# Properties and Applications of Shape Memory Actuators

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## Introduction

Shape memory alloys after a certain treatment show a temperature-depending shape change, which is based on a thermoelastic martensitic transformation. A thermoelastic martensitic transformation is realized, when martensite plates form and grow continuously as the temperature is lowered and disappear by the reverse way as temperature is raised. The main reason for the reversibility of the thermoelastic martensite is the fact, that only very small elastic strains are associated with the crystal structure transformation (1). Up to now there are three groups of technically applicable shape memory alloys: NiTi, Cu-Zn-Al and Cu-Al-Ni.

## 1. Types of Shape Memory Effect

### 1.1 One-Way Effect

If a specimen of a martensitic shape memory alloy is deformed in the range below a critical value only reversible deformation takes place by the movement of highly mobile boundaries (e.g. twin boundaries, martensite/martensite interfaces). Upon heating the specimen austenite crystallites with the initial orientation are formed and so the specimen reverts to its original shape. Because no additional shape change occurs on subsequent cooling, this effect is called one-way shape memory effect. This is schematically shown in Fig. 1 (2,3).

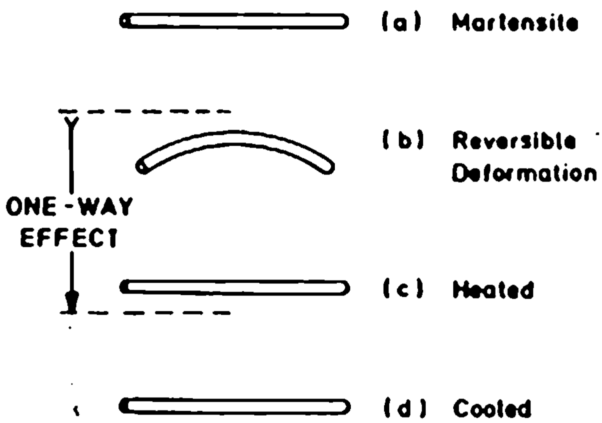



Fig. 1: Schematic illustration of the one-way effect.

The one-way effect can be repeatedly induced by deforming again the specimen in the martensitic state. Upon heating a specimen with an one-way effect there is no movement at first. The shape change starts at the so-called $A_S$-temperature and is completed in a small temperature range of e.g. 10 to 20 K.

The $A_s$-temperature of technically applicable shape memory alloys can be set everywhere between about -150°C and +150°C by corresponding selection of the chemical composition of the alloy. Guiding values for the maximal $A_s$-temperatures and the magnitude of the one-way effect are listed in Table 1 (3,4).

| Property \ Alloy | NiTi | Cu-Zn-Al | Cu-Al-Ni |
|---|---|---|---|
| Density ($g/cm^3$) | 6,4 - 6,5 | 7,8 - 8,0 | 7,1 - 7,2 |
| Electric Conductivity ($10^6$ [illegible]) | 1 - 1,5 | 8 - 13 | 7 - 9 |
| Tensile Strength ($N/mm^2$) | 800 - 1000 | 400 - 700 | 700 - 800 |
| Elongation (%) | 40 - 60 | 10 - 15 | 5 - 6 |
| Maximum $A_s$-Temperature (°C) | 120 | 120 | 170 |
| Maximum One-Way-Effect $\varepsilon_{1\,max}$ (%) | 8 | 4 | 5 |
| Maximum Two-Way-Effect $\varepsilon_{2\,max}$ (%) | 5 | 2 | 2 |
| Overheatable (Shorttime) up to (°C) | 400 | 160 | 300 |

Table 1: Properties of technically suitable shape memory alloys.

## 1.2 Reversible Effect

### 1.2.1 Two-Way Effect

Shape memory elements with a two-way effect "remember" both a high temperature shape and a low temperature shape. To produce a two-way effect it requires a special mechanical and thermal treatment of the shape memory alloy. One method to produce a two-way effect is based on a severe deformation in the martensitic state, as schematically shown in Fig. 2.

