinol wire and spring design determined that springs made of wire diameters less than 1,000μm may see exceptionally high shear stresses and should be thoroughly tested. Spring designers can calculate the stroke of an SMA actuator using the procedure described in this report. However, the dynamics of the loading can drastically affect the results. Therefore, designers should perform mechanical testing when either the stroke or total output force is a critical design constraint.

Using the Excel spreadsheet in the appendix, a spring designer can quickly calculate all of the engineering parameters necessary to design a Nitinol wire spring for a particular actuator design. As shape memory-powered linear actuators gain popularity in the aerospace and medical industries, this quick and powerful design tool can greatly reduce the time and expense associated with designing shape memory alloy springs.

INTRODUCTION

Although the experimental use of SMAs is widespread in aerospace and robotics research, much of the practical value of SMA technology is realized in linear actuators. This report will introduce some of the mechanical and material

TABLE 1: NITINOL WIRE MATERIAL AND MECHANICAL PROPERTY DATA

Transformation Properties	
Transformation Temperature	-200 to 110° C
Transformation Strain (for polycrystalline material)	
for a single cycle	max 8%
for 100 cycles	.6%
for 100,000 cycles	4%
Hysteresis**	30 to 50° C
Mechanical Properties	
Young's Modulus***	
austenite	approx. 12E6 psi
martensite	approx. 4E6 to 6E6 psi
Yield Strength	
austenite	28 to 100 ksi
martensite	10 to 20 ksi
Poisson's Ratio	0.33

** Values listed are for a full martensite to austenite transition. Hysteresis can be significantly reduced by partial transformation or ternary alloys.

*** Highly nonlinear with temperature

First Place
1998 Springs Magazine Technical Writing Contest

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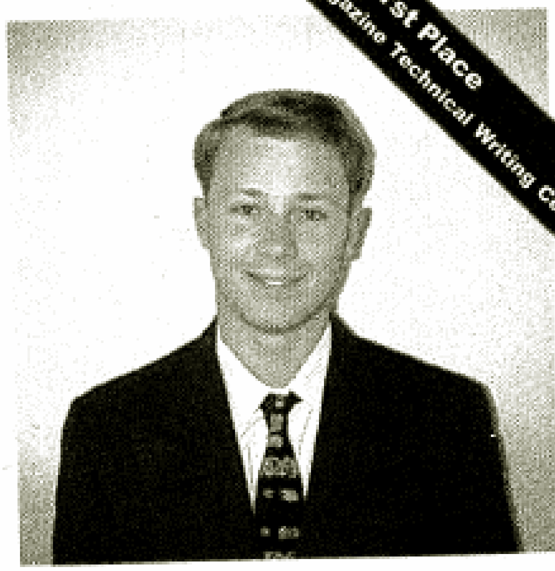


properties of shape memory metals, and attempt to develop a practical procedure to design shape memory springs for actuator service.

At the heart of these actuators is the helical compression spring made of thermally sensitive wire that, when heated, contracts and provides useable mechanical energy. Using common engineering principles for various types of springs, I will demonstrate how to design a spring for a typical SMA actuator.

A review of current literature determined that SMA spring design for actuators has not been publicly addressed to date. Since SMA technology is still in its infancy and SMA actuator development is conducted mostly by universities and small research firms, publications may not be widely available or accessible.

This analysis will show the importance of proper material processing and the limitations of small wire diameters. It will also demonstrate the value of SMA actuators as small, inexpensive mechanical devices.

Methods

Mechanical and Material Properties of Nitinol Wire

Nitinol is the trade name for a group of nickel-titanium alloys that were discovered to possess shape memory properties (4). Discovered by William J. Beuhler at the Naval Ordinance laboratory in White Oak, MD, Nitinol is one of the most widely used commercially available shape memory alloys (4).

