Thermo Variable Rate Springs: A New Concept for Thermal Sensor-Actuators

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THERMO-VARIABLE RATE SPRINGS

A New Concept for Thermal Sensor-Actuators

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The aim of conventional spring design is to produce a mechanical element that will store energy by generating the desired forces at given deflections. A variety of different configurations is available, ranging from helical compression or extension springs to Belleville, wave, and finger washers. The designer uses standard formulas based on linear elastic theory to determine the geometry of the spring. With conventional materials, such as steel, titanium, or copper alloys, the force deflection behavior of most springs obeys Hooke's law, that is, there is a linear relationship between the force and the deflection of the spring. The constant of proportionality is known as the spring rate. By creating non-uniform geometrical configurations like barrel, hourglass, and variable-pitch springs, non-linear relationships between force and deflection can be achieved.

The spring rate is directly proportional to the shear modulus of the spring material. In conventional materials, the shear modulus is little temperature dependent. Therefore, the spring rate and thus the performance of the spring is basically temperature independent. Certain materials, however, exhibit a rather dramatic change in shear modulus within the operating temperature range. Springs made from these materials, accordingly, show a pronounced change in their spring rate with changing temperature.

The change in modulus with temperature is the result of a solid-state phase transformation, commonly known as thermal-elastic martensitic transformation. This is the basis for the so-called shape memory effect, the ability of certain materials to "remember" a previous shape even after deformation. Thermo-variable rate springs are, in fact, shape memory springs. However, the concept of using the rate change instead of the shape memory effect is considered a more universal approach.

The most important alloys showing this particular martensitic transformation are Ni-Ti alloys. They are the standard shape memory alloys and have been used for a variety of applications for about 20 years. In the following, the use of the rate change of Ni-Ti springs for thermal sensor-actuators will be described.

1. Thermo-Elastic Martensitic Transformation in Ni-Ti Alloys

Above a certain transformation temperature, the crystalline structure of Ni-Ti alloys is "body centered cubic" with a very specific arrangement of the

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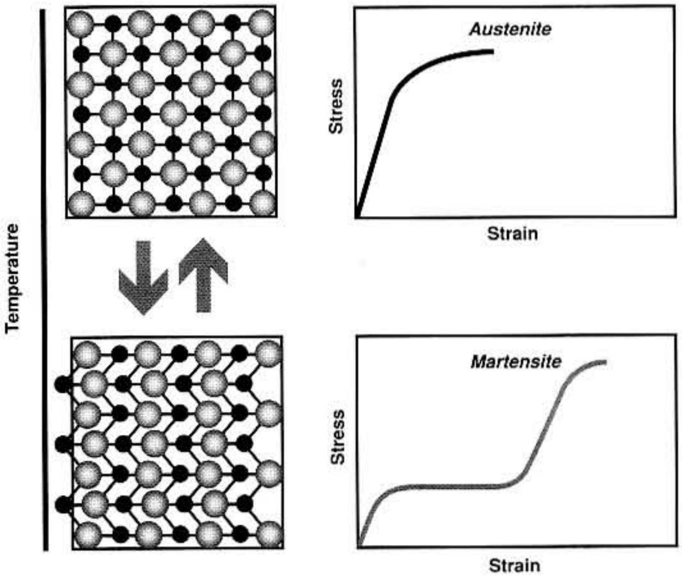


Fig. 1. Martensitic transformation and tensile behavior of Ni-Ti alloys.

nickel and titanium atoms. In this condition, the alloys are "austenitic." Cooling below the transformation temperature converts the material into the "martensitic" state. This transformation is diffusionless, i.e., the atoms do not change their locations relative to each other in the lattice. The martensitic structure is a zigzag or harmonica-type arrangement of the lattice planes, called "twinned structure." There is no macroscopic shape change concomitant to the transformation from austenite to martensite. The transformation is reversible, i.e., heating above the transformation temperature will convert the martensite into austenite.

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 curve is quite unusual. On exceeding a first yield point, a strain of several percent can be accumulated with only little stress increase. After that, stress increases rapidly with further deformation.

