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A REVIEW STUDY ON BIOCOMPATIBLE IMPROVEMENTS OF NITI-BASED SHAPE MEMORY ALLOYS

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Abstract

Review paper

NiTi-based shape memory alloys (SMAs) have many applications, especially for implantation, however since they are not a passive material so it is important to investigate them from different biocompatible perspectives. In this study, we introduced the important physical characteristics of NiTi alloys, then we explained different biocompatible terminologies, including carcinogenic, genotoxic, cytotoxicity, mutagenic, allergic, and corrosivity. We collected some important previous works that investigated the biocompatibility of NiTi-based SMAs and the different techniques used for improving the alloy and diminishing the hazard due to Ni-leakages.

Keywords: *NiTi, shape memory alloys, biocompatibility, toxicity, Carcinogenic, Mutagenic*

1 Introduction

Smart materials are a group of engineering materials that have many technological applications [1, 2], besides, shape memory alloys (SMAs) are a special type of smart materials which are received more attention compared to other types of smart materials because they are able to recover and a deformed shape through some specific mechanisms [3-7]. SMAs have two main phases which are austenite and martensite phases. Austenite is stable at high temperatures while martensite is stable at low temperatures, and the phase transformation from austenite to martensite and vice versa can be obtained through the heating/cooling process [8-20]. Also, the ability of SMAs to return to their previous shape is specified into two different categories, which are shape memory effect (SME) and superelasticity (SE). Because of these interest behaviors, SMAs are widely used in modern technological applications, such as robotics, automotive, aerospace, and medical application [21]. Additionally, some SMAs, especially NiTi-based alloys, are used as biomedical materials. Biocompatibility is an ability of biomedical materials since they are implanting in the human body, so they should be passive and do not damage the living tissues [22]. Besides, the biocompatibility of SMAs is relative, therefore they can be improved by some basic techniques such as heat treatment and alloying process. In the past few decades, many studies in the literature could improve the biocompatibility of SMAs. For example, Jin et al. used a filtered arcing ion plate technique to coating NiTi alloy with the tin element. They reported that Sn enhanced the biocompatibility of their sample [23]. Likewise, Zhang and coworkers improved the biocompatibility and anti-corrosion resistance of a binary NiTi SMA by coating its surface with graphene [24]. Also, Tao and coworkers performed the oxidation treatment on a NiTi SMA using H_2O_2 solution, and they stated that the wettability, blood compatibility, and fibroblasts compatibility were improved after coating the sample with a titanium oxide layer [25].

In this article, most studies conducted about improving the biocompatibility of NiTi-based shape memory alloys have been reviewed. Firstly, we discussed the main features of shape memory alloys, then we explained some biocompatible terminology used for biomedical materials. Also, the techniques used to improve and minimize the risks of using these smart materials are highlighted.

2 General Characteristics of SMAs

As we mentioned before, SMAs have two main phases which are austenite and martensite. Also, they can be transferred from one phase into the other counterpart, also they able to return to their previous shape only by manipulating temperature. This ability is based on two main characteristics, which are known as SME and SE.

2.1 Shape Memory Effect (SME)

When the SMA phase is converted from a low-temperature phase (martensite) to a high-temperature phase (austenite) by thermoelastic conversion, it can return to its original state under the influence of the heating process. This behavior is called the shape memory effect [26]. Figure 1 depicts a stress-strain-temperature diagram that determines the SME mechanism. The austenite is phase transformed to the martensite phase under the effect of the stress and cooling process; firstly, the austenite phase transforms into twinned-martensite (1→2), and then its

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crystal structure changes to detwinned-martensite (2→3). When the effect of mechanical stress is removed through the (3→4) process, its crystal structure stays constant, but under the effect of the heating process, the alloy can recover to its parent phase (austenite) through (4→1) [26].

Based on the SME, two different types of SMAs have been classified: one-way shape memory alloy (OWSMA) and two-way shape memory alloy (TWSMA). In OWSMA, the alloy can remember only one predetermined shape given in the austenite phase, while in TWSMA, the alloy can be trained to remember two different shapes in two various temperatures. Generally, OWSMAs have more commercial applications compared to TWSMAs [27].

