G.RAU
INNOVATIVE METALLE

THERMAL ACTUATORS

THERMAL ACTUATORS PLAY AN ESSENTIAL ROLE IN AUTOMOTIVE, DEVICE AND INSTALLATION TECHNOLOGY: THEY OPEN FAN FLAPS, PROTECT TOASTERS OR PROVIDE OVERHEATING PROTECTION.
IN ORDER TO CHOOSE THE RIGHT ACTUATOR FOR THE APPLICATION, IT IS ABSOLUTELY ESSENTIAL TO KNOW THE EXACT DIFFERENCES BETWEEN THERMOBIMETALS, EXPANDING MATERIALS AND SHAPE MEMORY ALLOYS.

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THERMAL ACTUATORS IN AUTOMOTIVE AND APPLIANCE TECHNOLOGY

Thermal actuators in device manufacturing design and installation technology are usually active components which transform thermal energy into mechanical energy. The mechanical energy is used to perform actuating processes whereby such components are usually both, temperature sensitive (sensor) and actuating element (actuator) in one. Thermal actuators can be manufactured with thermobimetals, expanding materials or shape memory alloys. In order to be able to choose the right actuator for the application, differences should be known.
Shape Memory Alloys (SMA) are particularly suitable for thermal actuators because they can perform traction, compression, bending and torsion movements.

Shape Memory Effect

The shape memory effect is based on a thermal-elastic, martensitic transformation which can only be observed in a few alloy systems. The reason for this extraordinary effect is a temperature-dependent change in the crystal structure, whereby the participating phases austenite and martensite have ordered lattice structures. Figure 1 shows the mechanism of this transformation.

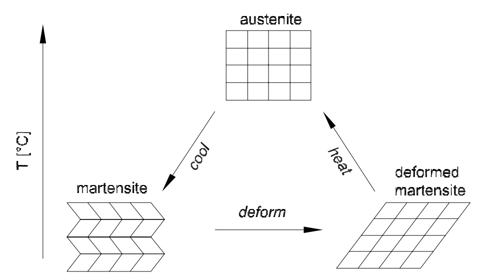

Figure 1: Schematic diagram of the shape memory effect

The alloy is austenitic at high temperature and martensitic at low temperature. If a component made of a martensitic shape memory alloy undergoes a deformation below a critical temperature, a reversible change in shape takes place only by moving the highly mobile twin limits. As soon as the component is heated up above the transformation temperature, austenite with the originally existing orientation is formed so that the component returns to its original shape.

The structural transformations when heating up or cooling down take place at different temperatures, i.e. a hysteresis loop is run through.

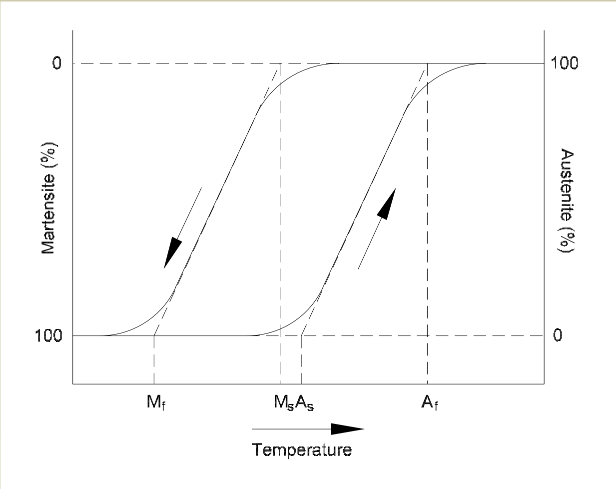

Figure 2: Temperature dependence of the martensite and austenite proportion

This hysteresis is described by the transition temperatures As, Af, Ms and Mf (austenite start, austenite finish, martensite start, martensite finish). The structure consists of different amounts of martensite and austenite depending on the temperature (figure 2).

Both phases differ significantly in their properties. Whilst the alloy in the austenitic state has a stress-strain characteristic as in conventional alloys, the change in shape in martensitic state initially takes place by shifting the highly mobile twin limits.
When this forming possibility is exhausted, the material in the martensitic state also has a conventional stress-strain characteristic with elastic and plastic area (figure 3).

