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REVIEW

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Cite this: *RSC Adv.*, 2025, **15**, 33046

Shape memory alloys in modern engineering: progress, problems, and prospects

Md. Ismail Hossain, [a] M. S. Rabbi *[a] and M. T. Ali [b]

Received 26th June 2025
Accepted 24th August 2025

DOI: 10.1039/d5ra04560f

rsc.li/rsc-advances

Modern industrial innovation demands smart materials capable of fulfilling multifaceted objectives. Epitomizing mechanical adaptability, shape memory alloys address the escalating need for high-performance materials in today's technological sphere. These unique materials with high actuation strain, energy density and biocompatibility have remained conspicuous in various fields for many years. However, despite their transformative potential, SMA applications face persistent challenges that hinder their full industrial adoption. Recent advancements have dramatically expanded SMA capabilities, yet these developments remain fragmented across disparate disciplines. Hence, this review outlines modern trends in SMA technologies to identify performance gaps and establish a roadmap for future applications. A concise exposition on the intrinsic properties of SMAs that empowers them with idiosyncratic abilities has been illustrated. Subsequently, the article discusses the technological frontiers of SMAs in diverse fields spotlighting the novel designs. The performance and applicability of SMAs are intrinsically governed by their processing methodologies. Industrial adoption hinges not just on material potential, but on scalable processing methods that balance cost and performance. This further delves into the intricacies of manufacturing and machining techniques that have facilitated precision and optimization of these materials. The study aspires to serve as an exhaustive compendium for researchers, delineating prevailing breakthroughs, unresolved challenges while envisioning potential avenues for future research.

1 Introduction

Technological progress demands increasingly sophisticated materials. This need for materials that adapt and respond to their environment, is a need rooted not in modernity but in antiquity. Early humans selected materials not merely for utility or durability, but for their malleability, sharpen-ability, and adaptability. These rudimentary criteria laid the groundwork for today's "smart materials". Smart materials are defined as those which sense environmental stimuli, respond autonomously and adapt their functionality. Such materials have redefined engineering by serving as bidirectional transducers between mechanical and physical domains. Shape Memory Alloys (SMAs) represent a paradigm shift in the evolution of smart materials. SMAs are a class of active materials with an idiosyncratic ability to recover their shape after being deformed responding actively to change in temperature or pressure. This distinctive ability coupled with high energy density, enables them to outperform conventional materials while being very compact and lightweight. Additionally, SMAs can promote sustainability through eco-friendly alternatives.[1]

SMAs are indispensable in medical implants and vital for civil infrastructure due to their excellence in biocompatibility, corrosion resistance and high damping property.[2–4] Their integration into Superelastic Tensegrity Systems (TSs) enhances structural stability under load.[5] Aerospace and automotive industries leverage SMAs for lightweight, high-strength components.[6,7] Functionally Graded SMAs (FG-SMAs) unlock novel possibilities in MEMS devices due to their microstructurally driven dual properties.[8] These materials have proven to be an asset to researchers because of their broad range of modern-day applicability. The transformative potential of SMAs is marked by innovation of bidirectional rotational antagonistic SMA actuators with remarkably high rotational frequency (up to 200 Hz), pushing the limitations of actuator technology.[9] Integration of SMAs into soft robotics unlocks new horizons in biomimetic models and microbots.[10–12] Emerging technologies include SMA-origami hybrids for self-folding robots and deployable structures in space and auxetic metamaterials-offering programmable mechanical properties.[13,14] These cutting-edge applications demonstrate SMAs' remarkable versatility across various disciplines. By illuminating these advancements, this paper seeks not merely to validate SMAs' multifaceted utility but to motivate novel investigative pathways in the field.

The inclusion of SMA processing techniques including manufacturing and machining in this review is essential

[a]Department of Mechanical Engineering, Chittagong University of Engineering & Technology, Chattogram-4349, Bangladesh. E-mail: rabbi@cuet.ac.bd
[b]Department of Naval Architecture and Marine Engineering, Bangladesh University of Engineering & Technology, Dhaka-1000, Bangladesh

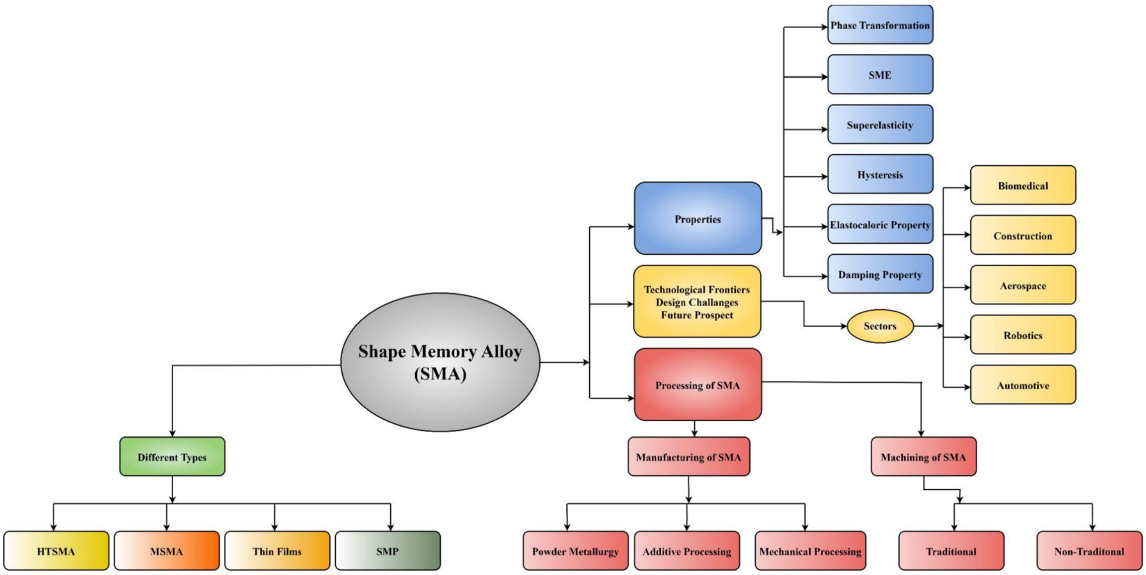

Fig. 1 Structure of this study.

because these techniques fundamentally dictate the alloys' performance, reliability, and applicability across industries. The microstructural characteristics, phase transformation behaviors, and functional properties of SMAs are all profoundly influenced by their processing routes. Additive Manufacturing (AM) has revolutionized fabrication of SMAs by enabling intricate geometries and multi-material composition which are unattainable *via* traditional methods.[15,16] Although, SMAs being engineered for their multifunctional abilities, their intrinsic limitations in machinability and exorbitant manufacturing cost resulted in sporadic commercial interest for SMAs. Conventional machining suffers from excessive tool wear, imprecision and time-consuming process. Non-conventional methods facilitate precision machining which play a pivotal role in determining the feasibility of SMA components in miniaturized systems. This paper aims to provide an in-depth review of the classification and development of processing methods that determine whether SMAs can meet the stringent demands of applications. Besides, it identifies critical gaps such as scant research on AM of Fe-SMAs and Cu-based SMAs, and limited exploration of 4D-printing in shape memory alloys compared to polymers of the same kind. Moreover, this discussion sheds light on the existing advancements in non-conventional SMA machining techniques and highlights the urgent need for expanded research into processing methods for other variants of SMAs. The development of scalable, cost-effective machining solutions for these alternative systems remains a crucial step toward unlocking their full industrial potential.

A plethora of research papers have been published highlighting the diverse domains of SMAs.[17–22] Alongside promoting the latest technological advancements in diverse fields, prior studies have discussed atomic-scale behavior,[23] performance of AM architected materials.[24] The authors in ref. 25 provided an in-depth exploration of recent trends of non-conventional machining of SMA. The authors in ref. 26 provided a thorough exploration regarding the manufacturing methods of Fe-SMAs, emphasising them as an affordable alternative due to their low cost. However, none of these papers synthesize these domains cohesively to bring them together in one platform. This work bridges that gap, offering an integrated review of SMA advancements, processing, and machinability.

Science is inherently dynamic. In recent years, Shape Memory Alloys (SMAs) have witnessed remarkable progress, both in theoretical understanding and practical applications. Given the rapid evolution of materials science, a critical reassessment of SMA capabilities and contemporary challenges have become imperative. This necessitated a comprehensive study to examine the modern developments in this field, identify persistent limitations, and evaluate emerging solutions aligned with cutting-edge technological paradigms. Recognizing this gap, the authors envisioned a systematic, concept-driven literature review which accounts for transformative SMA applications across diverse fields. The motivation behind this paper lies in consolidating fragmented knowledge by making a definitive resource so that it works as a one stop solution to the potential researchers entering the exquisite realm of shape memory alloys.

Fig. 1 demonstrates the structural outline of this study. In the subsequent sections the paper delves into intricate details of SMA properties, the technological frontiers and processing methods.

2 Properties of shape memory alloy

The initial observation of the shape memory effect can be described as a serendipitous incident.[27] After the initial observation and delineation of the term "Shape Memory" researchers first found about its work generating capacity at 1951.[28,29] The discovery of NiTi lead to more research due to its distinctive abilities.[30] In the following years, SMAs have been steadily

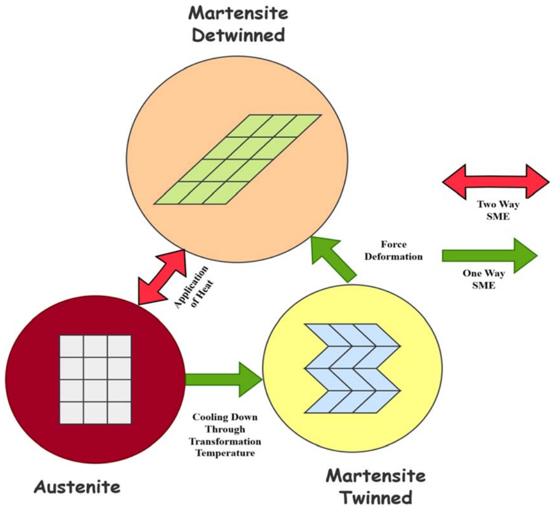

Fig. 2 Two crystal structures of SMA and their transformation relationship.

embraced as a practical engineering solution to address a wide range of issues. Two possible approaches were proposed by the researchers to advance on studies regarding SMAs: (i) traditional approach of developing novel alloys (ii) alternative approach of combining two or more existing materials and allowing superposition of their properties and thereby creating hybrids. The traditional approach resulted in formation of High Temperature SMAs (HTSMA), Magnetic SMAs (MSMA) and Shape Memory Polymers (SMP). The alternative approach signifies a rather exciting realm incorporating materials with different phases with SMAs as either reinforcement or composite matrix and porous media.[31] Shape memory materials share core phase transformation and recovery properties but are categorized by distinct functional characteristics.

2.1. Shape memory effect (SME)

SMAs can restore their original shape when mechanically deformed, either by heating (thermal/resistive) or stress removal. Their key advantage is cyclic stability referring to their ability to maintain shape memory functionality even after numerous mechanical deformation cycles. This makes them uniquely energy-efficient and durable among smart materials. This polymorphism characteristic of Shape Memory Alloy is rooted to the non-diffusive transformation between two different phases with subsequent alteration in their crystal structures when mechanical or thermal load is applied. These two phases are: (i) the austenite phase, stable at high temperatures and low stress values. (ii) The martensite phase, stable at low temperature and high stress values. The austenite ⇆ martensite relationship is shown in Fig. 2.

Phase transformation involves a diffusionless, displacive mechanism where atoms collectively shift positions without changing neighbors. Twinned martensite structure consists of self-accommodating variants that maintain overall shape compatibility.[32] When subjected to mechanical stress, these variants reorient into a detwinned structure aligned with the applied load direction. SMAs typically exhibit anisotropic behavior due to their crystallographic structure, influencing their mechanical response in different orientations.[33] Fig. 3 shows the phase transitions in different states. At ambient temperatures, SMAs initially exist in a twinned martensitic phase. Stress induces detwinning and causes macroscopic deformation. The material retains significant residual strain upon load removal. Subsequently, heating triggers austenite recovery through which shape and energy is restored. Cooling reverts it to martensite, demonstrating thermo-mechanical responsiveness. This process in particular emblems SME. Most of the SMAs show One Way Shape Memory Effect (OWSME). Introducing irreversible slip enables Two-Way SME (TWSME), remembering both initial and deformed states without external load. TWSMAs recover 50% less strain than OWSMAs, but thermomechanical training can improve recovery rate. It is shown that higher applied stress can lead to better strain recovery.[34]

Beyond conventional martensitic transformations, certain SMAs exhibit strain glass transitions (TSGT), characterized by frozen, randomly oriented martensitic nanodomains that disrupt long-range strain order.[35] These transitions introduce additional complexity in phase behavior, potentially influencing functional properties such as hysteresis and transformation stability.

2.2. Pseudoelasticity

Pseudoelasticity is the elastic deformation caused by stress-induced phase transformation between martensite and austenite. Being subjected to sufficient load in the high temperature austenite state, stress gradually increases more than the critical stress of phase transformation and the material transforms directly into detwinned martensite as shown in Fig. 2. Nonetheless, due to the instability of martensite phase in high temperature, SMA returns to the initial Austenite state with removal of stress. This typical characteristic is known as superelasticity or sometimes interchangeably denoted as pseudoelasticity.

The phase transformations are characterised by four distinct transformation temperatures which are essential to understand the reversible phase change shown in Fig. 4. They are:

M_f: martensite finish temperature
M_s: martensite start temperature
A_s: austenite start temperature
A_f: austenite finish temperature

As illustrated in Fig. 4, SMA is entirely martensitic under the temperature M_f and fully austenitic at A_f. The phase change phenomena of austenite and martensite initiates respectively from A_s and M_s. However, M_d denotes threshold temperature beyond which superelasticity is forfeited.

Fig. 5 shows different types of SMAs with their Phase Transformation temperatures. These critical temperatures delineate the initiation and cessation of the phase transitions between the structural phases. The forward and reverse transformation between these phases is characterised by

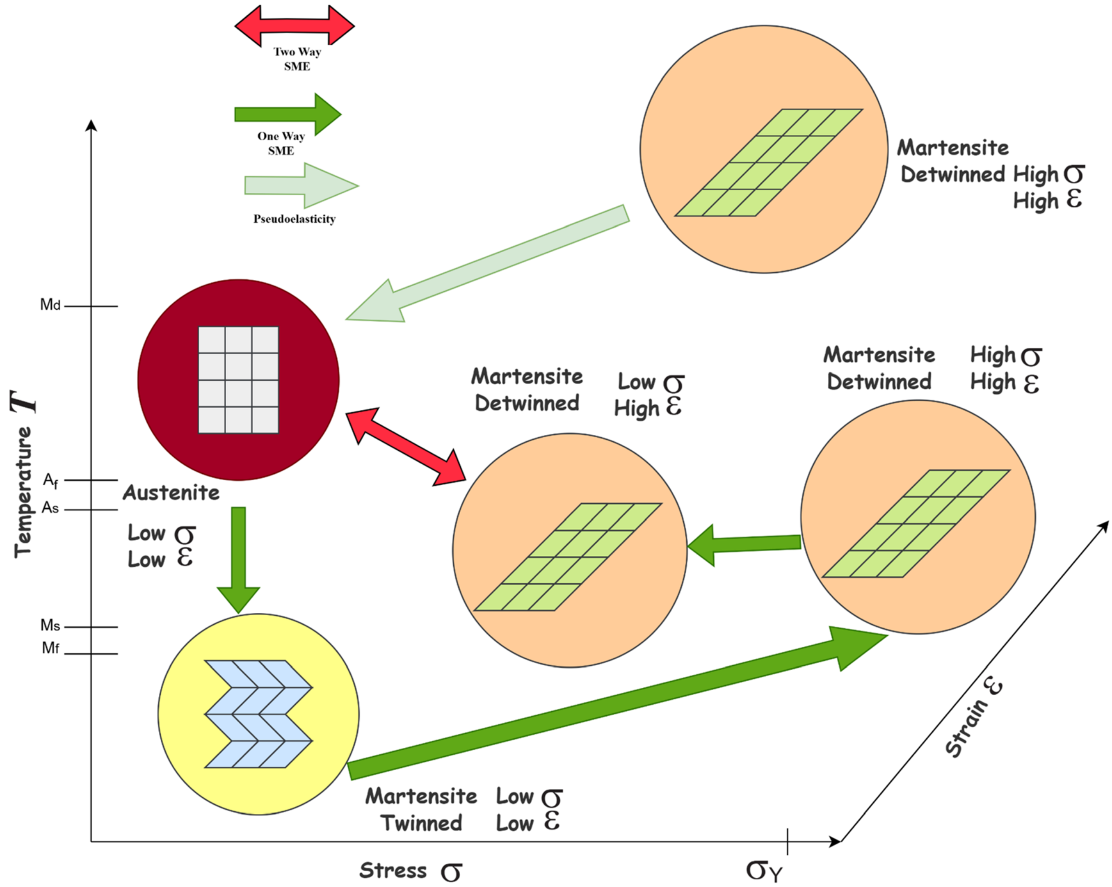

Fig. 3 Phase transformation behaviour of SMA.[17]

a discernible lag in the phase transition relative to the temperature variation of 20–40 °C.

2.3. Hysteresis

A critical characteristic of SMAs is the presence of transformation hysteresis during their thermomechanical cycle. In superelastic states, they typically show consistent hysteresis loops with fixed widths, reflecting the energy barrier between martensite and austenite. In some cases however, stress and temperature hysteresis are observed to possess interdependent variations.[37]

Hysteresis manifests as thermal (ΔT) or stress ($\Delta\sigma$) losses during cycling. Rather than a drawback, hysteresis is a tunable property. Thermomechanical training and crystallographic control can optimize transformation pathways. Soft actuators leverage tailored hysteresis for precise response speeds.[38]

Integrating SMAs into practical applications necessitates careful microstructural engineering as it governs their complex thermomechanical behavior. Specific compositional and thermal conditions may lead to an intermediate rhombohedral transformation between austenite and martensite phases known as R-phase transition.[39,40] Secondly, the functional stability of SMAs faces challenges from performance degradation mechanisms, particularly slip-mediated plasticity that accumulates during cyclic loading.[41] Further, SMA's pronounced anisotropic behaviors create heterogeneous material responses that must be accounted for in component design.[42]

The controlled hysteresis in SMAs directly enables adaptive stiffness and damping behavior during cyclic loading, where a significant portion of the mechanical energy is converted to heat rather than being elastically recovered. Peak damping occurs when stress exceeds the martensitic transformation threshold.[43] Furthermore, microstructural engineering through

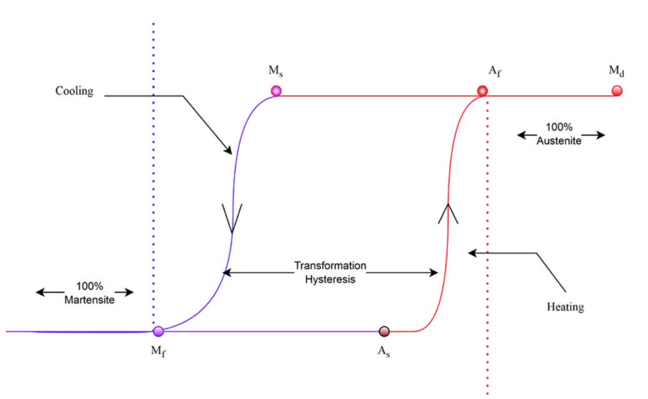

Fig. 4 Transformation temperatures in a phase transformation cycle.[36]

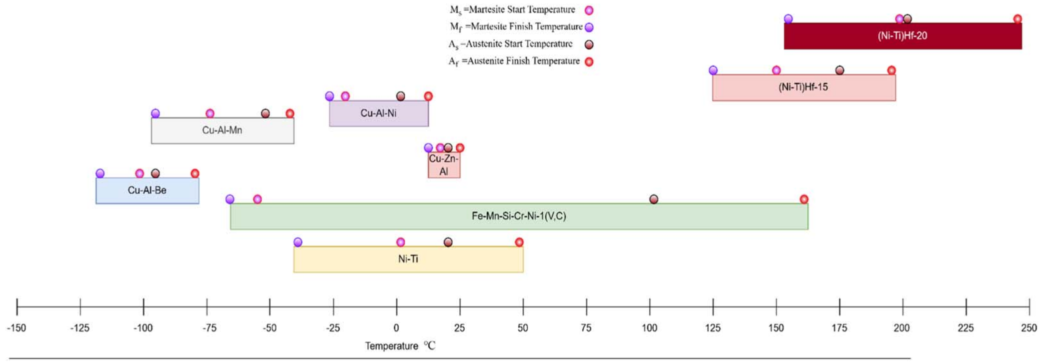

Fig. 5 Working temperature ranges of different SMAs.[17]

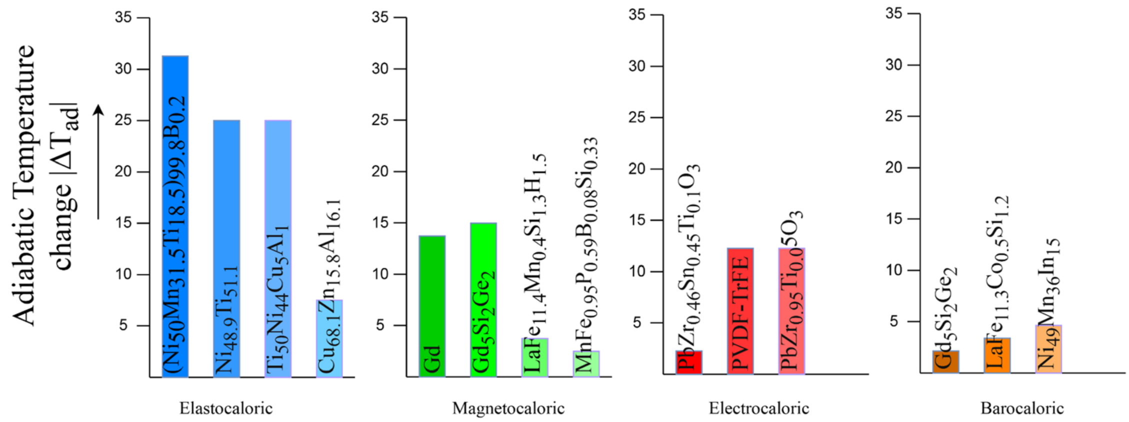

Fig. 6 Comparison of cooling effect of some caloric materials.[45]

thermal treatments allows precise tuning of damping properties.[44] This enables custom SMA designs for diverse engineering applications.

