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The World's "Smartest" Metal

Who said being backwards is a bad thing? Who said that inanimate objects can't have a memory? This time around we're going to look at a metal alloy that not only does things backwards, but it's smart. "Impossible!" you might say. "How can a metal be 'smart'?" If your education is a bit wanting in that area, then let me introduce our star pupil, *Nitinol.*

Nitinol is an alloy of nickel and titanium that belongs to a class of materials called *shaped-memory alloys* (SMA). SMAs have interesting mechanical properties. For example, Nitinol *contracts* when heated—the opposite of what standard metals do when heated (expand). Not only does the alloy contract, but it also produces a 100X greater thermal movement (expansion, contraction) than standard metals.

Another interesting property of SMAs is the *shaped-memory effect* (SME). The alloy can be heat treated to "remember" a particular shape. Afterwards, if the shape is bent and distorted, the alloy may be heated to regain its original shape. The SME property is used in a few toys like the "Livewire," shown in Fig. 1.

The Livewire is a fun little toy. The directions tell you to place it in cold water, bend the wire into any shape you want, and then place it in hot water—and the wire pops back into shape.

The Livewire toy is made of a particular Nitinol formula that has a low transition temperature—the temperature of hot water. When placed in hot water, the wire will unfold and unbend itself (if bent out of shape), reverting back to its original shape. If hot water isn't readily available, you could also pass an electric current through the Livewire to heat it up.

History

Although people have known about and experimented with SMAs since 1932, it wasn't until 1961 that SMAs came out of the laboratory. William Beuhler, working at the U.S. Naval Ordinance Laboratory, discovered the SME effect in an alloy of nickel and titanium. At the time, the scientific team was trying to develop a heat- and corrosive-resistant alloy. What they discovered was a relatively inexpensive and safer (non-toxic) SMA.

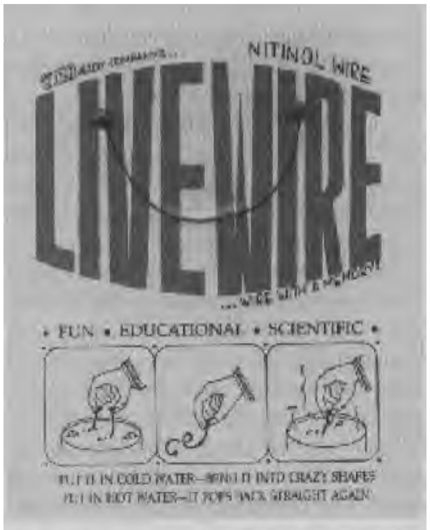

Fig. 1. Livewire is a Nitinol-wire product that demonstrates the shape-memory effect.

The team named the new alloy Nitinol (pronounced "night-in-all"). The name represents its elemental components and place of origin. The "Ni" and "Ti" are the atomic symbols for nickel and titanium. The "NOL" stands for the Naval Ordinance Laboratory where it was discovered.

SOURCE INFORMATION

Images Company
39 Seneca Loop
Staten Island, NY 10314
718-698-8305
www.imagesco.com

Livewire—$5
6-mil Nitinol wire (70° C transition temperature)—$5 per foot
15-mil Nitinol wire (70° C transition temperature)—$12.50 per foot

The mixture of nickel to titanium in Nitinol is about equal. The smallest change in the ratio of the two compounds has a dramatic effect on the transition temperature of the resulting alloy. For instance, a 1% difference in the ratio varies the transition temperature from –100° to +100° C. Every company manufacturing Nitinol products must hold the ratio of the components to a precise level to insure a stable and repeatable transition temperature. The Nitinol alloy we are experimenting with has a transition temperature of 70° C.

How It Works

The properties of Nitinol rely on its dynamic crystalline structure. The molecular structure is sensitive to external stress and temperature. The alloy has three defined temperature phases:

Austenite Phase—This is when the temperature is above the *transition temperature.* The transition temperature varies depending upon the exact composition of the Nitinol alloy; commercial alloys usually have transitional temperatures between 70° to 130° C (158° to 266° F). The yield strength with which the material tries to return to its original shape is considerable: 35,000 to 70,000 psi. The crystalline structure is cubic.

Martensitic Phase—A low-temperature phase. The crystal structure is needle-like and collects in small *domains.* Within the small domains, the needle-like crystals are aligned. The alloy may be bent or formed easily. The deformation pressure ranges from 10,000 to 20,000 psi. Bending transforms the crystalline structure of the alloy producing an internal stress.

