Interactive Demonstrations and Laboratories
Using Shape Memory Alloys

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Abstract

Shape memory alloys (SMAs) constitute a unique class of materials that undergo a reversible phase transformation allowing the material to display dramatic stress-induced and temperature-induced deformations that are recoverable. Nickel titanium (NiTi) is a shape memory alloy used in a wide variety of biomedical, aerospace, automotive and other applications. The austenite-martensite phase transformation that occurs in these alloys with changes in temperature or applied stress is responsible for the unique properties of this material. The unusual behavior of SMAs provides an exciting way to engage students and can be incorporated into a variety of courses under topics such as phase transformation behavior, constitutive relations, and smart materials and structures. Three modules that can be used as either demonstrations or experiments will be described. In the first, an apparatus for demonstrating the actuation abilities of NiTi SMA via an overhead projector has been created for classroom demonstrations using Dynalloy, Inc. components. The second experiment involves visualizing the latent heat of transformation during loading using a liquid crystal paint. In addition to exploring temperature-induced and stress-induced transformation, students can also get first-hand experience with the influence of heat treatment on this alloy in a laboratory environment. The third experiment uses an inexpensive training jig that allows students to shape set a piece of NiTi wire into any desired shape and see its shape memory abilities through subsequent deformation and heating.

Introduction

Overview of Shape Memory Alloys

SMAs undergo a reversible phase transformation that allows the material to display dramatic and recoverable stress-induced and temperature-induced transformations. These materials have a
crystallographic structure that can change reversibly and reproducibly, allowing the material to display large recoverable deformations. The behavior of an SMA is governed by a phase transformation between austenite and martensite crystal structures. Transformation between the austenite (B2) and martensite (B19') phases can be produced by temperature cycling between the high temperature austenite phase and the low temperature martensite phase (shape memory effect), or loading the material to favor the high strain martensite phase or unloading to favor the low strain austenite phase (superelasticity). Thus, as is shown by Figure 1, both temperature and stress influence the transformation between the austenite and martensite phases.

The martensitic transformation is a diffusionless phase transformation in which atoms move cooperatively by a shear-like mechanism. The behavior is well understood by the phenomenological theory of martensites where transformation consists of three operational processes: lattice deformation, lattice invariant shear, and lattice rotation.

For more detailed background information and state of the art advances see references [1-5]. The books by Hodgson and Brown [1] and Srinivasan and McFarland [2] provide material at a level easily accessible to undergraduates, whereas the new book by Bhattacharya [3] would be most valuable for a graduate level course. The compilation edited by Otsuka and Wayman [4] and the MRS Bulletin issue devoted to shape memory alloys [5] are excellent sources for detailed background and current research advances.

![Figure 1](image)

**Figure 1.** Schematic depiction of (a) temperature-induced transformation (and thus elongation) under constant stress, and (b) a typical stress/strain curve showing stress-induced transformation.

**Shape Memory Alloy Applications**

Shape memory alloys have been employed in wide ranging applications. One example of this class of materials is nickel-titanium (NiTi), also known as Nitinol (named after its place of discovery, the Naval Ordinance Lab). This alloy is the most commercially successful SMA and is already in use in biomedical, aerospace, automotive and other applications. More than 4,000 patent applications involving SMAs were filed between 1984 and 1988 alone [4]. Industrial applications for NiTi include couplings, connectors, safety valves and vibration controls. Consumer devices include eyeglass frames, antenna wires, and antiscalding valves [6].
Additionally, NiTi is being applied in an increasing number of implantable medical devices. NiTi has been approved for use in orthodontic dental archwires, endovascular stents, vena cava filters, diagnostic and therapeutic catheters, laproscopic instruments, intracranial aneurisms clips, bone staples, and various orthopedic implants [7]. Several characteristics make NiTi extremely attractive for use in medical devices: the material has good biocompatibility [8], the devices can be pseudo-elastically or thermally deployed, and the material can apply a constant transformation stress over a wide range of shapes [9]. Of the SMAs available, NiTi is the only material with an appropriate level of biocompatibility for use in medical devices.