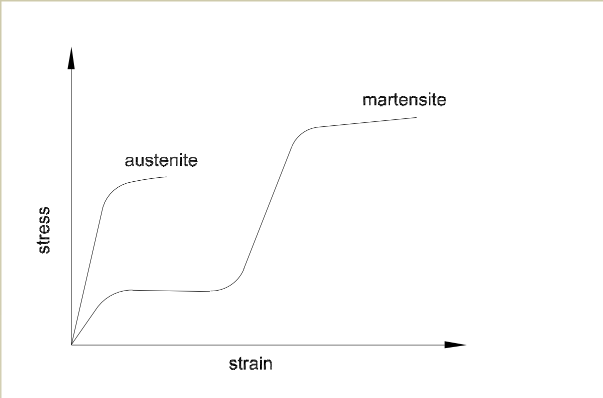

Figure 3: stress-strain characteristic of austenite and martensite

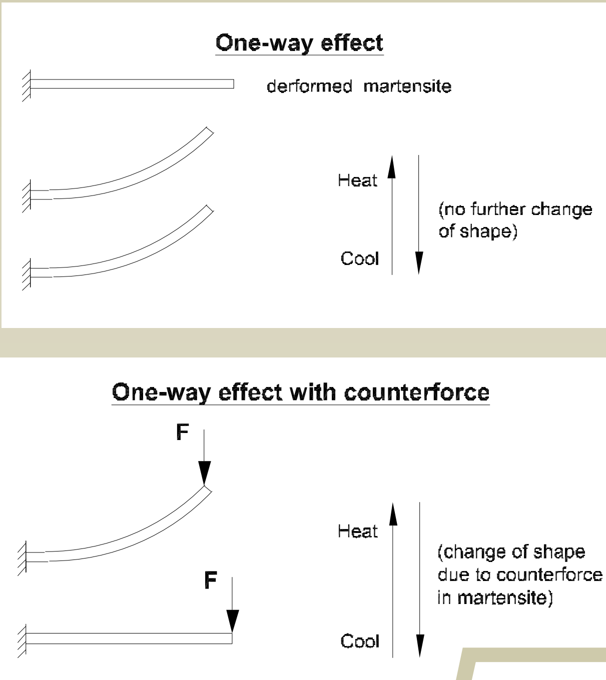

Figure 4: Representation of the one-way effect

If an actuator is formed from a shape memory alloy in the martensitic state in the area of the martensite plateau, only a shifting of the highly mobile twin limits takes place. Transformation to austenite takes place when heating up above the Af temperature. This restores the original sample shape. Since subsequent cooling causes no further change in shape, we refer here to the one-way effect (figure 4). However, the actuator can be reformed in the martensitic state by a suitable counterforce.

Components with two-way effect remember both a high temperature shape and a low temperature shape. Special pre-treatment in which a dislocation movement occurs is necessary to set this two-way effect. This is only partially reset when subsequently heating up.
The influence of the dislocations achieves formation of preferred martensite variants which cause a specific low temperature shape (figure 5). However, lower effect values can be set in the two-way effect compared the one-way effect but the reset force is omitted.

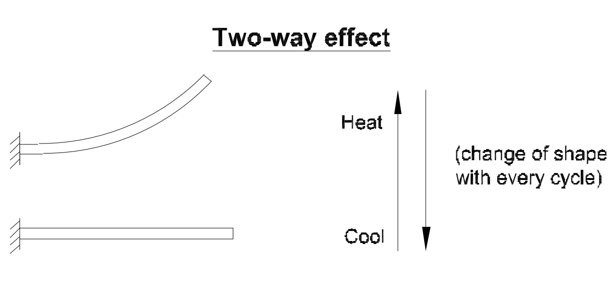

Figure 5: Representation of the two-way effect, remembering high and low temperature shape

Different shape memory alloys

From a large number of alloy systems with martensitic transformation, the following alloys, among others, have emerged for practical application:

- binary NiTi alloy
- ternary NiTi alloy systems with Co, Cr, Cu, Fe or Nb

The ternary alloys with Co, Cr, Fe feature reduced transformation temperatures in comparison with the binary alloy system. NiTi alloyed with Cu generates a lower hysteresis. The hysteresis can be extended uniquely up to 150 K in NiTi alloyed with Nb by special pre-treatment.

