

# INTRINSIC

Intrinsic Devices, Inc.  
2353 Third Street  
San Francisco, CA 94107 USA  
Tel: 415 252 5902  
Fax: 415 252 1624  
Email: [sales@intrinsicdevices.com](mailto:sales@intrinsicdevices.com)  
<http://www.intrinsicdevices.com/>

## **Actuation and Fastening with Shape Memory Alloys in the Automotive Industry**

Stoeckel, Borden  
Metall Wissenschaft + Technik  
Juli 1992, 46. Jahrgang, Heft 7  
pp. 668-672  
1992

## Actuation and fastening with Shape Memory Alloys in the automotive industry<sup>1)</sup>

D. STOECKEL, T. BORDEN<sup>2)</sup>

Keywords: Ni-Ti-Formgedächtnislegierungen, Anwendung, Automobilindustrie

As a result of a phase transformation, shape memory alloys can change their shape when the temperature changes. This unusual effect can be utilized in actuation and fastening components for automotive applications. Springs made from Ni-Ti shape memory alloys change their rate in a predetermined temperature range due to a significant change in the elastic modulus of the material. They can be used as sensor-actuators in pressure control valves or oilcooler bypass valves in automatic transmission or to compensate for oil viscosity changes in shock absorbers or thermal expansion of dissimilar materials in gear boxes. If the recovery is constrained, i. e. a shape memory element is physically prevented from returning into its original shape, a potentially high stress is generated. This effect is used in fastener rings. Fasteners made from Ni-Ti alloys provide high reliability and easy installation for braid terminations, locating of shaft mounted components, connectors and hose clamps.

**Betätigungs- und Befestigungsvorrichtungen mit Formgedächtnislegierungen in der Kraftfahrzeugindustrie**

Formgedächtnislegierungen sind aufgrund der Phasentransformation in der Lage, bei Temperaturänderungen ihre Form zu verändern. Dieses ungewöhnliche Verhalten läßt sich im Kraftfahrzeugbau für Betätigungs- und Befestigungsteile ausnutzen. Federn aus Ni-Ti-Formgedächtnislegierungen ändern ihre Federkonstante innerhalb eines vorbestimmten Temperaturbereichs aufgrund einer deutlichen Veränderung des Elastizitätsmoduls des Werkstoffs. Sie eignen sich als Sensoren und Stellglieder in Druckregelventilen oder Ölkühler-Bypass-Ventilen in Automatikgetrieben sowie zum Ausgleich von Ölviskositätsänderungen in Stoßdämpfern und zur Kompensation der wärmebedingten Ausdehnung unterschiedlicher Werkstoffe in Getrieben. Wo der Grad der Formerholung eingeschränkt wird, d. h. ein Bauteil aus einer Formgedächtnislegierung durch physikalische Maßnahmen daran gehindert wird, seine ursprüngliche Form wieder anzunehmen, wird eine potentiell hohe Spannung erzeugt. Diese Eigenschaft wird bei Befestigungsringen genutzt. Befestigungsteile aus Ni-Ti-Legierungen bieten hohe Zuverlässigkeit und problemlosen Einbau zum Abschluß von Litzekabeln, zur Positionierung von Bauteilen an Wellen sowie als Verbindungselemente und Schlauchklemmen.

### 1 Introduction

Shape memory alloys respond to temperature changes and mechanical stresses in non-conventional and highly amazing ways. They are therefore sometimes called "smart or intelligent materials". For instance, springs made from Ni-Ti shape memory alloys can change their rate when temperature changes. Shape memory actuators have not yet penetrated the automotive market significantly. This is due in part to low market awareness about shape memory technology, as well as little engineering data for the alloys. However, as the scientific and engineering communities come to understand the metallurgy and discuss it more openly, shape memory components are becoming increasingly popular for automotive applications.

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 ac-

<sup>1)</sup> Paper presented at the 3<sup>rd</sup> Int'l ATA conference on Materials Innovation and Their Applications in the Transportation Industry, Turino, Italy, June 1991

<sup>2)</sup> Prof. Dr. Dieter Stoeckel, Thomas Borden, MS ME; Raychem Corporation, Menlo Park, California, USA

tuators, 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).

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.

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 ( $A_s$ ), austenite finish temperature ( $A_f$ ), martensite start temperature ( $M_s$ ) and martensite finish temperature ( $M_f$ ). Transformation temperatures can be varied between approximately  $-100^\circ\text{C}$  and  $+100^\circ\text{C}$ , the width of the hysteresis between  $2^\circ\text{C}$  and  $150^\circ\text{C}$ .