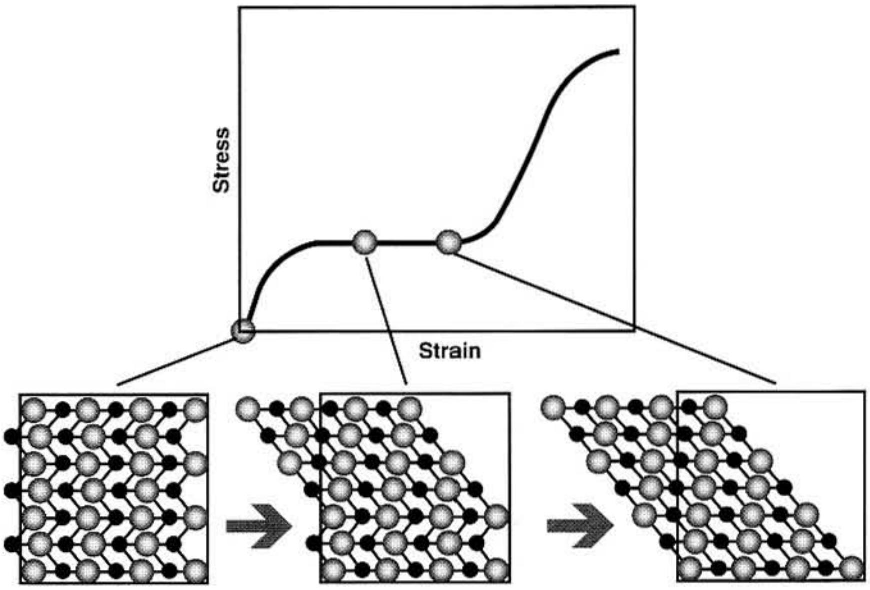
The deformation in the "plateau region" is nonconventional in nature. Deformation occurs by reorientation of the twins to form a parallel register, which is essentially complete at the end of the plateau (after approx. 8 percent strain). This process, also called "detwinning" (Fig. 2), is fundamentally 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.

2. Thermo-Variable Rate Springs

The most important material property determining the performance of a spring is the shear modulus. In Ni-Ti alloys the shear modulus changes almost an order of magnitude over a rather narrow temperature range (Fig. 4), increasing from low to high temperature. This produces a concomitant increase in spring rate, since spring rate is directly proportional to the shear modulus:

$$R = \frac{Gd^4}{8nD^3}$$

Consequently, TVR springs have a low spring rate below the transition temperature of the Ni-Ti alloy and a high spring rate above this temperature. Figure 5 shows the force/displacement characteristics of a Ni-Ti TVR spring at room temperature and at 80°C. The geometrical data of the spring are also given.



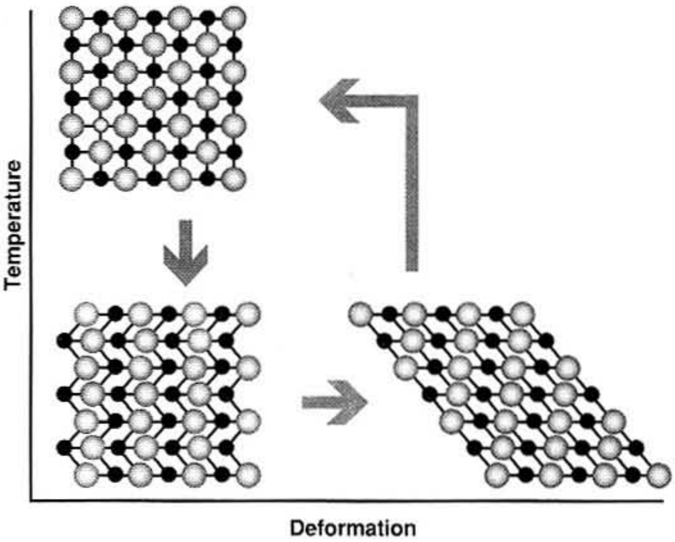


Fig. 3. Martensitic transformation and shape memory effect in Ni-Ti alloys.

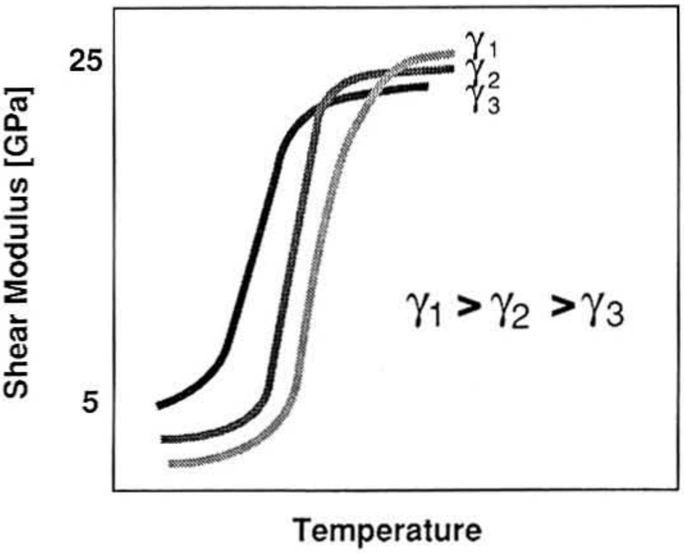


Fig. 4. Influence of temperature and strain on the shear modulus of Ni-Ti alloys (Funakubo, 1986).

