Industrial Applications of Nickel-Titanium Shape Memory Alloys

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Introduction

The shape memory properties in NiTi alloys were accidentally discovered in the early 1960's at the Naval Ordnance Laboratory by Buehler et al., who called the alloy *Nitinol* (1). Shortly after, Raychem Corp. built and commercialized the first NiTi shape memory products, coupling members for hydraulic lines in aircraft. For many years, these couplings were the only technically successful application of NiTi shape memory alloys. Since a few years, however, the technology of NiTi alloys, and the shape memory effect in general, is sufficiently advanced that rapid commercialization is also starting to occur in areas other than fluid fittings. This is mainly due to the better understanding of melting and processing techniques, availability of improved ternary and quaternary alloys, as well as growing awareness for these materials in the marketplace.

Nickel-Titanium Alloys

The intermetallic compound NiTi with a Nickel content of about 50 at% is considered the standard alloy exhibiting the shape memory effect. The transformation temperatures of NiTi alloys vary dramatically with composition. By doping with third and fourth elements the concentration dependence of the transformation temperatures as well as some mechanical properties of the alloys can be influenced. NiTi alloys are produced in industrial quantities with transformation temperatures ranging from -150°C to about +100°C. Under certain conditions (e.g. one time or low cycle applications) even higher temperatures (up to 150°C) can be achieved.

Binary NiTi alloys are produced with transformation temperatures form -30°C to +100°C. They can show shape memory or pseudoelasticity and are widely used for orthodontic archwires, other medical applications, eyeglass frames and undergarment wires. The shape memory of binary alloys can be used for actuator type applications without specific requirements regarding hysteresis, work output and high cycle stability.

NiTi alloys with transformation temperatures below -50°C are called cryogenic alloys. They are used mainly for coupling applications with operating temperature ranges from -50°C to well above 100°C. They are optimized with regard to austenitic strength and provide high retention forces in a wide temperature range. While elements out of cryogenic alloys have to be stored and installed at cryogenic temperatures after deformation in the martensitic state, alloys with extended hysteresis can be stored at room temperature. The hysteresis of certain ternary NiTi alloys can be widened to about 150 K by special processing (2).

Unlike couplings and fasteners, actuators require two way performance. Cu-doped NiTi alloys provide high austenite strength and low martensite strength, thus allowing low reset forces and improved work output. Moreover NiTiCu alloys have a narrow hysteresis and show stable cyclic performance (3). Transformation temperatures range from -30°C to +75°C. For applications which require only one or very few thermal cycles NiTi alloys with transformation temperatures up to 150°C are available. They are used mainly for over-temperature protection.

The shape memory effect per se is a "thermal memory" effect. Pseudoelasticity on the other hand can be considered to be a "mechanical memory" effect. Martensite can be stress induced in shape memory alloys when deformed at temperatures above A_f and below M_d. Pseudoelastic alloy are mainly used for medical applications. They can be elastically deformed up to about 8% compared with a maximum of 1% for conventional metallic materials. This is why these alloys are also called "superelastic" The term "pseudo" is used because the stress-strain relation is non linear (4).

NiTi alloys are generally ductile and can be deformed reasonably well. Moreover available shape memory strain, strength, corrosion resistance, electrical resistivity and elevated temperature stability are substantial advantages over Cu-based shape memory alloys.

Applications of Nickel-Titanium Shape Memory Alloys

In order to systematize the applications of NiTi shape memory alloys, four different categories can be defined (5)

- free recovery
- constrained recovery
- work generation
- pseudoelasticity

Free recovery simply consists of a deformation of the martensite and then heating to recover the original shape. An example would be to bend a wire at room temperature, release it, and then heat to recover the original shape. The most common use of the event today is in toys and demonstrations. In November 1988, for instance, the Second German Television ZDF used a NiTi wire as a starter for a popular scientific show, generating the title of the show out of a crumbled piece of wire by immersing it into hot water.

