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Applications of Shape Memory

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APPLICATIONS OF SHAPE MEMORY

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1. INTRODUCTION

Shape memory applications can generally be divided into four categories: free recovery, constrained recovery, work production (actuators) and superelasticity. These groupings are made according to the primary function of the memory element, but are useful in defining common product screening criteria, pitfalls and engineering design parameters. We define the groups as follows:

1. Free recovery includes applications in which the sole function of the memory element is to cause motion or strain. For example, one could cool a wire into the martensitic regime, bend it to a new shape, then heat to recover the original shape. Key descriptors of the event would include the recovery temperature A_s, the recovery strain, and the presence of a two-way effect (sometimes desired and sometimes not).

2. Constrained recovery includes applications in which the memory element is prevented from changing shape and thereby generates a stress. The ideal case would be the recovery of a ring onto a solid, rigid rod. In this case there may be some free recovery before contact is made, but the primary function of the memory element is to generate a stress. Key descriptors would be the recovery stress, the dimensional tolerances that can be allowed (i.e. the dependence of recovery stress upon the contact strain), the stress rate, and the transformation temperatures.

3. Actuator, or work production applications are those in which there is motion against a stress and thus work is being done by the memory element. The ideal case would be a wire or spring which lifts a weight when heated (and perhaps drops the weight again when cooled). More usual would be to have the memory element working against a biasing spring. Key descriptors would be the work output, operating stress and strain, fatigue life, stress rate and transformation temperatures.

4. Superelastic or pseudoelastic applications are isothermal in nature and involve the storage of potential energy. Although memory elements can operate as "supersprings", the temperature range over which the effect is found is rather narrow (usually only 80°C). Key descriptors would be the stress rate, permanent set, fatigue life, and effective temperature range.

The various engineering aspects of these groups have been treated previously in detail [1,2]. In this paper the focus will be on the applications themselves.

2. FREE RECOVERY

Applications involving the free recovery of a shape memory device are rare; more often than not, there is some small stress resisting recovery. The classical example is the space antenna originally developed in the USA [3] and later in China [4]. Although the antenna has never been deployed in space, it remains an ideal example of free recovery: a thin mesh of Ni-Ti wire is crumpled into a small ball while in the martensitic state, then deployed to full size by heating to the austenite phase.

There are few commercially successful free recovery applications, perhaps the best example being the Ni-Ti eyeglass frames [5]: the martensitic Ni-Ti makes the frames soft and comfortable to wear, but if accidentally deformed they can be returned to their original shape by immersing in hot water (Figure 1).

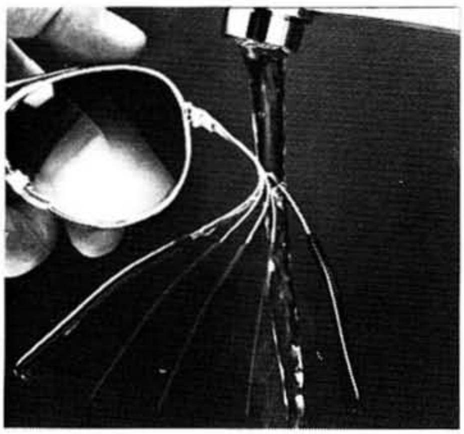


Figure 1. Ni-Ti eyeglass frames are comfortable to wear, and if accidentally deformed, they can be returned to their original shape by warm water. (The Beta Group)

3. CONSTRAINED RECOVERY

Constrained recovery is certainly the most successful and time tested scheme for using shape memory: products tend to be simple, material intensive, single cycle in nature and completely reliable.

Couplings for joining aircraft hydraulic tubing [6-9] constituted the first application of shape memory and remain today the largest in number and monetary sales. To date, well over one million couplings have been installed without a single reported failure. The couplings were originally intended for use on 21 MPa (3000 psi) titanium and aluminum lines on the F-14 and were designed to survive over 10,000,000 bending cycles to 80% of the yield strength of the tubing. Higher performance versions are now available for 28 MPa and 35 MPa systems, and prototypes of a 55 MPa version are now being tested. Tube sizes have ranged from 4.8 mm to 38 mm inches (Figure 2). The advantages of these couplings over competitive joining techniques are exceptional reliability with no leaks and lower installation costs. Historically, couplings have been expanded cryogenically, shipped to the site in liquid nitrogen, and installed by allowing parts to warm to room temperature. Recently developed alloys (outlined below) are now allowing the production of aircraft couplings that can be stored at room temperature and then installed by heated to 200°C (usually by induction heating).