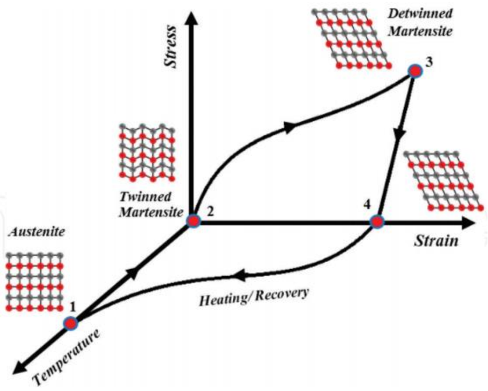

Figure 1. Schematic diagram of SME [26]

2.2 Super Elasticity (SE)

SE is another unique property of SMAs, which has more technological applications. SE does not need temperature change [28], but in a specific temperature between austenite finish and martensite deformation, the superelasticity can be obtained from an SMA [28]. Figure 2 shows the superelasticity mechanism in a stress-strain diagram. After the applying stress exceeds elastic (A→B) deformation, a martensite phase transformation takes place (B→C). After austenite is compactly transformed to the martensite phase, the crystal structure of the alloy changes from cubic to a detwinned martensite crystal structure. The stress is stored as elastic energy so after removing the external load, the restoring energy returns the deformed alloy to its original shape, however, by over-stressing the alloy, a slip can happen that leads to permanent deformation.

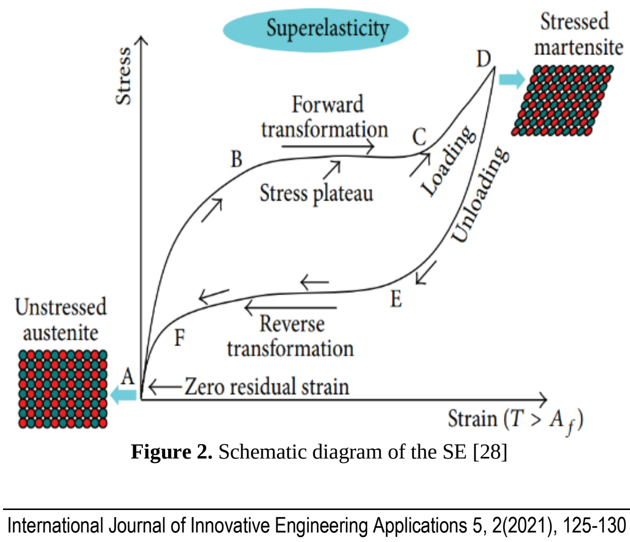

Figure 2. Schematic diagram of the SE [28]

3 Biocompatible Properties

In this chapter, the main well-known biocompatible properties of materials, especially NiTi-based alloys were discussed. Table 1 lists the biocompatibility of some elements, includes Ni and Ti.

3.1 Carcinogenic

Carcinogenic is one of the most imperfections or harmful properties that must be taken into account for the substances which are used in medical treatments and manufacturing medical devices that are implanted into the human body [29]. Also, carcinogenic can increases cancer [30]. Chemical carcinogenic which refers to some chemical substances such as arsenic (As), cadmium (Cd), nickel (Ni), and selenium (Se), can destroy DNA that directly or indirectly causes a mutation in the essential oncogene or immune cell gene that causes cancer [31]. The NiTi-based shape memory alloys are the most popular ones that are used in biomedical applications, however, one of the big problems of using NiTi as a biomaterial is the release of the carcinogenic Ni and Ti ions into the human body [32]. There are more works in the literature where they were treated this problem by surface modifications and coating methods to improve the corrosion resistance by reduced the carcinogenicity of Ni-Ti alloy [33-36].

O'Brien et al. carried out the passivation process on a NiTi SMA; they treated samples thermally and then they passivated them in a nitric acid solution. They stated that the biocompatibility of the NiTi alloy was improved. The surface analysis indicated that after the passivation process Ni and NiO content were reduced and TiO_2 increased on the surface. Also, they concluded that the corrosion resistance of the alloy was proportional to the quantity of nickel removed [37]. Likewise, El Abedin and coworkers improved the biocompatibility of a NiTi alloy by reducing the carcinogenic Ni content. They coated the NiTi SMA with a thin layer of Ta using a 3.5% NaCl solution; they stated that the corrosion resistance was improved after coating the alloy [32].

