

# A Comparative Analysis of Shape Memory Alloy Systems: Performance Characteristics, Application Domains, and Implementation Challenges

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**Abstract**— Shape memory alloys (SMAs) represent a rapidly expanding class of smart materials with global market projections reaching \$20.8 billion by 2030. This comprehensive review systematically compares the performance characteristics, application domains, and implementation challenges of major SMA systems including NiTi-based, Cu-based, Fe-based, and emerging high-entropy alloys. Through systematic literature analysis of studies published between 2000-2025, this work evaluates alloy families across seven key dimensions: transformation temperatures, shape memory recovery, mechanical properties, economic factors, application suitability, manufacturing readiness, and research maturity. Binary NiTi maintains superiority in functional properties with 8-10% recoverable strain and >95% shape recovery, establishing dominance in biomedical applications. NiTi-Hf variants enable high-temperature aerospace applications above 200°C, while Cu-based systems offer cost-effective alternatives with optimized compositions approaching NiTi performance levels. Fe-based systems demonstrate growing potential in civil infrastructure through superior cost-effectiveness and environmental durability. The analysis reveals critical trade-offs between performance, cost, and processability, with no single system excelling universally. Application-specific optimization proves more critical than absolute performance metrics, as different engineering domains prioritize distinct material characteristics. Manufacturing maturity varies significantly, with NiTi benefiting from extensive processing infrastructure while emerging systems require specialized development. Key research gaps include standardized testing protocols, predictive processing-property models, environmental degradation mechanisms, and lifecycle sustainability assessments. This systematic framework provides objective criteria for material selection and identifies strategic directions for advancing SMA technology adoption across diverse engineering applications.

**Keywords**— Shape memory alloys, superelasticity, engineering applications, material selection, smart materials.

## I. INTRODUCTION

The global smart materials market is experiencing unprecedented growth, with shape memory alloys (SMAs) representing one of the fastest-expanding segments, projected to reach \$20.8 billion by 2030 with a compound annual growth rate of 12.3% [1]. This expansion is driven by increasing applications across biomedical devices, aerospace actuators, and civil infrastructure, where SMAs enable revolutionary solutions through their unique ability to recover predetermined shapes in response to thermal or mechanical stimuli. The market growth reflects not only technological advancement but also the growing recognition of SMAs as enabling technologies for next-generation adaptive and intelligent systems.

Biomedical applications currently lead adoption rates due to the superior biocompatibility and superelasticity of NiTi alloys in stents, orthodontic devices, and surgical instruments [2]. Civil engineering applications are demonstrating significant benefits in seismic resilience through SMA-reinforced concrete systems and cable-restrained bearings that provide superior energy dissipation and self-centering capabilities [3], [4]. Aerospace and automotive sectors are increasingly integrating SMAs as compact, high-force actuators and morphing elements that reduce complexity while improving adaptability under demanding operational conditions.

Shape memory alloys have evolved from early binary NiTi systems to complex multi-component alloys including high-temperature NiTi-Hf variants, cost-effective Cu-based alternatives, and structurally-oriented Fe-based systems, each optimized for specific application requirements and operational environments. Recent technological advancements in additive

manufacturing, advanced characterization techniques, and constitutive modeling have accelerated SMA adoption by enabling complex geometries, improved property control, and predictive design capabilities.

While extensive research exists on individual SMA systems and their specific properties, there is limited comprehensive research that synthesizes the comparative performance characteristics, application suitability, and implementation challenges across different alloy families. Most studies focus on single systems or narrow application domains, leaving gaps in understanding the trade-offs and selection criteria necessary for optimal material choice across diverse engineering applications. To the best of the researcher's knowledge, there is limited research that comprehensively analyzes the comparative performance and application suitability of different SMA families through systematic evaluation frameworks that enable direct comparison across multiple criteria.

Therefore, this study aims to investigate the comparative performance characteristics, application domains, and implementation challenges of major SMA systems including NiTi-based, Cu-based, Fe-based, and emerging high-entropy alloys. More specifically, it addresses the following research questions:

RQ1: What are the comparative performance characteristics of different SMA systems and how do they influence application suitability?

RQ2: What are the specific advantages and limitations of major SMA families (NiTi-based, Cu-based, Fe-based, and emerging systems) across different application domains?

RQ3: What are the key implementation challenges and future research opportunities for advancing SMA technology adoption?.

## II. LITERATURE REVIEW

Shape memory alloys (SMAs) are a distinct class of smart materials capable of recovering their pre-deformed shape in response to thermal or mechanical stimuli. This remarkable functionality originates from reversible solid-solid phase transformations between austenite, the high-temperature, high-symmetry phase, and martensite, the low-temperature, low-symmetry phase [5], [2]. Two hallmark behaviors emerge: the shape memory effect (SME), where deformed martensite regains its shape upon heating above the austenite finish temperature, and superelasticity (SE), which enables large recoverable strains upon unloading above the austenite start temperature [2], [6].

SMAs can sustain strains of 8-10%, at least one order of magnitude greater than conventional metals, recovering through either thermal activation or stress removal [7]. The discovery dates to 1932 with Au-Cd alloys, though widespread interest surged in the 1960s following identification of SME in near-equiatomic NiTi alloys by Buehler and colleagues [2]. Since then, research has progressed significantly in alloy design, microstructural control, and advanced applications. Recent developments include additive manufacturing of complex SMA lattices [8], integration into polymer composites enhancing damping and impact resistance [9], and investigations into the temperature memory effect revealing new sensor applications [6].

### 2.1 Fundamental Mechanisms and Behavior:

The SME and SE mechanisms are intrinsically tied to the crystallography of martensitic transformations. The diffusionless nature of the transformation permits variant reorientation and twinning within martensite, enabling recoverable macroscopic strains of up to 8-10% [5]. The thermomechanical behavior of SMAs is characterized by four critical transformation temperatures: martensite start (Ms), martensite finish (Mf), austenite start (As), and austenite finish (Af). Below Mf, residual deformations can be recovered by heating above Af, resulting in the shape memory effect. Above Af, martensite formation occurs during loading, followed by reverse transformation during unloading, producing superelastic behavior [7].

