Memory Metal: Using Shape Memory Metals in Simple Machines

Teacher Materials (includes Student Materials)

Memory Metals

Purpose

To familiarize middle and early high school students with memory metals. To help students understand the connection between memory metal's atomic structure and its physical characteristics. To identify how Nitinol's memory metal characteristics can be used to solve engineering problems.

Time Frame

The entire set of 8 lessons will take 10-12 class periods to complete (assuming 50 minute class period)

Overview of Memory Metals

What is memory metal?

Memory metal is an alloy that can be "trained" to take on a predetermined shape in response to a stimulus such as a change in temperature. For example, a linear wire can be twisted and bent, yet will return to its original shape when heated above a characteristic temperature.* Many alloys exhibit this characteristic, although the effects are not always as dramatic. Some examples of shape-memory alloys include copper-zinc-aluminum, iron-manganese-silicon, gold-cadmium, copper-aluminum, copper-aluminum-nickel, and the subject of this module, nickel-titanium (NiTi).

*There are some limits to the distortions that the wire will accommodate; for example if bent into a knot, the wire typically cannot return to its linear shape.

What is Nitinol?

Nickel-titanium shape memory alloy, or Nitinol, was discovered in 1965. Nitinol is an acronym for **Ni**ckel **Ti**tanium **N**aval **O**rdnance **L**aboratory, where the alloy's remarkable properties were discovered. Nitinol is an alloy containing nearly equal numbers of nickel and titanium atoms, leading to its common compositional representation as NiTi. The relative amounts of Ni and Ti can be varied by a few percent in order to control the temperature of the phase change responsible for its "smart" behavior. A more accurate representation of its composition is Ni_xTi_{1-x} where x represents the percentage of Ni in the alloy.

Nickel-titanium (NiTi) is a remarkable metal alloy that is representative of "smart materials" that respond to a stimulus in a predictable manner. The wire samples of NiTi used in this unit can be bent at room temperature, but will return to its linear shape when heated by hot air or water as its atoms move in a kind of "atomic ballet." Moreover, the wire can be heated to the much higher temperature of a flame (~500 degrees C), where it can be trained to "remember" a new shape. Subsequently, when the wire is distorted at room temperature and heated by hot air or water, it will return to this new shape. Rods of NiTi can be used to show that the flexibility, hardness, and even the acoustic characteristics of the alloy are all affected by temperature.

The unusual properties of this smart material are derived from two crystal structures that can be inter-converted by changes in temperature or pressure. At temperatures between about 0 and 100 degrees Celsius, there are two important phases or crystal structures of NiTi that can be referred to as the high temperature and low temperature phase, or as austenite and martensite, respectively. The austenite phase has the symmetry of a cube and is characterized by hardness and rigidity. When a rod of NiTi in the austenite phase is dropped, a sound wave propagates relatively unimpeded through the material, yielding a ringing sound.

Martensite

Austenite

b a

γ

c

a, b, and c are not equal,
γ is about 96°

CsCl Structure (cubic)
a = b = c
α = β = γ = 90°

Key

Nickel

Titanium

When cooled, the austenite phase transforms to martensite, which is less symmetric and in fact can have 24 different relative orientations (called variants) of groups of atoms comprising the crystal. When pressure is applied to this low temperature phase, groups of atoms can change their relative orientation to accommodate the pressure, causing the material to be softer and more flexible than the austenite phase. In contrast to NiTi in its austenite phase, when a rod of NiTi in the martensite phase is dropped, its different orientations of groups of atoms act as sound absorbing boundaries and create a muffled thud sound.

Because martensite is also slightly denser than austenite, by LeChatelier's principle, which states that an increase in pressure favors the denser phase of multiple phases at equilibrium, pressure can be used to convert austenite to martensite. This is analogous to the pressure from ice skates helping to melt the ice: application of pressure from the skate helps transform the less dense ice to denser liquid water. This property of Nitinol makes it very useful eyeglass frames. At room temperature, the NiTi of the frames is in the austenite (rigid) phase. When pressure is applied by bending the glasses, the NiTi is compressed into the slightly denser (and more flexible) martensite phase. When the pressure is removed, the frames revert to the less dense, more rigid austenite phase.

The ability to change the shape of the NiTi "smart" material stems from defects, irregularities in the packing of atoms that occur in samples of the material. The defects, which can be altered at the high temperature of a flame where NiTi is in the austenite phase, are used to create the shape to be "remembered" by forcing groups of atoms to have particular positions relative to one another.

Nitinol and the BB Board Analogy

Through an analogy to the atomic scale, structural changes that Nitinol undergoes can be shown with a transparent, empty plastic CD case and BB's.

