

# Recent Advances in the Applications of Magnetic Shape Memory Polymers in Electronic Devices and Biomedical Engineering

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**Abstract.** As electronic devices continue to evolve toward flexibility and miniaturization, and biomedical technologies advance toward precision and intelligence, the demand for smart materials has become increasingly urgent. Magnetic shape memory polymers (MSMPs), owing to their advantages of contactless magnetic actuation, multiple shape-memory effects, excellent processability, and remote controllability, have emerged as a focal research topic in both fields. This paper provides a systematic review of recent progress in the application of MSMPs in electronic devices and biomedical engineering. Emphasis is placed on material design strategies and fabrication techniques, followed by an analysis of underlying performance mechanisms and representative application cases. In-depth research on MSMPs not only helps to promote the innovative development of the next generation of intelligent devices, but also provides a brand-new technical path for disease diagnosis and treatment as well as tissue engineering repair. In addition, the major challenges currently faced by MSMPs and potential future development directions are discussed.

**Keywords:** Magnetic shape memory polymers; Electronic devices; Biomedical applications; 4D printing; Multi-stimuli responsiveness.

## 1. Introduction

In recent years, with the rapid development of electronic devices toward flexibility, miniaturisation, and intelligence, conventional rigid materials can no longer meet the requirements of next-generation flexible sensors, wearable devices, and micro-electro-mechanical systems (MEMS) for lightweight structures, high responsiveness, and programmable functionality. Within the field of electronic devices, the growing trend toward flexible architecture and functional integration places higher demands on materials in terms of stretchability, remote controllability, and sensitivity. Meanwhile, in the biomedical field, the emergence of precision medicine and minimally invasive therapy has created an urgent need for novel materials with remote actuation capability, rapid responsiveness, and excellent biocompatibility for applications such as targeted drug delivery, implantable devices, and tissue engineering.

Against this background, smart polymeric materials—particularly shape memory polymers (SMPs)—have gained significant attention due to their low density, ease of fabrication, and programmability. However, conventional SMPs are primarily activated by thermal or optical stimuli, which suffer from limitations such as slow response speed, restricted stimulus types, and limited suitability for vivo applications. To overcome these drawbacks, researchers have incorporated magnetic particles (e.g.,  $\text{Fe}_3\text{O}_4$ ,  $\text{NdFeB}$ ,  $\text{Sm}_2\text{Fe}_{17}\text{N}_x$ ) into polymer matrices to develop magnetic shape memory polymers (MSMPs). Compared with traditional shape memory alloys (SMAs), MSMPs offer advantages of low weight, printability, and high processability, while enabling contactless remote actuation, multi-stimuli responsiveness, and programmable multistate deformation. These features establish MSMPs as a promising material platform for flexible electronics and biomedical engineering.

At present, MSMPs have demonstrated unique advantages across multiple frontier domains. In electronic systems, they have been employed as flexible actuators, stiffness-tunable execution units, and multistate information storage elements, enhancing system integration and functional diversity. In biomedical applications, MSMP-based drug delivery platforms, implantable medical devices, and



soft robots provide new opportunities for personalised therapy and intelligent surgical intervention. Despite these advances, challenges remain in long-term stability, large-scale fabrication, and adaptability to complex biological environments.

Therefore, a systematic summary of the material design, fabrication strategies, working mechanisms, and application progress of MSMPs is of great significance for advancing both fundamental research and practical implementation. This review focuses on recent developments of MSMPs in electronic devices and biomedical engineering, with emphasis on their design principles, representative applications, existing challenges, and future development prospects.

## 2. Material Design and Mechanisms

### 2.1. Material Systems

Typical polymer matrices used in MSMPs include polylactic acid (PLA), thermoplastic polyurethane (TPU), and polyethylene glycol (PEG) [1]. Each of these polymers provides intrinsic flexibility, low density, and excellent processability, forming the structural foundation of the composite.

