Manufacture Technologies for Magnetoactive Deployable Structures

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Abstract. Nowadays, smart materials like magnetoactive materials are utilized to manufacture deployable structures, enabling these mechanisms to self-fold under external magnetic fields. Fabrication of magneto-sensitive deployable structures have evolved from using discrete magnets to applying 4D printing—an emerging technique. The new printing concept expands the application area of magnetoactive mechanisms because properties of them can be predetermined and precise arrangement of magnetic domains are realized. This review summarizes fabrication technologies for magnetoactive deployable structures, including 4D printing.

1. Introduction

Deployable structures can transform and realize pre-set configurations. Traditional stretchable mechanisms usually need external force to reassemble. Contemporarily, smart materials are adopted to fabricate self-assembly structures and among them, magnetoactive materials gain increasing currency. Structures made of magnetic materials can be remotely controlled by external magnetic field, shaping the transformation of the deployable structure. Discrete magnets are common in early studies and are usually combined with elastomeric materials to pattern planar sheets with magnetic dipoles. But these mechanisms lack the ability to realize complex motion and precise control. However, another method is to incorporate magnetic micro- or nano-sized particles into soft elastomers according to morphing features of deployable mechanisms. The new technique boosts the application of an emerging technology-4D printing.

The concept of 4D printing was brought up by S.Tibbits from Self-assembly Lab of MIT in 2013 [1], where the fourth dimension is time. Based on conventional 3D printing technique, including direct ink writing (DIW), stereolithography (SLA) and fused deposition modelling (FDM), this new method enables the predetermination of deployment of stretchable structures made of smart materials, including magnetoactive materials, and printed objects can reshape themselves or self-fold according to the change of external environment, e.g. temperature [2], light [3], magnetic field, etc. Moreover, 4D printing makes it easier to manufacture magnetoactive deployable structures in small size, which are widely used in medical fields.

This review documents several types of common technologies that are utilized in the manufacture process of magnetoactive deployable structures as well as examples in previous literatures. Printing methods, including DIW, SLA and FDM and their applications in the fabrication of magnetoactive deployable mechanisms are elaborated successively and other manufactures are also included.
2. Manufacture technologies
In early studies, discrete magnets are combined with elastic panels to achieve remote control of deployable structures under external magnetic field. But mechanisms based on these materials do not satisfy researchers’ demands because it is hard to realize complicated transformation and accurate control. Hence, magneto-sensitive continuums, like magnetoactive soft materials (MSMs) and magnetic shape memory polymers (M-SMPs), gradually become the new material.

To use magneto-sensitive continuum (MSMs and M-SMPs), instead of discrete magnets to manufacture origami models, especially those requiring accurate control in confined space, traditional manual methods are not suitable compared with printing methods. However, though addictive manufacture (3D printing) has been applied to make deployable models [4], these stretchable mechanisms are not reconfigurable once printed, meaning that they are static and inanimate [5]. But 4D printing helps overcome this drawback. Also, patterns of deployable structures like origami mechanisms provide the prototype to rearrange material properties according to domains between creases on structure, enabling different transformations of one model under an applied magnetic field. Owing to the maturity of printing technology, some metamaterials and auxetic structures emerge, (e.g., those with negative Poisson’s ratio based on Miura-ori structure [6]).

2.1 Direct ink writing (DIW)
DIW refers to a printing technique based on extrusion through a nozzle under pressure. It uses a computer-controlled machine to change the position of dispenser filled with printing ink to manufacture deployable structure geometries layer-by-layer, where magnetic field is applied near the nozzle to magnetize the printed stuff [7], (see Figure 1a). The inks for DIW are usually polymers embedded with magnetizable microparticles (e.g., hard magnetic material neodymium-iron-boron (NdFeB)). The details of magnetic particles in the composite ink are given in Figure 1b and they are incorporated into composite polymers.

Based on advanced finite element analysis (FEA), models of deployable structures are set up and their transformations are simulated before printing. According to the results, volume fraction of raw materials in the printing ink can be further adjusted to realize expected morphing under the applied magnetic field after printing. For instance, programmed ferromagnetic domains are arranged based on the transformation of an origami structure [8]. Subsequently, magnetic torques are induced on them, creating stresses that collectively contribute to a macroscale structure response. Figure 1c shows the programmed ferromagnetic domains on a Miura-ori structure and its transformation in FEA simulation and experiment. Prediction methods are also set up with following consideration: $M$ is the magnetization (magnetic moment density) at a certain part of an origami structure before morphing and $FM$ represents the magnetization at the same part in the deformed body, where $F$ is the deformation gradient tensor expressed at this point. The magnetic potential energy per unit volume under the external magnetic field $B$ equals to $-FM \cdot B$, assuming that high-order terms in the real results of calculation are negligible. Then, Cauchy stress tensor raised by the external magnetic field on the magnetic moments is expressed as $\sigma_m = -B \otimes FM$, where the symbol $\otimes$ denotes the dyadic product [8].