A. B.

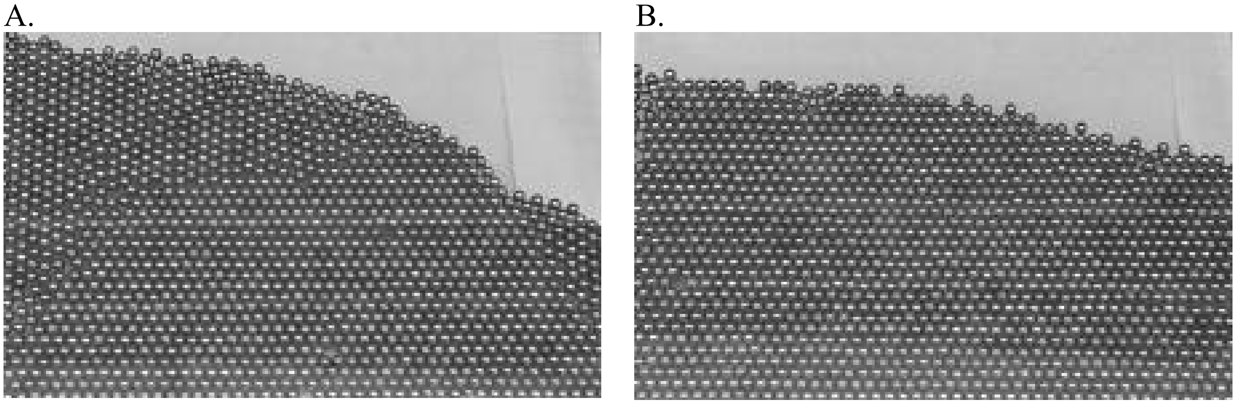


Figure 1. BB board with defects (A), and without defects (B).

Fill the case with a single layer of BB's until it is two-thirds full. Observe the pattern of BB's while holding the case almost horizontal. (Using an overhead projector to display this is also a good method of illustrating it to a class.) Several small groups of BB's, each with a regular internal pattern, are separated from each other by gaps. These gaps form defects. Analogous defects in Nitinol are composed of myriad three-dimensional crystalline regions called grains. Similar to the two-dimensional groups of BB's in the CD case, these grains are of random size, shape, and orientation. When Nitinol is heated to 500-550 degrees Celsius to fix the shape, the defects are minimized but not eliminated. Shifting atoms minimizes the defects, as the grains are re-shaped. This shifting allows the atoms to fit closer together. You can use the CD case filled with BB's to illustrate how the atoms create this new arrangement. Shaking the CD case gently will add energy to the system (analogous to adding heat), and the BB's produce a similar effect. During heating, Nitinol's grains are restructured into the high-temperature austenite phase.

Uses and Capabilities

Since Nitinol has the capability of remembering its shape, this "smart" material can sense changes in its environment. It can respond to disturbances in a pre-programmed way. This new high-tech solid can consequently be used in a variety of artistic, medical, and engineering applications. These include eyeglass frames, surgical stents, golf clubs, coffee pot thermostats, electrical connectors, aircraft de-icers, solar collectors, clamps, sculptures, and structural damping elements, which are used to lessen the damage caused by earthquakes. For the practical joker, a magic spoon that bends when placed into a hot beverage cup also exists. The biocompatibility of NiTi allows it to be used in medical applications such as vascular stents for holding arteries open, anchors for attaching tendons to bone, medical guide wires, medical guide pins, root canal files, bendable surgical tools, and devices for closing holes in the heart as well as the common arch wire for braces. Research that uses memory metal to deploy solar arrays, to create antennae on satellites and to control the balance on helicopter rotor blades is underway. Currently, these as well as many other uses are being developed. See the MRSEC website at http://mrsec.wisc.edu/EDETC/memmetal/index.html for more detailed information on products, for a short movie demonstrating memory metals, and for on-line references about memory metals.

Expected Outcomes

Students will be able to identify the crystalline structures of the austenite and martensite phases of Nitinol and will be able to explain how these crystalline structures affect the strength, rigidity, and sound produced by Nitinol in each phase. Students will determine various methods of heating memory metals. Students will design a way to use Nitinol's properties to solve a given engineering problem.

Memory Metals
Alignment with the Wisconsin Model Science Standards

<u>Standard A: Science Connections</u>
A.8.3 Defend explanations and models by collecting and organizing evidence that supports them and critique explanations and models by collecting and organizing evidence that conflicts with them

A.8.6 Use models and explanations to predict actions and events in the natural world

<u>Standard C: Science Inquiry</u>
C.8.1 Identify questions they can investigate using resources and equipment they have available

C.8.2 Identify data and locate sources of information including their own records to answer the questions being investigated

C.8.3 Design and safely conduct investigations that provide reliable quantitative or qualitative data, as appropriate, to answer their questions

C.8.4 Use inferences to help decide possible results of their investigations, use observations to check their inferences

C.8.5 Use accepted scientific knowledge, models, and theories to explain their results and to raise further questions about their investigations

C.8.6 State what they have learned from investigations, relating their inferences to scientific knowledge and to data they have collected

<u>Standard D: Physical Science</u>
D.8.1 Observe, describe, and measure physical and chemical properties of elements and other substances to identify and group them according to properties such as density, melting points, boiling points, conductivity, magnetic attraction, solubility, and reactions to common physical and chemical tests

D.8.2 Use the major ideas of atomic theory and molecular theory to describe physical and chemical interactions among substances, including solids, liquids, and gases

D.8.3 Understand how chemical interactions and behaviors lead to new substances with different properties

D.8.4 While conducting investigations, use the science themes to develop explanations of physical and chemical interactions and energy exchanges