The mechanical properties of SMAs exhibit significant sensitivity to loading rate. Qian et al. [7] demonstrated that stress changes during martensitic transformation follow power functions and logarithmic relationships with strain rate, indicating that both deformation magnitude and rate significantly influence stress-strain response, with implications for energy dissipation and damping applications

### 2.2 Material Systems and Compositions:

#### 2.2.1 NiTi-Based Systems:

NiTi-based alloys are the most widely studied and commercially exploited shape memory alloys due to their excellent shape memory effect, superelasticity, and biocompatibility [2]. Binary NiTi exhibits strain-rate-dependent hysteresis under cyclic loading, critical for seismic and vibration applications [7]. Kong et al. [10] demonstrated that higher annealing temperatures

reduce residual stresses and improve superelastic recovery, while pre-deformation promotes favorable martensitic variant reorientation. Ternary NiTi-based alloys extend transformation temperature ranges and improve functional stability. Bigelow et al. [11] studied Ni<sub>50.5</sub>Ti<sub>27.2</sub>Hf<sub>22.3</sub>, demonstrating high transformation temperatures and stable superelastic behavior for high-temperature actuators. Santosh et al. [12] showed that Si addition promotes grain refinement and reduces impurity inclusions, while Liu et al. [13] found that Cu substitution alters transformation sequences and improves strain-sensing capabilities.

### **2.2.2 Cu-Based Systems:**

Cu-based alloys provide cost-effective alternatives to NiTi. Ito et al. [14] investigated Mn-rich Cu-Mn-Al alloys, revealing robust martensitic transformations but lower ductility than NiTi. Fakhraei et al. [15] demonstrated that higher Al content improves thermal stability but reduces ductility in Cu-Al-Fe alloys. Saud et al. [16] showed that Ta additions enhance damping behavior and shape memory response by stabilizing martensitic variants. While these alloys exhibit lower recoverable strain and functional fatigue resistance compared to NiTi, their low cost and ease of processing make them attractive for large-scale applications where cost efficiency outweighs absolute performance.

### **2.2.3 Fe-Based, High-Entropy, and Magnetic Systems:**

Fe-based SMAs offer a compelling balance of cost, strength, and environmental durability for structural applications [17], [4]. High-entropy alloys (HEAs) present tunable transformation characteristics, though functional fatigue and processing scalability remain challenges [18]. Magnetic SMAs like Ni-Mn-Ga enable rapid actuation but face brittleness and narrow transformation range limitations [19].

### **2.2.4 Applications and Engineering Implementation:**

Biomedical devices represent the earliest and most successful SMA applications, with NiTi alloys dominating due to their biocompatibility, superelasticity, and corrosion resistance. Stents and orthodontic wires exploit NiTi's large recoverable strains and near-constant recovery forces, improving patient comfort and reducing clinical interventions [2]. In civil and structural engineering, SMAs provide seismic resilience through cable-restrained bearing systems and reinforced concrete shear walls that demonstrate superior re-centering and energy dissipation capabilities [3], [4]. Embedded SMA fibers in concrete composites improve crack closure, stiffness retention, and damping performance, enabling self-healing and prestressing applications [20]. Aerospace and automotive sectors increasingly integrate SMAs as compact, high-force actuators and morphing elements. High-temperature NiTiHf alloys enable reliable actuation in demanding environments such as turbine components [11]. Consumer and assistive technologies leverage SMAs in tactile displays for visually impaired users and precision micro-actuators [21], [22]. Integration into polymer composites enhances structural damping, impact resistance, and energy absorption through reversible stress recovery, opening pathways for advanced damping systems and adaptive structural components [9].

## **2.3 Fundamental Properties of Shape Memory Alloys:**

### **2.3.1 Transformation Temperatures:**

The functionality of SMAs is governed by transformation temperatures, which define the start and finish of martensitic (Ms, Mf) and austenitic (As, Af) transformations. These temperatures vary with composition, processing, and heat treatment. For example, NiTi-based alloys display transformation ranges from sub-zero to above 100°C, with additions such as Hf raising transformation temperatures significantly [11], while Si additions refine microstructure without drastically shifting transformation points [12]. In Cu-based systems, Al and Mn content strongly influence stability and transformation ranges [15], [14]. Control over transformation temperatures allows designers to match SMA activation to environmental and operational demands.

### **2.3.2 Shape Memory Recovery:**

Shape memory recovery describes the ability of SMAs to return to their original form upon heating. Recovery depends on transformation completeness, training, and cycling history. Liu et al. [13] demonstrated enhanced strain-sensing properties in NiTiCu systems due to stable recovery behavior. Gopalakrishnan et al. [9] reported that embedding SMAs in composites improves recovery stress, enabling self-healing and prestressing applications. In high-temperature systems such as NiTiHf, recovery is sustained over elevated cycles [11], confirming the compositional influence on recovery stability.

### 2.3.3 Mechanical Properties:

SMAs exhibit unique mechanical properties, including recoverable strains of up to 8–10%, superelastic hysteresis, and high damping capacity. Biffi et al. [22] investigated NiTi micro-elements, showing their capability to generate large recoverable deformations suitable for actuation. In civil engineering, SMA fibers enhance stiffness retention and mechanical toughness of composites [20]. Cu-based alloys typically show lower ductility and recoverable strain compared to NiTi but are more cost-effective [14].

### 2.3.4 Strain Rate Effects:

SMA response is sensitive to strain rate due to thermomechanical coupling. Qian et al. [7] demonstrated that higher strain rates increase transformation stresses and hysteresis loop areas in NiTi wires. Roh [23] confirmed that thermo-mechanical models must incorporate strain-rate effects to capture pseudoelastic behavior accurately. These findings are essential for dynamic applications such as seismic dampers, where strain rates vary rapidly.

### 2.3.5 Fatigue and Cycling Performance:

Fatigue and cycling stability are critical for long-term use of SMAs. Simoes et al. [24] showed that fatigue crack growth in NiTi is influenced by stress amplitude, environmental effects, and microstructural defects. Mehrpouya et al. [8] emphasized that additive manufacturing strategies can tune microstructures to improve functional fatigue in architected SMA lattices. Kong et al. [10] demonstrated that pre-deformation and annealing improve superelastic cycling by stabilizing martensitic variants. Understanding cycling behavior is vital for ensuring SMA reliability in biomedical implants, actuators, and structural systems.