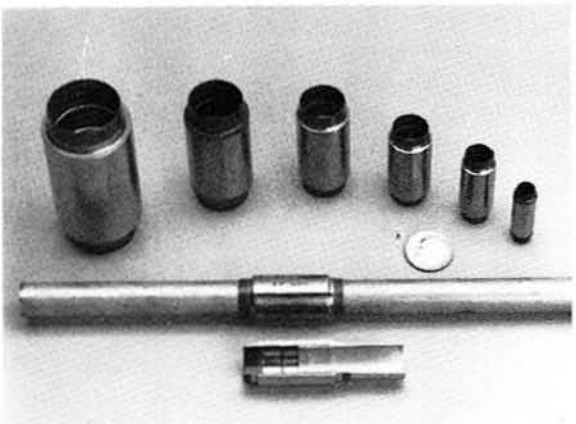


Figure 2. More than 1.5 million Ni-Ti based hydraulic couplings have been installed since 1971 without any reported in-service failures. (Raychem Corp.)

Another recent fluid fitting development is a demateable fitting called Cryolive®. The sealing arrangement is shown in Figure 4: here only the olive-shaped sleeve is shape memory. The sleeve is shrunk onto the tube to form a metal-to-metal seal, and a nut then compresses and seals the outside of the sleeve to a union. Conventional demateable fittings for titanium tubes are most often made by internally swaging the tube out against a titanium sleeve to form a seal: a costly and cumbersome process.

Figure 3. Demateable aircraft couplings are now being used which use a Ni-Ti based sleeve shrunk unto the hydraulic tube as a sealing surface. (Raychem Corp.)

Couplings for the marine and industrial environments have also been in use for many years [10,11]. These tend to be heavier and are designed to work on pipe sizes and materials. Corrosion resistance and cost are key in such applications, and for this reason three basic designs are available: monolithic Ni-Ti, Ni-Ti sleeves with a thin liner, and a design using thicker-walled bodies with Ni-Ti rings on each end (Figure 3). The first makes the most efficient use of the Ni-Ti and delivers the best performance of the three. The primary advantage of the second is that a liner can be chosen which may be more compatible with the system fluid than Ni-Ti. The third design has the added advantage that various shapes are available, such as tee's, elbows, reducers and the like. All have significantly improved fire resistance over brazed joints: an advantage that is now getting a great deal of attention by various navys. A fourth type of coupling shown in Figure 3 is the Permacouple®, made of a Cu-Zn-Al-Mn alloy and primarily used for joining air conditioning tubing. This consists of an aluminum liner coated with a heat curing epoxy, surrounded by a Ni-plated or anodized shape memory sleeve.

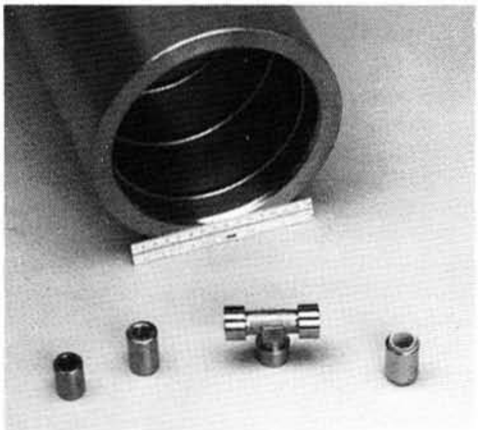


Figure 4. Shape memory couplings of various designs are used in the marine and commercial industries. From left to right are the monolithic, driver-liner, ring-body, and Permacouple designs. The largest coupling above) is over 15 cm in diameter. (Raychem Corp.)

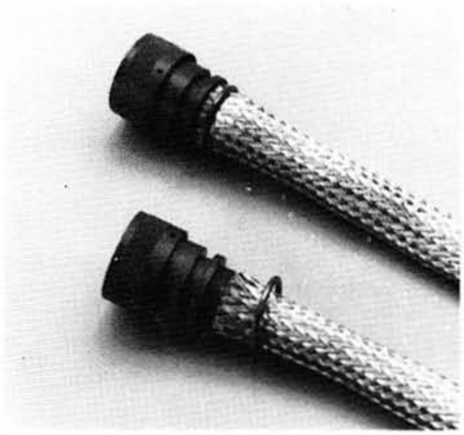


Figure 5. The most successful shape memory fastener is a welded Ni-Ti-Nb ring used to fasten a shielding braid to the back of an electrical connector shell. (Raychem Corp.)