With respect to magnetic fillers,  $\text{Fe}_3\text{O}_4$  is commonly employed as a soft magnetic nanoparticle due to its ability to generate rapid inductive heating under an alternating magnetic field [2]. NdFeB, as a hard magnetic material, offers strong remanent magnetisation and enables rapid and precise magnetic actuation [3].  $\text{Sm}_2\text{Fe}_{17}\text{N}_x$ , a new type of rare-earth permanent magnet, exhibits a high Curie temperature and superior thermal and chemical stability [1], making it particularly suitable for harsh or temperature-varying environments.

The integration of polymer matrices with magnetic fillers allows MSMPs to combine mechanical flexibility with remotely controllable shape-memory behaviour. By tailoring the type, content, and spatial distribution of magnetic particles within the polymer network, it is possible to precisely regulate key material properties, including mechanical strength, actuation speed, energy conversion efficiency, and programming capability.

### 2.2. Preparation Methods

Conventional fabrication techniques for MSMPs primarily include melt blending and solution casting. In melt blending, thermoplastic polymers and magnetic particles are mixed at elevated temperatures to achieve uniform dispersion, followed by molding or extrusion. Solution casting, in contrast, involves dissolving the polymer in an appropriate solvent, dispersing the magnetic fillers, and subsequently removing the solvent to form a composite film or bulk structure.

In recent years, the rapid development of 4D printing technologies has provided new strategies for the programmable construction of MSMPs. Representative methods include: 1. NIR-II light-controlled printing, which enables localized heating and precise shape programming under near-infrared irradiation; 2. Magnetic field-assisted digital light processing (DLP) printing, in which external magnetic fields are applied during photopolymerization to guide the orientation and distribution of magnetic particles; 3. Fused deposition modeling (FDM) printing of  $\text{Sm}_2\text{Fe}_{17}\text{N}_x/\text{Fe}_3\text{O}_4$  composite filaments, where permanent magnetic or soft magnetic fillers are incorporated into thermoplastic filaments to achieve magnetically responsive printed structures.

These emerging additive manufacturing techniques not only improve the spatial distribution accuracy of magnetic particles but also allow complex geometries, multi-material integration, and reconfigurable actuation to be realised in a single fabrication process.

### 2.3. Mechanisms

The actuation mechanisms of MSMPs can be broadly classified into three categories. (1) Magnetic induction heating mechanism. This mechanism relies on soft magnetic particles such as  $\text{Fe}_3\text{O}_4$ , which generate magnetic loss—primarily Néel and Brownian relaxation losses or hysteresis loss—under an

alternating magnetic field. The dissipated magnetic energy is converted into thermal energy, leading to localised heating of the polymer matrix. When the temperature exceeds the glass transition temperature or melting point of the polymer, the stored elastic strain is released, enabling shape recovery.(2)Permanent magnetic programming mechanism.In this approach, high-performance rare-earth magnetic particles such as  $\text{Sm}_2\text{Fe}_{17}\text{N}_x$  are embedded within the polymer network. These particles possess stable remanent magnetisation, allowing the material to be magnetically programmed and reoriented multiple times. The presence of permanent magnetic domains enhances the shape-memory effect, enables directional actuation, and allows the material to maintain a programmed shape even without an external magnetic field.(3)Electro–magnetically coupled actuation mechanism. This mechanism is achieved by integrating a conductive layer (e.g., carbon nanotubes, CNTs) together with magnetic fillers into the polymer system. The conductive network enables Joule heating or electrothermal actuation, while the magnetic phase provides remote magnetic responsiveness. The synergistic coupling of electrical and magnetic stimuli allows multistage or multimodal deformation, offering precise and programmable control of device motion.