The design of TVR springs is based on the different force/displacement curves of the austenite and the martensite, and thus the spring rates. As an example, Figure 6 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 (warm), the spring is compressed along A-B with the displacement Δ1 (B). Upon cooling below the transition temperature, the spring converts into martensite (cold). 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

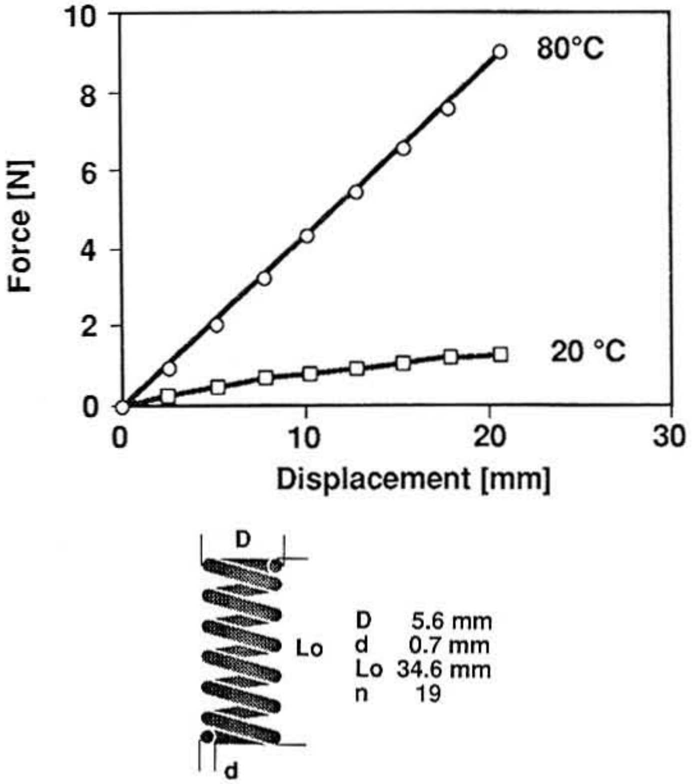


Fig. 5. Spring rate of a Ni-Ti TVR spring at high and low temperatures.

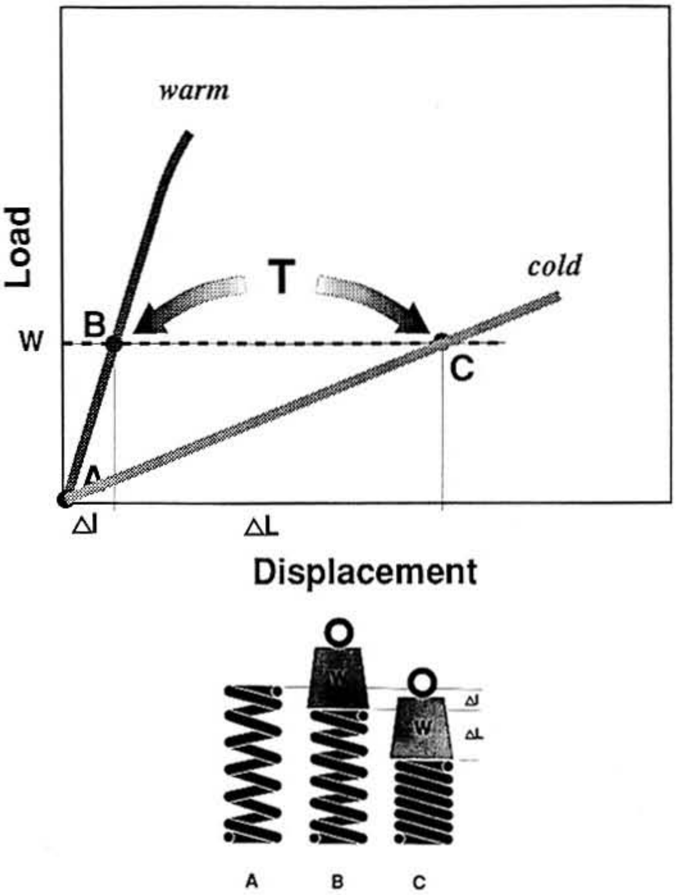


Fig. 6. TVR spring working against a constant load.