## III. METHODOLOGY

### 3.1 Literature Search and Selection Strategy:

A systematic literature search was conducted to identify relevant studies on shape memory alloys published primarily between 2000 and 2025. The search strategy employed multiple electronic databases including Web of Science, Scopus, IEEE Xplore, and Google Scholar. Search terms included combinations of "shape memory alloy," "superelasticity," "martensitic transformation," "NiTi," "Nitinol," "Cu-based SMA," "Fe-based SMA," and "high-entropy alloys" using Boolean operators (AND, OR).

#### Inclusion Criteria:

- Peer-reviewed journal articles and conference proceedings
- Studies reporting experimental data on SMA properties and performance
- Articles focusing on metallic shape memory alloys
- Publications in English language
- Studies with clear methodology and quantifiable results

#### Exclusion Criteria:

- Review articles without original experimental data (except seminal review papers)
- Studies focusing solely on theoretical modeling without experimental validation
- Conference abstracts without full papers
- Studies on polymeric SMAs (outside scope of this review)
- Publications with insufficient technical detail for analysis

### 3.2 Data Extraction and Categorization:

From each selected study, the following information was systematically extracted and documented:

#### Technical Parameters:

- Alloy composition and processing conditions
- Transformation temperatures ( $M_s$ ,  $M_f$ ,  $A_s$ ,  $A_f$ )

- Shape memory recovery percentages and strain levels
- Mechanical properties (strength, ductility, cycling performance)
- Processing methods and heat treatments

**Performance Metrics:**

- Functional properties (recovery strain, transformation stress)
- Durability characteristics (fatigue life, cycling stability)
- Environmental resistance (corrosion, temperature stability)
- Manufacturing feasibility and processing challenges

**Application Context:**

- Primary application domains (biomedical, aerospace, civil engineering)
- Commercial deployment status
- Cost considerations and economic factors
- Technology readiness level indicators

**3.3 Alloy System Classification:**

Studies were systematically categorized into distinct alloy families based on primary alloying elements:

- NiTi-based systems: Binary NiTi, NiTi-Hf, NiTi-Si, NiTi-Cu variants
- Cu-based systems: Cu-Al-Fe, Cu-Al-Ni, Cu-Mn-Al compositions with various additions (Ta, etc.)
- Fe-based systems: Fe-Mn-Si-Cr-Ni alloys designed for structural applications
- High-entropy alloys: Multi-component systems (CrMnFeCoNi variants)
- Magnetic SMAs: Ni-Mn-Ga and related magnetically actuated systems

This classification enabled systematic comparison while recognizing the fundamental differences between alloy families.

**3.4 Qualitative Comparative Analysis Framework:****3.4.1 Multi-Dimensional Assessment Approach:**

A comprehensive comparative analysis was conducted across seven key dimensions:

- 1) Thermal Characteristics: Transformation temperature ranges and thermal stability
- 2) Functional Performance: Shape memory effect, recovery strain, and cycling behavior
- 3) Mechanical Properties: Strength, ductility, and processability
- 4) Economic Factors: Raw material costs, processing complexity, and commercial availability
- 5) Application Domains: Current market deployment and suitability for different sectors
- 6) Manufacturing Readiness: Fabrication methods and processing maturity
- 7) Research Status: Technology readiness level and future development potential

**3.4.2 Performance Rating System:**

A standardized rating scale was developed to enable consistent evaluation across different alloy systems:

- Excellent (9-10): Superior performance with established commercial success
- Very Good (7-8): High performance with demonstrated applications
- Good (5-6): Adequate performance with limited commercial use

- Moderate (3-4): Below-average performance, research/prototype stage
- Poor (1-2): Inadequate performance, fundamental research only
- Unknown: Insufficient data available for assessment

### 3.4.3 Comparative Methodology:

For each dimension, alloy systems were evaluated using:

- Literature-based evidence: Performance data and characteristics reported in selected studies
- Quantitative benchmarks: Specific numerical criteria (e.g., >8% recovery strain for "excellent")
- Application context: Commercial deployment and market penetration indicators
- Technology maturity: Research volume, development stage, and industrial readiness

## 3.5 Data Analysis and Synthesis:

Results were organized into structured comparison tables for each evaluation dimension. This approach facilitated:

- Direct system-to-system comparisons
- Identification of performance trade-offs
- Recognition of application-specific advantages
- Assessment of research gaps and opportunities

### 3.5.1 Pattern Recognition:

Cross-dimensional analysis was conducted to identify:

- Performance hierarchies: Overall ranking of systems across multiple criteria
- Trade-off relationships: Inverse correlations between different properties (e.g., cost vs. performance)
- Application matching: Alignment between system capabilities and market requirements
- Development trends: Evolution of different technologies over time

## 3.6 Quality Assessment and Validation:

### 3.6.1 Literature Quality Evaluation:

Selected studies were assessed for:

- Experimental rigor and methodology clarity
- Sample sizes and statistical treatment
- Reproducibility of results
- Peer review quality and journal impact

### 3.6.2 Classification Validation:

The alloy system categorization was validated through:

- Consistency with established metallurgical classifications
- Cross-referencing with multiple literature sources
- Expert knowledge from foundational SMA textbooks and reviews
- Verification of compositional ranges and processing methods

### 3.6.3 Rating System Assumptions:

The comparative rating system assumes:

- Linear relationship between numerical scores and qualitative categories
- Equal weighting of different performance criteria
- Comparability across different experimental conditions
- Relevance of current performance indicators to future applications

### 3.6.4 Analytical Framework Justification:

The qualitative comparative analysis approach was selected over quantitative meta-analysis for several reasons:

- 1) Data heterogeneity: Extreme variability in experimental conditions, sample preparations, and measurement protocols across studies
- 2) System diversity: Fundamental differences between alloy families make statistical pooling inappropriate
- 3) Scope appropriateness: Systematic comparison better suited for undergraduate-level research scope
- 4) Practical utility: Comparative framework provides actionable insights for material selection and research prioritization

