Paper presentation

MUSCLE METAL:

SHAPE MEMORY ALLOYS

SUBMITTED BY

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Abstract

The shape memory effect, superelasticity, and good damping properties, uncommon in other implant alloys, make the nickel-titanium shape memory metal alloy (Nitinol or NiTi) a fascinating material for surgical applications. It provides a possibility to make self-locking, self-expanding and self-compressing implants. The purpose of this work was to determine if NiTi is a safe material for surgical implant applications.

This paper deals with the history, working, various kinds of shape memory alloys, and characteristics of NiTi alloy and its mechanical properties, Fabrication and programming.

SHAPE MEMORY ALLOYS

Have you ever thought of a metal remembering its previous shape exactly even after being deformed?
Shape memory alloys are combination of two or more metals. After being alloyed they exhibit a peculiar property of reverting back to their original shape even after they are stressed by simply increasing its temperature. All this is possible because of the molecular rearrangement of the metal when they are subjected to heat.

Introduction

The term Shape Memory Alloys (SMA) is applied to that group of metallic materials that demonstrate the ability to return to some previously defined shape or size when subjected to the appropriate thermal procedure. Generally, these materials can be plastically deformed at some relatively low temperature, and upon exposure to some higher temperature will return to their shape prior to the deformation. Materials that exhibit shape memory only upon heating are referred to as having a *one-way shape memory*. Some materials also undergo a change in shape upon recooling. These materials have a *two-way shape memory*.

Although a relatively wide variety of alloys are know to exhibit the shape memory effect, only those that can recover substantial amounts of strain or that generate significant force upon changing shape are of commercial interest. To date, this has been the nickel-titanium alloys and copper-base alloys such as CuZnAl and CuAlNi.

A shape memory alloy may be further defined as one that yields a thermoelastic martensite. In this case, the alloy undergoes a martensitic transformation of a type that allows the alloy to be deformed by a twinning mechanism below the transformation temperature. The deformation is then reversed when the twinned structure reverts upon heating to the parent phase.

History of Shape memory alloys

The first recorded observation of the shape memory transformation was by Chang and Read in 1932. They noted the reversibility of the transformation in AuCd by metallographic observations and resistivity changes, and in 1951 the shape memory effect (SME) was observed in a bent bar of AuCd. In 1938, the transformation was seen in brass (CuZn). However, it was not until 1962, when Buehler and co-workers discovered the effect in equiatomic nickel-titanium (NiTi), that research into both the metallurgy and potential practical uses began in earnest. Within 10 years, a number of commercial products were on the market, and understanding of the effect was much advanced. Study of shape memory alloys has continued at an increasing pace since then, and more products using these materials are coming to the market each year .

As shape memory effect became better understood, a number of other alloy systems that exhibited shape memory were investigated. Of all these systems, the NiTi alloys and a few of the copper-base alloys have received the most development effort and commercial exploitation.

Alloys having a shape memory effect

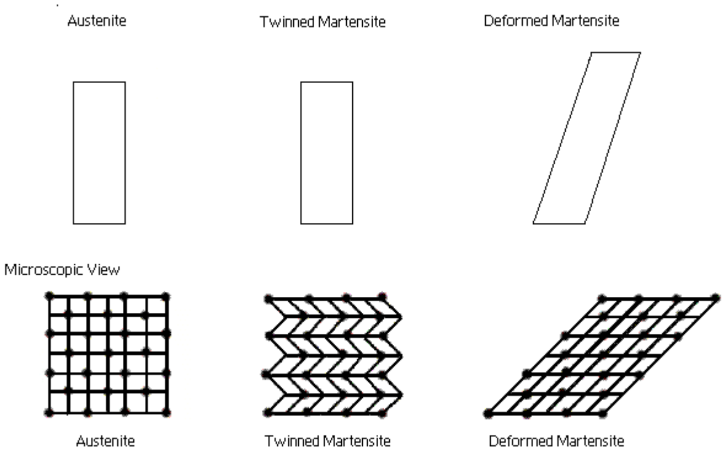
Here are few important alloys having shape memory effect presented in the table below.