If a sample after being deformed in the martensitic condition is constrained, i.e. physically prevented from returning into its original shape, then considerable forces can be generated on heating. This is called "constrained recovery" and is the basis for the most successful applications of NiTi shape memory alloys so far. As the stress generated on constrained recovery during heating can be greater than the yield stress of the martensite, shape memory elements can actually do work, e.g. by moving objects, lifting loads etc.

As described earlier, when a shape memory alloy is deformed at temperatures above A_f and below M_d, martensite is stress-induced. During unloading, the martensite again becomes unstable and the material reverts to its original shape. Since it returns to its original shape even after straining to about 8%, the material is "superelastic".

Shape Memory Alloy Couplings

A shape memory coupling basically is a hollow cylinder, the inner diameter (i.d.) of which is smaller than the outer diameter (o.d.) of the tubes or pipes to be joined (6). The cylinder is expanded in the martensitic condition (i.e. at temperatures below Mf) to an i.d. which is larger than the tube or pipe o.d.. The expanded coupling must stay at temperatures below As during shipping and storage, so that no premature recovery occurs. In the case of cryogenic alloys, expanded couplings therefore are shipped and stored in liquid nitrogen. Installation requires inserting the tubes or pipes into the coupling and allowing it to warm to room temperature. The coupling tries to recover to its original dimension and bites down onto the tubes forming a highly reliable joint. Throughout its service life, the coupling then remains in the high temperature austenitic phase where it maintains its strength (Fig. 1).

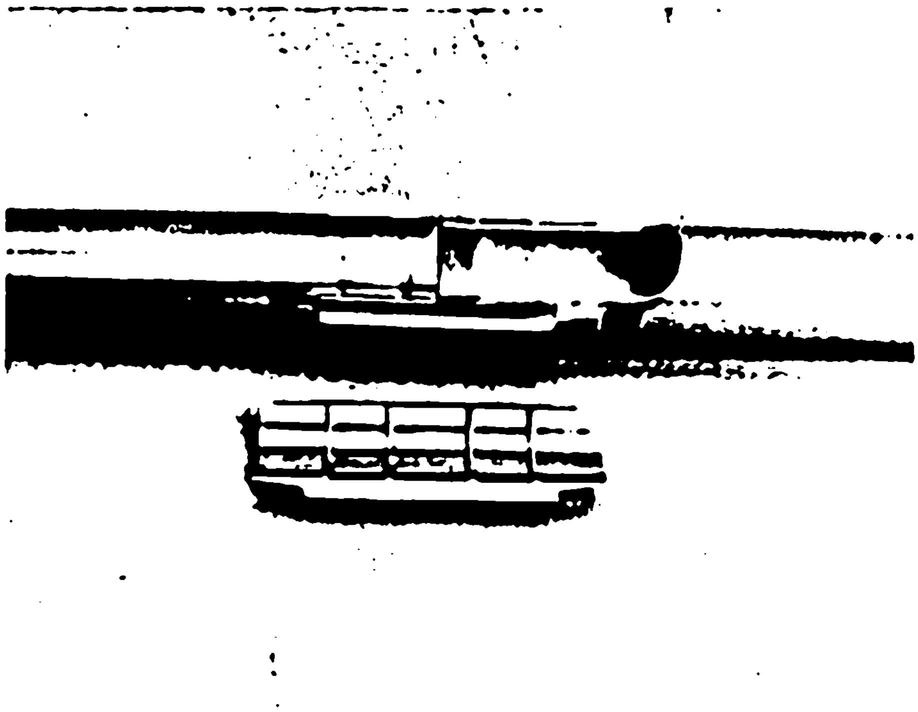

Fig. 1: Cut-away section of an installed aircraft coupling

Using wide-hysteresis NiTi alloys, components can be shipped and stored at ambient temperature in the martensitic condition, then installed by heating using any appropriate heating technique. Once installed, the alloy remains functional down to -65°C. Premature recovery does not occur unless the coupling is exposed to temperatures in excess of +55°C.

