Applications of Shape Memory Alloys in Biomedical Engineering

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Abstract- Shape Memory Alloys (SMA) playing significant role in wide range of biomedical applications. The unique thermomechanical properties of SMA attacking researches and manufacturer in medical field to develop super-elastic biomaterials for clinical applications. Recently, SMA biomaterials are used successfully in surgical fields including; orthopedics, dental and vascular.

Index Terms- Shape memory alloys (SMAs), Nickel-Titanium alloys, Crystallography, Thermomechanical, Austenite and Martensite phase.

I. Introduction

Memory shape Alloys (SMAs) compose of metallic materials that have unique and attractive characteristics. SMAs are able to return to their original shape after subjected to large deformation load by unique feature known as pseudoelasticity. As well as, memory shape effect enabling SMAs to recover original shape after the effect of heat by thermochemical deformation. However, SMAs show high restitution forces during limitation of original shape return [1].

Interestingly, the peculiar properties of SMAs are characterized by crystallography structure and thermodynamic features. In addition to that, stability and symmetry at high temperature playing significant role during austenitic phase. In parallel to that, stability at low temperature promotes martensitic phase. Totally, the transformation between austenite and martensite is associated with stress-temperature function stimulated a thermal diffusion less thermoelastic martensitic transformation (TMT). In practical, SMAs found in two well-known crystallographic phases; martensite phase is characterized by high level of stability during no stress load at low temperature. Martensite phase is stimulated by temperature or stress load to form monoclinic or orthorhombic structure. While, austenite phase shows stable crystal structure with body center cubic orientation during high temperature only [2, 3].

The functional properties of SMAs influenced the researchers in medical field to successfully introduce these materials in medical applications. Wide range of metal shape memory alloys specially based on Nickel, Titanium, Chromium and Cobalt are suggested to play significant role in medical devices and medicals implants regarding to their unique response of human tissues. Mainly, biocompatibility of metal shape memory alloys provides very interesting profile when interacted with human tissues as host, leading to accept SMAs without undesirable immunity response, allergic reactions, inflammatory or chronical problems. Also, other properties promote the applications of SMAs such as; high level of resistance to fatigue and corrosion, low stiffness and wider range of elastic behavior [4].

Recently, most SMAs used in medical applications are produced based on Nickel-Titanium alloys (*Ni-Ti*) regarding to excellent workability during martensite phase, good resistance to corrosion and high level of biocompatibility. Practically, several researches and studies have been performed to investigate and analyze these properties during medical applications of SMAs. In 1997, Wever and his team examined and compared the thermomechanical behavior and biocompatibility profile between (*Ni-Ti*) alloys, stainless steel and pure titanium. The obtained results showed that (*Ni-Ti*) alloys provide high resistance to corrosion and good biocompatibility profile compared with conventional biomaterials introduced in medical applications [5]. Another study which was performed by Ryhanen in 2000 to evaluate cytotoxicity and corrosion rate of (*Ni-Ti*) alloys by using osteoblast and fibroblast cell culture. Interestingly, the results showed that (*Ni-Ti*) alloys are safe to use indirect contact with human tissues because no toxic effects, no inhibition of cell growth and proliferation. In addition to that, SMAs based on Ti-Ni showed better performance rate of femoral bone osteotomies, higher resistance to corrosion and better treatment outcomes compared with stainless-steel [6]. Furthermore, several studies *in-vivo* and *in-vitro* achieved during the last decade to review the properties of SMAs specially cytotoxicity and genotoxicity. Es-Souni et al 2005, found that SMAs based on (*Ni-Ti*) alloys have superior characteristics including good biocompatibility, good corrosion rate, low cytotoxicity and low genotoxicity compared with traditional metal alloys [7].

In addition to that, surface properties of SMAs playing significant role in biocompatibility profile and corrosion. For example (*Ni-Ti*) alloys, showed that Ti is oxidized faster than Ni to produce TiO_2, which generates protected film against Ni release and increasing the corrosion resistivity [8].