### 3. Advances in Electronic Device Applications

#### 3.1. Flexible Electronics and Sensors

In the field of flexible and wearable electronics, MSMPs enable remote actuation and rapid responsiveness, significantly enhancing device performance [3]. Additionally, fibre-based sensors integrated with magnetic alloys have been developed to achieve dual responsiveness to mechanical stimuli and magnetic fields [4][5]. To address the limitations of conventional magnetically driven soft actuators—such as insufficient load-bearing capability and the difficulty of achieving localised deformation—Zhou Weifan and colleagues proposed a stiffness-tunable magnetic shape memory actuator (STMA) composed of a shape memory polymer and hard-magnetic NdFeB particles. In this system, an epoxy-based shape memory polymer serves as the matrix, while 50 wt% NdFeB microparticles are incorporated as magnetic fillers. Furthermore, silver nanoparticle conductive ink is screen-printed onto the surface to form Joule heating circuits, enabling localised heating. By adjusting the input current, the elastic modulus of the material can be reversibly tuned from 4.1 GPa at 25 °C to 10.9 MPa at 70 °C, spanning nearly three orders of magnitude.

Structurally, independent Joule heating circuits are embedded in multiple segments of the actuator, allowing each section to be heated and softened individually. This design enables precise modulation of temperature and stiffness in localised regions, thereby producing distinct deformation modes within the same external magnetic field. The magnetic anisotropy programming is achieved via a thermo–magnetic coupling strategy, in which a strong magnetic field (5 T) is applied while the composite is in a softened state, thus encoding spatially distributed magnetic moments. Through this approach, complex programmable deformations can be realised.

At the application level, Zhou’s team demonstrated the STMA in flexible magnetically controlled grippers and biomimetic robotic hands. Each finger segment can be independently actuated via localised Joule heating and subsequently driven by an external magnetic field to perform gripping, locking, and releasing motions. Owing to the reversible transition between high stiffness and high flexibility, the actuator exhibits both strong load-bearing capacity (capable of lifting rigid objects) and rapid, reversible response with a reaction time of approximately 0.2 s. This significantly enhances the practicality of magnetically responsive polymers in electronic and electromechanical systems.

Overall, this design integrates high stiffness tunability, multi-degree-of-freedom actuation, programmable magnetic anisotropy, and dual electrical–magnetic compatibility, offering a new structural paradigm for flexible electronic actuators, wearable grasping devices, and intelligent actuation modules. It also demonstrates substantial potential for future applications in smart materials and reconfigurable electronic systems.

### 3.2. Information Storage and Actuation Devices

Magnetic shape memory polymers (MSMPs) are not only employed in information-related devices such as reconfigurable antennas and magnetically actuated switches [4] but are also utilised in the development of stiffness-tunable actuators [6]. Table 1 is a performance comparison of different fabrication methods and filler systems in electronic devices.

**Table 1.** Performance comparison of different fabrication methods and filler systems in electronic devices.

Material system	Fabrication method	T <sub>g</sub> (°C)	Fixity ratio (%)	Recovery ratio (%)	Recovery rate	Application
SMP/LSMO (20 wt%)	FDM Printing	≈ 57	≈ 88	81	179.5%·min <sup>-1</sup>	Programmable honeycomb structure
TPU/PLA + Sm <sub>2</sub> Fe <sub>17</sub> N <sub>x</sub> /Fe <sub>3</sub> O <sub>4</sub>	FDM Printing	80–90	91.67	97.22	Enhance the response speed	Six-claw soft robot

## 4. Advances in Biomedical Applications

### 4.1. Drug Delivery

A magnetically actuated drug delivery system enables site-specific release and precision therapy [7]. In the field of precision drug therapy, Vakil et al. developed a magnetically actuated shape memory polymer (SMP)-based drug delivery system that enables site-specific and on-demand drug release. The system employs polyurethane-based SMPs (such as PPG-TEG and HPED-TEG) as the matrix and incorporates Fe<sub>3</sub>O<sub>4</sub> magnetic nanoparticles as magneto-thermal responsive units. After being mechanically deformed and fixed into a “closed” configuration, the material can be remotely activated by an external alternating magnetic field. The magnetic nanoparticles generate localized heat, elevating the polymer temperature above its glass transition temperature, thereby restoring the material to its original “open” configuration and triggering drug release.

