Brazilian Journal of Medical and Biological Research (2003) 36: 683-691
ISSN 0100-879X Review

Medical applications of shape memory alloys

L.G. Machado[1] and M.A. Savi[2]

[1]Departamento de Engenharia Mecânica e de Materiais,
Instituto Militar de Engenharia, Rio de Janeiro, RJ, Brasil
[2]Departamento de Engenharia Mecânica, COPPE,
Universidade Federal do Rio de Janeiro, Rio de Janeiro, RJ, Brasil

Correspondence
M.A. Savi
Departamento de Engenharia
Mecânica
COPPE, UFRJ
Caixa Postal 68.503
21945-970 Rio de Janeiro, RJ
Brasil
E-mail: savi@ufrj.br

Research supported by CNPq.

Received July 3, 2002
Accepted December 4, 2002

Abstract

Shape memory alloys (SMA) are materials that have the ability to return to a former shape when subjected to an appropriate thermomechanical procedure. Pseudoelastic and shape memory effects are some of the behaviors presented by these alloys. The unique properties concerning these alloys have encouraged many investigators to look for applications of SMA in different fields of human knowledge. The purpose of this review article is to present a brief discussion of the thermomechanical behavior of SMA and to describe their most promising applications in the biomedical area. These include cardiovascular and orthopedic uses, and surgical instruments.

Key words
- Shape memory alloys
- Biomaterials

Introduction

Shape memory alloys (SMA) constitute a group of metallic materials with the ability to recover a previously defined length or a shape when subjected to an appropriate thermomechanical load (1). When there is a limitation of shape recovery, these alloys promote high restitution forces. Because of these properties, there is a great technological interest in the use of SMA for different applications.

Although a relatively wide variety of alloys present the shape memory effect, only those that can recover from a large amount of strain or generate an expressive restitution force are of commercial interest. Particularly important among them are alloys based on Ni-Ti and on Cu, such as Cu-Zn-Al and Cu-Al-Ni (1). SMA based on Ni-Ti are the alloys most frequently used in commercial applications because they combine good mechanical properties with shape memory.

The remarkable properties of SMA have been known since the 1930's. In 1932, Chang and Read noted the reversibility of the Au-Cd alloy not only by metallographic observations, but also by the observation of changes in resistivity. In 1938, Greninger and Mooradian observed the shape memory effect in Cu-Zn and Cu-Sn alloys. Nevertheless, it was only in the 1960's that SMA attracted some technological interest. In 1962, Buehler and co-workers, of the U.S. Naval Ordnance Laboratory, discovered the shape memory effect in an equiatomic Ni-Ti alloy which began to be known as Nitinol, as a reference to the initials of the laboratory. Raychem developed the first industrial application of SMA for the aeronautic industry during the 1960's. In 1975, Andreasen, of Iowa University, made the first implant of a superelastic orthodontic device (1,2). Today, these applications are being developed in different fields of science and engineering.

Basically, SMA present two well-defined crystallographic phases, i.e., austenite and martensite (3). Martensite is a phase that, in the absence of stress, is stable only at low temperatures; in addition, it can be induced by either stress or temperature. Martensite is easily deformed, reaching large strains (~8%) (1). Depending on the type of transformation experienced by these alloys, the crystal structure of martensite can be either monoclinic or orthorhombic (4,5). When martensite is induced by temperature, it is called twinned martensite. The twinned martensite has 24 variants, i.e., 24 subtypes with different crystallographic orientations (6). On the other hand, when martensite is induced by stress, these 24 variants of twinned martensite become only one variant. As a consequence, there is a crystallographic orientation, aligned with the stress direction, which is called detwinned martensite. The austenite phase is stable only at high temperatures, having a single variant with a body-centered cubic crystal structure.

Martensitic transformation explains the shape recovery in SMA. This transformation occurs within a range of temperatures which varies according to the chemical content of each alloy (7). In general, four characteristic transformation temperatures can be defined: M_S and M_F, which are the temperatures at which the formation of martensite starts and ends, respectively, and A_S and A_F, which are the temperatures at which the formation of austenite starts and ends, respectively.

Recent studies have shown that, depending on specific conditions, some SMA can present another crystallographic phase known as R-phase. The R-phase transformation can appear before the martensitic transformation according to the following sequence: austenite → R-phase → martensite. The crystal structure of the R-phase is rhombohedric (4,5).

Because of their remarkable properties, SMA can be used in a large number of non-medical applications (8-10). SMA can solve problems in the aerospace industry, especially those related to vibration control of slender structures and solar panels, and non-explosive release devices (11,12). Micromanipulators and robotic actuators have been employed in order to mimic the smooth movement of human muscles (13,14). SMA are commonly used as external actuators or as SMA fibers embedded in a composite matrix so that they can alter the mechanical properties of slender structures for the control of buckling and vibration (15).