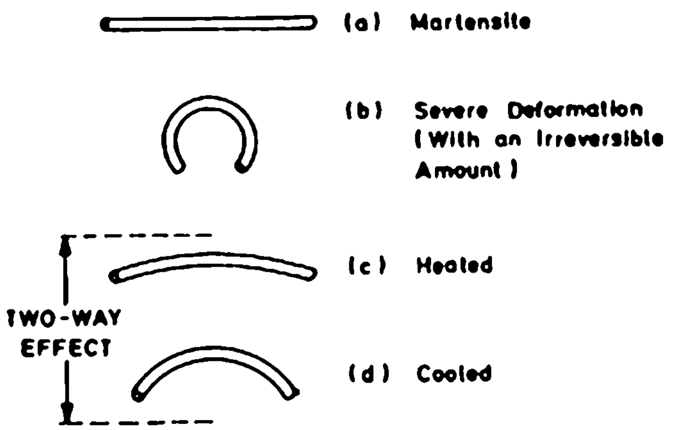



Fig. 2: Schematic illustration of the two-way effect.

If the deformation of a specimen in the martensitic state exceeds a critical value, then in addition to the reversible martensite deformation also irreversible deformation occurs by the movement of dislocations, which cannot be recovered upon heating. However the irreversible deformation induces a certain dislocation structure. On heating the specimen will move towards its original shape (a) and the high temperature shape (c) forms. On cooling again the pre-existing martensite plates will accomodate the stress field of the induced dislocation structuro and prefered martensite variants form which give rise to the low temperature shape (d). Thus by temperature cycling one gets the two-way effect according to Fig. 2 (2).

This method of the production of the two-way effect can be used especially with the NiTi alloys, since this material shows the necessary high ductility.

In addition to severe deformation of martensite there are some other methods to produce a two-way effect like:

- Two-way effect due to shape memory effect training
- Two-way effect due to stress-induced martensite training
- Two-way effect due to combined training
- Two-way effect due to the forces of inactive surface layers
- Two-way effect due to precipitations (1,5-9).

Fig. 3 shows examples of shape memory elements with a two-way effect. The temperature-displacement curve of such an element is

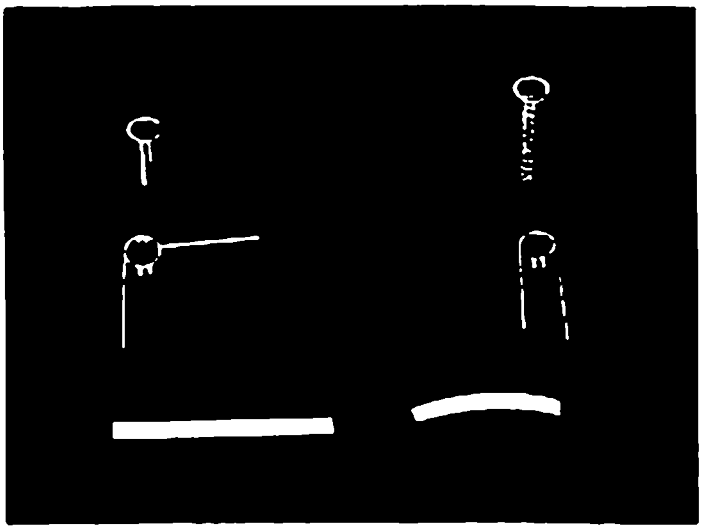


Fig. 3: Shape memory elements of Cu-Zn-Al with a two-way effect ($A_s \approx 65°C$, $A_f \approx 80°C$, $M_s \approx 65°C$, $M_f \approx 50°C$).
Left side: low temperature.
Right side: high temperature.

schematically shown in Fig. 4. Similar to the one-way effect upon heating a specimen with a two-way effect the shape change starts at the so-called $A_s$-temperature.
On further heating the complete shape change takes place in a small temperature range (e.g. 10 to 20 K). The displacement-tempe-

