Memory Metals

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Memory Metals

Abstract

This module explores the properties of shape memory alloys, commonly called “memory metals”. These alloys, when made into wires or thin structures, exhibit the shape memory effect: if bent or deformed, the metal will revert to its original shape upon heating. This module explains this effect in terms of the metal’s crystalline structure at the nanoscale. An activity is provided that allows students to manipulate the memory metals directly.

Outcomes

After completing this module, students will

- Know about the crystalline structure of metals
- Be able to explain the behavior of memory metals in terms of crystal structure

Prerequisites

Students should have some exposure to the following physical science concepts typically encountered in eighth grade science:

- basic understanding of atoms
- the basics of chemical bonds

Alignments to Education Standards

See appendices.

Science Concepts

- Atomic bonding
- Phase and phase changes

Nanoscience Concepts

- Crystal lattice structure

Background Information

Crystals

A shape memory alloy is a crystal that reverts to its original shape after heating to a certain degree. A crystal (or crystalline solid) is a solid material whose constituent atoms, molecules, or ions are arranged in an orderly repeating pattern extending in all three spatial dimensions. The process of crystal formation is called crystallization or solidification. The word crystal is derived from the ancient Greek word κρύσταλλος (krustallos), meaning both “ice” and “rock crystal”, which comes from κρύος (kruos), meaning “icy cold” or “frost”. Examples of crystalline solids include water ice, minerals such as quartz and halite (rock salt), and many gem stones, such as rubies and diamonds. Most common metals, including gold, silver, iron, and copper, have a crystalline microstructure.

It is possible for a metal to have several different crystal structures at the same composition, and these different structures may have different physical shapes. Often, one crystalline structure in particular is favored energetically, that is, if the atoms in the crystalline solid are given sufficient heat energy to move around, they will occupy the available positions with lowest energy and assume the most energetically favorable crystalline form. Once they have assumed this form and the metal is cooled, the atoms are generally fixed in position, and the change is not reversible. This is the basis of heat treating metal, an industrial process used to harden steel and other metals.

In some metals, this crystal transformation is fully reversible: the crystals of the metal will revert to their original shape after heating. Metals made of these types of crystals will act the same on the macroscopic scale. If bent or deformed, they will revert to their original shape upon moderate heating, which has earned them the name shape-memory alloys or memory metals. A reversible transformation does not involve the diffusion of atoms. Instead, all the atoms in the crystalline materials shift at the same time to form a new structure, much as a parallelogram can be made out of a square by pushing on two opposing sides. At different temperatures, different structures are energetically preferred.

Crystal Structures

In mineralogy and crystallography, crystal structure is a unique arrangement of atoms or molecules in a crystalline solid. A crystal structure is composed of a pattern, a set of atoms arranged in a particular way, and a lattice exhibiting long-range order and symmetry. Patterns are located upon the points of a lattice, which is an array of points repeating periodically in three dimensions. The points can be thought of as forming identical tiny boxes, called unit cells, that fill the space of the lattice. The most common crystal structures are BCC (body centered-cube), FCC (face centered-cube), and a hexagonal crystal structure. These structures are illustrated in Figure 1.

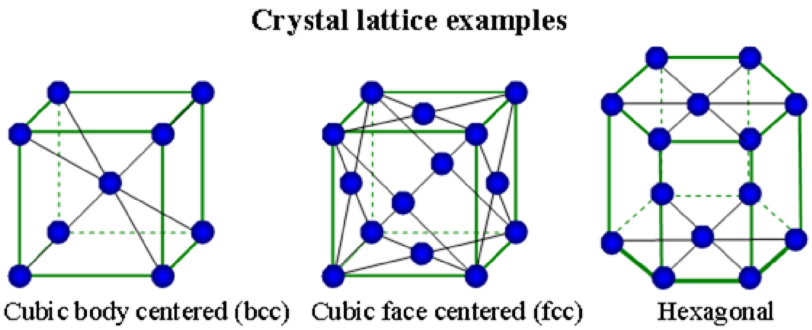


Figure 1. Some common crystal types. The dots represent atoms that make up the material.

Shape-memory alloys

A shape-memory alloy is an alloy that "remembers" its original, cold-forged shape, returning to the pre-deformed shape by heating. Memory metals can also be “trained” to take on a predetermined shape in response to 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), commercially known as *Nitinol*. The wire used in this lab is a NiTi alloy.