Fasteners form a second type of constrained recovery application [12-14]. Unlike couplings, a hermetic seal may not be required in these cases. The most successful example of a fastener is the Tinel Lock® ring used to fasten braided shielding to the back of a connector (Figure 5). Although there are other approaches to solving this problem, memory rings provide joints of the greatest mechanical and electrical integrity. Other examples range from large rings to join segments of missiles, to small rings to locate bearings on shafts (Figures 6 & 7). In all these examples it is necessary to keep M_d below the range of possible service temperatures; if the temperature were to drop below M_d, recovery stresses would decrease and performance deteriorate. Both Ni-Ti and Cu-Zn-Al based alloys have been used, the main advantage of Cu-Zn-Al being a decreased material cost. This advantage, however, is often balanced by lower recovery stresses and strains usually requiring one to use more material. Thus performance-based costs often exceed those of Ni-Ti. A significant problem with Ni-Ti is that it is difficult to consistently achieve alloys with low enough M_d temperatures. For this reason iron additions are made: iron lowers M_d and provides significant advantages in ductility and toughness over simpler binary alloys.

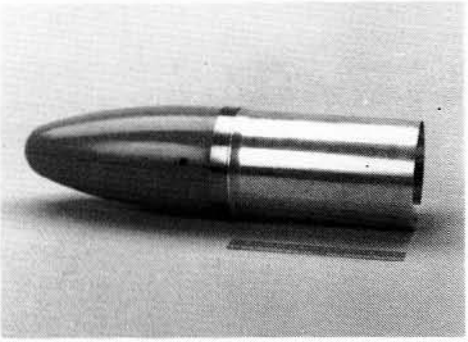


Figure 6: Large diameter, thin-walled Ni-Ti bands are used to join segments of missiles. (Raychem Corp.)

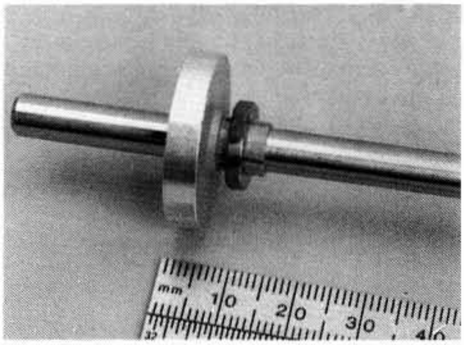


Figure 7. Small Ni-Ti ring is used to locate and fix the position of a bearing on a shaft. (Raychem Corp.)

One should also note the importance of wide hysteresis, or "heat-to-shrink" alloys [15]. In both CuZnAl and Ni-Ti alloys it is possible to significantly increase thermal hysteresis by processes called preconditioning. This allows one to increase A_s while leaving M_s and M_d in the cryogenic temperature range, and thereby to store and ship parts at room temperature without danger of premature recovery. Clearly some products, particularly small ones, cannot be marketed any other way. A second type of new alloy that in the future may affect the constrained recovery field are the Fe-Mn-Si-based alloys: these have the potential to be far less expensive than Ni-Ti and have an inherently wide hysteresis. Thus far, however, tensile memory strains are under 4% and recovery stresses are well below those of Ni-Ti.

Finally we consider one other class of application: electrical connectors. These products really fall in between the constrained recovery and actuators groupings. The purpose of the memory element is to generate stress, however M_d is generally not exceeded (or if it is, an overload protection device must be incorporated into the design). They are also multiple cycle applications, and in this sense might better constitute an actuator device. Four connector concepts have been introduced to the market. The first is a device known as Cryocon®[16] (Figure 8), consisting of a series of Cu-Be fingers pushing out against a Ni-Ti ring with an M_s of about -60°C. At room temperature, the austenitic memory ring overpowers the Cu-Be and constricts against a pin, forming a highly vibration resistant and reliable connection; when cooled with Freon, the Cu-Be fingers push the martensitic ring open and freely release the pin. This device can be mated and demated several hundred times without degradation. The second concept is the Cryotact® device shown in Figure 9; its operation is very similar to the Cryocon, though it is able to accommodate larger tolerances in pin size and is more resistant to overheating by virtue of the Cu-Be tail acting as a protective spring (allowing one to exceed M_d without damage). These devices are usually linearly grouped to form Dual In-line Package (DIP) connectors [17].