Over one Million NiTi couplings have been installed in aircraft hydraulic systems, marine and process piping connections as well as semiconductor gas tubing connections. The first commercial application was the fitting system for the Grumman F14 "Tomcat" in 1969. In the meantime, NiTi couplings are almost standard for new military aircraft and are beginning to penetrate the commercial aircraft industry. Their main advantages are extremely high reliability and easy installation even under severe space constraints.

Another widely publicized application was the first installation of a NiTi coupling to repair a gas line on the bottom of the North Sea in 1977. Under-water labor time was much shorter than with conventional methods like welding, resulting in remarkable cost savings. Simplicity, duration and cleanliness of installation, too, are the major reasons for the use of NiTi shape memory couplings in nuclear power plants, the chemical industry and similar areas.

Shape Memory Fasteners

NiTi alloys can be used to solve a variety of fastening and sealing problems (7). This is particularly true in the case of wide hysteresis alloys, which don't have to be stored and shipped in liquid nitrogen. A preferred shape is a welded wire ring. These rings are widely used to permanently attach shielding braid to the backshell of a connector (Fig. 2). The rings can be recovered in less than 10 seconds with a resistance heater.

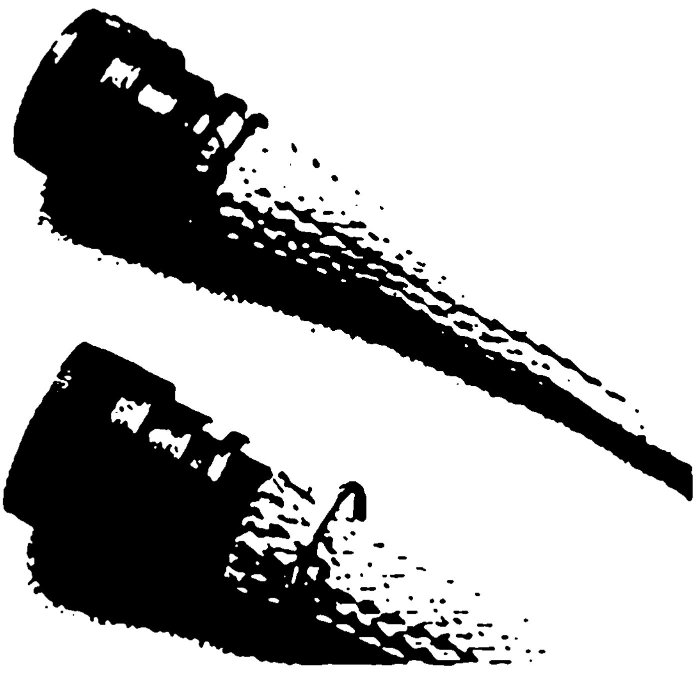

Fig. 2: Installation of a fastener ring for braid termination

NiTi rings provide substantial advantages over conventional hose-clamps presently used in the automotive industry, like high reliability connections and easy automation by robot assembly. Serious investigations are currently under way to prove the concept.

Shape memory rings offer an alternative technique for sealing thin walled metal cylinders to metal, ceramic, and plastic bases. The ring is expanded to fit over the cylinder and positioned over a recess in the base component. On heating, the ring recovers, forcing the cylinder into the groove and plastically deforming the interior of the cylinder at its two contact lines with the edges of the groove.

Shape Memory Connectors

Another important field of application for shape memory alloys is interconnection systems (8). Such a system provides zero insertion/extraction force, when the alloy is cooled and very high retention force when the alloy is "warm", since it develops a high force during recovery. At operating temperatures it provides a highly reliable electrical connection that maintains absolute continuity even during severe shock and vibration.

Different designs are presently on the market. Most of them use a NiTi actuator or driver which closes the contacts in the operating temperature range and opens them when being cooled below the minimum operating temperature. Single-line and multi-line connectors as well as DIP (dual-in-line-package) and PGAP (pin-grid-array-package) sockets and sockets for other electronic packages are available (Fig.3). Because of their high reliability they are mainly used in aerospace applications.