Alloys	Composition Atomic or Weight Percent	Transformation Temperature Range (Celsius)
Ag - Cd	44/49 at.%	-190 to -50
Au - Cd	46.5/50 at.%	30 to 100
Cu - Al - Ni	14/14.5 wt% 3/4.5 wt%	-140 to 100
Cu - Sn	approx. 15 at%	-120 to 30
Cu - Zn	38.5/41.5 wt%	-180 to -10
Cu - Zn - (Si,Sn,Al)	a few wt.% of (Si, Sn,Al)	-180 to 200
In - Ti	18/23 at%	60 to 100
Ni - Al	36/38 at%	-180 to 100
Ni - Ti	49/51 at%	-50 to 110
Fe - Pt	approx. 25 at% Pt	approx. -130
Mn - Cu	5/35 at% Cu	-250 to 180

How shape alloys work?

The two unique properties described above are made possible through a solid state phase change, that is a molecular rearrangement, which occurs in the shape memory alloy. Typically when one thinks of a phase change a solid to liquid or liquid to gas change is the first idea that comes to mind. A solid state phase change is similar in that a molecular rearrangement is occurring, but the molecules remain closely packed so that the substance remains a solid. In most shape memory alloys, a temperature change of only about 10°C is necessary to initiate this phase change. The two phases, which occur in shape memory alloys, are Martensite, and Austenite.

Martensite, is the relatively soft and easily deformed phase of shape memory alloys, which exists at lower temperatures. The molecular structure in this phase is twinned which is the configuration shown in the middle of Figure 2. Upon deformation this phase takes on the second form shown in Figure 2, on the right. Austenite, the stronger phase of shape memory alloys, occurs at higher temperatures. The shape of the Austenite structure is cubic, the structure shown on the left side of Figure 2. The un-deformed Martensite phase is the same size and shape as the cubic Austenite phase on a macroscopic scale, so that no change in size or shape is visible in shape memory alloys until the Martensite is deformed.

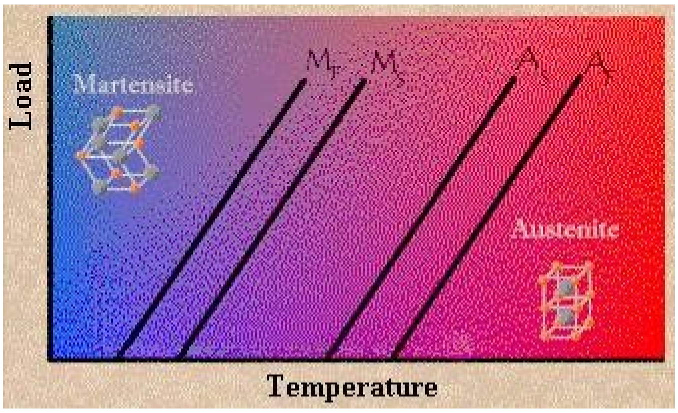


The temperatures at which each of these phases begin and finish forming are represented by the following variables: Ms, Mf, As, Af. The amount of loading placed on a piece of shape memory alloy increases the values of these four variables as shown in Figure 3. The initial values of these four variables are also dramatically affected by the composition of the wire (i.e. what amounts of each element are present).

