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Status and Trends in Shape Memory Technology

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Proc. "Actuators" VDI/VDE Bremen
pp. 79-84

1992

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STATUS AND TRENDS IN SHAPE MEMORY TECHNOLOGY

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Abstract:
The shape memory effect is the result of a thermoelastic, martensitic transformation occuring in some Ni-Ti and some copper based alloys. These alloys show a distinct difference in their mechanical poperties at high and low temperatures. Shape memory alloys can generate motion and/or force. Therefore, they can be used in sensor-actuators responding to changes in ambient temperature, or electrical actuators performing a task on demand by passing current through the material. Shape memory actuators combine large motion, high forces and small size, thus providing high work output. They usually do not require sophisticated mechanical designs. Shape memory thermal actuators have been successfully used in the areas of thermal protection. Electrical actuators have been used to replace solenoids, electric motors etc. in applications, where quiet operation, small dimensions, small or large forces and simplicity of the design is required. Recent developments include "smart structures", composites with integrated shape memory wires to change the shape or stiffness of a composite structure.

Introduction

Certain metallic materials will, after an apparent plastic deformation, return to their original shape when heated. The same materials, in a certain temperature range, can be strained up to approx. 10% and still will return to their original shape when unloaded. These unusual effects are called thermal shape memory and superelasticity (elastic shape memory) respectively (1). Both effects depend on the occurrence of a specific type of phase change known as thermoelastic martensitic transformation. Shape memory and superelastic alloys respond to temperature changes and mechanical stresses in non-conventional and highly amazing ways. They are, therefore, sometimes called "intelligent materials". The shape memory effect can be used to generate motion and/or force in thermal and electrical actuators, while superelastic components might reduce the complexity of handling and manipulation devices. In the following, only the shape memory aspect of this phenomenon will be described.

Shape Memory Alloys

The shape memory effect as the result of a martensitic transformation has been known since the mid 1950's, when the effect was discovered in copper base alloys. In the early sixties, researchers at the Naval Ordnance Laboratory found the shape memory effect in Ni-Ti alloys (Nitinol - **Ni-Ti N**aval **O**rdnance **L**ab). Today, these alloys are the most widely used shape memory and superelastic alloys, combining the most pronounced shape memory effect, corrosion resistance, and superior engineering properties (2). Copper based alloys like Cu-Zn-Al and Cu-Al-Ni are commercially available, too. These alloys are less stable and more brittle than Ni-Ti, and therefore, although less expensive, have found only limited acceptance for actuator applications. In recent months, Iron based shape memory alloys have been widely advertised. However, with their limited shape memory strain, lack of ductility and other essential properties, these alloys will have to prove themselves as viable engineering materials.

The transformation temperatures of shape memory alloys can be adjusted through changes in composition. Ni-Ti as well as Cu-Zn-Al alloys show transformation temperatures between -100°C and +100°C, Cu-Al-Ni alloys up to 200°C. Unfortunately, Cu-Al-Ni alloys are not stable in cyclic applications
Some ternary Ni-Ti-Pd alloys also are reported to exhibit transformation temperatures up to 200°C (3). Although not commercially available today, these alloys could eventually expand the applicability of the shape memory effect to much higher temperatures.

Shape Memory Effect

"Shape Memory" describes the effect of restoring the original shape of a plastically deformed sample by heating it. This phenomenon results from a crystalline phase change known as "thermoelastic martensitic transformation". At temperatures below the transformation temperature, shape memory alloys are martensitic. In this condition they are soft and can be deformed quite easily. Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic, condition (Fig. 1).