Memory alloys work because of their two crystalline phases. Nitinol's properties are a result of its ability to undergo a solid-to-solid phase change between the *austenite* phase at high temperatures and its *martensite* phase preferred at lower temperatures. The nickel and titanium atoms undergo slight shifts in the metal's overall structure as it changes from the low-temperature martensite phase to the high-temperature austenite phase and vice versa. This process is called phase change.

Crystal Phases

Austenite, also known as the gamma phase iron (γ-Fe), is a non-magnetic form of iron with an alloying element. One of the differences between the two phases is that martensite has a body-centered tetragonal (BCT) crystal structure, whereas austenite has a face-centered cubic (FCC) structure. The transition between these two structures requires very little thermal activation energy, because it does not depend on the process of diffusion, which results in a subtle but rapid rearrangement of atomic positions.

Martensite, named after the German metallurgist Adolf Martens (1850–1914), most commonly refers to a very hard form of steel crystalline structure, but it can also refer to any crystal structure that is formed by displacement of atoms. This phase change occurs without the long-range diffusion of atoms but rather by some form of cooperative, homogeneous movement of many atoms that results in a change in crystal structure. Martensitic structures have since been found in many other practical materials, including shape memory alloys. The martensite phase is formed by rapid cooling (quenching) of austenite which traps carbon atoms that do not have time to diffuse out of the crystal structure. This martensitic reaction begins during cooling when the austenite reaches the martensite onset temperature (M_s) and the parent austenite becomes mechanically unstable. At a constant temperature below M_s, a fraction of the parent austenite transforms rapidly, and then no further transformation will occur. When the temperature is decreased, more of the austenite transforms to martensite. Finally, when the martensite final temperature (M_f) is reached, the transformation is complete.

One-way Memory Phase

When a shape-memory alloy is in its cold state (below A_s), the metal can be bent or stretched and will hold those shapes until heated above the transition temperature. Upon heating, the shape changes to its original. When the metal cools again it will remain in the hot shape, until deformed again.

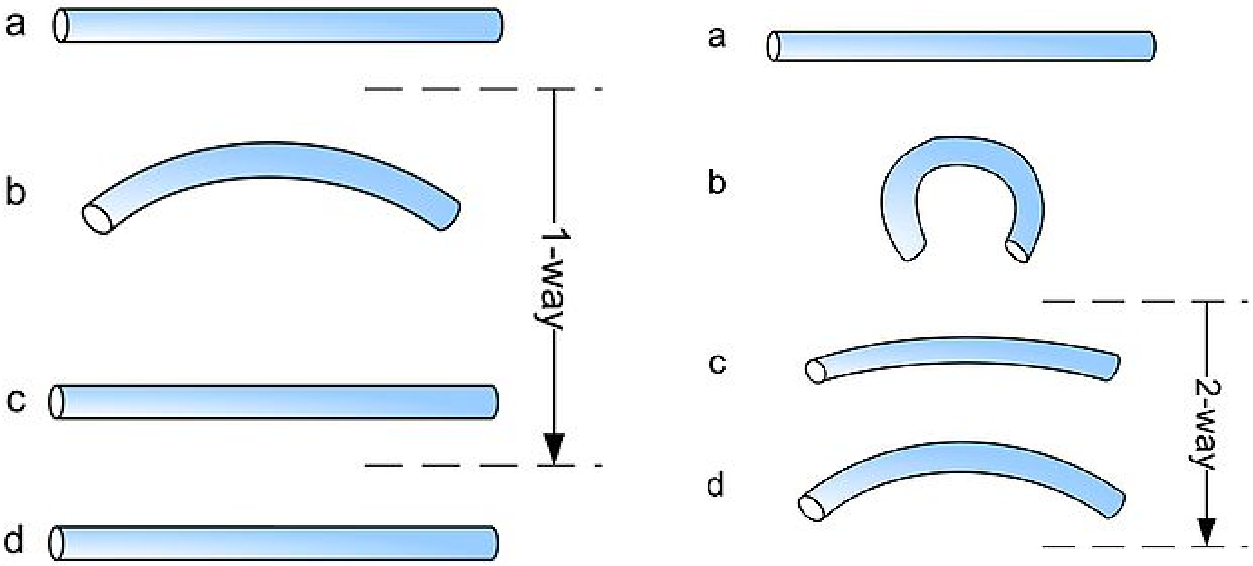


Figure 2. One-way and two-way shape memory materials.

