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Research Paper

A Review of Shape Memory Alloys: Fundamental, Microstructure Property, and Emerging Trends in Industrial Applications

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Abstract

Shape Memory Alloys (SMAs) are an exceptional category of functional materials that can restore predefined shapes or sustain substantial reversible deformations through thermoelastic martensitic transformations. In recent years, SMAs have attracted significant interest due to their unique combination of mechanical adaptability, durability, and multifunctionality, making them highly relevant for advanced engineering applications. This review provides a detailed examination of SMAs, including their classification into Ni, Cu, Fe-based, and emerging high-entropy alloy (HEA) systems, as well as a historical perspective on the development of the Shape Memory Effect (SME) and Superelasticity (SE). The discussion addresses critical factors influencing SMA performance, such as alloy chemistry, microstructural characteristics, processing techniques, quenching and homogenization treatments, and transformation temperatures (M_s , M_f, A_s, A_f). Applications are explored with a focus on NiTi alloys in biomedical devices and precision actuators, Fe–Mn–Si for structural use, and Cu–Zn–Al for energy-efficient and cryogenic applications. Emerging directions, including soft robotics, thermal energy devices, and architected SMA structures enabled by additive manufacturing, are reviewed, along with strategies to mitigate issues such as cyclic degradation, hysteresis, and reliability concerns. By integrating theoretical insights with practical considerations, this review highlights the growing industrial relevance of SMAs as versatile, high-performance materials for next-generation adaptive systems.

Keywords: *Shape Memory Alloy, Phase, Transformation*

INTRODUCTION

Shape Memory Alloys (SMAs) are functional materials that recover their original shape after plastic deformation when heated above their phase transformation temperature. This phenomenon is known as the shape memory effect (SME), which is the ability of an alloy to recover its original shape and dimensions after deformation (q). In addition to SME, the functional behavior of SMAs can also appear in the form of pseudoelasticity (PE) or superelasticity, so that, in general, the unique properties of SMAs are classified into these two main categories. SMAs with SME properties show shape recovery after deformation in the martensitic state, followed by heating beyond the austenite temperature (Ovat et al., 2012). This mechanism is driven by a reversible martensitic transformation, where the austenite phase (parent phase) at high temperatures transforms into martensite at low temperatures. This transformation involves a complex twinning mechanism and atomic reorganization in the crystal lattice, thus enabling reversible deformation.In contrast, PE or superelasticity occurs when the alloy is austenitic due to rapid quenching. When a load is applied, stress-induced martensite forms, and when the load is released, the structure returns to austenitic, resulting in reversible deformation without the need for additional heating

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(Lohan et al., 2014; Amran et al., 2022). An illustration of the SME and PE mechanisms can be seen in Figure 1.

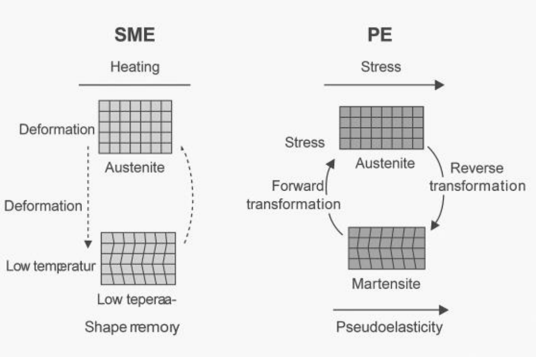

Figure 1. Schematic atomic transformation in shape memory alloy

LITERATURE REVIEW

In recent decades, the development of smart materials has become a major focus in materials engineering and manufacturing. Among the various types of smart materials, Shape Memory Alloys (SMAs) stand out due to their ability to return to their original shape after undergoing plastic deformation, a phenomenon known as the shape memory effect (SME), which occurs under the influence of heat (Alaneme et al., 2016; Mohammed et al., 2023; Srivastava et al., 2022). This shape memory (SME) ability is caused by the thermoelastic transformation of the parent phase, known as austenite, into the β' martensite phase. Pseudelasticity (PE), on the other hand, is a state in which a material can return directly to its original shape after being loaded without requiring heating (Gu et al., 2022; Patel et al., 2020). In general, the need for materials that combine superior mechanical properties, adaptability, and resistance to extreme conditions is increasing, particularly in current technologies such as aerospace, biomedical, automotive, renewable energy, precision actuator systems, and sensors. SMAs offer a unique solution to meet these demands through a reversible phase transformation mechanism between martensite and austenite. Furthermore, control of the alloy's microstructure and composition provides high flexibility in tailoring its thermomechanical properties to specific applications (Tatverthi et al., 2022). However, despite their extensive development and application, various challenges remain that require in-depth review, such as phase stability during thermal cycling, aging effects, and limitations in fabrication processes and production costs. Therefore, it is important to systematically review the fundamental aspects, microstructure–property relationships, and recent trends in industrial applications to understand the future direction of these materials.