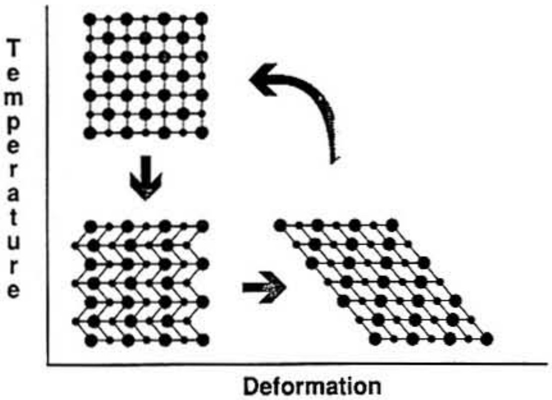

Fig. 1: The martensitic transformation and the shape memory effect

The design of shape memory components, e.g. "intelligent actuators", sensor-actuators that respond to a change in temperature with a shape change (4), is based on the distinctly different stress/strain curves of the martensite and austenite, and their temperature dependence. Figure 2 shows tensile curves of a Ni-Ti alloy in the martensitic and austenitic conditions. While the austenitic curve looks like that of a "normal" material, the martensitic one is quite unusual. On exceeding a first yield point, several percent strain can be accumulated with only little stress increase. After that, stress increases rapidly with further deformation. The deformation in the "plateau region" is non-conventional in nature and can be recovered thermally. Deformation exceeding the second yield point cannot be recovered. The material is plastically deformed in a conventional way.

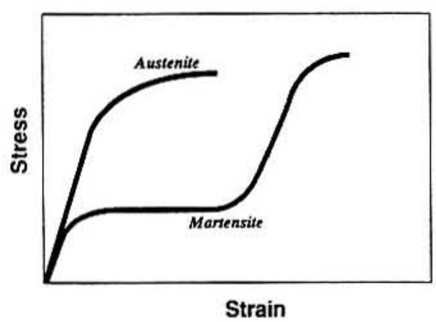

Fig. 2: Tensile behavior of the martensite and austenite

The transformation from austenite to martensite and the reverse transformation from martensite to austenite do not take place at the same temperature. A plot of the volume fraction of martensite, or more practically, the length of a wire loaded with a constant weight, as a function of temperature provides a curve of the type shown schematically in Figure 3. The complete transformation cycle is characterized by the following temperatures: austenite start temperature (As), austenite finish temperature (Af), martensite start temperature (Ms) and martensite finish temperature (Mf).

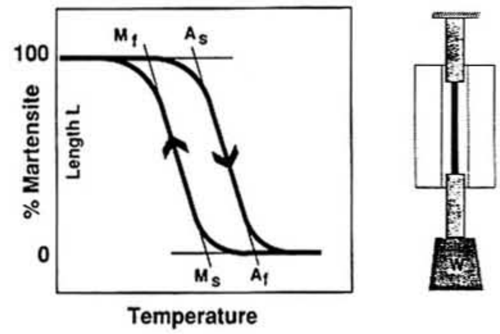

Fig. 3: Temperature hysteresis curve of the shape memory effect

The hysteresis is an important characteristic of the heating and cooling behavior of shape memory alloys and actuators made from these alloys. Depending on the alloy used and/or its processing, the transformation temperature as well as the shape of the hysteresis loop can be altered in a wide range. Binary Ni-Ti alloys typically have transformation temperatures (As) between 0°C and 100°C with a width of the hysteresis loop of 25°C to 40°C. Copper containing Ni-Ti alloys show a narrow hysteresis of 7°C to 15°C with transformation temperatures (As) ranging from -10°C to approx. 80°C. An extremely narrow hysteresis of 0 to 5°C can be found in some binary and ternary Ni-Ti alloys exhibiting a premartensitic transformation (commonly called R-phase). On the other hand, a very wide hysteresis of over 150°C can be realized in Niobium containing Ni-Ti alloys after a particular thermomechanical treatment.

The standard thermomechanical processing of Ni-Ti alloys generates a steep hysteresis loop (a greater shape change with a lesser change in temperature), which generally is desirable in applications where a certain function has to be performed upon reaching or exceeding a certain temperature. Special processing can yield a hysteresis loop with a more gradual slope, i.e. a small shape change with temperature. This behavior is preferred in applications where proportional control is required (5).

The shape of the hysteresis loop is not only alloy and processing dependent, but is also influenced by the application itself. If a wire (standard processing) works against a constant load, e.g. by lifting a certain weight, the transition from martensite to austenite or vice versa occurs in a very narrow temperature range (typically 5°C). However, if the wire works against a biasing spring, the transition is more gradual and depends on the rate of the spring.