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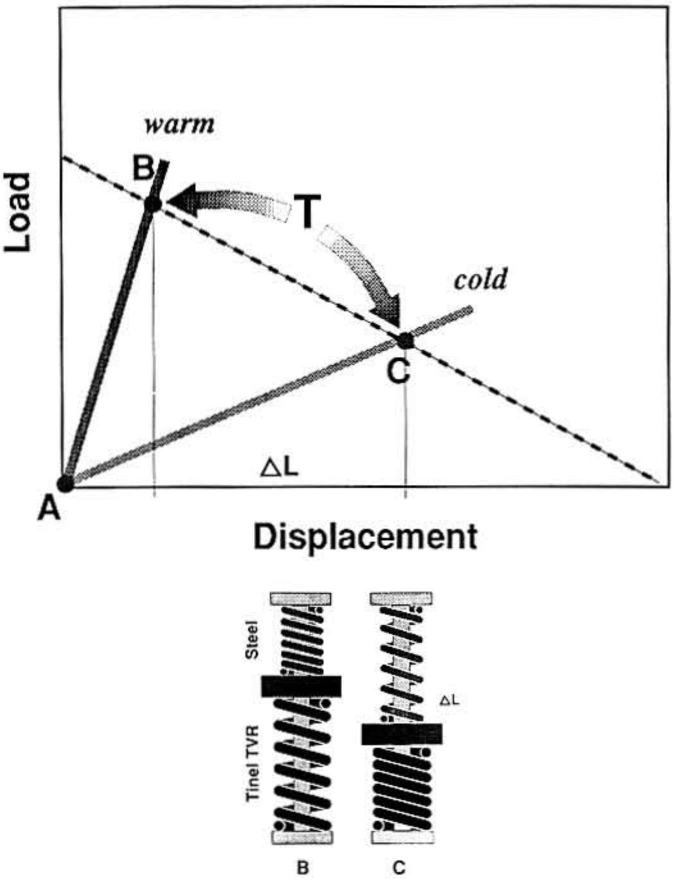

Fig. 7. TVR spring working against a biasing spring.

spring must be superimposed to the austenitic and martensitic spring characteristics of the Ni-Ti spring. This is schematically shown in Figure 7. A Ni-Ti TVR compression spring works against a steel biasing 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. Again, repeated heating and cooling cycles between points B and C.

In some cases, the TVR spring must pick up a certain load at a certain displacement and to drop off the load before completely resetting. In these cases, the TVR spring works against a biasing spring as well as a constant load. This situation is schematically shown in Figure 8. Again, a Ni-Ti TVR compression spring works against a steel biasing spring. At temperatures below the transition temperature, the TVR spring is completely compressed by the biasing spring (A). Upon heating above the transition temperature, the TVR spring overcomes the biasing force and expands along A-B. At B it picks up the constant load and lifts it until it reaches C.

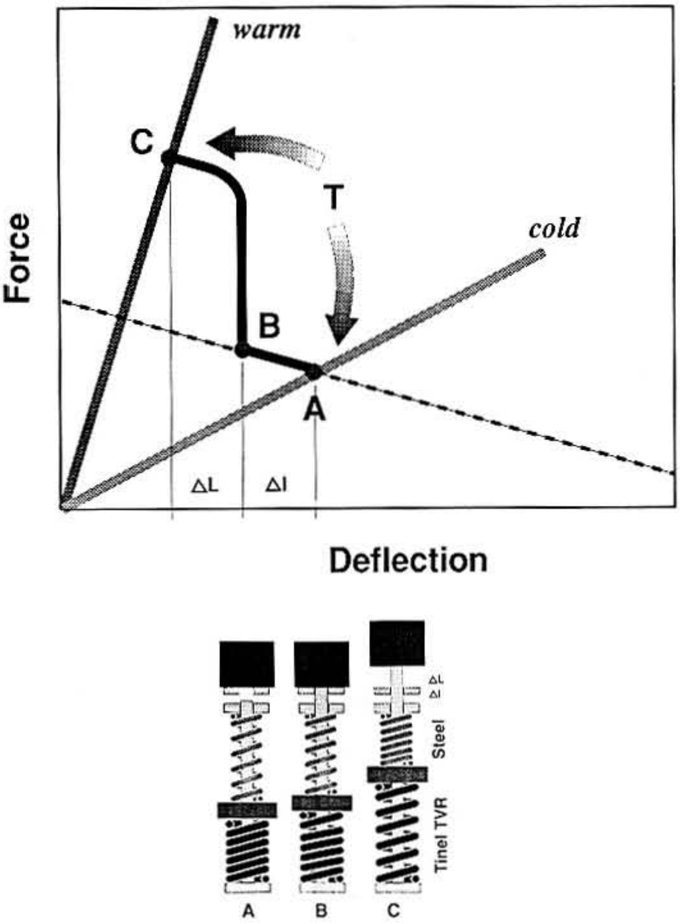

Fig. 8. TVR spring working against a constant load on a biasing spring.