This platform is capable of loading chemotherapeutic or immunosuppressive agents such as doxorubicin (Dox) and 6-mercaptopurine (6-MP). Moreover, a dual-drug compartmental design can be achieved, allowing different drugs to be embedded within the same implant while exhibiting distinct release rates, thus enabling sequential or combinational therapy. Compared with conventional intravenous injection, which often results in systemic drug distribution, high toxicity, and frequent dosing requirements, this strategy achieves localised delivery at the lesion site, remote and contactless activation, and repeatable on-demand release. These features significantly enhance treatment efficacy while reducing adverse effects on healthy tissues. In addition, in vitro experiments demonstrated cell viability above 75%, confirming the system’s favourable biocompatibility and establishing a foundation for its potential use as an implantable drug delivery platform in the treatment of tumours and chronic diseases.

### 4.2. Implantable Devices

Magnetic shape memory polymers (MSMPs) exhibit excellent biocompatibility and biodegradability, offering a promising platform for the development of implantable medical devices [8]. To address the limitations of conventional shape memory polymers (SMPs) in biomedical applications—such as excessively high activation temperatures, poor thermal conductivity, and the inability to achieve remote triggering—Choudhury and colleagues developed a magnetically responsive, biodegradable

nanocomposite system based on 4D printing. In their design, poly(L-lactide-co-trimethylene carbonate) (PLMC) was selected as the shape memory matrix due to its glass transition temperature of approximately 33 °C, which is close to physiological body temperature. To impart magnetic heating capability, 5 wt% Fe<sub>3</sub>O<sub>4</sub> nanoparticles were incorporated into the polymer. A solution-dispersion process followed by extrusion-based 3D printing enabled the fabrication of PLMC–Fe<sub>3</sub>O<sub>4</sub> scaffolds with high geometric accuracy ( $\approx 95\%$ ).

Under an alternating magnetic field, the composite scaffolds were able to undergo remote inductive heating and trigger shape recovery. The material exhibited a shape fixity ratio of 97% and a recovery ratio of 99%, with an activation temperature of only  $\sim 40$  °C, well within the safe physiological range. Complex 3D-printed architectures—such as flower-like, fish-like, and disk-shaped structures—could fully recover their original shapes within 15 s under magnetic stimulation, demonstrating rapid responsiveness and excellent reversibility. Moreover, the scaffolds could be deployed *in vivo* through magnetically induced, contactless expansion, indicating their suitability for minimally invasive implantation and adaptive tissue repair.

From a biological perspective, *in vitro* experiments showed that the composite scaffolds supported high levels of adhesion, proliferation, and viability for NIH-3T3 fibroblasts and MC3T3-E1 pre-osteoblasts. After 14 days of culture, substantial calcium deposition was observed, confirming their osteoinductive capability. *In vivo* subcutaneous implantation in Wistar rats revealed no significant inflammatory response or organ toxicity, suggesting favourable long-term biocompatibility and biosafety. This study establishes a solid foundation for the application of MSMPs in bone tissue engineering, minimally invasive implantable devices, and programmable bio-scaffolds, and highlights their potential as remotely actuated, controllably deployable biomaterials for next-generation biomedical applications.

### 4.3. Tissue Engineering and Robotic Surgery

Magnetic shape memory polymers (MSMPs) have demonstrated considerable potential in soft robotics and surgical assistance due to their programmable deformation, remote actuation capability and high energy efficiency. For instance, magnetically responsive micro-grippers with dual electro-magnetic actuation have achieved an exceptionally high load-to-weight ratio of up to 2380 [9]. In addition, a soft robotic system composed of Sm<sub>2</sub>Fe<sub>17</sub>N<sub>x</sub> and Fe<sub>3</sub>O<sub>4</sub> has been developed with six magnetically actuated arms capable of complex motions such as crawling and flipping [1], providing a feasible strategy for minimally invasive manipulation within confined environments.