Biomedical applications of SMA have been extremely successful because of the functional properties of these alloys, increasing both the possibility and the performance of minimally invasive surgeries (2,16,17). The biocompatibility of these alloys is one of the important points related to their biomedical applications as orthopedic implants (18), cardiovascular devices (2), and surgical instruments (16), as well as orthodontic devices and endodontic files (19-21).

This article presents a brief discussion of the thermomechanical behavior of SMA, and a description of their main applications in the biomedical field as cardiovascular and orthopedic devices and as surgical instruments.

Thermomechanical behavior

SMA present typical thermomechanical behaviors, like pseudoelasticity and shape memory effects (one-way and two-way). This section presents a short discussion of these behaviors, explaining the macroscopic phenomenological aspects related to each one (22).

Pseudoelasticity

Pseudoelasticity occurs whenever an SMA sample is at a temperature above A_F (the temperature above which only the austenitic phase is stable for a stress-free specimen). Thus, one can consider an SMA sample subjected to a mechanical loading at a constant temperature above A_F. The stress-strain curve (σ-ε) in Figure 1, left side, illustrates the macroscopic behavior of SMA, showing the pseudoelastic phenomenon.

A mechanical loading causes an elastic response until a critical value is reached, point *A*, when the martensitic transformation (austenite → martensite) arises, ending at point *B*. At this point, the crystal structure of the sample is totally composed of detwinned martensite. For higher stress values, SMA presents a linear response. During the unloading process, the sample presents an elastic recovery (*B* → C). From point *C* to *D* one can note the reverse martensitic transformation (martensite → austenite). From point *D* on, the sample presents an elastic discharge. When the loading-unloading process is finished, SMA have no residual strain. However, since the path of the forward martensitic transformation does not coincide with the reverse transformation path, there is a hysteresis loop associated with energy dissipation.

Another way to observe the pseudoelastic effect is indicated on the right side of Figure 1. First, let us consider an SMA at a temperature above A_F, ①. At this temperature, there is only one phase, i.e., austenite. At a constant temperature, a mechanical loading is applied promoting the appearance of the detwinned martensite, ②. During the unloading process, reverse transformation takes place (detwinned martensite → austenite) and when load vanishes, ③, the sample presents no residual strain.

Shape memory effect

The second thermomechanical behavior that can be observed in SMA is the shape memory effect. Figure 2, left side, shows the stress-strain curve of an SMA sample at a low temperature (less than M_F, the temperature below which only the martensitic phase is stable) where the shape memory effect can be noted. When the sample is subjected to a mechanical loading, the stress reaches a critical value, point *A*, when the transformation of the twinned martensite into the detwinned martensite begins, ending at point *B*. When the loading-unloading process is finished, the SMA sample presents a residual strain (point *C*). This residual strain can be recovered by sample heating, which induces the reverse phase transformation. This is the shape memory effect, also known as one-way shape memory effect. This phenomenon can be understood from a motion of the hysteresis loop shown on the stress-strain curve in Figure 1. Since the temperature goes down, the hysteresis loop moves down as well.

The right side of Figure 2 presents an alternative way to observe the shape memory effect. At first, the SMA sample is at a temperature above A_F, ①. At this temperature, the sample has only the austenitic phase. When the temperature of the SMA sample

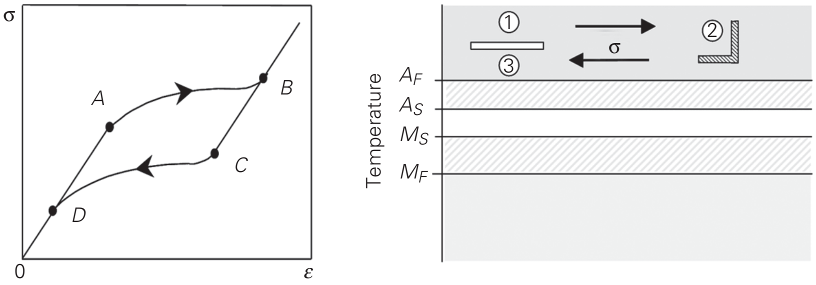

Figure 1. Pseudoelasticity. A_S, A_F and M_S and M_F = temperature at which the formation of austenite and martensite starts and ends, respectively. σ-ε = stress-strain curve. See text for explanation of process.