The unique mechanical properties of shape memory alloys make them ideal candidate materials for the stent application [10-11]. Using NiTi, the stent is collapsed into a catheter without permanently deforming the device. It is then transported to the implantation site in this compact form allowing precise positioning, and, once it is ejected from the catheter, the material self-expands to provide a mechanical superstructure. These NiTi devices have sufficient rigidity to keep the vessel open, but the radial forces are low enough to avoid damaging the vessel tissue. A NiTi stent can also be designed to have adequate frictional coupling with the vessel wall to prevent device migration. In contrast to other stent materials, NiTi has superior crush resistance for use in superficial vessels and the device can be appropriately sized to prevent damaging over-expansion of the arterial wall.

Because SMAs are capable of producing large actuation forces and high recoverable strains, these materials are also ideal for use as microscale sensors and actuators in advanced controls and microelectromechanical systems (MEMS) applications. The actuation work density of SMAs is more than an order of magnitude higher than the work densities of the other actuation schemes [12]. With this unique capability, shape memory materials enable creation of devices that cannot be attained otherwise.

Demonstrations and Laboratories

Three modules that can be used as either demonstrations or laboratory experiments for exploring the properties of shape memory alloys are described below. These modules have been successfully employed in undergraduate courses in mechanics, materials and chemistry. Still images and video movies from these modules, as well as a variety of other educational materials, are available at the University of Wisconsin Materials Research Science and Engineering Center (UW MRSEC) on Nanostructured Materials and Interfaces website [13].

Overhead Projector Demonstration of Actuation

The FLEXINOL® Overhead Projector Demonstration is shown in Figure 2. This demonstration is based on materials in the Sample Kit available from Dynalloy, Inc., www.dynalloy.com, and the description provided here is adapted from the accompanying Dynalloy documentation [14]. Movies of this demonstration are available for individual viewing or classroom use at http://www.mrsec.wisc.edu/edtc/cineplex/OHP_NiTi/html. The NiTi actuator wires contract like muscle fiber when electrically driven. Electricity (in this case provided by two AA batteries) resistively heats the wire, which causes the wire to get shorter while exerting considerable force (330 grams [14]). When used properly, NiTi can be used to produce devices that are smaller,
lighter, and easier to use than motors or solenoids. This demonstration shows some basic ways the actuator wires may be used. Although designed to be employed on the stage of an overhead projector, this demonstration may also be used “one-on-one” on a tabletop with a piece of white paper underneath the Plexiglas board. A parts list (with suppliers) and measured drawings for the apparatus are available on the MRSEC website at http://www.mrsec.wisc.edu/edetc/cineplex/ohp_niti/index.html.

Figure 2. a) Photograph of the FLEXINOL® Overhead Projector Demonstration apparatus used to illustrate linear contraction (top left), right angle movement (right side), and double lever movement (bottom) of NiTi actuator wires. b) The demonstration as implemented in the classroom.

All wires in the demonstration are 0.006” diameter, 3.0” ± 0.010” length (working wire length) NiTi with a 90 °C transition temperature. The wires have brass ring terminals crimped to both ends to assist in fastening them to the board. Crimping specifications and technical characteristics of the NiTi FLEXINOL® actuator wires are available from Dynalloy.

Overheating of the actuator wires will result in their failure. They will literally melt, stretch, and break if the batteries are attached for more than a few seconds. Therefore, during the demonstration one end of each actuator wire is attached to the batteries by an alligator clip while the other end is briefly touched (less than one second) by a wire lead to complete the circuit. You should wait several seconds before re-actuating the wire to prevent overheating.