This is suitable, for example, for cryogenic shrink elements for which the expensive low temperature storage can be dispensed with.
The Cu-based alloy systems which were originally considered promising have not been able to establish them selves in practice. The same applies for other alloy systems with martensitic transformation such as Fe-based SMA.

Influence of stress on the transformation temperature and fatigue life

In practical cases, actuators develop forces and at the same time perform movements, i.e. they perform work in the physical sense. The value of the stress has an influence on the transformation temperature and the effect variable here (figure 6). The transformation temperature is increased in all element shapes with increasing stress. The external counterforce cannot be increased infinitely, however, because the fatigue behaviour is negatively influenced with increasing force (figure 7).

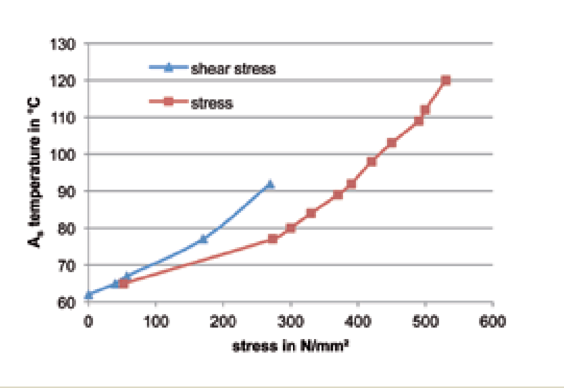

Figure 6: Influence of stress and shear stress on the transformation temperature

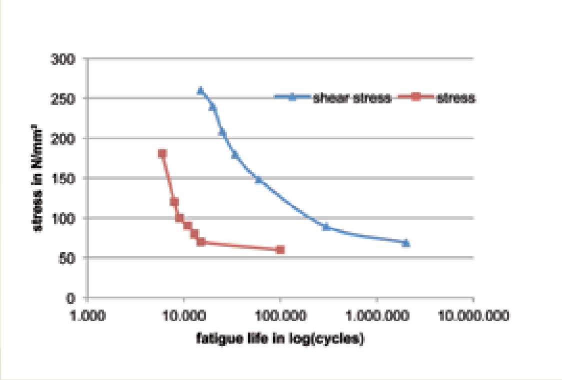

Figure 7: Influence of stress and shear stress on the fatigue life

The parameters shown in figure 6 and figure 7 apply for an effect variable of 2%. At a load of 70 N/mm2 up to 100,000 cycles can be achieved for straight wires. Up to 1,000,000 cycles are possible for cylindrical screw springs at the same load.

SMA actuator elements in practice

Typical areas of application for shape memory actuators are where mechanical work is to be performed at an increase in temperature.They enable space-saving problem solutions because of their great work capacity. Some of these applications are described below.

Cover lock on toasters

Certain toaster types have a plastic cover plate which can be locked at room temperature and serves as dust protection when the toaster is not being used. The first time it is used, the heating current can only be switched on after manually releasing and opening the cover due to an electrical switch-off.
Temperatures of more than 140°C are then produced by the toaster slots in operation. The plastic cover would melt if closing and locking would be possible at these temperatures. Therefore a compression spring made of NiTi shape memory alloy (SMA) activated by the dissipated heat prevents the cover from locking when it is closed too early after toasting (figure 8a).
Only when the temperature has dropped to the extent that the plastic cover can no longer be deformed, the NiTi spring is compressed to block length by a steel spring. The cover can be locked again (figure 8b).