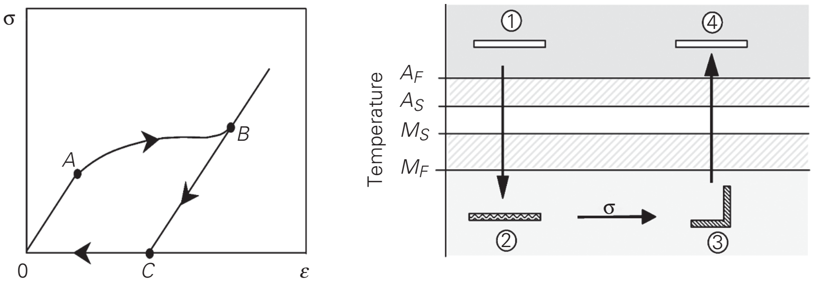

Figure 2. Shape memory effect. For abbreviations, see legend to Figure 1. See text for explanation of process.

decreases and crosses the line related to M_S, the phase transformation begins to take place and the twinned martensite replaces the austenite. This transformation is concluded when the sample temperature is below M_F, ②. Under a constant temperature, a mechanical loading is applied (②→③), promoting the appearance of the detwinned martensite. When this load vanishes the sample presents a residual strain, ③. The former shape of the sample can be recovered through a heating process (③→④) which causes the reverse martensitic transformation (detwinned martensite → austenite).

Two-way shape memory effect

Another phenomenon concerning martensitic transformation is the two-way shape memory effect. The primary characteristic of the two-way effect is associated with the presence of a specific phase in a specific setting. In this way, the sample has a shape in the austenitic state and another in the martensitic state. The change of temperature produces a change in sample shape without any mechanical loading.

In order to obtain the two-way effect, it is necessary that the SMA sample be trained. Typically, there are two training procedures (23): shape memory effect cycling (cycles of shape memory effect) and the training through the appearance of the detwinned martensite, the stress-induced martensite training. Both induce considerable plastic strains.

Figure 3 shows a schematic presentation of the two-way effect. First of all, let us consider that a trained SMA sample is at a temperature above A_F, ①. Sample cooling promotes a phase change (austenite → martensite), which leads to a change in shape, ②. When the temperature is increased above A_F, the sample experiences another phase transformation (②→③), recovering its original shape, ③. Another cooling returns the sample to its low temperature shape, ④. It should be pointed out that, in contrast to the one-way shape memory effect, it is not necessary to apply mechanical loading in order to alter the sample's shape at low temperature.

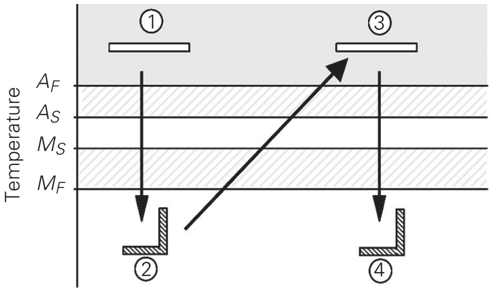

Figure 3. Two-way shape memory effect. For abbreviations, see legend to Figure 1. See text for explanation of process.

Biocompatibility of shape memory alloys - Ni-Ti

Biocompatibility is the ability of a material to remain biologically innocuous during its functional period inside a living creature (24). This is a crucial factor for the use of SMA devices in the human body (25). A biocompatible material does not produce allergic reactions inside the host, and also does not release ions into the bloodstream. The period during which a biomaterial remains inside the human body is an important aspect to be considered concerning its use.

Generally, the biocompatibility of a material is strongly related to allergic reactions between the material surface and the inflammatory response of the host. Several aspects can contribute to these reactions such as patient's characteristics (health, age, immunological state, and so on), and material characteristics (rugosity and porosity of the surface and individual toxic effects of the elements present in the material) (25).

Several investigations have been conducted in order to establish the biocompatibility of Ni-Ti-based alloys, and to exclude intrinsic hazards involved in their applications (24,25). The analysis of aspects related to the biocompatibility of these alloys is performed by assessing each of their elements, nickel and titanium, separately.

Nickel, although necessary to life, is a highly poisonous element (2). Studies have shown that persons having systematic contact with nickel present problems such as pneumonia, chronic sinusitis and rhinitis, nostril and lung cancer, as well as dermatitis caused by physical contact.

Unlike nickel, titanium and its compounds are highly biocompatible; moreover, due to their mechanical properties, they are usually employed in orthodontic and orthopedic implants (2). The oxidation reaction of titanium produces an innocuous layer of TiO_2 which surrounds the sample. This layer is responsible for the high resistance to corrosion of titanium alloys, and the fact that they are harmless to the human body.