Designing with the shape memory effect

The shape memory effect can be used to generate motion and/or force. The function of the different events as shown the stress/strain perspective in Fig. 4 can be explained in simple terms using a straight tensile wire. The wire is fixed at one end. Stretching it at room temperature generates an elongation after unloading. The wire remains in the stretched condition until it is heated above the transformation temperature of this particular alloy. It will then shrink to its original length As no load is applied, this is called *free recovery* (Fig. 4 a). Subsequent cooling below the transformation temperature does not cause a macroscopic shape change.

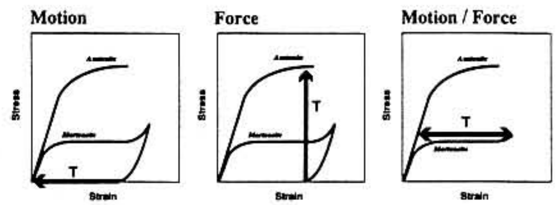

Fig. 4: Free recovery, constrained recovery and motion against force in the stress / strain perspective

If, after stretching at room temperature, the wire is prevented from returning to its original length, i.e. if constrained to the extended length upon heating above the transformation temperature, it can generate a considerable force (Fig. 4b). This so-called *constrained recovery* is the basis of many successful applications (6).

If the opposing force can be overcome by the shape memory wire, it will generate motion against a force, and thus do work. Upon heating, the wire will contract and lift a load, for instance. Upon cooling, the same load will stretch the now martensitic wire and reset the mechanism (Fig 4c). This effect is called *two-way-effect with external reset force.* Shape memory alloys can, under certain conditions, show a true two-way-effect, which makes them remember two different shapes, a low and a high temperature shape, even without external force. However, it is smaller and its cyclic behavior is not as well understood as that of the one-way-effect. Because there is no special treatment necessary, the cyclic use of the one-way-effect with external reset force in many cases is the more economic solution.

Engineering Aspects

Most actuator designs work against a biasing mechanism of some sort, e.g. a constant load, a spring force, air or oil pressure etc. Depending on the kind of biasing mechanism, different force/displacement characteristics can be obtained (7). In Figure 5 and 6, five commonly used scenarios are compared with regard to the force/displacement response. The level of the force in Fig. 5a obviously is given by the weight of the "dead load", while the slope of the force/displacement line in Fig. 5b represents the spring rate of the biasing steel spring. In Fig. 5c, two shape memory wires are working in opposing directions. When wire 1 is heated (e.g. through electrical heating), it contracts, moves an object, and simultaneously stretches wire 2. The object can be moved in the opposite direction by heating wire 2 after cooling of wire 1.

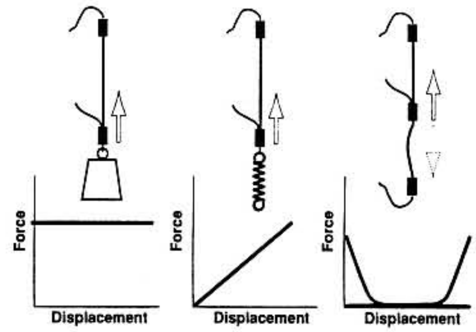

Fig. 5: Commonly used biasing mechanisms

Socalled reverse biasing is shown in Figure 6. The magnet in Fig. 6a causes the shape memory wire to generate a high static force, that drops sharply when the magnet is separated from its holding plate. A slower drop in force can be achieved by using a cam arrangement with a decreasing lever during actuation of the shape memory wire. Reverse biasing is beneficial when high cyclic stability is important.