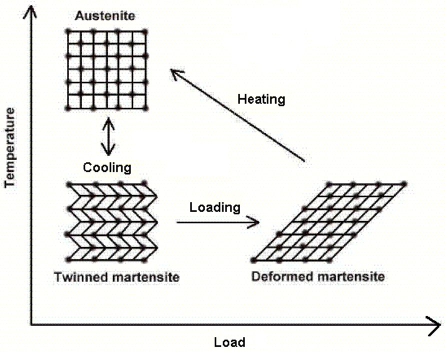
Unique properties SMA

- Shape Memory Effect
- Pseudo-Elasticity

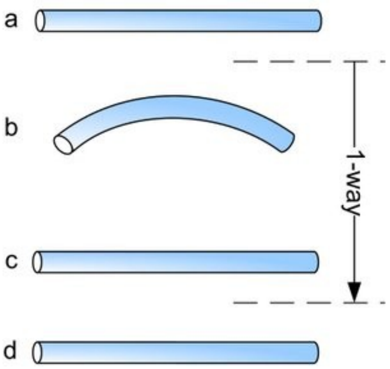
Shape Memory effect in SMA

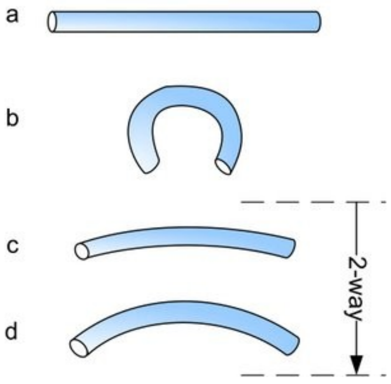


The shape memory effect is observed when the temperature of a piece of shape memory alloy is cooled to below the temperature Mf. At this stage the alloy is completely composed of Martensite which can be easily deformed. After distorting the SMA the original shape can be recovered simply by heating the wire above the temperature Af. The heat transferred to the wire is the power driving the molecular rearrangement of the alloy, similar to heat melting ice into water, but the alloy remains solid. The deformed Martensite is now transformed to the cubic Austenite phase, which is configured in the original shape of the wire. Microscopic Diagram of the Shape Memory Effect



One-way vs. two-way Shape Memory





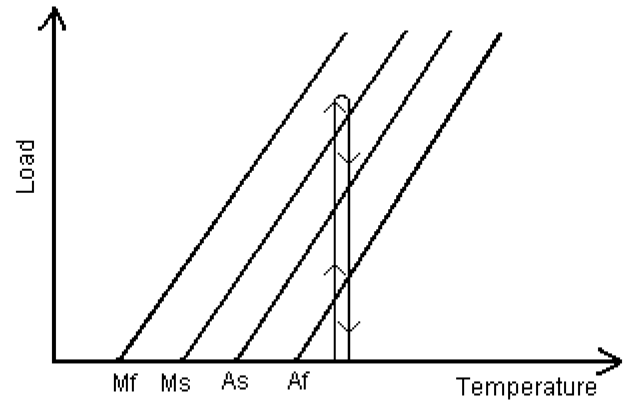
Shape memory alloys may have different kinds of shape memory effect. The two most common memory effects are the one-way shape memory and the two-way shape memory. A schematic view of the two effects is given in the figure above.
In the figure above, the procedures are very similar: starting from martensite (a), adding a reversible deformation for the one-way effect or severe deformation with an irreversible amount for the two-way (b), heating the sample (c) and cooling it again (d). With the one way effect, cooling from high temperatures does not cause a macroscopic shape change. A deformation is necessary to create the low temperature shape. On heating, tranfromation starts at A_s and is completed at A_f (typically 2 to 20°C or hotter, depending on the alloy or the loading conditions). A_s is determined by the alloy type and composition. It can be varied between -150°C and maximum 200°C.The two-way shape memory effect is the effect that the material remembers two different shapes: one at low temperatures, and one at the high temperature shape. This can be obtained also without the application of an external force (intrinsic two-way effect). The reason the material behaves so diffently in these situations lies in training. Training implies that a shape memory can learn to behave on 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 phase. There are several ways of doing this.

The Shape memory effect is currently being implemented in:

- Coffeepots
- The space shuttle
- Thermostats
- Vascular Stents
- Hydraulic Fittings (for Airplanes)

Pseudo –Elastic behavior of SMA:

Pseudo-elasticity occurs in shape memory alloys when the alloy is completely composed of Austenite (temperature is greater than Af). Unlike the shape memory effect, pseudo-elasticity occurs without a change in temperature. The load on the shape memory alloy is increased until the Austenite becomes transformed into Martensite simply due to the loading; this process is shown in Figure 5. The loading is absorbed by the softer Martensite, but as soon as the loading is decreased the Martensite begins to transform back to Austenite since the temperature of the wire is still above Af , and the wire springs back to its original shape.