2.4. Elastocaloric effect

The elastocaloric effect represents a fundamental thermodynamic phenomenon in SMAs, characterized by the reversible temperature changes during stress-induced phase transformations. The queer property of absorption or release of latent heat during the forward and reverse martensitic transformation during cyclic loading and unloading makes SMA an elastocaloric material. This cyclic process enables solid-state refrigeration through direct conversion between mechanical work and thermal energy.[45,46] Fig. 6 summarises some caloric materials which shows the highest temperature change for Elastocaloric materials.

Elastocaloric SMAs, especially NiTi alloys, offer major cooling advantages. They outperform vapor-compression systems by eliminating greenhouse gases and using water-based fluids.[47] While NiTi SMAs have established applications in biomedical and aerospace fields, their implementation in solid-state cooling represents an emerging frontier.[48] Current research focuses on enhancing the elastocaloric performance of SMAs through microstructural engineering. Precipitate-strengthened NiTi alloys demonstrate particularly promising characteristics. High-density Ni_4Ti_3 nanoprecipitates reduce transformation hysteresis through strain glass-like martensitic transformation and improved cyclic stability *via* effective suppression of dislocation slip.[49] These improvements address key challenges in durability for repeated cycles. However, elastocaloric cooling needs further optimization in materials, designs, and operation before commercialization.[50] Its energy efficiency, eco-friendliness, and solid-state operation make it a potential game-changer for future refrigeration.

3 Different forms of shape memory materials

Classification of SMM depends on transformation temperatures, magnetic responsiveness, and material composition. Each type demonstrates unique behaviors. Such as, SMAs exhibit superelasticity while SMPs show viscoelastic properties. Though this review concentrates on shape memory alloys, it will briefly address other variants to provide complete technological context. This overview establishes the broader landscape of smart materials with shape memory capabilities.

3.1. High temperature shape memory alloys (HTSMAs)

High-temperature shape memory alloys (HTSMAs) exhibit critical advantages for extreme thermal environments, maintaining

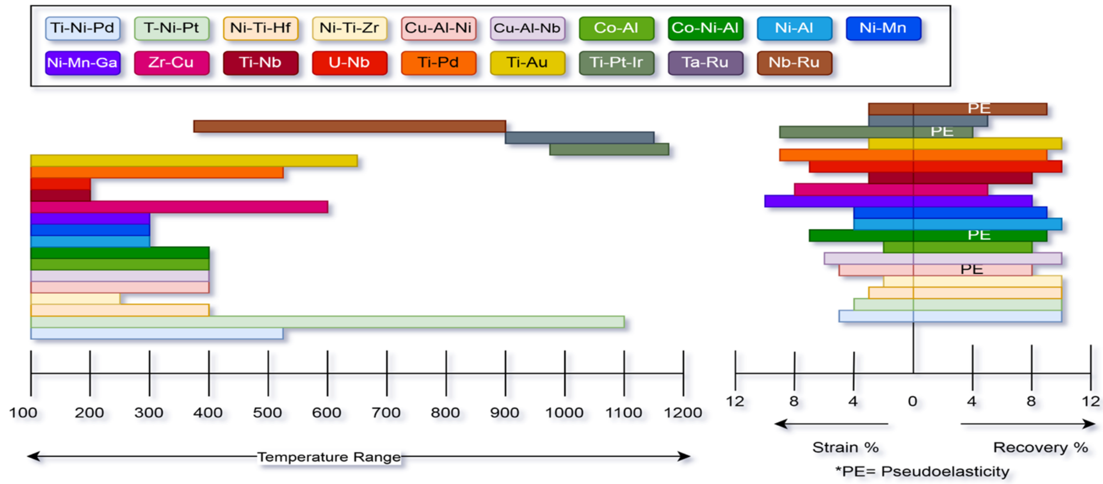

Fig. 7 Temperature range of some HTSMAs with their pseudoelasticity.[17]

functionality up to 700 °C compared to conventional SMAs limited below 100 °C.[51,52] The thermal stability range illustrated in Fig. 7 makes HTSMAs indispensable for demanding applications in aerospace and automotive industries, where conventional SMAs would fail due to thermal limitations. However, HTSMAs present unique engineering challenges including increased creep susceptibility and reduced shape memory effectiveness. As temperatures increase, the narrowing gap between critical stresses promotes plastic deformation over shape memory recovery.[52]

Current research continues to explore novel alloy compositions and processing methods to expand the operational limits of these materials while maintaining their unique functionality under extreme thermal conditions, particularly for aerospace and automotive areas.

3.2. Magnetic shape memory alloys (MSMAs)

Magnetic Shape Memory Alloys (MSMAs) represent a remarkable class of smart materials capable of reversible morphological transformations when exposed to magnetic fields. MSMAs exhibit the following dual responses for field-induced strain generation: (i) reorganization of martensitic variants in the martensite state (ii) direct initiation of phase transitions. In former mechanism, the magnetic field generates substantial Magnetic Field Induced Strain (MFIS) without undergoing full phase transformation. The underlying mechanism involves twin variant rearrangement within the martensitic phase, where applied magnetic fields create energy differentials between crystalline variants. For this phenomenon to occur, the magnetic energy difference must surpass the energy required for domain boundary movement. This is a fundamental constraint regarding MSMA behavior.[53,54] The anisotropic nature of these alloys allows for preferential crystal lattice reorientation when subjected to perpendicular mechanical loads relative to magnetic fields which effectively convert magnetic energy into mechanical work.[55] The secondary mechanism occurs in some specific compositions such as, Ni–Co–Mn–In, where sufficiently strong magnetic fields can directly induce austenite-to-martensite phase transformations.[56] This phenomenon is analogous to conventional stress or temperature-induced martensitic transformations. Both mechanisms originate from the fundamental magneto-structural coupling in MSMAs. However, variant reorientation produces immediate actuation strain that provides several distinct advantages over traditional SMAs, including faster actuation response times, improved control precision, and the ability to generate stresses without significant temperature variations. These properties stem from the alloys' multiferroic nature, combining ferromagnetic and ferroelastic (martensitic) domains, which properly classifies them as Ferromagnetic Shape Memory (FSM) alloys.[57–60]

Notable MSMAs include Iron–Palladium (FePd), Cobalt–Nickel–Gallium (Co–Ni–Ga), and Nickel–Iron–Gallium (NiFeGa) alloys. Among these, Ni–Mn–Ga alloys have demonstrated exceptional potential with magnetostrain capabilities reaching 12%, enabling their use in microscale actuators, precision sensors, micropumps, and energy conversion devices.[61–63] These materials show particular promise for advanced applications such as high-speed linear actuators and next-generation micro magnetomechanical systems (MAMS).

However, significant challenges currently limit broader implementation of MSMA technology. The materials exhibit inherent brittleness and restricted operational temperature ranges. Additionally, their general workability remains problematic for large-scale production. These limitations constrain their use primarily to specialized applications requiring substantial displacements with moderate force outputs, such as specialized valves and motors. Ongoing research efforts continue to address these material limitations while exploring new application areas that can benefit from their unique combination of magnetic and shape memory properties. Current investigations focus on improving mechanical durability, expanding operational temperature windows, and developing more reliable manufacturing processes to facilitate wider industrial adoption of this promising technology.

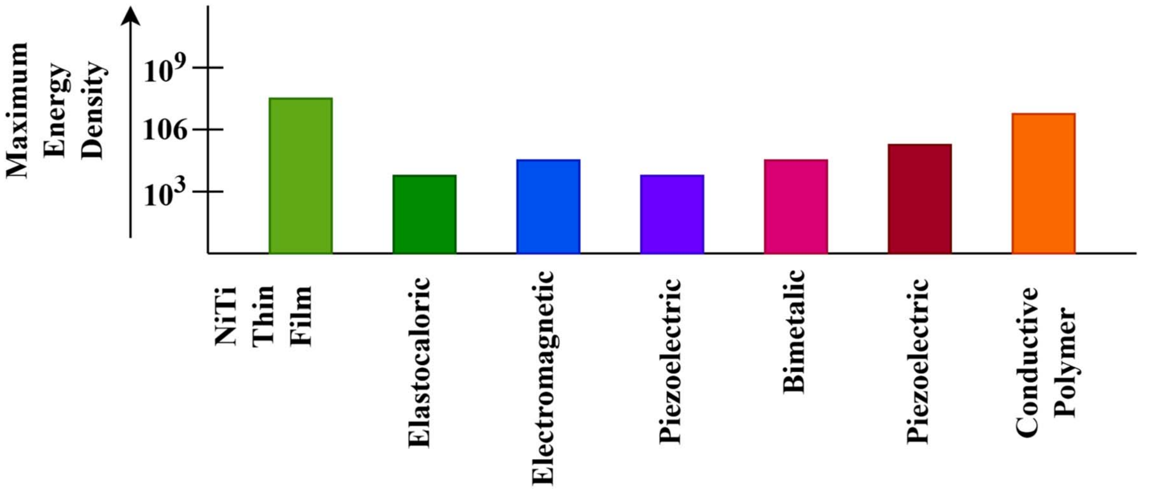

Fig. 8 Superior energy density of NiTi thin film.[17]

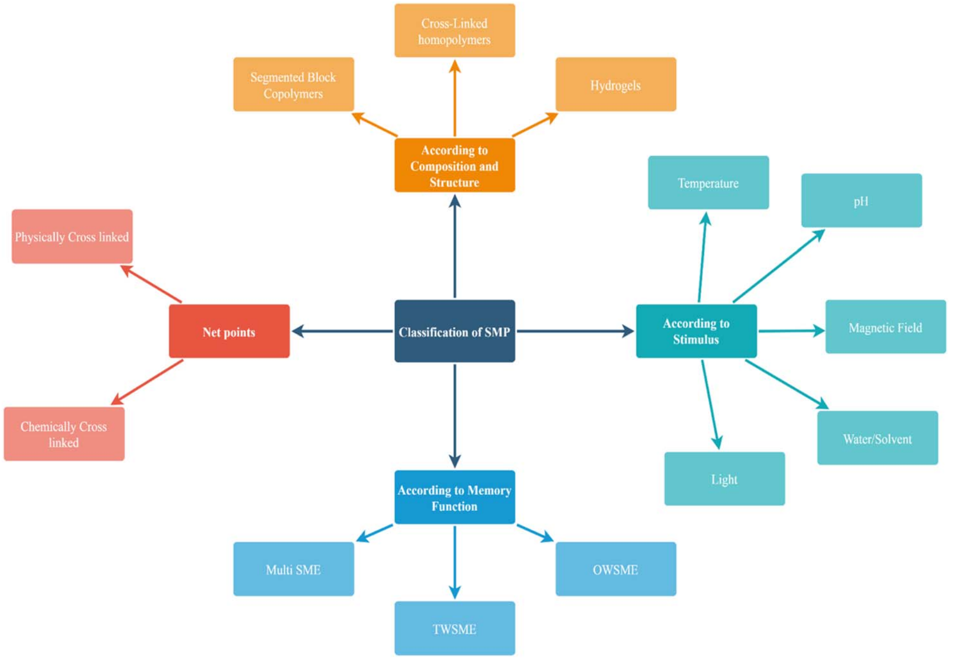

Fig. 9 Classification of shape memory polymer according to stimulus.

3.3. Shape memory thin films

Thin films fabricated from SMAs represent a transformative advancement in functional materials, combining nanoscale precision with macroscopic SME. These films are typically produced through sophisticated deposition techniques including magnetron sputtering and photolithography, which enable atomic-level control over crystalline structure and phase transformation characteristics. The resulting SMA thin films, particularly TiNi-based compositions, demonstrate remarkable mechanical properties including reversible intrinsic strains up to 8%. This capability enables large, repeatable deformations while maintaining structural integrity. This unique combination of flexibility and shape recovery makes them ideal for demanding applications in stretchable electronics and minimally invasive biomedical implants.

The superelastic behavior of SMA thin films provides distinct advantages over bulk counterparts, especially in dynamic operational environments. Recent advancements have integrated SMA thin films with auxetic metamaterial architectures, creating composite structures capable of withstanding extreme deformations up to 57.4% strain before failure.[64] This development opens new possibilities for compact, stretchable electronic systems and advanced wearable medical technologies. The comparative analysis presented in Fig. 8 highlights the superior actuation force capabilities of NiTi thin films relative

Table 1 Applications of SMP in different sectors[69–71]

Sector	Applications	Polymer used	Remarks
Biomedical	Drug eluting stents (DES)	Acrylic polymers, (PCL), poly(glycolic acid) (PGA)	Used as coatings in metal stents for inhibiting cell proliferation
	Biodegradable stents	Tyrosine-derived polycarbonate, PCL, PGA, PLA [poly(L-lactide)], poly(D-lactide) and their Co-polymers	Mechanically support the arterial wall during the healing process and leave no foreign-body material behind
	PET stents in porcine arteries	PET [poly(ethylene terephthalate)]	Very successful in clinics as bypass grafting material
	Cardiovascular applications	PAT [poly(alkylene terephthalate)]	Improved cardiovascular interventions due to their resistance to compression, hydrolytic stability
	Human skeletal muscle	Hydration programmable shape memory polymer (HP-SMP)	Enable human like motion using renewable biosourced material
Textile	Dynamic aesthetic textiles	Shape memory polyurethane (SMPU)	It was demonstrated that polyurethane could be grafted on cotton surface resulting in high washable fabrics
	Finishing for wrinkle-free property	SMPU water-borne emulsion [SMPU oligomers]	SMPU finishing of cotton increases the mechanical strength of the fabric remaining wrinkle free after hundreds of laundering cycle
	Electroactive SMP fibers	SMPU fibers	The conductivity of fibers needs to be further improved so that a low voltage is enough to trigger the shape recovery
	Biological safety textiles	SMP fibers	SMP fabric changes modulus as a response to body temperature change. Thus, the pressure applied on the wound may be tuned and a low pressure can be applied
Construction	Tunable hybrid SMP vibration absorber	SMP sleeve (pyro-condensation cannula sleeve)	Damping properties can be leveraged in vibration control systems
	Sensors and actuators	Poly(cyclooctene) PCO	SMPs with reversible temperature-sensing capabilities have the potential for structural health-sensing technology applications

to alternative materials, underscoring their potential for microactuator applications.

3.4. Shape memory polymers

Shape memory polymers (SMPs) represent a class of stimuli-responsive materials distinguished by their ability to undergo controlled morphological changes. As members of the 'active polymer' family, SMPs exhibit dual-shape functionality which is fundamentally different from the diffusionless phase transformations observed in metallic shape memory alloys.[65] This intrinsic property derives from their unique polymer architecture and chemical functionalization. When exposed to external stimuli, these materials can memorize a programmed shape or be reconfigured to adopt one or more intermediate forms, which can subsequently be recovered with minimal energy input after deformation. While thermal activation remains the predominant stimulus for most SMPs, it is also possible to achieve indirect actuation *via* irradiation with IR lights or exposure to alternating magnetic fields.[66,67] Fig. 9 Characterizes SMP according to classifications.

Shape memory polymers (SMPs) achieve their shape memory effect through molecular structure. They contain netpoints (physical or chemical crosslinks) and switching segments. When heated above transition temperature (T_{trans}), SMP networks become mobile for deformation. Cooling below T_{trans} fixes the temporary shape. Reheating recovers the original shape, guided by netpoints.[68] SMPs outperform SMAs in processability, weight, and flexibility. Their T_{trans} is tunable through chemical/physical modifications. This enables customized applications in textiles, aerospace, and biomedicine.[69–71] Table 1 shows some of the applications of SMP in different areas.

4 Area-wise impact, challenges and future prospects

Shape memory alloys (SMAs) are functional materials that reversibly change shape when stimulated. They uniquely convert thermal, magnetic, or mechanical energy into controlled movement. Ongoing research improves SMA formulations and processing, expanding their applications in 4D printing and self-healing systems. This review analyzes recent SMA advances, focusing on overcoming limitations and future opportunities. Each section discusses implementation challenges and potential solutions. The goal is to guide continued innovation in SMA technology and applications. By synthesizing current research with forward-looking analysis, this work aims to chart a course for continued innovation in shape memory material science and its translation into transformative technological applications. Fig. 10 displays the primary application areas of SMAs.

4.1. Biomedical

4.1.1. Impact of SMAs in biomedical field. Global healthcare sector faces unprecedented demands for implantable

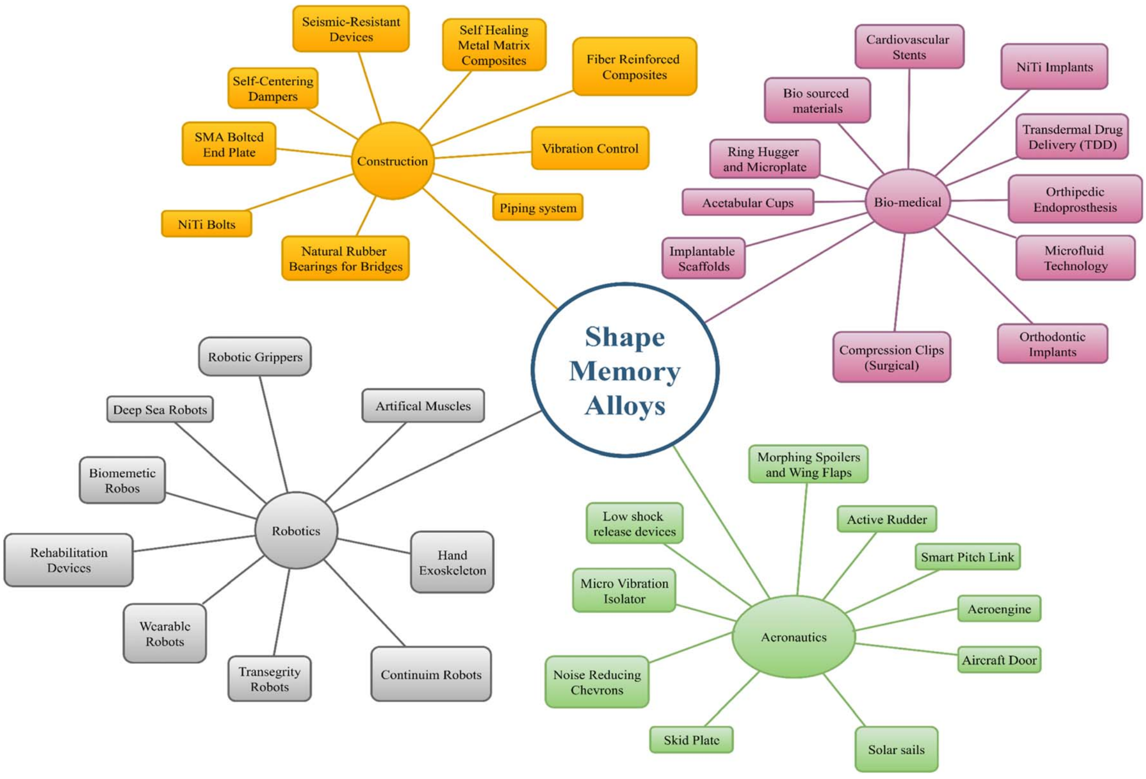

Fig. 10 Major application areas of SMA.

devices and surgical tools from the growth of the senescent generation combined with increasing prevalence of vascular diseases. Revision hip surgeries are expected to grow by 137% by 2030, driving the need for advanced biomaterials.[72] This challenge has propelled SMAs, particularly NiTi, to the forefront of medical innovation. NiTi SMAs have emerged as superior alternatives to traditional materials due to their exceptional combination of corrosion resistance, fatigue life, and mechanical durability. NiTi alloys offer distinct advantages over conventional biomaterials, overcoming the thermal instability of polymers and brittleness of ceramics while maintaining excellent biocompatibility.[73,74] NiTi offers enhanced ductility, shape recovery, and electrical activation. Its superelastic behavior mimics human bone tissue, making it ideal for orthopedic and vascular implants,[75] making it exceptionally suitable for orthopedic and vascular implants. Proper addition of heat results in a biocompatible TiO_2 coating which protects against corrosion and nickel release rendering a critical safety advantage. A depicted in Fig. 11, NiTi imparts elevated recovery strain than conventional SS steel, making it an optimal choice particularly for stents, implants and minimally invasive surgical solutions[76]

The medical application of SMAs has evolved significantly since the first cardiovascular implementation of the Simon Nitinol Filter. The introduction of self-expanding vascular stents in 1986 marked a major advancement, leveraging SMA