D.8.7 While conducting investigations of common physical and chemical interactions occurring in the laboratory and the outside world, use commonly accepted definitions of energy and the idea of energy conservation

D.8.8 Describe and investigate the properties of light, heat, gravity, radio waves, magnetic fields, electrical fields, and sound waves as they interact with material objects in common situations

Standard G: Science Applications
G.8.4 Propose a design (or re-design) of an applied science model or a machine that will have an impact in the community or elsewhere in the world and show how the design (or re-design) might work, including potential side-effects

G.8.6 Use current texts, encyclopedias, source books, computers, experts, the popular press, or other relevant sources to identify examples of how scientific discoveries have resulted in new technology

Investigation 1: Exploring Memory Metals

<u>Supplies</u>

hot water
cold water
tongs
beakers
Nitinol wire (##########)

<u>Teacher Notes</u>

1. Students will have little or no previous knowledge of memory metals before this investigation. The first two investigations are meant to introduce students the memory metal phenomenon, and to evoke questions. The only background information that should be discussed is the definition of an alloy. More background information will be provided in later investigations.
2. Before class, prepare hot water by boiling water. Have beakers available to students.
3. Distribute "Investigation 1: Exploring Memory Metals" sheet. Students will be observing what happens to memory metal as they are heated and cooled. Students should bend (or try to bend) the metal in each phase. Tongs will be necessary to bend the wire after it has been placed in the hot water. **CAUTION** Splashing of hot water may occur as the Nitinol quickly returns to the martensite phase. Student should use caution. Splash guard safety goggles are required.
4. Students should answer the questions, and their answers should be discussed as a whole class. It is especially important for students to share questions generated by the investigation.

Investigation 1
Exploring Memory Metals

You will have a chance to investigate the piece of wire that has been provided by your instructor. This wire is part of a general group of metals called “memory metals” or “smart metals”**.** This particular metal is called Nitinol. It is a metal **alloy**. An alloy is a combination of two or more metals. Nitinol contains roughly equal numbers of nickel and titanium atoms.

Please use extreme caution when using hot water in the procedures below. Wear safety goggles when working with the hot water.

1. Your teacher will give you a piece of memory metal. Make coils in the wire by wrapping it around your pencil several times. Is the wire easy or difficult to bend?

2. Place the wire into a beaker of hot water. What happened?

3. Use two tongs to try to bend the wire while it is in the hot water. What happens? Take the wire out of the hot water using the tongs. How is the wire different than it was when it was at room temperature?

4. Set the metal on a table and watch what happens as the metal cools. Try to bend it as it cools. What happens?

5. What questions came to mind as you performed this experiment? What questions do you have about the things you have just observed? What else would you like to know about memory metals?

6. Why do you think these wires fall into a category called “smart materials” or “memory metals”?

7. What do you think might be happening when the metal is heated up and cooled down? What do you think might be happening to the atoms inside the metal?

8. Have you ever seen memory metals used before? Can you think of ways engineers might use these memory metals to solve problems.

Investigation 2: Form and Function

Supplies

one or more of the following for constructing unit cell models

- Solid State Model Kits*(optional)
- construction sets like K'nex or Tinker Toys
- materials such as styrofoam balls, marshmallow, gumdrops, toothpicks

cobs of corn (optional)

sugar cubes or wooden cubes (optional)

*Available from the Institute for Chemical Education (ICE), University of Wisconsin-Madison, Department of Chemistry, 1101 University Avenue, WI 53706-1396, Phone: 608/262-3033, 800/991-5534, Fax: 608/265-8094, ICE@chem.wisc.edu, http://ice.chem.wisc.edu/.

Teacher Notes

Since an understanding of the features of the shape-memory metal cycle is dependent upon the relationship between the structures of the high- and low-temperature phases of this material, it is suggested that these structures be discussed at an early stage of this unit.

Students should have an opportunity to develop an understanding of the concept of the **unit cell** before proceeding with the investigation. Crystalline materials like NiTi have a repeated pattern of atoms that extends in all directions to the surfaces of the sample. A useful way of describing this pattern is to consider a three-dimensional cube, which, when reproduced and moved along each of its edges by a length equal to that of the edge, generates the entire structure of atoms in the crystal. Such a cube is called a unit cell and it provides a template for the atoms and the empty spaces between the atoms in the structure. See Appendices A and B for a more detailed discussion of unit cells.

Another useful way demonstrating a unit cell is to use a piece of corn. Each kernel could represent a unit cell. All the unit cells are essentially (or generally) the same size and shape. They are repeated over and over again in a regular pattern to form a complete cob.

To build an understanding of the unit cell and the connections between atomic structure and function, students should be given opportunities to see and build simplified unit cells for each phase. Students might view an overhead transparency of the structures as show below. The teacher can build or have students build models of both the austenite (high temperature) and martensite (low temperature) structures using the Solid State Model Kit* that the entire class may view.

Alternatively, students might use gumdrops (or marshmallows or other appropriate connectors) and toothpicks or other construction sets like K'nex or Tinker Toys (although placing the center nickel atom in the model may be difficult with these construction kits. For simplicity, in the martensite phase, students can make the connections between all the corners the same length. Students should have enough materials so that they can build models for austenite and martensite phases.