II. Methodology

The special thermomechanical behavior of SMAs including pseudoelasticity and shape memory return promote innovative applications in medical applications. SMAs have the ability to perform reversible martensitic transformation by variation of crystal structure depending on variation in load and temperature. Radical differences in crystal structure are appeared based on yield and elastic points below and above glass transition temperature. The stress-strain curve of SMAs show that elastic module is high at temperature below glass transition temperature, and low at temperature above glass transition temperature. However, the initial phase of transformation is described as macroscopically homogeneous and it occurs before the stress-strain knee. While during yield point localized transformation occurred and described as band area. At higher strain more deformation occurred and more band area appeared leading to overlap and increasing the SMAs' temperature followed by significant increase of transformation stress.

Pseudoelasticity and shape recovery effects occur when SMAs are subjected to load at temperature above austenitic phase, the load causes elastic response until critical value at point A in figure 1. Followed by the martensitic transformation ending at point B. higher stress value leading to elastic recovery phase from point B to point C. After that, reverse martensitic transformation is shown by elastic discharge from point C to point D. However, the curve of forward transformation does not correspond with reverse transformation curve meaning hysteresis loop of energy dissipation.

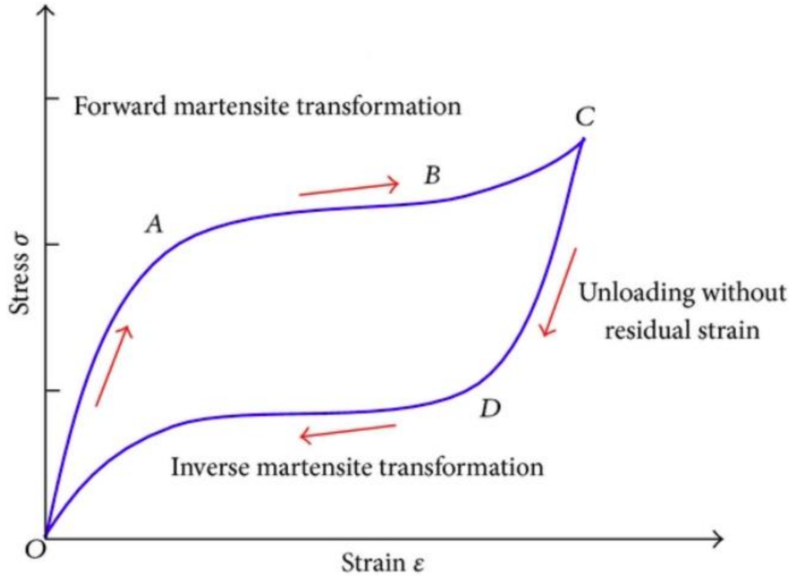


Figure 1: Stress-Strain Curve of SMAs

III. Medical Applications

The remarkable properties of SMAs promoted wide range of medical applications in different fields such as Orthopedic, Cardiovascular, and Orthodontic.

i. Orthopedics

SMAs are widely used in orthopedics surgeries regrading to their thermomechanical features. For example, fixation plates made of SMAs are used to reunion broken bone and maintain correct alignment of bone during healing stage. As well as, fixation plates should provide suitable compression between the two segments. SMAs can provide the previous features and have the ability to support human bone healing with good biocompatibility, high resistance for corrosion and provide appropriate compression to enhance bone growth [9]. Moreover, stability of SMAs at room temperature is significant to promote easily shaped and facilitate insertion of fixation device during surgery. Figure 2 presents two types of external devices used for Tibia, hand and wrist fixation.