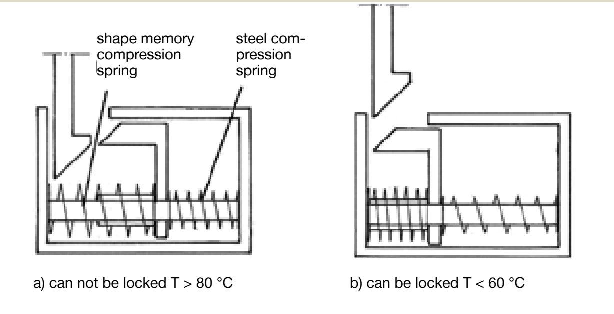

Figure 8: Design principle of a locking mechanism in toasters

Locking a sterile container

Surgical instruments are placed in metal containers and are sterilised in these containers by heating. A special locking mechanism was designed to lock the sterile containers and to ensure that the instruments have reached sterilisation temperature. On reaching the sterilisation temperature a compression spring made of SMA pushes a bolt into the lock position and a coloured mark appears. The container is locked (figure 9b).

To ensure that the required temperature was reached and the sterile container was not opened since sterilisation, the coloured mark must still be visible before removing the instruments. After cooling down to room temperature, the bolt is pushed back to open the container and the cooled memory spring is compressed, the coloured mark is concealed again and the container lid can be opened (figure 9a).

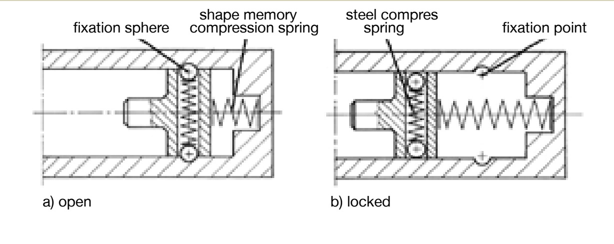

Figure 9: Principle diagram of the lock on a sterile container

Scalding protection in the sanitary field

To protect persons when using showers etc., the hot water flow must be interrupted on reaching approx. 50°C since this is when it begins to become painful. The ball valve is installed in the screen in water taps and in the shower head in showers. It consists of a compression spring made of SMA and a steel counter-spring (figure 10). The installation of these safety valves is obligatory for hotels and hospitals in some US states. The lock can be removed manually if temperatures of more than 50°C are desired.

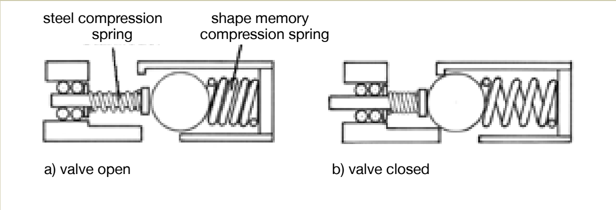

Figure 10: Ball valve of a scalding protection

Overheating protection in a continuous flow water heater

In electric flow water heaters, the electric heating must be switched off at a critical temperature for safety reasons. This must take place quickly and at the same time it must not be possible to switch it back on immediately. This can be achieved with a bending element made of a CuZnAl alloy with a two-way effect because of its good heat conductivity. The change in shape takes place within a very narrow temperature interval of approx. 65°C. The SMA bending strip which is flat during operation bends outwards on reaching a temperature of 65°C and activates a snap disk which interrupts the heating current. After the CuZnAl element has cooled down and returned to the flat (martensitic) state, the circuit can be closed again by resetting the snap disk manually (figure 11).

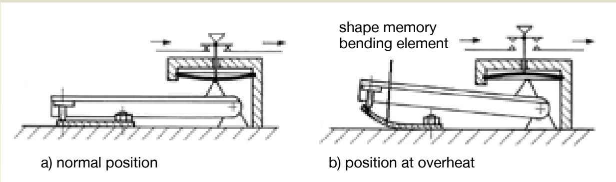

Figure 11: Overheating protection of a continuous flow water heater

Flap opening in fans

The slatted flap of a fan is actuated by a NiTi bending element with two-way effect. The strip-shaped element fixed at one end is heated by a PTC element. The movement of the free end opens and closes the slats. Resetting can be supported by a steel counter-spring. The low heat conductivity of the SMA element produces an intentionally delayed reset movement of the slats (see figure 12).

