Advances in Engineering Research : Possibilities and Challenges
ISSN Print: 3079-5192
ISSN Online: 3079-5206
https://doi.org/10.63313/AERpc.9024

Research Progress on Performance Regulation and Application of Ti-Ni-Based, Fe-Based, and Cu-Based Shape Memory Alloys

Furong Zou. Shuai Ma*. Yuxing Jiang and Zhixiang Peng
Hu'nan University of Arts and Science Furong College, Changde, Hu'nan 415000, China
Email: 1255843321@qq.com

How to cite this paper: Zou, F. R., Ma, S., Jiang, Y. X., & Peng, Z. X. (2025). Research Progress on Performance Regulation and Application of Ti-Ni-Based, Fe-Based, and Cu-Based Shape Memory Alloys. Advances in Engineering Research : Possibilities and Challenges, 1(3), 17-24. ISSN Print: 3079-5192; ISSN Online: 3079-5206.
Published: 2025-06-05

Abstract

This paper reviews the system characteristics and application progress of shape memory alloys (SMAs). SMAs realize the shape memory effect (SME) and superelasticity (SE) through solid-solid phase transformations (such as B2↔B19'), and their performance is regulated by phase transformation temperatures (Ms/As), hysteresis width, and strain recovery rate. Among the three main alloy systems: Ti-Ni-based alloys dominate high-end medical and aerospace fields due to their highly reversible thermoelastic transformations and biocompatibility, though noble metal doping is needed to improve high-temperature performance; Fe-based alloys exhibit potential for low-cost engineering applications through non-thermoelastic transformations (such as $\gamma \rightarrow \varepsilon$ martensite); Cu-based alloys balance cost and performance via stacking fault energy regulation, with fatigue resistance optimization being the core challenge. Studies show that annealing processes (e.g., annealing Ti-Ni alloys at 673–773 K) and composition design (e.g., Fe-Mn-Al-Ni gradient alloys) can significantly enhance phase transformation stability. Future work should integrate multi-scale phase transformation mechanisms and advanced manufacturing techniques (such as 4D printing) to expand the engineering applications of SMAs in intelligent systems and extreme environments.

Keywords

Shape memory alloys; Ti-Ni-based shape memory alloys; Fe-based shape memory alloys; Cu-based shape memory alloys

1. Introduction

Shape Memory Alloys (SMAs), as intelligent materials, have rapidly become a research focus in materials science since their discovery in the 1960s due to their unique integration of sensing and actuation properties. With the growing demand for adaptive materials in aerospace, biomedical, intelligent manufacturing, and other fields, SMAs, owing to their reversible deformation capability and high energy density, have gradually become core materials for high-end equipment and precision devices12. In recent years, the development of additive manufacturing technologies (such as 4D printing) has further promoted the functional customization and performance optimization of SMAs, providing new directions for their applications in extreme environments.

The core characteristics of Shape Memory Alloys (SMAs) encompass three interrelated mechanisms:

The Shape Memory Effect (SME) manifests as the material's ability to recover its original shape upon heating to a critical temperature after being deformed at low temperatures. This effect fundamentally arises from the reversible phase transformation between austenite (high-temperature phase) and martensite (low-temperature phase) — for example, the transition between B2 austenite and B19' martensite in Ni-Ti alloys — which drives the reconstruction of the crystal structure.

Superelasticity (SE) refers to the material's ability to undergo large strains (up to 8%) under external stress within a specific temperature range, and spontaneously return to its original shape upon unloading without heating. This behavior is primarily governed by stress-induced martensitic phase transformation.

The physical basis of both SME and SE is the solid-solid phase transformation mechanism, wherein the crystal structure undergoes reversible reconstruction under external stimuli (temperature or stress), accompanied by significant volume and shape changes. For example, the phase transformation temperatures of Ni-Ti alloys can be precisely tuned by adjusting the composition to meet different application requirements.