## IV. RESULTS

**TABLE 1**  
**TRANSFORMATION TEMPERATURE RANGES AND THERMAL CHARACTERISTIC**

| Alloy System        | Transformation Temperature Range | Thermal Stability              | Key Studies                            | Notes                                                          |
|---------------------|----------------------------------|--------------------------------|----------------------------------------|----------------------------------------------------------------|
| Binary NiTi         | Room temperature to ~100°C       | Good                           | Qian et al. (2013), Kong et al. (2024) | Most studied system; highly tunable through composition        |
| NiTi-Hf             | 126°C to >200°C                  | Excellent                      | Bigelow et al. (2022)                  | High-temperature applications; stable at elevated temperatures |
| NiTi-Si             | 342-380K (69-107°C)              | Good                           | Santosh et al. (2024)                  | Cost-effective alternative to Hf additions                     |
| Cu-Al-Fe            | 455-617K (182-344°C)             | Good                           | Fakhraei et al. (2020)                 | Highest temperature capability among systems studied           |
| Cu-Al-Ni-Ta         | Not specified                    | Enhanced                       | Saud et al. (2017)                     | Improved thermal stability through Ta additions                |
| Cu-Mn-Al            | 125-316K (-148-43°C)             | Moderate                       | Ito et al. (2025)                      | Low-temperature applications; novel system                     |
| Fe-based            | Variable                         | Good in corrosive environments | Kulkarni et al. (2025)                 | Designed for structural applications                           |
| High-Entropy Alloys | 210-350K (-63-77°C)              | Under investigation            | Lim et al. (2025)                      | Experimental stage; tunable through composition                |

As seen in Table 1, the transformation temperature characteristics reveal distinct patterns across different alloy families. NiTi-based systems dominate the moderate to high-temperature range, with Hf additions enabling the highest operating temperatures among all systems studied. Cu-based systems demonstrate the broadest temperature range capability, spanning from very low temperatures in Cu-Mn-Al compositions to very high temperatures in Cu-Al-Fe variants. Fe-based systems are designed primarily for structural durability rather than optimized for specific temperature ranges, reflecting their intended application in civil engineering contexts. High-entropy alloys represent an emerging field with potentially tunable properties, though their transformation characteristics remain under investigation.

**TABLE 2**  
**SHAPE MEMORY EFFECT AND RECOVERY PERFORMANCE**

| Alloy System        | Recovery Strain (%)    | Recovery Completeness | Cycling Stability   | Key Studies                | Performance Level |
|---------------------|------------------------|-----------------------|---------------------|----------------------------|-------------------|
| Binary NiTi         | 8-10%                  | Excellent (>95%)      | Very Good           | Multiple studies           | Excellent         |
| NiTi-Hf             | Comparable to binary   | Very Good (~90-95%)   | Excellent           | Bigelow et al. (2022)      | Very Good         |
| NiTi-Si             | Not reported           | Not specified         | Under investigation | Santosh et al. (2024)      | Unknown           |
| Cu-Al-Fe            | Variable (26-84%)      | Moderate              | Fair                | Fakhraei et al. (2020)     | Moderate          |
| Cu-Al-Ni-Ta         | Up to 100% (1st cycle) | Excellent             | Good with training  | Saud et al. (2017)         | Good              |
| Cu-Mn-Al            | 1.3% (single crystal)  | Limited               | Poor                | Ito et al. (2025)          | Poor              |
| Fe-based            | Not specified          | Good                  | Good                | Nasiri & Ghassemieh (2025) | Good              |
| High-Entropy Alloys | 1.2% maximum           | Limited               | Under study         | Lim et al. (2025)          | Poor              |

The shape memory recovery performance data in Table 2 reveals significant disparities among different alloy systems. Binary NiTi clearly outperforms all other systems in terms of both recovery strain magnitude and completeness, maintaining its position as the benchmark material. Cu-based systems exhibit high variability in performance, though optimized compositions such as Cu-Al-Ni-Ta are approaching NiTi performance levels under specific conditions. Novel systems including Cu-Mn-Al and high-entropy alloys currently demonstrate limited recovery capabilities, with maximum strains below 1.5% reported in the literature. Fe-based systems prioritize structural properties over maximum recovery performance, reflecting their design philosophy for civil engineering applications where mechanical strength and durability take precedence over shape memory functionality.

**TABLE 3**  
**MECHANICAL PROPERTIES AND PROCESSABILITY**

| Alloy System        | Strength Level  | Ductility            | Machinability           | Processing Challenges             | Key Studies            |
|---------------------|-----------------|----------------------|-------------------------|-----------------------------------|------------------------|
| Binary NiTi         | High            | Good                 | Poor (strain hardening) | Surface oxidation, Ni evaporation | Immanuel et al. (2022) |
| NiTi-Hf             | Very High       | Good                 | Poor                    | High-temperature processing       | Bigelow et al. (2022)  |
| NiTi-Si             | Good            | Good                 | Moderate                | Impurity control                  | Santosh et al. (2024)  |
| Cu-Al-Fe            | High (>800 MPa) | Poor to Moderate     | Moderate                | Brittleness issues                | Fakhraei et al. (2020) |
| Cu-Al-Ni-Ta         | Good            | Improved             | Good                    | Porosity control                  | Saud et al. (2017)     |
| Cu-Mn-Al            | Moderate        | Good (cold workable) | Good                    | Limited transformation strain     | Ito et al. (2025)      |
| Fe-based            | High            | Good                 | Good                    | Corrosion in chlorides            | Kulkarni et al. (2025) |
| High-Entropy Alloys | Variable        | Good                 | Under study             | Complex processing                | Lim et al. (2025)      |



As Table 3 shows, the mechanical properties and processability characteristics demonstrate significant variation across alloy families. NiTi systems generally offer the best combination of strength and functional properties but are difficult to machine, presenting manufacturing challenges that affect production costs and design flexibility. Cu-based systems are more processable and easier to work with using conventional manufacturing methods, but often suffer from brittleness that limits their reliability in demanding structural applications. Fe-based systems offer good structural properties and processability, benefiting from decades of established steel processing knowledge and infrastructure, which facilitates their adoption in large-scale civil engineering applications. Novel systems such as high-entropy alloys require further development for practical processing, as their complex compositions and limited understanding of processing-property relationships present significant barriers to manufacturing scalability and commercial implementation.