3. Hysteresis

As can be seen from Figure 9, the transformation and thus the rate change does not occur at the same temperature on heating and cooling. An important characteristic of the effect is the temperature *hysteresis.* Standard Ni-Ti alloys show a hysteresis of 30-50°C. Through alloy modifications, however, it is possible to either reduce the hysteresis to about 10-15°C, or extend it to over 100°C. In some Ni-Ti alloys a premartensitic transformation (commonly called R-phase) with an extremely narrow hysteresis (0-5°C) can be found. TVR springs made from these R-phase materials, therefore, also show a narrow hysteresis. The hysteresis loop is described by the transformation temperatures As, Af and Ms, Mf (*Austenite Start, Austenite Finish, Martensite Start, Martensite Finish*). Transformation temperatures can be altered between approximately −100°C and +100°C by changing the alloy composition.

The shape of the hysteresis loop is not only alloy dependent, but is also influenced by the application itself. When a TVR spring works against a constant load, e.g., by lifting a certain weight, the transition from low to high stiffness or *vice versa* takes place in a very narrow temperature range (typically 5°C). This is schematically shown in Figure 10. However, if the TVR spring works against a biasing spring,

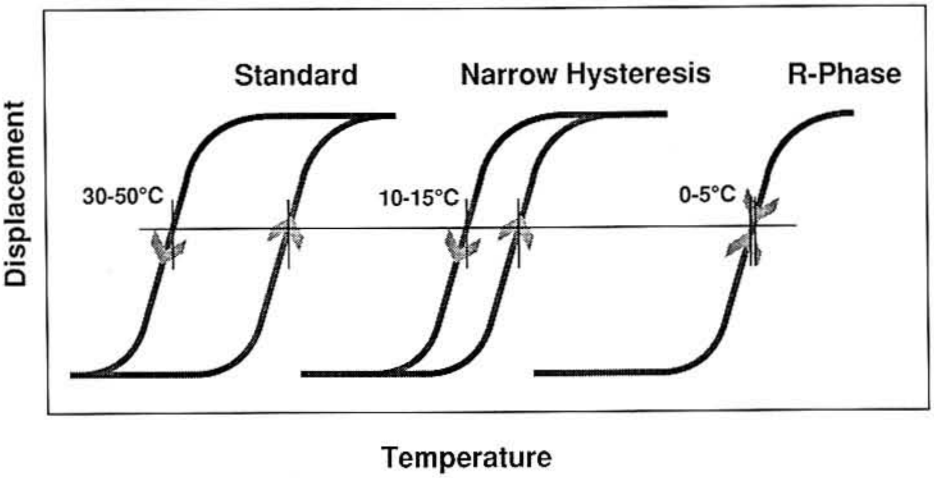

Fig. 9. Motion/temperature hysteresis of different Ni-Ti alloys.

the transition is more gradual and depends upon the rate of the bias spring (Figure 11). This is because the transition temperatures depend on the stress level, increasing with shear stress. Figure 12 shows the relationship between transformation temperatures and stress level for a Ni-Ti-Cu alloy with narrow hysteresis.

Figures 10 and 11 show the hysteresis of the displacement of TVR springs as a function of temperature when loaded with a constant load or a spring force. However, similar curves for the force *versus* temperature can be obtained when the TVR spring is kept at a certain length and subsequently heated and cooled. Figure 13 shows the force/temperature hysteresis of the TVR compression spring described in Figure 5, when compressed to a length of 22.7 mm. and constrained to this length during heating and cooling. It should be also mentioned here that the martensitic spring force upon cooling under load is generally lower than the force of the spring in the low-rate condition after cooling without load. This is caused by the formation of martensite with preferred orientations when the material is cooled from austenite under load (or stress).

4. Applications of Ni-Ti TVR Springs for Thermal 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 path, without restricting the flow. Thus, they provide fast response to changes in temperature.

One application is a temperature-sensitive governor valve, which controls the shifting point in automatic transmissions. This valve's function is shown schematically in Figure 14. At low temperatures, the spring force of a steel bias spring is higher than that of the Ni-Ti spring in the low-rate condi-

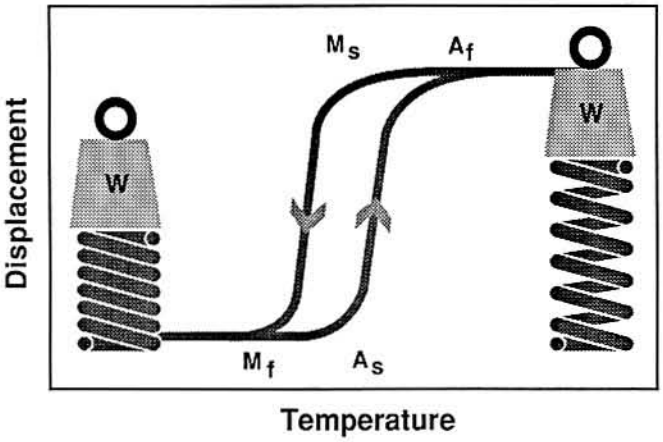

Fig. 10. Hysteresis under constant load conditions.