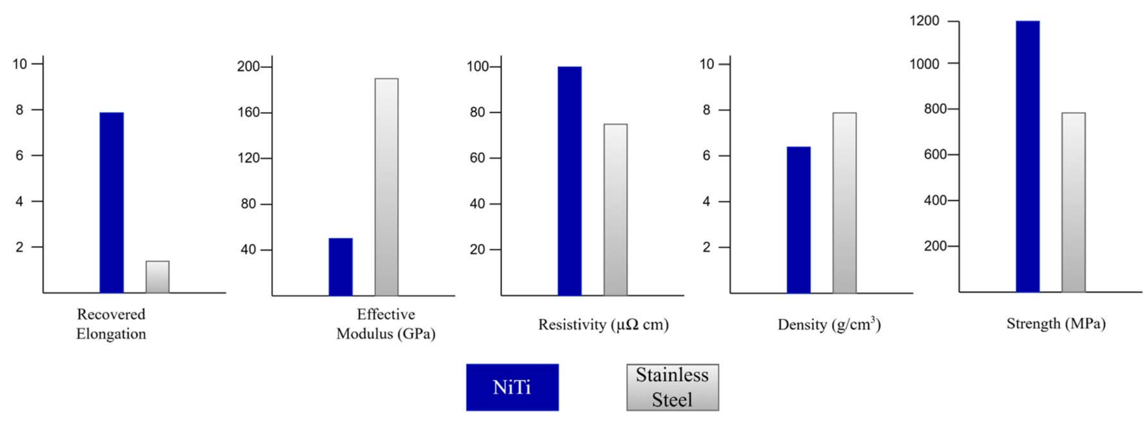

Fig. 11 Comparison of some properties between NiTi and SS.[76]

Table 2 Applications of SMAs in biomedical

Sector	Part	Application	Material	Effect	Reference
Hip joint prostheses	Acetabular cups	Actuator formed by heat treated SMA wire could be thermally activated to release the ceramic inlay from the cup	NiTiCuCr	Successfully addresses the challenges during revision surgery of modular acetabular cups to replace the ceramic inlay without damage	83
Clavicle fracture	Embracing fixator/Ring hugger	Applied SMA plates instead of traditional steel micro-plate	NiTi	Enhance compressive strength and aid fracture healing by reducing bone stress shielding	84
Gastroenterology	Compression clip in enterostomy surgery	SMA wire used to compress two spurs of intestine for better healing	NiTi	Reduce the loss of intestinal chyme avoiding further surgery by restoring intestinal patency	85
	Compression clip in anastomosis surgery	SMA wire used for tissue approximation in minimally invasive surgery	NiTi	FE analysis confirmed that the clips effectively reunite severed colons without contamination	86
	Stents in endoscopic surgery	Stents consisting uncoated meshes of NiTi wire used in the catheter	NiTi	Surgical studies confirm that nitinol stents effectively palliate malignant colorectal obstructions	87
Rib prostheses	Porous monolithic material for implant	TiNi powder sintered on monolithic TiNi substrate and treated with electron beam	NiTi	Improved corrosion resistance, biocompatibility and potential for cell growth on their surface	88
Chest wall reconstruction	Artificial rib knitted mesh	Implants were 3D printed with SMA materials	NiTi	Postsurgical follow-up was carried out after months with no complications	89
Orthodontic archwires	Braces, brackets	SMA wires used to move teeth in a control manner	NiTi		90
Tissue engineering	Spring in a distractor device	A spring was placed between two bones to test the distractor's role in new bone formation	NiTi	The device successfully provided a constant force for an efficient distraction osteogenesis	91
Orthopedic	Staples	Staples made from near atomic NiTi was used to fix fractured part of head	NiTi	Provided stable fixation, ease of placement and promoted primary healing of fracture	92
	Interspinous implant	Numerical simulations were used to quantify biomechanical behavior	NiTi	SMA outperformed the non-SMA implant in testing	93
	Intramedullary nail	SMA elements incorporated in the design for functionality enhancements		Thermally activated SMA plays crucial role in the feasibility of the design	94
	Prosthetic hand	SMA wires used in the development of the actuator		Joule's heating is applied to achieve 2 way actuation, providing a faster response	95
	Active knee orthotic	SMA wires annealed into springs	NiTi	Although SMA actuators enabled full knee motion, their slow response time resulted from low actuation force	96
Otolaryngology	Self-crimping prosthesis	Prosthesis made from NiTinol was used to replace diseased stapes bone in the ear	NiTi	Superelasticity enabled the prosthesis a unique self-crimping capacity	97

superelasticity to maintain vessel patency against compressive forces.[77,78] Modern medicine continues to uncover new applications for SMA technology. Today's sophisticated Drug Eluting Stents are capable of combating the damage done in the inner lining of the vessel after Stent implantation, a phenomenon well known by Neointimal Hyperplasia (NIH) in medical terminology.[79] Transcatheter aortic valve implantation (TAVI) has revolutionized cardiac care by replacing open-heart procedures with minimally invasive alternatives.[80] Beyond cardiovascular uses, SMAs are transforming orthopedic implants, neurosurgical tools, and rehabilitation devices. Innovative SMA-powered hand exoskeletons now restore natural movement patterns with unprecedented precision,[81] while emerging shape memory scaffolds promise dynamic tissue integration for next-generation implants.[82] Table 2 summarizes some of the reputable contributions of SMAs in the biomedical sphere.

4.1.2. Designing challenges and strategies. Despite the exceptional functional properties of NiTi shape memory alloys

Table 3 Surface engineering techniques for biocompatibility of SMAs[113]

Technique	Advantages
Air or stream oxidation	Cost-effective process that results in increased thickness as the temperature rises
Electrochemical oxidation	Simple and efficient low temperature method
Ion implementation	Can be conducted in the room temperature preventing any adversity on the SME property alongside enhancing stress resistance
Laser treatments	Provides high precision while avoiding the need for additional chemical or materials, thus eliminating the risk of contamination
Sol–gel method	Low cost and simple
Chemical vapor deposition (CVD)	Chemical reaction produces a dense and pure coating which also contributes to improved corrosion resistance
Physical vapor deposition (PVD)	Sputtering or evaporation of alloy provides smooth and high purity coating with adhesive bonding, increasing corrosion resistance and reducing wettability
Plasma electrolytic oxidation (PEO)	Allow thick, porous and adherent oxide layer, enhancing hardness and wire resistance alongside biocompatibility while enabling precise control of tailoring properties in a clean and safe environment
Low-temperature plasma treatments	Enables coating in components with complex geometry and capable of tailoring properties with superior control over surface composition

(SMAs), concerns over cytotoxicity due to nickel ion (Ni^{2+}) release have hindered their widespread acceptance in biomedical applications.[98] Additionally, the formation of fibrous tissue capsules around NiTi implants can lead to interfacial failure, further complicating their long-term viability.[99] To address these challenges, researchers have pursued three primary strategies: alloy modification, nickel substitution, and advanced surface engineering.

Alloy modification involves enhancing binary NiTi alloys by incorporating additional elements to improve biocompatibility. Quaternary TiNiCuAg SMAs, for instance, exhibit strong antibacterial properties and reduced cytotoxicity, making them promising candidates for infection-resistant implants.[100] Meanwhile, cost-effective alternatives such as Cu-based SMAs (*e.g.*, Cu–Al–Ni and Cu–Zn–Al) have been explored, though their mechanical stability remains a limiting factor.[101] A more radical solution involves replacing nickel entirely with biocompatible elements like Mo, Nb, Ta, and Zr, leading to the development of β-type Ti-based SMAs (*e.g.*, Ti–Nb–Zr, Ti–Nb–Mo) that retain shape memory and superelasticity while eliminating Ni-ion toxicity.[102] Surface modification has emerged as a critical method for mitigating Ni^{2+} release. Techniques such as oxidation treatments, electrochemical polishing, and thin-film deposition (*e.g.*, PVD, CVD) have been employed to create protective oxide layers.[103–105] Among these, atomic layer deposition (ALD) stands out for its ultra-thin and conformal coatings, offering precise control over surface properties.[106,107] Recent innovations include multifunctional nanolayers (*e.g.*, Ag–TiO_2, hydroxyapatite-doped composites) that enhance biocompatibility while preventing bacterial adhesion.[108,109] Hybrid surface treatments, combining plasma polymerization with electrochemical processing, have further improved corrosion resistance and biointegration.[110–112] The following Table 3 sums up some modification techniques highlighting their advantages.

Beyond material and surface modifications, structural design plays a crucial role in implant performance. Porous NiTi alloys, for example, promote bone ingrowth while silver(Ag) nanoparticles embedded within their matrix enhance antibacterial efficacy.[114] Meanwhile, the rise of biodegradable implants has shifted focus toward Fe-based SMAs. Implants made from Fe-SMAs can degrade harmlessly after fulfilling their function,

Table 4 Current challenges of SMA applications in biomedical

Challenges	Effects	Potential solutions	Reference
Nickel ion toxicity	Ni^{2+} release from NiTi SMAs causing cytotoxicity	Alloy modification	100
		Nickel substitution	101
		Surface engineering	
Osseointegration	Fibrous encapsulation leading to interfacial failure	Porous NiTi for bone ingrowth	114
		Bioactive coatings (hydroxyapatite, Ag–TiO_2)	106 and 107
		Biodegradable Fe-SMAs	115
		Hybrid surface treatments	110–112
Corrosion & degradation	Oxide layer breakdown in physiological environments leading to implant failure	Electrochemical polishing	104 and 105
Long-term durability	Fatigue under cyclic loading causing premature failure	Zr–Nb–Al alloys for wear resistance	116 and 117

eliminating the need for secondary removal surgeries.[115] Further, high-entropy SMAs and novel Zr–Nb–Al alloys are also gaining attention for their superior mechanical properties, wear resistance, and MRI compatibility, offering new possibilities for next-generation biomedical devices.[116,117] However, challenges persist, particularly in ensuring long-term durability under cyclic loading and physiological corrosion. The degradation of NiTi's protective oxide layer at elevated temperatures, along with fatigue-induced failure, underscores the need for continued innovation in alloy design and surface engineering. Table 4 shows the contemporary challenges that the SMAs are facing in biomedical applications. As research progresses, the integration of advanced materials, nanostructured coatings, and biodegradable systems will be pivotal in overcoming these limitations, paving the way for safer, more reliable SMA-based biomedical implants.

4.1.3. Future perspective

4.1.3.1. Advances in surface modification techniques. From the light of the above overview, it can be reaffirmed that advances of surface modification techniques to promote bi-ofunctionality are certainly prosperous. Nonetheless, further efforts should concentrate on incorporating hybrid techniques so that surface modified SMA implants can achieve stringent biocompatibility with improved wear resistance. This task can be quite challenging considering the indispensability of cost efficiency in healthcare. With the ability to precisely navigate through the body, SMAs should allow for novel treatments to be administered. This could include targeted drug delivery, the precise placement of stents or medical devices and even the exciting possibility of robot-assisted minimally invasive surgeries with the help of active catheters moving dynamically based on real-time feedback. Additionally, the development of a biocompatible "smart" surface with self-healing mechanism could present another noteworthy prospect. This may also lead to development of smart drug delivery systems.

4.1.3.2. 3D-printed SMAs for personalized medicine. 3D printed SMAs present unprecedented opportunities for personalized medicine and bio-device innovation.[118] Despite the excellent physical properties of 3D-printed SMA, it is important to ensure that it does not cause adverse reactions or toxicity to organisms in *in vivo* applications. In-depth research is needed to address these challenges in the future and seek interdisciplinary collaboration and innovation. Through technological innovation, cost control, and improvements in biocompatibility and safety, it is believed that 3D-printed SMAs will play an even more important role in the field of biomedical engineering, bringing more efficient, safe and personalized medical solutions to patients.

4.1.3.3. Untapped potential of MSMAs. Despite getting limited attention in the medical sector, Magnetic Shape Memory Alloy (MSMA) holds considerable untapped potential.[119] The solitary capability of MSMA to exhibit up to 10% shape morphing[120] in response to magnetic fields, positions them in highly promising remote manipulation. MSMAs can provide dynamic control to permanent implants or devices such as stents *via* magnetic fields. This would permit post calibration without the need of any surgical procedures. Research is going on to develop such implants based on FePd shape memory due to their magento-mechanical property and biocompatibility. Additionally, FePd based ferromagnetic alloys are also presumed to be good candidates for temporary self-expanding coronary stents. On another note, MSMAs can be particularly impactful in Microfluidic pumps.[61] The integration of Ni–Mn–Ga in a micropump prototype showed outstanding candidacy in ameliorating contemporary drug delivery mechanisms.[121] Looking ahead, the metamorphic potential of MSMA provides adaptable solutions making them an attractive material in the near future. As research in Shape Memory Alloys (SMAs) progresses, we can anticipate transformative advancements in biomedical applications with personalized, adaptive and patient-oriented healthcare solutions.

4.2. Construction

4.2.1. Impact of SMAs in civil engineering. Next generation structures with self-diagnosis, self-healing and self-adaptation capability necessitates integration of smart materials.[122] In this context, SMA's contributions to smart structures bring about auspicious possibilities. High damping capacity and fatigue resistance of SMAs have enumerated numerous possibilities of utilizing them in civil structures to attenuate unwanted energies.[123] Hitherto, civil structures were built with materials that mainly relied on the strength of the materials to bear loads rather than energy absorption. Hence, they have low capacity to dissipate energy and can not adapt themselves in sudden excitation. For decades, researchers have been investigating new materials with alacrity that can automatically compensate for undesirable disturbances. The broader perspective that incorporates post-seismic functionality and rapid recovery in structural design has incited novel SMA-based contrivances and technologies in the construction arena. The infusion of SMAs enables edifices to adapt to external forces or respond to changing weather conditions without enduring damage and marks a significant leap towards sustainable and resilient urban development.[124] The thermoelastic phase transformation inside these alloys enables them to be suited for actuation applications and controlled vibration isolation systems. The integration of SMA control systems into the structural paradigm can be active, passive or semi active. Active control systems offer superior performance compared to passive control systems; however, they are contingent upon external power sources for actuation, whereas passive systems provide inherent adaptability without the need for any active controller. Semi-active system does not actively control the structure; rather it adapts to mitigate loads and vibration upon actuation. The Fig. 12 classifies the structural control systems by using SMAs.

The potentiality of seismic resilience, particularly self-centering, lies in their superelastic (SE) phenomena, while energy dissipation is largely attributable to the intrinsic hysteresis. These exceptional capabilities coupled with excellent corrosion resistance have positioned SMA as a worthier option for both steel and concrete infrastructures. The integration of SMA in steel structures has led to several innovations

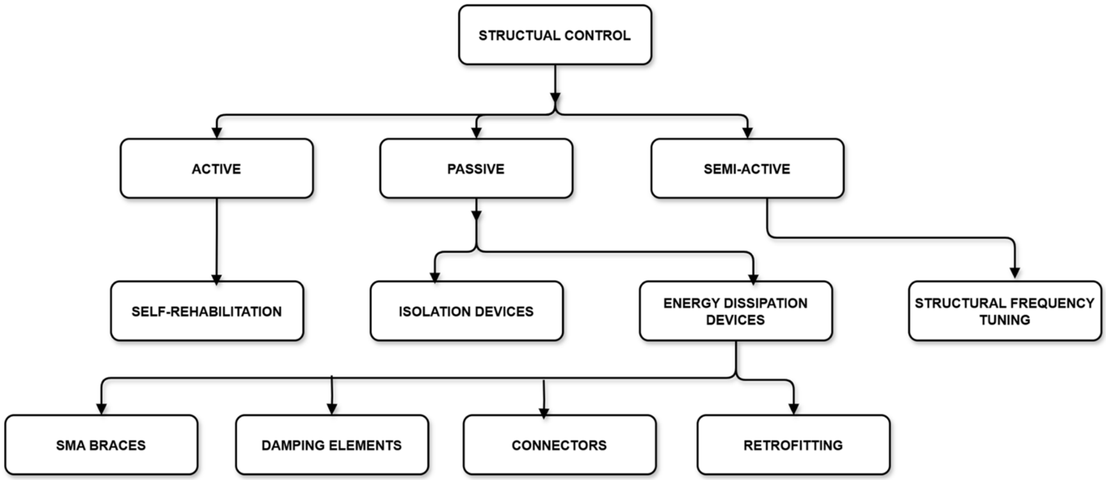

Fig. 12 SMA-based structural control systems.[125]

underscored by seismic resilient beam-column connectors, self-centering bracing system[126] and energy dissipating damper controllers. Superelastic SMAs demonstrate large flag-shaped hysteresis under cyclic loading which permits both recentering and dissipation of subsidiary energy in the steel structure restricting inter-storey drift. Additionally, SMA cables and wires are appropriate for active and passive reinforcements as they are capable of creating peerless bonds with concrete and offer enhanced flexural strength and improved shear behavior. SMA fibers can be added to the concrete mixture providing ductility and reducing crack propagation.[127] While the steel fibers show permanent deformation after yielding, SMA fibers can regain the deformation and dissipate large amounts of energy simultaneously owing to their intrinsic hysteretic behavior. Although, the core functionality remains similar, application of SMAs varies due to structural difference in steel and concrete constructions as shown in Fig. 13. Tables 4 and 5 summarises several studies by distributing them according to the SMA functionalities and applied structures.

Recent advances in SMA applications for civil engineering have demonstrated their versatility across multiple domains. The unique properties of SMAs have been successfully employed in retrofitting solutions for historical structures, as evidenced by case studies at the Valle dei Templi archeological

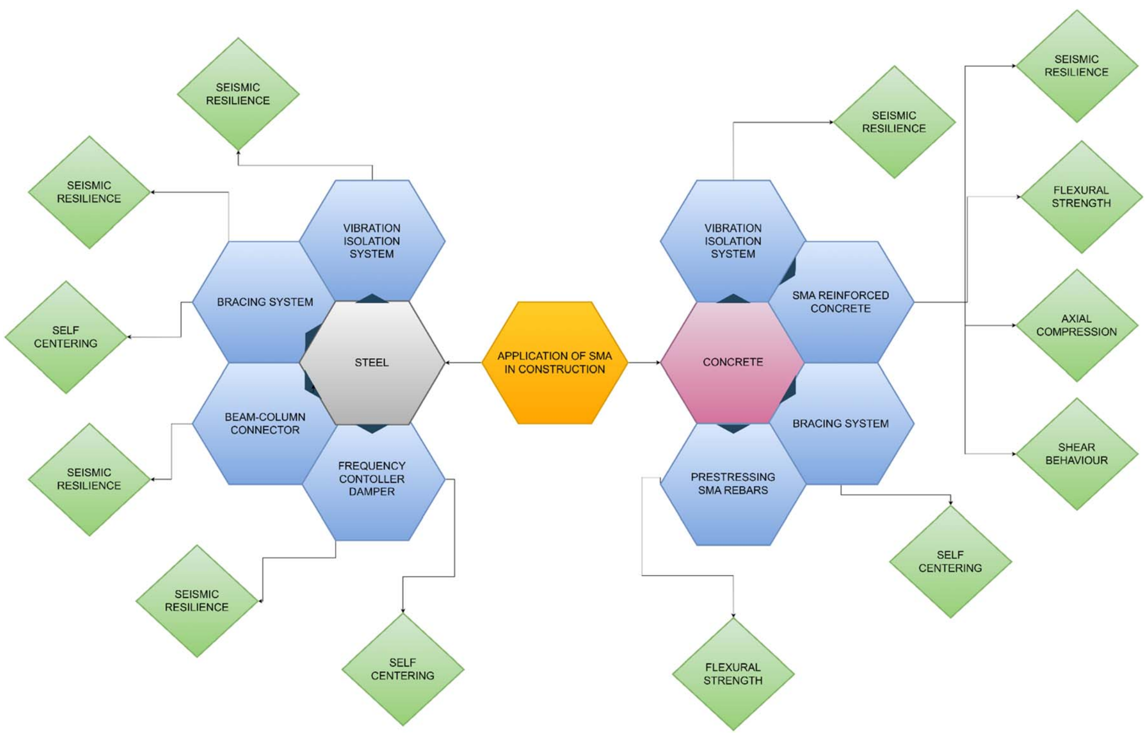

Fig. 13 SMA-based systems in construction engineering.

