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Springs Vol. 31, May

1992

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Shape Memory Actuators Improve Car Performance

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Actuators are devices which perform a task, like moving an object, either on demand or in response to certain changes in their environment (temperature, pressure etc). In a modern car more than 100 actuators are used to control engine, transmission and suspension performance, to improve safety and reliability and enhance driver comfort. Most of these actuators today are electric motors, solenoids, thermostatic bimetals, wax motors, vacuum or pressure actuators . However, in recent times, shape memory actuators are becoming increasingly popular for automotive applications, providing small size and low weight, high work output and simplification of designs.

1. 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 "thermoelastic martensitic transformation", which is found only in a few alloy systems, the most important being the Ni-Ti system. Ni-Ti shape memory alloys have been around since more than twenty years, commonly known as NITINOL (NiTi Naval Ordnance Laboratory) or TINEL, the brand name of a family of Ni-Ti alloys from Raychem Corp. in California, who pioneered the shape memory technology in the United States.The shape memory effect in Tinel alloys can be used to generate motion and/or force in actuators, fasteners and couplings. At temperatures below the 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 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. Plotting the plateau stress or the first yield point versus temperature produces a curve as shown in Figure 2.

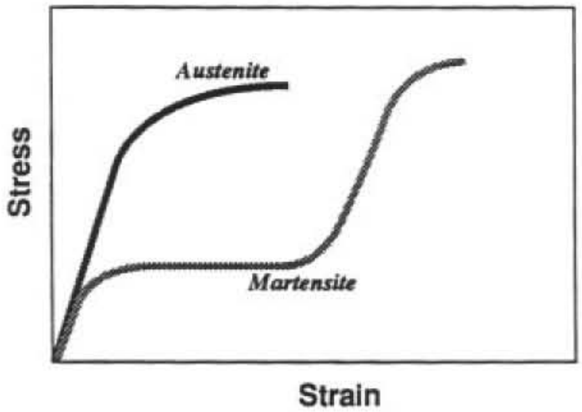


Figure 1: Tensile Behavior of Tinel Alloys in the Martensitic and Austenitic Phase

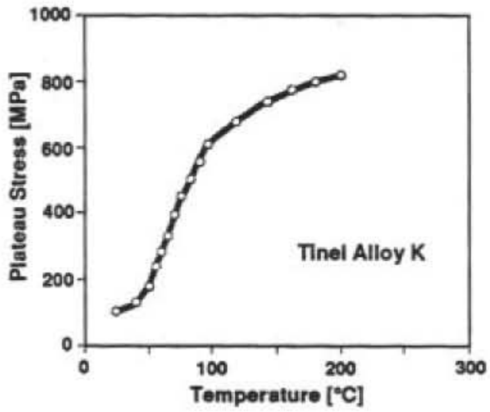


Figure 2: Influence of Temperature on Plateau Yield Stress

The shape memory effect can be explained in simple terms using a straight Ni-Ti tensile wire. As schematically shown in Figure 3, the wire is fixed at one end. For the sake of simplicity, a constant load is applied to the other end. This load or force must be high enough to stretch the wire in the martensitic condition. On the other hand it must be sufficiently small not to cause excessive deformation of the austenite . This effect is called *two-way effect with external reset force* or *extrinsic two-way effect.*

As can be seen from Figure 3, the transformation 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° to 50°C. Through alloy modifications, however, it is possible to either reduce the hysteresis to about 15°C, or extend it to over 100°C. The hysteresis loop is described by the transformation temperatures As, Af and Ms, Mf (*Austenite Start, Austenite Finish* and *Martensite Start, Martensite Finish*). Transformation temperatures can be varied between approximately -100°C and +100°C.

