The Use of Shape Memory Alloys in Switchgear Technology

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ABSTRACT

In shape memory alloys a diffusionless transformation occurs when austenite, the high temperature phase of the alloy, is cooled, and transforms into a different crystalline structure, martensite. When deformed in the martensitic state, shape memory alloys return to their initial shape when they are heated to a critical elevated temperature. This effect is called "mechanical memory". Besides this unique effect memory alloys have some interesting properties like superelasticity and a high damping capacity depending on the structure. The paper deals with the properties and possible applications of NiTi, Cu-Zn-Al and Cu-Al-Ni shape memory alloys. The temperature depending mechanical memory can be used in a large variety of temperature sensing switching devices. The superelasticity of these alloys can be utilized for contact springs with a very high bending and fatigue strength. Contact bouncing may be decreased by the use of alloys with high damping capacity.

INTRODUCTION

In the last years considerable attention has been devoted to a special group of alloys, which exhibit the so-called shape memory effect. If a shape memory alloy undergoes a certain permanent deformation at low temperature it reverts to its original shape on heating to some higher temperature.

The shape memory effect is based on a thermoelastic martensitic transformation, at which the high temperature phase (austenite) transforms into the low temperature phase (martensite) and vice versa by a shear-like mechanism. 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. There always exists a balance between the chemical free-energy difference between the two phases as a driving force and some non-chemical opposing energy terms like the elastic strain energy built up around the martensite crystallites.

When cooled shape memory alloys consist of groups of self-accomodating martensite plates, which themselves are internally twinned or faulted. Thus the elastic strains developed during the phase transformation are effectively accomodated and so there is no irreversible deformation by dislocation movement, which could reduce the reversibility of the transformation [1].

Below a critical value the deformation of a martensitic specimen is a reversible one and occurs by the movement of highly mobile boundaries like martensite/martensite interfaces or twin boundaries within the martensite plates. If the deformed specimen is heated to a critical temperature austenite crystallites with the initial orientation are formed and a shape recovery takes place.

The mechanism of the shape memory effect is shown in a very simplified manner in Fig. 1, where (a) represents a single crystal of a shape memory alloy in the high temperature phase, which upon cooling transforms into a twinned martensitic phase with no macroscopic shape change (b). When stress is applied, deformation occurs by the migration of twin boundaries (c). On heating above a certain temperature the deformed specimen reverts to its original shape (d) by the virtue of the crystallographic reversibility of the thermoelastic martensitic transformation [2].

In addition to the shape memory effect per se shape memory alloys exhibit other interesting properties like super-

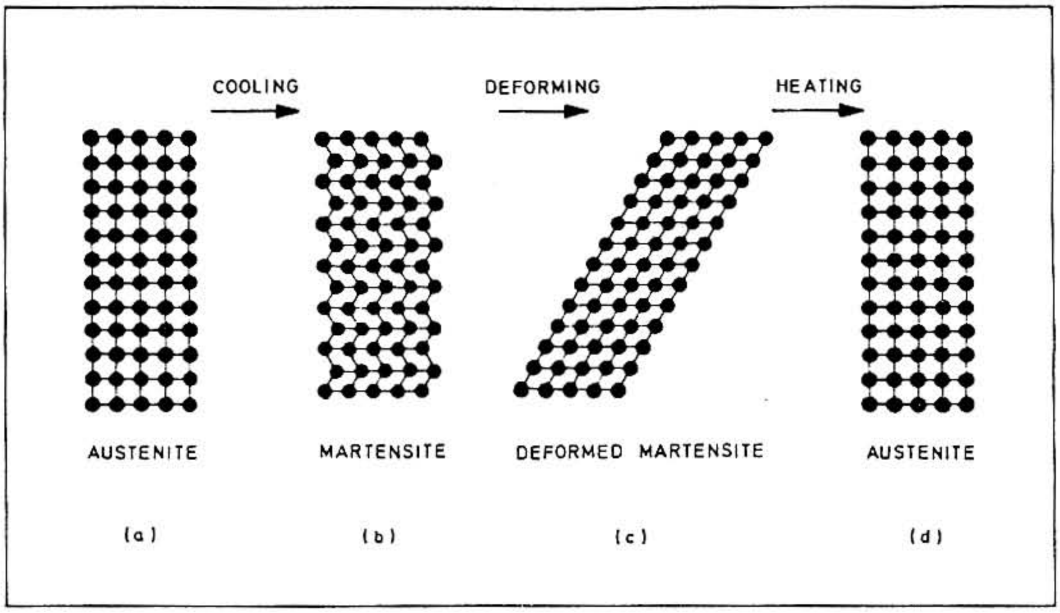

Fig. 1 Schematic illustration of the shape memory effect using a single crystal

elastic behaviour and very high damping capacity under certain conditions. In the following sections these properties will be discussed in more detail. Until now only a few practical applications of shape memory alloys have been realized and therefore this paper deals mainly with some possible applications.