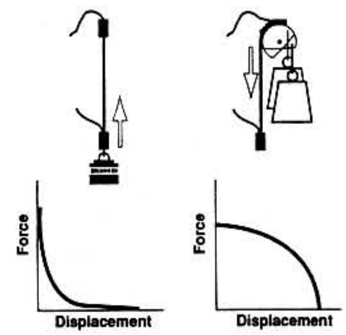

Fig. 6: Reverse biasing mechanisms

Under optimum conditions and no load the shape memory strain can be as high as 8%. However, for cyclic applications the usable strain is much less. The same applies for the stress; for a one-time actuation the austenitic yield strength may be used as maximum stress. Much lower values have to be expected for cyclic applications. The following numbers may be used as guidelines:

Cycles	Max. Strain	Max Stress
100	4%	275 MPa/43 ksi
10000	2%	140 MPa/20 ksi
100000+	1%	70 MPa/10 ksi

The shape memory effect is not limited to the linear contraction of wires. Even larger shape changes can be achieved in the bending or torsional deformation mode. Accordingly, there are many possibilities regarding the shape of the actuator. Preferred configurations are :

- straight tensile wires (high force, small motion)
- helical compression springs (large motion, less force)
- helical extension springs (large motion, less force)
- cantilever springs (bending)
- "Belleville"-type disc springs (high force, small motion)

Applications of Shape Memory Actuators

Shape memory actuators respond to a temperature change with a shape change. The change in temperature can be caused by a change of ambient temperature or by electrically heating the shape memory element. In the first case, the shape memory alloy acts as a sensor and an actuator (thermal actuator). In the second case, it is an electrical actuator that performs a specific task on demand. Thermal as well as electrical shape memory actuators combine large motion, rather high forces and small size, thus they provide high work output. They usually consist of only a single piece of metal, e.g. a straight wire or a helical spring, and do not require sophisticated mechanical systems.

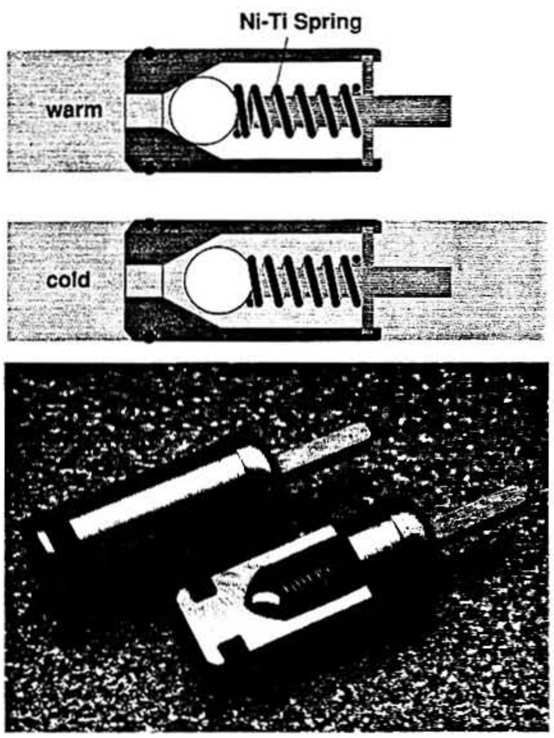

Fig. 7a: Oilcooler By-pass valve

Shape memory thermal actuators have been successfully used in the areas of thermal compensation, thermal actuation and thermal protection. They often fit into tight spaces in existing designs, where other thermal actuators, like thermostatic bimetals or wax actuators, would require a major redesign of the product. In flow-control or oil pressure control valves, for example, helical springs can be placed in the fluid path, without restricting the flow. Thus, they

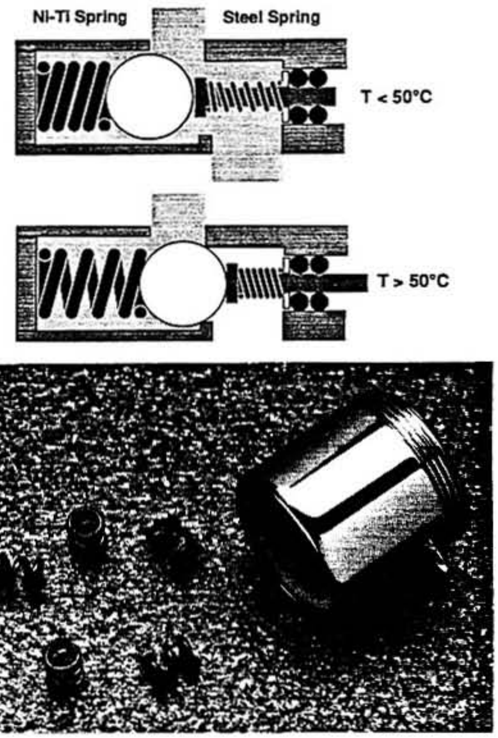

Fig. 7b: Aerator with anti-scald feature (International Scaldguard)