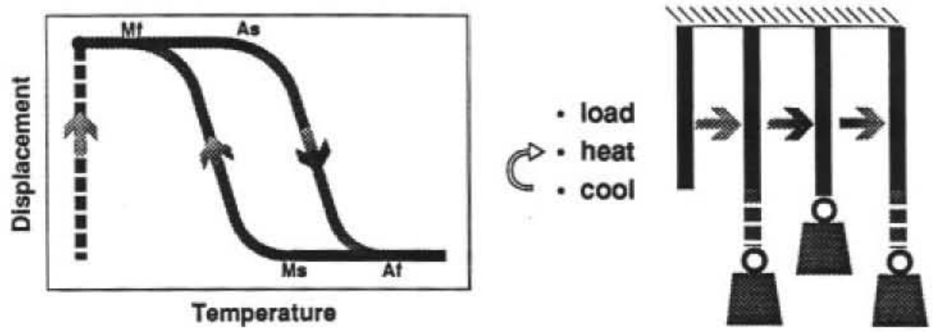


Figure 3: Two-Way Effect with External Reset Force (Extrinsic Two-Way Effect)

2. Designing Ni-Ti Shape Memory Actuators

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. Prefered 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)
- wave-washer springs (high force, small motion)
- torsion wires/rods
- torsion tubes
- helical torsion springs

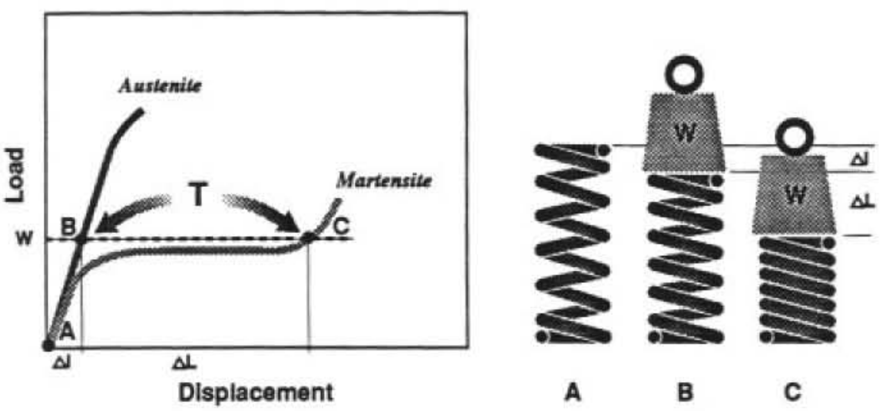


Figure 4: Work Against Constant Load

The design of shape memory actuators is based on the different stress/strain curves of the austenite and the martensite. As an example, Figure 4 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 A_f) the spring is compressed along A - B with the displacement Δl (B). Upon cooling below M_f 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.The temperature/displacement diagram for this arrangement is similar to that in Figure 3.

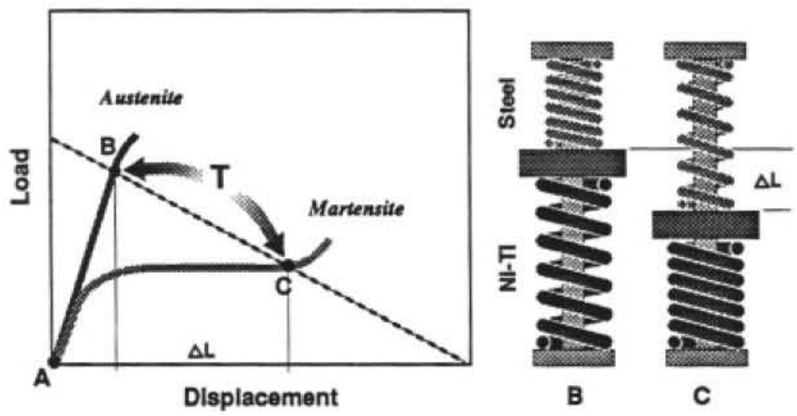


Figure 5: Work Against Biasing Spring

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. This is schematically shown in Figure 5. A Ni-Ti shape memory 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. Work against a biasing or reset spring is the most common case in automotive actuator applications.