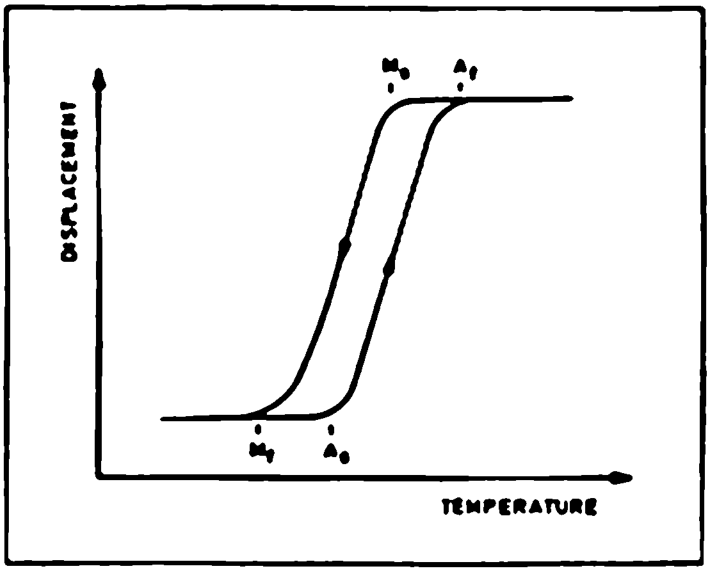



Fig. 4: Temperature-displacement curve of a shape memory element with a two-way effect.
$A_s$ and $A_f$: temperature at which on heating the shape change starts and is completed respectively.
$M_s$ and $M_f$: temperature at which on cooling the shape change starts and is completed respectively.

rature curve shows a hysteresis, which ranges from about 10 to 30 K depending on the respective shape memory alloy. Examples of possible types of shape memory elements are shown in Fig. 5 (3,4).

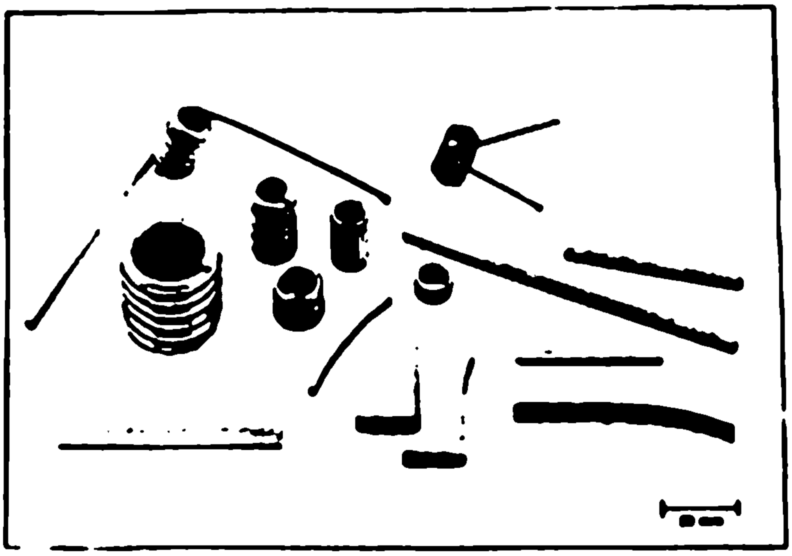


Fig. 5: Examples of possible types of shape memory actuators.

### 1.2.2 Reversible Effect Based on the One-Way Effect and a Bias Force

Elements with a two-way shape memory effect show a reversible shape change without external supporting forces. In addition a reversible shape change can be produced if one always repeats the one-way effect by the means of an external bias force (e.g. bias load or spring). This reversible effect is based on the fact that shape memory alloys show a low strength in the martensitic state and a high strength in the austenitic state.

### 1.2.3 Reversible Effect Based on the R-Phase

In Ni-rich NiTi alloys with more than 50.5 at % nickel after a certain aging a two-step transformation takes place, which includes the R-phase (Rhombohedral phase). Similar to martensite the R-phase shows a thermoelastic behaviour and therefore gives rise to a shape memory effect. This effect has a maximum magnitude of about 1% but the hysteresis is a very small one (about 1-2 K) (2,5-7). The small hysteresis of the R-phase transformation can be used for example in the field of control technics.

In general the reversible effect associated with the R-phase is based on the one-way effect and a bias spring.

## 2. Properties of Technically Suitable Shape Memory Alloys

At this time there are three groups of technically suitable shape memory alloys: NiTi, Cu-Zn-Al and Cu-Al-Ni (see Table 1).

The prototyp shape memory alloy is NiTi, which shows a big shape memory effect, a good overheatability, a high stability of the effect, a high volume of work and a good corrosion resistance (10).