The third concept of connector design consists of a guillotine design, in which a shape memory element causes two grids to slide across one another, constricting against a grid of pins (Figure 10). These devices are extremely valuable in cases where Pin Grid Array Packages (PGAP) must be periodically installed and removed making soldering impossible. PGAP connectors provide very high pin retention forces with zero insertion forces [18]. The newest example of a memory electrical connector is the Betaflex® connector (Figure 11) in which a memory element is heated to push against a C-shaped spring and thereby release the connection. Some advantages of this sort of approach are a lower cost per line and that no freon or liquid nitrogen need be used.

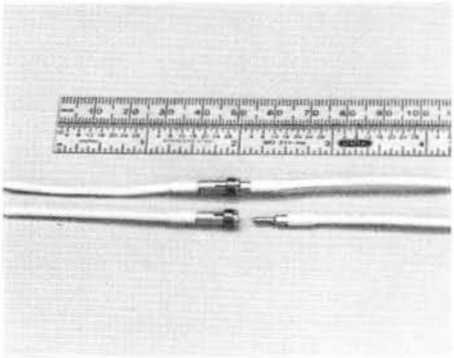


Figure 8. The first shape memory connector was the Cryocon®: a single pin socket released by a cold freon spray. (Raychem)

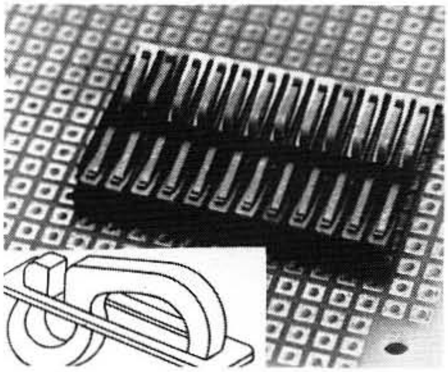


Figure 9. A Dual In-line Package socket uses shape memory to provide individual pin contacts with zero insertion forces. (Raychem Corp.)

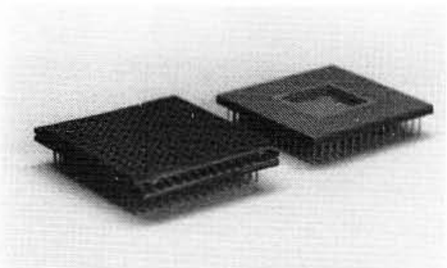


Figure 10: A Pin-Grid Array Package uses a Ni-Ti guillotine mechanism to provide exceptionally high performance with easy installation. (Raychem Corp.)

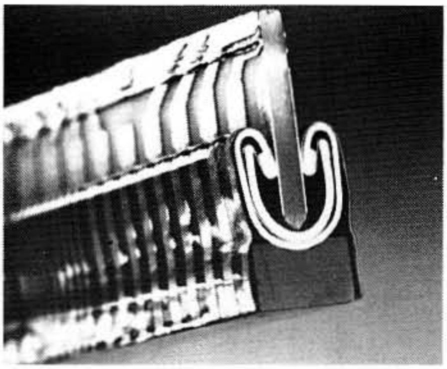


Figure 11: The new Betaflex® connector uses the electrical heating of a Ni-Ti sheet .to release a flexible polyimide ribbon imprinted with copper conductors. (Betaphase, Inc.)

4. ACTUATORS:

Actuator devices have often been thought to be the type of shape memory application with the greatest potential, but to date there have been relatively few large scale successes. These devices should be classified into two groups: those driven by changes in ambient temperature, and those driven electrically. Thermal actuators are generally in competition with thermal bimetals, often in conjunction with a conventional actuator. Electrical actuators must compete against servo-motors, solenoids and the like. From both a design and market point of view, the two are distinct and will be treated separately.

4.1 Electrical actuators

The first electrical actuator unit to be commercially marketed was the VEASE® actuator (Figure 12): a self contained unit with a Ni-Ti-Cu spring, a biasing return spring, and an overload protection device to prevent the memory spring from damaging itself should it be temporarily prevented from moving [19]. The device was capable of lifting 0.5 Kg a distance of 2 cm over 10,000 times, and could be actuated by a 6 volt battery. It was originally used to open the louvres of an automobile fog lamp, and although it has since been used in several prototype applications it has never been used on a large scale.