Shape memory actuators can be used in two basically different ways: as thermal or as electrical actuators. *Thermal actuators* combine the sensing and the actuating functions, responding to a temperature change by changing shape and/or generating a force. The function of *electrical actuators*, on the other hand, is simply to move an object or perform a task on demand. Usually, a current is passed through the shape memory actuator, internally heating it above A_s to recover its shape .

3. Thermal Actuators

As mentioned earlier, thermal actuators respond to changes in temperature by changing their shape and/or generating a force. Shape memory actuators, in this area, generally compete with thermostatic bimetals and wax motors, and sometimes with electric/electronic devices or vacuum/pneumatic systems. Thermal actuators have a variety of applications in cars. Figure 6 schematically shows areas of both potential and realized applications for shape memory thermal actuators.

There are three different temperature ranges, in which thermal actuators either are already used or could provide significant benefits:

< 0°C:	- low temperature performance (engine, transmission, suspension,brakes) - cold start performance
0 - 60°C:	- cold start performance - climate control
60 - 120°C	- cooling systems (engine, brakes) - restart ability - climate control - rattling (engine, transmission)

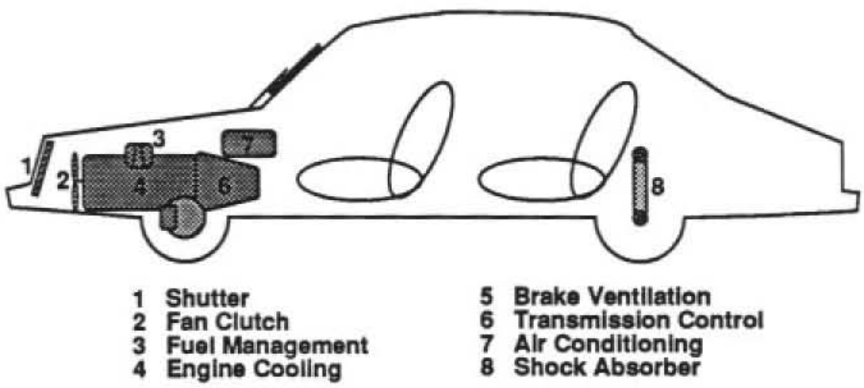


Figure 6: Potential Applications of Thermal Actuators in Cars

Most of these temperature ranges can be covered by Ni-Ti shape memory alloys available today. However, certain limitations, like transformation temperature ranges vs. required number of cycles, hysteresis width, and stability, have to be considered. Figure 7 shows the transformation temperature ranges of the most common Ni-Ti alloys. For multiple cycle applications, standard binary Ni-Ti alloys with transformation temperatures from -20°C to approximately +80°C perform well. These alloys exhibit a hysteresis width of about 30 to 50 degrees and are reasonably stable during cycling. Binary alloys with higher transformation temperatures (up to +120°C) tend to *walk* and, therefore, can only be used for single or low cycle applications.