Load Diagram of the pseudo-elastic effect Occurring

Some examples of applications in which pseudo-elasticity is used are:

- Eyeglass Frames
- Bra Underwires
- Medical Tools
- Cellular Phone Antennae
- Orthodontic Arches

Mostly used metals of SMA are:

- Nitinol (commercialized under the name of nickel titanium naval ordinance laboratories)
- Iron base alloy
- Copper base alloys

Iron-base SMA alloy

It is a Shape-Memory Alloy that, after being strained, at a certain temperature revert back to its original shape. The most important Iron based shape memory alloy is iron-manganese-silicon.

They base their shape-memory effect on a different physical principle than conventional Shape Memory Alloys. They can recover only less than 4% strain. Important developments are expected in the future.

Copper base SMA alloys

It is a Shape-Memory Alloy that, after being strained, at a certain temperature revert back to its original shape.
Copper-zinc-aluminum and copper-aluminum-nickel alloys are commercially available Shape Memory Alloys. Their transformation temperature ranges between -180 and +200 oC and -140 and +100 oC respectively.

They are cheaper than Nickel-Titanium alloys, can be melted in air with ease, and have a shape-memory strain up to 4-5 %. Hot work in air is well suitable, while cold work is suitable only for low aluminum-content alloys ***(< 6 % wt.).***

Nickel-Titanium alloy

It is a Shape-Memory Alloy that, after being strained, at a certain temperature revert back to its original shape.
Nickel-Titanium (NiTi) alloy is the most used Shape Memory Alloy. It is an equiatomic compound of NiTi, whose transformation temperature can range between -100 and +110 C.
It has great shape-memory strain (up to 8%), is thermally stable, and has excellent corrosion resistance. Because of the reactivity of titanium, all melting of it must be done in a vacuum. Forging, bar rolling and extrusion are also used.

Mechanical properties of NiTi

For orthopedic biomaterial applications, the two properties of major importance are strength (mechanical) and reactivity (chemical). Generally, there are two basic mechanical demands for the material and design of the implant. Service stresses must be safely below the yield strength of the material, and in cyclic loads the service stress must be kept below the fatigue limit .
The mechanical properties of NiTi depend on its phase state at a certain temperature. Fully austenitic NiTi material generally has suitable properties for surgical implantation. The common mechanical properties of martensitic and austenitic NiTi are presented in Table . There are some exceptional properties that might be useful in surgery. NiTi has an ability to be highly damping and vibration-attenuating below A_s. For example, when a martensic NiTi ball is dropped from a constant height, it bounces only slightly over half the height reached by a similar ball dropped above the

A_f temperature. From the orthopedic point of view, this property could be useful in, for example, dampening the peak stress between the bone and the articular prosthesis. The low elastic modulus of NiTi (which is much closer to the bone elastic modulus than that of any other implant metal) might provide benefits in specific applications. NiTi has unique high fatigue and ductile properties, which are also related to its martensitic transformation. These properties are usually favorable in orthopedic implants. Also, very high wear resistance has been reported compared to the CoCrMo alloy . NiTi is a non-magnetic alloy. MRI imaging is thus possible. Electrical resistance and acoustic damping also change when the temperature changes.

Effect of alloy composition, heat treatment and mechanical working on NiTi properties

It is feasible to vary the critical transition temperatures either by small variations of the Ti/Ni composition or by substituting metallic cobalt for nickel. Lowering of A_f is possible by adding nickel. If nickel is added above 55.6 Wt%, a stable second phase (Ti-Ni3) forms and the NiTi properties are lost. To avoid this problem, the cobalt substitution can be used to lower the TTR. The properties of NiTi can also be greatly modified by mechanical working and through heat treatment (time and temperature)

Selected mechanical properties of NiTi, implant stainless steel (316LVM), titanium (cp-Ti, grade IV) and Ti-6Al-4V alloy.