SMAs derive their "memory" capabilities from the crystalline phase transformation, between the martensitic and austenitic phases, as the material is warmed by Joule heating (8). Below the transformation temperature, Nitinol wire has a martensitic crystal structure. As the material is heated through the transformation temperature, the austenitic transformation causes the crystals to return to their "parent" location in the crystalline lattice. Springmakers set the parent state by precisely heat treating the material at temperatures around 500°C while tightly holding it in the desired shape. During this "training" process, coils of a Nitinol wire spring can grow as much as 25% in diameter (6). Springmakers should consider this growth when designing fixtures for winding and heat treatment. In addition, cold working of the material can result in "marked changes in the mechanical and physical properties of the alloy" (3).

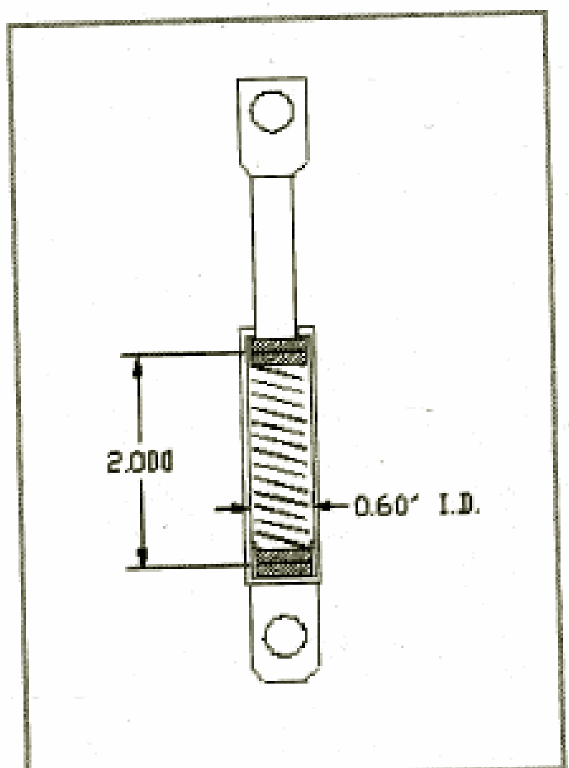


FIGURE 1: SHAPE MEMORY-POWERED LINEAR ACTUATOR

The material property data in Table 1, page 24, taken from a property sheet by Scott Russell of Shape Memory Applications Inc., shows some of the important physical and mechanical properties of Nitinol wire (6).

Actuator Mechanical Design

This analysis uses a standard actuator housing, similar in size and shape to Mondo-tronics' Electric Piston (5), to facilitate experimental testing and repeatability. For simplicity, let's assume the actuator is adequately designed to react to all forces imposed by the SMA phase transformation and external loads. In actual actuator design, the mechanical stability of the actuator housing should be considered in conjunction with the spring design. The actuator housing, shown in Figure 1, page 25, has an inner diameter of 0.60 inches and body length of two inches. This length accommodates three percent compression of the spring upon installation and prevents over-extension of the spring. Precompression, which I will discuss more later, provides a reaction force to return the push rod to the fully extended position.

Since Nitinol wire contracts when heated, we need to design our actuator to retract a given distance, or stroke. We can approximate the stroke parameter of the actuator, since accurate equations for the mechanical and thermo-electric behavior of shape memory alloys are not readily published. Additionally, "the contraction distance (or stroke) varies with the dynamics of how the stress is applied" (6). Changing the dynamics of the applied stress can alter the stroke by three to seven percent of the wire length (6). To capture the ends of the spring, the actuator design incorporates two small retainers that attach to each end. The stationary end is attached to the end of the actuator body by a small lip in the housing side wall. The moving retainer is attached to the end of the push rod and travels with the rod. As the actuator is assembled, the springs are threaded through the eyes in the retainers and locked into place.