Table 5 SMA applications in steel construction

System	Application	Function	SMA material	Results	Reference
Bracing system	SMA rods used instead of back tie/wire	Self-centering	NiTi rods	Offers a stable hysteretic response and substantial deformation capacity, making a promising component for high-performance earthquake-resilient structures	147
	SMA based bracing in 4 combinations in 4-storey steel frame	Seismic resilience	NiTi	Lessen the maximum inter-storey drift and improved seismic response	148
	SMA based bracing in a 6-storey steel frame	Self-centering	NiTi	Decrease the drift ratio, the peak floor acceleration and improve self-centering	149
	Diagonal SMA based bracing in a 4-storey steel frame	Seismic resilience	NiTi	Reduce roof displacement demand	150
	SMA wire used as back tie/wire	Self-centering	NiTi wire	Self-centering capacity ratio improved to 89.38%. Energy dissipation rate also improved	151
Beam-column connector	SMA tendons in system	Seismic resilience	NiTi	Provide good energy dissipation capacity and ductility	152
	SMA tendon used in the system	Seismic resilience	Niti tendon	Use of SMA tendon resulted in excellent ductility, energy dissipation, and self-centering capabilities	153
	Confined SMA plates in plastic hinge region	Seismic resilience	NiTi	Mitigate the permanent deformations and prevent local buckling	154
	SMA angle, SMA bolted end plates were used for connection	Seisemic resilience	NiTi, FeMnAlNi	SMA angles resolve the issue of replacing energy-dissipating elements, with Fe-based SMAs exhibiting superior performance	155
	SMA angle used in the connector	Seismic resilience	NiTi	Satisfactory energy dissipation and self-centering capabilities encouraging potential use of SMA angles in earthquake engineering	156
Frequency controller damper	SMA restrainer in a simply supported bridge	Seismic resilience	NiTi	Reduces relative hinge displacements	157
	SMA wires in a 5-storey steel frame	Seismic resilience	NiTi	Increases natural frequency about 32%	158
	SMA plates were used in an unique U-shaped damper	Self-centering	NiTi plates	More than 98% of deformations could be recovered after multiple loading cycles	159
	Damper developed with buckling restrained SMA bars	Self-centering	NiTi	The proposed damper effectively reduces inter-story drift ratios in structures	160
Vibration isolation system	Natural rubber bearing with SMA wires	Seismic resilience	NiTi, FeNiCuAlTaB	SMA wires enhance reentering capability and energy dissipation in rubber bearings	161
	SMA supplemented rubber bearing in a 3-storey frame	Seismic resilience	NiTi	Reduce residual displacement	162
	SMA bending bars into the lead rubber bearing base	Seismic resilience	NiTi	Reduce residual displacement	163

Table 6 SMA applications in concrete construction

System	Application	Function	SMA material	Results	Reference
SMA reinforced concrete	Shear wall reinforced with SMA bar	Seismic resilience	NiTi	SMA reinforcements improved seismic response, reduced permanent strain and enhanced stiffness compared to conventional steel reinforcements	164
	SMA Rebar in the plastic hinge region of bridge piers	Seismic resilience	NiTi	Reduced permanent drift and seismic damage	165
	SMA bars anchored underneath RC beams	Flexural strength	Fe-SMA	The strengthened beams show significant enhancement of flexural capacity with significantly improved ductility	166
	Prestrained SMA spirals to repair damaged RC column	Seismic resilience	NiTi	Increased lateral stiffness about 150%	167
	Shear wall reinforced with SMA strips and ECC sheets	Seismic resilience	NiTi	Energy dissipation significantly improved	168
	SMA reinforcement in plastic hinge region	Seismic resilience	NiTi	Hybrid SMA-reinforcement demonstrated superior self-centering and significant energy dissipation capacity compared to steel-reinforced walls with similar property	169
	Shear wall slotted with SMA bars	Seismic resilience	NiTi	The slotted RC walls showed a superior response under different axial load	170
	Column confined with external SMA strips	Axial compression	FeMnSiCrNi	Experiments reveal that active confinement of Fe-SMA strips markedly improve the compressive strength and ultimate axial deformation of axially loaded columns	171
	Column confined with external SMA strips	Axial compression	Fe-SMA strips + FRP layer	Three confinement types were tested: passive, active, and hybrid. Hybrid method significantly improves load capacity	172
	Internal SMA stirrups were used in column	Shear behavior	Fe-SMA	Activating the Fe-SMA stirrups has reduced the number of diagonal shear cracks	173
	Column confined with external SMA strips	Axial compression	FeMnSiCrNi	Numerical testing showed significant improvement in the lateral ductility	174
Prestressing of concrete	SMA tendon used during prestress	Flexural strength	Fe–Mn–Al–Ni	Prestressing and thermal activation of SMA rebar enhances concrete's compressive and flexural strength	175
	SMA bars used during prestress	Flexural strength	FeMnSiCrNi	Larger diameter Fe-SMA bars significantly improve strength and ductility	140
	SMA spring washers are installed and precompressed in the bridge pier	Self-centering	NiTi washer spring	Hysteric energy dissipation was provided with minimal residual deformation	176
Bracing system	SMA wire used as back tie/wire	Self-centering	NiTi wire	SMA devices allow large deformations without residual displacements in structures	177
Vibration isolation system	SMA reinforced concrete	Seismic resilience	Ni–Ti	This experiment shows stable hysteretic responses of SMA bar and minimal repair needs in post-earthquake after full scale test	178
	SMA material bolts were used in connection	Self-centering	Ni–Ti	Moderate energy dissipation capacity observed with stable damping at large deformations	179

site in Agrigento, Sicily, where they contributed to the anastylosis of ancient constructions.[128,129] Their exceptional damping characteristics have proven valuable in specialized applications such as undersea tunnel construction.[130] This shows further promise in building multifunctional dampers in tunnel construction. The ability of SMAs to undergo reversible deformation makes them ideal candidates for designing reusable energy-absorbing structures.[131] Their damping properties are being actively explored for vibration control in energy harvesting systems from smart roadways. Additionally, in combination with piezoelectric materials, these alloys serve as mechanical dampers that absorb load fluctuations and protect PZT layers from cyclic fatigue.[132–134] The application of SMAs in concrete technology has seen particularly innovative developments, especially in the realm of prestressing and crack healing. Engineered cementitious composites (ECC) incorporating NiTi SMA cables have shown potential to enhance crack self-closure and self-repair capabilities.[135] While initial research focused heavily on NiTi fibers for prestressing applications, recent investigations have shifted toward more economical Fe-based SMAs. Numerous studies have established these alloys as viable alternatives.[136–139] Testing of Fe-SMA as reinforcement materials indicates their potential for creating cost-effective SMA-FRC composites in infrastructure projects.[140,141] Fe-SMAs are being practically employed in prolonging the lifespan of dilapidated bridges, indicating huge potential for prestressed reinforcement of existing roadway structures.[142–144] Fe-SMA can additionally improve the fire resistance of RC beams and significantly reduce residual deformation and crack width after failure.[145] The development of ternary Ni–Ti–Co SMAs with enhanced superelastic properties and optimized phase transformation characteristics further expands the range of potential seismic applications in civil engineering, as the addition of cobalt to binary Ni–Ti alloys modifies critical stress levels and transformation temperatures to better suit structural requirements.[146]

Tables 5 and 6 shows SMA implementations in Steel and concrete structures respectively.

4.2.2. Designing challenges and strategies. While NiTi shape memory alloys have shown promise in seismic-resistant construction, several critical limitations are identified in the literature. The martensitic transformation temperature of NiTi beginning at 0 °C curbs the application of superelasticity in colder regions. It significantly limits geographical applicability. Furthermore, civil engineering demands large-diameter SMA reinforcement bars that present substantial manufacturing challenges due to material complexities. The massive quantities required to withstand structural forces in civil projects escalate costs. This further exacerbates the already high price of NiTi and compounds the overall cost. Machining the larger diameter NiTi bars involves an arduous process of traditional method that adds another constraint to their employment. Complicated welding between NiTi and Steel just adds into the bargain.[180] These collective limitations have driven exploration of alternative SMA systems better suited for civil infrastructure applications.

Iron-based SMAs offer potential advantages through superior low-cycle fatigue resistance and reduced material costs. However, Fe-SMAs demonstrate notably lower recovery strains compared to NiTi, while high-temperature oxide formation diminishes their magnetic properties. Alloying with chromium and nickel shows promise in mitigating these effects, though significant research gaps remain. Table 7 depicts some design challenges of SMAs in construction sector.

Copper-based alloys have emerged as attractive alternatives, combining exceptional damping characteristics with cost-effectiveness. These materials are regarded as the most affordable replacement of NiTi.[181,182] Substitution of Ni with Cu in a NiTi alloy can improve the SME by narrowing the transformation hysteresis. Recent developments in quaternary NiTiCuW alloys demonstrate precise temperature control through Cu/W ratio adjustments, with reduced Af-Mf ranges suggesting potential for broader Cu-based alloy adoption in civil engineering.[183] These advances highlight ongoing progress in developing SMA solutions tailored to the specific demands of seismic-resistant construction.

4.2.3. Future perspective

4.2.3.1. Economic viability and manufacturing challenges. As we stride towards sustainable practices in construction engineering, SMAs holds the potential to shape the way we design, build and maintain infrastructure. However, further research in a number of areas is required in order to make the transformative shift in construction commercially. From mercantile point of view, widespread acceptance of an innovation largely

Table 7 Challenges in construction sector for SMAs

Challenges	Effects	Potential solutions	Reference
Temperature limitations	Martensitic transformation starts at 0 °C, limiting cold-region use	Quaternary alloys with adjustable transformation ranges	183
Manufacturing issues	Difficulties in producing large-diameter SMA bars	Advanced manufacturing techniques	
Cost constraints	High material and processing costs of NiTi	Alternative SMAs (Fe-based, Cu-based) with lower costs	181 and 182
Welding challenges	Complex welding between NiTi and steel	Adhesive bonding and adhesive-bolted hybrid connections	180, 184, 136 and 185
Fe-based SMA limitations	Lower recovery strains than NiTi, oxide formation		

depends on the expenses associated with it. At present some of the innovations are economically impractical on account of exorbitant expenditures involved. Although Fe-SMA and Cu-SMA emerged a lucrative option for the market, it is still not viable for their complex alloying process and higher price than other reinforcement materials such as carbon fiber. This demands rigorous exploration of cost-effective ways of alternative manufacturing processes. Despite the promises, current challenges in the manufacturing of Fe-SMA through LPBF technique call for further investigation in controlling the process parameters. Improving the weldability of Fe-SMAs with other dissimilar alloys is another area which can be focused in order to reduce material joining cost. These researches are necessary to provide cost-competitive solutions to the market. Moreover, properties at macroscale of these alloys can be altered by heat treatment or rolling temperatures which opens up new research avenues of optimising properties in terms of application. On the other hand, there is a lack of comprehensive resources regarding stochastic behaviour of these alloys particularly in the cases of creep, fatigue and fracture. Therefore, simple computational models can be utilized for numerical and analytical simulations of SMA structures under different loading conditions to properly understand the behaviour of Fe-SMA and Cu-SMA at macroscopic level.

4.2.3.2. Innovative anchoring methods. Most of the Fe-SMA reinforcement techniques use bolt based anchoring methods mainly because of the convenient installation process but they involve drilling processes which are vulnerable to stress concentrations. Adhesive bonding and adhesive-bolted hybrid connections offer promising solutions to this issue, yet, experimental research on this innovative approach is limited. Further research can be conducted in this area to improve structural integrity. Full scale realistic set-up is needed for better understanding of SMA applications in full-scale structures.

4.2.3.3. Smart concrete. Smart concrete[186,187] stands out as a game-changing material in the future of construction owing to the self-healing and self-adjusting mechanisms. This promising arena paves the way for more resilient, low-maintenance buildings and reduce the need for costly repairs. A concept of embedding nano-SMA particles in the concrete matrix for functioning as an autonomous healing agent has been proposed[188] but it has not been demonstrated yet. Research can be progressed in processing such concrete that heals itself without external stimuli. With the rapid advancements in sensing technology, structural health monitoring systems can now be integrated with SMA actuators, enabling the development of kinematic buildings with a wide range of scope of research and innovation.

4.2.3.4. Sustainability and recyclability of SMAs. As a final remark, an auspicious future for SMAs in construction could lie in the development of recyclable SMA materials. As we move toward a more sustainable future, the challenges of material disposal at the end of a structure's life cycle must be addressed. Recyclability in SMAs would ensure that these advanced and valuable materials can be reused. Hence, the focus on recyclability will be of utmost importance.

4.3. Aerospace

4.3.1. Impact of SMAs in aircraft and space technology. Shape memory alloys are revolutionizing aircraft design through their unique reconfigurability and multifunctional capabilities. These advanced materials provide substantial actuation forces at relatively low frequencies while simultaneously offering vibration damping through nonlinear hysteresis effects. Their ability to contract, expand, twist, and bend with precise control enables simplified systems that outperform conventional electromechanical actuators in weight-critical aerospace applications.

The aviation industry has embraced SMAs for adaptive wing systems that optimize aerodynamic performance.[189,190] Utilizing the SME, bio-inspired morphing aircrafts are able to achieve aerodynamic efficiency by adapting to multiple aerial conditions and reducing fuel consumption. Most morphing aircraft involve SMAs working in passive roles through linear actuation by means of SMA wires. Twisting actuators are also used in flap elements so that twist angles and bend of the wing could be adjusted according to the cruising condition.[191] Notable programs including Smart Wing and SAMPSON have demonstrated successful integration of these smart materials into operational aircraft systems. Following them, several innovative concepts contributed to the evolution of morphing wings. The feasibility of reducing fuel consumption by improving laminar flow over an active wing body was rigorously investigated by the scientific community. From this perspective, a variable-thickness morphing wing was designed with two actuator groups consisting of SMA wires and bias springs.[192] Recent innovations feature hybrid designs combining both SMA and PZT materials to develop a wave generating MEMS based active skin. Wind tunnel testing showed that the active skin could effectively minimise fuel consumption by reducing drag.[193] Recently, composite structures with embedded SMA actuators have been developed to amplify morphing capabilities across larger airframe sections.[194,195] Apart from morphing wings or flaps, SMAs are being implemented in other components such as active rudder systems, aircraft doors and helicopter pitch links. Furthermore, energy dissipation capacity of the SMAs are being used in safety systems such as landing gears and aero-engine brackets. A pithy overview of all these applications underscoring the effect of using SMAs are presented at Table 8.

The applications of SMA have transcended beyond the terrestrial boundaries with significant strides in space technology. Their exceptional thermoelastic properties have unlocked new potential in heat switches for advanced thermal control systems in space. As humanity ventures further into deep space, the demand on thermal control systems is intensifying which necessitates more sophisticated and reliable methods. NASA has implemented three-way splitter valves utilizing intrinsic shape memory behavior to regulate fluid flow without external power.[209] Additive manufacturing techniques now produce NiTi heat pipes with integrated porous wicks for efficient capillary-driven thermal transfer. For deep space missions, heat turndown ratios are expected to reach 12 : 1. Advanced morphing radiators combining SMA tensile elements

Table 8 SMA applications in aircraft

Model/Part	Application of SMA	Actuator material	Effect	Research method	Reference and year
Morphing wing	Utilized variable stiffness SMP composites to enhance aerodynamic performance	SMP + spandex fiber	10 mm thick skin illustrated the ability to endure high speed flight and alter at low speed	Numerical	(Ref. 196) 2013
	A matrix of crosswise SMA wires facilitates wing twisting motion	NiTi wires	Provides nearly 13% increase of lift-to-drag ratio	Experimental	(Ref. 197) 2016
	Changing of camber by means of SMA actuator		Maximum deflection of 0.6 mm at the trailing edge top was achieved	Numerical	(Ref. 198) 2018
	SMA micro-spring actuators arranged within the wing	NiTi spring	The system generates adequate force to deform the profile, even under critical conditions	Experimental	(Ref. 199) 2019
	Antagonistic SMA actuator fixed with morphing wing	NiTi wire	Preisach model exceeded traditional limitations enabling full control by replacing bi-stable actuation	Numerical	(Ref. 200) 2019
	Embedded SMA wires in the wings spanwise to increase actuation displacement	NiTi wires	Numerical study confirms that the wing orientation can be adjusted for optimal performance	Numerical + experimental	(Ref. 201) 2021
Wave generating active skin	Thin-film SMA created a bimorph actuator, generating a traveling wave to minimize drag	TiNiCu	MEMS based active skin developed and wind tunnel tested. Found matching profile	Numerical + experimental	(Ref. 193) 2008
Variable geometry chevron	Bendable SMA sheets laminated in the morphing chevrons to minimize noise	NiTi sheets	Effectively reduced noise without compromising engine performance	Experimental	(Ref. 202) 2007
Aircraft door	SMA based plates attached with Al door for sealing	NiTi	Repeating transformation cycle of SMA plates can control deformation of aircraft sealing door	Numerical + experimental	(Ref. 203) 2022
Pitch link	Use of SMA mini coil springs in link for passive vibration control	NiTi	Satisfactory performance in vibration attenuation and energy dissipation	Experimental	(Ref. 204) 2024
Active rudder	Use of SMA torsion springs to initiate rudder movement	NiTi spring	Compact and kinetically simple mechanism produces 30 movement to the right and 40 to the left	Experimental	(Ref. 205) 2024
Morphing spoiler and flap	SMA springs exerting bistable actuation and manipulating spoilers and flaps	NiTi spring	Improved performance with extended lifespan by eliminating the need for continuous power	Numerical	(Ref. 206) 2024
Skid plate	Bistable actuator using SMA spring for plate movement	NiTi spring	The skid plate could rotate 12° around the fixed hinge, facilitating 42 mm vertical displacement	Numerical	(Ref. 207) 2024
Aeroengine bracket	Bracket struts replaced with SMA for vibration control	NiTi	Stiffness of bracket increased by 36.71% and resonance peak amplitude decreased by 17.7%	Numerical	(Ref. 208) 2024

Table 9 SMA applications in space

Model/Part	Application of SMA	Actuator material	Effect	Research method	Reference, year
Low shock release devices	Exploits the controlled and continuous heating of SMA	NiTi	Invented device functions with negligible energy and bolsters safety by circumventing explosive methods	Experimental	(Ref. 216) 1992
Vibration isolation	SMA mash washer is used for cryocooler vibration isolation	NiTi	Isolator showed adaptability with the amplitude of the vibration level providing superior image quality from satellites	Experimental	(Ref. 217) 2015
Morphing radiator	SMA wires and strips affixed to a conductive radiator block inducing morphing behavior		Numerical analysis demonstrated heat turndown ratio of 27 : 1 can be achieved through this system	Numerical + experimental	(Ref. 210) 2018
Solar sail	SMA wires used in the sail films	NiTi wires	Deployment of SMA wires yields 75% surface reduction and good planarity degree	Experimental	(Ref. 218) 2019
Mars rover tyre	SMA springs in construction of Mars tire for durability	NiTi springs	Data extracted from prototype and used in numerical model enabling tire design with fewer iterations	Numerical	(Ref. 215) 2024

with composite laminates achieve exceptional 35 : 1 heat turndown ratios through temperature-responsive emissivity modulation.[210] Cryogenic shape memory alloys are another emerging solution to thermal control systems. This novel application is specifically appealing in space environments where the temperature drops extremely low. Cryogenic CuAlMn alloys demonstrate phase transformation below 90 K.[211] It was also observed that heat treatment could alter the phase transformation temperatures of CuAlMn alloy offering new advances in the area of cryogenic research. The continuous exploration of SMAs have led the researchers to successfully synthesise new Ti–Al-based SMA ($Ti_{75.25}Al_{20}Cr_{4.75}$) with robust properties for temperature change. In advanced applications such as aerospace and space exploration, materials must balance lightness, functionality and extreme thermal fluctuation resistance. The new shape-memory alloy that adheres to these stringent criteria characterized by a low density and high specific strength that can maintain remarkable 7% recovery strain across a broad range of temperatures, from deep cryogenic 4.2 K to above room temperature.[212]

Minimising the intervention of human need is a priority during designing space structures. Since space systems often require minimal manual involvement, SMAs are perfect for autonomous mechanisms. Solar-activated hinge systems with embedded NiTi wires are triggered by thermal stimulus from a printed heater powered by solar panels. This shows the possibility of using bending actuators in space.[213] Another novel application of SMAs is in the active suspension system of space vehicles. Adaptive rover suspensions outperform hydraulic alternatives, enhancing rover mobility even further.[214] Robust numerical model for the spring tires has been made at NASA for space rovers. The designs are validated through advanced computational models that are user-defined, detail-oriented, and computationally efficient.[215] Table 9 shows SMA applications in space technology.

4.3.2. Designing challenges and strategies. Understanding wear characteristics and thermal sensitivity of shape memory materials remains paramount for aerospace reliability. The expanding space sector demands ultra-high-temperature SMAs (UHTSMAs) capable of withstanding extreme mechanical stresses, rapid motion, and severe thermal conditions. These materials frequently serve in actuation systems and morphing wings, where compromised functionality from wear or temperature effects could prove catastrophic.

SMAs exhibit distinct deformation mechanisms compared to conventional materials due to thermoelastic transformations. NiTi alloys demonstrate exceptional wear resistance through pseudoelasticity. Elevated temperatures promote protective Ti-oxide layer formation under load, reducing wear rates through compressive stress generation. However, research indicates dissipated strain energy better explains wear behavior at extreme loads, rather than oxidation effects.[4,219,220] Laser surface texturing (LST) has emerged as a prominent technique for enhancing SMA tribological performance in aerospace settings.[221]

Superelasticity's temperature dependence restricts conventional SMAs like binary NiTi and Cu-based alloys, with

Table 10 Challenges in aerospace sector for SMAs

Challenges	Effects	Implications	Potential solutions	Reference
Wear characteristics	Complex deformation mechanisms	Difficult to predict long-term performance under cyclic loading	Laser surface texturing (LST) to improve wear resistance	219–221
Temperature sensitivity	Conventional SMAs limited to near-ambient temperatures	Restricted use in high-temperature aerospace environments	High-temperature SMAs (NiTiHf, NiTiPd, NiTiPt)	222
	Excessive hysteresis at high temperatures	Reduced actuation efficiency due to widened thermal cycles	Alloying with Hf, Zr, Pd, or Pt to stabilize properties	
	Oxidation above 300 °C alters SMA behavior	Compositional changes degrade SME		
Creep & strain recovery	High temperatures reduce strain recovery and cause creep development even at low stress	Long-term reliability concerns in structural components	High-entropy alloys (HEAs) for improved stability	52 and 223
Cost & manufacturing	High material costs (NiTi, Pt/Pd alloys)	Economic barriers for large-scale aerospace adoption		

transformation ranges near ambient conditions. High-temperature SMAs (Nb–Ru, Ta–Ru, NiTiHf, TiNiPd, TiNiPt) better suit space applications, though excessive hysteresis diminishes actuation efficiency through widened thermal cycles. Microstructural instability, including precipitate formation, further complicates high-temperature operation. In this context, controlling the thermoelastic nature through alloying represents a better solution.