	NiTi		**Stainless Steel**	**Titanium**	**Ti-6Al-4V**
	Austenitic	**Martensitic**			
Ultimate tensile strength (Mpa)	800 - 1500	103 - 1100	483 - 1850	540 - 740	920 - 1140
Tensile yield strength (Mpa)	100 - 800	50 - 300	190 - 1213	390	830 - 1070
Modulus of elasticity (GPa)	70 - 110	21 - 69	190 - 200	105 - 110	100 - 110
Elongation at failure (%)	1 - 20	up to 60	12 - 40	16	8

Fabrication

Solid NiTi alloys are manufactured by a double vacuum melting process, to ensure the quality, purity and properties of the material. After the formulation of raw materials, the alloy is vacuum induction melted (1400°C). After the initial melting, the alloy transition temperature must be controlled due to the sensitivity of the transition temperature to small changes in the alloy chemistry. This is followed by vacuum arc remelting to improve the chemistry, homogeneity and structure of the alloy. Double-melted ingots can be hot-worked (800°C) and cold-worked to a wide range of product sizes and shapes.

Porous NiTi can be made by sintering or using self-propagating high temperature synthesis, also called ignition synthesis. The possibility to make composite SMA products (combination with polymers) is under investigation .

Programming

The use of the one-way shape memory or superelastic property of NiTi for a specific application requires a piece of NiTi to be molded into the desired shape. The characteristic heat treatment is then done to set the specimen to its final shape. The heat treatment methods used to set shapes in both the shape memory and the superelastic forms of NiTi are similar. Adequate heat treatment parameters (temperature and suitable time) are needed to set the shape and the properties of the item . They must usually be determined experimentally for the requirements of each desired part. Rapid cooling of some kind is preferred, such as water quenching or rapid air cooling.

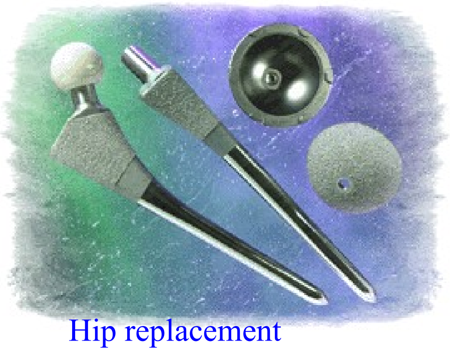
The two-way shape memory training procedure can be made by SME training or SIM training. In *SME training,* the specimen is cooled below M_f and bent to the desired shape. It is then heated to a temperature above A_f and allowed freely to take its austenite shape. The procedure is repeated 20-30 times, which completes the training. The sample now assumes its programmed shape upon cooling under M_f and to another shape when heated above A_f.

In *SIM training,* the specimen is bent just above Ms to produce the preferred variants of stress-induced martensite and then cooled below the Mf temperature. Upon subsequent heating above the A_f temperature, the specimen takes its original austenitic shape. This procedure is repeated 20-30 times.

Applications of Shape memory alloys:

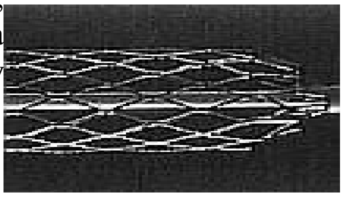
Shape memory alloys are widely used in the many fields. Let us have a detailed view of some of the applications of shape memory alloys.

Applications in Bio-engineering:



Hip replacement

- **Bones**: Broken bones can be mended with shape memory alloys. The alloy plate has a memory transfer temperature that is close to body temperature, and is attached to both ends of the broken bone. From body heat, the plate wants to contract and retain its original shape, therefore exerting a compression force on the broken bone at the place of fracture. After the bone has healed, the plate continues exerting the compressive force, and aids in strengthening during rehabilitation. Memory metals also apply to hip replacements, considering the high level of super-elasticity. The photo aside shows a hip replacement.
- **Reinforcement for Arteries and Veins:** For clogged blood vessels, an alloy tube is crushed and inserted into the clogged veins. The memory metal has a memory transfer temperature close to body heat, so the memory metal expands to open the clogged arteries.
- **Dental wires:** used for braces and dental arch wires, memory alloys maintain their shape since they are at a constant temperature, and because of the super elasticity



of the memory metal, the wires retain their original shape after stress has been applied and removed

- **Stents:** The stent is used for reinforcing weak vein walls and for widening narrow veins. The chilled stent is brought into position through a probe, and expands to its original size when warmed up to body temperature. The stent replaces similar stainless steel stents that are expanded with a little balloon.