In any case, make sure that students do not know in advance of the class discussion, which phase is the high temperature phase and which is the low temperature phase. In this investigation, they will have an opportunity to figure out which phase matches each structure using their observation skills.

Students can then observe the relative strength and flexibility of each model and answer the questions at the end of the investigation. When students have completed their own models, they may join them with others to create a large model of each material.

Unit cells of NiTi in the martensite and austenite phases.

Martensite
(flexible, low temp)

b a
γ

c

a, b, and c are not equal,
γ is about 96°

Austenite
(rigid, high temp)

CsCl Structure (cubic)
a = b = c
α = β = γ = 90°

<u>Key</u>

Nickel

Titanium

Investigation 2
Form and Function

In Investigation 1, you had the opportunity to observe how Nitinol behaves when heated and cooled. Scientists studying Nitinol have determined that there are two different phases of Nitinol, one is a high temperature phase and the other is a low temperature phase. In this investigation, you will use your observation skills to match the structures presented below with the phase at which that structure is found.

The structures below each show two **unit cells**. A unit cell is a small portion of a material's atomic structure. This unit cell can be repeated in all directions to show the full structure of the material. One analogy is to use 27 sugar cubes to build one larger cube. Another oversimplified analogy is a cob of corn. Each individual kernel of corn represents one unit cell of the structure. The basic kernel shape is repeated over and over again in regular patterns to form the entire cob of corn.

The diagram below shows the martensite and austenite phases of Nitinol. One of the phases is the high temperature phase and the other is the low temperature phase. You'll have to figure out which one is which.

Martensite

Austenite

b

a

γ

c

a, b, and c are not equal,
γ is about 96°

CsCl Structure (cubic)
a = b = c
α = β = γ = 90°

<u>Key</u>

Nickel

Titanium

1. As assigned by your teacher, build simple models of austenite and martensite. Use these model and/ or the diagrams above to answer the following questions.

2. Compare the models of austenite and martensite. How are their basic structures different?

3. Test the strength and flexibility of the martensite and austenite phase models. Which one is stronger? Which one is more flexible?

4. From what you have learned about these structures and by testing the strength of your models, which do you think would be the more flexible low temperature phase of the wire in Investigation 1? Explain.

Investigation 3: Properties of Austenite and Martensite

Supplies

2 samples of NiTi , one in the austenite phase at room temperature and the other in the martensite phase at room temperature (######)
string
400 mL beaker
method of bringing water to boiling (hot plate, Bunsen burner)
thermometer
tongs
gloves
Safety goggles
Liquid nitrogen (local sources include dermatologists, welders, universities, hospitals, research institutions). An alternative would be to use dry ice and acetone bath.

Teacher Notes

In the first part of this investigation, students will be given opportunities to observe different samples of NiTi, one in the martensite phase at room temperature and the other in the austenite phase at room temperature. They will determine which sample is martensite and which is austenite. Next, if the materials are available, students will cool the austenite sample using liquid nitrogen or a dry ice/ acetone bath (using extreme CAUTION) to transform it to the martensite phase so it can be bent (using gloves). After that, students will have an opportunity to determine the **transition temperature** of the martensite sample by slowly heating the sample until it becomes rigid (austenite phase). This transition temperature is determined by the relative amounts of nickel and titanium in the sample. Small changes in the composition of the metal can greatly affect the transition temperature of the wire. Temperatures at which Nitinol samples change from one phase to another vary widely as a direct result of very small changes in nickel/titanium ratio. By changing the relative amounts of nickel and titanium in the wire, wire can be made to respond to a wide range of temperatures and can be used for a variety of purposes.

A diagram of the set up for this part of the lab is shown in Figure 3. It is very important that the neither the thermometer nor the memory metal sample touch the bottom of the beaker or hot pot since the temperature of the heat element or the beaker will not be the same as the temperature of the water.

In this investigation, the transition temperature is defined as the temperature at which the wire has become completely rigid. Students should the average their transition temperature data with the rest of the class data. Students can then use this average transition temperature data and the graph provided to determine the percentage of nickel contained in their samples.

Investigation 3
Properties of Martensite and Austenite

<u>Part I: Review</u>

1. In the last investigation, we matched each phase of NiTi with its structure. Martensite is found in which temperature phase, high temperature or low temperature?__________ . Austenite is found in which temperature phase, high temperature or low temperature? __________

2. What we learned in Investigation 2 can be summarized by the following equations:

   Equation 1: martensite + energy = austenite

   Equation 2: austenite – energy = martensite

In your own words, restate what each equation means.

Equation 1:

Equation 2:

3. As you have already learned, Nitinol is a mixture of nickel and titanium. By slightly changing the amount of nickel that is mixed with the titanium, material scientists can change the temperatures at which Nitinol changes from martensite to austenite. Depending on the mixture, Nitinol can be in the martensite phase at room temperature or in the austenite phase at room temperature.
4. You will be given two samples of Nitinol. One is in the austenite phase, the other in the martensite phase. One is called Sample A and the other Sample B. Try to bend each sample. Which sample is the martensite phase? __________________How can you tell?

