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Use of Ni-Ti shape memory alloys for thermal sensor-actuators

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ABSTRACT

Ni-Ti shape memory actuators respond to temperature changes with a shape change. Therefore, they are sensors and actuators. They combine large motion, rather high forces and small size, thus providing high work output. They usually consist of only a single piece of metal, e.g. a helical spring, and do not require sophisticated mechanical systems. They often fit into tight spaces in given 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. Shape memory actuators have been used successfully in the areas of thermal compensation, thermal actuation and thermal protection.

1. INTRODUCTION

Thermal actuators, by definition, are devices which convert thermal energy into mechanical energy. They utilize effects like the thermal expansion of solid materials, e.g. in thermostatic bimetals, or volume changes during phase transformations like solid/liquid or liquid/gaseous, e.g. in wax actuators. These devices sense changes in ambient temperature and react to these changes by bending, as in the case of thermostatic bimetals, or with the linear movement of a piston, as in the case of wax actuators. Shape memory alloys, on the other hand, can change their shape in many different ways during a solid state transformation. Therefore, they provide new possibilities for intelligent designs of sensor-actuators.

The most important shape memory alloys are the near equiatomic Ni-Ti alloys, commonly known as Nitinol (from Nickel-Titanium Naval Ordnance Laboratory) and Tinel (Raychem brand name). Although there are other shape memory alloys, only Ni-Ti alloys have proven themselves to be technically viable materials.

2. 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 "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

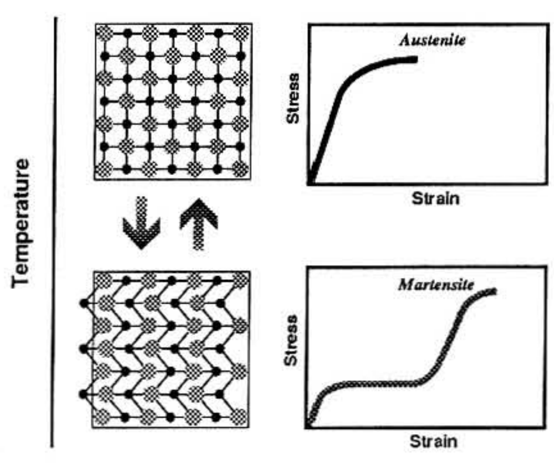

Fig. 1. Martensitic transformation and tensile behavior of Ni-Ti alloys

transformation temperature, Tinel 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).

Figure 1 shows tensile curves of Ni-Ti alloys 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 (up to 8%) 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[1].

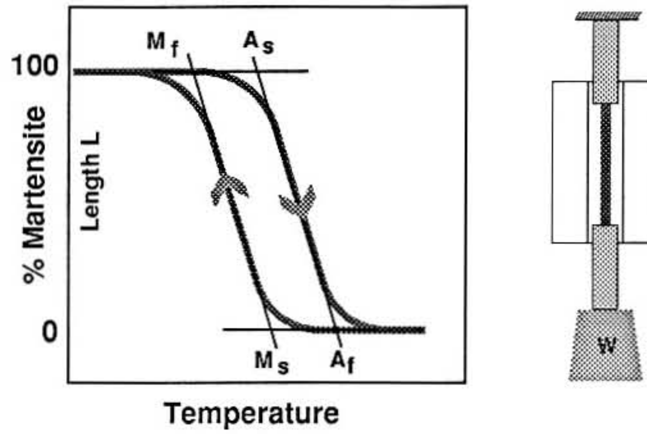

Fig. 2. Hysteresis of the martensitic transformation and the shape memory effect

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 2. 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). Transformation temperatures can be varied between approximately -100°C and +100°C, the width of the hysteresis between approx. 2°C and 150°C.

3. ACTUATION WITH SHAPE MEMORY ALLOYS

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

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

The design of shape memory elements for sensor-actuators is based on the different stress/strain curves of the austenite and the martensite, as well as the change in modulus during the transformation. As an example, Figure 3 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 converts 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.