Stents for veins

- **Coffee pot thermostat:** A Nickel-Titanium spring in coffeepots marketed in Japan is trained to open a valve and release hot water at the propertemperature to brew a perfect pot of coffee.

Coffeepot thermostat

- **Anti-scalding protection:** Temperature selection and control system for baths and showers. Memory metals can be designed to restrict water flow by reacting at different temperatures, which is important to prevent scalding. Memory metals will also let the water flow resume when it has cooled down to a certain temperature.
- **Fire security and Protection systems:** Lines that carry highly flammable and toxic fluids and gases must have a great amount of control to prevent catastrophic events. Systems can be programmed with memory metals to immediately shut down in the presence of increased heat. This can greatly decrease devastating problems in industries that involve petrochemicals, semiconductors, pharmaceuticals, and large oil and gas boilers.
- **Golf Clubs:** a new line of golf putters and wedges has been developed using shape memory alloys. Shape memory alloys are inserted into the golf clubs. These inserts are super elastic, which keep the ball on the clubface longer. As the ball comes into contact with the clubface, the insert experiences a change in metallurgical structure. The elasticity increases the spin on the ball, and gives the ball more "bite" as it hits the green.
- **Helicopter blades:** Performance for helicopter blades depend on vibrations; with memory metals in micro processing control tabs for the trailing ends of the blades, pilots can fly with increased precision.
- **Eyeglass Frames:** In certain commercials, eyeglass companies demonstrate eyeglass frames that can be bent back and forth, and retain their shape. These frames are made from memory metals as well, and demonstrate super-elasticity.

The photo to the right Demonstrates flexible eyewear

- **Super elastic glasses:** These glasses are made from a superelastic metal alloy.
  Therefore, they can be bended quite drastically without permanent damage. The glasses utilizes the superelastic property of Ni-Ti alloys.

Super elastic glasses

- **Tubes, Wires, and Ribbons:** For many applications that deal with a heated fluid flowing through tubes, or wire and ribbon applications where it is crucial for the alloys to maintain their shape in the midst of a heated environment, memory metals are ideal.

- **Extending the application range for both low and high temperatures:**

The shape memory wires used to gently hold the shape of women's lingerie have achieved great popularity in the market. We have developed nickel-titanium alloy as a base shape memory material that is superior in elasticity, fatigue strength, and cycling durability and has a recovery point at less than 0^0C We are also developing new materials that recover at higher temperatures of around 150^0C, which would extend the application of shape memory alloys to the automotive and other industries.

CONCLUSION

There are many possible applications for SMAs. Future applications are envisioned to include engines in cars and airplanes and electrical generators utilizing the mechanical energy resulting from the shape transformations. Nitinol with its shape memory property is also envisioned for use as car frames. Other possible automotive applications using SMA springs include engine cooling, carburetor and engine lubrication controls, and the control of a radiator blind ("to reduce the flow of air through the radiator at start-up when the engine is cold and hence to reduce fuel usage and exhaust emissions").

SMAs are "ideally suited for use as fasteners, seals, connectors, and clamps" in a variety of applications. Tighter connections and easier and more efficient installations result from the use of shape memory alloys .

The many uses and applications of shape memory alloys ensure a bright future for these metals. Research is currently carried out at many robotics departments and materials science departments. With the innovative ideas for applications of SMAs and the number of products on the market using SMAs continually growing, advances in the field of shape memory alloys for use in many different fields of study seem very promising.

Imagine a world of shape-shifters. A surgeon inserts a small lump of plastic into an anesthetized patient and, like magic, it expands into a life-saving mesh tube that keeps a formerly clogged artery open. Or maybe the shape-shifter starts as a microscopic metal claw with talons ready to pounce. Once the claw is in a patient's body, a doctor zaps it with electricity and the device clamps down, as though it had muscles of its own, and performs a biopsy. Or think of something less health-oriented. Perhaps the shape-shifter is a tiny oscillating membrane that drives a motor in a missile's guidance system. Maybe it's the panel on a car door that got dented by a shopping cart--heating the door with a hair dryer makes it as good as new.

