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Actuation and control with Ni–Ti shape memory alloys

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ABSTRACT: Ni-Ti shape memory actuators respond to temperature changes with a shape change. The change in temperature can be caused by a change in the environment or by electrically heating the Ni-Ti 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 Ni-Ti actuators combine large motion, rather high forces and small size, thus they provide high work output.

1. INTRODUCTION

"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". The shape memory effect in Ni-Ti alloys can be used to generate motion and/or force in actuators, fasteners and couplings. At temperatures below the transformation temperature, Ni-Ti alloys are martensitic. In this condition they are very soft and can be deformed easily (like soft copper). Heating above the transformation temperature recovers the original shape and converts the material to its high strength, austenitic, condition (like steel).

2. MECHANICAL PROPERTIES

The mechanical properties of the austenite and the martensite are quite different. As shown in Figure 1, the austenitic curve looks like that of a "normal" material. However, the martensitic one is quite unusual. On exceeding a first yield point, often called "plateau stress, several percent strain can be accumulated with only little stress increase. After that,

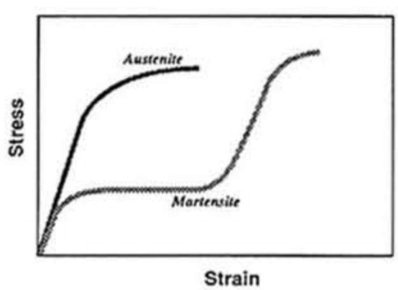

Fig. 1. Tensile Behavior of Ni-Ti alloys

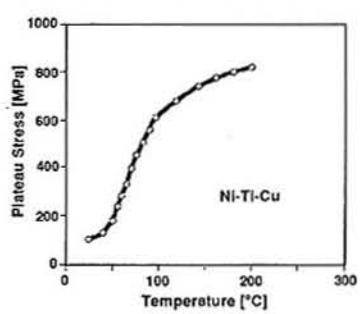

Fig. 2. Influence of temperature on the plateau stress of a Ni-Ti-Cu alloy

stress increases rapidly with further deformation. The deformation in the "plateau region" is non-conventional in nature. It is fundamentally different from the conventional deformation by gliding, and can be recovered thermally. I.e. heating above the transformation temperature will restore the original shape. Deformation exceeding the second yield point cannot be recovered. At this point, the material is plastically deformed in a conventional way. Plotting the plateau stress or the first yield point versus temperature produces a curve as shown in Figure 2. A similar curve is obtained, when the modulus is plotted versus temperature.

3. HYSTERESIS

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 1. 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).

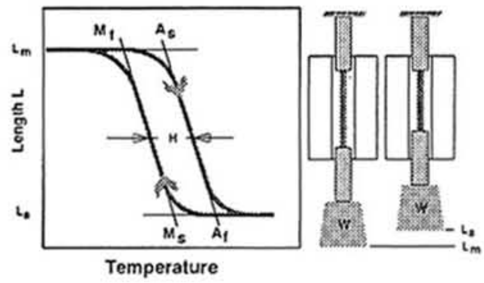

Fig. 3. Schematic length/temperature hysteresis of a shape memory wire loaded with a constant load

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.

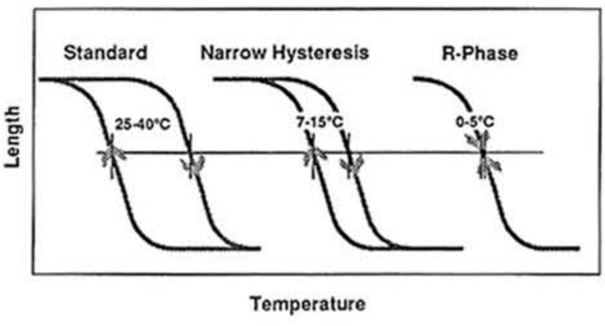

Fig. 4. Schematic length/temperature hysteresis of different Ni-Ti alloys

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.