The copper-based alloys Cu-Zn-Al are less expensive, but their shape memory effect is smaller and less stable. The overheatability and the corrosion resistance are smaller than with NiTi. On the other hand these copper-based alloys show an enhanced electric and thermal conductivity (11).

The copper-based alloys Cu-Al-Ni have been developed in order to have higher $A_s$-temperatures. Unfortunately these alloys show a bad ductility and a small stability of the shape memory effect (9).

Important physical and mechanical properties and some shape memory data of these three groups of alloys are shown in Table 1. The listed properties depend on different parameters like chemical composition and crystal structure and therefore the properties are given as ranges or maximum values (4).

The data for the overheatability are valid only for short time. The admissible maximum temperatures for long time applications are lower. E.g. for NiTi actuators the temperature for long time should not exceed 200°C, because otherwise a deterioration of the shape memory effect takes place.

The temperature hysteresis for the reversible effect is about 20-30 K for binary NiTi, about 10-15 K for ternary NiTiCu and only 1-2 K for the R-phase transformation of binary NiTi. The temperature hysteresis for the reversible effect of Cu-Zn-Al is about

7-15 K and of Cu-Al-Ni about 20-40 K.

## 3. Effect-Stability and Working Capacity of Shape Memory Actuators

Rough values for the stability of the shape memory effect measured with a mechanical limitation at low temperature are given in Table 2 for the case that the magnitude of the effect, the stress, the temperature range and the overheating don't exceed certain

| Alloy | Number of Thermal Cycles | Diminution of the Effect |
|---|---|---|
| NiTi | 100 000 | practically no degradation |
| Cu-Zn-Al | 10 000 | ca. 10% |
| Cu-Al-Ni | 1 000 | ca. 10% |

Table 2: Stability of the two-way effect with a mechanical limitation at low temperature.

values. The stability of the shape memory effect is primarily given by the magnitude of the used working capacity, which is the product of the effect-magnitude and stress.

Table 3 shows the rough values for the maximum two-way effect and the admissible stress for the three technically important groups of shape memory alloys. With these values one gets a working capacity per unit volume of about 1-5 MJ/m³ depending on the group of shape memory alloy (12). The values in Table 3 can be used only for applications in which a reduced stability of the shape memory effect can be accepted.

| Property \ Alloy | NiTi | Cu-Zn-Al | Cu-Al-Ni |
|---|---|---|---|
| Maximum Two-Way Effect $\varepsilon_{2\,max}$ (%) | 5 | 2 | 2 |
| Admissible Stress $\sigma_{adm}$ (N/mm²) | 250 | 75 | 100 |

Table 3: Maximum two-way effect and admissible stress.

To get the stability according to Table 2 one has to use a smaller effect-magnitude and lower stresses. E.g. for NiTi the stability according to Table 2 can be realized with an effect-magnitude of 1-1,5%, a stress of about 100 N/mm² and a maximum $A_S$-temperature of about 80°C. For $A_S$-temperatures as high as 120°C (Table 1) binary NiTi alloys show a great deterioration of the shape memory effect after a few thermal cycles even if the strain and stress are low (12).

The real stability of shape memory actuators for a given application in general can't be predicted by means of a simple shape memory specimen but it has to be tested in the respective complete device under the specific parameters of the application.

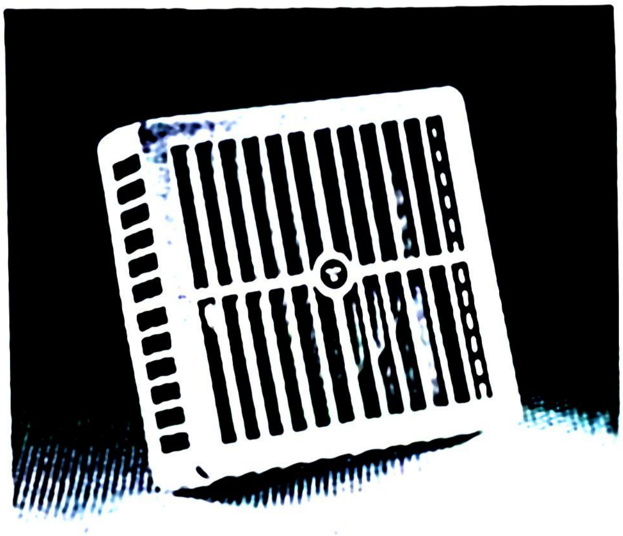
## 4. Applications of Shape Memory Actuators

The characteristic properties of shape memory elements can be summarized as follows (4):

- Performance of the complete mechanical work in a selected and relatively narrow temperature range (hysteresis)
- High mechanical work per unit volume
- Possibility to exhibit different types of shape change (elongation, contraction, bending, torsion)
- The shape memory effect can be restricted to certain parts of the element.