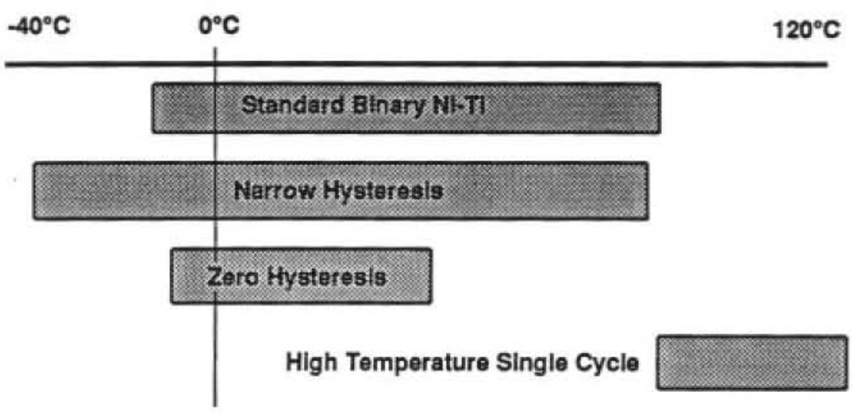


Figure 7: Transformation Temperatuture Ranges For Ni-Ti Alloys

Most actuator applications require Ni-Ti alloys with both a narrow hysteresis and high stability of the shape memory effect. The hysteresis width of ternary and quaternary Ni-Ti-Cu alloys, with transformation temperatures from -30°C to +70°C, is only about 15°C. They show excellent stability even after 100,000 thermal cycles. Another important advantage of Ni-Ti-Cu alloys is the low martensitic strength, which allows low reset forces and thus improved work output.

Zero-hysteresis alloys use the so-called R-phase, a premartensitic transformation with very narrow hysteresis. They provide only approx. 0.5% shape memory strain, but very good cyclic stability.

Unfortunately, presently available Ni-Ti alloys having transformation temperatures above 80°C are not sufficiently stable for multiple cycle applications. However for single cycle applications (e.g. over-temperature protectors) binary and ternary Ni-Ti alloys with transformation temperatures up to 150°C are available. Besides having the highest transformation temperatures, ternary alloys can provide high austenitic and martensitic strength.

Patent literature proposes many applications for shape memory thermal actuators. One successful application, developed by Mercedes-Benz of West-Germany, is a temperature-sensitive governor valve, which controls the shifting RPM in automatic transmissions. This valve's function is shown schematically in Figure 8. At low temperatures, the spring force of a steel bias spring is higher than that of the Ni-Ti shape memory spring in the 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 transforms into austenite. It then expands, overcoming the steel spring force, and eventually, pushing the piston into the "open" position. This governor valve controls the warm-up phase of the engine, automatic transmission and other components through increased shifting RPM at low temperatures. This reduces the warm-up time, increasing the efficiency of the catalytic converter, and thus reducing smog emission and fuel consumption.