Demonstration One – Linear Contraction (Fig 2a top left): This demonstration requires the least force or strength from the NiTi wire. Force is directly related to the cross sectional area or diameter of the wire. The alligator clip is attached to the ring terminal on the left end, and the wire is activated by touching the other lead to the ring terminal on the right end. The NiTi wire heats up and contracts. When the current is removed the wire cools and transforms back to martensite, allowing the spring to pull the NiTi wire back to its original length. Students are able to measure the stroke or distance the wire contracts by observing how far the ring terminal
attached to the spring moves. In this configuration, the stroke is approximately 4\% of the total length (0.12” change for this 3.0” wire).

Demonstration Two – Right Angle Movement (Fig 2a right side): This demonstration shows one way to easily convert some of the strength of the NiTi wire into more movement or travel. The alligator clip is attached to the ring terminal on the top end, and the wire is activated by touching the other wire to the bottom ring terminal. In this configuration, the stroke that was hardly visible in Demonstration One is now an almost 18\% stroke. This configuration does not have a reverse bias, but it would make a good latch or lock mechanism.

Demonstration Three – Double Lever Movement (Fig 2a bottom): This demonstration produces the most force. The alligator clip is attached to the ring terminal on the left end of the actuator wire, and the wire is activated by touching the other lead to the ring terminal on the right end. The point where the NiTi wire is connected to the lever arm moves further away from the pivot point as the wire contracts, and the pointer sweeps over a range of angles on the protractor. This gives NiTi wire more leverage as it contracts making it easier for the actuator wire to pull as it contracts. This is called a reverse bias effect. This is very important for achieving maximum stroke over very long life (millions of cycles) and is incorporated into optimum designs in real-life applications.

Stress Induced Transformation Experiment using a Liquid Crystal

The solid-solid phase transformation displayed by SMAs such as NiTi is at the heart of their unique behavior. Students are able to easily grasp the concept of the transformation event when they are able to observe it visually. A dramatic method to observe the NiTi transformation is by employing a liquid crystal that changes color in the appropriate temperature range. In fact, if phase change is the topic of class discussion, the liquid crystal itself is an excellent additional example to consider.

If an austenite wire is loaded in tension, transformation to martensite can be induced. Accompanying this transformation is the release of latent heat. Thermocouples mounted at intervals along the wire can be used to measure the temperature, or a liquid crystal can be used to visualize the transformation front and watch its movement. In a temperature sensitive liquid crystal, an environmental effect such as temperature change impacts the orientation of the liquid crystals. The subtle change in molecular structure affects the wavelength of light that is absorbed or reflected by the liquid crystal, resulting in a noticeable change in color of the material.

To conduct the experiment, acquire NiTi wire (alloy type SE-508 (austenite) straight, black oxide finish, diameter 0.02 in., from Nitinol Devices and Components, www.nitinol.com) and liquid crystal (liquid crystal BM/R25C5W/C17-10, 15 g; and Black Primer: BB-G1, 15 g, both from Hallcrest, Figure 3. NiTi wire during transformation from austenite to martensite is shown. The wire has been painted with a temperature sensitive liquid crystal so that the transformation front can be distinguished by the color change seen.
Coat the wire with the black primer and allow it to dry fully (multiple coats may be necessary). Coat the wire with liquid crystal paint and allow it to dry fully. Uniformity of both the black primer paint and the liquid crystal paint is key to the success of the experiment. Although it is possible to do the application with a paintbrush, an airbrush produces the best results.

Mount the sample in a mechanical testing device (capable of loading to 100 lb) and load in tension to observe the transformation. When the austenite NiTi wire is loaded, a phase transformation front moves through the wire. Initially the wire is cold and the liquid crystal is disordered and appears black. As the transformation front moves from the top to the bottom of the image, the color changes from red at the front with a trailing rainbow of yellow-green-blue behind the front. The liquid crystal stays blue until the wire slowly cools. A movie of this experiment is available for viewing at http://www.mrsec.wisc.edu/edtc/cineplex/NiTi/html.