### 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)

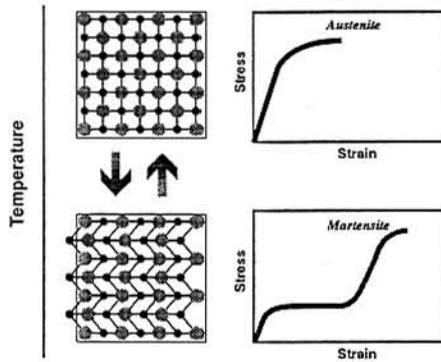


Fig. 1. Martensitic transformation and tensile properties of austenite and martensite

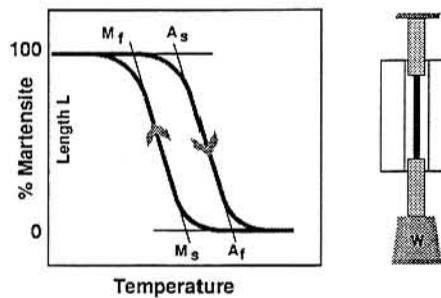


Fig. 2. Hysteresis of the martensitic transformation and the shape memory effect

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 [3]. The high temperature shape of the spring with no load is  $L_0$  (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  $\Delta l$  (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  $\Delta L$ . Repeated heating/cooling cycles between points B and C.

placement  $\Delta l$  (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  $\Delta L$ . 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. 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. Because the Ni-Ti springs change their rate with temperature, they are called thermovisible rate springs (TVR springs). The following describes some applications of TVR springs.

Automotive 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. 4). This concept was successfully introduced in Mercedes-Benz automatic transmissions in diesel-powered passenger cars. 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.

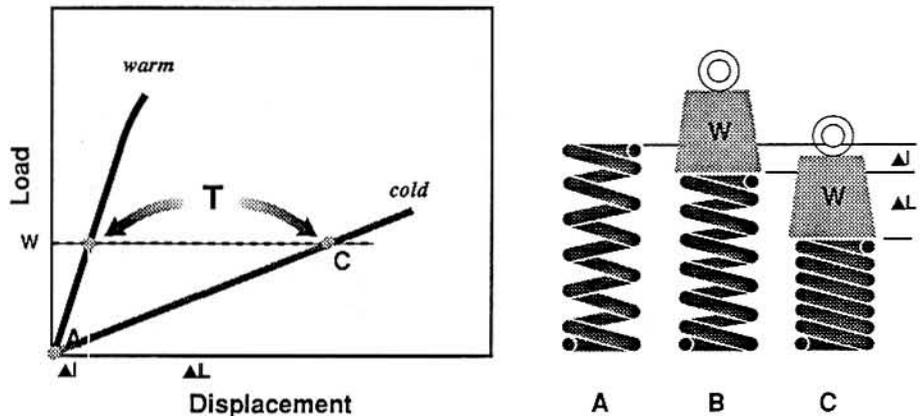


Fig. 3. Load/displacement characteristics of a Ni-Ti spring with constant load

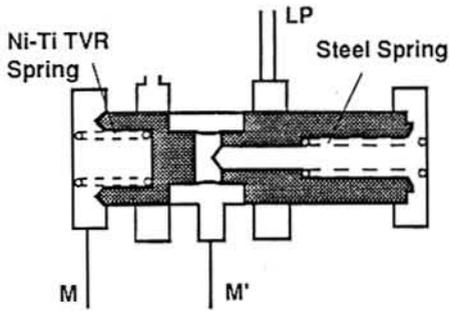


Fig. 4. Schematic of a thermostatic control valve (left) and valve plate with cut-away sections

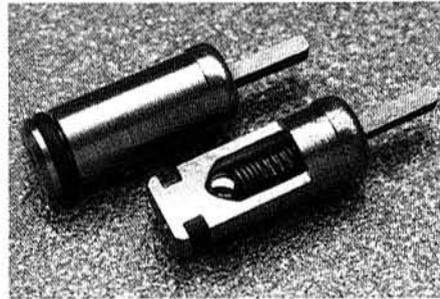
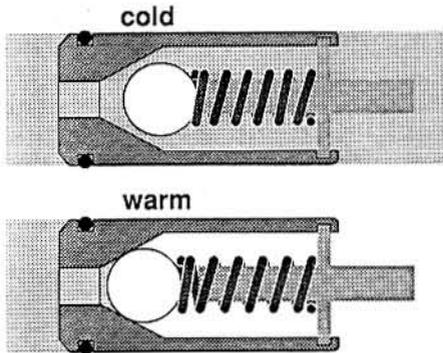