To overcome the limitations of conventional metallic micro-coils in intracranial aneurysm embolization—particularly their inability to adapt to patient-specific vascular geometries—Liu Jiancheng and co-workers proposed a programmable magnetic–radio-frequency (RF) responsive SMP robot. The device is fabricated from a polyurethane acrylate (PUA, B270) matrix incorporating NdFeB hard magnetic particles and Fe<sub>3</sub>O<sub>4</sub> nanoparticles, forming a dual-responsive MSMP system. UV crosslinking results in a highly cross-linked network that enables both magnetic locomotion and RF-induced shape memory activation. Under an external magnetic field of 5 mT (1–5 Hz), the robot is capable of precise navigation and locomotion, including uphill motion along artificial vascular pathways, while RF heating to approximately 42 °C triggers recovery to a pre-programmed aneurysm-conforming configuration, enabling personalized embolization.

Structurally, the robot consists of a magnetic SMP core containing NdFeB particles and a chitosan/Fe<sub>3</sub>O<sub>4</sub> shell; the core supplies magnetic actuation, whereas the shell provides rapid inductive heating. During *in vitro* vascular simulations, the robot autonomously followed predetermined trajectories, achieved 45° climbing, and reached a maximum locomotion speed of 2.23 cm s<sup>-1</sup>. Upon heating to its activation temperature, the structure transformed from a 5 mm spherical body into a customized embolic scaffold capable of filling aneurysms of various shapes and sizes.

This system exhibits several notable advantages. First, it provides accurate and remotely controllable manipulation through the synergistic action of magnetic three-dimensional motion and RF-triggered

shape recovery, thereby improving surgical precision and safety. Second, the material demonstrates superior mechanical robustness, with the B270-based SMP exhibiting a tensile modulus of 276 MPa and a bending modulus of 421 MPa—approximately 50 times higher than conventional hydrogels—effectively preventing mechanical failure during navigation in complex physiological environments. Third, the low activation temperature (~42 °C) ensures rapid actuation while minimizing the risk of thermal tissue injury, complying with clinical safety requirements. Fourth, the system offers excellent customizability, allowing pre-programmed shaping according to patient-specific aneurysm geometries, which is essential for personalized medicine. Moreover, the composite exhibits outstanding biocompatibility and long-term durability, maintaining a shape recovery ratio exceeding 97% and stable performance over repeated actuation cycles.

In summary, this work bridges controllable locomotion and adaptive deformation within a single system and establishes a robust materials and structural foundation for next-generation implantable intelligent medical devices. It demonstrates significant promise for clinical translation in the treatment of cerebrovascular diseases, minimally invasive surgery, and embolization-based interventional therapies.

## 5. Cross-Disciplinary Comparisons and Challenges

In the field of electronic devices, current challenges mainly lie in the insufficient level of system integration and limited cycling durability, whereas in the biomedical domain, the lack of research on long-term in vivo stability and magnetic-field penetration significantly restricts clinical translation. In addition, both fields share several fundamental issues, including non-uniform dispersion and weak interfacial bonding of magnetic particles within the polymer matrix, as well as the absence of scalable and reproducible manufacturing strategies [1][2].

A comparative analysis of application requirements in the electronic and biomedical fields reveals distinct differences in performance priorities for magnetic shape memory polymers (MSMPs). In electronic systems, rapid actuation and immediate feedback are of primary importance, with the demand level reaching 5, whereas biomedical applications are rated at 3, suggesting that clinical systems place greater emphasis on safety and operational stability rather than extreme response speed. In contrast, biomedical applications exhibit a stronger demand for precise control and actuation accuracy, rated at 5 compared with 4 in electronic devices, due to the necessity of high spatial precision in procedures such as intravascular navigation, localised drug release, and minimally invasive surgery.