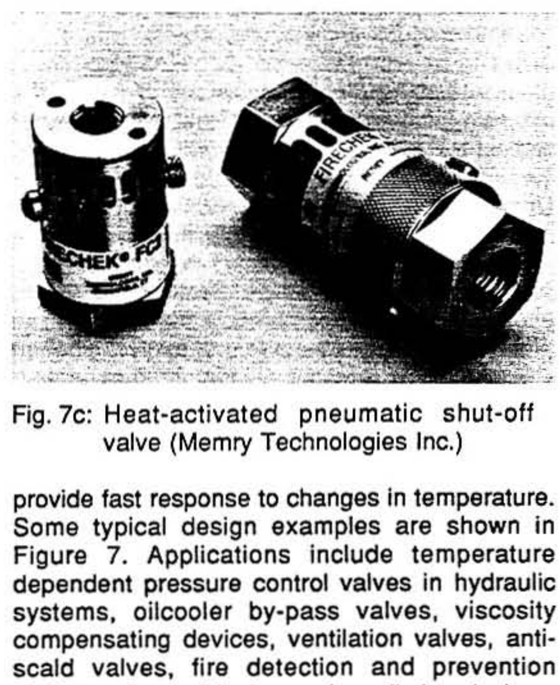

Fig. 7c: Heat-activated pneumatic shut-off valve (Memry Technologies Inc.)

provide fast response to changes in temperature. Some typical design examples are shown in Figure 7. Applications include temperature dependent pressure control valves in hydraulic systems, oilcooler by-pass valves, viscosity compensating devices, ventilation valves, anti-scald valves, fire detection and prevention devices, air conditioning and ventilation devices, etc (8).

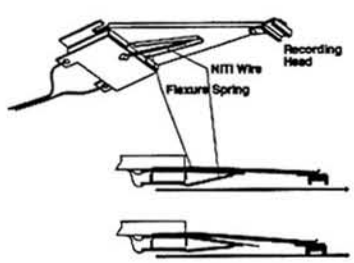

Fig. 8a: Recording head lift mechanism for disc drives

Electrical actuators have been used to replace solenoids, electric motors etc. in applications, where quiet operation, small dimensions, small or large forces and simplicity of the design is required. By controlling the power during electrical actuation, specific levels of force and/or specific positions can be maintained. A variety of valves, triggering devices, animated objects, toys etc. are presently being marketed (Fig. 8). The integration of Ni-Ti wires in composite structures

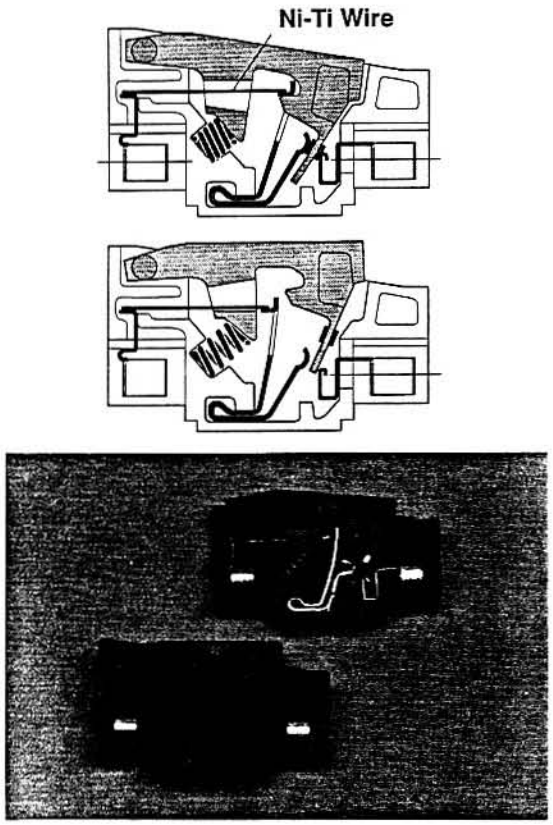

Fig. 8b: Micro circuit breaker

has been suggested, to allow the structure to change shape on demand. These "smart composites" can also actively attenuate acoustic noise in structures by having fundamental control over structural stiffness. Strain-compliant shape memory composites can be used as integrated members in truss structures,