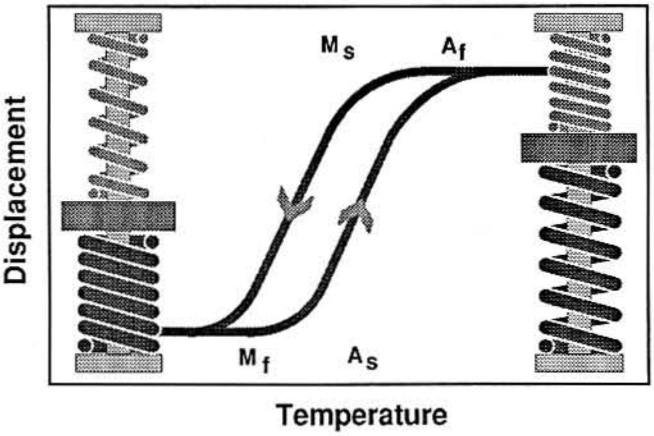

Fig. 11. Hysteresis under biasing force conditions.

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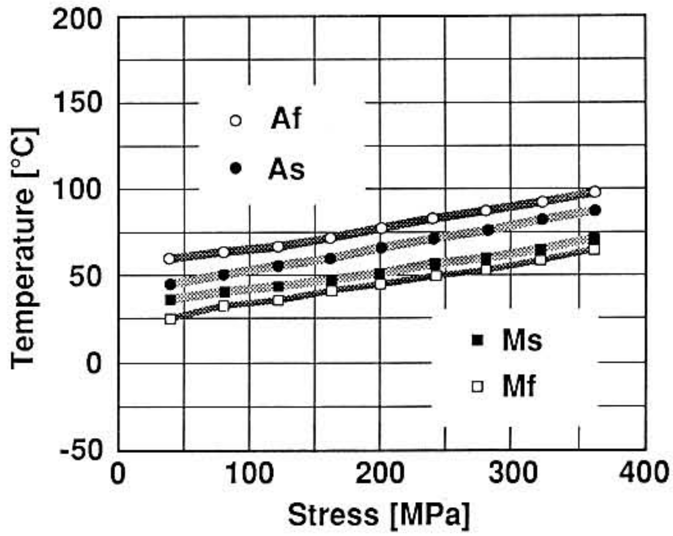

Fig. 12. Influence of applied stress on the transformation temperatures of a Ni-Ti alloy with narrow hysteresis.

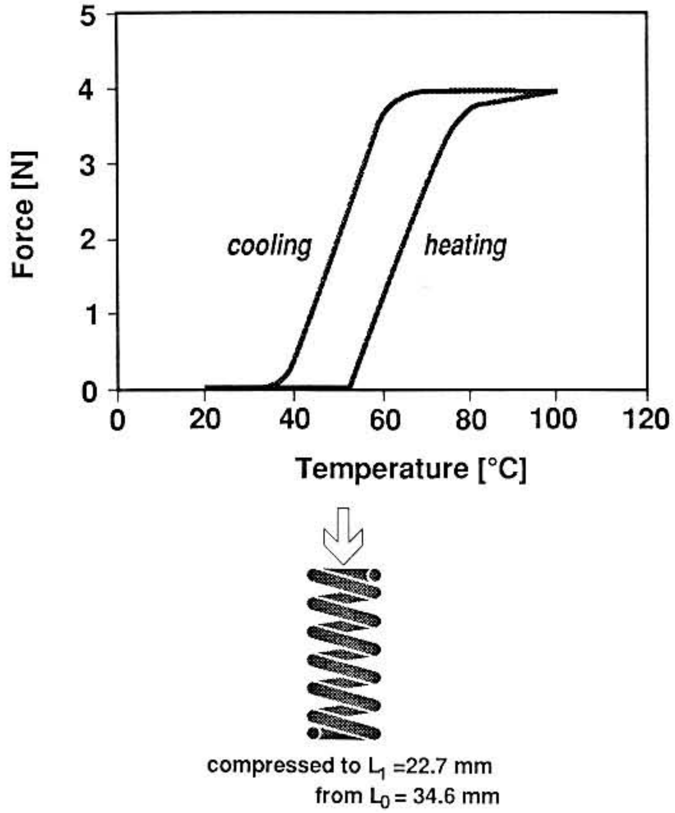

Fig. 13. Force/temperature hysteresis of the TVR compression spring shown in Figure 5.