Figure 12. The VEASE® actuator was designed to be a complete electrical actuator package; an overload spring on the outside of the device protected the memory spring from deforming itself. (Raychem)

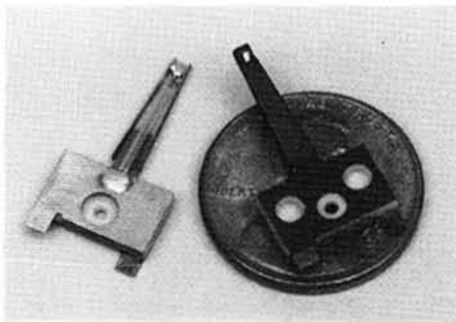


Figure 13. A prototype of a disk drive head lifter used a short piece of Ni-Ti-Cu wire to gently lift magnetic heads during shut downs. (Raychem Corp.)

It has since become apparent that a generic actuating device would probably not be successful due to high costs, and that shape memory would be better applied through simple designs specific to the task being done. One example that remains of some interest is a disk drive head lifter [20], that gently lifts heads off a magnetic disk during a power shut-down and thus avoids damage to the disk (Figure 13). Another is the SMArt Clamp® which uses three short lengths of Ni-Ti wire to control the flow of fluid in an Intravenous feeding tube. Current is passed through one wire (Figure 14), which pulls back on a blade that normally constricts flow through the IV tube. When the correct constriction is obtained, the other two wires are activated to lock the position of the blade and to unlock it again in the event that further adjustment needed. Still other examples are of a robotic nature [21,22], such as the artificial hand shown in Figure 15 which uses shape memory to actually sense forces and control the pressure used to pick up objects. One problem with all these robotic devices, however, is that shape memory actuators tend to reset rather slowly, making high speed movements very difficult.

Ni-Ti-based alloys are preferred for electrical actuator applications due to their greater electrical resistivity, work outputs, and fatigue lifetimes. Their one disadvantage is that A_s temperatures above 100°C are difficult to achieve; this means that reset times can be long and there is a possibility of self-actuation. This is a particularly important limitation for automobile applications where temperatures under the hood or in the passenger compartment on a hot day can exceed 150°C. Work on the Ti-Pd system using Ni additions to control M_s indicates that significantly higher transformation temperatures are possible, but costs are extremely high [24,25].

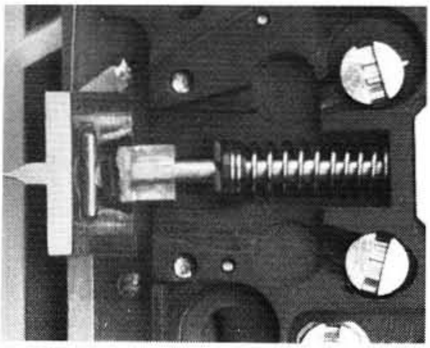


Figure 14: The SMArt Clamp is one of the few electrical actuators now in production. It uses four Ni-Ti wires to control the pressure of a blade (left) on an IV tube. (Betaphase, Inc.)

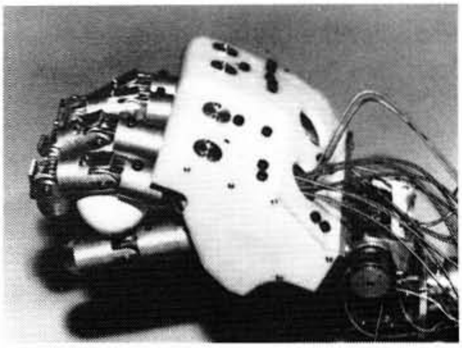


Figure 15. A robotic hand uses Ni-Ti both to provide actuation and tactile feedback. (The Furukawa Electric Co.)

4.2 Thermal Actuators:

Thermal actuators have been far more successful than electrical. Perhaps the first thermal actuator of note was the greenhouse window opener (Figure 16) which used a Cu-Zn-Al spring to open windows when the inside temperature became too warm for optimum plant care, and would close the windows when the temperature dropped. Although not a huge commercial success, it neatly demonstrated thermal actuator concepts. There are many other examples of thermal actuator applications: air conditioning louvres (Figure 17) are used to deflect air up or down depending upon its temperature [26]; Ni-Ti springs are used to control the shifting of automatic automobile transmissions (Figure 18) and compensate for changes in ambient temperature; a Ni-Ti spring in a coffee maker (Figure 19) controls brewing temperature; a Cu-Zn-Al spring in an anti-scald device (Figure 20) shuts-off water flow when it becomes too hot [27].