5. Try scratching the samples with one another. Which sample is scratched by the other? _____________________

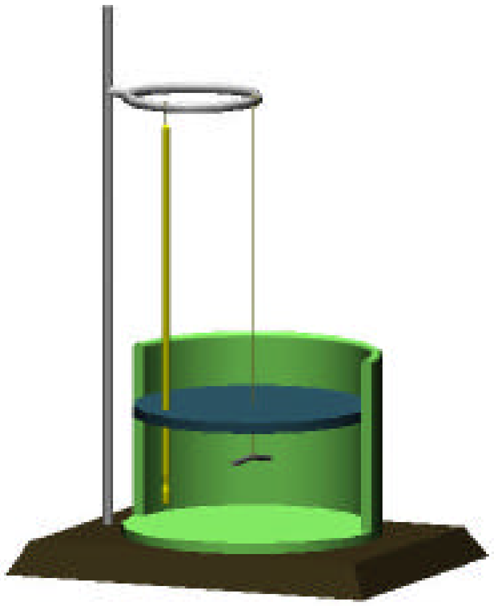
<u>Part II: Moving from Austenite to Martensite</u>

6. Place the austenite sample in the liquid nitrogen or dry ice/ acetone bath. What happens? Why?

7. After bending the cold sample, how do you return it to its original shape?

Part III: Transition Temperature

As you found out in Investigation 1, a martensite sample can be returned to it original shape by heating it with hot water. By changing how much nickel is in the NiTi, material scientist can change how warm the martensite has to be before it returns to the austenite phase. This is called the **transition temperature**. This is the temperature at which the wire changes from austenite to martensite and vice versa.



8. Bend the martensite sample. Set up your equipment as shown above (beaker is cut open to show placement of the Nitinol and thermometer). It is very important that the neither the thermometer nor the memory metal sample touch the bottom of the beaker or hot pot since the temperature of the heat element or the beaker will not be the same as the temperature of the water. Tie a string to the martensite rod so it can be suspended in the hot water. Slowly heat up the water in the beaker. As the water is heated, you will probably notice that the wire begins to straighten out. Carefully observe the wire. When it has become completely rigid and has returned to its original shape, record the temperature. This is the transition temperature. At what temperature does the sample fully transform into austenite? _______________

Part IV: Analysis

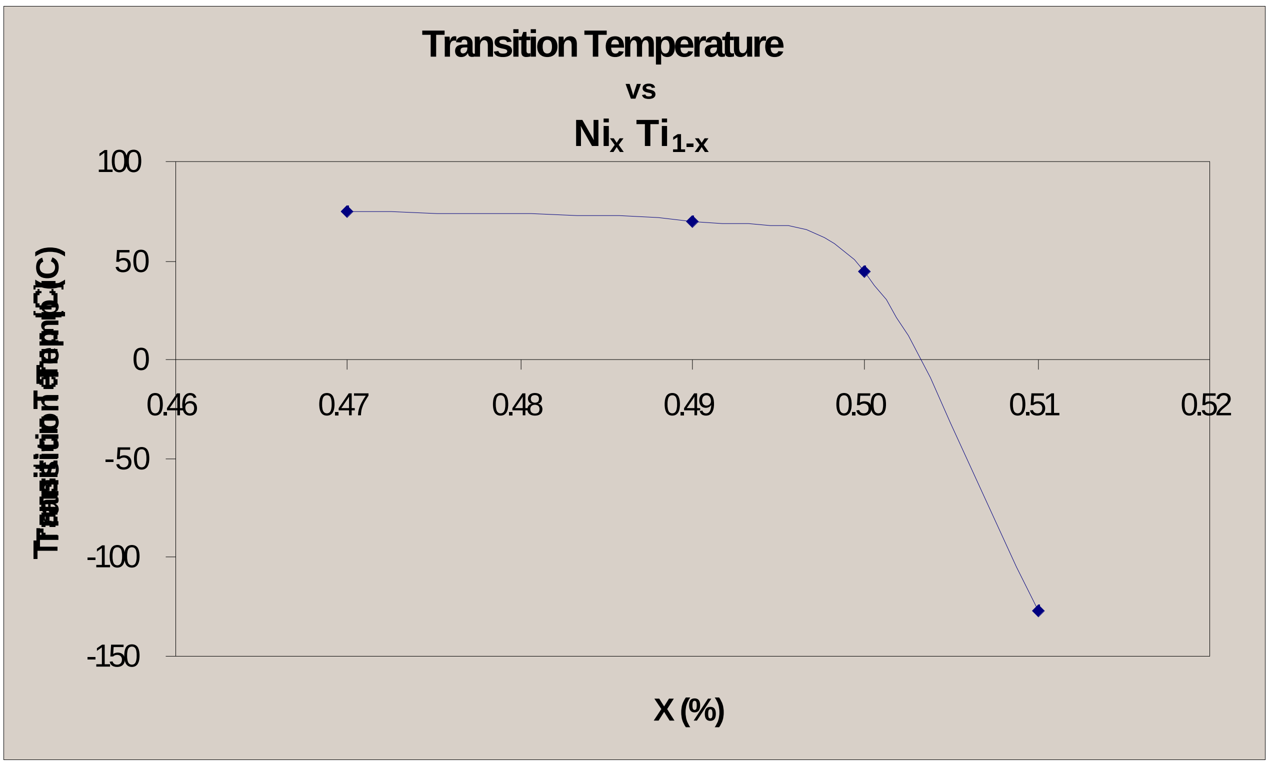
9. Obtain the transition temperatures of all the other students in the class. Average the data. What is the average transition temperature? _______________