Nomenclature

Symbols	Definitions	Dimensions
Do	Outer coil diameter	inches
Dh,o	Outer housing diameter	inches
t	Housing wall thickness	inches
c	Clearance (spring OD & housing ID)	inches
d	Nitinol wire diameter	inches
C	Spring Index	-
Lh	Actuator housing length	-
yi	Precompression displacement	inches
p	Pitch	-
Lo	Free length of spring	inches
Na	Number of active coils	-
Nt	Total number of coils	-
Ks	Shear stress correction factor	-
Kw	Wahl Factor	-
Kb	Bergstrasser Factor	-
Kc	Curvature Correction Factor	-
t	Shear stress in wire	psi.
F	Useable force (shape memory force)	lbf.
y	Spring deflection	inches
k	Theoretical spring constant	lbf./in.
Fmin	Installation Preload	lbf.
Fmax	Shape memory force (=F)	lbf.
Fa	Alternating fatigue force	lbf.
Fm	Mean fatigue force	lbf.
ta	Alternating shear stress	psi.
tm	Mean shear stress	psi.

Engineering Analysis of SMA Spring Design

The process of designing traditional springs is fairly straightforward, since many of the required equations and material properties have been tested and refined over many years of practical use. Shape memory alloy springs, however, have less proven design parameters and equations. Based on the limited engineering data available, this analysis should provide a basic blueprint for designing SMA springs with a reasonable amount of accuracy. For more accurate results, mechanical testing is strongly recommended.

To perform this analysis, I first had to determine the forces expected from a range of Nitinol wire diameters. The data was plotted to determine the relationship between expected force and wire diameter. Because data was available only for a limited range of wire diameters, it was extrapolated using both linear and exponential relationships, and evaluated for accuracy. Using the force vs. wire diameter data, material property data from Table 1, and the following engineering analysis, nearly anyone can design a SMA spring.

The SMA spring design process begins by determining the desired actuator properties, such as allowable outer diameter of housing, housing wall thickness, desired actuator stroke and allowable housing length. Once these design variables are established, start with a given wire diameter, which you can change later as needed to provide the desired spring performance. Calculate the following spring parameters using the variables defined in the Nomenclature chart:

Coil Outer Diameter = $D_o = D_{h,o} - 2t - c$ (1)

Mean Coil Diameter = $D = D_o - d$ (2)

Spring Index = $C = \frac{D}{d}$ (3)

3% Precompression Displacement = $y_1 = L_s * 0.03$ (4)

Free Length of Spring = $L_s + y_1$ (5)

Using Shigley's Table 10-2 and subsequent equations, we can calculate the remaining spring parameters and analyze the shear stresses and effects of fatigue in the wire.

Pitch = $p = \frac{(L_o - 2d)}{N_a}$ (6)

Solid Length = $L_s = dN_t$ (7)

Note: Solid length must be less than housing length minus stroke value.

Shear Stress Calculation

Shear Stress Correction Factor = $K_s = \frac{2C+1}{2C}$ (8)

Wahl Factor = $K_w = \frac{4C-1}{4C-4} + \frac{0.615}{C}$ (9)

Bergstrasser Factor = $Kb = \frac{4C+2}{4C-3}$ **(10)**

Curvature Correction Factor =

$$K_c = \frac{K_b}{K_s} = \frac{2C(4C+2)}{(4C-3)(2C+1)} \quad (11)$$

Shear Stress = $\tau = Kc\frac{8FD}{\pi d^3}$ **(12)**

Deflection and Theoretical Spring Constant

Note: Spring constant should be verified by experimentation

Spring Deflection (Shigley 10-8) = $y = \frac{8FD^3N_a}{d^4G_{heated}}$ **(13)**

Theoretical Spring Constant = $k = \frac{d^4G_{heated}}{8D^3N_a}$ **(14)**

Fatigue Loading Considerations

Installation preload (using k above) = $F_{min} = ky$ **(15)**

Force developed by SMA phase transformation = F_{max} **(16)**

Alternating Fatigue Force

(Shigley 10-26) = $\frac{F\max - F\min}{2}$ **(17)**

Mean Fatigue Force

(Shigley 10-27) = $\frac{F\max + F\min}{2}$ **(18)**

Alternating Shear Stress = $\tau_a = K_s\frac{8F_aD}{\pi d^3}$ **(19)**

Mean Shear Stress = $\tau_m = Ks\frac{8F_mD}{\pi d^3}$ **(20)**

To avoid yielding the spring or inducing a permanent set, the design should limit the applied shear stresses to approximately 85% of the yield point of Nitinol wire (see Table 1). This factor of safety may be changed as necessary. While these values can be iteratively calculated to arrive at the proper spring performance, the Appendix contains an Excel spreadsheet that will allow the user to manipulate the various parameters until the optimal design is created.