Ternary NiTi alloys with Pd, Pt, Hf, or Zr additions effectively expand operational ranges while preserving thermomechanical properties. NiTiHf has gained particular prominence, demonstrating ideal actuation characteristics for aircraft in projects like SAW and RCA wind tunnel models.[222] Hf alloying elevates transformation temperatures cost-effectively while maintaining dimensional stability. However, oxidation becomes problematic above 300 °C, altering composition and transformation behavior through oxide layer formation.

Table 10 highlights the current material constraints of SMAs in aerospace arena. The pronounced temperature sensitivity of the abovementioned materials presents a significant challenge for their application in aerospace environments. Additionally, high operating temperature deteriorates strain recovery and work output which also provokes the development of creep even at low stress.[52] As a solution, the high-entropy alloy concept offers promising avenues for developing next-generation HTSMAs with superior superelastic and shape memory properties to address these limitations.[223]. This innovative approach may overcome the issues for SMAs in extreme aerospace environments.

4.3.3. Future perspective

4.3.3.1. 4D-printed SMAs for adaptive wing. Shape memory alloys are poised to redefine the future of aviation technology. The future prospect of an automatic adaptive wing in different flight conditions promises unprecedented aerodynamic efficiency. In this context, leveraging 4DP to create complex, self-morphing components that respond autonomously to thermal or stress stimuli presents an exciting future to further research. Recently, 4DP has gathered a lot of advancements. The integration of 4DP with SMAs have catalysed significant progress by the emergence of shape shifting with time alongside multi-functionality such as reconfigurability and self-healing.[224,225] Its application to create morphing aircraft could lead to a key research path. The most prevalent variable-sweep wing aircraft to date are F-14, MiG-23, B-1, and X-53 suffer from their structural weight.[226] However, the reconfigurability of SMAs holds significant promise through the pioneering application of 4D printing, contingent upon rigorous and thorough research. Optimizing printing parameters for aerospace-grade SMAs and integrating with *in situ* sensors for real-time feedback could pave the way for groundbreaking advancements. Moreover, integrating machine learning with SMA actuators to optimize wing morphing could result in sufficient drag reduction leading to the development of lightweight control systems for hypersonic vehicles.

4.3.3.2. Ultra-high temperature SMA development. The aerospace industry has been engaged in a relentless pursuit of HTSMAs. NiTiHf has been reported to show SMA behavior in ultra-high range (up to 800 °C).[227] Despite the immense potential in aerospace sector, comprehensive research on Ultra High NiTiHf is scarce. The hysteresis behavior in NiTiHf remains elusive and is not yet thoroughly understood. Therefore, a thorough investigation on the intricacies of this potential alloy is urgent. Developing NiTiHf/Pd-based alloys for use in variable-geometry chevrons, turbine seals, or fan blades to enhance efficiency under extreme temperatures represents a promising scope of research.

4.3.3.3. Self-healing aerospace composites. The incorporation of SMAs into carbon fiber-reinforced composites offers a groundbreaking approach to enabling damage sensing and self-repairing functionalities in spacecraft and satellite panels. By embedding SMAs, these composites would be able to detect structural damage autonomously and activate self-healing processes. The self-repairing capabilities of SMA-enhanced composites not only reduce maintenance expenses but also improve reliability and performance of the structures which would be a significant step towards sustainability.

4.3.3.4. Hypersonic thermal management. SMAs offer a promising solution for mitigating aerodynamic heating in hypersonic vehicles through SMA-activated thermal heat switches, leveraging their thermomechanical properties to regulate heat transfer. Recent research has demonstrated the potential of integrating SMAs into scramjet engines, where their adaptive capabilities have been analyzed to enhance performance under high thermal loads.[228] This exploration has opened new avenues for the application of SMAs in hypersonic systems. Adaptive skins with SMAs can act as variable-emissivity surfaces and dynamically manage heating effects to preserve aerodynamic performance. These advancements highlight SMAs' potential to enhance thermal management in hypersonic systems.

Overall, these directions align with global trends in sustainability, digitalization, and hypersonic technology, positioning SMAs as pivotal materials for next-generation aerospace innovation.

4.4. Robotics

4.4.1. Technological frontiers in robotics leveraging SMAs. SMAs have revolutionized robotics, delivering unmatched benefits in actuation, adaptability, and miniaturization. Their ability to endure significant deformation and revert to their original form *via* thermal or mechanical triggers makes them indispensable for compact, energy-efficient robotic systems. While conventional rigid robots excel in precision, they often struggle in delicate or confined settings due to inflexibility. SMAs, conversely, enable lifelike movements in soft robots, allowing them to emulate human and natural behavioral patterns by replicating their locomotive mechanisms. This fusion narrows the divide between human and machine interaction, fostering seamless collaboration. Biocompatible and environmentally adaptive, SMA-driven systems eliminate the need for complex controls. Their use in grippers, exoskeletons, and autonomous machines boosts dexterity, strength, and responsiveness, unlocking advanced applications across industries.

The primary use of SMAs in robotics lies in soft actuators.[229] These incorporate SMA wires or springs within elastic matrices, amplifying their inherent deformation (4–8%) to produce muscle-like contractions. Often referred to as artificial muscles, they emulate the high energy density and compliance of biological muscles and enable anisotropic bending, twisting, and multimodal deformations which makes them viable for various bionic robots.[230] By arranging SMA wires or springs in arrays, engineers achieve intricate motions in compact, lightweight systems. This versatility positions SMAs as a linchpin for bionic applications, particularly in the development of artificial muscles for biomimetic robots.

Inspired by the parsimony and efficacy of biological systems, researchers have perennially harnessed SMAs to replicate complex motions. SMA actuators power robots that emulate earthworm peristalsis,[231,232] snake undulation,[233] fish swimming,[234,235] and bat flight.[236] Insect-inspired robots harness SMA-driven wing flapping for thrust.[237] Froghopper-inspired designs enable directional micro-jumping.[238] Turtle-like flipping actuators[239] and cilia-like robots with NiTi-PDMS composites[240,241] facilitate fluid transport. Underwater vehicles like Robojelly mimic jellyfish propulsion.[242] Insect-scale robots, blending PZT and SMA materials, replicate cockroach crawling and flea jumping.[243] Despite design hurdles, SMA actuators dominate biomimetic robotics, offering novel solutions for lifelike movement.

The confluence of SMA's stress–strain behavior with human musculature and their tunable rigidity, coupled with ongoing miniaturization of technologies has spurred the emerging field of humanoid and wearable robotics. SMA artificial muscles animate facial expressions,[244,245] robotic necks,[246] arms,[247] and fingers.[248] Stiffness is considered a critical parameter in soft robotics as the robots should be able to achieve deformation easily while also maintaining its integrity by resisting external disturbances. With this point, SMA becomes an easy preference showing variable stiffness capabilities. Agonist-antagonist SMA systems deliver compliant actuation and energy efficiency.[249] Modular SMA robots with gooseneck backbones maintain its posture in three-dimensional space and resist external disturbances without consuming energy.[250]

While most SMA-enabled wearable robotic systems remain in nascent phases, they are gradually revolutionizing rehabilitation and therapeutic practices.[95,251,252] The market for wearable technology has continued to grow in the past years at 14.6% annually.[253] Table 11 shows several studies where SMA has been implemented in different robotic systems.

The integration of SMAs into wearable robots confers significant advantages, including portability and seamless enhancement of human movement. Flexible and lightweight soft actuators are suitable for muscle mimicry and soft wearable robots, making them for mimicking knee movement.[256] The prodigious force-to-weight ratio and noiseless operation make SMAs ideal for assistive devices. Exoskeletons can be built to amplify human strength up to 100 times, endowing users with herculean capabilities for exigent tasks.[276,277] Surface electromyography (sEMG)-driven exoskeletons synchronize with neuromuscular signals promises to offer seamless motion assistance for medical rehabilitation and performance enhancement.[278] Such innovations highlight SMA's potential to mediate human–machine symbiosis in clinical and industrial contexts.

In deep-sea exploration, SMA grippers overcome traditional limitations.[273,274,279] While rigid manipulators handle heavy tasks, they fail in delicate operations, crushing fragile specimens. SMA-embedded soft grippers offer gentle, precise handling, even at 3600-meter depths, This is crucial for protecting marine ecosystems during specimen retrieval.

Medical robotics benefits from SMA-driven continuum robots. Flexible and precise, they outperform rigid counterparts in confined spaces. The SURS surgical robot, powered by superelastic NiTi wires, bends and rotates for minimally invasive procedures.[280] Magnetic continuum robots, using NiTi wires and reprogrammable magnets, deform under external

Table 11 SMA applications in robotics

Types	SMA applied on	Reference
Wearable and rehabilitation devices	Soft orthosis	96
	Myocardial assistive device	252
	Soft hand	254
	Artificial hand	255
	Artificial knee	256
	Elbow	257
	Artificial arm	69
	Artificial wrist	258
	SMART brake	259
	Wearable robot for forearm	260
	Wearable wrist with coolant vessel	261
	Wearable gloves	262
Biomimic	Snake	233
	Jellyfish (Robojelly)	242
	Octopus	263
	Inchworms	264
	Caterpillar (GoQBot)	265
	Seal (SEALicone)	266
	Bat	267
	Cockroaches	243
	Springtails	11
	Ladybirds	12
Robots	Control model for human robot interactions (HRI)	268
	Parallel manipulators	269
	Tensegrity robots	270
	Continuum robots	271
	Magnetic continuum robots	272
Robotic gripper	Deep seawater gripper	273 and 274
	Soft gripper with fast actuation	274
	Gripper with water cooling	275

fields without redesign.[272] SMA springs also enable locomotion in tensegrity robots, blending rigid struts with dynamic actuation.[270]

4.4.2. Designing challenges and strategies. Despite their promise, SMA actuators confront inherent limitations such as low strain capacity, sluggish response times and nonlinear behavior, all of which has been the focal point of extensive research lately.[21] First, the linear operation of SMA wires yields a modest strain-to-length ratio (typically 2–5%), necessitating longer wires for greater displacement. This undermines the miniaturization critical for wearable robotics and prosthetics.[281,282] Designers must thus negotiate a trade-off between actuation force and range of motion, customizing solutions for specific applications. Since strain limitations are intrinsic to SMAs, only innovative mechanical designs can amplify motion and partially circumvent this constraint.

Second, delayed heat dissipation during phase transitions throttles response frequency, restricting real-world utility. While active cooling such as fans[283] or hydrogel-based evaporative systems[284] accelerates recovery, such additions often compromise portability. More elegant solutions focus on minimizing thermal transport paths to boost cycling rates.[285] Additionally, SMAs exhibit nonlinear behavior due to intrinsic hysteresis, leading to control inaccuracies and system instability. Machine learning algorithms now help mitigate these effects by narrowing thermal hysteresis.[286] NiTicu SMA presents an excellent solution in this regard with low hysteresis and outstanding actuation capabilities. Recent developments in 3DP promises processing of tailorable NiTiCu alloy in requirement specific applications, specifically beneficial to address these issues in the robotics arena.[287] Table 12 sums up the discussion for applicability of SMAs in robotics sector.

In spite of these advancements, challenges remain. The intricate actuation mechanics of SMA wires warrant deeper study.[289] In wearable robots, SMA wires must be insulated to prevent unintended thermal activation due to close contact with the human body. The requirement for high currents for SMA wire's Joule heating further complicates their use in rehabilitation devices. In applications like soft grippers, pneumatic actuators often outperform SMAs in generating substantial force, limiting SMA actuators primarily to superelastic configurations. Though fine ray grippers with SMA wires show potential, they lack self-sensing capabilities and require further development.[290] Collectively, these hurdles highlight the imperative for sustained innovation to unlock SMA actuators' full potential across robotics and related fields.

4.4.3. Future perspective. As the field progresses, there is an increasing demand to explore novel research trajectories aimed at optimizing SMA performance for robotic applications. Prioritizing energy efficiency, manufacturability and multifunctional integration would be the key to addressing the current limitations.

4.4.3.1. Performance optimization for soft grippers. SMA soft grippers remain inferior to pneumatic grippers in terms of performances largely due to the degradation of the polymeric matrix in which SMA actuators are embedded. Additionally, it is found from several studies that superelastic properties also reduce with the increase of strain.[291,292] Both of these issues are particularly responsible for poor performance of robotic grippers. The former calls for research on optimized materials to improve SMA-matrix interaction. Experiments with the different

Table 12 SMA actuator challenges in robotic applications

Challenge	Impact	Potential solutions	Reference
Low strain capacity	Limits miniaturization and displacement	Motion-amplifying mechanical designs	281 and 282
Sluggish response times	Reduces actuation frequency	Active cooling Optimized thermal pathways	283–285
Nonlinear behavior	Causes control inaccuracies	Thermal hysteresis control through ML	286
High current requirements	Complicates wearable applications	Improved insulation, alternative heating methods	288

embedding techniques of SMA wires in the matrix can be conducted to check results. In order to solve the degradation of SMAs, heating management can be done by exploiting the self sensing properties of SMA based on electrical resistivity.[293] Future research can be done on improving self sensing capabilities by means of ML/DL. Real time feedback can result in avoiding unnecessary overheating and overall improved thermal management. In addition, upon feedback from resistivity change with strain during grabbing, grasping force can be adjusted to elevate a more dynamic response. Moreover, AI can be trained to predict fatigue life enabling predictive maintenance.

4.4.3.2. Low-power alternatives for wearable robots. While joules heating remains the preference for heating SMA actuators, it results in high electricity consumption due to poor resistance of SMA wires which creates an issue specifically for biomedical applications like wearable robots, surgical robots and rehabilitation devices. Using nichrome wire as the heating element with spring actuator has shown impressive active cooling but not much study has been found further on fast and active cooling methods of SMA actuators.[288] Future research in this area can ensure SMA activated devices triumph over current pneumatic preference.

4.4.3.3. 4D printed rehabilitation devices. The use of 4D printing can initiate a new era in rehabilitation devices. Future research can include using LPBF to print porous NiTi structures that stiffen/soften with body heat, which would aid rehabilitation robots in providing dynamic support.

4.4.3.4. Microactuators for bionic robotics. Developing microactuators for insect-scale bionic robots for rapid wing movements is another area where future research can be conducted. While SMA based microactuators are still in their infancy, creating appropriate microactuators is a key area of development in the MEMS field. NiTi with high work per volume rate is an excellent choice for these actuator types to be used in insect-scale robots. Maintaining SME at a miniaturized level is the key factor in this research.

4.4.3.5. Fe-SMAs for underwater applications. Fe-SMA has become an insanely popular choice for excellent corrosion resistance and affordability. Underwater robotic grippers and manipulators can exploit this hugely potential alloy where the aforementioned properties would render substantial advantage.

4.5. SMA in automotive

4.5.1. Impact of SMA in automotive applications. The automotive industry's gradual transition toward smart materials reflects its commitment to advancing safety, comfort, and performance. Among these materials, shape memory alloys (SMAs) have carved a niche as innovative actuators, offering lightweight, durable, and vibration-resistant alternatives to conventional systems. With modern vehicles incorporating over 200 actuators on average, SMAs present a compelling solution for miniaturization and weight reduction by replacing bulkier electromagnetic actuators with compact and silent mechanisms. However, despite their advantages of simplified design and energy efficiency, inherent limitations challenge their widespread adoption.

The adaptive properties of SMAs work as the key factor in achieving aerodynamic efficiency. Adjustable spoilers and flaps can minimise the drag to reduce fuel consumption. Tumble flaps that are used in internal combustion (IC) engines to create a swirling motion to improve the fuel–air mixture, are traditionally activated with pneumatic or electronic actuators which are both complex and space-consuming. SMA springs offer a streamlined alternative by enabling bidirectional linear displacement in automotive tumble flaps which improves the mixture as well as avoiding complexity.[294] Adaptive fender skirts in another application of morphing panels contributing to the fuel efficiency of the automobile. SMA wires laminated composite with programmable curvature serves as morphing fenders that address conflicting aerodynamic demands of flat profile to eliminate the turbulence caused by wheels rotating at high speed and dome-shaped profile to avoid collision during steering.[295] One concept that has gathered significant attention lately is the Active Grill Shutter(AGS) system, consisting of bi-stable actuators to regulate engine temperature autonomously. By opening at low speeds for cooling and closing at high speeds to reduce drag, AGS improves fuel economy without continuous power consumption, while maintaining optimal thermal conditions during parking.[296]

SMAs also elevate vehicular comfort and convenience through silent, low-power automation. SMA wires work as an actuating element in a bi-stable anti-glaring rear view mirror[297] which provides automatic operation avoiding manual adjustment by the driver. Gear-driven side-mirror mechanism has similarly been supplanted by SMA actuator[6] offering cost-effective alternative. SMA actuators controlled by Joule's heating are designed to be used in pneumatic valves and implemented in vehicle seats to simulate a "messaging effect" for enhancing user experience. Further, SMA wires have been implemented in adaptive sealing systems and auto open-close of hatch vents improving the overall comfortability and noise reduction. The introduction of intelligent shock absorbers can drastically improve the convenience and comfort system of automobiles. Additionally, suspension systems benefit from SMA's tunable stiffness and damping properties which outperform traditional shock absorbers in adaptability and ride comfort. Table 13 shows different automobile parts classifying them with respect to the functions served by SMA systems.

SMS applications have been expanded to modern safety-centric designs. Their energy-absorbing properties make SMAs ideal for lightweight bumpers that enhance crash protection without compromising efficiency.[298,299] Rapid-actuating SMA systems enable automatic bonnet elevation which contributes in mitigating pedestrian injury risks during accidental collisions.[300]

Conventional clamping steering column causes knee injury to the driver during collision. SMA integration in the clamping system eliminates the need for manual force, facilitating the focus of the driver on road. Emerging concepts such as automotive sensors,[306] micro-scanners,[307] child lock systems[308] highlight untapped potential, though commercial deployment

Table 13 SMA in automobile

Function	Automotive parts	Mechanism/Goal	Reference
Aerodynamic performance	Spoiler and flaps	Minimise drag	17
	Tumble flaps	Improve the fuel-air mixture during injection	294
	Fender	Minimise drag	295
	Active grill shutter	Control engine temperature	296
	Transmission control	Control friction between two surfaces	—
	Valve		301
	Fan blade	Improve cooling performance	302
	Radiator	Flow control	—
	Couplings	Vibration damping	303
Comfort and convenience	Head light		—
	Wiper		—
	Rear view and side view mirror	Bi-stable actuation for anti-glare	6 and 297
	Suspension system	Shock absorbing	304
Safety	Shift lever	Moving the pawl to lock or release shift lock	—
	Steering column		305
	Bumpers	Vibration damping	298 and 299
	Lifting bonnet	Fast actuation	300
	Automotive sensors	Temperature detection and warning	306
	Micro-scaners	Bi-stable actuation	307
	Child locking system		308

remains incremental. Collectively, these advancements underscore SMAs' transformative role in redefining automotive innovation, bridging gaps between performance, safety, and sustainability.

4.5.2. Designing challenges and strategies. Despite burgeoning research and commercialization efforts, SMA actuators remain largely confined to theoretical proposals rather than practical implementation in the automotive sector. Some common issues regarding SMA actuators such as low operational frequency and narrow bandwidth have already been discussed in earlier sections. The deactivation or cooling relies on passive heat dissipation to the ambient environment, creating a critical asymmetry between fast actuation and slow deactivation. Additional cooling methods may contribute to cooling but they often add complexity to the system. This thermal latency creates a fundamental performance bottleneck for SMA actuators in automobiles. Further complicating matters are functional fatigue and nonlinear behavior, which undermine long-term reliability and precise control. The inherent hysteresis and strain-dependent degradation of SMAs necessitate sophisticated compensation strategies, yet these often prove impractical for mass-produced vehicle systems.

The most common actuation method of SMA in automobiles is by joules heating method. While it is straightforward to implement, it suffers from remarkably low energy efficiency and converts only a fraction of electrical input into useful mechanical work, dissipating most as waste heat. There is also the issue of overheating of the SMA component due to high current flow. These drawbacks have largely confined SMA applications to experimental prototypes, as manufacturers chooses more reliable and efficient conventional actuation systems in production vehicles. To this date, not many solutions have been found to mitigate these causes. Therefore, the commercial aspect of SMA in automobiles is still very low. Although SMAs present intriguing possibilities—from adaptive aerodynamics to energy-efficient valve actuation—their real-world deployment in automobiles remains circumscribed by these unresolved challenges. Overcoming these barriers will demand not only material innovations but also holistic system-level engineering to reconcile SMA performance with the rigorous demands of automotive environments.

4.5.3. Future perspective. Recent advancements in additive manufacturing are helping to overcome some of SMA's traditional limitations, particularly regarding fatigue life. These advanced manufacturing techniques enable the production of complex, durable geometries that were previously unattainable, making SMA components more viable for long-life automotive applications. The combination of material innovation and advanced manufacturing processes continues to push the boundaries of what's possible with SMA integration in transportation. While technical challenges remain, these cutting-edge applications demonstrate SMAs' potential to be a game-changer in automotive technology, particularly for electric vehicles and smart mobility solutions of the future.

4.5.3.1. Self-healing vehicle systems. SMAs are poised to revolutionize automotive technology through several groundbreaking applications, despite their current limited commercial adoption. One of the most promising areas is in self-healing systems, where SMAs could enable autonomous repair of minor dents and microcracks in vehicle bodies through heat-activated mechanisms. This capability would significantly reduce maintenance costs while improving vehicle longevity. When combined with 4D printing technologies, SMAs can create components that dynamically adjust their stiffness in real-time, optimizing aerodynamic efficiency and vehicle performance under varying driving conditions.