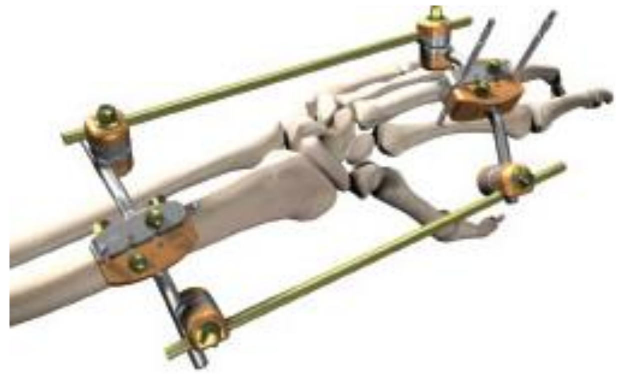


Figure 2: a. Tibia Fixation Device **b. Hand and Wrist Fixation Device**

Significantly, SMAs are used for spinal vertebra spacer as shown in figure 3. The main purpose of vertebra spacer is to prevent any traumatic motion during healing stage of spinal cord injuries. However, SMAs spacer promote healing and recovery of spinal to its original shape by the pseudoelastic phenomenon [10].

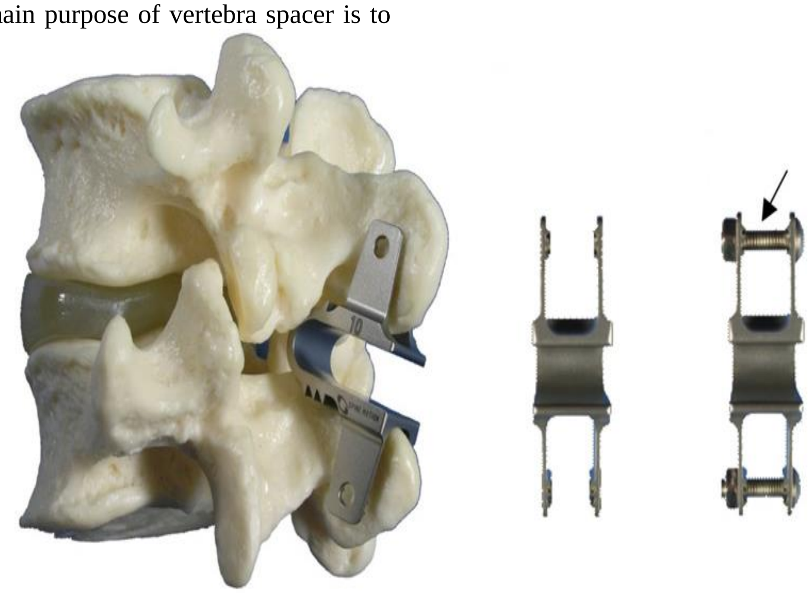


Figure 3: a. Spinal Vertebra Spacer

Figure 3: b. Spinal Vertebrae Spacer in the martensitic state (left) and in the original shape (right) [11].

ii. Cardiovascular

Simon filter is the most common application of SMAs in cardiovascular field. Simon filter was developed and introduced in cardiovascular application to help patients who can't take anticoagulant medications to prevent blood vessel interruption and pulmonary embolism. Therefore, the main function of Simon filter is to protect suggested patients from blood clots by filtration of blood stream. Also, the insertion of Simon filter in patient's tissue is achieved by applying the shape memory feature from its original shape in martensitic phase as shown in figure 4, then the filter is deformed and placed at catheter tip to introduce inside patient's body. When the catheter releases the Simon filter, the temperature of blood stream stimulates the Simon filter to return to its original shape [12].

