RECENT ADVANCES, MECHANISMS AND MULTIDISCIPLINARY ENGINEERING APPLICATIONS OF SHAPE MEMORY ALLOYS: A REVIEW

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ABSTRACT

Shape Memory Alloys (SMAs) are memory-enabled materials capable of remembering their original shape upon heating owing to the shape retention phenomenon. The shape memory effect originates from the reversible transformation between austenite and martensite phases. These alloys are biocompatible, meaning they cause no harmful reactions in the human body, and they are also lightweight, corrosion-resistant, and characterized by an excellent strength-to-weight ratio. SMAs have revolutionized applications in civil engineering, biomedical, industrial, aerospace, automotive, and robotics. This study critically examines the properties, history, recent advancements, material behavior, and frontier research areas, emphasizing their capability to address complex engineering problems and foster future technological advancements.

Keywords: Shape Memory Effect, Biocompatible, Phase Change, Alloys.

INTRODUCTION

Shape memory alloys (SMAs) are an inimitable type of intelligent material that can change shape in response to stress or temperature changes. These alloys have the ability to restore their original shape once deformation is relieved (Yüce, 2017). This property, termed the shape memory effect (SME), is achieved through a temperature-dependent phase transition from austenite to martensite and vice versa. SMAs have led to their adoption due to exhibiting high corrosion resistance, biocompatibility, high strain recovery, and their excellent properties in various industries such as biomedical, aerospace, robotics, automotive, and other industries. The latest innovation demands intelligent systems with advanced functionalities for automatic industries. Shape memory alloys offer significant improvements in performance, safety, and efficiency compared to conventional materials. This study examines both the smart material characterization and engineering application, exploring their potential applications in the engineering field (Balasubramanian et al., 2021; Das, 2018).

This paper has objectives related to SDG

1. History of Shape Memory Alloys

Table 1 shows the chronological development and advancements in shape memory alloy research, tracing progress from the earliest observations of the shape memory effect to modern innovations and applications across engineering and medical fields (Balasubramanian et al., 2021; Duerig et al., 1999; Naresh et al., 2016).

2. Fundamentals of Shape Memory Alloys of Phase Transformation

Figure 1 shows the phase transformation of SMA, where the martensitic phase transforms directly into austenite without any external load. During this transition, the macroscopic shape of the alloy remains unchanged, although its microstructure undergoes significant

Year	Development	Details
1932	Initial Discovery of SME	The shape memory effect was first observed in 1932 by Greninger and Mooradian in gold-cadmium alloys.
1962	Discovery of Nitinol	W.Buehler and Wang first identified the shape memory effect in the nickel-titanium (NiTi) alloy later named Nitinol.which exhibited excellent mechanical properties.
1960s-70s	Development of Nitinol Alloys	Researchers further developed NiTi alloys, exploring their applications in various fields such as actuators and sensors.
1971	First Commercial Application	Nitinol's first major commercial application was in the form of a self-expanding stent, marking a breakthrough in medical devices.
1980s	Advances in Material Processing	Improvements in the processing and manufacturing of SMAs enhanced their reliability and performance, leading to new applications in engineering.
1990s	Use in Aerospace, Automotive, and Robotics	The shape recovery properties of SMAs have enabled their use in aerospace, automotive actuators, and robotic applications.
2000s	Introduction of New SMA Variants	New SMA alloys (e.g., copper-aluminum-nickel, iron-based alloys) were developed to broaden the operational range and improve cost-effectiveness.
2010s	Advanced Biomedical and Industrial Applications	SMAs found applications in biomedical devices like stents, orthodontic wires, and robotic prosthetics, with notable developments in precision engineering.
Present	Ongoing Research and Innovation	Research continues to improve SMA properties, such as increased thermal stability, efficiency, and broader application scopes in advanced engineering and medicine.

Table 1. Chronological Development and Advancements in Shape Memory Alloy Research (Lagoudas, 2008; Lee et al., 2010; Sanusi et al., 2014)