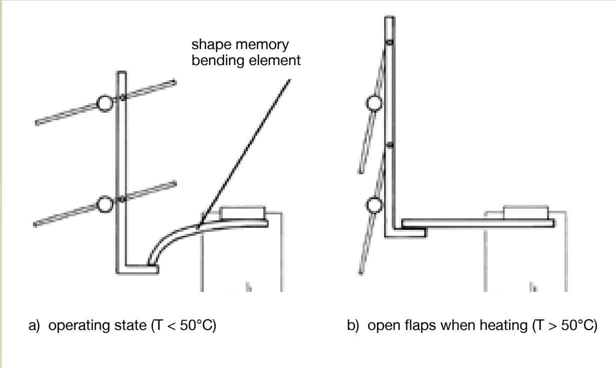

Figure 12: Flap actuation on fans

Conventional thermal actuators

Depending on the form of energy used, actuators are divided into electro-mechanical, hydraulic, pneumatic or thermal actuators. It is very difficult to compare these different actuators. Therefore only the group of thermally activate actuators is described in detail below.

Thermobimetal elements with continuous bending

Thermobimetals are layered composite materials consisting of at least two components with different expansion coefficients. Since one component expands more than the other when heated, a temperature-dependent curvature of the thermobimetal results. The value of this thermally related bending is standardized by DIN 1715. This defines the specific thermal bend A or the curvature k as a parameter. The bending does not exhibit a strictly linear curve with increasing temperature, but corresponds to a curve as illustrated in figure 13.

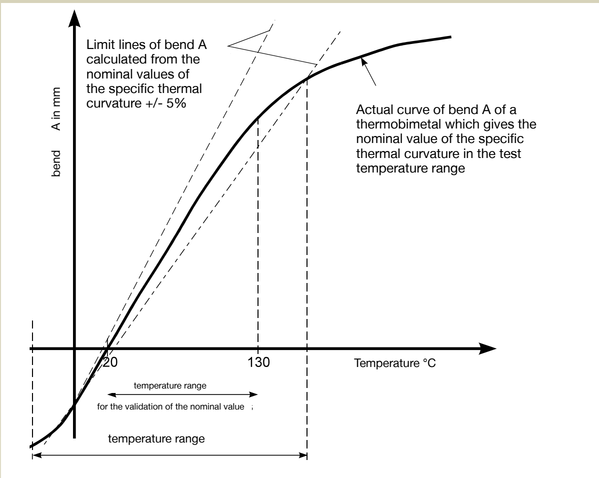

Figure 13: Bending of a thermobimetal in accordance with DIN 1715

The nominal value of the specific thermal bending or curvature is specified for the temperature range of 20 to 130°C. Linearity range defines the temperature range in which the thermal bending does not deviate from the nominal value of specific bending and nominal thickness by more than +/-5%. Outside the linearity range there is a diminishing bend within certain limits which is still sufficient for many applications. Therefore the application range is wider than the linearity range in many cases. Based on the temperature-dependent continuous bending of the strip-shaped element, different component shapes such as discs, spirals and helixes can be produced. Since thermobimetals can transmit forces when heating and cooling, they can be used as control elements in many areas.

Thermobimetal snap elements

Thermobimetal parts generally undergo a constant change in shape when heating and cooling. By applying stress, e.g. by appropriate mechanical pre-bending, a discontinuous behaviour or snap effect is achieved when certain limit conditions are observed. The geometrically simplest snap element is a spherically arched round disc. But other more complex snap element shapes are possible.

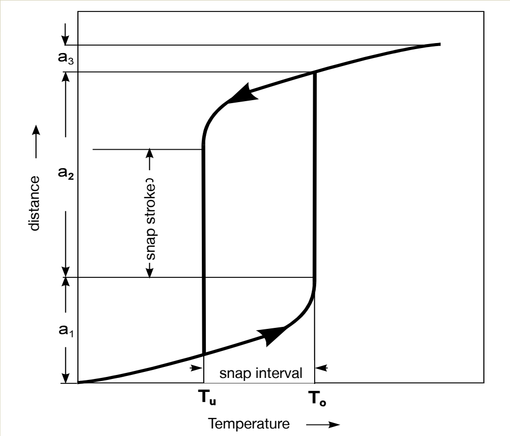

Figure 14: Distance-temperature curve of a snap element

As shown schematically in figure 14, such discs initially arch constantly by the amount a1 when the temperature increases. They reach an unstable stress condition at the upper snapping point Tu and jump to an opposite arched shape. They cover the distance a2 hereby. With increasing temperature the disc arches by the amount a3. When cooling with the corresponding hysteresis they spring back to the original position at the lower snapping temperature Tl.