10. Use the graph on the next page and determine what percentage of nickel the wire sample contains using the average transition temperature data above. What percentage of the sample is nickel? ____________________

11. If you wanted to use Nitinol that become soft and flexible when placed in an ice bath (0 C), about what percentage of nickel might you use? Select one.

a. 49.5%   b.50.0%   c. 50.5%   d. 51.0%

12. Flexible, "unbreakable" eyeglass frames are made with Nitinol memory metal in the austenite phase at room temperature. If the frames are made with 50.5% nickel, what might happen to eyeglass frames worn in Antarctica on a very cold day (about – 60 C)? Explain.



Investigation 4: Acoustic Properties of Nitinol

Supplies

NiTi rods used in Investigation 3 above
Hot water (at least 80 C)
Meter stick (optional)
tongs

Teacher Notes

In this investigation, students have a chance to examine the different acoustic properties of Nitinol in its two phases. Students will observe how these acoustic properties change as Nitinol cools. When dropped, martensite tends to make a “thud” while austenite makes ringing sound. It is not surprising that the two NiTi phases also exhibit a different “acoustic signature” as well as other physical properties. The propagation of sound is affected by a number of factors but most certainly depends upon structure. The uniform structure of austenite allows sound waves to travel through it readily. In martensite, on the other hand, the boundaries between regions with different orientations of the less symmetric monoclinic structure act to reduce the vibrations and muffle the sound. The net result is a noticeable “ringing” sound when the austenite rod is dropped, compared to a dull “thud” for the martensite.

Students will hold the martensite sample in the hot water for a few seconds. They should notice that it becomes rigid (transforms to the austenite phase). They will quickly take it out of the hot water, drop it, listen to the sound produced, and continue to pick it up and drop it until there is no more change in sound. Students should observe that as the rod cools, it goes from the austenite phase to the martensite phase and consequently the sound goes from ringing to thudding.

Investigation 4
Acoustic Properties of Nitinol

1. Compare the two Nitinol rods you have been given. Determine which of the rods is in the martensite phase. How can you tell it is in the martensite phase?

2. Drop each of the Nitinol rods onto the table from a height of one meter above the tabletop. . The rod should be held parallel to the tabletop as it is dropped. Note the nature of the sound that the rod produces. Would you categorize the sound of the martensite as a "thud" or a ring? How would you categorize the sound of the austenite?

3. Using tongs, drop the martensite rod in a beaker of boiling or near boiling. Remove it from the water with tongs. As in step 2, drop the rod onto the tabletop from a height of one meter (the rod should be held parallel to the counter as it is dropped). Note the nature of the sound that the rod produces (thud, ring, or an intermediate sound). Quickly pick it up with your fingers (it will cool off rapidly) and drop it again, making sure to note the nature of the sound. Continue to pick up and drop the rod until there is no more change in sound (about 2-3 times).

4. Describe the changes in sound produced as the rod cooled.

5. Knowing what you do about atomic structure of martensite and austenite, how might you explain the different sounds they make when dropped? How do you account for the change in sound as the rod moves from the martensite to austenite phase?

Investigation 5: Changing the Shape of a Memory Metal Rod

Supplies

NiTi wire (######)
Bunsen burners
Hot water
Gloves
Access to an art kiln (optional)
BB boards (optional)
Cobs of corn (optional)

Teacher Notes

Questions may arise as to how the memory was imparted to the metal in the first place or whether or not the memory may be altered. It should first be noted that if the transition between phases were represented by the thermochemical equation below:

Martensite + energy _ Austenite

the energy required would be in the neighborhood of only a few kJ/mol. The Ni and Ti atoms within one of the many crystalline regions (called grains) within a sample of memory metal in the austenite phase are almost perfectly arranged with a few imperfections here and there. (A piece of galvanized metal clearly shows such crystals, and the BB board discussed earlier in the Background Information section shows defects within the crystal) These defects in the austenite phase along with the grain boundaries, another kind of defect, are responsible for giving the austenite its "remembered" shape. To give the metal a new shape it is necessary to create a new set of defects that will in turn force the metal to return to this new shape upon mild heating through the martensite-to-austenite phase change. This new set of defects can only be obtained by heating the metal sample to approximately 500^{o}C while it is secured in the new shape. This large amount of thermal energy excites the atoms. As the metal cools, atoms settle into lower energy positions specific to the new shape, thus creating a new set of defects.

It is highly recommended that these phenomena be fully explained before proceeding with the investigation. The generally straight rows of corn on a corn cob can be used to demonstrate how some grains of corn that do not fit into these neat rows form a **defect** in the pattern. These unique defects in the corn are like the defects in the NiTi. These defects give the NiTi its "remembered" shape. BB boards are also very useful tools for helping students understand what is happening in this investigation.