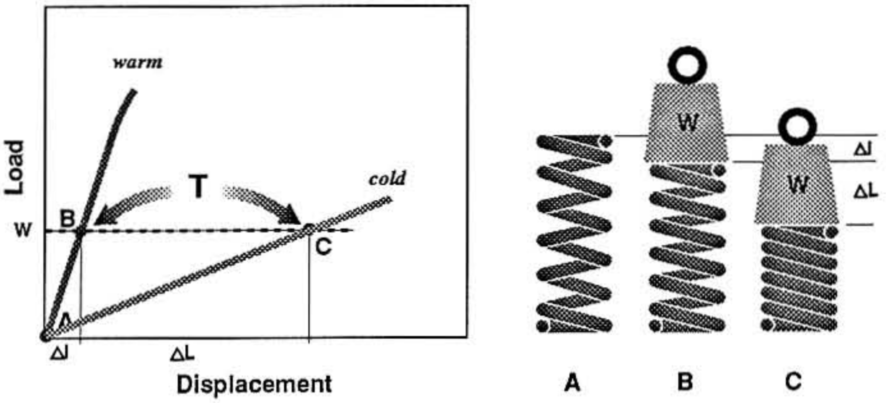

Fig. 3. Ni-Ti spring response to a constant load

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. At high temperatures (in the austenitic condition) the Ni-Ti spring is strong enough to compress the steel spring. However, at low temperatures (in the martensitic condition) the steel spring is able to compress the Ni-Ti spring (Fig.4). Because the Ni-Ti springs change their rate with temperature, they are called thermovariable rate springs (TVR springs). They have been successfully used as sensor-actuators in the areas of thermal compensation, thermal actuation and thermal protection[2].

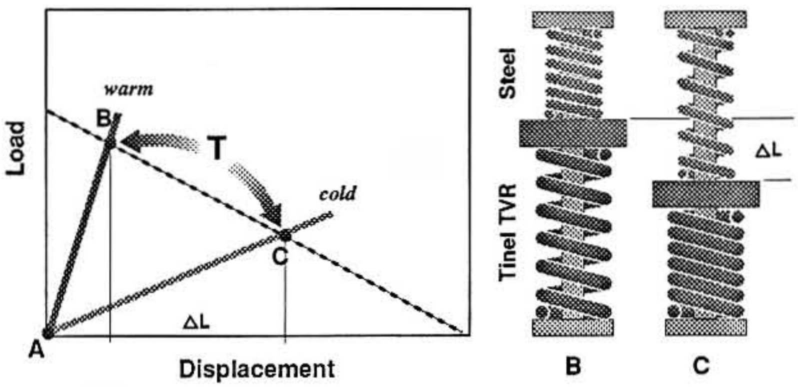

Fig .4. Ni-Ti spring response to a biasing force

4. APPLICATIONS OF NI-TI SPRINGS FOR THERMAL SENSOR-ACTUATORS

The temperature dependent rate change of Ni-Ti springs offers new possibilities for the design of thermal actuators for a variety of applications. TVR spring actuators combine large motion, rather high forces and small size, thus providing high work output. As the spring itself is the sensor and the actuator, they usually consist of only the Ni-Ti spring and in some cases a biasing steel spring, and do not require sophisticated mechanical systems. They, therefore, often fit into tight spaces in given designs, where thermostatic bimetals or wax actuators would require a major redesign of the product. In flow-control or oil pressure control valves, for example, TVR springs can be placed in the fluid or gas path, without restricting the flow. Thus, they provide fast response to changes in temperature. Fig.5 to 10 show some designs of thermostatic valves using Ni-Ti- springs. In all cases the Ni-Ti spring works against an opposing force like a biasing spring, water or oil pressure, or a magnetic force. In the following, we will describe a few of these applications in more detail.

Components like engines and transmissions are subjected to severe temperature differences in the time frame from cold start of the vehicle to reaching its final operating temperature . Viscosity changes and other influences can cause a variety of problems for the hydraulic controls of automatic transmissions. Therefore, a temperature dependent hydraulic pressure control system is required. This can be achieved in a very cost effective way by incorporating TVR springs into the pressure control valves of the transmission (Fig. 5). This concept was successfully introduced in Mercedes-Benz automatic transmissions. To improve the shifting comfort, the shifting pressure of the transmission is reduced during cold start situations and increased again when the transmission reaches operating temperature[3].