RESEARCH METHOD

This study employed a systematic literature review approach to identify fundamental developments, microstructure–property relationships, and industrial application trends of Shape Memory Alloys (SMA). Literature searches were conducted in Scopus, ScienceDirect, Web of Science, IEEE Xplore, and Google Scholar databases using the keywords: “shape memory alloy”, “martensitic transformation”, “microstructure”, “superelasticity”, and “industrial application” in the period 2000–2025. Selected articles met the following criteria: in English, published in peer-reviewed journals, book, and discussing fundamental aspects, microstructure, or applications of SMAs based on NiTi, Cu–Zn–Al, or Cu–Al–Ni. Articles that were irrelevant or without scientific data were excluded. The selection process was conducted through screening stages of titles, abstracts, and full-text articles. The obtained data were synthesized thematically based on three main categories, namely: (1) basic mechanisms and phase transformations, (2) the influence of microstructure on mechanical and thermal properties, and (3) development trends and industrial applications of SMAs.

FINDINGS AND DISCUSSION

Shape Memory Alloy Classification

The SMAs can be classified into three main groups based on their alloy composition: Ni-, Cu-, and Fe-based (Dasgupta et al., 2014). Ni-based alloys are renowned for their exceptional functional stability and are widely utilized in biomedical applications, precision actuators, and stent devices. Cu-based alloys, such as Cu–Zn–Al and Cu–Al–Ni, offer lower production costs and ease of fabrication. However, they tend to experience degradation of functional properties due to repeated cycling (Setyani et al., 2023). Meanwhile, Fe-based alloys, such as Fe–Mn–Si, offer advantages in mechanical strength and hold promise for large-scale structural applications. The functional behavior of SMAs is influenced by several important factors, including the chemical composition of the alloy, the electron-to-atom ratio (e/a ratio), grain size, intermetallic precipitation, and the applied heat and mechanical treatment conditions. In addition, the transformation temperatures (Ms, Mf, As, Af) are crucial parameters that determine the activation conditions of SMEs and PEs, making composition and processing control key to optimizing material performance. Current applications of SMAs include minimally invasive medical devices, adaptive actuators in aerospace and automotive applications, vibration-damping systems, and intelligent robotics, which emphasize their significance in modern engineering (Mohammed et al., 2023; Hui et al., 2024). To date, approximately 20 transition metal alloys have been identified that exhibit shape memory properties, including Ag–Cd, Au–Cd, Cu–Al–Ni, Cu–Al–Mn, Cu–Au–Zn, Cu–Sn, Cu–Au–Sn, Cu–Zn, Cu–Zn–Al, Cu–Zn–Sn, Cu–Zn–Ga, Cu–Zn–Si, In–Ti, Ni–Al, Ni–Ti, Fe–Pt, and Fe–Pd. However, the current focus of research and development remains on three major groups: Ni-Ti-based, Cu–Al, and Fe–Pd alloys (Dasgupta et al., 2014). Each alloy group has its own advantages and limitations. NiTi alloys exhibit superior shape memory properties and superelasticity. However, large-scale production is challenging due to high costs and the reactivity of Ti to oxygen, which complicates the melting and fabrication processes. Therefore, the development of alternative Cu and Fe alloys is attracting increasing attention. Cu alloys offer better effectiveness and efficiency in terms of functional performance and production costs than Fe-based alloys. In contrast, Fe alloys remain relevant for structural applications due to their superior mechanical properties.