One obstacle in this demonstration is delamination of the liquid crystal paint. Because the liquid crystal paint is fairly brittle and the NiTi undergoes such large strains, the paint is prone to cracking. Shorter sample length (3-5 inches) tends to work well.

Heat Treatment Training Experiment

The transformation of NiTi occurs within a temperature window, which can be adjusted from –50 °C to 160 °C by changing the alloy composition and heat treatment processing [9]. Shape memory alloy wire can be “set” into a new shape by heat treatment while holding the wire in the desired shape. Since SMAs exert substantial forces during this heating, a relatively strong heat resistant jig capable of withstanding the forces exerted by the NiTi wire and temperatures up to 600 °C must be used. The ability to custom shape SMAs has previously been limited to those with access to jigs produced on expensive tools in sophisticated machine shops. In this experiment, students assemble training jigs made of an inexpensive perforated aluminum plate and standard nuts and bolts. When bought in bulk, the NiTi wire is approximately 10 cents per inch, allowing students to custom shape an interesting design for under $2 each.

The modular nature of these jigs leads to the added advantages of 1) design flexibility (shapes, letters, words, and even three-dimensional objects are possible), 2) unique projects for each student (each student sets wire into his or her own individual shape), and 3) reusability of the jigs (a classroom set of jigs may be cycled through many sections of a laboratory). We have observed softening of the aluminum plates after several cycles of heating, but if the project design does not involve wrapping wire around a three-dimensional jig structure, the plate softening is not a problem. A sample training jig with a square array of holes is shown in Figure 4. Movies of this experiment are available for viewing at http://www.mrsec.wisc.edu/edtc/cineplex/jig/index.html.

The Nitinol wire is available in large quantities (300 ft. lot, alloy type SM-495 (martensite) straight, black oxide finish, diameter 0.0315 in., from Nitinol Devices and Components, www.nitinol.com). There are several options for the jig material. A jig with a square array of holes is thinner and uses smaller diameter nuts and bolts (20 gauge, aluminum cane, 3 ft. x 5 ft. sheet (cut to size of furnace), 9344T62; round head slotted screw w/ nut, 8-32, 1/2 in., 100/pk.,
90232A486, both from McMaster-Carr) Alternatively a thicker jig with a hexagonal array of holes and larger diameter nuts and bolts can be used (14 gauge, 0.1875 in. hole diameter, 36 in. x 40 in. sheet (cut to size of furnace), 9232T191; round head slotted screw w/ nut, 10-24, 1/2 in., 100/pk., 90232A505; both from McMaster-Carr, www.mcmaster.com).

Before the laboratory period, each student is instructed to design their NiTi wire shape on a paper template, created by scanning the jig plate. This planning stage prevents poor designs, allows students to experiment creatively before spending the time building the jig, and avoids waste of NiTi wire. Once the template is designed, bolts are threaded through the appropriate holes in the base plate and secured with hex nuts. Students then use string to measure the length of wire needed, and obtain the proper length of NiTi wire from the instructor. The wire is wrapped around the bolts and secured with a second hex nut where needed. The jig is then placed in a 550°C oven for approximately 15 minutes followed by quenching in a cold water bath. Students then check the response of the SMA wire by straightening the wire and looking for shape recovery after it is immersed in hot (boiling) water. Students can cycle through the phase transition several times to study repeatability.

**Figure 4.** Photograph of a NiTi training jig configured to train wire into the MRSEC shape (top), and the resulting heat treated NiTi wire (bottom).

**Summary**

Three modules that can be used as either demonstrations or experiments have been described for classroom use in exploring the properties of shape memory alloys. The unusual behavior of SMAs provides an exciting way to engage students and can be incorporated into a variety of undergraduate courses under topics such as phase transformation behavior, constitutive relations, and smart materials and structures. The authors have successfully used these modules in mechanics, materials and chemistry courses at their respective institutions.
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References


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