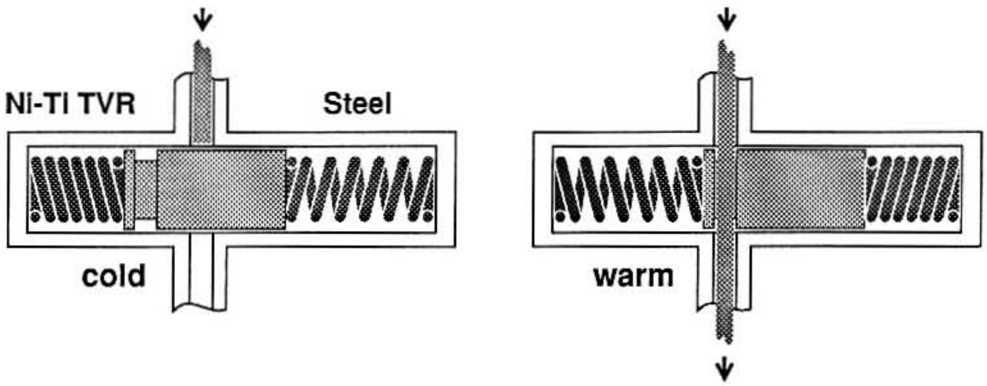

Fig. 5. Thermostatic governor valve for shifting pressure control in automatic transmissions

Smog emission and fuel consumption can be reduced by reducing the time required for warming up a cold engine to operating temperature. A governor valve with TVR spring can control the warm-up phase of the engine, automatic transmission and other components by changing the shift point to higher speed at low temperatures. Reduced warm-up time can also be achieved, by replacing the steel spring of an oilcooler bypass valve with a TVR spring. At low temperatures, the pressure in the hydraulic system of an automatic transmission is higher due to the higher viscosity of the oil. The TVR spring is in its low rate condition and allows the oil to bypass the cooler. At operating temperature, the valve is closed, forcing the oil through the cooler. However, the oilcooler can still be bypassed, if the pressure increases due to clogging of the cooler. Figure 6 shows the ball-valve used for this application.

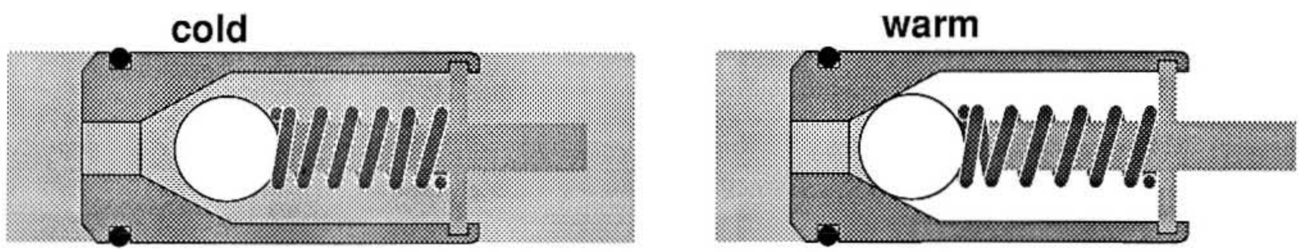

Fig 6. Thermostatic oilcooler by-pass valve

Another example of an intelligent design with TVR springs is the evaporative emission control valve in carburetors. As Ni-Ti TVR spring and biasing steel spring are integrated into the fuel vapor hose fitting, no redesign of the carburettor body or bulky side access devices are required. The valve is closed at low temperatures, keeping the evaporated fuel in the carburetor, and open at operating temperature for ventilation, improving restart ability and preventing flooding. Figure7 shows part of the carburetor as well as a schematic design of this valve. A different design of a ventilation valve is shown in Fig.8. This valve protects aballoon catheter from bursting during sterilization by relieving the pressure at temperatures around 50°C.

Ni-Ti TVR springs have also been used successfully in anti-scald valves that shut off the flow of hot water in faucets or showerheads at temperatures around 45°C. A possible design is shown in Fig. 8.