Results

As previously mentioned, one of the critical steps in performing this investigation was to develop a relationship between the useable force created by the shape memory phase transformation and the wire diameter. Using the available Nitinol wire data (2) and Flexinol wire data from Dynalloy(1), I developed Figure 2, page 31, to show the known relationship between the shape memory force and wire diameter.

As shown in Figure 2, the force vs. wire diameter data obtained from two independent sources shows close correlation at very small wire diameters, but says nothing about the relationship for much larger, more useful wire diameters. Using a linear relationship derived from the existing data, I obtained force values for wire diameters up to 5,000μm (0.197 in.). I also evaluated several exponential functions, but the linear relationship shown in Figure 3, page 31, provided the most reasonable results, considering the limited amount of data available. While not feasible at the time of this analysis, experimental testing of the various wire diameters could quickly determine the actual relationship between the shape memory force generated and the wire diameter. I used the force vs. wire diameter calculations shown in Figure 3 to perform the remaining spring design calculations.

Since the spring design procedure involves many variables that affect the overall performance of the spring, several iterations are often necessary to complete the design. I used an Excel spreadsheet to perform these repetitive calculations and to allow easy manipulation of large amounts of data. The spreadsheet allows the spring designer to quickly enter all known parameters, such as the critical actuator dimensions and suggested Nitinol wire diameter, and view the results immediately. Then, by changing different variables, the designer can optimize the spring design for a particular application. The spreadsheet also uses a simple lookup table to automatically provide the corresponding force value for the entered wire diameter. An example of a spring design calculation using this spreadsheet can be found in the Appendix.

While performing some spring calculations using the spreadsheet mentioned above, I discovered large shear stress values were for very small Nitinol wire diameters. Figure 4 page 32, demonstrates these large shear stresses in the wire for small wire diameters. The data in Figure 4 applies to a spring coil with an outer coil diameter of 0.75 inches, 75% service factor, and 15 active coils. The shear values rapidly diminish to near yield strength for diameters larger than 500μm, with the largest values of nearly 5.7 million psi at 150μm. For this particular spring, the data suggest a 1,000μm diameter wire as a minimum based on the shear stresses in the wire. Figure 4 also shows the calculated spring rate, k, for the range of wire diameters. This relationship, calculated using Equation 14, increases exponentially with