Inquiries concerning the biocompatibility of Ni-Ti alloys began shortly after their discovery in 1968. Corrosion analyses have shown that this alloy is easily changed to the passive condition in physiological solutions; moreover, its corrosion resistance is greater than that of stainless steel (24). In general, one can say that the properties of titanium confer good biocompatibility to Ni-Ti alloys.

Applications of shape memory alloys

As mentioned earlier, the remarkable properties of SMA have promoted several investigations related to their applications in different fields of human knowledge. In this section we present a discussion of the biomedical applications of SMA. Cardiovascular applications are presented first, followed by orthopedic applications and the use of SMA in surgical instruments.

Cardiovascular applications

The first cardiovascular device developed with shape memory was the Simon filter (25). The Simon filter (Figure 4) represents a new generation of devices that are used for blood vessel interruption in order to prevent pulmonary embolism. Persons who cannot take anticoagulant medicines are the major users of the Simon filter (26). The purpose of this device is to filter clots that travel inside the bloodstream. The Simon filter traps these clots that in time are dissolved by the bloodstream (16). The insertion of the filter inside the human body is done by exploiting the shape memory effect. From its original shape in the martensitic state (Figure 4A) the filter is deformed and placed on a catheter tip. Saline solution flowing through the catheter is used to keep a low temperature, while the filter is placed inside the body. When the catheter releases the filter, the flow of the saline solution is stopped. As a result, the bloodstream promotes the heating of the filter that returns to its former shape. This procedure can be seen in Figure 4B (16).

The atrial septal occlusion device is employed to seal the atrial hole (Figure 5) (20,26). The atrial hole is located between the two upper heart chambers upon the surface that splits the upper part of the heart into the right and left atria. The anomaly occurring when this hole is open can reduce life

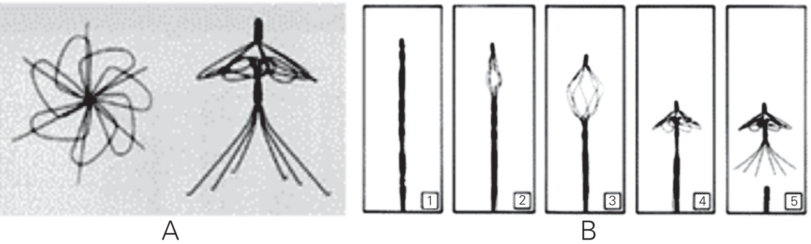

Figure 4. Simon filter. *A*, Filter in the recovery form. *B*, Filter release. Taken from Ref. 26 (http://www.nmtmedical.com).

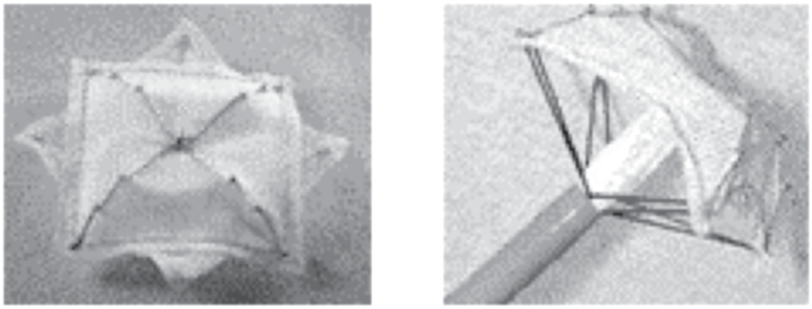

Figure 5. Atrial septal occlusion device. Taken from Ref. 26 (http://www.nmtmedical.com).

expectancy. The traditional surgery that fixes this anomaly is extremely invasive and dangerous. The thorax of the patient is opened and the atrial hole is sewn. Because of the intrinsic risks of this surgery, several problems might occur. The atrial septal occlusion device is an alternative to this surgery. This device is composed of SMA wires and a waterproof film of polyurethane (16). As is the case for the Simon filter, the surgery to place this device exploits the shape memory effect, being much less invasive than the traditional one. First, one half of the device is inserted through a catheter by the vena cava up to the heart, in its closed form. Then, it is placed on the atrial hole and opened, recovering its original shape. Next, the second half of the device is placed by the same route as the first one, and then both halves are connected. This procedure seals the hole, avoiding blood flow from one atrium to the other. It is expected that the device will stay in the heart for an indefinite period of time since the heart tissue regenerates (26). Figure 6A presents a scheme of the heart with the device in place.