The activity simply involves having the students bend the wire into a new shape. They hold it at its ends (using gloves) and heat the center in the flame of a candle. The wire resists bending until it reaches the temperature of the flame at which point it yields and can be bent into a V-shape. When it is cooled, it can be straighten, heated with hot water and returned to the V-shape. Note that memory metal samples may become brittle and break after repeated heating and cooling.

Extension

If a metal frame of some type is available, it is possible to produce more complicated shapes (even your name) with the memory metal. This would require that you have access to some sort of metal rack or basket capable of withstanding the annealing temperatures and a heat source capable of providing those temperatures. The kiln in the art department would certainly be adequate; or perhaps the physics department has a muffle furnace that would work as well. The wire would have to be secured to the template and the entire assembly placed in the heat source for a period of about 15 minutes, removed, and allowed to cool. Longer heating may destroy the memory feature of the wire. Annealing produces the "remembered" shape by creating a new set of defects. Prolonged heating, however, will destroy the shape memory feature that relies on these defects. See http://mrsec.wisc.edu/EDETC/memmetal/index.html to find out more about obtaining a memory metal kit that contains a piece of memory metal that has been "trained" to spell out a word.

Investigation 5
Changing the Shape of a Memory Metal Rod

So far in our investigations we have been changing NiTi rods from one phase to another using hot water or liquid nitrogen. We have found that heating the rods returns them to their rigid austenite phase. The rods we have used thus far straightened as they returned to the austenite phase.

You may have wondered if it is possible to change the shape of the Nitinol rod so that it returns to a different shape when heated. You may have also wondered how the rod's original shape is always "remembered." This ability to "remember" its original shape is caused by small gaps or defects. All the atoms in the metal are not perfectly arranged.

Consider the cob of corn we used to understand what a unit cell is. For the most part, the kernels of corn repeat over and over again in regular ways to form a full cob. Usually there are straight rows from one end of the cob to the other. However, some kernels of corn do not neatly fit into the rows and may even form small, distorted rows. There may even be gaps between rows in some places. We could call these areas of "misplaced" kernels and the gaps between rows **defects**. In a very similar way, "misplaced" atoms and gaps form defects in the NiTi. This unique set of defects and atom arrangements give the Nitinol its "remembered" shape, the shape to which it returns when heated. Your teacher might also show you another analogy using BB boards that demonstrates this same concept.

To give the metal a new shape it is necessary to create a new set of defects that will in turn force the metal to return to this new shape upon mild heating through the martensite-to-austenite phase change. This new set of defects can only be obtained by heating the metal sample to approximately 500^{O}C while it is secured in the new shape. This large amount of thermal energy excites the atoms. As the metal cools, atoms settle into lower energy positions specific to the new shape, thus creating a new set of defects.

1. Using two tongs, grasp the wire at its ends (CAUTION, the ends may be sharp!), and hold the middle of the wire over the flame. When the middle of wire becomes red hot, bend it into a V-shape using the tongs and place the middle of the V into the center of a candle flame.

2. Cool the wire by blowing on the wire, straighten out the wire, place in a cup or beaker, and cover with hot water. What happens?

3. In a similar fashion, return the wire to its original shape.

4. Why can't you use hot water to retrain the wire to "remember" a new shape?

Investigation 6: Heating Memory Metals

Supplies

Nitinol samples (######)

As many possible ways to heat memory metal as are available. These may include but should not be limited to the following possibilities:

- magnifying glasses
- batteries (1.5 V, 6V, 9V) and alligator clips
- black paper
- exothermic chemical reactions
- solar panels
- hair dryer

Teacher Notes

So far, we have only used hot water to change Nitinol from the martensite to austenite phase. For most applications of memory metals, it is far more practical to heat the memory metal using other methods than hot water. Hot air, an electric current, light passing through a magnifying glass, heat from a chemical reaction, and many other methods of heating are possible and probably more practical than immersion in a hot water bath. In this investigation, students brainstorm and test various ways of heating memory metals. Students might try hooking a memory metal sample to a battery, a solar panel, or a series of solar panels to see if they are able to cause a transition. Exothermic reactions may also work. Students should have ample time to brainstorm, gather necessary materials, and test their ideas.

Investigation 6
Heating Memory Metals

In the previous investigations we used hot water to change memory metal samples from the martensite to the austenite phase. If we want to use memory metals for practical applications, it is useful to find other ways of heating the memory metal.

1. What might be some other ways to heat the memory to its transition temperature? Brainstorm possibilities and list them below.

2. Design an experiment to test one of these possible ways of heating the wire. Describe your procedure below. Draw a diagram to show how you will test this heating method.

3. What materials will you need?

4. Carry out your experiment. Did your original idea work? Did you make any modification to the original design to make it work. Be ready to demonstrate your experiment and share the results with the rest of the class.

Investigation 7: Practical Applications

<u>Supplies</u>

paper
colored pencils
markers

<u>Teacher Notes</u>

Because of its ability to be trained and because Nitinol's transition temperature can be manipulated, it has a wide range of useful applications. Applications of Nitinol include eyeglass frames, golf clubs, coffee pot thermostats, electrical connectors, aircraft de-icers, solar collectors, clamps, sculptures, and structural damping elements, which are used to lessen the damage caused by earthquakes. For the practical joker, a magic spoon that bends when placed into a hot beverage cup also exists. The biocompatibility of NiTi allows it to be used in medical applications such as vascular stents for holding arteries open, anchors for attaching tendons to bone, medical guide wires, medical guide pins, root canal files, bendable surgical tools, and devices for closing holes in the heart as well as the common archwire for braces. Research that uses memory metal to deploy solar arrays, to create antennae on satellites and to control the balance on helicopter rotor blades is underway. Currently, these as well as many other uses are being developed. The following MRSEC website has detailed product information on many of these uses: http://mrsec.wisc.edu/EDETC/memmetal/index.html.