Figure 2: Shape Memory Force vs. Wire Size for Nitinol and Flexinol Wire

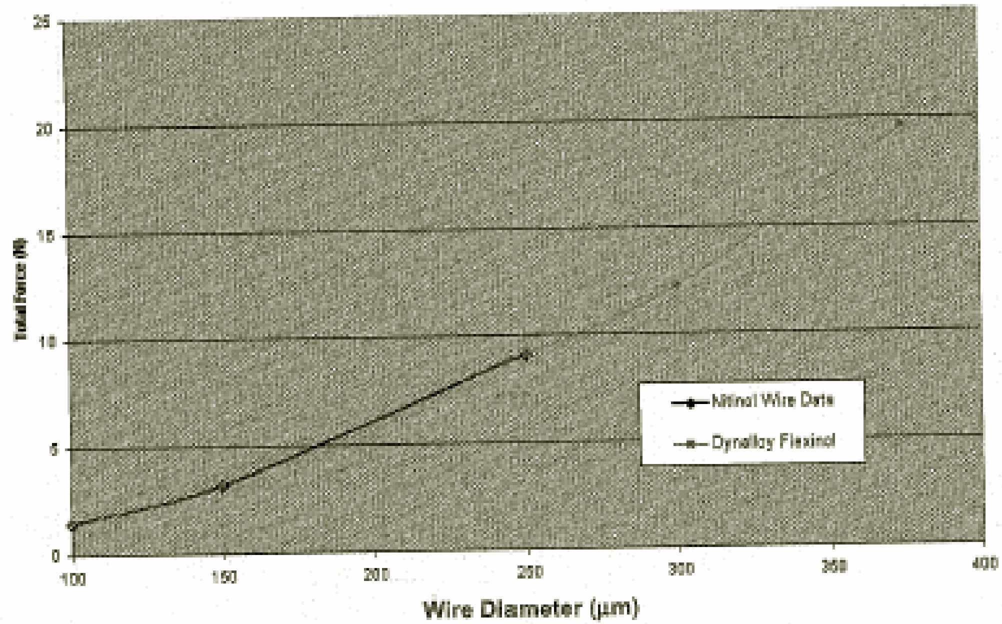
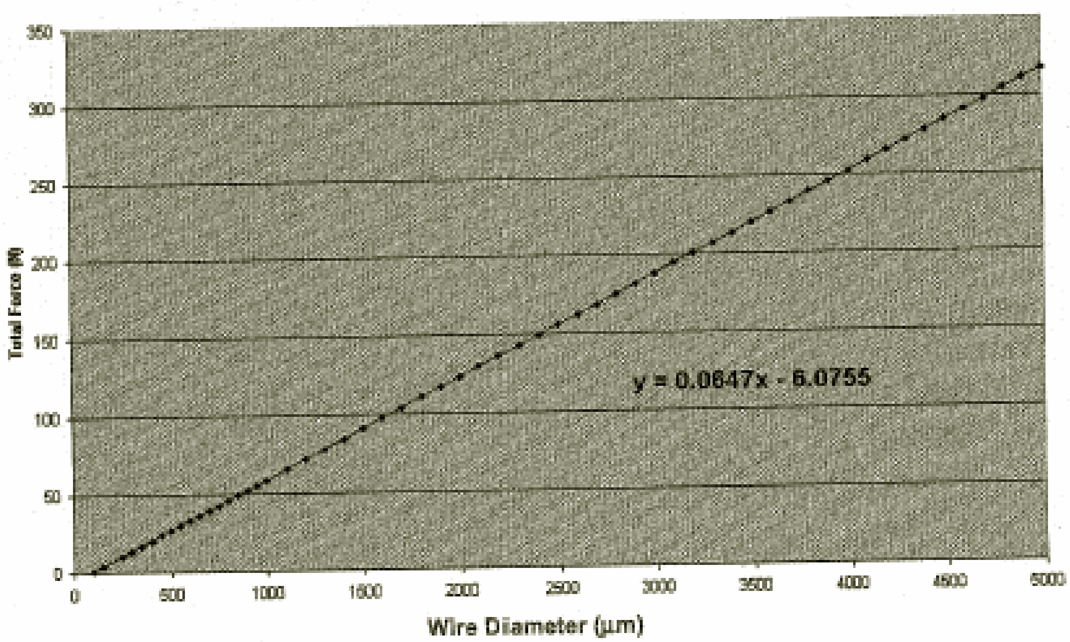


Figure 3: Calculated Shape Memory Force vs. Wire Diameter

Based on Numerical Extrapolation of Published Nitinol Wire Data



increasing wire diameter. The calculated value for a 5,000μm diameter wire spring is nearly 900 lbf./in. The spring rate, like the calculated shape memory force, should be evaluated experimentally, since limited data prevents a more thorough investigation.

Discussion

The purposes of this investigation were to introduce some of the mechanical and material properties of shape memory metals and to develop a practical procedure to design springs for SMA actuators.

There are many factors that affect shape memory spring performance, but manufacturing procedures are critical to the properties of the wire. Spring designers should consider the expansion of the metal during winding and shape "setting," and that cold working can greatly enhance the wire's mechanical properties.

Because the available data for useable output force vs. wire diameter was limited to small wire diameters, I used a linear extrapolation to derive the data for wire diameters up to 5,000μm. Although I evaluated several exponential relationships for the published data, the linear model provided the most reasonable prediction of the forces available at large wire diameters.