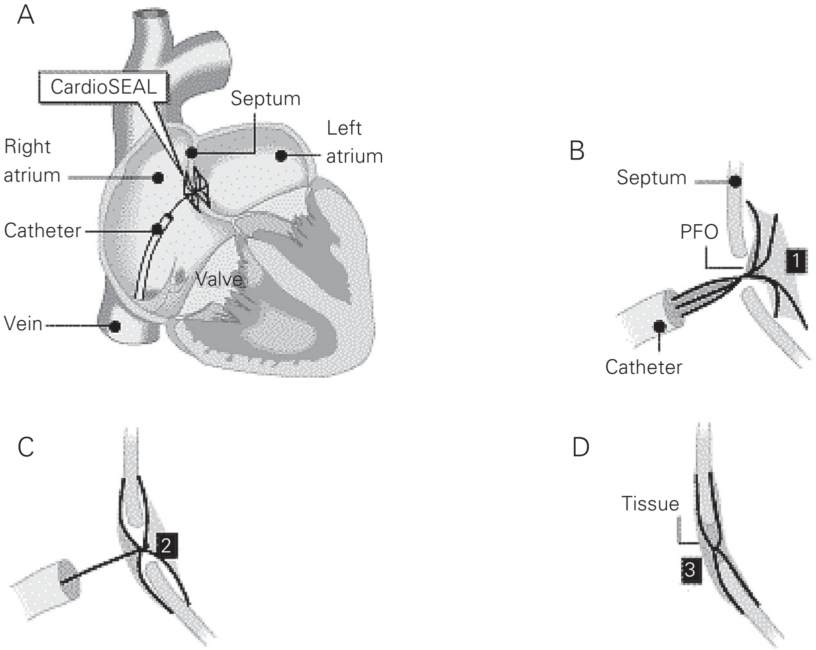

Figure 6. Atrial septal occlusion device. *A*, Scheme of the heart with the device in place. *B*, The first half of the device is placed in the left atrium. *C*, The second half of the device is placed in the right atrium. *D*, The catheter is withdrawn and the tissue begins its recovery. PFO = patent foramen ovale. Taken from Ref. 26 (http://www.nmtmedical.com).

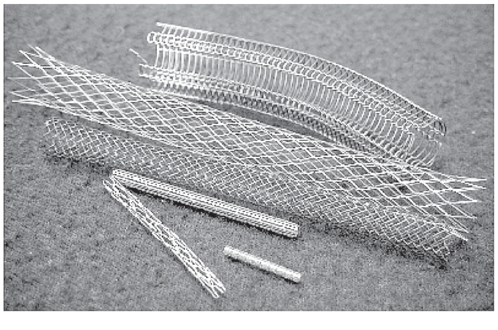

Figure 7. Shape memory self-expanding stents. Taken from Ref. 28 (http://www.raychem.com).

Self-expanding stents, named after the dentist C.T. Stent, are another important cardiovascular application that is used to maintain the inner diameter of a blood vessel. Actually, these devices are used in several situations in order to support any tubular passage such as the esophagus and bile duct (27), and blood vessels such as the coronary, iliac, carotid, aorta and femoral arteries (16). In this type of application, a cylindrical scaffold with shape memory (Figure 7) (28) is placed, for example, inside a blood vessel through a catheter. Initially, this scaffold is pre-compressed in its martensitic state. As the scaffold is heated, due to the body temperature, it tends to recover its original shape, expanding itself. This device can be used not only in the angioplasty procedure, in order to prevent another obstruction of a vessel, but also in the treatment of aneurysms for the support of a weakened vessel (16).

Orthopedic applications

SMA have a large number of orthopedic applications. The spinal vertebra spacer (Figure 8) is one. The insertion of this spacer between two vertebrae assures the local reinforcement of the spinal vertebrae, preventing any traumatic motion during the healing process. The use of a shape memory spacer permits the application of a constant load regardless of the position of the patient, who preserves some degree of motion (29). This device is used in the treatment of scoliosis (2). Figure 8 shows spinal vertebrae and a shape memory spacer. On the left side, the spacer is in the martensitic state, and on the right side, the spacer is in its original shape, recovered by the pseudoelastic phenomenon.

Another application in the orthopedic area is related to the healing process of broken and fractured bones (30). Several types of shape memory orthopedic staples are used to accelerate the healing process of bone fractures, exploiting the shape memory effect. The shape memory staple, in its opened shape, is placed at the site where one desires to rebuild the fractured bone. Through heating, this staple tends to close, compressing the separated part of bones. It should be pointed out that an external device performs this heating, and not the temperature of the body. The force generated by this process accelerates healing, reducing the time of recovery. Figure 9 presents an application of these staples during the healing process of a patient's foot fracture.