4.5.3.2. Next-gen lightweight materials with SMAs. The potential for next-generation lightweighting solutions represents another exciting frontier for SMA applications. By integrating SMAs with advanced materials like graphene, manufacturers could develop ultra-lightweight, morphing body panels capable of adaptive shape changes. These intelligent composites would not only reduce vehicle weight but also actively improve energy efficiency and performance through their ability to modify aerodynamic properties on demand. Such innovations could fundamentally transform vehicle construction paradigms and energy consumption profiles.

4.5.3.3. Energy harvesting for EV. In the realm of electric vehicles, SMAs offer innovative solutions for energy harvesting and efficiency optimization.[309,310] Their unique properties enable novel approaches to energy recovery, including vibration energy harvesting from vehicle motion that could power auxiliary systems. SMAs also show great promise in solar energy applications, where they could be integrated into photovoltaic layers to autonomously adjust panel angles for maximum sunlight capture. Additionally, SMA-based solar tracking systems could significantly improve the efficiency of vehicle-integrated solar panels, extending EV range and reducing charging requirements.

4.6. Other applications of SMA

Beyond the well-established uses, SMAs continue to demonstrate transformative potential across diverse and innovative domains. Their unique combination of mechanical properties and adaptive capabilities enables novel solutions to complex engineering challenges. As research progresses, the materials science community continues to explore SMAs with enhanced multi-functionality. The ongoing development of processing techniques promises to further expand their impact across engineering disciplines.

4.6.1. Miniaturized applications in advanced devices. Shape memory alloys demonstrate exceptional suitability for miniature mechanical systems, combining superior mechanical performance with compact dimensions and low mass.[311] These characteristics position SMAs as ideal actuating elements for small-scale devices requiring precise motion control and substantial force output relative to their size.

A notable implementation involves SMA wire actuators in innovative miniature braille cells designed for integration into wearable assistive technologies.[253] This application capitalizes on the alloys' ability to provide reliable, repeatable actuation in constrained spaces. The development highlights SMAs' potential to enhance accessibility through compact, efficient mechanical solutions. Heusler alloys, particularly Ni–Mn based compositions, emerge as promising candidates for advanced smart devices due to their unique structural and magnetic properties.[312] These materials exhibit complex crystallographic behaviors including order–disorder transitions and magnetic ordering phenomena, enabling applications spanning spintronics, magnetic refrigeration, and specialized shape memory implementations. Recent advancements in high-rate SMA actuation have significantly improved the technology's viability for active material applications.[313] Enhanced energy efficiency and reduced response times collectively address previous limitations, expanding potential uses in miniaturized systems. These developments continue to broaden SMA utilization across cutting-edge micro-mechanical and smart device applications.

4.6.2. Auxetic smart metamaterials. Recent advancements in SMA-based auxetic metamaterials capitalize on the thermoelastic and superelastic behavior of SMAs to develop structures with negative Poisson's ratios that can actively modulate their shape and stiffness. These innovative materials offer dynamic tunability for adaptive engineering applications. They demonstrate superior energy absorption capabilities. The integration of SMAs into auxetic architectures enhances impact resistance by maximizing energy dissipation upon collision. NiTi-based auxetic structures exhibit significantly higher performance compared to Fe-based or steel-based alternatives.[314] A key development involves the implementation of bidirectional actuation in SMA-auxetic composites through controlled Joule heating. This approach enables reversible transitions between low and high temperature phases using a single power input, allowing dynamic modification of material shape and stiffness.[14] Such capabilities prove particularly valuable for robotic applications requiring adaptive mechanical properties.

Additive manufacturing breakthroughs have facilitated the production of digitally reprogrammable auxetic metamaterials.[315] By capitalizing on the SME, these structures permit continuous tuning of mechanical characteristics including poisson's ratios and elastic moduli during deformation cycles. This adaptability enables unprecedented control over material behavior under varying operational conditions. Specialized configurations incorporate SMA springs within locally resonant metamaterials to create systems with tunable bandgap properties and enhanced damping performance.[316] These smart materials leverage temperature-induced phase transformations and stress-dependent hysteresis to actively adjust their vibration isolation characteristics.

For compact applications, SMA thin film auxetic structures demonstrate exceptional deformation capacity, sustaining strains up to 57.4%.[64] This remarkable flexibility makes them ideal candidates for next-generation stretchable electronics, advanced wearable medical devices, and innovative implant designs. The convergence of SMA technology with auxetic metamaterial principles continues to expand possibilities in fields demanding responsive, adaptive material systems.

4.6.3. Vibration control applications. Shape memory alloy springs demonstrate significant potential for intelligent vibration isolation systems, offering adaptive capabilities that respond to changing operational conditions.[317,318] These smart vibration systems leverage SMA properties to automatically adjust their characteristics based on environmental stimuli. Research has developed SMA-based adaptive-passive dynamic vibration absorbers that effectively diminish vibration amplitudes across broad frequency ranges in piping applications.[319] The unique properties of SMAs enable innovative solutions for vibration mitigation. Adaptive tuned mass dampers utilizing SMA components can autonomously avoid mistuning while tracking multiple eigenfrequencies independently.[320] This capability proves particularly valuable in structures subject to variable loading conditions. Advanced SMA applications include tunable metamaterial plates that effectively trap vibrations and reduce noise transmission, offering benefits for precision instrumentation and defense equipment requiring stringent vibration control.[321]

A notable development involves SMA sponges incorporated into pounding tuned mass dampers, which provide effective vibration reduction in suspended piping systems.[322] This approach presents a cost-efficient, non-invasive solution that maintains structural integrity while improving damping performance. The combination of SMA's adaptive characteristics with conventional damping mechanisms creates hybrid systems capable of addressing complex vibration challenges across industrial and infrastructure applications.

4.6.4. Smart textiles incorporating SMAs. Smart textiles represent an innovative class of materials that integrate conventional textile architectures with advanced electronic functionalities. The incorporation of SMA wires into woven structures has enabled the creation of three-dimensional morphing soft actuators with transformative potential.[323] These SMA-textile hybrid actuators have attracted substantial research attention due to their versatility across multiple domains, particularly in smart fabric development and wearable technology applications.[324] Current fabrication methods combine SMA elements with macro fiber composites (MFC) to produce advanced soft actuators. The inherent nonlinear behavior of SMAs presents both opportunities and challenges in textile integration. Through specialized knitting techniques, researchers have successfully engineered shape-morphing structures and actuation sheets using textile fiber-wrapped SMA wires. Innovative approaches blending traditional smocking methods with SMA components have yielded diverse shape-changing patterns and behaviors, expanding design possibilities.[325]

The strategic patterning of SMA elements within textile matrices enables precise generation of forces and torques. However, this sophisticated manufacturing process demands specialized expertise and considerable time investment, resulting in elevated production costs for functional actuation sheets. To address these challenges, researchers have developed computational models using finite element analysis, creating equivalent unit cell representations based on linear constitutive equations to analyze and optimize knitted SMA-textile actuator performance.[326] Practical implementations demonstrate the unique capabilities of these hybrid systems. Smart textile-composite actuators combining SMAs with knitting yarns exhibit exceptional gentle grasping performance. It can securely manipulate fragile or irregularly shaped objects without causing damage.[327]

Ongoing research focuses on developing advanced fabric structures using continuous fiber patterns to enhance actuation modes in fiber-type artificial muscles, targeting improvements in both strain capacity and actuation force. Recent innovations include the development of chain-based intelligent textile actuators, which have shown promising results in soft gripper applications. These systems demonstrate efficient grasping performance while opening new possibilities for flexible operation across textile applications, wearable devices, and specialized technical fields.[328] The convergence of SMA technology with textile engineering continues to push boundaries in smart material development, offering increasingly sophisticated solutions for interactive and adaptive fabric systems.

4.6.5. Bio-inspired solar tracking systems. The heliotropic behavior of sunflowers has inspired innovative solar tracking technologies. This biomimetic approach leverages SMA's intrinsic thermomechanical properties to create self-regulating solar trackers. Traditional electromechanical tracking systems employ complex networks of motors and actuators to maintain optimal photovoltaic alignment. In contrast, SMAs offer a simplified, energy-efficient alternative by directly converting thermal energy into mechanical motion without requiring external control systems.[329] When exposed to solar heating, SMA components undergo controlled deformation, precisely adjusting panel orientation throughout the day. The technology demonstrates particular advantages for sustainable energy systems, requiring minimal operational energy while offering long-term cost benefits compared to conventional tracking mechanisms.

The unique characteristics of SMAs enable diverse implementations across renewable energy technologies. Portable solar units benefit from their lightweight and scalable properties. Notable developments include NiTi wire-based heat engines that directly convert solar thermal energy to electricity[330] and printed heaters for space applications that utilize solar power to activate shape memory effects.[213] Current research focuses on optimizing SMA performance for smart photovoltaic systems, including a novel self-tracking design combining SMA actuators with parabolic trough concentrators to significantly enhance energy capture efficiency.[331] SMAs also address critical maintenance challenges in solar infrastructure. Self-cleaning PV systems utilizing SMA mechanisms effectively mitigate dust accumulation, maintaining panel efficiency and extending operational lifespan.[332] These implementations demonstrate SMA's versatility in solving multiple challenges across solar energy generation and maintenance.

5 Processing of shape memory alloy

The authors have discussed the processing of SMAs into two main categories. One includes details about the manufacturing processes and the other contains in depth exploration of modern-day machining methodologies. Both categories are coequal for accomplishing versatile objectives of SMA in various domains.

5.1. Manufacturing methods of SMA

The manufacturing of SMAs centers on optimizing shape recovery capabilities while satisfying application-specific mechanical demands. This intricate balance necessitates precise control of alloy composition and processing conditions to tailor phase transformation behavior. The NiTi alloy remains the benchmark SMA, with strategic elemental additions enabling precise property modification. Copper, hafnium, and

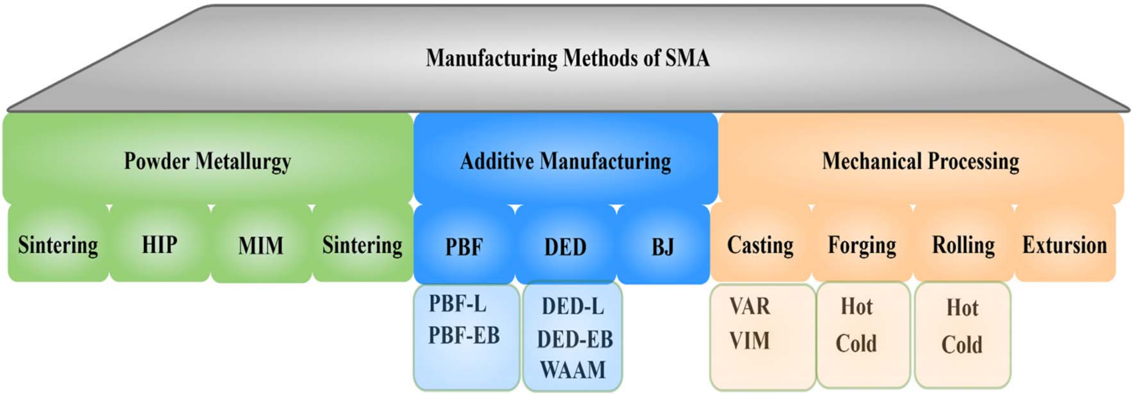

Fig. 14 Manufacturing methods of SMA (abbreviations are defined in the text upon first use).

zirconium serve as common alloying elements that adjust transformation temperatures and hysteresis characteristics for targeted operational environments. As illustrated in the accompanying Fig. 14, SMA processing encompasses multiple methodologies, each presenting distinct advantages and constraints.

SMAs fabricated by powder metallurgy provides better mechanical properties due to refined microstructure. Advanced manufacturing methods enable the production of complex geometry components with graded properties that would be impossible to achieve through conventional manufacturing.[333] Foundational mechanical processes like extrusion and rolling remain vital for producing standard forms. Extrusion generates uniform-diameter wires, while rolling creates thin sheets and foils for diverse applications.

Thermomechanical processing represents a critical stage for final property optimization. It involves careful calibration of post-production heat treatment techniques in order to achieve desired performance characteristics for pros SMAs. This processing versatility permits fabrication of materials spanning highly flexible superelastic alloys for medical devices to robust, high-strength formulations for automotive and aerospace components. Recent advancements in process automation and control have significantly improved manufacturing consistency and efficiency, accelerating industrial adoption of SMA technologies across diverse sectors.

The subsequent sections will systematically examine each processing method. Given its emerging status, additive manufacturing receives comprehensive analysis, while other established techniques are reviewed concisely to provide complete methodological context.

5.1.1. Powder metallurgy. Powder metallurgy (PM) enables precise fabrication of complex SMA geometries with controlled compositions. This manufacturing approach incorporates several specialized techniques, each offering unique microstructural and property advantages. Important procedures for PM are given in Fig. 15. Conventional sintering begins with powder compaction through cold isostatic pressing or powder injection molding. By this method a near net-shape is achieved known as the green compact. A sintered preform is created through particle bonding at atomic levels by subsequent furnace heating below melting temperatures. While cost-effective for mass production, this method typically yields porous components. Therefore, conventional sintering, in most cases, is restricted to applications primarily related to biomedical implants.[334–336]

Hot isostatic pressing (HIP) addresses porosity limitations by applying simultaneous high temperature (≤1200 °C) and isostatic pressure (100–200 MPa) *via* inert gas. This facilitates production of near-full-density SMAs with homogeneous microstructures which are ideal for high-cycle fatigue applications.[338,339] Metal injection molding (MIM) combines powder with polymeric binders for mold injection and later followed by binder removal and sintering. This enables mass production of intricate, net-shape SMA components. This process is valuable for mass-production of individual intricate SMA parts having the same shapes.[340–342]

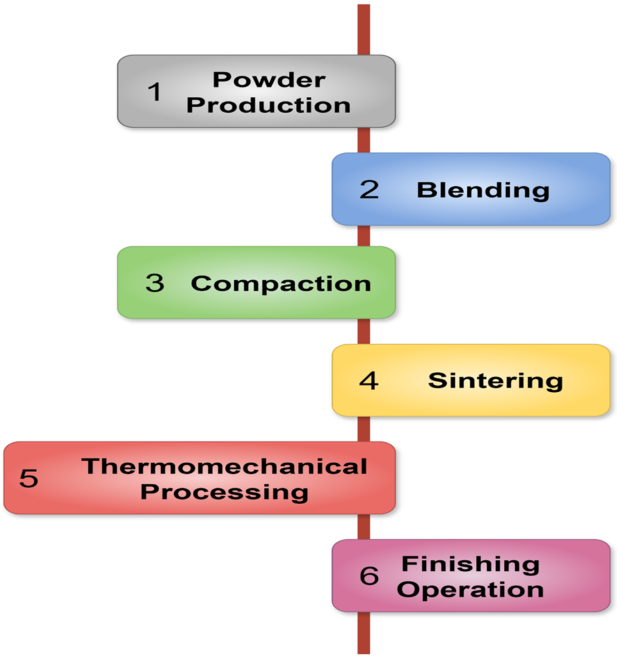

Fig. 15 Steps of powder metallurgy.[337]

Self-propagating high-temperature synthesis (SHS) utilizes exothermic reactions to synthesize SMAs directly from elemental powders. This combustion-based process achieves high throughput but requires precise ignition control to prevent composition inhomogeneity.[343–345] Among advanced techniques, spark plasma sintering (SPS) employs pulsed electric currents and uniaxial pressure for rapid, low-temperature consolidation. SPS produces high-density structures with nanoscale grains, enabling novel nanocomposite SMAs. However, it demands careful parameter optimization as the parameters are contingent upon power behaviours, compactness and the nature of the electric field.[346–348]

Each PM method presents distinct trade-offs in microstructure control, mechanical properties, and geometric capabilities. Recent developments focus on hybrid approaches combining multiple techniques' strengths while mitigating individual limitations.[349] The optimal method selection depends on specific application requirements for transformation behavior, mechanical performance, and production scale.

5.1.2. Additive manufacturing. Additive manufacturing (AM) represents a paradigm shift in SMA fabrication, enabling layer-by-layer construction through various 3D printing methodologies.[350] This technology fundamentally operates through two principal approaches: powder bed fusion (PBF) and direct energy deposition (DED). PBF employs high-energy beams to selectively fuse successive layers of metal powder, while DED utilizes a concentrated energy source to melt material during simultaneous deposition *via* a nozzle. PBF has often been studied for *in situ* alloying of NiTi SMA and is preferred over DED, particularly in achieving superior dimensional precision and surface quality compared to DED alternatives. The DED approach encompasses multiple variants including Laser Engineered Net Shaping (LENS), Laser Directed Energy Deposition (LDED), Electron Beam Fabrication (EBF), and Wire Arc Additive Manufacturing (WAAM). AM systems can be further differentiated by their energy sources, primarily: (i) electron beam-based systems (ii) laser-based systems (iii) plasma arc-based systems. Following sections provide comprehensive analysis of the primary AM techniques for SMAs. Each of these methods exhibits unique characteristics. These methodologies collectively offer tailored solutions for diverse SMA applications, balancing precision, production efficiency, and material properties.

5.1.2.1. Powder bed fusion. Powder bed fusion (PBF) ensures superior alloy density and uniformity, yielding SMAs with exceptional mechanical attributes. This methodology incorporates two distinct heat sources: PBF-LB (Laser Beam) and PBF-EB (Electron Beam). PBF-LB, commonly designated as LPBF (Laser Powder Bed Fusion), represents the conventional nomenclature for this technology. Techniques including selective laser melting (SLM), selective laser sintering (SLS), and laser solid forming (LSF) constitute analogous processes with negligible operational distinctions.

PBF-LB employs high-intensity lasers to consolidate successive layers of SMA powder into intricate geometries. Conversely, PBF-EB substitutes the laser with an electron beam. PBF-EB necessitates vacuum conditions to preserve beam integrity. This vacuum environment proves particularly beneficial for aerospace SMA components by precluding oxidation and airborne contamination. PBF-EB demonstrates superior deposition efficiency and diminished residual stresses. This method is capable of mitigating deformation and fracture risks. LPBF, however, affords greater precision and superior surface finish. Among contemporary additive manufacturing techniques, LPBF prevails as the predominant industrialized approach. This method excels in fabricating complex architectures. However, this process demands meticulous regulation of transformation temperatures to preserve functional shape memory properties.

Identifying optimal parameters constitutes the fundamental prerequisite for manufacturing near-defect-free components in LPBF. Critical variables include laser power, scanning speed, substrate thickness, build orientation and scanning patterns. Process parameters in LPBF significantly influence the superelasticity with lower energy densities resulting in better recovery rates and smaller stress–strain hysteresis.[351] Moreover, thermal regulation and quality assurance during LPBF necessitate thorough evaluation before it can be employed on SMA production. Recent investigations have prioritized advanced computational models to eliminate porosity in LPBF-produced components. The auricchio finite element model effectively simulates the mechanical response of SMAs, which facilitates the parameter optimization.[352]

LPBF offers distinct advantages through site-specific modifications like remelting protocols, rendering it particularly suitable for SMA synthesis. The multi-remelting technique has enabled *in situ* alloying of high-entropy SMAs comprising five or more constituent elements, enhancing chemical homogeneity during additive manufacturing.[353] Powder reutilization has emerged as a pivotal research focus in LPBF, given the substantial expense of metallic powders. However, studies indicate that NiTi powder reuse diminishes flow characteristics, accelerates oxidation, and exerts negligible influence on transformation temperatures.[354]

Over the last few years notable progress has been made in processing of NiTi alloys through LPBF approach.[355–360] Octahedral cellular configurations fabricated *via* LPBF AM with NiTi powder demonstrate exceptional damping performance. Bio-inspired Bouligand architecture exhibits exceptional strength and toughness, showcasing the potential of this method to produce structures that combine load-bearing capabilities.[361] Lightweight bionic hybrid structure (BHS) emulating cuttlebone morphology, was designed and manufactured by LPBF with NiTi powder which is capable of sustaining 25 000 times their mass.[362] NiTi alloy lattice structures with negative Poisson's ratio can be fabricated using the SLM technique, potentially solving bone inflammation and implant detachment issues in modern implants.[363] Further, LPBF shows high potential for producing functional digital components incorporated with Ni–Mn–Ga based MSMA, capable of rapid magnetic actuation.[364] PBF is applied to produce porous NiTi wicks and thermal conduits for spacecraft temperature regulation.[365]

LPBF also shows promise for manufacturing Cu-based and Fe-based SMAs.[366–369] For Cu-based SMAs, LPBF produces components demonstrating pronounced superelasticity at ambient temperatures while preserving refined microstructures.[370–372] A recent innovation involved graphene-reinforced Cu–Al–Ni SMA fabrication *via* LPBF, enhancing elevated-temperature performance without compromising memory properties or introducing defects.[373]

5.1.2.2. Direct energy deposition (DED). Direct energy deposition (DED) technologies have emerged as powerful alternatives for manufacturing larger-scale SMA components, particularly in construction and industrial applications where bulk production of relatively simple geometries is required. Compared to PBF methods, DED offers distinct advantages including higher deposition rates, faster cooling capabilities, and superior scalability for large parts.[374–378] This family of DED techniques has diversified into three primary variants based on their heat sources: laser-based (DED-L), electron beam (DED-EB), and plasma arc (DED-PA) systems, each offering unique benefits for SMA fabrication.

