SMART MATERIALS: NITINOL
TEMPERATURE vs. DIMENSIONAL CHANGES
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Abstract
Some materials display behavior that is unique and useful. An alloy of titanium and nickel (about 50:50) is branded Nitinol and shows a dramatic change in dimension when a certain temperature change occurs, and a resulting phase change happens (a change in the spacing and structure of the atoms).

This is different that a material expanding as temperature increases. Normal thermal expansion is characterized with a simple equation: \( \Delta x = \Delta T \times \text{Length} \times \text{CTE} \), where CTE is the ‘coefficient of thermal expansion’. CTE values are properties of materials, so we can look them up. Even Nitinol has a CTE value. This is used to as part of an analog ‘thermostat’ to control furnaces in houses. A coil of metal expands or contracts with changing temperatures. A coil geometry is used because you can get a lot of expansion (the ‘\( \Delta x \)’, above) if you have a long length (the ‘Length’ above): and coils are one way to put a long length into a small space. The first part of this module focuses on the use of CTE to correlate a change in temperature with movement.

The concept and use of CTE is not considered ‘smart’, or supporting our definition of a ‘smart material’. It is useful, but Nitinol offers a much more interesting behavior. At cool temperatures (about freezing), Nitinol can be deformed from one shape to another (up to about 6-8 % strain). Then, upon heating (around 100F), the structure quickly reverts to its original shape! This can be 20 or 30 times the change in dimension exhibited by simple CTE. Also, the stress generated by the phase change is high (up to 100ksi), meaning that it is possible to apply a lot of force to a device, almost instantaneously.

Part two of this module concerns our exploration of this ‘shape memory’ phenomena. There is a procedure for managing the memory process. First, the Nitinol is ‘reset’ (commonly termed ‘shape setting’) by annealing it (holding the material in a shape, and then heating to about 1000F). This is above the temperature of normal kitchen ovens (500F), so a special furnace or a candle flame is in order. But remember, you have to HOLD the Nitinol in a shape while heating it. Then cool the Nitinol and put it in an ice bath. Now deform it to some other shape, and then heat it to a couple hundred degrees (in boiling water), and it will ‘spring back’ to its original ‘set shape’.
These smart materials are very useful! Example applications include medical devices such as peripheral stents and heart valves. The stents start out as very thin diameter ‘webbed tubes’ that can be inserted through arteries. When in location, they are ‘warmed up’ and they expand to their ‘set shape’ which supports the arterial walls. Other uses include various actuators (i.e. mechanical action devices) that are controlled by temperature (either directly or via electric excitation).

Module Content: This module is accompanied by a PowerPoint presentation that may be used in presenting the unit.

Module Objectives: Students will be able to
- Measure the dimensional change by CTE and Shape Memory effects.
- Qualitatively compare the mechanical properties (e.g. strength) of the two effects.

MatEdU Core Competencies Addressed:
- 0B Prepare tests and analyze data
- 8A Demonstrate the Planning and Execution of Materials Experiments
- 9G Discuss advantages of Nickel alloys and their uses
- Xx Explain, predict and measure CTE

Type of Module / Mode of Presentation: This activity describes in-class, hands-on manipulation of the geometry of Nitinol by controlling temperature.

Key Words / Key Phrases: Nitinol, Shape Memory Alloy, Coefficient of Thermal Expansion

Time required: This activity takes an hour to perform and evaluate.

Pre-requisite knowledge: None

Target grade levels: Secondary education

Equipment and supplies needed (per participant or team of 2):
Environment: Each student or team will need:
- Table-top space (about four square feet)

A list of materials at a ‘common space’ (to be used by all groups) follows:
- Temperature: ice water bath, boiling water bath, candle flame (if desired)
- A heat-proof working surface (a foot-square floor tile works great)
- PPE (e.g. gloves, eyewear)
- Optional: two pliers (to constrain wire if needing to ‘set’ the Nitinol)

A list of materials for each group follows:
- Two three-inch lengths of Nitinol wire
Curriculum Overview and Instructor Notes:
Nitinol wire is inert, so there is no safety issue related to the material itself. However, both ice water and boiling water baths are used. Also, it may be appropriate to use a candle flame for annealing.

Safety: Please use normal PPE (Personal Protective Equipment) during this lab. This includes using gloves for handling hot or cold items, and eye protection as appropriate. Other items may be considered such as aprons to protect clothing.

The objective is to have students observe dimensional changes in Nitinol wire. Through a series of treatments, the Nitinol wires will display different dimensional changes: sometimes most dramatic changes.

Part 1: Procedure for demonstrating Coefficient of Thermal Expansion:

Activity Description:
In preparation, the instructor should run through this activity before using it. The scenario is to prep the space, run the activity, and then debrief. In general, small lengths of wire will be bent with fingers and/or pliers into different shapes, at two temperatures: freezing and boiling (in water baths). Various dimensions will be observed and discussed.