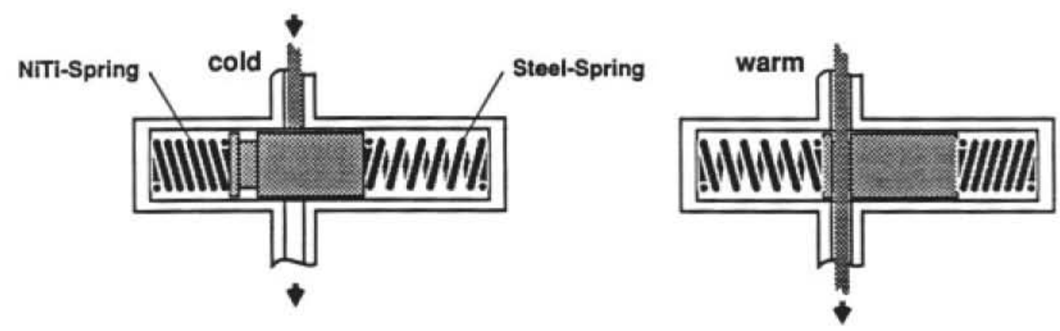
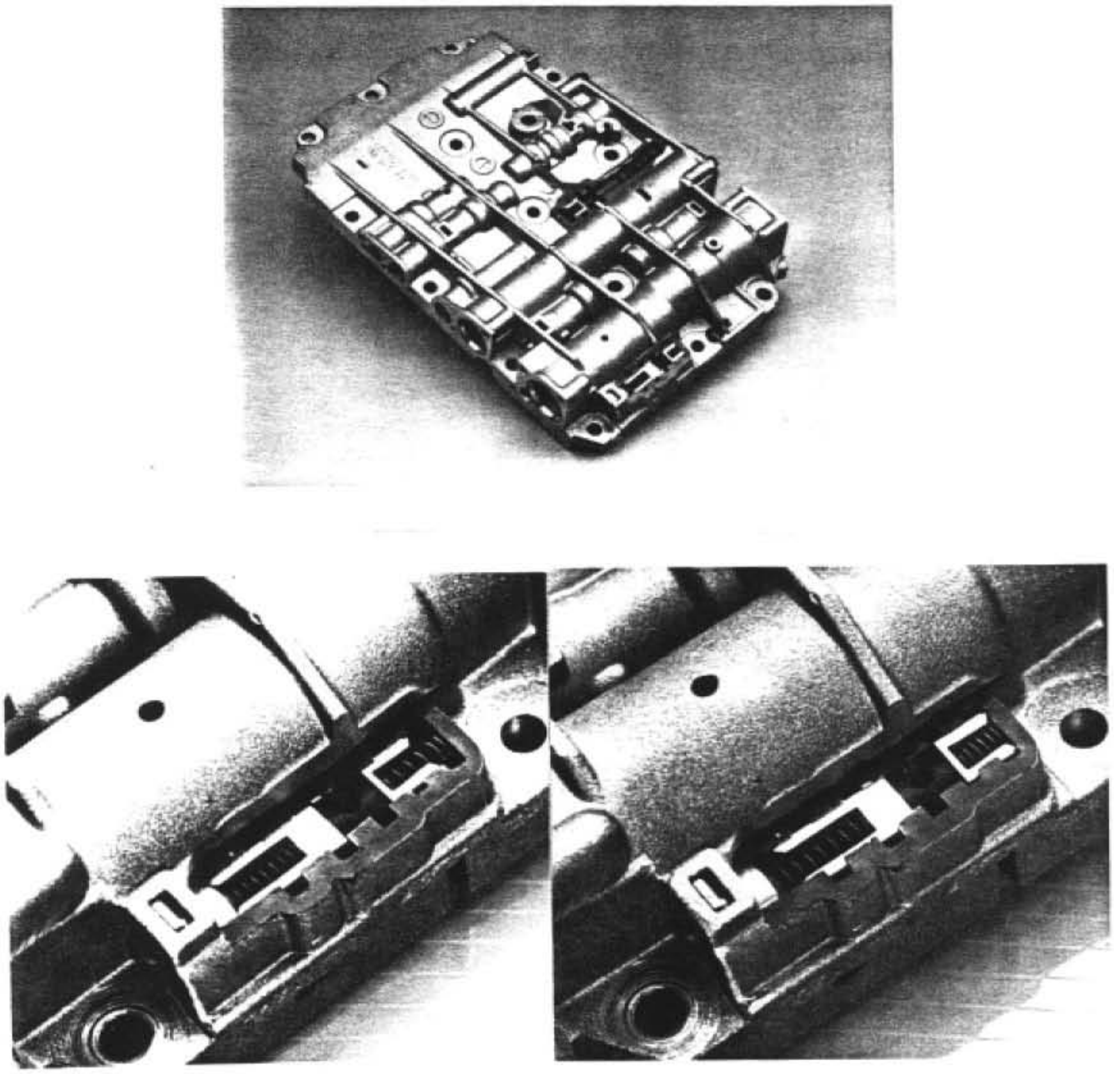


Figure 8: Thermostatic Governor Valve

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 warm-up phase, which, again, can be done with shape memory governor valves. When the engine temperature is low, the shape memory valve reduces pressure and helps reduce rough shifting. Figure 9 shows a valve plate of a Mercedes-Benz automatic transmission with two shape memory valves. The cut-away sections reveal the arrangement of the steel springs and the Ni-Ti springs.



warm **cold**

Figure 9: Valve Plate of an Automatic Transmission With Two Shape Memory Governor Valves

Another excellent example of an intelligent design with shape memory springs is the evaporative emission control valve in carburetors developed by Solex of France. 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 10 shows the schematic design of this valve. Similar vent control valves have been developed by Toyota of Japan for the use in Tercel cars.