**TABLE 4**  
**COST AND ECONOMIC CONSIDERATIONS**

| Alloy System        | Raw Material Cost       | Processing Cost | Commercial Availability | Cost-Effectiveness Rating |
|---------------------|-------------------------|-----------------|-------------------------|---------------------------|
| Binary NiTi         | High (Ni content)       | High            | Excellent               | Moderate                  |
| NiTi-Hf             | Very High (Hf addition) | Very High       | Limited                 | Low                       |
| NiTi-Si             | Moderate                | Moderate        | Limited                 | Good                      |
| Cu-Al-Fe            | Low                     | Low to Moderate | Good                    | Excellent                 |
| Cu-Al-Ni-Ta         | Low to Moderate         | Moderate        | Limited                 | Good                      |
| Cu-Mn-Al            | Very Low                | Low             | Research stage          | Excellent                 |
| Fe-based            | Low                     | Low             | Growing                 | Excellent                 |
| High-Entropy Alloys | Variable                | High            | Research stage          | Poor                      |

The economic considerations in Table 4 reveal stark disparities in cost-effectiveness across different alloy systems. Cu-based and Fe-based systems offer significant cost advantages over NiTi, with raw material costs often an order of magnitude lower, making them attractive for large-scale applications where budget constraints are critical. Hf additions make NiTi-Hf systems very expensive, with hafnium costs exceeding \$200/kg compared to less than \$10/kg for copper-based materials, significantly limiting their commercial applications to specialized high-value aerospace and defense sectors where performance justifies the premium pricing. Novel systems including Cu-Mn-Al and high-entropy alloys show promise for cost reduction due to their use of abundant and inexpensive constituent elements, but these materials need further development before they can achieve commercial viability and reliable performance. Commercial availability strongly influences practical cost-effectiveness, as established supply chains, processing infrastructure, and technical expertise for mature systems like binary NiTi provide economic advantages that extend beyond raw material costs alone, affecting the total cost of ownership for SMA-based solutions.

**TABLE 5**  
**PRIMARY APPLICATIONS AND MARKET SEGMENTS**

| Alloy System        | Biomedical                      | Aerospace/<br>Automotive     | Civil<br>Engineering  | Consumer/Assistive      | Research<br>Priority |
|---------------------|---------------------------------|------------------------------|-----------------------|-------------------------|----------------------|
| Binary NiTi         | Dominant (stents, orthodontics) | Moderate (actuators)         | Growing (dampers)     | Good (tactile displays) | Optimization         |
| NiTi-Hf             | Limited                         | Strong (high-temp actuators) | Limited               | None                    | Specialization       |
| NiTi-Si             | Potential                       | Potential                    | Limited               | Limited                 | Development          |
| Cu-Al-Fe            | None (not biocompatible)        | Limited                      | Good (high-temp)      | Limited                 | Optimization         |
| Cu-Al-Ni-Ta         | Limited                         | Potential                    | Moderate              | Limited                 | Development          |
| Cu-Mn-Al            | None                            | None                         | None                  | None                    | Fundamental research |
| Fe-based            | None                            | Limited                      | Dominant (structures) | None                    | Implementation       |
| High-Entropy Alloys | None                            | None                         | None                  | None                    | Fundamental research |

The application domains and market penetration patterns in Table 5 reflect distinct specialization among different alloy systems. Binary NiTi dominates biomedical applications due to its superior biocompatibility and reliability, with well-established use in stents, orthodontic devices, and surgical instruments that have demonstrated long-term clinical success and regulatory approval. NiTi-Hf serves specialized high-temperature aerospace applications where extreme operating conditions and stringent performance requirements justify the material's premium cost, particularly in actuators and morphing structures subjected to temperatures exceeding 200°C. Fe-based systems are becoming preferred for civil engineering applications due to their favorable combination of cost-effectiveness and corrosion resistance, enabling large-scale deployment in seismic retrofitting, bridge bearings, and reinforced concrete systems where economic constraints would prohibit NiTi use. Cu-based systems fill mid-range industrial applications where biocompatibility is not required, offering a compromise between the high performance of NiTi and the low cost of Fe-based alternatives for actuators, dampers, and mechanical components in non-medical sectors. Novel systems including Cu-Mn-Al alloys and high-entropy alloys remain primarily in research phases, with limited commercial deployment as they require fundamental property optimization and processing development before transitioning from laboratory demonstrations to practical engineering applications.

**TABLE 6**  
**MANUFACTURING AND FABRICATION METHODS**

| Alloy System        | Conventional Melting | Powder Metallurgy | Additive Manufacturing | Special Processing          | Key Studies             |
|---------------------|----------------------|-------------------|------------------------|-----------------------------|-------------------------|
| Binary NiTi         | Standard             | Good              | Excellent              | Extensive heat treatment    | Mehrpouya et al. (2024) |
| NiTi-Hf             | Vacuum required      | Limited           | Developing             | Complex thermal processing  | Bigelow et al. (2022)   |
| NiTi-Si             | Modified VIM         | Good              | Potential              | Argon backfilling           | Santosh et al. (2024)   |
| Cu-Al-Fe            | Standard             | Good              | Limited                | Homogenization critical     | Fakhraei et al. (2020)  |
| Cu-Al-Ni-Ta         | Standard             | Excellent         | Limited                | Microwave sintering         | Saud et al. (2017)      |
| Cu-Mn-Al            | Standard             | Good              | Unknown                | Hot rolling required        | Ito et al. (2025)       |
| Fe-based            | Standard             | Good              | Potential              | Heat treatment optimization | Kulkarni et al. (2025)  |
| High-Entropy Alloys | Induction melting    | Limited           | Unknown                | Complex composition control | Lim et al. (2025)       |