3.2 Genotoxic

Genotoxic is one of the properties of chemical elements that are concerning in biomedical applications to avoid cancer due to the change in the genetic information of the organs and mutation by damaging the DNA of the cells [38]. The indirect and direct DNA damage, due to genotoxicity includes induction of a mutation, and direct DNA damage, resulting in mutations. It induces immediate and inherited modifications which can be transmitted to subsequent cell generations [39]. It is known that NiTi-based alloys have several important and interesting properties such as superelasticity, shape memory, and high damping property, however, due to the presence of Ni element, the NiTi-based alloys are listed in genotoxic materials [38]. Assad et al. decreased the genotoxicity for a NiTi SMA by diminishing the amount of Nickel in a NiTi alloy. They found that the genotoxicity of pure Titanium is smaller than a binary NiTi, stainless steel, and pure nickel. Based on genotoxicity results, they sorted the materials as Ti < Ni-Ti < stainless steel < Ni [40].

3.3 Cytotoxicity

Cytotoxicity is one of the important properties of chemical elements or materials that causes cell damage or cell death when a cytotoxic material is implanted inside a human body. The prefix (cyto) means cell, and (toxic) means poison. Chemotherapy is used for treating the damage to cancer cells caused by cytotoxic material [41]. Cytotoxicity testing is so important for the biomedical element used for implanting applications [42]. NiTi-based shape memory alloys are one of the biomedical materials that are also cytotoxicity because nickel is one of the toxic chemical elements. However, this issue can be treated by diminishing Ni or substituting Ni with a third biocompatible element. Tabish, et al. added Fe as the third element into a NiTi alloy with composition of $Ti_{50}Ni_{48}Fe_2$, $Ti_{50}Ni_{47}Fe_3$, and $Ti_{50}Ni_{45}Fe_5$,. They implanted the samples inside the rabbit body, and they tested the blood and histology of various vital organs of the rabbit after 4, 8, and 12 weeks. Thus, they stated that the ternary NiTiFe alloys showed no sign of cytotoxicity and the alloys were passive and had no reaction with the living organs inside the rabbit body [43].

3.4 Mutagenic

Mutagenic is another property of materials that can cause a permanent change in the genetic code of a host cell [44, 45]. The permanent change in the amount or structure of the genetic code and chromosome of the organism is called mutation [46]. Normally, the human body has enough immunity to these mutations and it can recognize and repair some of the mutations, however, some of these mutations are not repaired and not recognized by the immunity system, therefore, they may produce a tumor and develop cancer [47]. Although, as aforementioned, a NiTi SMA has high biocompatibility, Nickel as a main constituent of the alloy is listed in mutagen elements that should be taken into account [48].

3.5 Allergic

An allergy is an immune system reaction to a foreign material that is not normally dangerous to the body. These materials are called allergens, and allergic reactions can be produced when these materials enter a body. These materials have many types such as pollen, foods, and pet dander [49, 50]. Sometimes, a NiTi shape memory alloy can also classify as an allergen material because Ni is one of the five elements (Amalgam, Gold, Nickel, Chromate, and Platinum) that are caused to allergic, and it ranks third among this list [51]. Also, generally, females have more sensitivity to Nickel than males. Somehow, up to 20% of females have sensitivity to nickel, while, only 1-2% of males are sensitive to this element [52-54]. This allergy can be treated by release the amount of Nickel in the alloy or by surface coating to avoid Ni-leakage [55]. Kim, et al. coated a NiTi alloy with both nitride and epoxy and they subjected the samples in dissolution with 0.9% NaCl and neutral PH at room temperature. The result showed that nitride has no significant effect on decreasing the allergy of the NiTi because it did not affect the corrosion of the alloy, while, they stated that epoxy decreased the allergy of the NiTi alloy because the epoxy increased the corrosion resistance of the alloy [56].