The first applications of shape memory elements were based on the one-way effect and have been realized in the field of the fastening technics (e.g. couplings for tubes). In the meantime shape memory elements for fastening are used in a great manner in technics.

In contrast to fastening elements there is only a limited number of applications of shape memory actuators in a technical scale. But there are great activities on this field. In the following there will be described some possibilities of application for shape memory actuators. Some of the applications are realized in a technical scale, in other cases there are described prototypes, that means those applications are possible but not yet realized commercially.



Ventilation technics: In Fig. 6 there is shown a ventilation valve, in which the passing of air is controlled by a helical compression spring. A corresponding spring one can see in Fig. 3. The heating is made by an PTC-heater in the shape of a bar, which is fitted into the spring. The shape change of the spring causes an

Fig. 6: Ventilation valve actuated by a helical compression spring of Cu-Zn-Al. (Moldrich, Wien)

axial displacement of the cover and thus opens and closes the ventilation valve (13).

Thermal protection: Figs. 7a and 7b schematically show a thermal protection device, which interrupts the electric circuit in case of overload. In this case a shape memory element works as a contact carrier and an elastic spring provides a certain contact pressure. In case of overheating the shape memory element bends away and opens the circuit, while the circuit is closed again, when the disturb is removed and temperature is low. In Fig. 7c there is shown a conception in which the shape memory element and the spring are integrated into one part (4).

Fig. 7d shows a thermal protection device with a two-way shape memory spring which is not heated by an electric current but by the ambient medium. Due to the great displacement of the shape memory element in a narrow and well-defined temperature range no adjustage is necessary. Such a device can be used for instance in an electric tea kettle providing switch-off, when the water begins boiling (14).

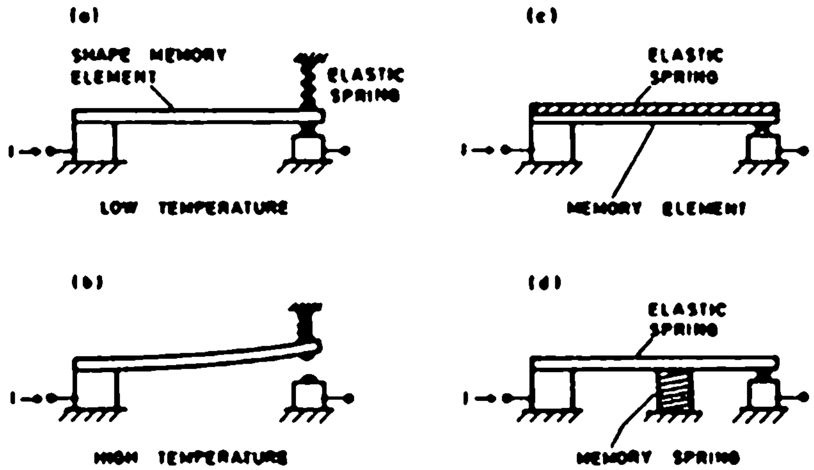



Fig. 7: Thermal protection devices based on shape memory elements (schematic).

An other thermal protection device is concerned with the field of sanitary facilities. For example an antiscald safety valve with a shape memory spring for a shower guard has been developed, to protect against hot water scalding caused by sudden changes in water temperatur (15).

Heat engines: Fig. 8 shows the prototyp of a water pump with a shape memory actuator, using solar energy. A special mirror with a fixed focus heats up a water reservoir. The heated water expands a shape memory compression spring with a two-way effect and so cold water is taken in. The cold water causes a contraction of the shape memory spring, so that a cyclic pumping effect is created (13).