Engineering analysis of the Nitinol wire and spring design determined that springs made with wire having diameters less than 1,000μm may see exceptionally high shear stresses and should be thoroughly tested. Spring designers can calculate the stroke of a SMA actuator using the procedure described in this report, but the dynamics of the loading can drastically affect the results. Therefore, they should perform mechanical testing when either the stroke or total output force is a critical design constraint.

Using the Excel spreadsheet in the Appendix on page 34, a designer can quickly calculate all the engineering parameters necessary to design a Nitinol wire spring for use in a particular actuator design. As shape memory-powered linear actuators gain popularity in the aerospace and medical industries, this quick and powerful design tool can greatly reduce the time and expense associated with designing shape memory alloy springs.

References

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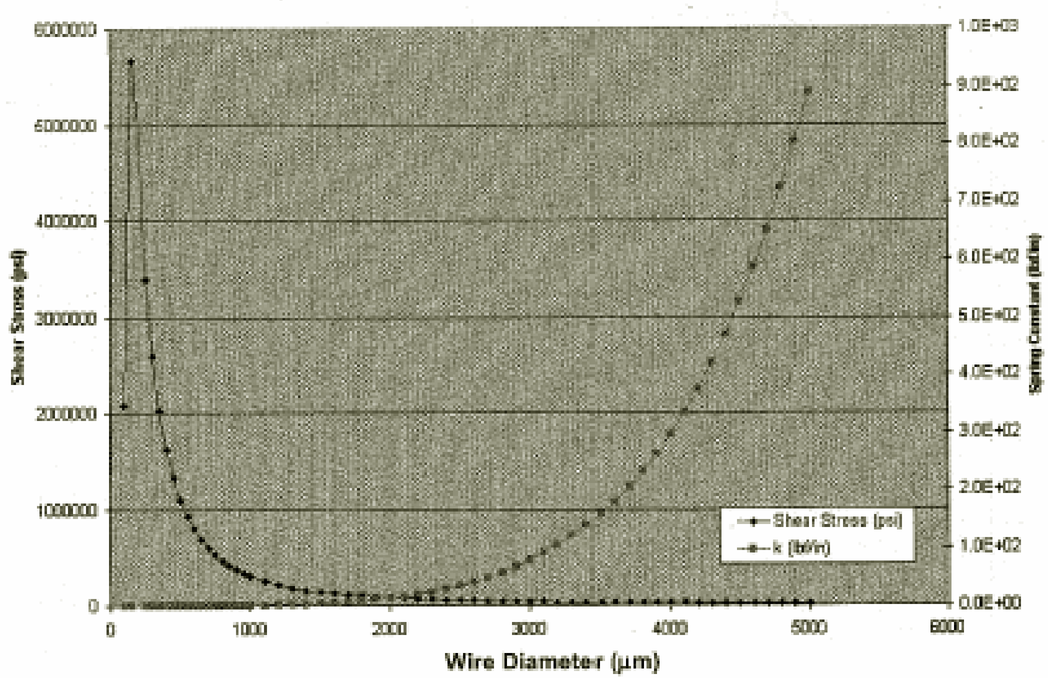
Figure 4: Shear Stress and Theoretical Spring Rate vs. Wire Diameter



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Appendix: Shape Memory Alloy Spring Design Aid For Linear Actuators

This spreadsheet will quickly design a shape memory alloy helical compression spring to fit in a designated actuator housing.

Input

Fill in the fields below to calculate the proper size and properties of SMA spring

1) Actuator Section ***(See "A" in Figure 1, page 25)***

	Dimension		
Allowable O.D. of housing (D_{ho})	A	0.75	inches
Desired wall thickness (t)	B	0.15	inches
Desired actuator stroke	C	1	inches
Allowable housing length (L_h)	D	2	inches

2) Nitinol Wire Spring Design Section ***(See "B" in Figure 1)***

	Variable		
Suggested or available Nitinol wire diameter	d	1,000	µm
Number of active coils	Na	14	coils
Modulus of elasticity – austenitic phase	Gheated	1.20E+07	psi.
Modulus of elasticity – martensitic phase	Gcold	4.00E+06	psi.
Applied force service factor (see note below)	SF	0.75	

Note: The amount of useable force actually transmitted to the actuator pushrod cannot easily be calculated. The service factor (SF) accounts for this uncertainty, effects of friction and uneven loading.