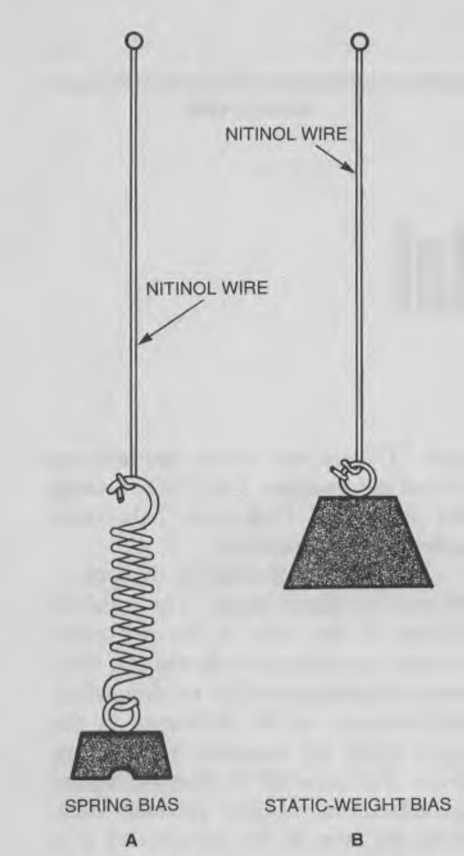

Fig. 2. Once Nitinol contracts, you need to "bias" it with some method to stretch the wire back to its relaxed position.

Annealing Phase—The high-temperature phase. The alloy will reorient its (cubic) crystalline structure to "remember" its present shape. The annealing phase for the Nitinol wire we are working with is 540° C.

The physical properties of our Nitinol wire sample are shown in Table 1.

TABLE 1

Physical Properties

Tensile Strength—200,000 psi
Melting Point—1250° C (2282° F)
Resistance—1.25 ohms per inch for 0.0060-inch diameter wire
Corrosion Resistant

When Nitinol is at room temperature, it is in the martensitic phase. When the alloy is bent, the needle-like crystalline structure within the domains deforms, creating internal stress. When the alloy is heated above its transitional temperature (austenite phase), the crystalline structure changes from needle-like to cubic. The cubic structure of the alloy doesn't fit into the same space as the needle-like domain structures formed when the alloy was bent. The alloy relieves the stress by returning to its "remembered" crystalline cubic shape.

If the alloy hasn't been deformed or stressed, the crystalline structure changes still occur, but it doesn't result in any net movement.

Nitinol Wire

Nitinol generates a shape-resuming force of 22,000 pound per square inch. In our experiments, we will work with either 6-mil (0.006-inch diameter) or 15-mil (0.015-inch diameter) wire. The 6-mil wire has a contractive force of 11 ounces; the 15-mil wire has a contractive force of 63 ounces (4 lbs.).

The wire can contract up to 8%-10% of its length. For a longer lifetime (greater than 1,000,000 cycles), you should restrict the contraction to only 6% of its length.

Contraction and relaxation depend solely on the temperature of the Nitinol alloy wire. Any method of heating and cooling may be used. An easy way to heat the wire—a common method—is passing an electric current through it. Nitinol wire has a high resistance, approximately 1.25 ohms per inch for the 6-mil wire. The resistance of the wire to the electric current generates sufficient heat (ohmic heating) to bring the wire through its transition temperature.

Nitinol wire usually has a counterforce applied to it in the opposite direction of its contraction. The counter force resets, or stretches, the wire back to its original length when in the low-temperature phase. This is called the *bias force.*

If the Nitinol wire is brought to its transition temperature without a bias force, it will contract; however, when it cools it will not return to its original length. Consequently, reheating the wire without a bias force will not produce any further contractions. In most applications, a bias force is applied to the wire constantly. Figure 2 illustrates two methods of applying a bias force: a spring and a static weight.

The speed and strength of the wire contraction depend upon how fast and how high the temperature of the wire is increased. For example, 400 mA of current through the 6-mil Nitinol wire will produce a maximum pull of 11 ounces and full contraction in one second.

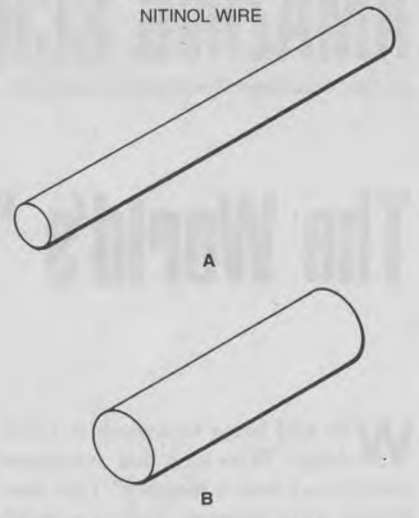

Fig. 3. Nitinol wire's volume remains constant whether relaxed or contracted.

Reaction time can be faster—in the millisecond range. To achieve that rate, high-current, short-duration pulses are used. When you use such pulses, you must consider the mass and speed of the material to move. The faster you move a given mass, the greater the inertia that must be overcome. If the inertia becomes greater than six pounds for the 6-mil wire, it will snap.

Full contractive force is produced at the *beginning* of a cycle. In contrast, standard electrical solenoids develop full strength near the *end* of their cycle.

Activating Nitinol Wire

As mentioned before, Nitinol wire may be heated by simply passing an electrical current through the wire. The resistance heats the wire and it contracts. The volume of the wire doesn't change during contraction; see Fig. 3. As the wire decreases in length, its diameter increases by a proportional amount, keeping the volume of the wire constant. Once again, the activation temperature of the wire is 70° C or 158° F.