ONE-WAY AND TWO-WAY SHAPE MEMORY EFFECT

As mentioned above, 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. 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.

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 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 one-way effect of technically suitable shape memory alloys are listed in Table I.

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 by the movement of

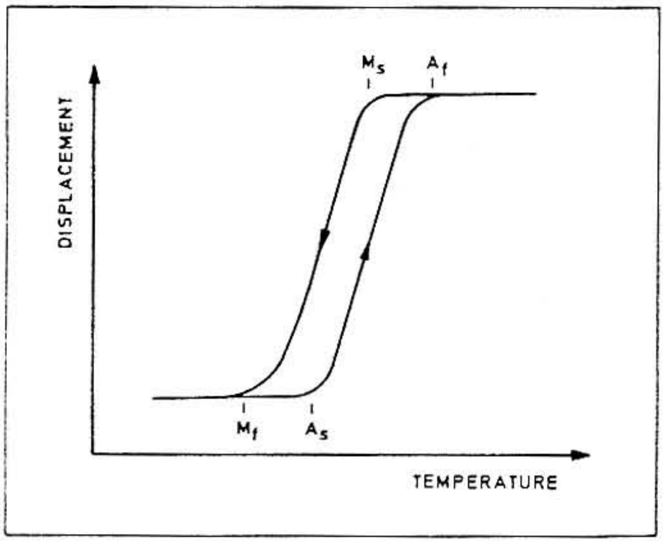

Fig. 2

Displacement-temperature 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

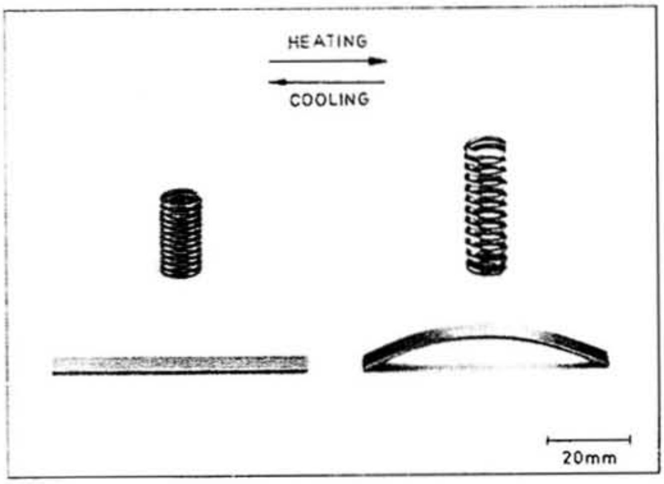

Fig. 3

Helical compression spring and bending strip of Cu-Zn-Al with a two-way effect ($A_S \approx 65°C$, $A_f \approx 80°C$, $M_s \approx 65°C$, $M_f \approx 50°C$)

dislocations occurs, which cannot be recovered upon heating. However the irreversible deformation induces a certain dislocation structure. On heating the specimen will move toward its original shape but on cooling the pre-existing martensite plates will accomodate the stress field of the induced dislocation structure and the specimen will partially move toward the deformed state of martensite. In this way the specimen remembers both a high temperature and a low temperature shape. This effect holds over a large number of temperature cycles and is called two-way shape memory effect [2].

The displacement-temperature curve of a specimen with a two-way memory effect is schematically shown in Fig. 2. Similar to the one-way effect upon heating a specimen with a two-way effect the shape change starts at the A_s-temperature and is completed in a small temperature range (e.g. 10 to 20 K). The displacement-temperature curve shows a hysteresis, which can be influenced by different ways.

Fig. 3 shows a helical compression spring and a bending strip with a two-way effect. Specimens with a two-way effect must not be overheated too much (see Table I) because it would give rise to deterioration of the shape memory effect.