Later applied forces and their direction of effect obviously influence the characteristic in comparison with the free disc.

Expanding material elements

Expanding material elements have a rigid, pressure-proof container which contains an expanding material. This expanding material melts when the temperature increases. The considerable increase in volume in the melting process is used by a piston to perform work.

When cooling down, the reverse movement is aided by an external return spring. The required counterforce is approx. 20 to 30% of the maximum permissible load capacity. The expanding material elements often operate with a linear curve.

Comparison of the properties of thermal actuators

Since the thermal actuators exploit different physical effects, they are only conditionally comparable. Table 1 shows a comparison of the most important parameters. The values listed here are guidelines. Special element shapes can be used depending on the application which may have quite different parameters.

SMA actuators have abrupt temperature-distance behaviour like thermal snap discs whilst thermobimetal strips and expanding material elements have a linear temperature-distance characteristic.
In comparison with thermal bimetals, however, memory elements have a much greater work capacity and space-saving problem solutions are often possible as a result. In addition, memory alloys have the great advantage that they can be used to make traction, compression, bending or torsion elements.

Thermal bimetals enable beneficial design solutions at high application temperatures or hysteresis-free control behaviour. Moreover, the resetting with thermal bimetals is automatic with the appropriate work.
In applications with very high actuating forces and almost hysteresis-free control behaviour, expanding material elements have the advantage but relatively slow control behaviour must be expected.

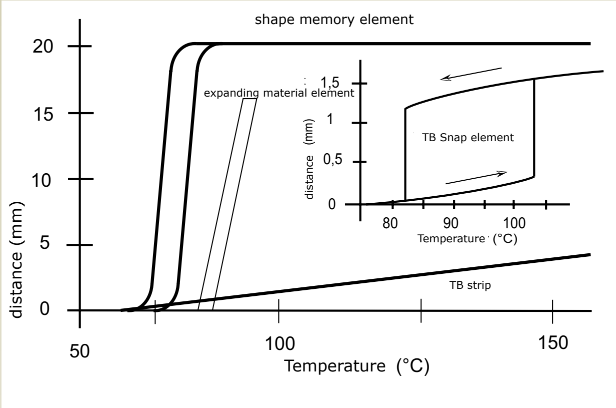

Figure 15: Schematic temperature-distance curves of thermal actuators. Dimensions of the elements: NiTi bending element: length 30 mm; thickness 1 mm; thermobimetal strip: length 30 mm; thickness 1 mm; thermobimetal snap element: disc diameter 40 mm; thickness 0.35 mm; expanding material element: length 51 mm; diameter 20.5 mm

	SMA actuators	Thermobimetal strips	Thermobimetal snap elements	Expanding material elements
Temp-distance dependence	abrupt	continuous	discontinuous	linear
Max. operating temperatures	80°C (120 - 170 °C)	- 40 - 550 °C	350 °C	approx. 110 °C
Hysteresis	15° - 30 °C	none	6° - 250 °C adjustable for forming	low
Change in shape	thermal-elastic transformation	thermal expansion	thermal expansion	volume expansion
Types of movement	traction, compression, torsion, bending, shrinkage	bending, compression	expansion, compression	expansion
Work capacity	high, typ. 50 Nmm	low, typ. 10 Nmm	low, typ. 5 Nmm	very high max. 15,000 Nmm
Reset	counterforce	automatic	automatic	counterforce
Work performed	only when heated	heating, cooling	heating, cooling	only when heated

Table 1: Comparison of thermal actuators

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