As seen in Table 6, the manufacturing and fabrication capabilities vary considerably across different alloy systems, reflecting their relative technological maturity and processing complexity. NiTi systems have the most developed manufacturing processes, especially for additive manufacturing techniques such as selective laser melting and electron beam melting, which enable complex geometries, lattice structures, and functionally graded designs that enhance performance beyond what conventional processing can achieve. Cu-based systems generally use conventional processing methods including casting, powder metallurgy, and thermomechanical treatment, with good powder metallurgy potential that enables near-net-shape manufacturing and reduced material waste, though homogenization treatments remain critical for achieving consistent properties. Fe-based systems leverage existing steel processing knowledge and infrastructure, allowing for cost-effective manufacturing using established melting, forging, and heat treatment procedures that require minimal specialized equipment or expertise, facilitating their adoption in large-scale structural applications. Novel systems including high-entropy alloys require specialized processing development due to their complex multi-component compositions, with challenges in achieving compositional uniformity, controlling phase formation, and establishing reproducible processing-property relationships that must be resolved before these materials can transition from laboratory-scale production to industrial manufacturing.

**TABLE 7**  
**RESEARCH MATURITY AND FUTURE POTENTIAL**

| Alloy System        | Technology Readiness Level | Research Volume | Commercial Maturity | Future Growth Potential           | Key Challenges              |
|---------------------|----------------------------|-----------------|---------------------|-----------------------------------|-----------------------------|
| Binary NiTi         | 9 (Deployed)               | Extensive       | Mature              | Moderate (optimization)           | Cost reduction, processing  |
| NiTi-Hf             | 7-8 (Demonstrated)         | Moderate        | Niche market        | Good (aerospace growth)           | Cost, processing complexity |
| NiTi-Si             | 4-5 (Development)          | Limited         | Emerging            | Good (cost-effective alternative) | Property optimization       |
| Cu-Al-Fe            | 6-7 (Prototype)            | Moderate        | Limited commercial  | Moderate                          | Brittleness, reliability    |
| Cu-Al-Ni-Ta         | 5-6 (Development)          | Limited         | Research/pilot      | Good (improved Cu-based)          | Scale-up, optimization      |
| Cu-Mn-Al            | 3-4 (Research)             | Very Limited    | None                | Uncertain                         | Fundamental properties      |
| Fe-based            | 6-7 (Prototype)            | Growing         | Emerging            | Excellent (infrastructure)        | Corrosion, recovery strain  |
| High-Entropy Alloys | 2-3 (Research)             | Limited         | None                | High (long-term)                  | Fundamental understanding   |

The research maturity and technological readiness levels reveal significant disparities in commercial development across alloy systems. Binary NiTi is the only fully mature commercial technology, having achieved widespread market deployment with established supply chains, standardized processing protocols, and regulatory approvals across multiple application sectors, particularly in the biomedical device industry. Fe-based systems show the highest growth potential due to infrastructure applications, as increasing emphasis on seismic resilience and sustainable construction drives demand for cost-effective shape memory solutions in civil engineering, where the large-scale material requirements favor economically viable alternatives to NiTi. Novel systems including high-entropy alloys and Cu-Mn-Al compositions require significant fundamental research before practical implementation becomes feasible, as these materials remain in early-stage laboratory investigation with limited understanding of their transformation mechanisms, long-term stability, and processing-property relationships. NiTi variants such as NiTi-Hf and NiTi-Si serve specialized niches where their unique capabilities justify development efforts, but face cost and processing barriers that limit their market expansion beyond high-value applications in aerospace and defense sectors, restricting their adoption despite demonstrated technical advantages in specific operating environments.

This comparative analysis reveals several important patterns:

1. Performance Hierarchy: Binary NiTi remains the gold standard for functional properties, followed by NiTi variants, then optimized Cu-based systems, with novel systems trailing significantly.
2. Application-Specific Optimization: Different systems excel in different domains - NiTi for biomedical, NiTi-Hf for aerospace, Fe-based for civil engineering, and Cu-based for cost-sensitive applications.
3. Trade-offs: There are clear trade-offs between performance, cost, and processability. No single system excels in all areas.
4. Research Gaps: Novel systems (HEAs, Cu-Mn-Al) show promise but require substantial fundamental research before practical implementation.
5. Manufacturing Maturity: Processing and manufacturing capabilities strongly influence commercial viability, with NiTi having the most developed infrastructure.

### Rating Scale and Classification Criteria

**TABLE 8**  
**COMPREHENSIVE RATING SCALE AND CLASSIFICATION CRITERIA FOR SHAPE MEMORY ALLOYS**

| Rating Category | Scale  | Performance Criteria                                                                                                   | Cost-Effectiveness Criteria                                                   | TRL Mapping                                                                       | Application Suitability                                       |
|-----------------|--------|------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|---------------------------------------------------------------|
| Excellent       | 09-Oct | • Recovery strain >8%<br>• >95% shape recovery<br>• Stable over >1000 cycles<br>• Commercial deployment successful     | Raw materials <\$5/kg, simple processing, high availability                   | TRL 9 (Deployed): Commercial products in widespread use                           | Dominant: >60% market share in application area               |
| Very Good       | 07-Aug | • Recovery strain 5-8%<br>• 85-95% shape recovery<br>• Stable over 500+ cycles<br>• Proven in specialized applications | Moderate cost materials, standard processing, good availability               | TRL 7-8 (Demonstrated): System prototypes demonstrated in operational environment | Strong: 20-60% market share or proven performance advantage   |
| Good            | 05-Jun | • Recovery strain 2-5%<br>• 70-85% shape recovery<br>• Moderate cycling stability<br>• Limited commercial use          | Moderate cost materials, standard processing, good availability               | TRL 5-6 (Development): Technology validated in relevant environment               | Good: 5-20% market share or demonstrated capability           |
| Moderate        | 03-Apr | • Recovery strain 1-2%<br>• 50-70% shape recovery<br>• Limited cycling data<br>• Research/prototype stage              | Higher cost materials or processing, limited availability                     | TRL 3-4 (Research): Analytical and experimental proof of concept                  | Moderate: <5% market share or limited demonstrations          |
| Poor            | 01-Feb | • Recovery strain <1%<br>• <50% shape recovery<br>• Poor cycling stability<br>• Fundamental research only              | Expensive materials (>\$50/kg), complex processing, very limited availability | TRL 1-2 (Basic Research): Basic principles observed and reported                  | Limited/None: No commercial presence or unsuitable properties |
| Unknown         | -      | • Insufficient data available<br>• Properties not reported<br>• Early research stage                                   | Insufficient data                                                             | Insufficient data                                                                 | Insufficient data                                             |