NiTi-based SMA

NiTi-based alloys, known as Nitinol, are the most widely used commercially available SMA systems. Their advantages include high recoverable strain (up to 8–10%), good thermomechanical stability, corrosion resistance, and biocompatibility, making them a prime choice for biomedical applications such as stents, orthopedic implants, and orthodontic archwires (Farber et al., 2020). Furthermore, Nitinol also finds applications in aerospace, robotics, and precision actuator devices. The stability of the martensitic transformation in NiTi is strongly influenced by Ni_4Ti_3 precipitation, which can modify the transformation temperature (Ms, Mf, As, Af) and control hysteresis. However, NiTi has limitations in the form of high production costs and fabrication challenges due to Ti's reactivity with oxygen, which can affect compositional homogeneity.

Cu-based SMA

Cu-based alloys, particularly the Cu–Zn–Al and Cu–Al–Ni systems, have been developed as an alternative with easier fabrication and flexibility in controlling the transformation temperature through composition control and heat treatment (Setyani et al., 2023). Microelements with elements such as Gd or Mn are known to increase the stability of the β phase, slow atomic diffusion, and reduce secondary precipitation that can inhibit martensitic transformation. These systems are widely considered for structural and actuator applications in mechanical devices. However, Cu-based SMA is relatively susceptible to degradation of functional properties due to repeated thermomechanical cycling; therefore, microstructural optimization strategies through grain refinement and controlled quenching treatments have become the focus of recent research.

Fe-based SMA

Fe-based SMAs, particularly Fe–Mn–Si and its derivatives, stand out for their high mechanical strength and potential for large-scale applications, such as concrete reinforcement systems and bridge structural components. The shape recovery mechanism in these systems is dominated by stress-induced martensite formation, which can be recovered by heating. Although the recoverable strain is lower than that of NiTi, recent research has shown that compositional modification (e.g., Fe–Mn–Si–Cr or Fe–Mn–Al–Ni) can enhance stress recovery and expand their application areas, including energy systems and vibration damping.

HEA-based SMA Systems

In addition to the three main groups, several other alloys are also being developed for specialized applications. Ti–Nb-based SMAs attract attention due to their β phase stability, which can produce superelasticity at room temperature and compatibility with additive manufacturing. Co–Ni–Al or Co–Ni–Ga-based SMAs, which fall under the ferromagnetic SMA (FSMA) category, can respond to external stimuli in the form of magnetic fields, thus offering potential applications in sensors and magneto-mechanical actuators. On the other hand, high-entropy SMAs (HE-SMAs) that utilize the principle of high-entropy configuration offer the opportunity to obtain wider transformation hysteresis, lower hysteresis, and better cyclic resilience (Hui et al., 2024).

History of Shape Memory Alloy Development

The shape memory effect (SME) phenomenon was first observed by Arne Ölander in 1932 while studying a gold–cadmium (Au–Cd) alloy. He discovered the alloy could return to its original shape after being plastically deformed and heated. This discovery began the understanding that some metal alloys can undergo a reversible martensitic transformation. In 1949, research on Au–Cd alloys advanced. These studies revealed the fundamental properties of SME and the alloy's thermoelastic behavior, and even began to be explored for biomedical applications such as dentistry. However, limitations such as Cd toxicity and high production costs prevented its continued use. A significant development occurred in the 1960s, when William Buehler and Frederick Wang of the Naval Ordnance Laboratory (USA) discovered a Ni–Ti alloy, later known as Nitinol (Nickel Titanium Naval Ordnance Laboratory). Nitinol exhibited high functional stability, strong SME, and superelastic properties, opening up opportunities for broad industrial applications. Since then, NiTi has become the most dominant SMA alloy. In the 1970s–1980s, Nitinol development focused on automotive, aerospace, biomedical, and robotics applications. This period marked the transition of SMA from a scientific phenomenon to a functional material with practical applications. Entering the 1990s, research attention shifted to the search for alternative alloys that were more economical while still possessing good functional properties. Copper-based alloys (Cu–Zn–Al, Cu–Al–Ni) and iron-based alloys (Fe–Mn–Si) began to be developed.

Factors Affecting Sma

The functional properties of SMA, both shape memory effect (SME) and superelasticity (SE), are the result of a complex interaction between chemical composition, processing conditions, and microstructural evolution (Wayman, 1990). These factors determine phase stability, martensite morphology, and transformation parameters (Ms, Mf, As, Af).