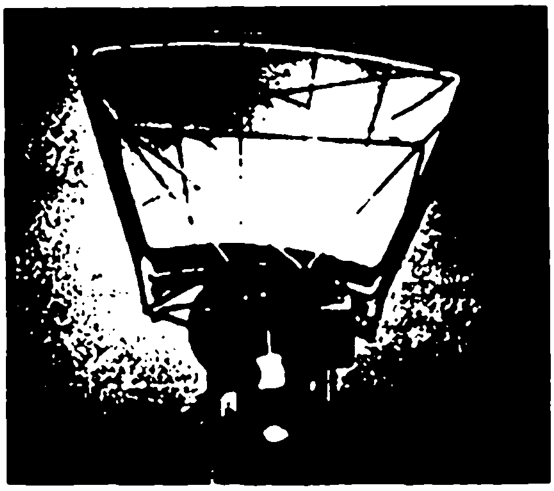


Fig. 8: Water pump with a shape memory actuator (arrow). (Bomin Solar, Lörrach)

Fire protection technics: In Fig. 9 there are shown examples of thermal valves, which interrupt the flowing of inflammable fluida (e.g. gas), when a critical ambient temperature is achieved. This is made by a shape memory compression spring with a two-way effect, which at a certain temperature moves a steel ball through an elastic ring of steel and thus closes the valve. A selfacting reset of the ball is avoided by the ring. For opening the valve at normal temperature the ball can be pushed manually in its initial position by a pin.

Fig. 9: Thermal valves with helical compression springs of Cu-Zn-Al. Left side: opened. Right side: closed. (Proteus, Belgium).

Additional fields of application of shape memory actuators are:

Automotive technics: Actuators for different temperature-depending processes in the engine, gearings and chassis. For example one should mention shape memory actuators for fan clutches of engines, for throttle devices connected to the fuel injector pump (14), for gear systems with optimized function (16), and so on.

Solar technics: E.g. actuators for the synchronization of a solar collector with the movement of the sun (13).

Actuators for robotics.

Actuators for electronics.

Toy industry (17).

## 5. Outlook Aspects

In contrast to shape memory elements for fastening technic until now there is only a small number of applications in a technical scale with shape memory actuators. Due to the complexity of the shape memory theme for greater introduction of shape memory actuators in technics there are necessary intensive discussions between producer and applier of these actuators. The great activities on this field probably will lead to a quick increase of the number of applications in the next years. The success will depend especially from the fact, in how far the producer of shape memory actuators can increase the transformation temperatures, the overheatability and the working life of the actuators and can offer these parts for an attractive price.

## References


(1) J. Perkins: Mat. Sci. Eng. 51 (1981) 181-192.

(2) K. Otsuka, K. Shimizu: Proc. of Int. Summer Course on Martensitic Transformations, Katholieke Universiteit Leuven (1982) 81.

(3) P. Tautzenberger, D. Stöckel: Zeitschrift für wirtschaftliche Fertigung 78 (1983) 10, 486-488.

(4) P. Tautzenberger, D. Stöckel: Zeitschrift für wirtschaftliche Fertigung 81 (12) (1986) 703-708.

(5) M. Nishida, T. Honma: Int. Conf. on Martensitic Transformations, Leuven 1982, Journal de Physique, Colloque C-4 suppl. No. 12 (1982) 225-230.

(6) M. Nishida, T. Honma: Scripta Met., 18 (1984) 1293-1298.

(7) T. Honma: Proc. Int. Symp. SMA Guilin (1986) 83-88.

(8) J. Perkins, R.O. Sponholz: Met. Trans. 15 A (1984) 313.

(9) T.W. Duerig, J. Albrecht, G.H. Gessinger: Journal of Metals 34 (12) (1982) 14-20.

(10) W.J. Buehler, J.V. Gilfrich, R.C. Wiley: J. Appl. Phys. 34 (1963) 1475.

(11) L. Delaey, A. Deruyttere, E. Aernoudt, J.R. Roos: INCRA REPORT 1978.

(12) P. Tautzenberger, D. Stöckel: METALL 41 (1987) 26-32.

(13) P. Tautzenberger: Magazin Neue Werkstoffe 1 (1987) 20-23.

(14) C.M. Wayman: J. Met. 32 (1980) 9, 129

(15) Memory Metals Inc., USA: Technical Report 1986.

(16) Raychem Corp., USA: Technical Report 1986.

(17) Innovative Technology International, Inc., USA, 1983.