The prototypical shape memory alloy is the nearly equiatomic NiTi alloy, which has been developed about 20 years ago in the USA [3]. As a second generation in the last years the copper-based shape memory alloys Cu-Zn-Al have been developed, which are relatively inexpensive but show a smaller memory effect and are less corrosion-resistant [4]. About three years ago the copper-based alloys Cu-Al-Ni have been developed for the temperature range above that of NiTi and Cu-Zn-Al [5]. Some physical and mechanical properties and the shape memory data of these three technically suitable groups of alloys are shown in Table I. The listed properties depend on different parameters and therefore they are given as ranges or maximal values.

	NiTi	Cu-Zn-Al	Cu-Al-Ni
Density (g/cm^3)	6,4-6,5	7,8-8,0	7,1-7,2
Electrical conductivity ($m/\Omega mm^2$)	1-1,5	8-13	7-9
Ult. tens. strength (N/mm^2)	800-1000	400-700	700-800
Ductility (%)	40-50	10-15	5-6
Maximal A_s-temperature (°C)	120	120	170
Maximal one-way effect (%)	8	4	5
Maximal two-way effect (%)	5	1	1,2
Overheatable to (°C)	400	160	300

Table I Properties of technically suitable shape memory alloys

Shape memory elements can exhibit the one-way or the two-way effect depending on the application. The particularities of these elements are:

- high mechanical work per unit volume
- performance of the complete mechanical work in a selected and relatively narrow temperature range
- 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

Fig. 4 shows a few examples of possible types of shape memory elements.

The earliest applications of shape memory alloys were based on the one-way effect. This type of element is used for instance in the area of self-actuating fasteners, like heat-shrinkable couplings and clamps. In the last years a certain number of possible applications based on the two-way effect have been disclosed in the literature, like thermally actuated switches, thermostatic radiator valves, cooling fan clutches for automobiles, excess diesel fuel devices [6].

Fig. 5 schematically shows the application of the two-way effect for an electrical connector. It is a so-called Cryocon connector, which exhibits both the features of permanent connections and of make-break connectors [7]. The tines of the socket consist of an usual material and are opened to some extend. They are surrounded by a ring of a shape memory alloy with a two-way effect, which closes or opens the socket, when it is warmed or cooled.

Another application of the two-way effect is in the field of thermal protection devices, which open an electrical circuit in case of overheating or short circuit. Figs. 6a and b schematically show such a device. 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 disturbance is removed temperature is low. Fig. 6c shows a concept in which the shape memory element and the spring are integrated into one part.

Fig. 6d shows a thermal protection device with a two-way memory spring, which opens, when heated by the ambient temperature. Due to the great displacement of the shape memory element in a narrow and well-defined temperature range no adjusting is necessary. Such a device can be used for instance in an electric tea kettle providing switch-off, when the water boils [6].

Further temperature indicators with shape memory springs have been discussed, which e.g. can be mounted on high current contacts and optically indicate abnormal temperature increase for e x. due to increase of contact resistance.

SUPERELASTICITY

With respect to thermoelastic martensitic transformations there are similar roles for temperature and stress. Thus when stress is applied to a specimen in the austenitic state, martensite plates form and grow continuously with

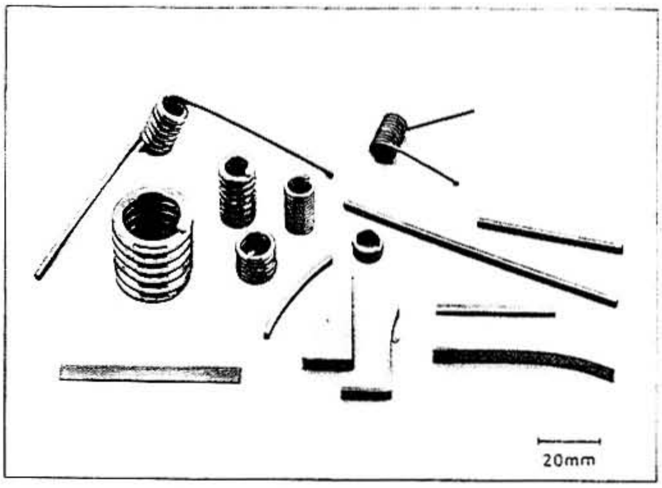

Fig. 4

Examples of possible types of shape memory elements
(the represented parts are so-called MEMOTAL-Elements from G. RAU GmbH & Co, Pforzheim, West Germany)