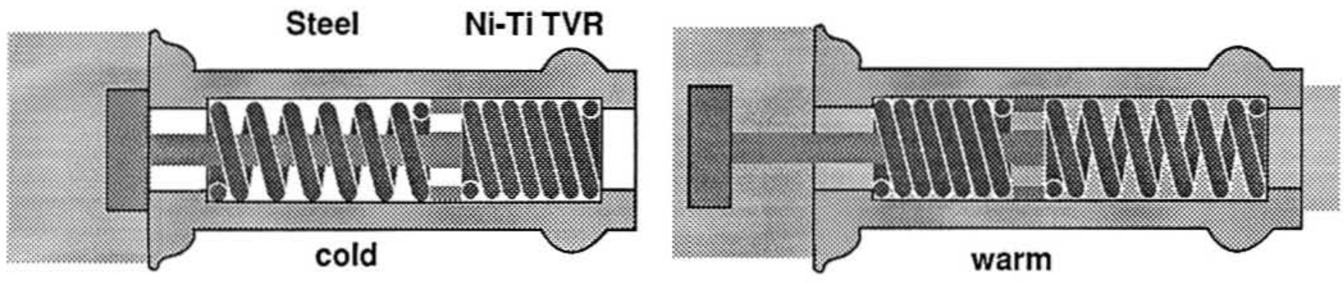

Fig. 7. Thermostatic evaporative emission control valve

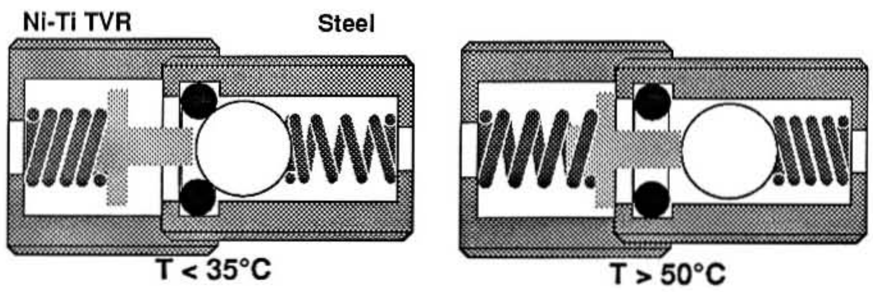

Fig. 8. Thermostatic ventilation valve for medical instrument

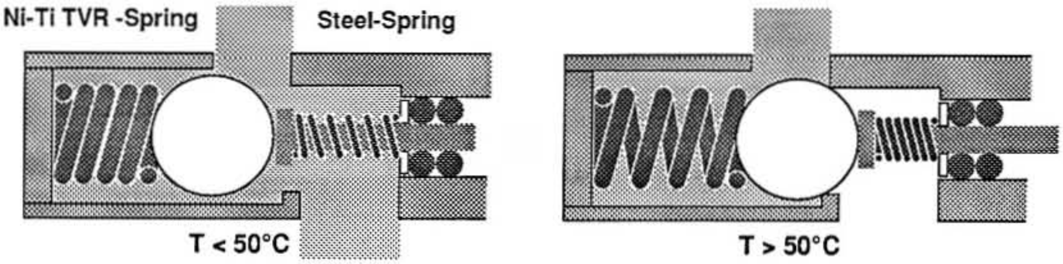

Fig. 9. Anti-scald valve

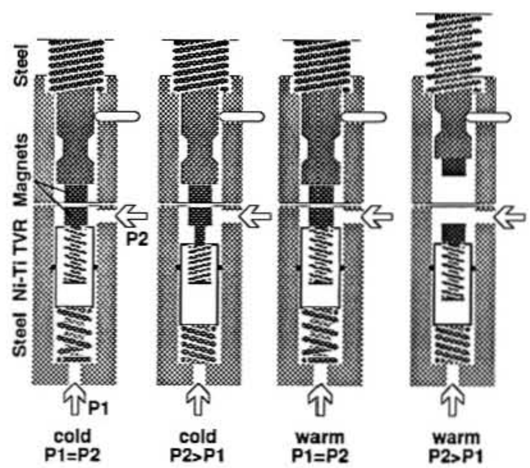

Fig. 10. Temperature compensated sensor for clogging indicators

In clogging indicators for jet engine oil filters increased oil pressure indicates the filter being clogged and maintenance being necessary. However, at low temperatures, this situation can also be caused by increased oil viscosity even with a perfectly well working filter. Incorporating a Ni-Ti TVR spring into the pressure sensing device eliminates "false alarms" due to high oil viscosity. Figure 10 shows the concept, in which a Ni-Ti spring works against a magnetic force[4].

Ni-Ti washers can be used when high forces and small motion is required, e.g. to compensate for different thermal expansion of dissimilar materials. In gearboxes with steel shafts and aluminum cases, for example, rattling noise is caused by the decrease in preload of the assembly with increasing temperature. Ni-Ti Belleville-type or wave washers can generate in excess of 1000 N with a deflection of approximately 0.5 mm, and, therefore, restore the preload in the gearbox, when it reaches operating temperature. Similar actuators can be used to separate structural components to interrupt the heatflow from one component to the other.

5. REFERENCES

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