Currently, more than 30 types of SMAs have been identified, which can be grouped into three major categories: Ni-Ti-based alloys, Cu-based alloys, and Fe-based alloys. Generally, Ti-Ni-based alloys have the highest performance but also the highest cost; Fe-based alloys offer great potential due to low cost; and Cu-based alloys strike a balance between cost and basic performance. The type of martensitic phase transformation (thermoelastic/non-thermoelastic) directly determines the activation mechanisms of SME and SE. Key parameters include transformation temperatures (Ms, As), hysteresis width, and strain recovery rate, which collectively form a quantitative evaluation system for alloy performance. The phase transformation behaviors differ significantly among alloy systems: Ti-Ni-based alloys feature highly cooperative crystal structure reconstruction; Fe-based alloys rely on stress-field-driven non-thermoelastic transformation paths; while Cu-based alloys achieve fine control over the phase transformation process through the movement of stacking fault interfaces.

2. Ti-Ni-based shape memory alloys

Ti-Ni shape memory alloys (SMAs) are costly and difficult to process, but they offer advantages such as high strength, fatigue resistance, corrosion resistance, wear resistance, high shape recovery rate, and excellent biocompatibility, which has led to their widespread application. Depending on the environmental temperature, Ti-Ni alloys exhibit three different phases: the high-temperature CsCl phase (B2 phase), the intermediate-temperature R phase, and the low-temperature martensite (M) phase.

The one-way shape memory effect of SMA materials manifests as follows: at room temperature, the material has a certain shape; when deformed under low temperature by an external force, heating it back restores it to the room temperature shape; returning it to the low temperature environment, the shape remains unchanged. Beyond the one-way shape memory effect, Ni-Ti alloys can exhibit two-way and full-shape memory effects after specific treatments such as multiple heating-cooling cycles, constrained heating, and aging. The realization processes of one-way, two-way, and full-shape memory effects are summarized in Table 1.1.

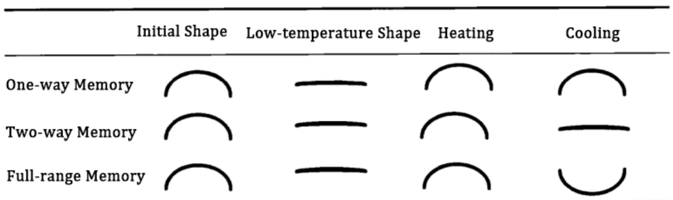

Table 1.1 One-way Memory, Two-way Memory, and Full Shape Memory Effects

He Zhirong [3][4] and others studied Ti-Ni alloy annealing behavior at different temperatures using differential scanning calorimetry (DSC) (Figure 1). Increased damping raises the density of Ti-Ni superelastic (SE) alloys but decreases energy storage efficiency. Annealing Ti-Ni alloys between 673 K and 773 K can achieve excellent shape memory properties; cooling methods and quenching frequency have minimal influence on phase transformation types and SME. With increasing Ni content in annealed Ti-Ni alloys, the transformation temperature decreases while thermal hysteresis widens. Near-equiatomic and Ni-rich Ti-Ni alloys exhibit superior shape memory performance compared to Ni-poor alloys. As annealing temperature rises, the hysteretic elastic area of SE alloys enlarges, damping characteristics strengthen, but energy storage density and efficiency decline. The phase transformation behavior and deformation characteristics of Ti-Ni alloys are significantly affected by both Ni content and annealing temperature.

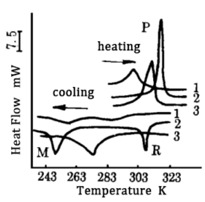

Figure 1:DSC curves of thermal analisis of Ti Ni alloy under differentprocessing states

1. Cold working state 2. 693K annealing

3. Solution-treated at 1113K + Annealed at 533K

Commercial Ti-Ni alloys typically have transformation temperatures below 100 ℃, constraining their service temperature range and limiting their applications in high-temperature environments. To address this, two series of alloys have been developed by substituting Ti with Zr or Hf (Ti-Ni-X, X=Zr, Hf), and Ni with Pd, Pt, or Au (Ti-Ni-Y, Y=Pd, Pt, Au). By adjusting alloy composition, their transformation temperatures can be tuned above 500 ℃, and they exhibit superior hot and cold workability compared to other high-temperature SMAs. Cai Wei [7] and colleagues found that adding Pd, Pt, or Au significantly increases the martensite start temperature (Ms). For example, in $Ti_{50}Ni_{50-x}Pd_x$ alloys, when the Pd content exceeds 10 atomic percent, Ms increases linearly at a rate of 15℃ per atomic percent. Ti-Ni-Pt alloys may have Ms temperatures exceeding 1000 ℃ but are costly. Zr and Hf additions also raise Ms but to a lesser extent than noble metals. The martensite phase adopts a B19' structure, primarily with (001) compound twins, differing from the <011>II-type twins found in binary Ti-Ni alloys.