## V. DISCUSSION

### 5.1 Performance hierarchy and material selection:

The comparative analysis reveals a clear performance hierarchy among SMA systems, with binary NiTi maintaining its position as the benchmark for functional properties. This dominance stems from the unique combination of large recoverable strains (8-10%), excellent shape recovery (>95%), and robust cycling stability demonstrated across multiple studies [7], [10], [22].

The crystallographic compatibility between B2 austenite and B19' martensite phases in NiTi enables the reversible transformation strains that underpin its superior performance.

However, the analysis also demonstrates that no single alloy system excels across all evaluation criteria, necessitating application-specific material selection. While NiTi variants like NiTi-Hf achieve transformation temperatures exceeding 200°C suitable for aerospace applications [11], they come at significant cost penalties that limit widespread adoption. Conversely, Cu-based systems, despite lower absolute performance metrics, offer compelling alternatives where cost-effectiveness outweighs maximum functionality.

The emergence of optimized Cu-based compositions, particularly Cu-Al-Ni-Ta systems showing up to 100% first-cycle recovery [16], indicates that performance gaps between alloy families may be narrowing through compositional engineering and processing optimization. This trend suggests that future developments may challenge the traditional NiTi dominance in specific application niches.

## **5.2 Application-driven technology development:**

The analysis reveals distinct application domains driving different aspects of SMA technology development. Biomedical applications continue to leverage NiTi's unique combination of biocompatibility, superelasticity, and corrosion resistance. The success of NiTi stents and orthodontic devices [2] has established both the commercial viability and technical requirements for biomedical SMAs. The consistent stress recovery over extended strain ranges addresses critical clinical needs for patient comfort and reduced intervention frequency.

Civil engineering applications present different requirements, emphasizing cost-effectiveness, structural integrity, and environmental durability over maximum functional performance. The growing adoption of Fe-based SMAs in seismic applications [4], [3] demonstrates how application-specific optimization can overcome traditional performance limitations. The self-centering capabilities and energy dissipation characteristics of Fe-based systems align well with earthquake resilience requirements, even though their transformation strains are lower than NiTi systems.

Aerospace applications drive high-temperature SMA development, with NiTi-Hf systems achieving stable operation above 200°C [11]. The demanding environmental conditions and stringent reliability requirements justify the higher costs associated with specialized compositions. The morphing structures and adaptive vibration control systems [26] represent applications where SMA functionality enables entirely new engineering solutions rather than simply replacing conventional materials.

## **5.3 Manufacturing and processing implications:**

The comparative analysis highlights significant disparities in manufacturing readiness across alloy systems. NiTi's extensive processing infrastructure, particularly in additive manufacturing [8], provides significant competitive advantages through design flexibility and customization capabilities. The development of complex lattice structures and graded porosity designs demonstrates how advanced manufacturing can enhance fundamental material properties.

However, processing challenges remain significant across all systems. The poor machinability of NiTi due to strain hardening effects [25] continues to limit cost-effective production for many applications. The requirement for specialized cooling and lubrication techniques adds complexity and cost to manufacturing processes. These challenges may create opportunities for alternative systems with better processability, even if their functional properties are somewhat lower.

The modified processing approaches for newer systems, such as the argon backfilling technique for NiTi-Si alloys [12] and microwave sintering for Cu-Al-Ni-Ta systems [16], indicate ongoing innovation in manufacturing methods. These developments may eventually impact the relative competitiveness of different alloy families by addressing cost and scalability limitations.

## **5.4 Economic and sustainability considerations:**

The stark cost differences between alloy systems significantly influence commercial adoption patterns. Raw material costs ranging from <\$5/kg for Cu-based systems to >\$200/kg for NiTi-Hf systems (as evidenced by hafnium pricing) create distinct market segments with different cost sensitivity. The analysis suggests that applications requiring the highest performance justify premium pricing, while cost-sensitive applications drive development of alternative systems.

Fe-based systems present particularly interesting sustainability implications due to their recyclability and abundance of constituent elements. The improved corrosion resistance demonstrated in heat-treated Fe-SMAs [17] addresses one of the

traditional limitations of iron-based systems. As infrastructure applications emphasize lifecycle considerations and environmental impact, the sustainability advantages of Fe-based systems may become increasingly important.

The energy consumption associated with different processing routes also varies significantly. Conventional melting and thermomechanical processing require substantial energy inputs, particularly for high-temperature processing of NiTi-Hf systems. Powder metallurgy routes, particularly successful for Cu-Al-Ni-Ta systems, may offer energy advantages while enabling net-shape processing that reduces material waste.

### **5.5 Technological integration and system-level considerations:**

The integration of SMAs into composite systems represents a significant opportunity for expanding application domains. The enhancement of damping capacity, crack closure, and impact resistance in SMA-reinforced composites [9], [20] demonstrates how SMA functionality can be leveraged at the system level rather than relying solely on monolithic components.

However, the analysis reveals that successful integration requires careful consideration of activation mechanisms, thermal management, and mechanical compatibility. The strain-rate sensitivity of SMA behavior [7], [23] indicates that dynamic applications require sophisticated control systems to achieve consistent performance. The development of predictive models that account for thermomechanical coupling becomes critical for reliable system design.

The fatigue and fracture behavior of SMAs [24], [27] remains a limiting factor for many applications. The complex interaction between transformation-induced strains, stress concentrators, and environmental effects requires continued research attention. The phase-field modeling approaches for fatigue crack growth represent promising tools for predictive design, but validation across different alloy systems and loading conditions remains incomplete.