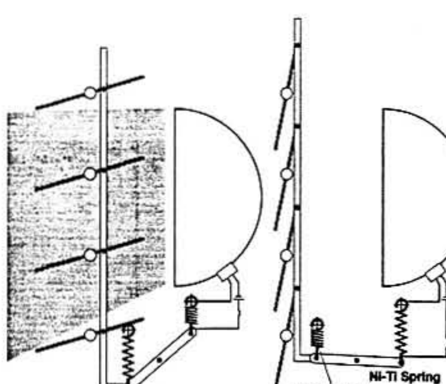

Fig. 8c: Louver mechanism for foglamp

performing passive and active roles in vibration and shape control.

Recently, a system to dampen the low frequency swing of large antennas or reflectors during space shuttle maneuvers has been proposed, using a shape memory controlled hinge system (Fig. 9)(9).

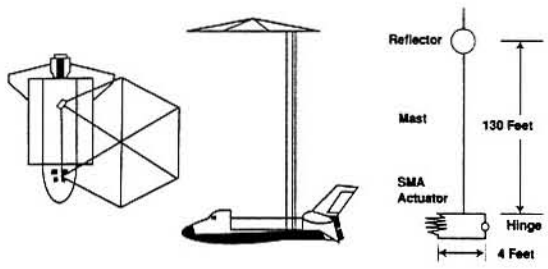

Fig. 9: Damping device for shuttle antenna (Martin Marietta)

Limiting factors for the use of shape memory alloys in electrical actuators are the transformation temperatures available today and the lack of control over cooling times. In order to work properly, the Mf temperature of the shape memory alloy must be well above the maximum operating temperature of the actuator. Commercially available alloys that are sufficiently stable in cyclic applications, have transformation temperatures (Mf) of around 70°C. Thus, an electrical actuator made from this alloy would fail to reset when ambient temperature reaches 70°C. Correspondingly, the actuator would self-trigger when ambient reaches its As temperature. For applications with high operating temperatures (e.g. automotive), alloys with transformation temperatures above 150°C are required. As mentioned above, Ni-Ti-Pd alloys with transformation temperatures up to 200°C might eventually become available.

The use of shape memory actuator for robots has often been proposed, and several prototypes have been presented. However, as the shape memory effect is a thermal phenomenon, response time is dictated by the heating and cooling of the material. While heating can be controlled through the power supplied to the actuator, cooling is less controllable. Depending on the size of the actuator (wire diameter, mass), cooling times can be seconds to minutes.

Conclusions

Although the shape memory effect has been known for some thirty years, only during the last three years have a multitude of actuator applications appeared on the market. This in part is due to the limited number of alloy producers, their secretiveness, and thus the lack of engineering data for the alloys. Today, shape memory properties and applications are being discussed more openly, training courses on design and engineering are available and the alloys can be purchased from several producers. The alloys available today are particularly suited for a variety of thermal applications, like thermal protection, thermal actuation and thermal compensation. Thermal shape memory actuators combine sensing and actuation. They compete mainly with thermostatic metals and wax actuators. Their advantages are simplicity of design, light weight, small dimensions, high forces, and large motion.

Electrical shape memory actuators perform a task on demand. They compete with solenoids, stepping motors and some thermoelectric actuators. Again, the high power/weight ratio represents a significant advantage, as well as the small driving voltage and current. In some applications, the noiselessness of the operation is appreciated. Major disadvantages are the limited operational temperature range, as well as the relatively long reaction time without forced cooling.

With the increasing number of producers of shape memory materials and components, the proof of reliable operation in existing applications, and the availability of engineering data, the market for shape memory actuators is expected to grow considerably during the next few years.

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