3.6 Prone to Corrosion

Despite implanting materials have more benefits in biomedical applications, they sometimes have side effects and cause additional health issues [57]. One of these side effects is corrosion which is the degradation of the implanting materials by an electrochemical attack when they are placed inside the host body. The implanted materials normally face various electrolyte environments, such as blood, water, chlorine, sodium, plasma, and amino acids, therefore, these fluids may cause corrode the implanted metals [58]. NiTi SMAs have comparably good corrosion resistance, but, they can be further improved by some different techniques. Jean et al. added Cu into Ni-Ti alloy, and they reported that the corrosion rate of the equiatomic NiTi is greater than the ternary NiTiCu alloy [59]. Likewise, Ruiz, et al. investigated the effect of both boron addition and heat treatment on the corrosion resistance of a NiTi alloy. They added 250, 500, and 1000 ppm of B into Ni55-Ti45, at the same time, and they performed heat treatment on the samples at 900 ℃ for 4 hours. Their results showed that after adding 250 and 500 ppm of B, the corrosion rate was decreased but 1000 ppm B increased the corrosivity of the alloy [60]. Also, Iijima, et al. performed a surface configuration method on a NiTi alloy. They polished the surface alloy with 0.9% NaCl and 1% lactic acid solutions, and they found that a thick oxide layer TiO2 was formed on the Ni-Ti surface by the heat treatment and subsequent pickling processes. Besides, they realized that this oxide layer improved both general and localized corrosion of the NiTi in [61].

Also, the corrosion resistance of a NiTi alloy can be improved by a chemical treatment method, which is called passivation. Passivation can be defined as the anti-corrosion mechanism or it is a loss of electrochemical activity, whereby the passive layer is produced as a barrier between the surface of the metal and the electrolyte, therefore this protection layer can increase the corrosion resistance of the material [62-67].

4 Conclusions

Since NiTi-based shape memory alloys (SMAs) are not a passive material, they widely are investigated from various biocompatible perspectives. In this review, the essential physical properties of the NiTi alloys were discussed. Additionally, the well-known biocompatible terms including carcinogenic, genotoxic, cytotoxicity, mutagenic, allergic, and corrosivity were clarified for NiTi alloys. Some significant studies that investigated the biocompatibility of NiTi-based SMAs and the various strategies used to improve the alloy and reduce the risk of Ni-leakages were reviewed. Researchers could achieve good results, however, there are still many issues that need more studies.

Table 1. The biocompatibility of some elements [29]

Periodic position	Element	Biocompatible	Carcinogenic	Genotoxic	Mutagenic	Cytotoxic	Allergenic	Pron to corrosion	Other
3d	Ti	✓	x	x	x	Med	x	x	x
	V	x	✓	✓	✓	High	Disputed	x	x
	Cr	x	Disputed	✓	x	High	✓	x	x
	Mn	x	x	✓	x	High	x	✓	x
	Fe	x	x	✓	x	Med	x	✓	x
	Co	x	✓	✓	✓	High	✓	✓	✓
	Ni	x	✓	✓	✓	High	✓	✓	✓
	Cu	x	x	✓	✓	High	✓	✓	✓
4d	Zr	✓	x	x	x	Low	x	x	x
	Nb	✓	x	x	x	Low	x	x	x
	Mo	x	Disputed	✓	✓	Low	✓	✓	✓
	Tc	x	-radioactive-						
	Ru	x	x	x	x	Med	x	x	✓
	Rh	x	✓	✓	✓	High	Unknown	x	x
	Pd	x	✓	x	Disputed	Med	✓	x	x
	Ag	x	x	x	x	High	✓	x	✓
5d	Hf	Unknown	Unknown	Unknown	Unknown	Med	x	x	Unknown
	Ta	✓	x	x	x	Low	x	x	x
	W	x	✓	✓	x	Med	x	✓	x
	Re	Unknown	Unknown	Unknown	Unknown	Unknown	x	x	Unknown
	Os	x	Unknown	✓	✓	High	x	✓	x
	Ir	x	x	x	✓	High	x	x	✓
	Pt	x	✓	✓	✓	High	✓	x	x
	Au	✓	x	x	x	High	x	x	x
Other	Al	x	x	✓	x	Low	x	x	✓
	Zn	x	x	x	x	High	x	x	✓
	Sn	✓	x	x	x	Low	x	x	✓

Declaration

The authors declare that the ethics committee approval is not required for this study.

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