These are among a plethora of shape-changing products in development or under consideration in labs around the world. Known as shape-memory materials, they are metal alloys or polymers that accomplish similar feats in different ways. Both types of materials can be preprogrammed with a permanent shape that can be recovered after a deliberate or accidental change. In most cases, applied heat brings the material back to its pre-set form. The metal alloys accomplish this switch by undergoing an internal change in their crystal structure. In a shape-memory polymer, different components control its form at different temperatures.

Known as "smart" metal alloys and polymers, these materials may literally reshape technologies ranging from warfare to medicine. MAGIC METALS Metal alloys are the older, more established class of shape-shifting materials. Thermally activated alloys have been around for decades, but they're finding more and more uses. The most widely employed shape-memory alloy--a blend of nickel and titanium commonly known as nitinol--is used in robots, satellites, and even coffee pots. It also serves as an alternative to surgical steel in medical implants, says Greg Carman of the University of California, Los Angeles.

Doctors implant the material in patients as stents, which are mesh tubes that hold open damaged blood vessels, and as venacava filters, which are metal webs placed in clot-prone blood vessels to break clots up as they pass through. The size of the nickel-titanium stent that a physician feeds into an artery can be smaller than that of a stainless steel stent. This makes the shape-memory stent ideal for such a delicate procedure, says Carman.

Steel stents are usually mechanically sprung into an expanded configuration after insertion in the vessel. Once in place, a shape-memory stent warms to body temperature, changing its internal crystal structure and expanding.

One of the promising aspects of shape-memory alloys is that "you can make very, very microscopic tools" with them, says Carman. He works with thin films of nickel-titanium alloys that are one-fiftieth the width of a human hair. In the past few years, he and his coworkers have been testing what he calls a microgripper. This cage or claw just 100 micrometers wide opens and closes like a hand when Carman heats it by passing a small electric current through the device. He envisions tiny tools such as this going into the body, grabbing suspicious cells for testing, removing cancerous tissue, and even stitching up internal incisions.

This microscopic tool is possible because some nickel titanium alloys are what scientists call two-way shape-memory materials. They can transform from their temporary shape to a preset shape and then return precisely to the temporary shape. These shifts occur when a current is applied and removed. A thin nickel-titanium alloy film, for example, might cycle about 100 times a second. "You can heat it up and cool it down real quick," says Carman.

He and his colleagues are now using these films to design and build powerful motors about the size of four stacked quarters. A thin oscillating membrane of nickel-titanium moves fluid that in turn drives a piston. The devices are being designed for missile-guidance systems that need small motors to move small parts.

Despite the successes of nickel-titanium alloys, newer shape-memory alloys wait in the wings. A few years ago, scientists discovered that it's possible to initiate a large, controlled shape change in certain metal alloys with a magnet rather than heat. But they don't yet know the alloys' capabilities and limitations. "People are trying to understand the phenomenon and the material," says Carman.

One of the most studied of these materials, called ferromagnetic shape-memory alloys, contains nickel, manganese, and gallium. "But that might not be the best," says Carman.

Robert O'Handley of the Massachusetts Institute of Technology is examining fundamental traits of the newly prized materials, which he thinks can change shape more quickly and extensively than heat-activated alloys. He and his coworkers are examining the basic properties of magnetically activated shape-memory alloys that the Navy would like to use in a variety of applications, such as suppressing loud or damaging vibrations in submarines.

When a large spinning turbine starts to vibrate, for example, small sensors on bearings within the machine would tell a computer that they're off-center by, say, 20 micrometers. Parts made from magnetic shape-memory alloys could then push or/the bearings to rebalance the machine. O'Handley is also exploring whether magnetic shape-memory alloys might be able to counter vibration or noise passively, by simply absorbing energy from vibrating parts.

The Navy might also use magnetic shape-memory alloys to send out the "pings"--or underwater vibrations--for submarines' sonar systems, O'Handley says. A piece of the alloy would be mounted on the outside of the ship, connected to a stiff rubber part. A pulse of electricity would create a magnetic field that changes the alloy's shape and moves the rubber to create the signal.