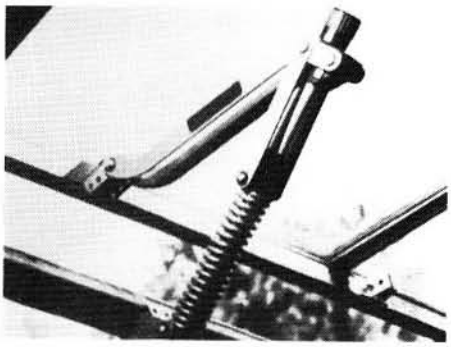


Figure 16. The first thermal actuator used a large Cu-Zn-Al spring to open and close greenhouse windows, serving both as a temperature detection device and actuator.

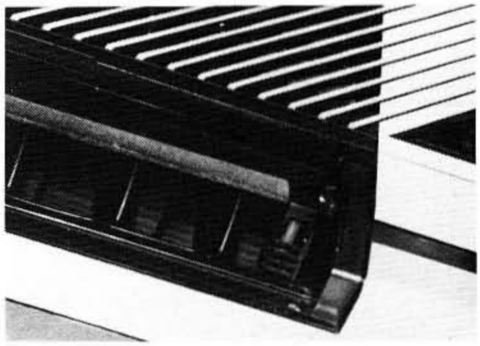
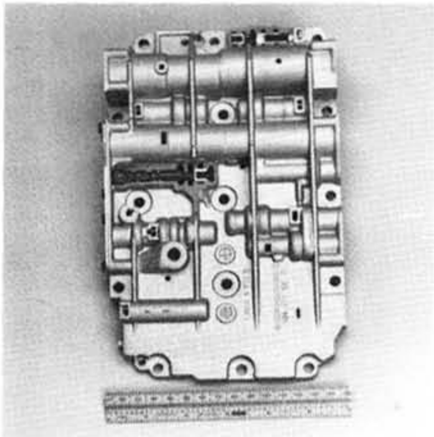


Figure 17. An air conditioner uses the nearly hysteresis-free R-phase to deflect air depending upon its temperature. (The Furukawa Electric Co.)



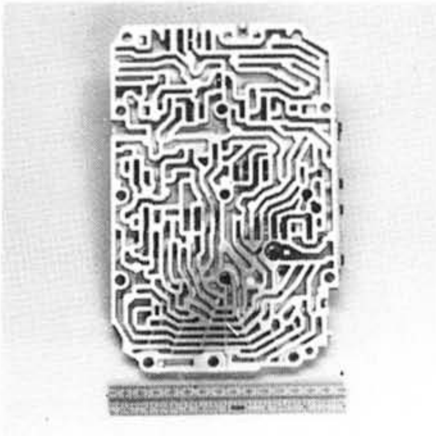


Figure 18. Three springs are used in the valve covers for automatic transmissions to control the shifting depending upon engine temperature. Shown on the left is the outside of the valve cover with two areas milled down to reveal the location of the memory springs. Shown on the left is the bottom of the cover and the fluid logic system; the memory springs control gates between various fluid passages. (Raychem Corp.)

Figure 19. A Japanese coffee maker uses Ni-Ti springs to control brewing temperature. (The Furukawa Electric Co.)

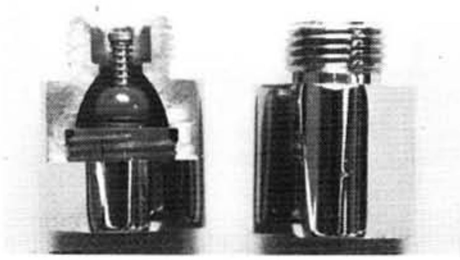


Figure 20. An anti-scald device uses a Cu-Zn-Al spring to interrupt water flow and prevent accidental scalding. (Memry Inc.)

Circuit breakers using shape memory (Figure 21) have been in development for quite some time. Some designs have used the power current itself to heat a memory element and interrupt the circuit at a critical current and temperature while others heat the element indirectly by passing the current through a nearby copper strip. In either case, shape memory appears to provide significant inherent advantages over the bimetals used today: they exhibit a dramatically increased motion over a narrow temperature range and are insensitive to installation errors and material inconsistencies. Unfortunately it has been difficult to directly substitute memory devices for bimetals without redesigning the rest of the breaker, which requires a significant investment by the manufacturers. For these sorts of application, it is usually necessary to have A_s significantly above the maximum operating temperature - requirements of 130°C would be typical. This eliminates Ni-Ti alloys as candidates, and normally leads people to consider Cu-Al-Ni alloys [28].