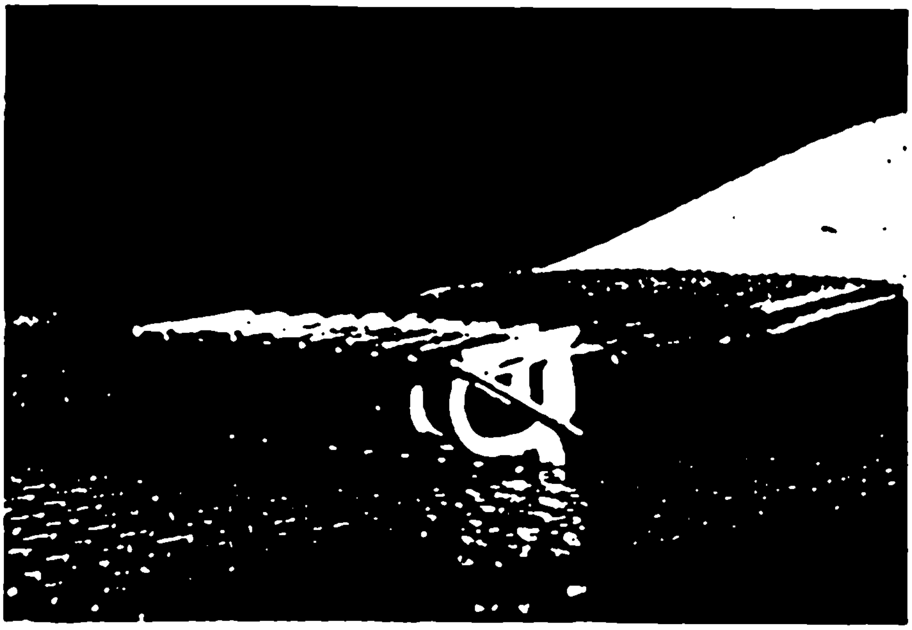

Fig. 3: Flat cable connector

Shape Memory Actuators

The capability of shape memory elements to do work, i.e. to move objects, lift weights or generally speaking generate motion against a force, makes them particularly interesting for actuator applications. Two basically different kinds of actuator applications can be distinguished. Thermal actuators sense changes in temperature and react by doing work. They generally compete with thermobimetal and wax actuators (9). In the automotive industry NiTi shape memory thermal actuators are becoming increasingly popular. Springs made out of NiTi alloys have different stiffness at high and low temperatures which makes them well suited for temperature compensation for oil viscosity or thermal expansion of different materials. As thermal actuators NiTi springs improve the performance of engines and transmissions at low temperatures, e.g. by opening or closing hydraulic valves. Incorporating a NiTi spring into diaphragm pressure sensors can add the feature of changing control characteristics at low and high temperatures (Fig. 4).