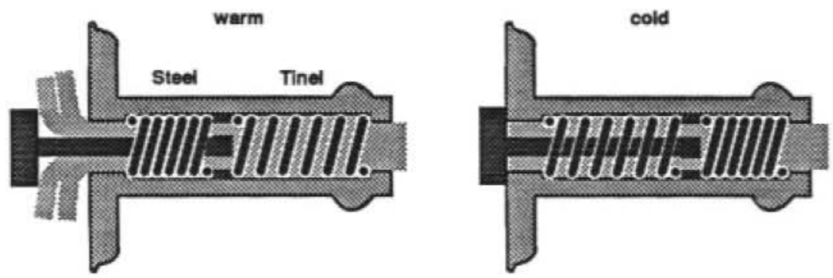


Figure 10: Evaporative Emission Control Valve

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. Figure 11 represents this situation schematically. A similar configuration is used by Toyota of Japan in their Sprint/Carib cars..

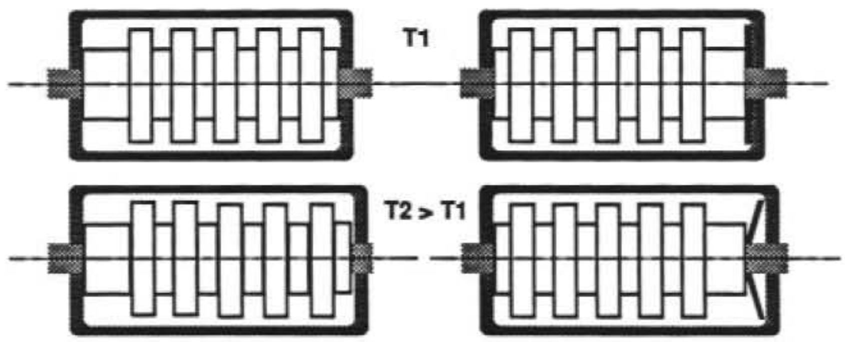


Figure 11: Compensation For Thermal Expansion With Ni-Ti Washer

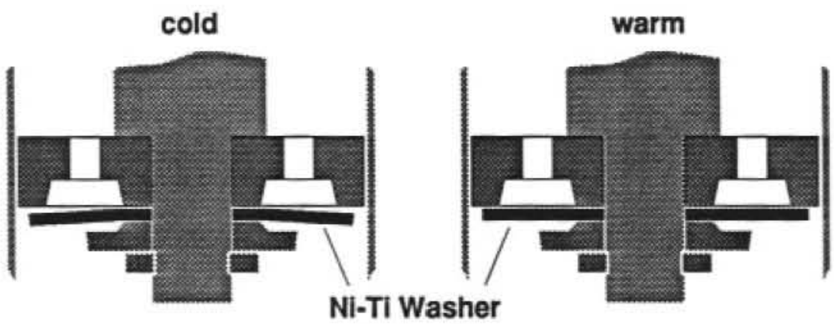


Figure 12: Thermostatic Valve For Shock Absorbers

Since conventional shock absorbers tend to be too hard at very low temperatures, they don't provide comfortable driving. This is caused by the high viscosity of the oil in the shock absorber, which usually is balanced for the temperature range of 0°C to 100°C.

A shape memory washer in the shock absorber's valve (Figure 12), which changes the pressure at low temperatures, compensates for the oil viscosity.

There are many other areas in a car, where shape memory thermal actuators can and will provide significant advantages over competing technologies. Some of the benefits are listed below:

- size
- high force
- large motion
- high work output
- few mechanical parts
- non-linear characteristic

Shape memory thermal actuators 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, therefore, often fit into tight spaces in given designs, where other thermal actuators would require a major redesign of the product. In flow-control or oil pressure control valves, as shown above, helical springs can be placed in the gas or fluid path, without restricting the flow. Thus, they provide fast response to changes in temperature.