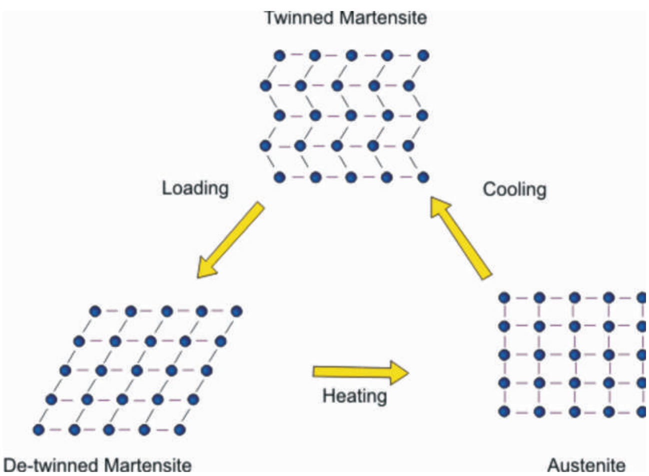

Figure 1. Phase Transformation of SMA (Ölander, 1932)

changes. Upon cooling, a reverse martensitic transformation occurs, and the austenite reverts back to twinned martensite. This process is referred to as self-regulation. When the SMA is loaded in the martensitic phase, detwinning of the twinned martensite occurs, resulting in significant stress generation within the material. The stress developed during the complete transformation of twinned martensite into de-twinned martensite is referred to as the transformation strain (Λt). This value represents the maximum strain that the SMA can recover upon heating. The phase transformation process in SMAs is characterized by four distinct temperatures: As (Austenite start), Af (Austenite finish), Ms (Martensite start), and Mf (Martensite finish). Here, 'A' and 'M' denote the austenite and martensite phases, respectively, while the subscripts 's' and 'f' indicate the start and finish of the respective transformations. The values of these temperatures vary depending on the loading conditions and are influenced by the applied stress (Ölander, 1932; Perkins, 1974).

Figure 2 shows the micro structural differences between martensite and austenite phases in a shape memory alloys. In martensite phase the circled region appears as thin and needle like pattern. This phase forms at low temperature or under mechanical stress due to this phase is soft and easily deformable. In austenite phase circle

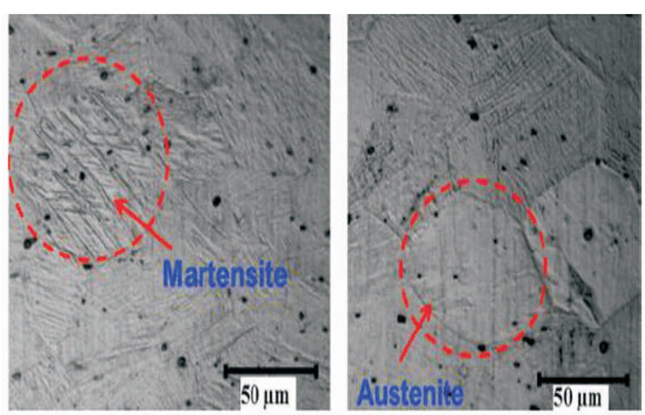

Figure 2 Martensite and Austenite Structure of Nitinol (Perkins, 1974)

region indicates that austenite structure, which is more uniform and less textured as compared to martensite. This phase occurs at high temperature and stronger than martensite. The dark round spot are imperfection in both phases but do not affect the identification of the phase.

3. SMA Composition

The most widely used SMAs are NiTi alloys, known as Nitinol, due to their excellent properties.

3.1 NiTi Alloys (Nitinol)

Made of titanium and nickel, they are well-known alloys for having a strong shape memory effect and being biocompatible, which qualifies them for use in medical applications (Jani et al., 2014; Rahul et al., 2023).By changing the composition, one can customize the transformation temperatures of nitinol.

3.2 Copper-Based Alloys

These alloys are used for purposes that require higher operating temperatures and offer high transformation temperatures, like copper-aluminum-nickel (Cu-Al-Ni) (Khan & Lagoudas, 2002). Alloys based on iron, such as iron-platinum (Fe-Pt) alloys, are less common but can have high transformation temperatures and be employed in specific applications (Kolekar et al., 2017).Numerous SMAs alloys have been developed in recent years. In this group Ni-Ti SMAs achieved potential interest due to their unique recovery strain and corrosion resistance. The high production cost and the complex nature of machining processes have been major challenges to the widespread industrial application of these materials (Lagoudas, 2008; Petrini & Migliavacca, 2011). Consequently, researchers have focused on developing alternative alloy compositions that can not only reduce production costs but also effectively exhibit the desired superelasticity, shape-recovery ability, and shape-memory characteristics. In recent years, various structure shape memory alloys (Cu-based (Cu-Zn-Al, Cu-Al-Be, Cu-Al-Ni, Cu-Al-Mn) and Fe-based (Fe-Mn-Si-Cr-Ni-1 (V, C), Fe-Ni-Co-Ti, Fe-Mn-Si) have been developed as viable alternatives due to their low production costs and simple manufacturing processes. The various structures of SMA suitable for civil engineering applications are presented in Table 2.