In this investigation, students brainstorm possible inventions using memory metals. Each team of students should develop the idea and produce a poster of this idea. Students' ideas in my classroom have been very creative. These ideas include memory metal hair weaves that curl or straighten when heated with a hair dryer, a memory metal Slinky that won't bend and kink, a memory metal safety toy that sends up a small flag if bath water is too hot. To help students get started, it may be useful to provide several examples of existing applications of memory metals. However, students should not be given to many examples since that may make it difficult for students to come up with their own original ideas. Individual, small group, and large group brainstorming sessions are useful for coming up with possible invention ideas. When they have completed the work with their own ideas, it might be interesting for students to visit the MRSEC website and explore various memory metal products now available or under development.

Investigation 7
Practical Applications

As you have learned in previous investigations, Nitinol can be retrained in different shapes and can be made to transition between phases at different temperatures depending on its composition. Because of these unique qualities, it has a wide range of uses in industry, health, art, and home use. It can be made into sheets of Nitinol, Nitinol tubes, or very thin wires. Since Nitinol has the capability of remembering its shape, this "smart" material can sense changes in its environment. It can respond to temperature changes in a pre-programmed way. This new high-tech solid can consequently be used in a variety of artistic, medical, and engineering applications.

As assigned by your teacher, brainstorm and identify real life problems that could be solved using memory metal or toys that could incorporate memory metals. When brainstorming is complete, choose one problem to solve or an idea for a memory metal toy. On posterboard, draft a diagram of the design for your solution to this problem or draft a design for a toy that uses this material. Clearly label the parts of the diagram. On the poster, write a paragraph describing how the device or toy might work. Be prepared to share your idea with other students.

<u>Possible Problems to Be Solved</u>

<u>Possible Memory Metal Toys</u>

<u>Toy or problem I have chosen:</u>

Design Draft:

Investigation 8: Motorless Motion

Teacher Notes

For engineers, one the most exciting aspects of memory metal is that it is capable of providing motion with out the use of a motor. Memory metal can easily be caused to contract by running an electric current through it. As the current passes through the wire, the wire heats up and moves from the martensite to austenite phases. When the current is remove, the metal cools and returns to its original phase. Use a current to heat the wire can provide a simple way to regulate the movement of the wire.

This investigation contains two plans. The first plan is for a simple paper airplane launcher. (It might also be used to launch many other projectiles.) It is relative simple, requires few materials, and uses a small length of 250 um of memory wire. The next project is an electronically activated catapult that is quite simple to make but is a little more expensive to make than the launcher (though it still costs less than $2 per catapult).

Supplies

See the attached *Memory Metals Projects: Muscle Wire* section for supplies, building and operating instructions.

Investigation 8
Motorless Motion

For engineers, one the most exciting aspects of memory metal is that it is capable of providing motion with out the use of a motor. Memory metal can easily be caused to contract by running an electric current through it. As the current passes through the wire, the wire heats up and moves from the martensite to austenite phases. When the current is removed, the metal cools and returns to its original phase. Use of a current to heat the wire can provide a simple way to regulate the movement of the wire.

You will be provided plans for building a catapult and a paper airplane launcher using a lynch pin that is pulled by a memory metal attached to a simple circuit. With the materials provided, build one of the two devices.

Memory Metal Assessment

Matching
Match the word with the best definition.

____ 1. Austenite

____ 2. martensite

____ 3. transition temperature

____ 4. Nitinol

____ 5. alloy

____ 6. smart material

____ 7. unit cell

____ 8. phase

a. a pattern than can be shifted repeatedly to create the entire structure of atoms in crystal

b. a solid solution composed of two or more metals

c. alloy containing nearly equal amounts of nickel and titanium

d. a physical state of matter

e. a substance that can respond to stimuli in its environment

g. high temperature phase

h. low temperature phase

i. the temperature at which a phase transformation occurs

Multiple Choice
Choose the best answer.

______ 9. Austenite exhibits which characteristic?
- a. contains more nickel than martensite
- b. is more rigid than martensite
- c. is more flexible than martensite
- d. both a and c

______ 10. At room temperature Nitinol can exist in either of two structures, which are dependent upon
- a. the mass of the sample.
- b. the exact ratio of Ni to Ti.
- c. the length of the sample.
- d. the diameter of the rod.

_______ 11. In some phase changes like that of ice and water, there is a noticeable change; however, there is no visible phase change between austenite and martensite because
- a. it only occurs at the atomic level.
- b. only two atoms exchange places.
- c. the structures are the same
- d. the temperature is too high
- e. no phase change occurs.

12. Describe why heating a memory metal sample to over 500 C causes it to take on a new “remembered” shape.