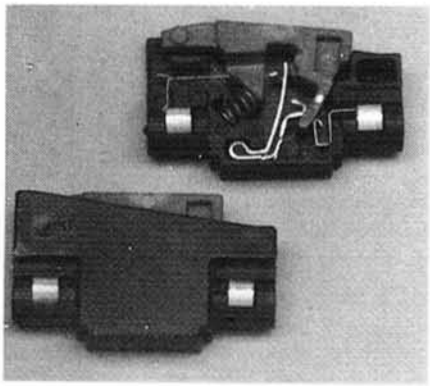


Figure 21. There have been many efforts use shape memory in circuit breakers such as the one shown above. This particular one opens a circuit when the current passing through a Ni-Ti-Cu wire exceeds a critical level. (Raychem Corp.)

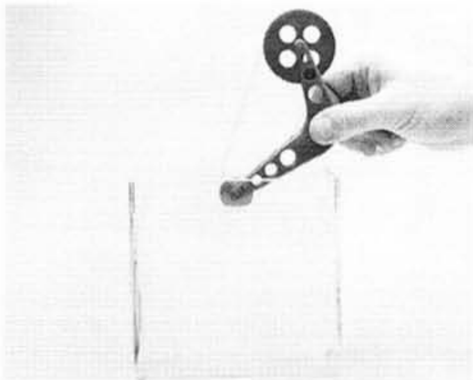


Figure 22. The Thermobile® uses the change in modulus that occurs in a loop of Ni-Ti-Co wire as it undergoes the R-phase transformation to demonstrate the concept of thermal-to-mechanical energy conversion. (Innovative Technologies)

A second type of application worth special note is the heat engine. Many papers have been written on heat engines, their efficiencies, and commercial feasibility [29-33]. Although there remains disagreement concerning the specifics, it appears clear that efficiencies will never exceed 2%, and that the capital cost per watt would be prohibitively high for most applications: typically watts per Kg of Ni-Ti. Perhaps the most famous of the heat engines is the Bank's engine but several other designs have received attention, including a demonstration model using the R-phase transition (Figure 22).

Although some mention of alloys has already been made there remain a couple of important comments. One of the largest problems in designing thermal actuators is that of thermal hysteresis. Improvements to Ni-Ti can be made by adding copper [34] which reduces hysteresis to 10-15 degrees. A second approach to solving the hysteresis problem is to use the R-phase transition, which has a 1-2 degree hysteresis but delivers only about 0.5% motion. Though it appears unlikely that much progress will be made in increasing motion, a 0.5% strain is really quite large in the world of springs, and can be effectively used in many applications. The two-way shape memory effect has received a great deal of attention in actuation designs. Although, it has the potential of eliminating the need for a biasing spring, it complicates processing and fatigue issues and has not yet been used in a commercially successful product (Figure 17).

5. SUPERELASTICITY

Superelasticity often seems to be a panacea for spring designers, but in fact has some serious limitations. Often talked about applications such as automobile valve springs with less than 10% the mass of current springs are likely impossible due to the wide variations in ambient temperature to which they may be subject. Such variations not only affect the permanent set and elastic range, but also the stiffness of the spring. The most successful applications have thus been those in which temperature is well controlled - more specifically, most have been medical applications.

The first superelastic application was as orthodontic archwire (Figure 23). The biggest advantages that Ni-Ti provides over conventional materials are an increased elastic range (reducing the need to retighten and adjust wires) and a nearly constant stress during unloading (tending to decrease treatment time and increase patient comfort) [35,36]. The second successful superelastic application was the Mammelok® breast hook (Figure 24), used to locate and mark breast tumors so that subsequent surgery can be more exact and less invasive [37].

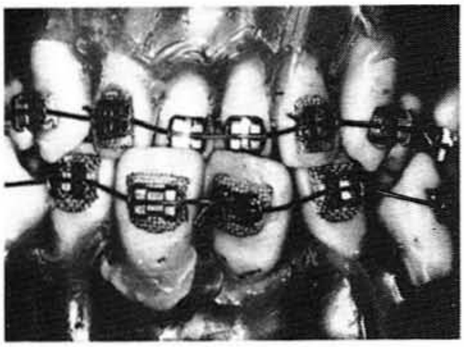


Figure 23. One of the most successful applications of a shape memory alloy is the use of Ni-Ti wire in orthodontics. (The Furukawa Electric Co.)