Ti-Ni SMAs possess excellent biocompatibility and are widely used in biomedical devices such as thrombosis filters and orthopedic bone plates. A Ti-Ni SMA thrombosis filter is a novel medical device; once implanted into a vein after being straightened, it gradually recovers into a mesh structure that blocks up to 95% of blood clots from flowing to the heart and lungs. In orthopedic treatments, Ti-Ni SMAs have replaced traditional bone plates and steel wires. The method involves cooling the Ti-Ni device in disinfectant saline at 0 – 5 ℃, configuring its shape to fit the fracture site, and implanting it. Once warmed to body temperature, the device recovers its original shape to firmly secure and support the fractured bone. This technique is simple, exhibits excellent biocompatibility, reduces manual injury, and provides strength four times that of stainless steel without bending or fracturing.

3. Fe-based Shape Memory Alloys

Since their development, Fe-based SMAs have drawn attention due to their low cost, excellent processing capabilities, and good weldability, being recognized as promising new shape memory materials. In typical Fe-based SMAs, phase transformations (MTs) are generally divided into two groups based on austenite and martensite crystal structures:

(1) Transformation between face-centered cubic (fcc) γ-austenite and body-centered cubic (bcc) α or body-centered tetragonal (bct) α′ martensite phases (e.g., Fe-Pt, Fe-Ni-Co-Ti, Fe-Ni-Co-Al, Fe-Ni-Co-Al-Ta alloys);

(2) Transformation between fcc γ-austenite and hexagonal close-packed (hcp) ε-martensite phases (e.g., Fe-Mn-Si, Fe-Ni-Cr alloys).

A distinctive advantage of Fe-based SMAs lies in their functional transformation from a soft Kfz high-temperature phase to hard bcc or hcp crystal structures, unlike Ti-Ni- or Cu-based SMAs that only have hard Kfz high-temperature phases without such transformation—this makes Fe-based SMAs uniquely competitive. Fe-based

SMAs are suitable for pipe joints with significant market potential, and Fe-Mn-Si shape memory pipe joints can be mass produced using conventional steel or stainless steel equipment.

Fe-Ni-Co alloys are not only low-cost and high-strength but also exhibit pronounced magnetic shape memory effects. Through aging treatment and composition optimization, these alloys can transition from non-superelastic to superelastic behavior, broadening their application scope. Fe-Mn-Si alloys primarily realize SME via stress-induced $\gamma \rightarrow \varepsilon$ martensitic transformation and its reverse. Alloying elements such as Mn, Si, C, and Ni have notable impacts on stacking fault energy, SME, transformation temperatures, and corrosion resistance. By optimizing composition and heat treatment processes, the SME of Fe-Mn-Si alloys has significantly improved. Moreover, Fe-Mn-Al-Ni alloys, a new type of Fe-based SMA, demonstrate excellent superelastic responses and low stress hysteresis with outstanding performance across a wide temperature range, offering promising application prospects.

The pitting corrosion sensitivity of Fe and Fe-based alloys is closely related to the electronic properties of their passive films. Parameters such as electron donor concentration in the passive film, formation potential, type of passivator, and alloy microstructure strongly influence pitting susceptibility. Interactions among different microstructures can also initiate and propagate pitting on more sensitive regions.

Atomic force microscopy (AFM) observations of fractured surfaces of Fe-based nanocrystalline thin strips reveal clear mesoscale structure differences between the roller-contacted face and the free surface after annealing crystallization. This phenomenon arises from residual internal stress differences caused by single-roll rapid quenching during strip preparation. AFM offers an effective tool to study mesoscale structures in Fe-based nanocrystalline strips.