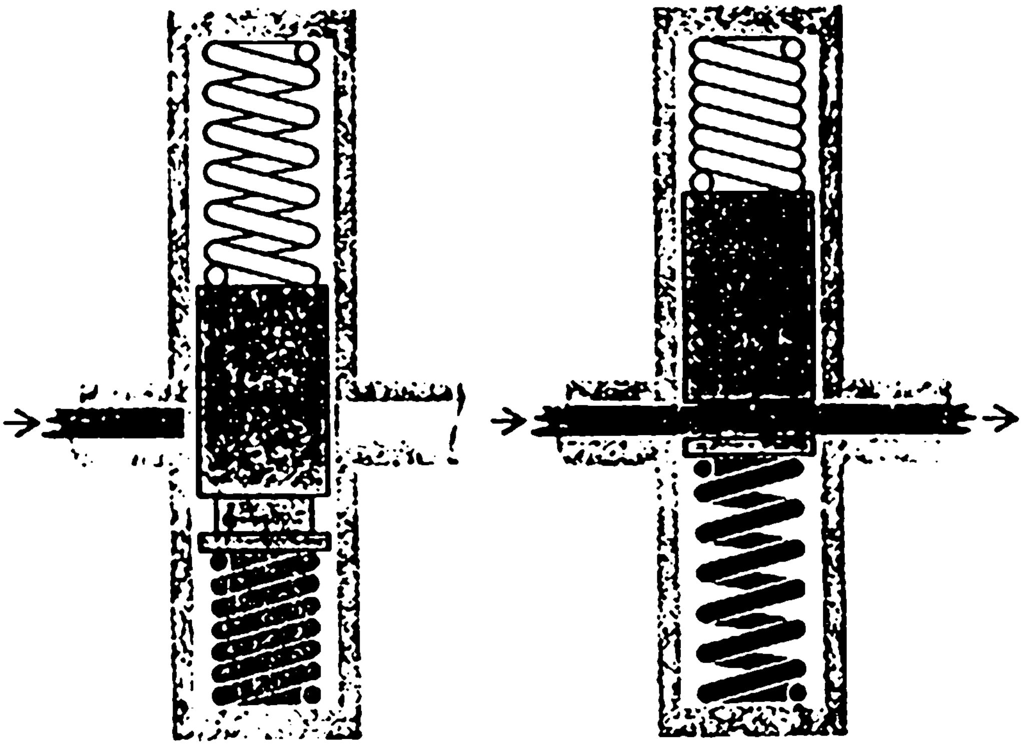

Fig. 4: Thermal-hydraulic valve. At low temperatures the NiTi spring is compressed by a steel spring

The rattling noise in gearboxes caused by different thermal expansion of dissimilar materials can be reduced by using washer-type NiTi elements which generate increasing force with increasing temperature.

Over temperature protection of electric and electronic devices is another area where NiTi thermal actuators provide significant advantages over conventional solutions. Easy miniaturization and shape change or force generation only when reaching the transformation temperature are the most important benefits provided by NiTi actuators. In most cases these applications require only one or very few cycles. Therefore alloys with transformation temperatures up to 150°C can be used.

Electrical actuators are generally competing with solenoids or servo-motors. Their function is simply to move an object or perform a task on demand. A current is passed through the shape memory alloy, internally heating it above A_s to recover its shape. Because of their high electrical resistance and longer fatigue life, NiTi alloys have substantial advantages over Cu-based shape memory alloys for these applications. Examples include drives for vent flaps and louvers, safety door locking systems and dispense mechanisms in appliances, circuit breakers , head lifters for disc drive units etc. Automotive applications already in use include remote louver opening devices (e.g. for fog lamps).

Superelasticity

The first application of superelasticity was the orthodontic arch wire. As NiTi superelastic wires generate almost constant stress (or force) even with considerable changes in strain (or elongation) fewer adjustments are necessary compared to conventional arch wire materials. Moreover it is more comfortable. Today about 10 Million NiTi arches per annum are produced worldwide. Figure 5 shows an example of an orthodontic arch, as well as a second example of a pseudoelastic device, a hook used to locate breast tumors during surgical procedures. Medical guide wires and spectacle frames using superelastic NiTi temples and/or glass-rim wires are other commercially available products. The most commented on superelastic NiTi product, however, is the undergarments wire, which provides comfortable support in brassieres.

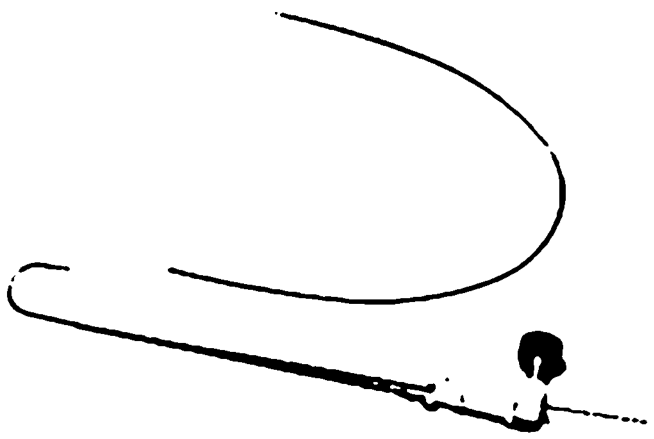

Fig. 5: Orthodontic arch and surgical hook

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