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

b a

γ

c

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

Key

Nickel

Titanium

Austenite

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

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.

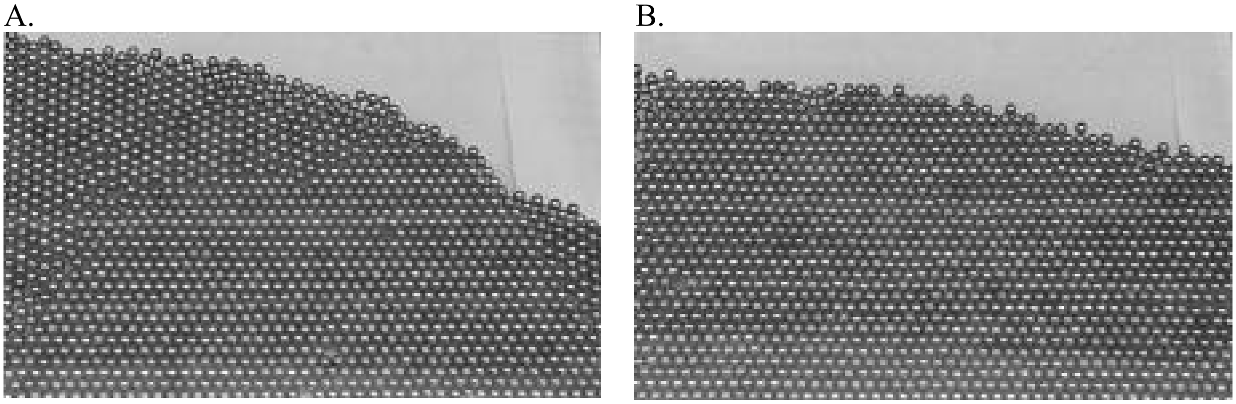

Figure 1. BB board with defects (A), and without defects (B).

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.