4. Cu-based Shape Memory Alloys

Cu-based SMAs mainly comprise two series: Cu-Zn and Cu-Al alloys. Among them, Cu-Al alloys generally feature higher Ms temperatures and superior structural stability compared to Cu-Zn alloys. Compared with Ti-Ni SMAs, Cu-based alloys have higher transformation temperatures, especially Cu-Al-Ni alloys that can develop into high-temperature SMAs. Cu-Sn and Cu-Zn-Al alloys tend to exhibit aging effects like martensite stabilization (aging effects in the martensite phase, primarily manifesting as an increase in As during reverse martensitic transformation).

Cu-Al-Ni SMAs, being economical with good aging stability, thermal stability, and high-temperature SME, should be widely applicable; however, they usually suffer from coarse grains and brittleness.

In high-temperature oxygen-containing environments, a metal surface forms an oxide layer whose chemical stability depends on the protective quality of the oxide film. Pure copper forms a dual-layer oxide film during oxidation (outer CuO and inner Cu_2O); however, this oxide film easily cracks or peels off, resulting in limited oxidation resistance. This has motivated researchers to improve properties through alloying.

The high-temperature oxidation behavior of binary alloys exhibits considerable complexity due to interactions between components: In single-phase alloys, if the solubility of the second element (e.g., Al, Ni) is high, element diffusion rates and oxide film density jointly determine whether a continuous external oxide film or internal oxidation forms; In duplex alloys, oxidation kinetics and oxide film structure are controlled by phase composition, distribution, and component solubility—for instance, in Cu-Al alloys, Al preferentially oxidizes to form an Al_2O_3 protective layer, though its stability depends on Al content and heat treatment. Although optimization of component ratios and microstructure can enhance oxide film protection, single-element additions often fail to balance mechanical properties and oxidation resistance. Modern high-temperature materials therefore tend to incorporate a third element (e.g., Cr, Si, rare earths) for synergistic optimization: trace rare earths can reduce the critical concentration for forming protective Cr_2O_3 or SiO_2 films, minimize main alloy element consumption, refine grain boundaries to inhibit oxide film spallation, and improve adhesion and service life. However, ternary systems feature more complex oxidation behavior due to competing thermodynamic and kinetic effects among components, with oxide films exhibiting gradient structures or mixed oxide layers. In situ characterization techniques are required to elucidate these dynamic mechanisms.

5. Applications of Shape Memory Alloys

SMAs have very broad applications, mainly including

5.1. Consumer Electronics

SMA smart devices can replace complex traditional mechanical structures, enabling miniaturization, lightweight design, and intelligent functions, extensively applied in consumer electronics.

5.2. Automotive

SMA applications in automotive fields include intelligent drive systems and adaptive suspension systems, enhancing vehicle intelligence and driving experience.

5.3. Medical

SMAs are widely utilized in medical fields for making medical clamps, prosthetics, etc., which can automatically adjust shape with body temperature changes for better fixation. Additionally, SMAs are used in medical equipment and rehabilitation devices to assist patient recovery.

5.4. Aerospace

In aerospace, SMAs manufacture morphing wings, antennas, and other components able to autonomously adjust shapes under varying environments, improving vehicle performance and adaptability.

5.5. Construction Engineering

SMAs are employed in making adjustable building components such as self-regulating windows and doors to adapt to environmental changes.

6. Conclusion

The three major SMA systems each have distinct advantages: Ti-Ni-based alloys dominate in medical and aerospace applications; Fe-based alloys highlight engineering potential; Cu-based alloys balance cost and performance. Annealing processes and compositional design can optimize phase transformation stability, while advanced technologies like 4D printing promote applications under extreme conditions. Future breakthroughs require enhanced high-temperature performance and grain boundary control, deeper multidisciplinary integration, and expansion toward large-scale applications in smart actuation and energy recovery.

Acknowledgments

The funding for the 2025 Hunan University of Arts and Science Furong College's Undergraduate Innovation and Entrepreneurship Project at the college level is self-raised；Key Research Project Support of Furong College, Hunan University of Arts and Sciences (FR23 ZD01).

References

[1] Gao Qianqian. Study on Influencing Factors of Self-Healing Performance of SMA Concrete Beams [D]. Shenyang Jianzhu University, 2015.

[2] Cai Jifeng, He Zhirong, Liu Yan, et al. Research Progress on Ti-Ni Based Shape Memory Alloys and Their Applications [J]. Metal Heat Treatment, 2009, 34(05): 64-69.