Output

The following fields calculate design parameters for the spring

Physical Spring Parameters

	Variable		
Nitinol wire diameter in inches (convenience)	d	0.039	inches
Useable force (actual force x SF)	**F**	**9.884**	**lbf**
Clearance (spring O.D. and housing I.D.) c=d/4	c	0.010	inches

ing the duties of vice chair of the Texas A&M Chapter of the American Society of Mechanical Engineers. He will graduate in May 1999 with a bachelor's degree in mechanical engineering and hopes to pursue a career in aviation or aerospace manufacturing and development. Stevens may be contacted at 2209 Truman, Bryan, TX 77801; e-mail: cgs6115@acs.tamu.edu; web site: www.fiftysix.org.

Editor's note: *This paper earned first place in the 1998* Springs *Magazine Technical Writing Contest, a competition that was open to all students enrolled at a university, trade school or other post-secondary institution. It is a true reflection of the student's work, and as such has not been altered by* Springs.

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Spring coil outer diameter (O.D.)	Do	0.440	inches
Spring coil mean diameter	D	0.401	inches
Spring index	C	10.18	unitless
Displacement for standard 3% precompression	yi	0.06	inches
Number of active coils	Na	14	coils
Number of end coils (2 for squared/ground)	Ne	2	coils
Total number of coils	Nt	16	coils
Free length of spring	Lo	2.06	inches
Solid length (compressed solid)	Ls	0.630	inches
OK if stroke minus solid length > 0?	–	***0.370***	***inches***
Actual stroke	**R**	**0.370**	**inches**
Pitch	p	0.142	
Shear Stresses in Wire			
Shear stress correction factor (Shigley 10-4)	Ks	1.0491	unitless
Wahl Factor (Shigley 10-5)	Kw	1.1421	unitless
Bergstrasser Factor (Shigley 10-6)	Kb	1.1326	unitless
Curvature correction factor (Shigley 10-7)	Kc	1.0795	unitless
Maximum shear stress	τ	**178,462**	psi.
Max Yield Strength (martensite 10-20 ksi)	YS_m	20,000	psi.
Max Yield Strength (austenite 28-100 ksi)	YS_a	100,000	psi.
Deflection and Theoretical Spring Constant			
Note: spring constant should be verified by experimentation			
Spring Deflection (Shigley 10-8)	y	2.47211	inches
Theoretical Spring Constant	k	3.998399	lbf/in
Fatigue Loading - Shigley			
Installation preload (calculated using k above)	Fmin	9.884484	lbf
Force developed by SMA phase transformation	Fmax	13.1793	lbf
Alternating force (Shigley 10-26)	Fa	1.647414	lbf
Mean force (Shigley 10-27)	Fm	11.5319	lbf
Alternating Shear Stress	**ta**	**31205**	psi.
Mean Shear Stress	**tm**	**202339**	**psi.**
Max Yield Strength (martensite 10-20 ksi)	YSm	20,000	psi.

7.7. Homework Lab Questions

Team Members: ____

To be turned in with helical spring assignment:

Transformation Temperature

Transformation temperature target ________

Actual transformation temperature ________

% Error ((target-actual)/target) ________

Documentation of Design Process

Attach calculations and description of design decisions made throughout this homework lab.

1. If the design needs more force than the original specification, what should be changed in the shape training process?

2. If there were more coils than what was originally designed for, what could that change?

3. If the wire diameter were smaller or larger, how would that affect the design specifications?

4. If the transformation temperature needed to be higher or lower, what would need to change about the shape-training process?