Chemical Composition

Composition is the most fundamental factor governing the stability of the austenite and martensite phases. The electron-to-atom ratio (e/a ratio) is critical in determining the relative free energies between phases. In the NiTi system, slight variations in Ni content (±0.1 at.%) can shift the transformation temperature by tens of degrees. In the Cu–Zn–Al system, Zn or Al concentration changes can determine whether the alloy is in the stable α+β or β domain. Adding microelements such as Si, Mn, or Ti has been shown to slow atomic diffusion, stabilize the β phase, and suppress secondary precipitation, ultimately affecting cycle life and functional durability.

Martensite Morphology

Martensite in SMAs generally forms in a twinned state to minimize internal elastic energy. Depending on the alloy system and cooling conditions, this morphology can be lath martensite, plate martensite, or needle-like martensite. During deformation, twinned martensite can reorganize into detwinned martensite, which is the basis of the SME mechanism. The stability of this martensite morphology is strongly influenced by defect density, precipitation, and crystal orientation.

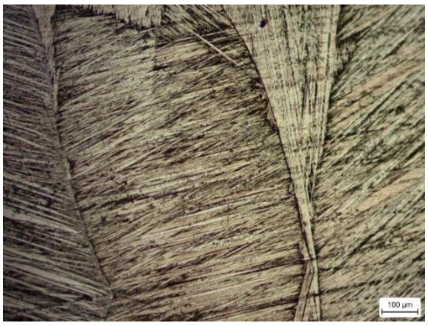

Figure 2. Microstructure of a shape memory alloy with a needle-like shape

Quenching Rate

The cooling rate after solution treatment or betatizing significantly determines the phase formed at room temperature. Rapid cooling (direct quench) can freeze the β phase at a metastable state, transforming into martensite when the temperature is lowered. However, excessively high cooling rates risk introducing crystal defects such as stacking faults or excessive dislocations, which reduce the homogeneity of the transformation. Conversely, step-quench or up-quench methods allow for partial relaxation of defects, improve atomic ordering, and produce a more homogeneous martensite responsive to thermoelastic deformation (Setyani et al., 2023; Lohan et al., 2014).

Dissolution and Homogenization Process

The homogenization and dissolution (betatizing) stage is crucial in controlling the microstructure of SMAs. Homogenization at high temperatures aims to reduce chemical segregation formed during the melting process. Segregation of Zn or Al in the Cu–Zn–Al system, or Ni in the NiTi system, is known to trigger the premature formation of the equilibrium α phase, thereby reducing the fraction of reversible martensite, a key requirement for the shape memory effect (SME) (Wayman, 1990). Therefore, effective homogenization is crucial for the quality of the initial phase formed before the martensitic transformation occurs. Betatizing is performed to form a single solid solution in the parent β phase, which is then quenched. In Cu–Zn–Al alloys, this process is carried out above the β transformation temperature (T > 527 °C), because the β phase is the parent phase capable of non-diffusional transformation into β′ martensite, which is the basis of SME (Lobo et al., 2015). The selection of the betatizing temperature must take into account the distance from the solidus line. If heating is carried out too close to the line, the formed austenite phase will produce stable martensite with limited shape recovery ability. Too high a betatizing temperature has the potential to cause excessive grain growth, pore formation, and changes in crystal plane orientation that affect the mobility of the martensite interface. Studies on NiTi have shown that Ni_4Ti_3 precipitation formed during this stage can modify the transformation temperature (Ms, Mf, As, Af), improve hysteresis, and increase cycle stability. The combination of effective homogenization, solutionizing at the appropriate β temperature, and rapid cooling is an important strategy to control the microstructural stability, martensite morphology, and transformation temperature. Optimization of these parameters not only determines the formation of the precipitation-free β phase, but also affects the long-term functional properties, including recoverable strain and resistance to degradation due to repeated cycling.

Microstructural Stability

The microstructure of SMAs consists of a parent phase (austenite) and a product phase (martensite), which can coexist with a second phase such as α in Cu–Zn–Al or Ni_4Ti_3 precipitation in NiTi. Composition, heat treatment, and cooling rate influence microstructural stability. A second phase, such as α, can increase mechanical strength but potentially reduce the homogeneity of the martensitic transformation. Therefore, controlling the fraction of the second phase is crucial to balance mechanical and functional properties.