O'Handley hopes that shape-memory alloys might have advantages over the materials now used to create such underwater sonar. Those generally require phone-booth-size equipment and high voltages, which produce electrochemical reactions in salt water that promote local corrosion, he says.

Civilians also stand to benefit from the new ferromagnetic alloys. Researchers in Finland, for example, have expressed interest in using such materials for reducing vibrations in paper-mill machinery.

ONE WORD: PLASTICS Although shape-memory polymers have been under investigation for many years, they've made it into only a few trivial products, such as fork and spoon handles that can be softened under hot water and then molded to fit a person's hand. Most of these products don't benefit from their shape-memory properties, but only from the way that the materials are pliable without melting.

Yet consider how a shape-memory polymer might change the rules for auto-body repair. During manufacture, a polymer-based car door--or bumper or side-mirror casing--would have its permanent shape molded at a high temperature. A component of the polymer dictates the shape at that temperature but loses its dominance when the structure cools, says Steffen Kelch of the Institute of Chemistry at the GKSS Research Center in Teltow, Germany. Should the part later get dented, instead of painstaking bodywork, the repair would amount to heating the damaged part to the temperature at which the key component reasserts its control of the part's shape. That temperature, called the switching temperature, would not be as high as the original manufacturing temperature.

In the June Angewandte Chemic International Edition, Kelch and Andreas Lendlein, head of the GKSS Institute of Chemistry, argue that products taking true advantage of shape-memory materials are likely to become far more prevalent in the next few years. Medical implants are particularly promising because polymers can be designed to be compatible with tissue and to degrade.

A significant step toward marketable medical applications occurred when Lendlein and Robert Langer of the Massachusetts Institute of Technology created biodegradable polymer strands that can knot themselves. The researchers first formed the strands at 90[degrees]C into the shape of tight sutures. At cooler temperatures, the researchers used physical force to reshape the strands into unlooped, pliable threads. After the researchers loosely stitched the threads into rats' skin, the polymer strands warmed to the animals' body temperature, about 40[degrees]C. There, the polymer component responsible for the pre-set shape took charge, and me sutures resumed their knotted conformation, Lendlein and Langer reported in the May 31 Science.

Shape-memory polymers like this one might serve in a variety of medical implants for the body, suggests Langer. One of the most important of these could be stents. A highly compacted shape-memory polymer might spring open once it's inside the blood vessel and warmed to its switching temperature. In some medical applications, polymers would be designed to be degradable.

"I'm a big believer in the polymers," says Langer. In 1998, he and Lendlein cofounded a company called mnemo-Science in Aachen, Germany, to explore the development of these materials. "I think if you look at the evolution of medicine, [implants] have gone from very crude kinds of things, like metals or ceramics, more toward polymers and ultimately towards cells," he says. "They're developed to be more and more natural"

Materials scientists are now looking at ways to make shape-memory polymers with new properties, says Kelch. One area of focus is on finding polymers that change shape in response to triggers other than heat, such as magnetic fields or light.

Another active area of research is on designing two-way shape-memory polymers. Although some shape-memory metal alloys possess this trait, no polymer that heat transforms from its temporary shape to a preset shape will return precisely to that shape when it cools down. In this regard, "at the moment, shape-memory alloys are superior to the polymers," says Kelch.

TWO DIFFERENT MATERIALS With both metal-alloy and plastic shape-memory materials available, engineers have the luxury of testing which one is better for any given application. "It's like having a buffet of different materials to choose from," says O'Handley.

"Medically, polymers are just more versatile," says Langer. "You can make them more biocompatible"

Moreover, "where you need elastic materials, the polymers are better," Kelch adds. Some polymers stretch to 10 times their length, whereas metals are relatively inelastic, he says. Also, the polymers can undergo much more dramatic shape changes than the metal alloys can as they convert between their permanent and temporary forms.

On the other hand, metals are tougher than polymers and remain hard and tough at temperatures at which polymers become soft and weak. Scientists can also use a wider range of temperatures to switch metals from one shape to another.