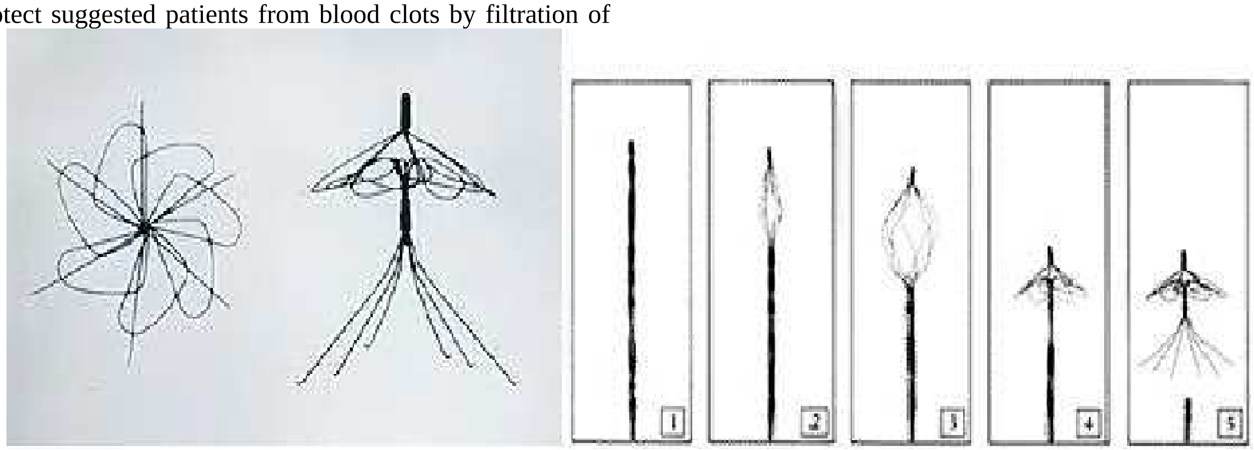


Figure 4: Simon Filter in recovery shape, Filter released from catheter

Another example of SMAs used in cardiovascular applications is atrial septal occlusion device which is particularly employ to seal atrial hole located between two upper chambers of heart. Catheter technique is used to introduce atrial septal device into human body after that the catheter is released and the device return to its original shape to close the hole as shown in figure 5.

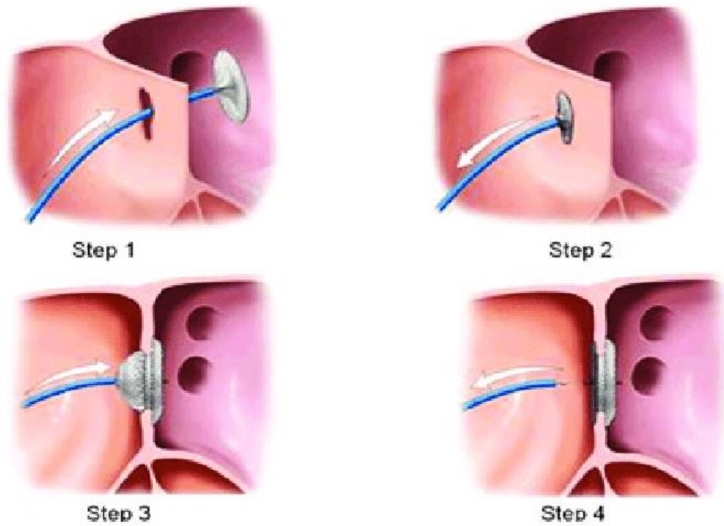


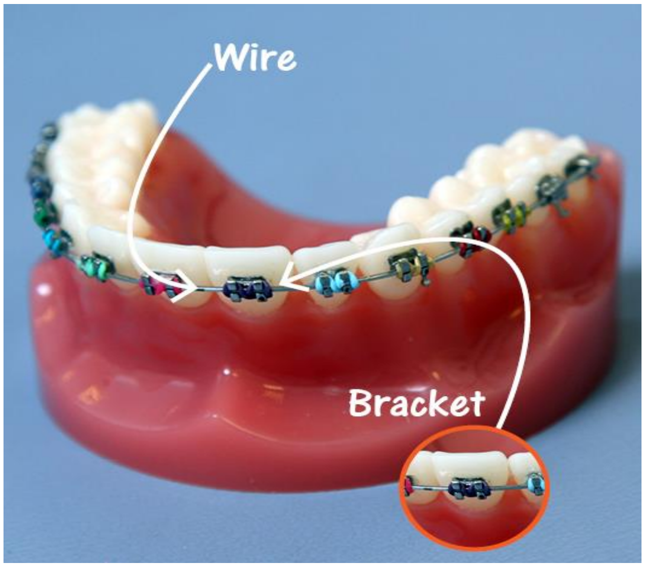
Figure 5: Installation of Atrial septal occlusion device