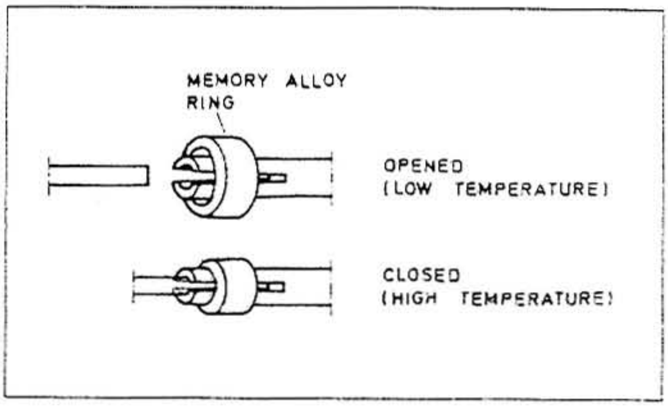

Fig. 5

Electrical connector using the so-called Cryocon principle [7]

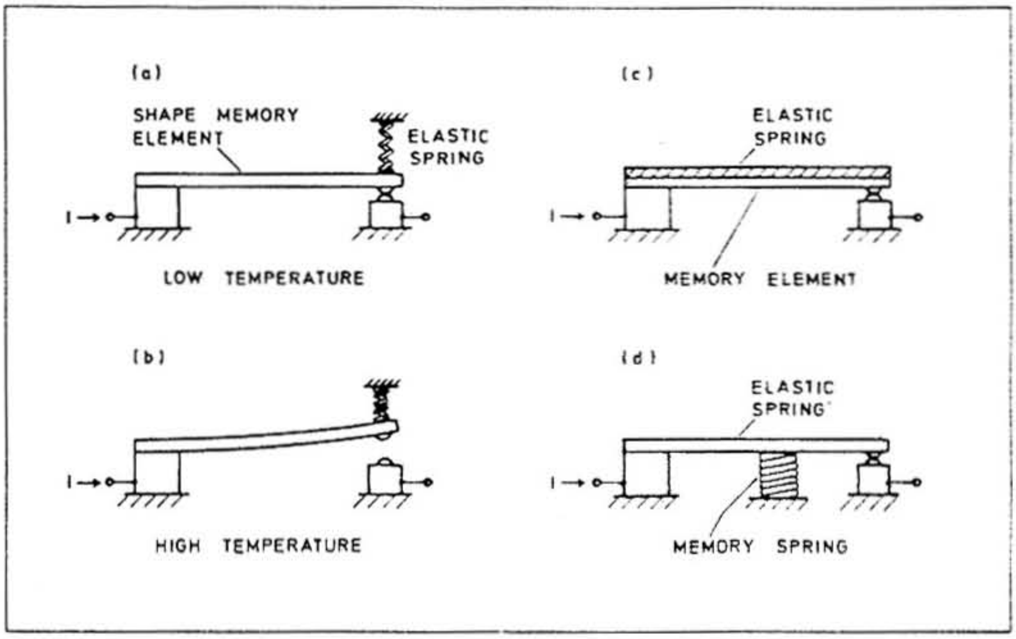

Fig. 6 Thermal protection devices based on shape memory elements

rising stress and disappear by the revers way as the stress is lowered [1].

Fig. 7 schematically shows the stress-strain curves at room temperature of a shape memory alloy in the austenitic state and for an usual alloy, which doesn't exhibit a thermoelastic martensitic transformation. While the usual alloy exhibits an elastic strain of about 0,2%, the shape memory alloy strained to about 1,5% in the austenitic state reverts to its original, pre-deformation geometry, when the stress is removed. After linear elastic deformation of the austenitic phase follows a non-linear elastic behaviour based on the stress-induced phase transformation. This behaviour is called pseudoelasticity or superelasticity. It can be obtained not only by stress-induced martensite formation but also by reorientation of martensite in a martensitic sample due to an applied stress.

The stress-strain dependence of the superelastic alloy shown in Fig. 7 is characterized by a hysteresis. Moreover the stress-strain curves are strongly temperature-dependent because of the interchangeability of stress and temperature as variables affecting the thermoelastic martensitic transformation.

When a shape memory alloy is cycled with strain amplitudes of e.g. 1%, deformation occurs by reversible phase transformation or martensite reorientation and nearly no dislocation movement takes place, so that in push-pull or bending tests very good fatigue properties are obtained compared with corresponding materials without thermoelastic martensitic transformation [4].