Two-way Memory Phase

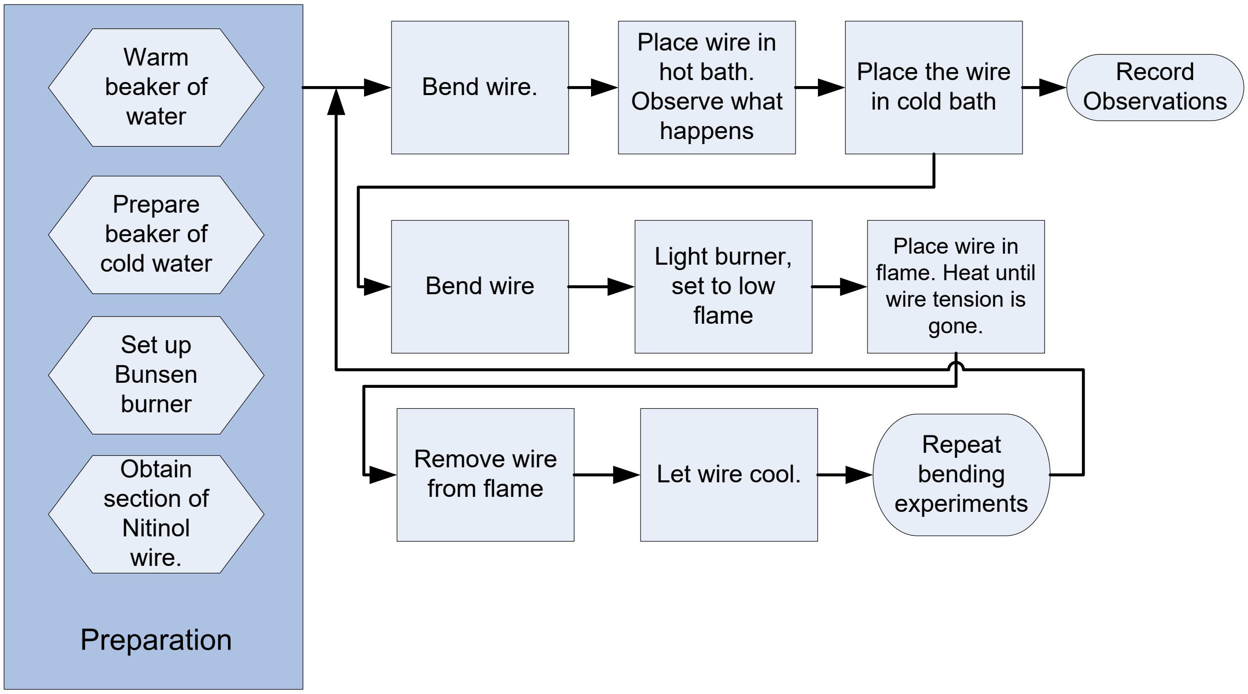
In the two-way shape-memory effect, the material “remembers” two different shapes: one at low temperatures, and a second shape at higher temperatures. A material that shows a shape-memory effect during both heating and cooling is said to have two-way shape memory. The reason the material behaves so differently in these situations lies in the process of training. Training implies that a shape memory can "learn" to behave in a certain way. Under normal circumstances, a shape-memory alloy "remembers" its high-temperature shape, but upon heating to recover the high-temperature shape, immediately "forgets" the low-temperature shape. However, it can be "trained" to "remember" to leave some reminders of the deformed low-temperature condition in the high-temperature phases. Figure 2 illustrates the training process.

Current and Future Applications

Since the introduction of Nitinol in the early 1960s, shape memory alloys have seen application in a wide range of fields. Memory metals have been used as actuators for many types of automatic switches and valves in automotive, industrial, and aircraft systems. Memory metal components are used in the auto focus mechanisms of cameras, and have been employed in metal eyeglass frames, where their memory effect can be used to easily straighten bent frames. One recent application has been in stents designed to prop open arteries. The stent can be inserted into the patient in a compact collapsed form, which then expands to full size under the elevated body temperature, fully opening the constricted artery.