The availability of various SMA compositions in the market allows customization based on specific requirements and applications across different sectors such as industrial, medical, and robotics. Ni-Ti–based SMA (Nitinol) is the most widely and easily available commercially in various forms due to its high demand and unique properties in biomedical and automotive industries, whereas Cu- and Fe-based SMAs are available but have fewer manufacturers and limited market presence.

Shape memory alloys are classified into two categories. One-way shape memory is the term used to describe a material that only displays the shape memory effect when heated. Two-way shape memory refers to a substance that exhibits a shape memory effect both when heated and cooled.

4. Properties of Shape Memory Alloys

SMAs are intelligent materials that can remember their original shape and return to it after deformation, due to the desirable performance and excellent characteristics make SMAs very useful application in medical devices, aerospace and robotics.

4.1 Shape Memory Effect

The ability of shape memory alloys to recover apparent permanent stresses and return to their normal shape when heated above a specific temperature is known as the shape memory effect. There are two stable phases for SMAs:

- The parent phase of austenite exhibits a cubic crystal structure, while the more robust austenite phase remains stable at elevated temperatures (Ho et al., 2004).

SMA Alloy	Composition (%)	M_f(°C)	M_s(°C)	A_f(°C)	A_f(°C)
Ni-Ti	55.7-44.3	-40.15	4.85	17.85	50.85
Cu-Zn-Al	25.63-42.-70.17	15.35	19.5	20.05	25.15
Cu-Al-Be	25.6-4.2-70.2	-116.5	-94.5	-104.15	-78.15
Cu-Al-Ni	82-1-44	-21.5	-27.5	0.85	11.85
Cu-Al-Mn	71.7-16.7-11.6	-91	-74	-54	-39
Fe-Mn-Si-Cr-Ni-I	64 17 5 10 4	-64	-60	103	162
Fe-Ni-Co-Ti	43.5-28-17-11.5	-	-	-	-
Fe-Mn-Al-Ni	44.4-32.8-15.2-7.6	-	-	-	-

Table 2. Different Composition of SMAs (Lagoudas, 2008)

- The monoclinic crystal structure of the softer martensitic phase makes it stable at low temperatures (Ho et al., 2004).

The SMA's relative softness allows for easy deformation during its martensitic phase. The body-centered cubic structure of the austenite phase is well-ordered and exhibits only one variation. Depending on the type of phase transformation, the martensite phase can exist in several variations and has a lower symmetry. Consequently, there is only one method for the martensite that is generated to return to austenite, even though there are multiple ways for it to form from austenite. In order to create and deploy Ni-Ti-based devices, it is crucial to comprehend the properties of Ni-Ti SMAs, such as SME and pseudo elasticity (Fu et al., 2014; Ho et al., 2004).

4.2Pseudo Elasticity

The Ni-Ti SMA's capacity to regain its original shape under load following significant deformation is referred to as pseudo elasticity, or hyper elasticity. This Ni-Ti SMA functional characteristic is present at nearly constant temperatures and deformations, as shown in Figure 3. Super elasticity, as illustrated in Figure 4, is linked to the stress plateau and inflection point upon unloading, whereas pseudo elasticity typically relates to the observed non-linear unloading characteristics. When the SMA is made up entirely of the austenitic phase, pseudo elasticity takes place, in contrast to the SME, where martensite is generated when the SMA is cooled below Ms. Martensite changes from austenite to martensite when stress is applied and back to austenite when the stress is removed. This transition produces a martensite that is referred to as stress-induced martensite (Mohammadgholipour & Billah, 2023; Mukhawana & Philander, 2006).

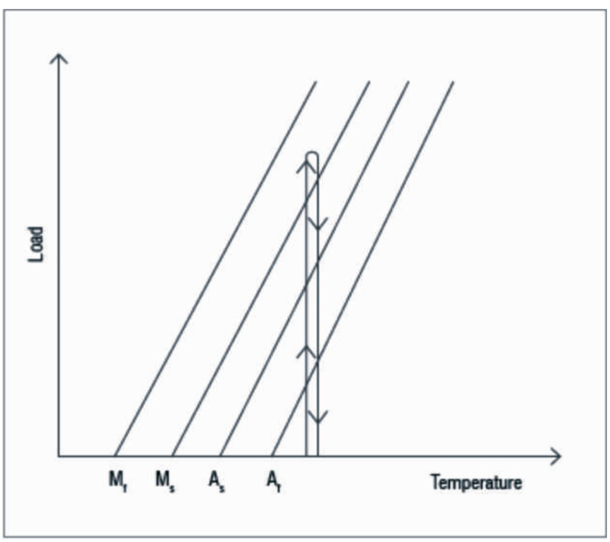

Figure 3. Load Diagram of the Pseudo Elastic Effect (Nasser & Guo, 2006)