Laser-based DED (LDED) operates by depositing successive layers of molten SMA powder onto a substrate using a high-power laser beam, typically within an argon-filled chamber. The Laser Engineered Net Shaping (LENS) is a variant that provides enhanced precision for smaller components like actuators.[379] Nonetheless, standard LDED excels at rapid production of larger parts due to its exceptional deposition rates.[380] Beyond size advantages, LDED enables *in situ* alloy mixing and repair of damaged SMA components.[381] However, these benefits come with trade-offs: LDED parts often require post-processing machining due to poor surface finish. Plus, *in situ* alloying processes can create microstructural variations leading to anisotropic behavior, particularly in temperature-sensitive alloys like Ni-rich NiTi.[382]

Electron beam DED (DED-EB) utilizes a focused electron beam in vacuum conditions to melt wire feedstock, offering unparalleled purity for reactive SMA compositions. The vacuum environment eliminates oxidation concerns entirely, making it ideal for processing reactive SMA compositions. The DED-PA method is also known as Wire Arc Additive Manufacturing (WAAM). This process employs electric arc welding principles with SMA wire feedstock to achieve the highest deposition rates among rapid manufacturing technologies.[383] While economically attractive, WAAM faces challenges in dimensional control due to thermal variations during deposition, requiring careful thermal management to preserve shape memory properties.[384–386] Laser Shock Peening (LSP) has emerged as an effective post-processing solution, significantly improving WAAM components by reducing porosity and enhancing mechanical performance,[387] making the WAAM-LSP combination particularly promising for biomedical implants.

Advanced WAAM variants like Twin/Dual Wire Arc Additive Manufacturing (T/D-WAAM) enable fabrication of multi-material and functionally graded SMA structures by simultaneously feeding two different alloy wires into the electric arc.[388–391] This approach allows precise control over material composition but introduces new challenges, including structural inhomogeneity and anisotropic properties along the build direction. Recent studies demonstrate that combining TWAAM with aging heat treatments can achieve more uniform micro-hardness distribution and significantly improved mechanical

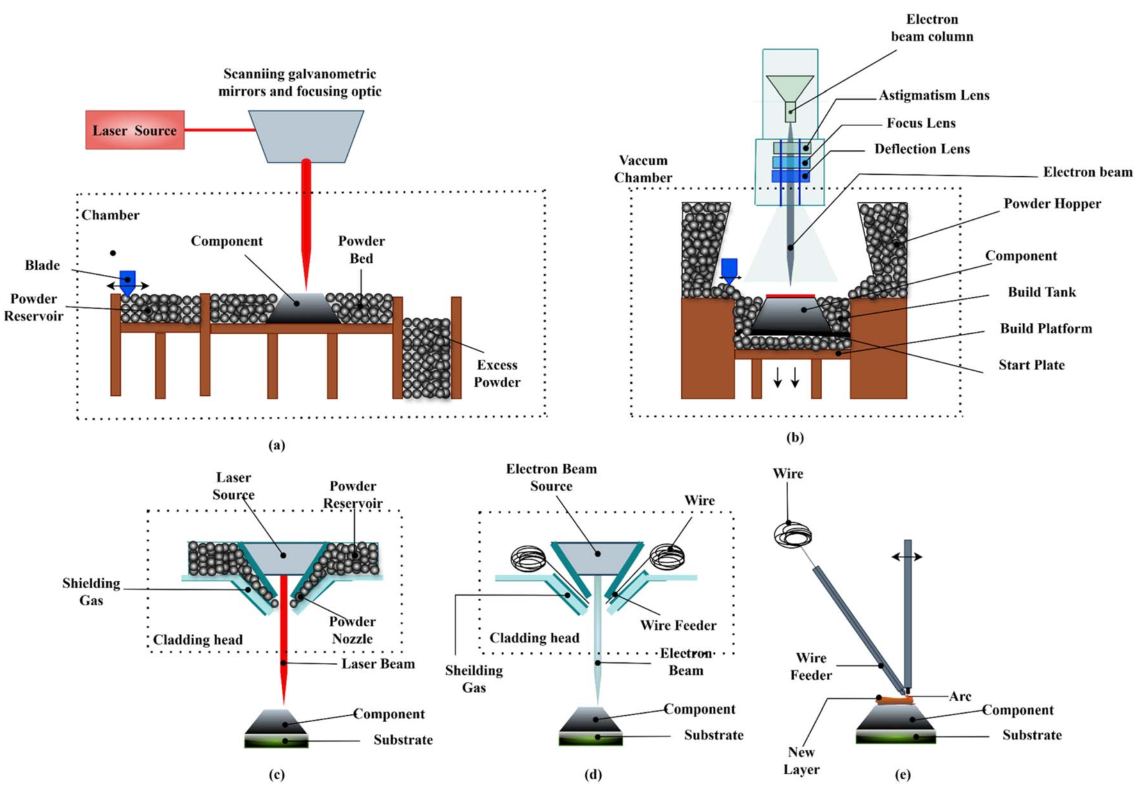

Fig. 16 Schematic of additive manufacturing processes (a) PBF-L (b) PBF-EB (c) DED-L (d) DED-EB (e) DED-Arc.[392]

properties in alloys like NiTiCu. The choice between DED variants ultimately depends on specific application requirements. Whether to prioritize deposition speed (WAAM), purity (DED-EB), or precision (LDED/LENS), with ongoing innovations in hybrid and post-processing techniques further enhancing their capabilities (Fig. 16).

5.1.2.3. Binder jetting. Binder jetting (BJ) has emerged as a viable additive manufacturing technique for shape memory alloys, complementing established methods like laser powder bed fusion (LPBF) and directed energy deposition (DED). This process utilizes a dual-material system consisting of metallic powder and a liquid binding agent that selectively bonds powder layers at ambient temperatures. The absence of high-energy heat sources distinguishes BJ from other metal AM processes, offering inherent advantages for SMA fabrication.

The cold-processing nature of binder jetting minimizes thermal-induced microstructural alterations and residual stresses, preserving the intrinsic properties of shape memory alloys.[393] This characteristic proves particularly valuable for SMAs sensitive to thermal history or phase transformations. Additionally, it provides a cost-effective method to customise porosity during fabrication, which is a huge upside for biomedical implants. While the process inherently produces porous components, parameter optimization enables fabrication of net-shaped parts combining structural integrity with controlled porosity, even for challenging materials like large magneto-active alloys.[394]

Current applications demonstrate BJ's potential for mass customization of SMA components, though the technology remains in developmental stages for commercial

Table 14 Advancement of additive manufacturing of SMAs

AM technique	SMA manufactured	Highlights of the study	Reference
LPBF	NiTi, NiTiNb	The flexibility of parameter selection and compositional control opens the possibility to print functional NiTi SMA parts or devices without post-processing	355–360 361, 362 and 400
	NiTiHf	Fabricated HTSMA display excellent thermal cycle stability of transformation temperatures with obtainable OWSMe AND TWSME by post heat treatment	401
	Ni–Mn–Ga	The results show that the deposition of Ni–Mn–Ga with a high relative density of 98.3% with a minimal loss of Mn is feasible using L-PBF	364
	Fe–Mn–Al–Ni	The study demonstrated regression modeling might not be the ideal choice as material properties are not only depended on individual parameters	366 and 368
	Fe–Mn–Si	Fabrication of Fe-based SMAs of complex structures with good dimensional accuracy is feasible where the printed complex-shaped objects demonstrated a pronounced SME	367 and 369
	Cu–Al–Mn	The method offers efficiency in tailoring the transformation temperatures through careful selection of process parameters	370
	Cu–Al–GN	Cu-SMA combined with graphane promises superior SME	372
	Co–Ni–Al	Fabricated microstructurally-sound, creep-resistant SMAs with unique thermal properties	371
L-DED	Co–Fe–Cr–Mn	Microstructural observations indicated uniform distribution of all elements within alloy system	375
	Ni–Mn–Ga	The results demonstrated that the deposition of multi-layered Ni–Mn–Ga is achievable using L-DED	376
	NiTi	DED approach to join two different TiNi-based parts into a bi-metallic SMA in order to exhibit multiple shape-memory behaviors	374 and 377
	NiTiCu	By adding Cu, a much lower thermal hysteresis was achieved, which shows good feasibility of fabricating ternary TiNiCu shape memory alloys, using elemental powders in the directed energy deposition to adjust the thermal hysteresis	378
WAAM	NiTi	High-quality NiTi parts with minimal defects were successfully produced, addressing challenges in manufacturing large and complex components	386
LENS	NiTi	Porous NiTi alloy samples with high purity and total porosity in the range of 12–36% have been successfully fabricated having potential to be used in load-bearing implants	
Twin WAAM	NiTi, NiTiCu	Effective approach to fabricate SMAs with controlled multi-material composition	388–391
Binder jet	NiTi	Porous NiTi was fabricated with excellent biocompatability providing insight into the use of binder jetted Ni–Ti for medical implants and tissue engineering applications	393 and 397
	Ni–Mn–Ga		398
	NiTiHf		399

implementation.[395–399] The method's unique advantages – including reduced thermal distortion, stress-free fabrication, and porosity control – position it as a promising alternative for producing complex SMA geometries that prove difficult with conventional AM processes. As the technology matures, binder jetting is expected to find increasing adoption in sectors requiring cost-effective production of customized SMA components, particularly in biomedical and functional material applications where controlled porosity and microstructural preservation are paramount.

Table 14 depicts some of the notable studies regarding additive manufacturing highlighting the key findings.

5.1.3. Mechanical processing. The mechanical processing of SMAs typically begins with casting. It is the most fundamental processing method involving melting constituent elements in precise proportions under controlled argon atmospheres or vacuum conditions to create homogeneous alloys. The specific casting technique varies according to the desired final geometry, with vacuum arc remelting (VAR) and vacuum induction melting (VIM) being the most common approaches.[402] Careful control of melting parameters is crucial, as variations in elemental composition or the addition of tertiary elements can significantly modify alloy properties. Multiple remelting cycles are often employed to enhance microstructural homogeneity. A critical concern in casting is the potential introduction of contaminants, which may originate from impurities in raw materials or during the casting process itself. This makes the need for proper selection of a non-contaminating condition extremely crucial. Usually, the condition is achieved by employing an inert atmosphere of argon or other noble gases, or utilizing vacuum conditions. The solidification phase requires particular attention, as excessive cooling rates may introduce defects that compromise material quality. Post-casting heat treatments are routinely applied to optimize the SME and mechanical characteristics.

For microstructural refinement and property enhancement, deformation-based processes demonstrate superior capability.[403] Forging represents a primary technique, typically performed at elevated temperatures to facilitate dynamic recrystallization and produce fine-grained microstructures with improved mechanical properties.[40,404] The process induces anisotropic characteristics through directional material flow. However, it requires careful parameter selection to maintain shape memory functionality. Cold forging is capable of higher strain rates but often results in surface imperfections and reduced shape memory performance due to unstable deformation patterns.

Constant grooved pressing (CGP) is an excellent deformation process with negligible material waste, improving the microhardness of SMAs.[405] Rolling operations, both hot and cold variants, effectively reduce thickness and elongate dimensions. The cold rolling is particularly effective for producing fine-grained or nanostructured SMAs. These processes demand precise parameter control, as improper conditions can severely degrade the alloy's shape memory characteristics. Wire and rod production predominantly utilizes cold-drawing techniques, where material is pulled through dies to achieve diameter reduction and length increase. The process typically incorporates intermediate annealing stages to relieve residual stresses and restore shape memory properties, with annealing parameters critically influencing the alloy's thermomechanical behavior. Equal channel angular extrusion (ECAE) presents a specialized alternative for thicker specimens, applying force through the die's bell section to produce unique microstructural modifications and transformation behavior alterations. This method proves particularly valuable for research applications requiring controlled microstructural evolution.

Each processing method offers distinct advantages and challenges in SMA fabrication, with the choice dependent on desired final properties, geometry requirements, and application-specific performance criteria. The common thread across all techniques is the necessity for precise process control to preserve and enhance the unique shape memory characteristics that make these materials valuable for advanced engineering applications.

5.1.4. 4DP of SMA. 4D printing represents a transformative advancement in additive manufacturing. It combines the geometric freedom of 3D printing with the dynamic responsiveness of smart materials. This technology enables fabricated components to undergo programmed transformations in shape, properties or functionality when exposed to specific environmental stimuli. While conventional 4D printing research has predominantly focused on polymeric systems, recent efforts are expanding this paradigm to incorporate shape memory alloys (SMAs).

At the core of 4D printed SMAs lies their inherent ability to undergo predictable configuration changes through SME when activated by external stimuli. Thermal activation remains the most widely used method due to its operational simplicity and biocompatibility. However, alternative approaches each offer distinct advantages. Electrical stimulation *via* Joule heating enables rapid and controllable actuation. Magnetic fields provide contactless operation and Light activation permits high spatial precision in triggering transformations. Moreover, chemical stimuli offer selective responsiveness though they raise potential biocompatibility concerns that require careful consideration.

The successful implementation of 4D printed SMA components requires careful attention to several interdependent design factors. Material selection must be tailored to achieve the desired transformation temperatures and mechanical properties specific to each application. Advanced computational modeling tools have become indispensable for predicting and optimizing the performance of these dynamic structures when dealing with complex geometries or multi-material systems. The choice of activation method must be carefully matched to both the material properties and the intended operational environment.

The field of SMA 4D printing faces several significant challenges that must be addressed. Current research efforts remain disproportionately focused on polymeric systems, with relatively few studies investigating metallic SMAs.[224] Fundamental understanding of magnetic-responsive alloys in particular remains limited. Process optimization for widespread NiTi and

Table 15 4D printing methods of SMA[406]

Printing technique	Printing method	SMA	Stimulus
PBF	SLM	NiTi	Heat
		Fe–Mn–Si	Heat
		Cu–Al–Ni	Heat
Binder jetting	BJT	Ni–Mn–Ga	Magnetic fields
		Ni based superalloy	Time
DED	Laser beam	Fe–Ni–Ti–Al	Time
	Electron beam	NiTi	Heat

Ni–Mn–Ga alloys is still in early developmental stages. The integration of SMAs with polymers in hybrid 4D structures presents both exciting opportunities and technical challenges that will require innovative solutions.

A groundbreaking design approach employing 4D printing technology and a bistable power amplification mechanism resulted in an insect scale SMA jumper, aptly named the “net-shell”. This innovative design showcases remarkable jumping capabilities, surpassing the performance of many biological counterparts. 4D-printed SMAs hold immense promise in biomedicine, offering the potential for personalized medicine through custommade, adaptive medical devices. Researchers must explore novel materials and optimize printing techniques for successful fabrication. Furthermore, our understanding of material behavior is limited. Current attempts largely center on thermally responsive SMPs, with lack of knowledge on magnetic responsive alloys. It is crucial to go beyond memory polymers and improve 4DP of alloys due to their vast range of applications. An overview of advancements in 4DP of SMA has been provided in Table 15. Further integration of SMAs with polymers as 4D printed structures remains a direction for future work.

5.1.5. Alloying elements used in SMA. Elemental alloying has emerged as a fundamental strategy for engineering SMAs with customized properties. This process enables precise control over phase transformation characteristics, mechanical performance, and functional stability. This approach proves particularly valuable for enhancing two-way shape memory effects and corrosion resistance in SMA systems. The nickel-titanium (NiTi) system, being the most technologically mature SMA, serves as the primary platform for these alloying modifications, with various elements imparting distinct property enhancements. Silver doping in NiTi alloys demonstrates remarkable biomedical potential, with studies confirming that even minimal silver additions (0.1 at%) optimize the balance between strength and ductility in TiNi–Ag wires.[341] Higher silver concentrations risk embrittlement but silver nanoparticles in porous TiNi significantly enhance both cytocompatibility and antibacterial properties.[407–409] Zirconium additions offer complementary benefits by reducing hysteresis while increasing work output, making Zr-modified NiTi particularly suitable for medical actuators. Copper stands out as a versatile alloying element, with its addition to NiTi effectively lowering transformation temperatures for applications requiring reduced activation thresholds. The Ni–Ti–Co system shows particular promise for civil engineering applications, where cobalt additions simultaneously decrease phase transformation temperatures and increase critical stress levels.[146] For high-temperature stability, hafnium-modified SMAs deliver exceptional performance in aerospace environments demanding concurrent shape memory functionality and thermal resistance. Recent breakthroughs in copper-based SMAs address long-standing brittleness challenges through strategic additions. Manganese and gadolinium additions with the alloy create outstanding SME and thermal stability.[410] Micro-additions of beryllium to Cu-alloys significantly widen transformation temperature ranges, expanding industrial applicability.[411] Lanthanum modifications in CuAlNiMn systems enhance mechanical properties, corrosion resistance, and thermal stability for aerospace and robotic applications.[412] Table 16 shows several alloying elements and their function.

Iron facilitates an improvement in the alloy's resistance to corrosion and enhances the material's stability at elevated temperatures. Introduction of Fe content in Cu–Al binary alloys improves SME. However, excessive Fe content can lead to sub-eutectic states and reduced SME.[413] Aluminum additions generally enhance mechanical strength and wear resistance, while vanadium and tin modifications in Ti-based systems improve high-temperature performance and biomedical compatibility respectively.[414] The selection and concentration of alloying elements requires meticulous optimization, as these parameters critically influence transformation temperatures, mechanical behavior, and environmental resistance during shape recovery, broadening potential applications. This tailored approach to SMA development continues to enable new generations of smart materials optimized for specific operational environments and performance requirements across biomedical, aerospace, and industrial sectors.

5.1.6. Future perspective

5.1.6.1. Closed-loop AM. Closed-loop additive manufacturing systems mark a transformative development in 3D printing technology, introducing real-time monitoring and adaptive control to overcome the quality inconsistencies of conventional AM processes. For SMAs, this approach remains largely unexplored despite its potential to revolutionize production quality. LPBF has demonstrated particular effectiveness for SMA fabrication, suggesting strong potential for closed-loop implementations that could dynamically optimize parameters during printing. The integration of artificial intelligence and machine learning could further enhance this

Table 16 Alloying elements in SMA[350,415–417]

Element	Effect	Applications
Aluminum	Reduces M_s transformation temperature Deteriorates strength and plastic properties Improves strength Increases hardness Promotes formation of the R phases	Robotics and medical devices
Beryllium	Widens the transformation temperature	Industrial
Cobalt	Reduces M_s transformation temperature Improves strength Improves ductility	Civil engineering applications
Copper	Lowers transformation temperatures Enhances thermoelasticity Improves corrosion resistance Narrow transformation hysteresis Reduces sensitivity of phase transformation temperatures to chemical compositions Prevent the formation of Ni_3Ti_4 Suppresses formation of the R phase Prolongs fatigue life	Areas with lower activation temperature
Chromium	Lowers transformation temperatures Improves biocompatability Improves corrosion resistance Improves rigidity Improves hardness Improves wear resistance	Diverse applications
Hafnium	Enhances high-temperature performance and phase stability Improves strength Improves two-way SME Increases transformation temperatures Contributes to formation of $(Ti + Hf)_2$ phase deteriorating the high-temperature performance	Areas with ultra-high temperature SMA (UHTSMAs) requirement such as aerospace and automotive
Iron	Improves corrosion resistance Enhances stability at high temperatures Improves damping capability	Civil construction, aersopace actuators
Magnesium	Increases transformation temperatures Increases biocompatibility Increase general corrosion resistance in biological media and susceptibility to local damage Better damping capacity Suppresses formation of Ti_2Ni phase Reduces hardness	Diverse applications
Manganese	Enhances SME Lowers hysteresis width Allows temperature adjustment during transformation Improves biocompatibility	Biomedical, applications requiring precision in transformation temperature
Niobium	Widens hysteresis Excellent biocompatibility Improve corrosion resistance Improve strength Improve radiopacity Enhance mechanical properties	Areas where HTSMAs are required
Silver (ag)	Increases M_s transformation temperature Reduces toxicity Increases biocompatibility Addition of minimum rate improves mechanical properties Increases cell viability	Biomedical
Tantalum	Improve corrosion resistance Affects fatigue life Improve strength	Biomedical
Tin (Sn)	Improve corrosion properties Improve wear resistance	Biomedical
Vanadium	Improves phase stability Enhance mechanical properties	Automotive
Zirconium	Decreases hysteresis Enhances superelasticity Enhances SME	Biomedical, aerospace

system's capability to produce defect-free, novel SMA compositions with precise property control.

5.1.6.2. Material purity and energy paradox in LPBF of NiTi. A critical challenge persists in LPBF processing of NiTi alloys – the fundamental trade-off between energy requirements and material purity. While high energy inputs are necessary to achieve fully dense 3D structures, they simultaneously increase impurity levels, potentially compromising the alloy's suitability for sensitive biomedical and industrial applications.[418] This paradox demands a strategic approach to solve the issue.

5.1.6.3. 4D-printed SMA metamaterials. The development of 4D-printed SMA structures represents one of the most promising research frontiers. Early demonstrations include bistable architectures fabricated by 4DP functioning as programmable metamaterials for unconventional information processing systems.[419] This suggests potential applications in environments unsuitable for conventional computing hardware. Future investigations should prioritize self-adaptive structures capable of autonomous morphological changes in response to environmental stimuli.

5.1.6.4. Multifunctional hybrid SMA manufacturing. Significant opportunities exist in combining SMAs with complementary materials such as hydrogels and polymers. Such hybrid systems could enable multifunctional 4D-printed structures with applications spanning aerospace, biomedicine, and soft robotics. Realizing this potential requires dedicated research into material compatibility, interface engineering, and synergistic behavior optimization. The concurrent advancement of these complementary technologies – closed-loop AM, 4D printing, and hybrid material systems – will collectively expand the application horizons for shape memory alloys in next-generation smart manufacturing.