## **VI. CONCLUSION**

This comprehensive comparative analysis of shape memory alloy systems reveals several critical insights for material selection and application development. The performance hierarchy clearly establishes binary NiTi as the benchmark for functional properties, achieving 8-10% recoverable strain with >95% shape recovery and excellent cycling stability. However, the analysis demonstrates that optimal material selection depends on application-specific requirements rather than absolute performance metrics.

The systematic evaluation across seven dimensions reveals distinct competitive advantages for different alloy families. NiTi-Hf systems enable high-temperature applications above 200°C for aerospace actuators, justifying their premium costs through unique capabilities. Cu-based systems, particularly optimized Cu-Al-Ni-Ta compositions, offer cost-effective alternatives with recovery performance approaching NiTi levels in specific applications. Fe-based systems provide structural integration opportunities for civil engineering applications where cost, corrosion resistance, and compatibility with existing materials outweigh maximum recovery performance.

The analysis also identifies clear trade-off relationships that guide material selection. High-performance systems invariably involve higher costs and processing complexity, while cost-effective alternatives require compromises in functional properties. Manufacturing readiness varies significantly across systems, with NiTi benefiting from extensive processing infrastructure while emerging systems require specialized development.

### **6.1 Implications for Application and Testing**

The findings have several important implications for SMA application and characterization. First, standardized testing protocols are needed to enable reliable comparisons across different alloy systems. The current heterogeneity in experimental conditions, measurement protocols, and reporting standards limits the ability to make quantitative performance comparisons.

Second, application-specific performance criteria should guide material selection rather than generic property optimization. Biomedical applications require biocompatibility and reliability over maximum transformation strain, while civil engineering applications prioritize cost-effectiveness and environmental durability. Aerospace applications justify premium materials for specialized high-temperature performance.

Third, system-level integration considerations often prove more critical than monolithic material properties. The successful implementation of SMA-reinforced composites and hybrid systems demonstrates that functional benefits can be achieved through strategic integration rather than relying solely on maximum individual component performance.

The analysis also highlights the importance of considering the entire material lifecycle, including processing requirements, manufacturing scalability, and end-of-life considerations. Sustainability factors, particularly relevant for Fe-based systems, may become increasingly important as environmental considerations influence material selection decisions.

## **6.2 Practical Implications:**

For researchers and engineers working with SMAs, this analysis provides several practical guidelines. Material selection should begin with clearly defined application requirements and constraints rather than pursuing maximum theoretical performance. The rating framework developed in this study offers objective criteria for comparing different systems across multiple performance dimensions.

For industrial applications, the analysis suggests that binary NiTi remains the preferred choice for demanding functional applications where cost is secondary to performance. However, optimized alternative systems may provide viable solutions for cost-sensitive applications or where specific environmental or processing requirements favor non-NiTi options.

The identification of research maturity levels across different systems also guides research investment priorities. While binary NiTi focuses on optimization and cost reduction, emerging systems like high-entropy alloys require fundamental property development before practical implementation becomes viable.

## **6.3 Technological Development Pathways:**

The analysis reveals several promising directions for SMA technology advancement. Additive manufacturing capabilities, particularly well-developed for NiTi systems, enable complex geometries and functional gradients that enhance overall system performance beyond what is achievable with conventional processing.

Compositional optimization within established alloy families shows significant potential, as demonstrated by the improved performance of Cu-Al-Ni-Ta systems compared to baseline Cu-based alloys. This suggests that systematic alloying approaches may narrow performance gaps between different system families.

Integration with smart systems and control technologies offers opportunities to compensate for material limitations through system-level optimization. Predictive control systems that account for strain-rate sensitivity and thermal management can enhance reliability and performance consistency across different operating conditions.

## **6.4 Limitations:**

Several limitations must be acknowledged in this comparative analysis. The heterogeneity of experimental conditions and measurement protocols across the reviewed literature limits the precision of quantitative comparisons. Different testing standards, sample preparation methods, and environmental conditions contribute to variability that cannot be completely eliminated through systematic analysis.

The rating system developed for this study, while providing objective criteria, necessarily involves subjective judgments about the relative importance of different performance criteria. The equal weighting of different evaluation dimensions may not reflect the actual importance of these factors for specific applications.

The scope of this review, while comprehensive across major alloy families, excludes some specialized systems and emerging compositions that may prove significant in future developments. The focus on metallic systems excludes polymeric and ceramic shape memory materials that serve related application needs.

Temporal bias may also influence the analysis, as newer systems appear less developed due to limited research history rather than fundamental limitations. The rapid pace of development in some areas means that current assessments may quickly become outdated.

The analysis relies primarily on literature reports rather than direct experimental comparison under standardized conditions. This introduces potential inconsistencies due to different measurement protocols, sample qualities, and testing environments across different research groups.

## **6.5 Future Research Directions:**

Several critical research needs emerge from this analysis. Standardization of testing protocols and performance metrics would greatly improve the reliability of comparative assessments and enable more informed material selection decisions.

Development of predictive models that link processing conditions to functional properties across different alloy systems would accelerate optimization efforts.

Investigation of hybrid and composite systems represents a particularly promising area, as demonstrated by the success of SMA-reinforced concrete and polymer composites. Understanding the interaction between SMA components and matrix materials could enable new applications that leverage system-level properties rather than individual material capabilities.

Environmental degradation mechanisms require more systematic investigation across all alloy systems. Understanding how different systems respond to thermal cycling, corrosive environments, and mechanical fatigue under real-world conditions is essential for reliable engineering applications.

The integration of machine learning and high-throughput experimental approaches offers opportunities for accelerated alloy development and property optimization. The complex relationships between composition, processing, and properties in SMAs make them suitable candidates for data-driven materials discovery approaches.

Finally, lifecycle assessment and sustainability considerations should be integrated into comparative evaluations as environmental concerns increasingly influence material selection decisions. Understanding the full environmental impact of different SMA systems, from raw material extraction through end-of-life disposal, will become increasingly important for responsible engineering practice.

This comparative analysis provides a foundation for informed material selection and identifies key areas for future research that can advance the practical application of shape memory alloys across their diverse application domains.

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