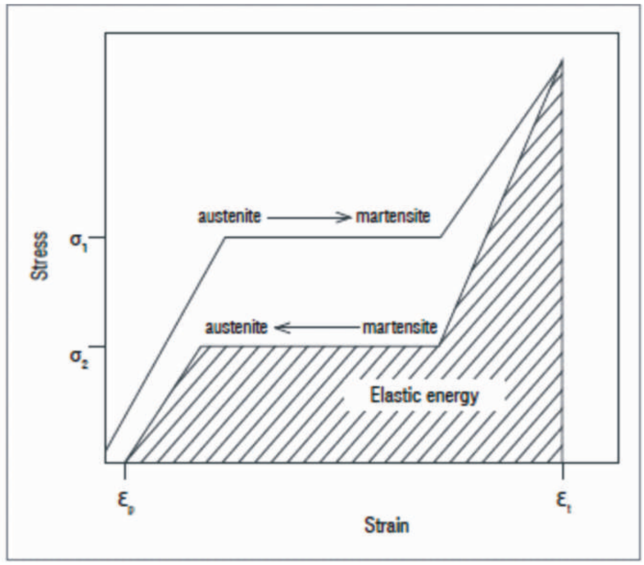

Figure 4. Stress Versus Strain Characteristics Showing Super Elasticity (Mukhawana & Philander, 2006)

5. Comparison of Various Types of Shape Memory Alloys (SMAs)

Table 3 presents a comparison of NiTi alloys with various types of shape memory alloys. In this paper, a comprehensive comparison of different SMAs is provided, highlighting their thermal and mechanical properties.

6. Applications of Shape Memory Alloys

The Ni-Ti SMA's capacity to regain its original shape under load following significant deformation is referred to as pseudo elasticity, or hyper elasticity. This Ni-Ti SMA functional characteristic is present at nearly constant temperatures and deformations. Super elasticity is linked to the stress plateau and inflection point upon unloading, whereas pseudo elasticity frequently relates to the observed non-linear unloading characteristics. When the SMA is made up entirely of the austenitic phase, pseudo elasticity takes place, in contrast to the SME, where

S. N.	Properties	Ni-Ti	Cu-Zn-Al	Cu-Al-Ni	Cu-Al-Be	Units
1	Melting point	1260-1310	950-1020	1000-1050	970-990	^{0}C
2	Density	6400-6500	7800-8000	7100-7200	7300	Kg/m^3
3	Electrical resistance	0.5-1.1	0.7-0.12	0.1-0.14	0.7-0.09	Ω
4	Thermal Conductivity at room temperature	10-18	120	75	-	W/mK
5	Expansion Coefficient	6.6-10	17	17	-	10^{-6}/K
6	Specific heat	490	390	440		J/Kg^{0}C
7	Transformation enthalpy	28000	7000	9000	7200	
8	Young's Modulus	95	70-100	80-100	90	GPa
9	Tensile resistance	800-1000	800-900	1000	900-1000	MPa
10	Fracture elongation	30-50	15	8-10	15	%
11	Yield fatigue resistances	350	270	350		MPa
12	Grain size	20-100	50-300	30-300	100-500	µm
13	Transformation domain	-100 to100	-100 to100	-100 to 170	-200 to 150	^{0}C
14	Hysteresis (As-Mf)	20-40	10-20	20-30	15-20	^{0}C
15	Spread (Af-As)	30	10-20	20-30	15-20	^{0}C
16	Maximum temperature use (1 hour)	400	160	300	400	^{0}C
17	Corrosion resistance	Excellent	Average	Good	Average	%
18	Biocompatibility	Good	Bad	Bad	Bad	-

Table 3. Comparison of NiTi alloys with Various Types of Shape Memory Alloys (Singh et al., 2021; Song, 2010; Song et al., 2006)

martensite is generated when the SMA is cooled below Ms. Martensite changes from austenite to martensite when stress is applied and back to austenite when the stress is removed. This transition produces a martensite that is referred to as stress-induced martensite (Mohammadgholipour & Billah, 2023; Mukhawana & Philander, 2006; Naresh et al., 2016).

Conclusion

Shape Memory Alloys represent an innovative group of materials that connect fundamental research with industrial applications. Continued collaborative research will ensure that these alloys not only address contemporary engineering requirements but also expand their scope in advanced technologies. Despite their remarkable properties, challenges such as cost, fatigue life, and large-scale manufacturing still persist. Therefore, future research should focus on the development of high-temperature SMAs, sustainable and cost-effective processing techniques, hybrid integration with composites and nanomaterials, and their applications in emerging fields such as soft robotics, micro-actuators, and space technology.

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