3. Electrical Actuators

As mentioned earlier, electrical actuators are devices which perform a task on demand. The stimulus is any voltage applied to the device,which is usually an electric motor or a solenoid. If electrically heated above As , such as by passing current through a wire or a spring, Ni-Ti shape memory elements become electrical actuators. They can provide interesting advantages over motors and solenoids like:

- small size
- noise-less operation
- few mechanical parts

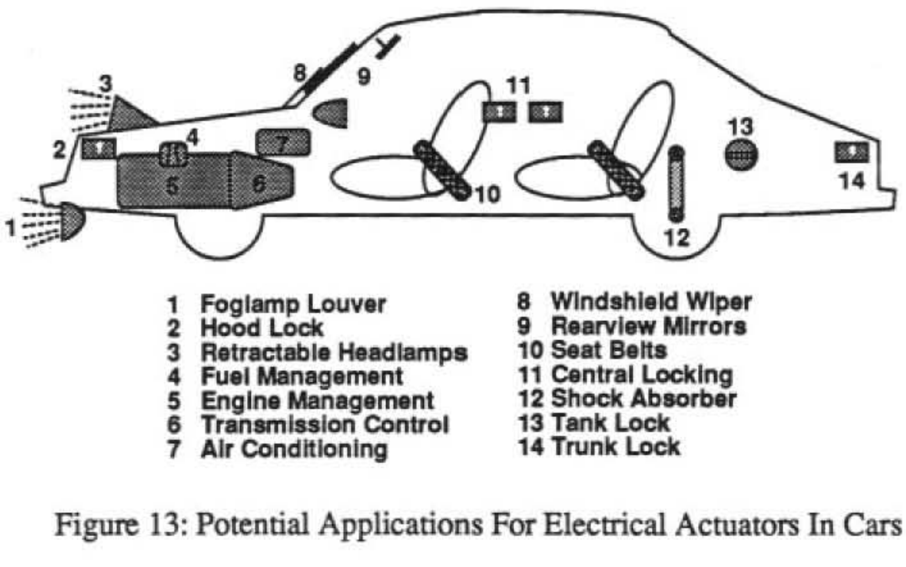


Figure 13: Potential Applications For Electrical Actuators In Cars

Therefore an almost unlimited number of potential applications can be found in the patent literature. Figure13 schematically shows the areas in a car where electrical shape memory actuators have been suggested. However, only very few have actually been implemented or seem technically and economically feasible because of the limited range of transformation temperatures of existing shape memory alloys. As shown in Figure 14, the operating temperature range of a car ranges from -40°C to approximately +100°C, with even higher temperatures in under-hood locations. In order to work properly at all temperatures, the shape memory alloy has to have an Mf temperature well above the maximum operating temperature. Today no Ni-Ti alloys with transformation temperatures above approximately 80°C are available for cyclic applications. Cu-Al-Ni shape memory alloys have transformation temperatures this high, but they are brittle and unstable. Ti-Pd-Ni alloys remain too expensive for routine applications.