Learning Activity: Memory Metals

Activity Flow Chart



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Video of Activity: http://www.youtube.com/watch?v=t4hfv1PeXRk

Memory Metals Learning Activity

Lab Materials

- Nitinol memory wire (from: Educational Innovations, Inc. or other sources)
- Bunsen burner
- Hot plate
- Petri dishes or shallow beakers
- Ice bath
- Tweezers
- Safety goggles

Procedure

1. Warm a beaker or Petri dish of water on a hot plate. **Do not bring to boil.**
2. Fill a separate beaker or Petri dish with cold water
3. Obtain a section of memory wire and then bend it into a coil.
4. Place wire in hot bath and watch what happens. Then using tweezers, place the wire into the cold bath before handling it.
5. Light a Bunsen burner and set the choke to a low flame. **Remember to wear goggles!**
6. Holding the wire carefully so as not to burn your fingers (or using tweezers), bend the wire and then bring the bent end above the flame.
7. Heat the wire slowly until you feel a release of tension. Immediately remove the wire and let it cool. **Do not over heat the wire.**
8. Repeat bending the wire and then dropping it into the hot bath to demonstrate the new set shape. Repeat these steps as many times as desired.
9. Record your observations and answer the questions.
10. Clean up as directed.

Discussion Questions

Questions (To be answered after the lab in lab book or separate sheet of paper**).**

1. What is a shape memory alloy?

2. What are crystal phases?

3. What causes the shape change and the memory effect?

4. Describe why heating the wire above 500°C causes the wire to be set into a new shape.

5. Which crystal structure (Austenite phase or Martensite phase) do you suspect to be stronger?
6. Observe the diagram in Figure 3 showing the two crystal structures in memory metal. How does this show which phase is stronger and which phase is more easily bent?
7. What questions came to mind during this experiment and what would you like to know about what is happening at the atomic level?

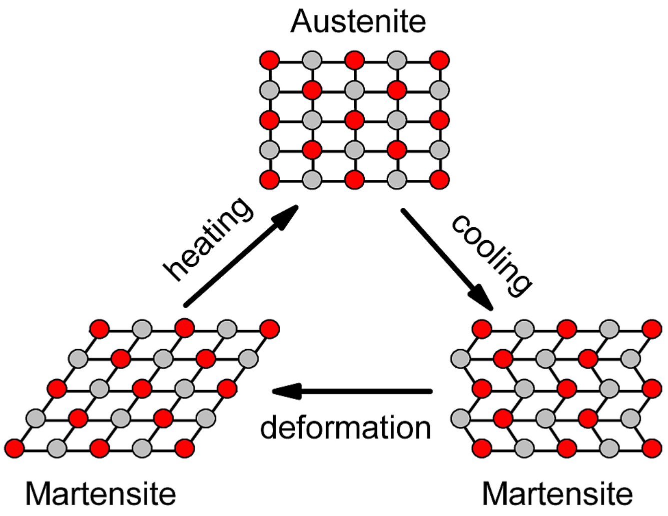

Figure 3. The Martensite to Austenite transformation.

Contributors

This module was written by Matthew Schultz and Deb Newberry of Dakota County Technical College, with additional material by James Marti of the University of Minnesota.

Multimedia Resources

Videos

- "Magic" Memory Metal - Nickel Titanium or 'Nitinol' Wire: www.youtube.com/watch?v=fLGaF6cWI04
- Memory Metal - Cool Science Experiment: www.youtube.com/watch?v=t4hfv1PeXRk
- Shape Memory Alloy: www.youtube.com/watch?v=QYp9rIJRM8s&feature=related

Articles

1. Memory Metal - MRSEC - University of Wisconsin-Madison
   http://education.mrsec.wisc.edu/Edetc/background/memmetal/index.html

2. Applications of Shape Memory Alloys in the medical field:
   http://www.keytometals.com/page.aspx?ID=CheckArticle&site=ktn&NM=212

3. Applications for Shape Memory alloys:
   http://depts.washington.edu/matseed/mse_resources/Webpage/Memory%20metals/applications_for_shape_memory_al.htm

Appendix 1: Alignment of Crystals, Part II: Memory Metals Module to the Next Generation Science Standards

The Next Generation Science Standards (NGSS) were published in April 2013. They consist of statements that convey performance expectations for students. Each performance expectation is a single statement that is built from three parts: science and engineering practices (Practices), disciplinary core ideas (DCI) and crosscutting concepts.

Since the Memory Module was created prior to the release of these standards one would expect that it aligns most readily to the individual statements that articulate the practices, DCIs, and crosscutting concepts. The background material, reading, and the slides from the module address the aspects of the NGSS shown in Table 1.