Furthermore, self-expanding cardiovascular stents are playing a significant role to maintain the correct inner diameter of blood vessel to ensure good oxygenation. Self-expanding stents are used widely in cardiovascular applications to support any tubular passage such as the esophagus and bile duct and blood vessels such as the coronary, iliac, carotid, aorta and femoral arteries [14]. Figure 6.a shows self-expanding stent as cylindrical scaffold with shape memory characteristics which is instated into human body by catheter technique. Firstly, the stent is compressed at the martensitic phase, then it is inserted into the correct position in cardiovascular system. When the SMAs stents is heated by blood and body temperature, it is started to return and recover the original shape and perform expanding process to prevent vessel obstruction or to support weak vessel [15].

Figure 6: a. Self-expanding stent **b. Self-expanding stent after insertion**

iii. Orthodontic

In 1975 the first application of SMAs was implemented by Lowa University by exploiting pseudoelastic feature of Ni-Ti wires used to fix orthodontics treatment with multibrackets at buccal cavity temperature in austenitic phase. Practically, deformation of wire during transformation stage from austenite to single-variant martensite. Pseudoelasticity effect is used to produce constant load after positioning the wire in brackets as shown in figure 7.a. Also, SMAs wires may inserted into steel arches as shown in figure 7.b which is used to apply rotating, expanding or torque load on superior molars by pseudoelasticity effects. The main function is to solve the problem of teeth overcrowding by generation expanding tensile force constant in time, these forces produce stress conditions to improve tissues growth and movement of teeth to the correct positioning.



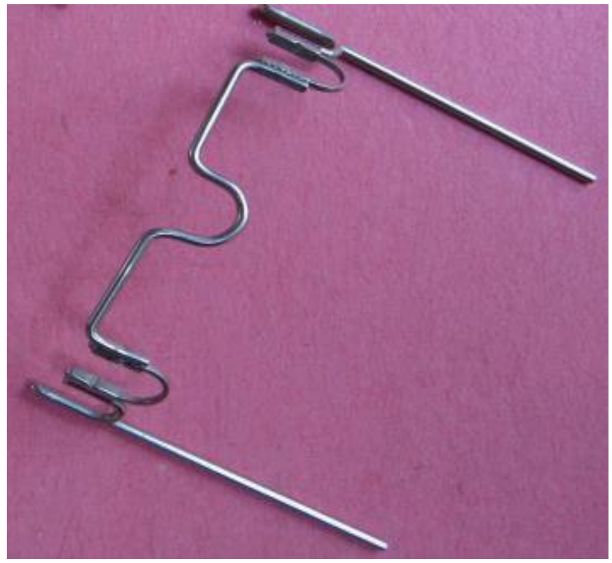


Figure 7: a. SMAs Orthodontic Wires **b. Palatal arch.**

In addition to that, SMAs are used to repair broken bone in facial area such as nose, jaw or eye socket where casting not applicable to injured area. SMAs material are placed instead of fractur bone and fixed with screw to maintain the original shape and alignment of broken bone, as well as promote cells and tissues generation. Regarding shape memory features, SMAs tends to return to the original shape and exerting constant force that play a vital role to rebuild separated parts of broken bones and stimulates the osteogenesis as shown in figure 8.

Figure 8: Matrix mandible SMAs

IV. Conclusion

Shape memory alloys (SMAs) are playing significant role in medical applications regarding to their unique features; shape memory effect and pseudoelastic effect. Leading to return to the original shape after large force of deformation which enable to maintain and support different type of human body structure such as blood vessel and bones. Interestingly, body temperature stimulates crystallographic structure of SMAs to recover into the original shape during transformation and austenite phases. In addition to that, SMAs have special attractive properties that comply with medical applications such as good biocompatibility, high resistance to corrosion, magnetic resonance compatibility and low biotoxicity for biological tissues. All these unique properties attract scientists and manufacturers to invest in researches and development to discover more applications in medical field for SMAs.

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