With respect to the healing of fractured bones, one can also point out shape memory plates for the recovery of bones (31). These plates are primarily used in situations where a cast cannot be applied to the injured area, i.e., facial areas, nose, jaw and eye socket. They are placed on the fracture and fixed with screws, maintaining the original alignment of the bone and allowing cellular regeneration. Because of the shape memory effect, when heated these plates tend to recover their former shape, exerting a constant force that tends to join parts separated by fractures, helping with the healing process (2). Figure 10 illustrates this device (31).

Orthopedic treatment also exploits the properties of SMA in the physiotherapy of semi-standstill muscles. Figure 11 shows gloves that are composed of shape memory wires on regions of the fingers (32). These wires reproduce the activity of hand muscles, promoting the original hand motion. The two-way shape memory effect is exploited in

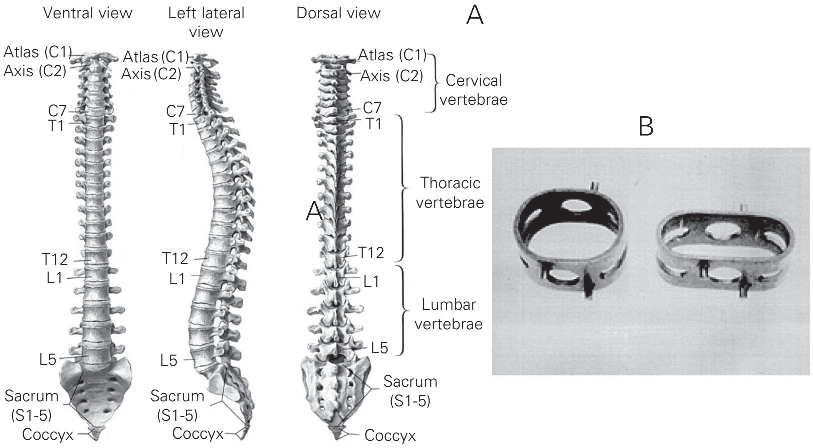

Figure 8. Spinal vertebrae (A) and shape memory spacers (B) in the martensitic state (left) and in the original shape (right). Taken from Ref. 20 with permission.

Figure 9. *A*, Orthopedic staples. *B*, Staples placed in a human foot. *C*, X-ray of a human foot. Taken from Ref. 30 (http://www.labosite.com/anglais/pages/summary.html).

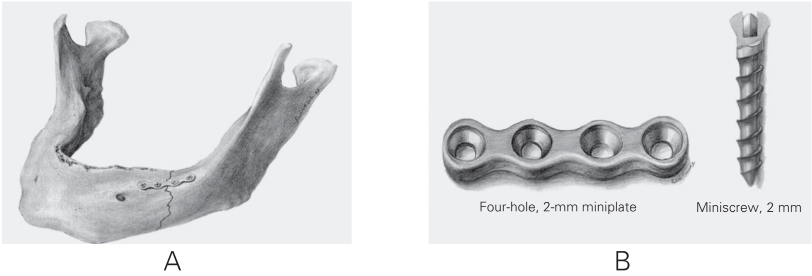

Figure 10. Shape memory bone plates. *A*, Plates fixed upon a human jaw. *B*, Detail of the plate and the screw. Taken from Ref. 31 (http://database.cs.ualberta.ca/MEMS/sma_mems).

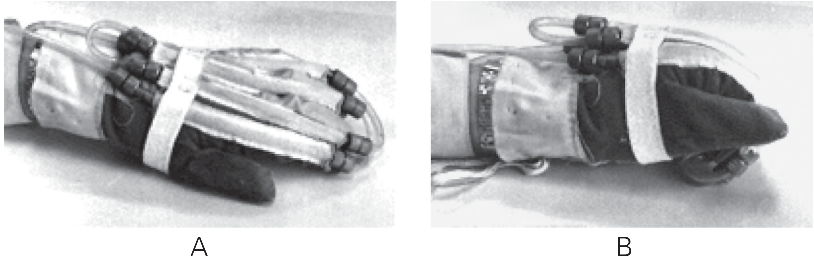

Figure 11. Shape memory alloy glove. *A*, Low temperature position. *B*, High temperature position. Taken from Ref. 32 (http://www.amtbe.com).

this situation. When the glove is heated, the length of the wires is shortened. On the other hand, when the glove is cooled, the wires return to their former shape, opening the hand. As a result, semi-standstill muscles are exercised.

Research for obtaining porous SMA is currently underway. These alloys have a great potential application in orthopedic implants since their porosity enables the transport of body fluids from outside to inside the bone, which is in the healing process. This fact optimizes the treatment and also helps the fixation of the implant (33).