Direct Electrical Heating

Nitinol wire can be activated using a low voltage DC (6-12volts) power supply. A simple system (Fig. 4) need be no more complicated than a battery, a

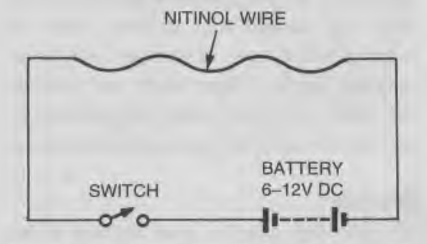

Fig. 4. A DC-battery power supply is ample to test Nitinol wire's unusual properties.

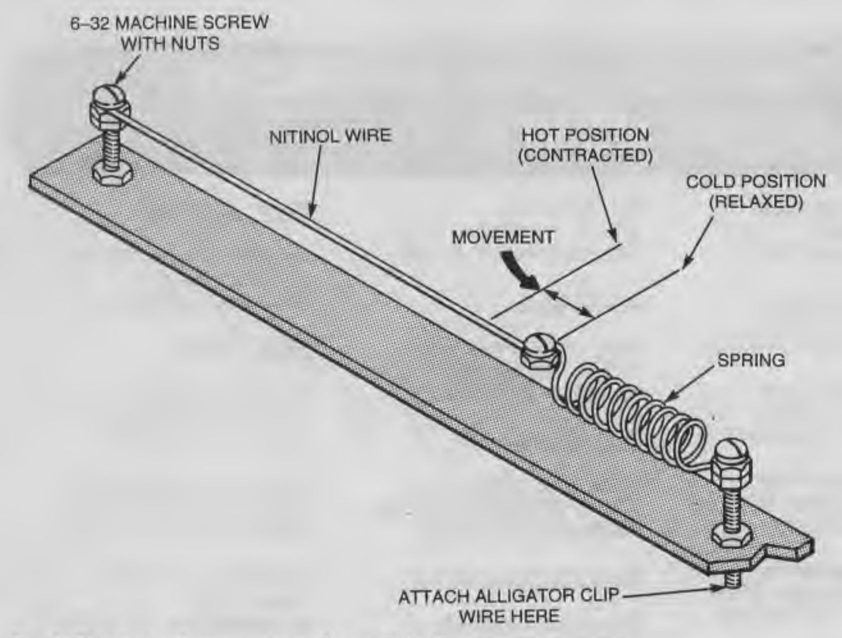

Fig. 5. This device demonstrates and tests Nitinol's contraction property.

switch, and a small length of Nitinol wire. When activating a wire using DC current, it is important not to overheat the wire, or its properties will degrade. Direct current doesn't heat the wire evenly. A better method is to heat the wire using pulse-width modulation.

Annealing a New Shape into Livewire

Here's some more fun you can have with the Livewire toy. You can "teach" the Livewire a new shape. Twist the Livewire into a new shape, holding the new shape using a pair of pliers. Place the Livewire into the flame of a candle until it is slightly red and it stops trying to straighten out. Remove the Livewire from the flame and dip it into cold water. Now the Livewire will "remember" this new shape.

To test the Livewire, bend it into another shape, heat it, and it will return to its new "remembered" shape.

A simple shape that I used for training is a coil. I wrapped the Livewire around a machine screw, held it in place with pliers, and placed it in a flame. It takes a little longer to work (get red hot), because the screw acts like a heatsink.

A Simple Nitinol Demonstration

Figure 5 is a simple mechanical demonstration to display the properties of Nitinol wire: flexing an electric "muscle." The materials you need are three machine screws (6-32 X 2 inches) with nine nuts; a piece of wood or plastic about 12 inches long; a small expansion spring (about 2 to 3 inches long); and, of course, a length of Nitinol wire.

The machine screws, nuts, and expansion spring may be purchased at a local hardware store. To make the device, drill two holes in the wood on opposite ends as shown to accommodate a machine screw and nut. The third screw and nut connect the Nitonol wire to the spring. That screw/nut is *not* secured to the wood, but is free standing. The Nitinol wire is connected to the left screw, see detail in Fig. 5. Loop the spring around the right end screw.

Keep in mind that the 6-mil Nitinol wire has a pull of about 11 ounces; stretching the spring too far will create too much tension for the Nitinol wire to overcome. At the same time, it should be tight enough to take the slack of the relaxed Nitinol wire.

To make the connections from the DC power supply to the demonstration, use small alligator clips and jumper wires to the back of the two end screws. The machine screws as well as the spring are electrically conductive, allowing current to flow to the Nitinol wire.

When you switch on the current to the Nitinol wire demonstration unit, the wire heats up quickly, contracts and pulls the freestanding machine screw closer to the right side. If you mark the starting position of the freestanding machine screw, you can accurately measure the contraction of the wire. When power is removed, the wire cools, allowing the spring to elongate the Nitinol wire and return it to its initial position.

Because we are using a DC power supply, it's too easy to overheat the wire and degrade the Nitinol properties. So it's important to only connect the power momentarily.

But Wait...There's More

Next month, we will finish experimenting with Nitinol. We will build a PWM circuit for the Nitinol wire, which will allow us to keep the power on for longer periods, build a few more Nitinol devices, and examine heat engines that use Nitinol.