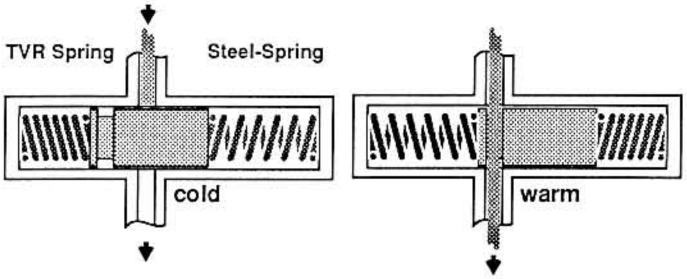

Fig. 14. Thermostatic governor valve (*Machine Design*, 1990).

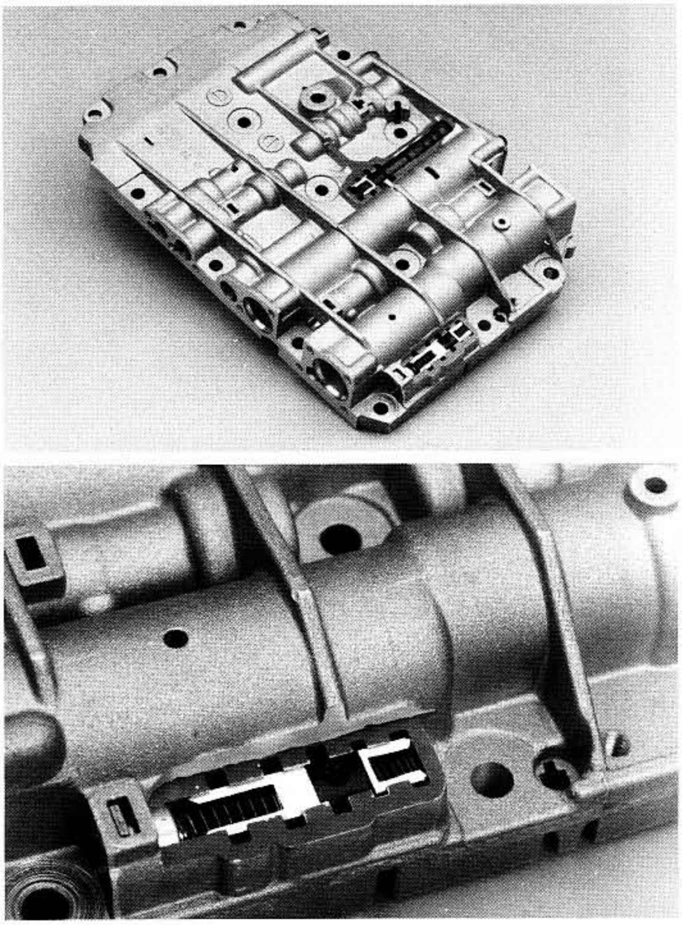

Fig. 15. Valve plate of an automatic transmission with two TVR valves and cut-away section of one of the valves.

tion (martensitic state). Consequently, the steel spring can compress the Ni-Ti spring, pushing the moveable piston of the valve into the "closed" position for this particular application. When the temperature of the transmission and the transmission fluid increases to operating temperature, the Ni-Ti spring changes its rate upon transforming into the austenitic state. In the high-rate condition it overcomes the steel spring force, and eventually pushes the piston into the "open" position. This governor valve controls the warm-up phase of the engine, automatic transmission, and other components by changing the shift point to higher speed at low temperatures. This reduces the warm-up time, increasing the efficiency of the catalytic converter, and thus reducing smog emission and fuel consumption.

The smoothness of shifting in automatic transmissions is strongly affected by the balance of engine power output and shifting pressure. Especially in diesel-powered cars, the power output of the engine is rather low during cold weather, causing the automatic transmission to shift roughly until the engine and all other systems warm up to operating temperature. This problem can be eliminated by reducing the shifting pressure during the