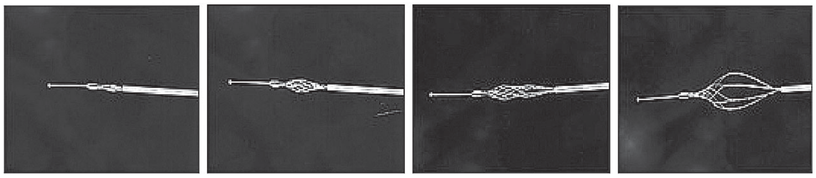

Figure 12. Sequence of opening of the shape memory basket. Taken from Ref. 34 (http://smet.tomsk.ru/eng/prod.htm).

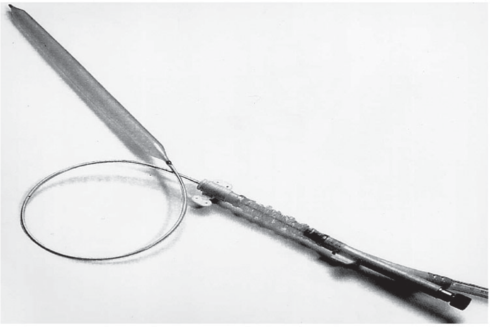

Figure 13. Intra-aortic balloon pump. Taken from Ref. 16 with permission.

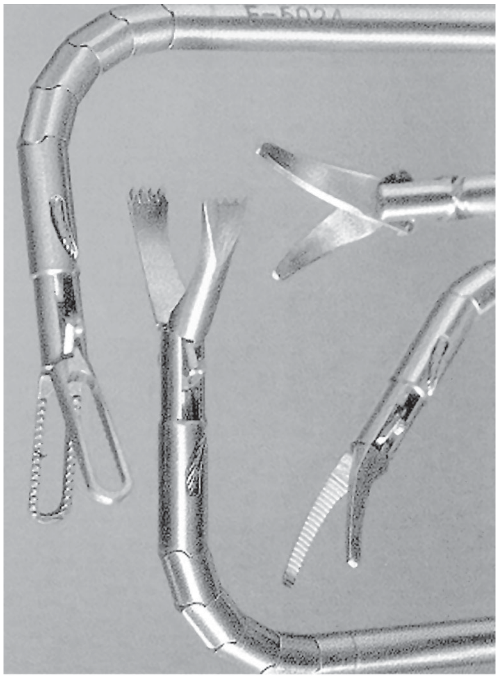

Figure 14. Laparoscopy tools. The actions of grippers, scissors, tongs and other mechanisms are performed by SMA. Taken from Ref. 16 with permission.

Applications to surgical instruments

In recent years, medicine and the medical industry have focused on the concept of less invasive surgical procedures (29). Following this tendency, shape memory surgical instruments have been created and are becoming noticeable. Among the advantages of these tools, one can emphasize their flexibility as well as their possibility to recover their former shape when heated.

The SMA basket is used to remove kidney, bladder and bile duct stones (20). This basket is inserted into the human body in the same way as the Simon filter. Figure 12 presents a sequence of pictures related to the basket opening as it is heated.

The intra-aortic balloon pump (Figure 13) is used to unblock blood vessels during angioplasty. The device has an SMA tube whose diameter is reduced compared to polymer materials due to its pseudoelastic effect. Moreover, it also allows greater flexibility and torsion resistance when compared to the same tube made of stainless steel (16).

Laparoscopy is another procedure where SMA have been employed. Figure 14 shows some surgical tools where the actions of grippers, scissors, tongs and other mechanisms are performed by SMA. These devices allow smooth movements tending to mimic the continuous movement of muscles. Moreover, these devices facilitate access to intricate regions.

Final remarks

Applications of SMA to the biomedical field have been successful because of their functional qualities, enhancing both the possibility and the execution of less invasive surgeries. The biocompatibility of these alloys is one of their most important features. Different applications exploit the shape memory effect (one-way or two-way) and the pseudoelasticity, so that they can be employed in orthopedic and cardiovascular applications, as well as in the manufacture of new surgical tools. Therefore, one can say that smart materials, especially SMA, are becoming noticeable in the biomedical field. Probably, the adverse characteristic of biocompatibility of nickel is one of the most critical point concerning the spreading use of Ni-Ti alloys.