Superelasticity naturally should be used in applications, where very high elastic strains are required. For instance superelastic alloys could be used for contact springs with minimized dimensions.

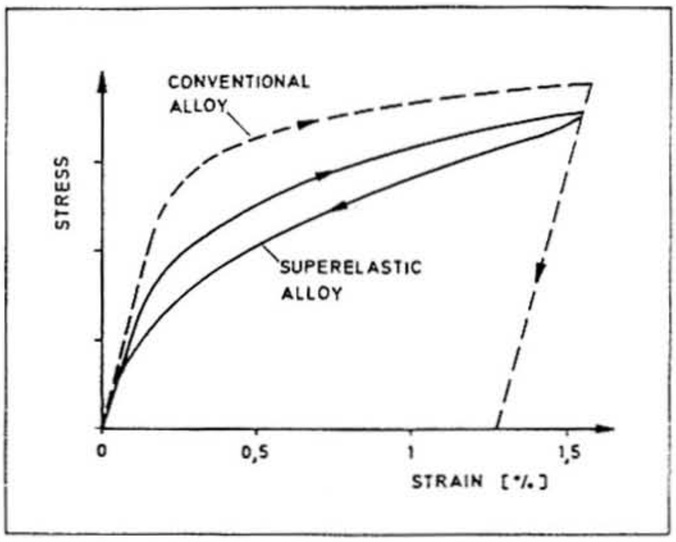

Fig. 7

Stress-strain curves of a superelastic alloy and a conventional alloy

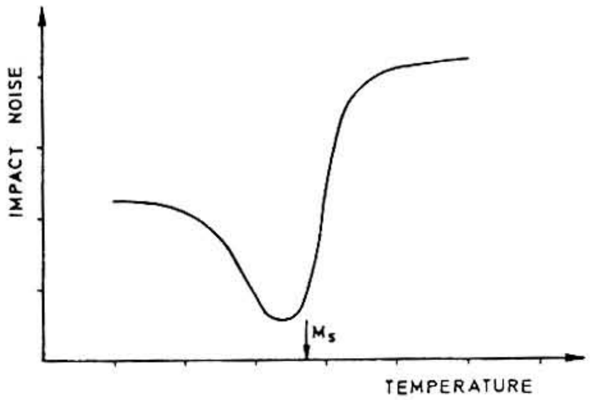

Fig. 8

Impact noise as a function of temperature for a Cu-Zn-Al-plate
(M_S: temperature at which martensite formation starts on cooling an austenitic alloy)

DAMPING

As already mentioned, in alloys which exhibit a thermoelastic martensitic transformation there are different highly mobile defects, like austenite/martensite and martensite/martensite interfaces or twin boundaries within the martensite plates. The migration of these defects under alternating strain causes a high internal friction and a high damping respectively.

The most important parameter which influences the damping behaviour of shape memory alloys is the temperature. Fig. 8 schematically shows the impact noise as a function of temperature for a plate of a shape memory alloy which is hit for instance by a metallic sphere. In the austenitic state the damping is a low one and it is produced by the movement of dislocations. Upon cooling near the so-called M_S-temperature stress-induced martensite with highly mobile boundaries forms and the damping capacity strongly increases. On further cooling just below the M_S-temperature maximum damping occurs and far below this temperature damping is still high [8].

Besides the temperature the amplitude also strongly influences the damping behaviour, however there is practically no frequency dependence.

Due to the very high damping capacity shape memory alloys can be used to reduce detrimental vibrations and noise. It should be possible to use these alloys for mountings or other parts of electrical devices and switches. Fig. 9 schematically shows a switch with a contact spring plated with a suitable shape memory alloy in order to diminish contact bouncing. Further the contact support or spring themselves could be made out of a shape memory alloy. Moreover the conception in Fig. 9 could be used to reduce the noise produced by high-current switches, which in many cases show high contact acceleration and impact.

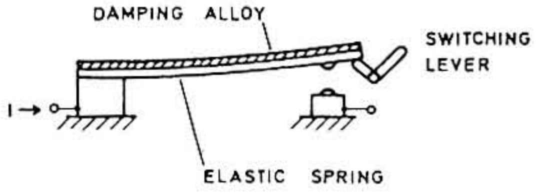

Fig. 9

Scheme of a switch using an elastic spring plated with a damping memory alloy

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