Fig. 5. Thermostatic oilcooler by-pass valve for automatic transmission

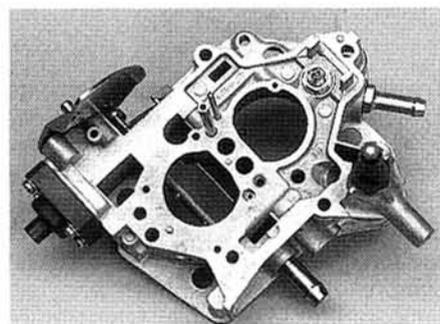
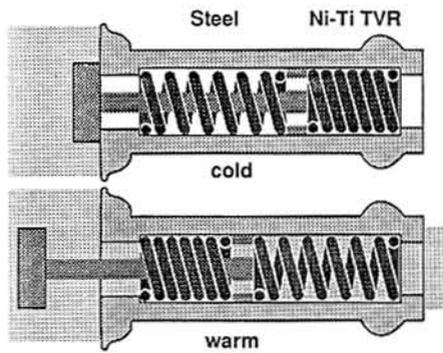


Fig. 6. Schematic of evaporative emission control valve (left) and carburetor (right) [5]

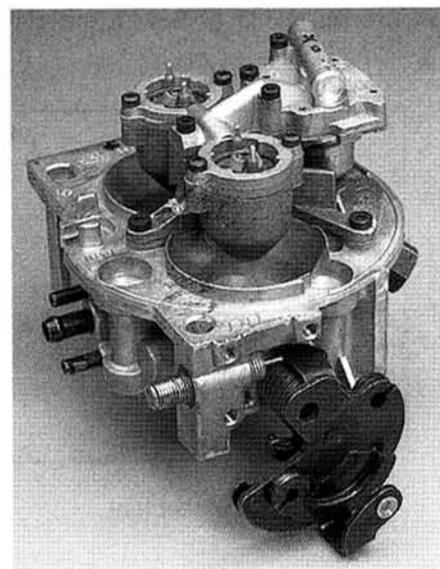
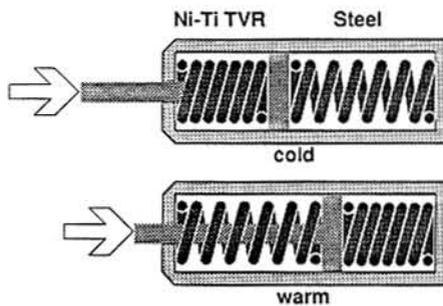


Fig. 7. Schematic of "Smart Idle Screw" (top) and throttle body (right) [6]

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 by-pass 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 by-pass the cooler. At operating temperature, the valve is closed, forcing the oil through the cooler. However, the oilcooler can still be by-passed, if the pressure increases due to clogging of the cooler. Figure 5 shows the ball-valve used for this application.

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 carburetor 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. Figure 6 shows part of the carburetor as well as a schematic design of this valve. An improvement in cold start performance of engines with throttle bodies can be achieved by using a "smart idle screw". A Ni-Ti TVR spring is built into the idle screw. It automatically opens the butterfly valve to a certain degree at low temperatures. No additional components are necessary (Fig. 7).

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. A similar configuration is used by Toyota of Japan in their Tercel cars.

Since conventional shock absorbers tend to be too hard at very low temperatures, they don't provide comfortable driving. Again, 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, which changes the pressure at low temperatures, can compensate for the oil viscosity.

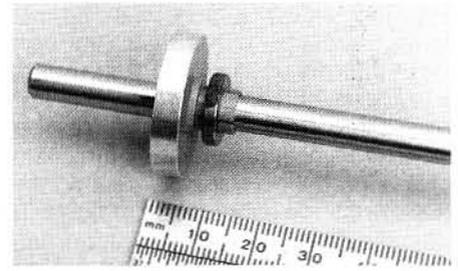
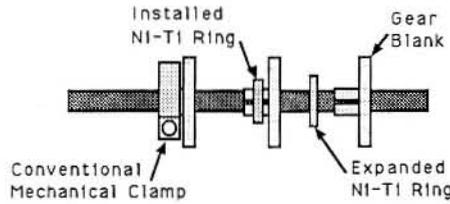


Fig. 8. Locating of shaft mounted components with Ni-Ti fastener rings

#### 4 Fastening with Shape Memory Alloys

If a sample after being deformed in the martensitic condition is constrained, i.e. physically prevented from returning into its original shape, then a stress is generated on heating. This unique property of Ni-Ti shape memory alloys affords them distinct advantages over conventional materials when utilized in fastening and joining applications. It is particularly useful when the shape memory alloy is configured as a ring. Shape memory fastener rings are most often used for making permanent joints, though de-mateable joints can also be produced. For example, Ni-Ti rings may be used to:

- terminate electromagnetic shielding braid to a connector
- terminate heat shielding braid to an oxygen sensor
- fix the location of a bearing or gear at any point on a shaft, if desired, locking in a controlled axial preload force
- assemble a cluster of radially disposed elements by compressing them with controlled uniform radial pressure.