[3] He Zhirong, Wang Fang, Zhou Jingen. Effects of Ni Content and Heat Treatment on Phase Transformation and Deformation Behavior of Ti-Ni Shape Memory Alloys [J]. Metal Heat Treatment, 2006, (09): 17-21.

[4] He Zhirong. Effects of Heat Treatment Processes on Phase Transformation and Shape Memory Behavior of Ti-Ni Alloys [J]. Metal Heat Treatment, 1999, (01): 6-8.

[5] Lü Zhonghua. High-Temperature Deformation Properties of Ti-Ni Shape Memory Alloys [J]. Journal of Jiamusi University (Natural Science Edition), 2008, (02): 175-177.

[6] Zhou Jianjie, Ma Fengcang, Liu Ping, Liu Xinkuan. Effects of Heat Treatment on Surface Properties of Ni-Ti Alloys [J]. Nonferrous Metals Materials and Engineering, 2019, 40(6): 6-13.

[7] Cai Wei, Meng Xianglong, Zhao Xinqing, et al. Martensitic Phase Transformation and Shape Memory Effect of TiNi-Based High-Temperature Shape Memory Alloys [J]. Progress in Materials Science China, 2012, 31(12): 40-47.

[8] Meng Xianglong, Cai Wei. Research Progress on TiNi-Based Shape Memory Materials and Their Applications [J]. Progress in Materials Science China, 2011, 30(09): 13-20+56.

[9] Li Weishan, Chen Hongyu, Yuan Zhongzhi, et al. Electrochemical Study on Pitting Sensi-

tivity of Passive Films on Fe-Based Alloys [J]. Electrochemistry, 2004, (04): 397-403.

[10] Fang Yunchang, Wu Fengmin, Wu Wenhui, et al. AFM Study of Mesostructure of Fe-Based Nanocrystalline Thin Strips [J]. Chinese Science Bulletin, 2004, (18): 1835-1839.

[11] Qu Naiqin. Research and Development of German Shape Memory Alloys [J]. Shanghai Nonferrous Metals, 1997, (04): 174-177+182.

[12] Xie Hua, Liu Jian, Huo Yanqiu, et al. Preferential Orientation and Microstructure Evolution of Directionally Solidified Ferromagnetic Shape Memory Alloy Co-Ni-Ga [J]. Acta Metallurgica Sinica, 2007, (04): 417-421.

[13] Huo Yanqiu, Long Xiuhui, Xie Hua, et al. Effect of the γ Phase on Martensitic Transformation and Shape Memory Effect of Magnetic Shape Memory Alloy Co-Ni-Ga [J]. Rare Metal Materials and Engineering, 2010, 39(07): 1279-1283.

[14] Zou Qin, Dang Shang, Li Yanguo, et al. Research Progress of Fe-Based Shape Memory Alloys [J]. Materials Review, 2019, 33(23): 3955-3962.

[15] Guo Mingxing, Wang Mingpu, Li Zhou, et al. Research on High-Temperature Copper-Based Shape Memory Alloys [J]. Functional Materials, 2004, (03): 5-8.

[16] Zuo Shungui, Jin Xuejun, Jin Mingjiang. Research Progress of High-Temperature Shape Memory Alloys [J]. Mechanical Engineering Materials, 2014, 38(01): 1-5+46.

[17] Li Lihui, Wan Farong, Long Yi. Influence of Heat Treatment Methods on Shape Memory Effect of Cu-Al-Mn Alloys [J]. Nonferrous Metals, 2003, (04): 13-16.

[18] Wu Genhua. Shape Memory Alloys and Their Applications [J]. Journal of Anqing Normal University (Natural Science Edition), 2004, (04): 20-23.

[19] Cao Zhongqiu, Yu Long, Li Fengchun. Research Status on High-Temperature Chemical Stability of Cu-Based Alloys [J]. Journal of Shenyang Normal University (Natural Science Edition), 2010, 28(03): 321-326.

[20] Wang Ermin, Zhao Weibiao, Zhao Zhenye, et al. Microstructure Evolution of Ni-Ti Shape Memory Alloys under High-Temperature Hot Deformation Conditions [J]. Materials Science and Technology, 1999, (S1): 251-254.