5.2. Machining of shape memory alloys

Machining operations for SMAs encompass both conventional and non-traditional material removal techniques, each presenting unique advantages and limitations for processing these advanced materials. Traditional subtractive methods include turning, milling, and drilling. Abrasive processes such as grinding are also part of the cutting processes of great importance in contemporary industry. The manufacturing sector simultaneously employs advanced non-contact methods such as electrical discharge machining (EDM), laser processing, and waterjet cutting to address specific SMA machining challenges.

NiTi alloys and their ternary derivatives remain the primary focus of SMA machining research. These alloys reveal several persistent obstacles. They are thermomechanically sensitive which contributes to the alteration of material behavior due to cutting-induced phase changes. Their adhesion tendencies promote built-up edge formation on cutting tools. These characteristics collectively result in suboptimal machining performance, manifesting as rapid tool degradation, excessive burr formation, and compromised surface integrity. Current investigations focus on balancing material removal rates with surface quality requirements while developing specialized tooling solutions capable of withstanding the unique challenges posed by these shape-changing alloys.

5.2.1. Conventional machining of SMA. Conventional machining of shape memory alloys presents significant difficulties, including excessive heat generation, accelerated tool wear, dimensional inaccuracy, and poor cost-effectiveness. Various cutting tools have been evaluated for turning operations. Tools coated with cemented carbide demonstrate superior performance through reduced wear rates compared to alternatives.[420] Uncoated carbide tools exhibit excessive wear. Ceramic tools prove ineffective regardless of cutting parameters. Polycrystalline diamond (PCD) tools suffer from notch wear leading to catastrophic failure and cubic boron nitride (CBN) tools, despite their hardness, show higher wear rates than coated carbides. Thermal management remains a critical challenge, particularly in dry turning where chip burning necessitates cutting fluids or cryogenic cooling systems.[421,422] Milling operations face amplified difficulties due to SMAs' exceptional static and dynamic strength. Even coated carbide tools experience shortened lifespan. Increase of feed rate leads to increase in surface roughness, however, very small feed rate presents high surface roughness. Tool flank wear progression further exacerbates surface roughness.

While conventional processes (turning, milling, drilling, grinding) remain industrially dominant for SMA machining, their limitations for precision applications, particularly micro-scale features, have driven increased research into non-conventional methods.[423] The fundamental conflict between SMAs' unique thermomechanical properties and traditional machining mechanics continues to motivate investigations across both conventional and alternative processes to address these persistent manufacturing challenges. Due to the chip burning issues in dry turning, the use of a cutting fluid as lubricant/coolant was proposed. Additionally, cryogenic cooling was also investigated for being advantageous in some cases. Milling of SMAs is very difficult as the material presents high strength in static and dynamic conditions. Even coated carbides provide shorter tool life. Increase of feed rate leads to increase in surface roughness, however, very small feed rate presents high surface roughness. By correlation, increase in the flank wear of the tool increases surface roughness. Investigation of CNC end milling on Cu–Al–Mn SMA encourages potential advancements in this technique.[424] However, in case of drilling, the use of coated instead of uncoated cemented carbide tools exhibits no advantage. Micromilling was investigated as complex geometries required in microparts to be used for microactuators. It turns out that micromachining is as difficult as conventional machining processes if not more so and the ranges for optimal cutting conditions are rather limited.

5.2.2. Nonconventional machining of SMA. Non-conventional machining encompasses material removal techniques that eliminate direct tool-workpiece contact, thereby minimizing or completely preventing tool wear. These processes instead rely on alternative energy forms such as thermal, electrical, or chemical to achieve material erosion. While this contactless approach circumvents traditional tool degradation issues, it introduces thermal effects that can

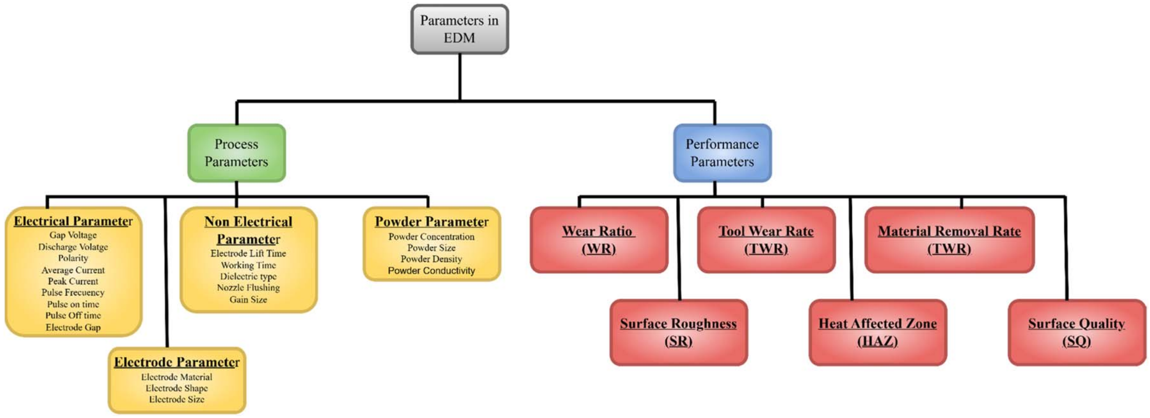

Fig. 17 Several process parameters affecting machining of SMAs.[427]

compromise surface integrity through heat-affected zones, microcracks, or altered microstructures. The primary research focus in this domain examines surface and subsurface modifications induced by energy discharge mechanisms, particularly the relationship between process parameters and material removal rates (MRR). Spark-based systems dominate current investigations, with electrical discharge machining (EDM) and wire electro-discharge machining (WEDM) receiving predominant attention due to their precision capabilities for conductive materials. These methods utilize controlled electrical discharges to erode material, generating complex geometries unachievable through conventional machining while avoiding mechanical stresses. However, their thermal nature necessitates careful parameter optimization to balance removal efficiency against surface quality requirements, especially for advanced materials where subsurface damage could impair functional performance.

5.2.2.1. Electrical discharge machining (EDM). EDM employs controlled electrical discharges between an electrode and workpiece to achieve precise material removal through thermal erosion.[425] The process generates successive sparks in a dielectric medium, each producing localized temperatures sufficient to melt and vaporize minute portions of the workpiece. Key operational parameters fall into two categories: process variables (including current, voltage, and pulse duration) and performance metrics (such as material removal rate and surface finish), as detailed in Fig. 17. Electrode selection critically influences machining outcomes. Brass electrodes demonstrate high material removal rates but suffer from rapid wear and inferior surface quality. Tungsten alternatives provide superior surface finish with reduced wear rates but it provides lower removal efficiency.[426] This trade-off necessitates careful electrode selection based on application requirements.

The process offers distinct advantages for SMA machining, particularly for medical devices and microelectronics. Its non-contact nature permits intricate geometries independent of tool shape while minimizing mechanical workpiece stresses. However, energy input parameters require precise optimization. Increased current, voltage, or pulse duration elevates material removal rates but simultaneously degrades surface quality through thicker, irregular melting zones.[425] Surface roughness further correlates with the workpiece's intrinsic thermal properties, particularly melting point and conductivity.

EDM has proven particularly effective for ternary NiTi alloys.[428,429] Its ability to machine complex features without inducing bulk deformation preserves the material's SME characteristics. The process's precision and geometric flexibility compensate for its relatively slow material removal rates in these specialized applications. Nonetheless, proper parameter selection remains essential to balance machining speed against surface integrity requirements, especially for components where microstructural changes could impair functional performance.

5.2.2.2. Wire electro-discharge machining (WEDM). WEDM operates on spark erosion principles similar to EDM but distinguishes itself through the use of a thin wire electrode that creates localized heating at the workpiece interface. This process relies on repetitive short-duration sparks that melt and partially vaporize the material to achieve desired geometries. Finish cut in the WEDM process with less pulse energy produces a good surface finish with less residual stress without changing the base material's mechanical properties. WEDM operation utilizes dielectric fluid which is a key factor in environmental issues. This gave rise to another variant called near dry-WEDM. In this hybrid configuration, combination of minimal deionized water and compressed gas demonstrates enhanced machining performance.[430,431] Surface integrity in SMA processing proves highly sensitive to spark parameters, where elevated energy density correlates with increased roughness and foreign element contamination.[432] The process creates extremely high temperatures, often hotter than the material's melting point. When followed by rapid cooling, sudden temperature changes cause strong thermal stresses in the material leading to the formation of microcracks. In this regard, process optimization reveals that increased pulse voltage enhances wire feed rates while improving surface homogeneity and dimensional accuracy.[433] Additionally, current and pulse on time significantly affect the SME along with microhardness and surface roughness.[434] Due to the use of a thin wire electrode, WEDM has a relatively slower machining speed but can achieve higher precision and surface quality. On the other hand, EDM, with its block electrode and sinking machining method, has a relatively faster machining speed but may have slightly lower precision and surface quality compared to WEDM. WEDM shows potential in machining quaternary NiTi alloy though with significant scope of improvement.[435] To address inherent limitations in surface finish and material removal rates, powder-mixed EDM (PMEDM) has emerged as an innovative solution. This technique suspends metallic particles in the dielectric fluid, reducing insulation properties while expanding the spark gap.[436] Various nano-powders demonstrate particular efficacy. Al_2O_3 nanoparticles leverage moderate thermal conductivity for balanced machining performance.[437] Expanded graphite offers exceptional thermal/electrical properties that enhance surface topology.[438] Nano-graphene significantly improves Nitinol surface quality.[439,440] Another variant is ultrasonic-assisted WEDM which is basically the machining of WEDM coupled with an ultrasonic transducer that removes debris from the sparking gap using vibrations at a specified frequency. This method significantly improves MRR by 8.6%.[441] These technological developments collectively address the critical challenges of SMA machining, offering improved process control and surface integrity for demanding applications.

5.2.2.3. Laser machining. Laser machining has emerged as a highly promising technique for processing shape memory alloys.[442] The process demonstrates particular effectiveness for surface modification. Laser texturing of NiTi alloys is capable of achieving a notable 17% reduction in friction coefficient.[221] Its mechanism involves focused high-frequency monochromatic light that removes material through photon-induced vaporization. Similar to EDM, laser machining also generates a heat-affected zone. This approach offers substantial advantages over conventional forming methods, especially due to the beneficial thermal gradients it creates. The intense, localized heating characteristic of laser processing actually benefits shape setting in SMAs by suppressing martensite formation. This enables better preservation of the material's intrinsic properties.[443] However, the technique does introduce challenges including residual stress accumulation and surface alterations in machined regions.[444] Recent investigations into femtosecond laser machining reveal superior performance. In this method, ultrashort pulses limit the thermal damage by capitalizing on SMAs' thermal sensitivity. This advanced approach enables more uniform material ablation and significantly reduces microstructural variations, resulting in surfaces with fewer melt droplets and improved quality.[445]

Process optimization remains critical, as reducing heat input to mitigate thermal damage concurrently decreases machining efficiency. Comparative studies show pulsed Nd:YAG lasers offer an effective balance. It delivers good cut quality and high speed at lower costs than alternatives such as ultrashort pulse.[446] While Nd:YAG machining of NiTi typically produces recast and ablated layers due to thermal effects, proper parameter selection can yield defect-free regions with minimal recast material.[447] These findings underscore the importance of precise parameter control in laser processing of SMAs to achieve optimal surface integrity while maintaining processing efficiency.

5.2.2.4. Waterjet machining. Waterjet machining (WJM) represents an advanced non-traditional cutting technique that utilizes ultrahigh-pressure water streams for material processing. This method operates by propelling pressurized water through a precisely engineered orifice, generating a supersonic jet capable of sectioning diverse materials.[448] WJM offers several advantages over conventional and some non-traditional methods. It is a cold cutting process. It does not generate significant heat in the workpiece. Therefore, this process can offer significant advantages by minimizing both thermal distortion and mechanical stresses during processing. For NiTi alloys specifically, WJM provides distinct benefits owing to the material's exceptional ductility and unique mechanical

Table 17 Nonconventional machining techniques

AM technique	SMA	Highlights of studies	Reference
EDM	NiTi Ni–Ti–Cr Ni–Ti–Zr Ni–Al–Fe	MRR linearly increased with increasing discharge level. Additionally, studies indicate that, with an increase of the working energy, surface roughness worsens; increase of working current, voltage, and pulse on time results in a thicker and more abnormal melting zone. EDM has a relatively faster machining speed but may have slightly lower precision	426 429 428
WEDM	Ni–Ti–Co Ni rich NiTi Ni–Ti–Zr Ni–Ti–Cr Fe–Mn–Si Fe–Mn–Si–Cr	Increasing pulse voltage significantly improves wire feed rate and surface quality in WEDM machining, resulting in better homogeneity and machining accuracy. WEDM has a relatively slower machining speed but can achieve higher precision and surface quality	 450 and 434 435 451
Laser machining	NiTi Ni–Mn–Ga	Ultrashort pulses performed better due to uniform ablation of SMAs. Therefore, femtosecond lasers are capable of producing better surface quality and dimensional accuracy	445 444
Water jet machining	NiTi	Advantageous concerning cutting time, thermal impact on the work-piece, and total cost of the machining. But, technology is generally slower than other cutting approaches	449

characteristics that complicate conventional machining. The absence of heat-affected zones and mechanical deformation makes this approach particularly suitable for preserving the intrinsic properties of SMAs. However, the technique presents notable constraints, including relatively slow processing speeds compared to thermal cutting alternatives like laser or plasma systems. This reduced throughput may prove prohibitive for high-volume production scenarios or time-sensitive applications. Precision limitations further restrict WJM's applicability for components demanding micron-level tolerances. A critical consideration for NiTi processing involves the overlapping ranges between waterjet operating temperatures and the alloy's phase transformation thresholds,[449] which may inadvertently influence material behavior during cutting. While WJM excels in preserving material properties and avoiding thermal degradation, these inherent limitations necessitate careful process evaluation for SMA manufacturing applications where either production efficiency or extreme precision are paramount requirements. Table 17 shows several non-conventional machining techniques that show promising advancements.

5.2.3. Recent trends of micromachining. In recent years, there has been a substantial expansion in micromachining applications driven by the increasing need for miniaturized, high-performance devices. Micromachining has emerged as a transformative approach for processing SMAs, particularly for microscale devices where the shape memory effect enables precise actuation in constrained spaces. This has spurred the development and refinement of various micromachining techniques each presenting distinct advantages and limitations. Micro-electrical discharge machining (micro-EDM) has become the predominant method for microscale fabrication due to its superior capabilities. Its ability to machine hard, conductive materials with high precision and minimal mechanical stress makes it particularly suitable for shape memory alloys, which are sensitive to thermal and mechanical processing.

Recent advancements in micro-EDM technology have achieved previously unattainable precision in micromachining applications. This technique offers significant benefits over conventional EDM, including lower discharge energy and higher frequency, resulting in improved surface finish and dimensional accuracy. However, successful implementation requires careful selection and maintenance of optimal process parameters. The inherent electrode wear during micro-EDM presents challenges for parameter optimization and can compromise machining precision. Establishing ideal input variables remains critical for effective SMA micromachining.

For NiTi alloys, micro-EDM enables fabrication of intricate geometries with exceptional precision, though parameter optimization and surface quality control are particularly vital for biomedical implementations.[452] There are alternative methods that demonstrate promising results. Electrochemical micromachining using citric acid–sulfuric acid electrolyte produces narrower grooves and reduced surface roughness.[453] Femtosecond laser micromachining of medical-grade NiTi tubes enhances processing efficiency.[454] Drilling micro-holes represents a crucial application across multiple industries including aerospace, biomedical engineering, microelectronics, and fluidics.[455–457] These micro-holes are essential for applications such as drug delivery systems, fuel injectors, micro-heat exchangers, and surgical tools. Non-traditional methods like micro-EDM and electrochemical micro-drilling (ECMD) offer superior solutions for NiTi alloys.[426,458–460] While micro-EDM remains widely used, controlling material removal rates presents ongoing challenges. ECMD demonstrates advantages including higher removal rates and faster production, but requires further development. Emerging technologies such as electron beam and ultrasonic vibration-assisted drilling show potential. Another innovation, laser micro-drilling is efficient but faces problems of poor dimensional accuracy and the creation of recast layers.

5.2.4. Welding of SMA. The fabrication of SMA components necessitates thorough examination of welding techniques, as joining these alloys presents unique complexities. Powder metallurgy-produced SMAs prove particularly challenging to weld compared to cast variants due to inherent porosity issues. Among various investigated methods,[461] laser beam welding has emerged as the most promising approach for NiTi alloys, offering superior weld quality, concentrated energy density, and minimal heat-affected zones.[462,463] This technique has also shown applicability for Ti–Nb SMAs.[464]

A critical limitation of laser welding involves chemical composition alterations from nickel vaporization and intermetallic compound formation, which detrimentally affect weld mechanical properties. Friction stir welding circumvents this issue through solid-state processing, utilizing frictional heat from rotating tools instead of melting. However, this method compromises superelasticity[465] and demonstrates variable outcomes depending on rotational speeds.[466] Notably, friction welding of NiTi to steel reinforcement bars enhances seismic performance in concrete structures.[467]

Resistance welding has developed as a cost-effective solution for dissimilar metal joining, producing high-strength NiTi joints suitable for actuator applications.[468] While research predominantly focuses on NiTi systems due to their commercial prevalence, investigations into other SMA compositions remain an active research frontier.[469–471] Each welding method presents distinct advantages and limitations that must be carefully considered for specific SMA applications.

5.2.5. Future perspective

5.2.5.1. Next-gen SMA machining technologies with digital twin. The machining of SMAs is poised for transformative advancements through the convergence of artificial intelligence, sustainable practices, and hybrid processing techniques. Emerging technologies such as cryogenic UVAM, self-optimizing digital twin systems, and closed-loop swarf recycling processes will revolutionize precision manufacturing of SMAs for critical applications across medical, aerospace, and automotive sectors. Apart from experimental tests, digital twin simulations extensively analyze material behavior during machining.[472,473] Research can be driven to develop computational models on coolant-assisted machining simulations focusing on cryoMQL. Most importantly, leveraging digital twin, simulation can be done on SMA machining processes virtually to preemptively address tool wear or thermal distortion.

5.2.5.2. Advanced tool coating solutions. While tool coatings have demonstrated potential for extending tool life and thermal management in conventional SMA machining, this area remains underexplored in current research. Cryogenic cooling has shown particular promise in dramatically reducing tool wear rates during NiTi alloy machining.[474] Textured surfaces effectively mitigate temperatures by maintaining lubricant retention through grooved interfaces. Further investigation can focus on advancing tool technology by optimising tool performance *via* multilayer coatings. Graphene augmentation improves corrosion resistance and electrical conductivity without compromising structural integrity. Graphene-coated TC drill bits exhibit enhanced efficiency and durability.[440] This innovation enables conventional SMA machining through superior thermal dissipation. Subsequent research should examine tribological interactions between coated tools and machined SMA surfaces.

5.2.5.3. Advanced research on EDM/WEDM. Phase transformation temperatures present substantial obstacles in non-traditional machining. Yet, a knowledge gap persists regarding microstructural evolution during EDM/WEDM processes. While additive manufacturing enables tailored SMA compositions, few studies examine EDM/WEDM processing of AM-produced SMAs. Ultrasonic vibration assisted WEDM demonstrated superior efficiency in machining which opens up new opportunities to improve its efficiency. Laser-assisted conventional machining enhances geometric precision and reduces tool forces to 30–40% by pre-softening SMAs.[475] Future research can be directed towards tribological investigations regarding this promising technique. Further association of machine learning can pave the way to an effective machining solution.

6 Conclusion

This comprehensive review has examined the transformative potential of shape memory alloys (SMAs), from their unique programmable characteristics to their diverse applications across aerospace, biomedical, automotive, and construction industries. However, the widespread implementation of SMAs as viable alternatives to conventional materials ultimately depends on achieving cost-effective mass production. Our critical analysis reveals several key challenges and emerging solutions across sectors:

(a) In biomedical applications, Ni^{2+} leaching-induced cytotoxicity remains a primary concern. Current mitigation strategies focus on surface modification and alloy engineering. Fe-based SMAs shows particular promise for biodegradable implants, though further biocompatibility studies are required.

(b) Exorbitant material cost persists a serious impediment for SMAs to be used in construction sector. Also, their limited martensitic transformation temperature circumvents their applicability regionally. Developing economical alternatives like Fe- and Cu-based SMAs could address these limitations.

(c) High-temperature SMA (HTSMA) characterization represents a significant knowledge gap. Breakthroughs in HTSMA and ultra-HTSMA production could revolutionize high-performance applications in aerospace and automotive industries.

(d) Robotic and prosthetic applications face limitations due to slow actuation response and restricted strain capacity. While active cooling systems and thermal hysteresis optimization show potential, more sophisticated control mechanisms need development.

(e) SMA-based auxetic metamaterials constitute an emerging frontier, combining programmable functionality with exceptional energy absorption. Thin-film SMA architectures demonstrate particularly impressive deformation characteristics, opening new possibilities for adaptive material systems.

SMA processing paradigms are being reshaped by advanced manufacturing and machining techniques. Additive manufacturing enables complex geometries. 4D printing introduces self-healing capabilities. Non-conventional machining such as ultrasonic vibration assisted WEDM provides precision fabrication with minimal material waste which particularly valuable for large-scale aerospace and civil engineering applications. These are impressive achievements, nevertheless, challenges remain in achieving consistent material properties, precise transformation temperature control, and cost reduction. Looking forward, SMAs are poised to transition from specialized applications to mainstream engineering solutions. As research addresses current limitations, these intelligent materials will likely become sustainable substitutes for conventional systems across multiple industries, enabling a new generation of adaptive, high-performance technologies.

Conflicts of interest

There is no conflicts to declare.

Data availability

Data will be available on request.

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