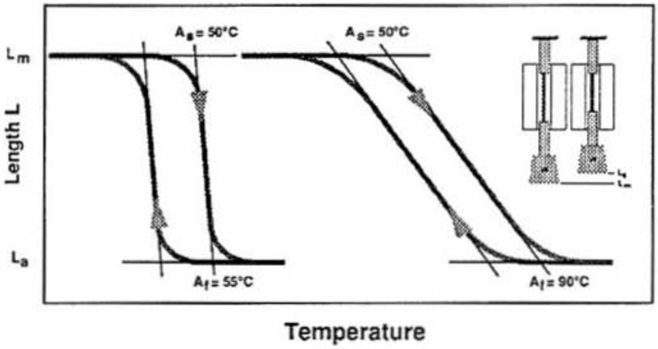

Fig. 5. Influence of processing on the shape of the hysteresis loop

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. The reason for this behavior is the stress dependency of the transformation temperatures. As can be seen from Figure 6, the transformation temperatures increase with increasing operating stress.

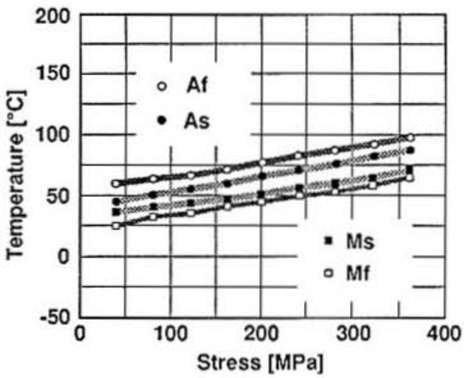

Fig. 6. Influence of the applied stress on the transformation temperatures

4. ACTUATOR DESIGN

The shape memory effect in Ni-Ti alloys 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)

The design of shape memory elements for thermal actuators is based on the different stress/strain curves of the austenite and the martensite. As an example, Figure 7 shows the force/deflection curves of a helical compression spring at high and low temperatures. The high temperature shape of the spring with no load is Lo (A). If the spring is loaded with a constant load W in the austenitic condition (at temperatures above Af) the spring is compressed along A - B with the displacement Δl (B). Upon cooling below Mf the spring transforms into martensite. Now the load W compresses the spring to point C on the martensite curve with the displacement ΔL. Repeated heating/cooling cycles between points B and C. If, instead of a constant load, a steel biasing spring is used, the force/deflection curve for this spring has to be superimposed to the austenitic and martensitic spring characteristics of the Ni-Ti spring.

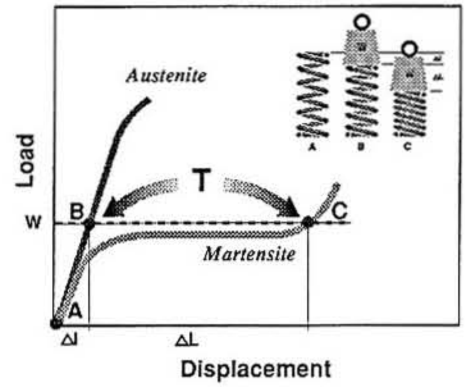

Fig. 7. Design concept for actuators working against constant load

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:

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

5. APPLICATIONS OF SHAPE MEMORY ACTUATORS

Ni-Ti 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 Ni-Ti 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 Ni-Ti 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.

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 provide fast response to changes in temperature.

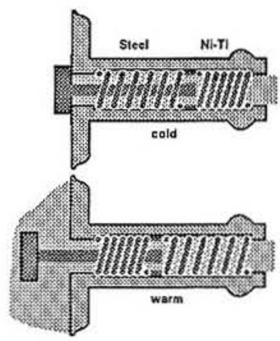

Fig. 8. Shape memory flow control valve

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 triggering devices, animated objects, toys etc. are presently being marketed. The integration of Ni-Ti wires in composite structures has been suggested, to allow the structure to change shape on demand.