Preparation:
Preparation for the activity:
- Determine the workspace (tables for teams)
- Distribute the Nitinol wires (two each)
- Plan the location of tools (e.g. pliers, temperature baths: ice water and boiling water, candle and igniter)

Procedure: Students will conduct an experiment to measure the CTE of Nitinol, as well as demonstrate the usefulness of using a metal to obtain dimensional movement under a change in temperature.

To begin with, the Coefficient of Thermal Expansion (CTE) is a material property. However, it does depend on the ‘structure’ of the material. And many materials have different structures at different temperatures. Nitinol has a ‘face-centered cubic’ structure at high temperatures, and a ‘body-centered tetragonal’ structure at lower temperatures. Thankfully, we will do our experiment at the lower temperatures: between freezing and boiling. For Nitinol, that means we use a CTE of 6.6x10^-6/C instead of 11x10^-6/C.

To predict a change in length (dL), we simply use dL = L*dT*CTE; with L=3”, dT=20C. Multiplying it out results in a change of 0.0006” or just less than a thousandth of an inch. Not much to see, but it turns out that other factors (beyond the scope of this activity) accentuate the expansion, and it will be visible.

To show CTE, we take the wire and place it in the ice bath. After a minute, take it out and form it into a circle (so the ends just touch). Put it back into the ice bath for a minute. Now take it out
and put it on the palm of your hand. Look at the ends again, and see if they are still touching…. Do you notice how the ends separate? This change in expansion is caused by an increase in temperature. This is what is used to control your furnace or other devices (though there are better ways to accomplish this, such as using bimetallic strips). It’s not much to look at, but it is very effective and reliable.

Part 2: Procedure for demonstrating Shape Memory:

Activity Description:
Shape -Memory Alloys, like Nitinol, show dramatic movement when it experiences a certain temperature change. Nitinol shows this well in our common temperature range of freezing to boiling temperatures.

Preparation: First, Nitinol usually comes in a wire form. Wires a few inches long are adequate for our purposes. If the wire is reasonably straight, or even curved some: it’s OK. If the wire is bent up at angles, then it is appropriate to ‘shape set’ it to be more ‘straight’. As described above, use pliers to straighten it, and then heat over the flame until it glows: WHILE HOLDING IT. Then let it cool in air. This new ‘shape’ is now ‘set’.

Procedure: Dunk the wire in the ice bath for a minute. Take it out and bend it into a coil or some other bent up shape. Now for the fun part. Grab the wire by one end and immerse it in the boiling water. It should immediately spring back to its original shape!

This is quite fun, so you may want to try different shapes and watch it ‘jump back’ to the original shape. In an engineering application, you might imagine different scenarios in which you want to actuate some device using Nitinol. And remember, you can increase its temperature by running current through it: so, you don’t need a boiling water bath to cause the shape memory effect.

Debriefing: Debriefing is an important aspect of the activity. There are questions concerning both the CTE and Shape Memory activities (reflecting the module objectives).

- Did the wire expand as much as you imagined from freezing to room temperature?
- How much more expansion did the shape memory effect have, compared to CTE?

Further, after the activity can student describe other interesting aspects of both CTE and Shape Memory effects. For example, what other applications could you think of utilizing CTE or Shape Memory effects?

Reflection Questions:
The following is a list of questions that might be used in a Socratic scenario:

- When describing the change in length due to CTE, did it occur suddenly or gradually?
- Did the shape memory effect occur suddenly or gradually?
How might you describe the atomic structure changes during CTE, compared with Shape Memory effects?

Is there a way to speed up (or slow down) either process (and what are the related issues)?

Comments:
Coefficient of Thermal Expansion occurs with all materials and must be accommodated in all engineering devices. Bridges have ‘expansion joints’ because the road itself expands and contracts with temperature changes. It is interesting that there are alloys developed that exhibit zero CTE, like Inconel (another nickel iron alloy).

Nitinol is one shape memory alloy of interest because it changes shape in an appropriate temperature range, while other alloys are not as easy to control.

Evaluation of students: (questions, discussion or quiz items):
1) Explain how you could measure and compare the dimension change of a CTE event vs. a Shape Memory event over 200F.
2) What other methods could be used to both cool and heat the Nitinol?
3) Nickel can be incompatible with human biology, so how might we modify Nitinol to prevent the nickel from interacting?
4) How might you determine the force generated from a shape memory event?

Instructor (user) evaluation questions:
1. At what grade level was this activity used?
2. Did the activity succeed in facilitating the outcomes of interest?
3. Did the references and content suffice for your needs?

Course evaluation questions: (to be filled out by the students)
1. Did the activity help you better understand the concept of CTE?
2. Did the activity help you better understand the concept of shape memory?
3. Did the instructor explain and facilitate the activity well?
4. Were you able to get your questions answered easily?
5. Did you have what you needed to demonstrate CTE and Shape Memory effects?
6. Were you able to test and measure both CTE and Shape Memory dimension changes?
7. What was the most interesting thing that you learned?
References:

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