With respect to mechanical strength, both fields show comparable demand levels—4 for electronics and 3 for biomedical applications—although their focus differs. Electronic devices prioritise fatigue resistance and structural durability, while biomedical systems value mechanical compliance and adaptability to soft tissues. The divergence becomes more pronounced when considering biocompatibility and degradability. Biomedical applications require the highest level of biocompatibility and biodegradability (both rated 5), whereas electronic devices assign only 2 and 1, respectively. This difference reflects the necessity for non-toxic degradation and immune safety in implantable or tissue-related applications, as opposed to the long-term stability and environmental resistance required in electronic systems.

Long-term stability also shows a shift in emphasis: biomedical applications are rated at 4 compared with 3 for electronics, indicating that implanted devices must not only maintain consistent functionality but also avoid chronic toxicity, inflammatory responses, or structural failure. Overall, electronic applications tend to favour high responsiveness, reliability, and structural robustness, whereas biomedical applications prioritise precision control, biosafety, and degradability. These contrasting requirements offer clear guidance for tailoring the material design, processing strategies, and functional optimisation of MSMPs in different application scenarios.

## **6. Future Directions and Outlook**

### **6.1. Current Limitations in Practical Applications**

Although magnetic shape memory polymers (MSMPs) have demonstrated significant potential in flexible electronics and biomedical applications, several limitations still hinder their practical implementation. First, magnetic particles are often non-uniformly dispersed within the polymer matrix and poorly bonded at the interface, resulting in low magneto-thermal conversion efficiency and restricted response speed [10]. Second, repeated deformation and recovery cycles may lead to thermal fatigue and performance degradation, causing insufficient shape retention and long-term instability [6]. Furthermore, most reported MSMPs are still fabricated as small-scale laboratory samples, and scalable manufacturing techniques for large or complex structures remain underdeveloped. Although 4D printing enhances structural precision and actuation efficiency, issues such as printing stability, production cost, and controlled magnetic particle alignment have yet to be fully resolved [1-3]. In biomedical applications, the long-term biosafety, biodegradability, and magnetic field penetration of MSMPs in vivo remain insufficiently validated, and prolonged implantation may induce thermal damage or particle leakage, posing potential health risks [7].

### **6.2. Future Technological Prospects**

Future research on MSMPs should advance across three key dimensions: multi-stimuli coupling, intelligent manufacturing, and sustainable material design. At the material level, the development of electro-magnetic-optical synergistic stimulation systems is essential for achieving faster response rates and higher spatial resolution [2]. In terms of processing, 4D printing combined with magnetic field-assisted manufacturing is expected to play a central role, enabling rapid fabrication and programmable deformation through controlled particle alignment and optimized multilayer architectures [1][3]. Moreover, the integration of artificial intelligence with high-throughput computational modeling will facilitate formulation optimization and performance prediction, accelerating the transformation of MSMPs from “designable” to “manufacturable” and ultimately “reconfigurable” materials [10]. In parallel, the development of biodegradable polymer matrices and bio-safe magnetic fillers will greatly enhance the safety of MSMPs in biomedical applications [7]. At the device level, the incorporation of dual-stimuli actuation and stiffness-tunable architectures will enable high load-bearing capacity and multi-degree-of-freedom control, offering new pathways for flexible electronics, soft robotic systems and intelligent implantable devices [6][9].

## **7. Conclusion**

Magnetic shape memory polymers (MSMPs), owing to their advantages of remote controllability, rapid responsiveness, and programmable structural configurations, have shown substantial application potential in both flexible electronics and biomedical engineering. In recent years, significant progress has been achieved in actuation precision, structural design, and functional integration through the incorporation of magnetic particles and the development of advanced techniques such as 4D printing and magnetic field-assisted manufacturing.

Despite these advances, MSMPs still face several challenges, including low magneto-thermal conversion efficiency, limited cycling stability, concerns regarding long-term biosafety, and the absence of scalable fabrication strategies. Future research should therefore focus on the development of multi-field synergistic response mechanisms, intelligent manufacturing technologies, and biodegradable MSMP systems. Such efforts are expected to bridge the gap between laboratory studies and practical implementation, thereby providing a new material foundation for the advancement of flexible electronic devices and intelligent medical systems.

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