Phase Transformation

Nondiffusional martensitic transformation (β → β′ or β → γ′) is the core of the functional properties of Shape Memory Alloys (SMA). This process occurs due to the difference in relative free energy between the phases, where the parent β phase (austenite), which is stable at high temperatures, transforms into martensite at low temperatures through a collective atomic shear mechanism without diffusion (Wayman, 1990). The characteristics of this transformation are determined by four critical parameters: M_s (martensite start), M_f (martensite finish), A_s (austenite start), and A_f (austenite finish). The M_s and M_f values describe the temperature range from the start to the end of martensite formation during cooling. At the same time, A_s and A_f indicate the temperature range in which austenite reforms during heating. These four parameters determine whether SMA will behave as a material with a shape memory effect (SME) or superelasticity (SE). A narrow transformation temperature range (hysteresis) with high cyclic stability is highly desirable for practical applications, as it ensures deformation reversibility and consistent performance. However, this transformation temperature stability is strongly influenced by chemical composition, cooling rate, and heat treatment. For example, increasing the Zn or Al content in Cu–Zn–Al can lower the M_s . At the same time, the presence of excess α phase due to segregation widens the hysteresis and reduces the fraction of reversible martensite. Homogenization and solutionization followed by quenching are crucial in producing a precipitation-free β phase that can fully transform to martensite.

Furthermore, varying quenching methods can modify the internal energy distribution and crystal ordering, shifting the M_s value or narrowing the hysteresis. UQ, for example, can reduce crystal defects caused by rapid cooling by introducing a reheating step, increasing martensite homogeneity, and improving cyclic stability. From a deformation perspective, martensite forms in a twinned state to balance internal stresses, and during external loading, it can undergo a detwinning mechanism. This process reverses the deformation that can be recovered when the material is heated beyond A_f. The transformation temperature parameters (M_s , M_f, A_s, A_f) are not merely indicators of thermal characteristics but also direct reflections of the microstructure, morphology of the martensite, and the internal energy state generated by the composition and heat treatment. Controlling the alloy composition, homogenization treatment, cooling rate, and post-treatment are key to achieving controlled, reversible, and long-term stable martensitic transformation in industrial applications.

Shape Memory Alloy Applications

Shape Memory Alloys (SMAs) show a growing trend in industrial applications, ranging from aerospace and automotive applications to civil construction, energy, biomedicine, and robotics. Due to its functional resilience, NiTi is used in stents, precision actuators, and seismic mitigation systems. Meanwhile, Fe–Mn–Si has the potential to be developed for structural applications, and Cu–Zn–Al continues to be researched for applications ranging from energy-efficient actuators to cryogenic applications (Basak et al., 2021; Patel, 2018). The latest innovations in the use of SMA include soft robotics, thermal switch-based energy devices, and additive manufacturing (AM) that enable complex porous designs with dual functions. Integrating data-driven modeling, CALPHAD, and machine learning further accelerates composition engineering and functional property optimization. Key challenges, such as cyclic degradation, wide hysteresis, and reliability issues, are now being addressed through microevolution, grain refinement, and targeted post-processing. With this development direction, SMA is projected to become a key material for future technologies that demand adaptive, lightweight, and high-performance systems.

CONCLUSIONS

Shape Memory Alloys (SMAs) exhibit unique functional responses, shape memory effect (SME) and superelasticity (SE), arising from reversible martensitic transformations governed by composition, microstructure, and heat treatment parameters. The optimization of phase stability and transformation behavior depends strongly on homogenization, solution treatment, and cooling processes. Despite remarkable progress, SMAs still face issues such as cyclic degradation, wide hysteresis, and narrow temperature ranges. From a practical standpoint, enhanced thermomechanical optimisation and the adoption of additive manufacturing can improve transformation stability and broaden the applicability of SMAs in actuators, sensors, and biomedical systems. Future research should focus on integrating CALPHAD-based modelling, machine learning, and sustainable alloy design to develop more durable, reversible, and adaptive smart materials for next-generation industrial applications.

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