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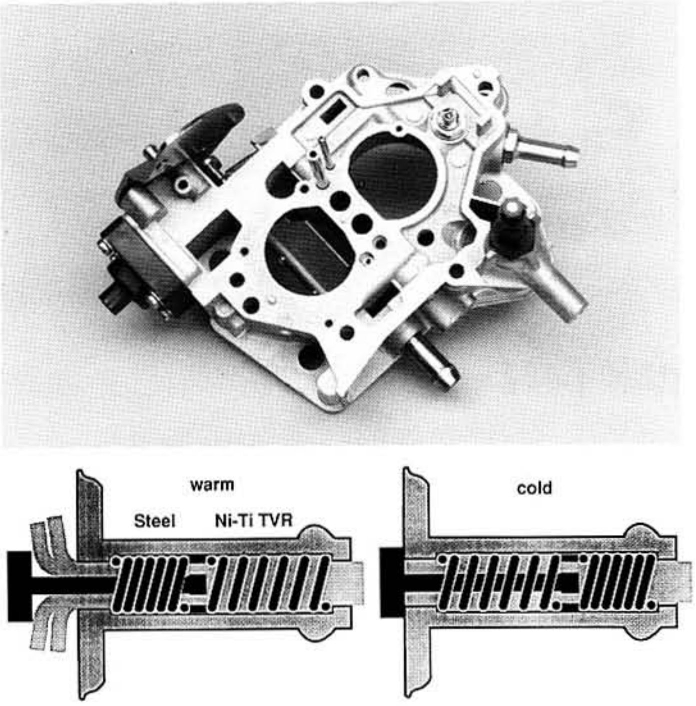

Fig. 16. Carburetor with integrated TVR ventilation valve (Solex).

warm-up phase, which, again, can be done by using TVR springs in governor valves. When the engine temperature is low, the valve reduces pressure and helps reduce rough shifting. Figure 15 shows a valve plate of a Mercedes-Benz automatic transmission with two thermal valves. The cut-away section reveals the arrangement of the steel spring and the Ni-Ti TVR spring.

Another excellent example of an intelligent design with TVR springs is the evaporative emission control valve in carburetors. Ni-Ti spring and biasing steel spring are integrated into the fuel vapor hose fitting. 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. Figure 16 shows part of the carburetor as well as a schematic design of this valve.

In clogging indicators for jet engine oil filters, increased oil pressure indicates that the filter is clogged and maintenance is necessary. However, at low temperatures, this situation can also be caused by increased oil viscosity even with a perfectly working filter. Incorporating a Ni-Ti TVR spring into the pressure-sensing device eliminates "false alarms" due to high oil viscosity. Figure 17 shows this concept.

The detector is connected to the filter outlet (not shown here) through channel P1 and to the filter inlet through channel P2. Under normal operating conditions (P1=P2), the plunger in the lower part of the device is held in place by a steel spring and additionally by magnetic forces through a membrane that separates the pressure sensing part of the device from the signal (upper) part. In case of P2>P1 at low temperatures, the pressure differential pushes the plunger down, compressing the TVR spring which is in its low-rate condition. The magnets are not separated and, therefore, there is no signal. In case of P2>P1 at operating (high) temperature, the TVR spring in the plunger is in its high-rate condition. As the TVR spring cannot be compressed by the pressure differential, the magnets are separated when the plunger is moved. This triggers a signal in the upper part of the device.

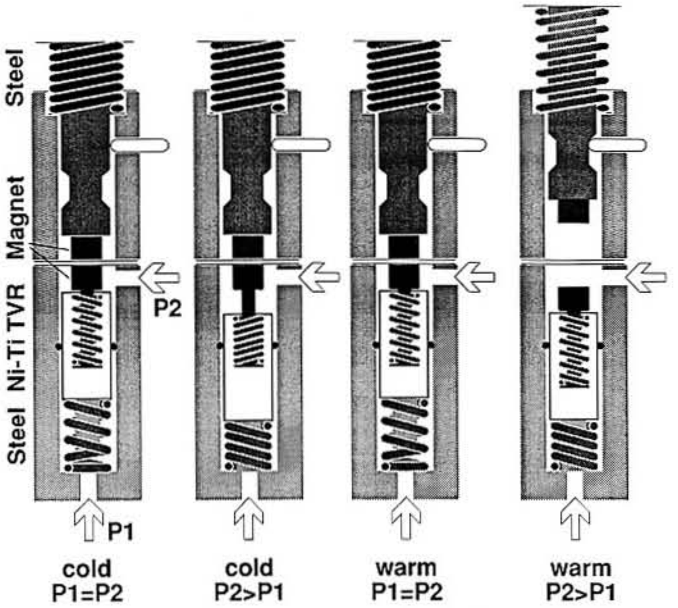

Fig. 17. Thermally compensated clogging indicator (Le Bozec et Gautier).

5. Conclusion

Springs made from Ni-Ti shape memory alloys show a dramatic increase in spring rate with increasing temperature in a relatively narrow temperature range. This phenomenon can be effectively used for thermal sensor-actuators. Actuators using TVR springs combine large motion, rather high forces, and small size, thus providing high work output. They usually consist of only the TVR spring and a biasing spring and do not require sophisticated mechanical systems. Therefore, these actuators often fit into tight spaces in given designs, where other actuators would require a major redesign of the product.

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