TABLE 1. ALIGNED PRACTICES, DISCIPLINARY CORE IDEAS, AND CROSSCUTTING CONCEPTS

PRACTICE	***DCI***	***Crosscutting Concept***
HS. Obtaining, evaluating, and communicating information: Communicate scientific and technical information (e.g. about the process of development and the design and performance of a proposed process or system) in multiple formats	*MS.PS1-A:* Solids may be formed from molecules, or they may be extended structures with repeating subunits (e.g., crystals).	*MS Stability and Change:* Explanations of stability and change in natural or designed systems can be constructed by examining the changes over time and processes at different scales, including the atomic scale.
Where is this Practice found in the lesson plan? The Discussion Questions include questions that require students to communicate scientific information about crystal.	***Where is this DCI found in the lesson plan?*** Within the Power Point slides, the teacher Background material, and the Discussion Questions.	***Where is this Crosscutting Concept found in the lesson plan?*** This concept is embedded in the Background and Optional Background information, and is accessible if students connect the Power Point presentation with the Activity.
How well is this Practice aligned? Weak alignment, due to scope. Students are only asked to	***How well is this DCI aligned?*** Strong alignment to the material found in the Power Point presentation.	***How well is this Cross Cutting Concept aligned?*** Weak alignment, as students are not explicitly helped to

TABLE 1. ALIGNED PRACTICES, DISCIPLINARY CORE IDEAS, AND CROSSCUTTING CONCEPTS		
communicate scientific information textually, while the Practice specifies multiple formats.		understand this concept, and are not assessed on their understanding.

Appendix 2. Alignment of Crystals, Part II: Memory Metals Module to the Common Core State Standards for English Language Arts/Literacy and Mathematics

The Common Core State Standards (CCSS) were published in June 2010. They articulate student skills for English language arts/literacy and mathematics. The content of the module addresses the concepts and skills shown in Tables 3.

For English language arts/literacy, the CCSS is organized around College and Career Anchor Standards (CCR) that articulate the over-arching skills that students need to be prepared for college and career. There are grade level versions of each Anchor Standard, as well as versions for science and social studies classrooms (literacy standards). Alignments in Table 3 were made to the Anchor Standards, unless a more specific version of the standard was a closer fit to the skills in the module. Additional alignments may be warranted, depending on the use of associated reading passages and videos that are provided as links in the module and whether students engage in peer discussions.

Table 3. Aligned Common Core Standards for English Language Arts & Literacy
STANDARD CCR.L.6: Acquire and use accurately a range of general academic and domain-specific words and phrases sufficient for reading, writing, speaking, and listening at the college and career readiness level; demonstrate independence in gathering vocabulary knowledge when encountering an unknown term important to comprehension or expression.
Where is this standard found in the module? Scientific words and phrases are used throughout the module, including within the background information, PowerPoint slides, procedural instructions, and discussion questions.
How well is this standard aligned? Partial alignment. Familiarity with some scientific vocabulary is prerequisite (e.g., atoms, chemical bonds), while some other conceptual vocabulary may be part of instruction (e.g., crystal lattice structure, shape-memory alloys). Students must use scientific (domain-specific) words and phrases to accurately respond to the discussion questions.
STANDARD RST.11–12.3: Follow precisely a complex multistep procedure when carrying out experiments, taking measurements, or performing technical tasks; analyze the specific results based on explanations in the text.
Where is this standard found in the module? Students read and follow multi-step procedure when completing the activities; students analyze the specific results through discussion.
How well is this standard aligned? Weak alignment. The ability to follow written procedures is prerequisite to the module and not part of direct instruction; students' analysis of results is not based on explanations in the text.
STANDARD RST.6–8.7: Integrate quantitative or technical information expressed in words in a text with a version of that information expressed visually (e.g., in a flowchart, diagram, model, graph, or table).

Where is this standard found in the module? Students must understand a variety of graphics that are used within the background information and PowerPoint slides.
How well is this standard aligned? Weak alignment. The ability to connect graphic images with a description of phenomena is assumed (prerequisite) and not part of instruction or assessment in the module.

For mathematics, Table 4 shows alignments to standards found in the 8th through 12th grade levels.

TABLE 4. ALIGNED COMMON CORE STANDARDS FOR MATHEMATICS
None Found