5. For what creative application might one use the spring actuator as designed?

7.8. Grade Sheet

Team Members: ____

____ Prelab Questionnaire (5%)

____ In-Class Workshop (25% total)

- ____ Transformation temperature reporting (5%)
- ____ Shape matching/explanation (10%)
- ____ Temperature application question (10%)

____ Homework Lab (70% total)

- ____ Targets met within ±20% (25%)
- ____ Analysis/design equations (30%)
- ____ Open-ended questions (10%)
- ____ Creative application for spring actuator (5%)

____ Overall Tutorial Grade (100%)

7.9. Lab Evaluation

Fall 2004

Lab being evaluated: ____SMA Shape-Training____________________

What was the purpose of the lab?

What did you learn during the lab?

What were the highlights of the lab?

Please suggest specific ways that the lab can be improved:

7.10. Supplemental Figures

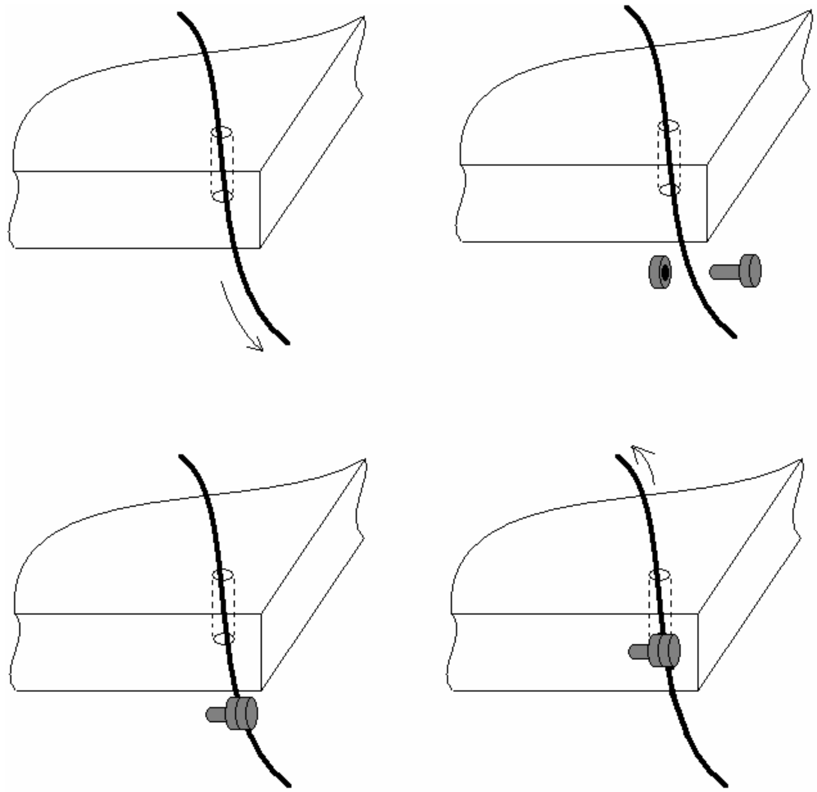

Figure 8: *Fixture fastening scheme*

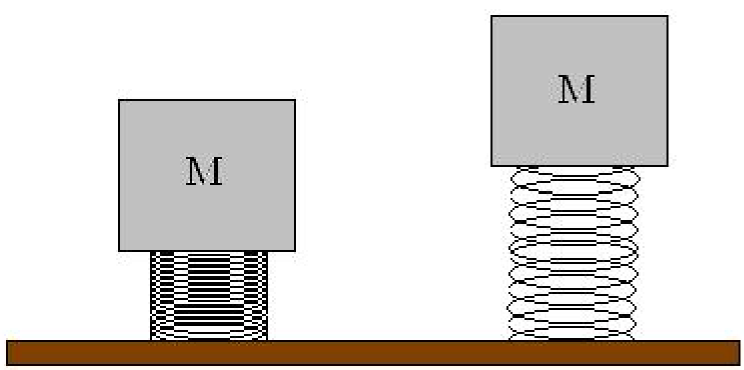

Figure 9: *Test fixture for spring measurements*