References

1. Hodgson DE, Wu MH & Biermann RJ (1990). *Shape Memory Alloys, Metals Handbook*. Vol. 2. ASM International, Ohio, 897-902.
2. Mantovani D (2000). Shape memory alloys: Properties and biomedical applications. *Journal of the Minerals, Metals and Materials Society*, 52: 36-44.
3. Shape Memory Alloy Research Team (Smart) (2001). http://smart.tamu.edu
4. Otsuka K & Ren X (1999). Recent developments on the research of shape memory alloys. *Intermetallics*, 7: 511-528.
5. Wu SK & Lin HC (2000). Recent development of TiNi-based shape memory alloys in Twain. *Materials Chemistry and Physics*, 64: 81-92.
6. Funakubo H (1987). *Shape Memory Alloys*. Gordon & Bleach, New York, NY, USA.
7. Shape Memory Applications, Inc. (2001). http://www.sma-inc.com
8. van Humbeeck J (1997). Shape memory materials: state of art and requirements for future applications. *Journal de Physique IV*, 7: 3-12.
9. van Humbeeck J (1999). Non-medical applications of shape memory alloys. *Materials Science and Engineering A*, 273-275: 134-148.
10. Schetky LMcD (2000). The industrial applications of shape memory alloys in North America. *Materials Science Forum*, 327-328: 9-16.
11. Denoyer KK, Erwin RS & Ninneman RR (2000). Advanced smart structures flight experiments for precision spacecraft. *Acta Astronautica*, 47: 389-397.
12. Pacheco PMCL & Savi MA (2000). Modeling and simulation of a shape memory release device for aerospace applications. *Revista de Engenharia e Ciências Aplicadas.*
13. Webb G, Wilson L, Lagoudas DC & Rediniotis O (2000). Adaptive control of shape memory alloy actuators for underwater biomimetic applications. *AIAA Journal*, 38: 325-334.
14. Rogers CA (1995). Intelligent materials. *Scientific American*, September: 122-127.
15. Birman V (1997). Theory and comparison of the effect of composite and shape memory alloy stiffeners on stability of composite shells and plates. *International Journal of Mechanical Sciences*, 39: 1139-1149.
16. Duerig TM, Pelton A & Stöckel D (1999). An overview of nitinol medical applications. *Materials Science and Engineering A*, 273-275: 149-160.
17. Pelton AR, Stöckel D & Duerig TW (2000). Medical uses of nitinol. *Materials Science Forum*, 327-328: 63-70.
18. Chu Y, Dai K, Zhu M & Mi X (2000). Medical application of NiTi shape memory alloy in China. *Materials Science Forum*, 327-328: 55-62.
19. Airoldi G & Riva G (1996). Innovative materials: The NiTi alloys in orthodontics. *Bio-Medical Materials and Engineering*, 6: 299-305.
20. Lagoudas DC, Rediniotis OK & Khan MM (1999). Applications of shape memory alloys to bioengineering and biomedical technology. *Proceedings of the 4th International Workshop on Mathematical Methods in Scattering Theory and Biomedical Technology*, Perdika, Greece, October 8-10, 1999.
21. Jordan L, Goubaa K, Masse M & Bouquet G (1991). Comparative study of mechanical properties of various Ni-Ti based shape memory alloys in view of dental and medical applications. *Journal de Physique IV*, 1: 139-144.
22. Savi MA, Paiva A, Baêta-Neves AP & Pacheco PMCL (2002). Phenomenological modeling and numerical simulation of shape memory alloys: A thermo-plastic-phase transformation coupled model. *Journal of Intelligent Material Systems and Structures*, 13: 261-273.
23. Zhang XD, Rogers CA & Liang C (1992). Modeling of the two-way shape memory effect. *Philosophical Magazine A,* 65: 1199-1215.
24. Shabalovskaya SA (1995). Biological aspects of TiNi alloys surfaces. *Journal de Physique IV*, 5: 1199-1204.
25. Ryhänen J (1999). Biocompatibility evolution of nickel-titanium shape memory alloy. Academic Dissertation, Faculty of Medicine, University of Oulu, Oulu, Finland.
26. NMT Medical, Inc. (2001). http://www.nmtmedical.com
27. Medical Devicelink (2001). http://www.devicelink.com
28. Raychem (2001). http://www.raychem.com
29. Duerig TM, Pelton A & Stöckel D (1996). The use of superelasticity in medicine. *Metall*, 50: 569-574.
30. TECHNOSITE MEDICAL (2001). http://www.labosite.com/anglais/pages/summary.html
31. SMA/MEMS Research Group (2001). http://database.cs.ualberta.ca/MEMS/sma_mems
32. @medical technologies (2001). http://www.amtbe.com
33. Li B, Rong L, Li Y & Gjunter VE (2000). A recent development in producing porous NiTi shape memory alloys. *Intermetallics*, 8: 881-884.
34. SMET (2001). http://smet.tomsk.ru/eng/prod.htm