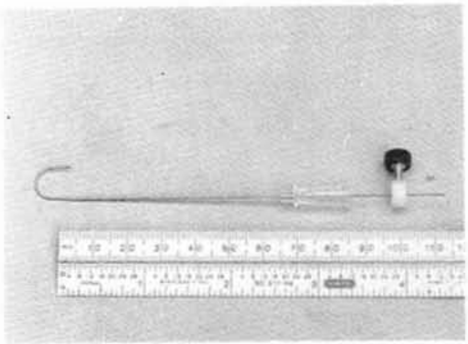


Figure 24. A superelastic Ni-Ti-V wire shaped into a hook is passed through a cannula a hooks around breast tumors to help surgeons accurately locate and remove the tumor. (Mitek Inc.)

A third successful medical application is the guidewire (Figure 25), which is passed through blood vessels and used as a guide for catheters [38]. These wires must be extremely kink resistant and flexible, and thus Ni-Ti has provided large advantages over stainless steel or titanium. A more recent application is the suture anchor (Figure 26): a small arc of Ni-Ti injected though a cannula into a hole drilled into the bone, but once free of the cannula it springs back to its arc configuration and anchors itself into the bone. A suture tied to the anchor is then used to reattach ligaments to the bone. This sort of surgery has proven to be far less invasive than conventional methods using large stainless steel screws.

Finally, one of the most unique and successful applications is the Ni-Ti underwire brassiere (Figure 27). The soft apparent yield strength of the superelastic Ni-Ti wire makes the brassiere comfortable to wear, but nearly impossible to bend out of shape. Conventional underwires can be engineered to be either comfortable or durable, but not both. These bras have been very successfully marketed in Japan.

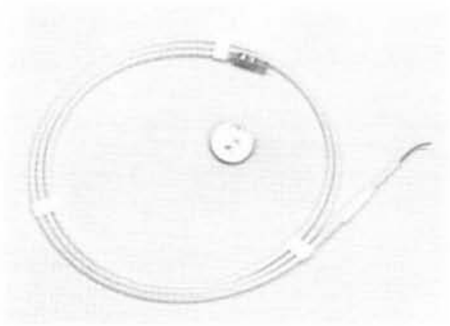


Figure 25. Radiologist have found the extreme kink resistance of Ni-Ti wire to dramatically improve the performance of guidewires. (Terumo Corp.)

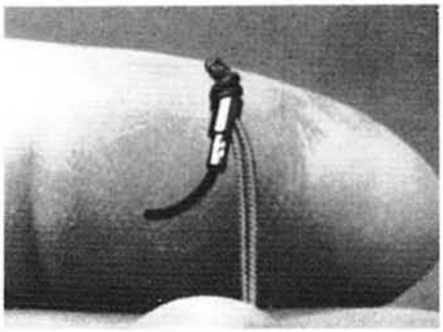


Figure 26. A suture is anchored to bone using a curved superelastic wire injected into the bone through a cannula. (Mitek Inc.)

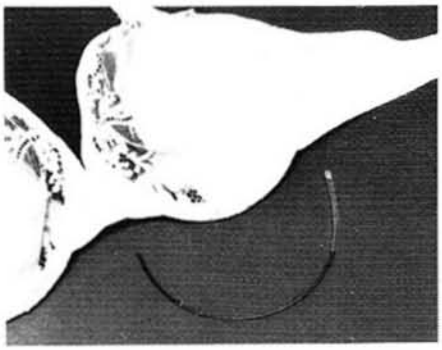


Figure 27. Superelastic underwires for bras have become extremely popular in Japan due to their great flexibility, comfort and resistance to damage during washing. (The Furukawa Electric Co.

6. SUMMARY

Shape memory technology continues to make substantial progress in alloy development, processing capabilities, and in application engineering. New alloys include superelastic Ni-Ti alloys with greater stiffnesses, wide and narrow hysteresis Ni-Ti alloys, Cu-Al-Ni-Mn alloys with increased stability and Fe-Mn-Si-based alloys of substantially less cost than Ni-Ti. Advances in processing capability now make it possible to make Ni-Ti in wire of less than 0.02 mm diameter, sheet up to a meter wide and 0.15 mm in thickness and tubing down to 2 mm diameter. Although all these increased capabilities will certainly provide new product development opportunities, most of the currently successful applications are simple in design, using conventional materials (Ni-Ti-based or Cu-Zn-Al-based) and involve common shapes (generally wire or bar).

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