Using the memory properties of Ni-Ti alloys to effect a mechanical joint was one of the first major commercial uses of shape memory alloys. In order to use the high mechanical strength of the austenitic phase, the shape memory part, e.g. a fastener, should be austenitic after installation and throughout its service life. Until recently, cryogenic alloys (alloys with transformation temperatures below the lowest operating temperature) had to be used. Using cryogenic alloys, the fastener, which has been deformed (stretched, expanded etc.) in the martensitic state, must stay at temperatures below  $A_s$  (usually in liquid nitrogen) during shipping and storage, so that no premature recovery occurs. Installation only requires the fastener to warm to room temperature after assembly. Throughout its service life, the fastener then remains in the high temperature austeni-

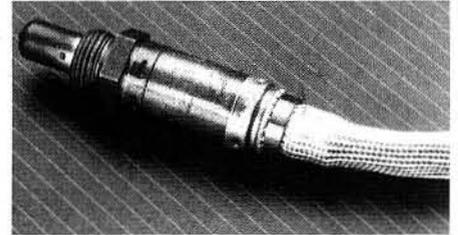
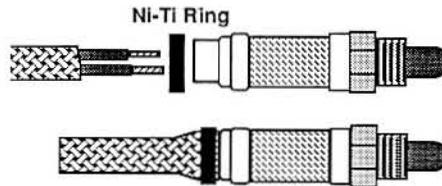


Fig. 9. Termination of heat shielding braid on oxygen sensor with Ni-Ti fastener ring

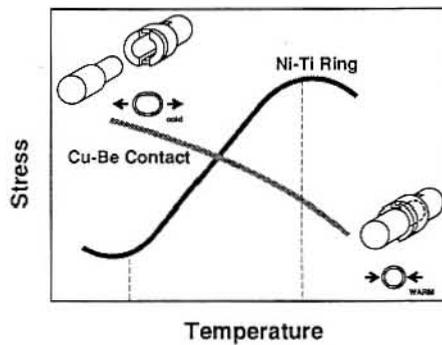


Fig. 10. De-mateable connector with Ni-Ti fastener ring



tic phase where it maintains its strength.

For some applications cryogenic installation is an advantage. However, in many instances - e.g. in the automotive industry - assembly procedures do not allow the use of a part that will recover shortly after it is removed from the dewar. Because of this limitation, a new heat-to-recover (HTR) alloy with an extremely wide one-time hysteresis has been developed.

The deformed martensitic ring can be stored/handled at temperatures up to 50°C. It is installed by heating it to approx. 150°C. Once installed, the part maintains its grip down to -100°C.

When assemblies are made up on shafts it is often necessary to have an axially adjustable locating collar to take up the accumulated tolerances of the components on the shaft. In addition, it is often necessary to apply a controlled axial preload to the stack of components for the proper functioning of bearings, etc. A shape memory collar

can fill these needs. The installation procedure is to slip the collar onto the shaft, preload the collar and components, and heat the collar to lock it in place. Figure 8 shows a typical example.

The cables of oxygen sensors used for tuning race car engines have to be thermally insulated. To do that, a glass fibre braid has to be permanently attached to the body of the oxygen sensor. Ni-Ti HTR rings proved to provide the most reliable termination even in severe environments with temperatures up to 300°C and heavy vibration. Figure 9 shows the sensor with insulating braid.

High amperage electrical connections in harsh thermal and vibration environments often suffer reliability problems. Screw terminals are typically used, but are prone to loosening. Ni-Ti rings can be used to make semipermanent connections, shown in Figure 10. When recovered, the Ni-Ti ring compresses a copper alloy collet onto a mating pin.

The ring exerts a very high normal force, producing a gas tight seal between the contacts surfaces. This results in a connection with a very stable, low resistance. The high normal force also results in a high pin retention force and high vibration resistance. Below the transformation temperature of the Ni-Ti ring, the spring force of the collet is high enough to expand the ring and release the connector.

Ni-Ti shape memory rings could also provide substantial advantages over

conventional hose-clamps presently used in the automotive industry, like high reliability connections and easy automation by robot assembly.

#### References

1. Duerig, T. et al.: Engineering Aspects of Shape Memory Alloys, Butterworth-Heinemann (1990)
2. Stoeckel, D.: Advanced Mat. & Proc., Vol. 138 Oct. (1990) 33
3. Stoeckel, D.: Proc. Actuator 90, Bremen (1990)
4. Stoeckel, D.; Tinschert, F.: SAE Conference, Detroit (1991)
5. Solex, private information
6. McGuane Industries, private information
7. Aishin Seiki
8. Toyota Motor, Kokai No. 62-50361 (1987)
9. Borden, T.: in [1], 158
10. Duerig, T. et al.: in [1], 130
11. Garretson, C.; Stoeckel, D.: METALL, 41 (1987) 22