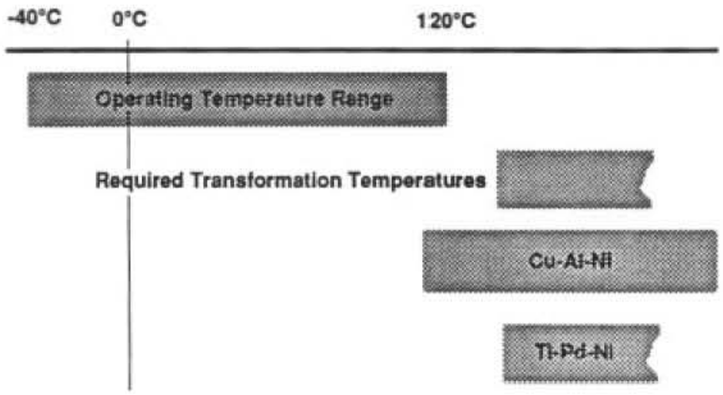


Figure 14: Temperature Range For Electrical Actuators

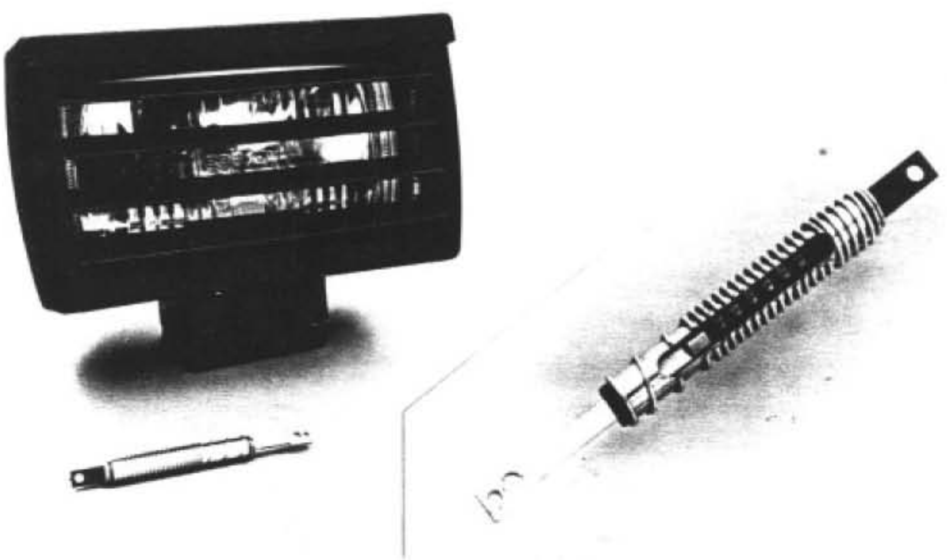


Figure 15: Foglamp With Shape Memory Actuated Louver

Among those applications that are in production is the remote fog-lamp louver opening device. A shape memory spring is wired in series with the lamp. Turning on the fog-lamp passes the lamp current through the actuator, which heats up, contracts and opens the louver. A reset spring closes the louver when the lamp is turned off. Figure 15 shows the design of the actuator with an integrated over-load spring. The area where fog-lamps are located on a car is usually very well ventilated, so that the low transformation temperature of the actuator (~ 65°C) is not an issue.

The same applies for windshield wipers. Shape memory actuators could provide an elegant solution for increasing the pressure at high speeds. Figure 16 shows different designs incorporating a Ni-Ti spring or tensile wire into the wiper arm.

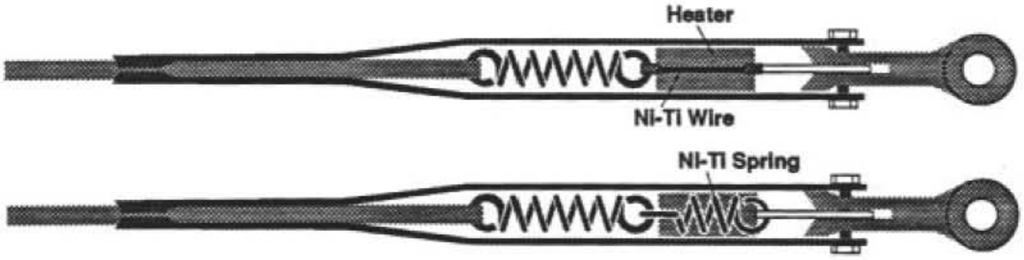


Figure 16: Windshield Wipers With Shape Memory Pressure Actuators

Because of their small size and noiseless operation, shape memory actuators have also been suggested for central locking systems, trunk locks and fuel tank cap locks. However, there are serious problems when ambient temperature approaches the transformation temperature of the shape memory alloy, for instance when the car is parked in the sun. In this case, the shape memory actuator could self-actuate or fail to reset.

4. Conclusion

Although shape memory actuators can provide significant advantages over conventional devices in certain areas, they have only slowly been penetrating the automotive market. This is mainly caused by poor information and the lack of engineering data for shape memory alloys. However, with the better understanding of the metallurgy and a more open discussion in the scientific community, shape memory actuators are becoming increasingly popular for automotive applications.