However, though substrate-free remote actuation and fast, reversible transformation of deployable structures are realized, problems (e.g., agglomeration of imparted particles) still emerge due to lack of structural stability and magnetic attraction. In order to cope with this kind of difficulties and improve the control of locomotion, the rheological behavior of the printing ink are changed to dibutyl phthalate and fumed silica nanoparticles [9]. Besides, another challenge is to realize fully reversible actuation of origami structures between designed origami patterns. A significant hysteresis effect often occurs in the printed structures, owing to the resistance of internal elastic torque raised by magnetic actuation deformation [8].
Figure 1. (a) Diagram of printing process and components of materials. (b) Scanning electron microscope images of microparticles NdFeB with an average size of 5 \( \mu m \). (c) Arrangement of magnetization on the Miura-ori and the transformation process of a magnetoactive Miura-ori under the applied magnetic field, FEA simulation (the colourful one) and experiment (the red ones) respectively [8].
2.2 Stereolithography (SLA)

Conventional additive manufacture based on stereolithography (SLA) refers to the solidification of a liquid photosensitive polymer by a laser beam scanned across its surface [10]. To conduct self-assemble structures using SLA, magnetic particles are embedded into photosensitive polymers used in SLA.

The manufacture of magnetoactive deployable structures using SLA usually includes two steps, reorientation of embedded magnetic particles and selective curing of ultraviolet (UV) resin respectively. Moreover, based on the prediction of FEA simulation, magnetization is arranged according to folding features of a deployable structure before printing. The magnetic particles embedded in polymer composites are either magnetically soft, not maintaining magnetization when an external magnetic field is removed, or magnetically hard retaining part of magnetization. Soft magnetic particles synthesized in the printed materials are usually of nanometre size [11]. As a consequence, it can be lithographically imparted into some artificial composites [12], like hydrogel sheets [13]. Therefore, it is contributive to the stability of origami structures owing to the thin thickness of structure and the formation of arranged soft magnetic nanoparticle chains. In contrast, hard magnetic particles used in SLA were usually of micron size. Besides, its ability to remain magnetization brings other capabilities for origami structures, including fast speed of transformation from 2D panel to 3D structure [8], sophisticated assembly and manipulation [14]. The hysteresis curves of common soft and hard magnetic materials are depicted in Figure 2a&b. Moreover, in order to reduce heavy mental toxicity especially important to magnetoactive deployable structures used for biomedicine, hard magnetic NdFeB particles has also been universally selected as one of the printing raw materials.

Before the process of printing magneto-origami structures, composite materials are prepared by imparting magnetic particles into flexible UV resin. Then, these particles are precisely rearranged by the applied magnetic field above the printing substrate. During the selective curing process, digital light processing projector emitted UV light on specific regions of the origami substrate, initiating polymerization and fixing the magnetic particles within these selected areas [15]. The representation of the physical apparatus for patterning permanent magnetic particles in a UV-curable elastomeric matrix composite is shown in Figure 3.

Compared with DIW, the assemblage process of magnetoactive deployable structures using SLA is sophisticated and time-consuming because most models consist of both stimuli-responsive component and nonreactive segment. Hence, to avoid the deformation between sheets when printing multi-layer origami structures, Z.Ji proposed combining magnetic resin and nonmagnetic resin to one-step build soft models with the advantages of 4D printing on computer-assisted design and fabrication. [21] Similar to DIW techniques, the reversibility of magneto-origami structures based on SLA needs to be improved, considering the elastic properties of photosensitive resins.

![Figure 2](image)

Figure 2. (a), (b) The $M - H$ curves of hard and soft magnetic material, where $M$ represents the magnetization, $H$ represents the applied magnetic field, $M_r$ represents the remanence magnetization and $H_{ci}$ represents coercivity.
2.3 Fused deposition modelling

Fused deposition modelling (FDM) has been one of the most universally-used additive manufacture technology in various fields [17]. Similar to the other two printing methods (DIW and SLA) aforementioned, magnetic structural elements, including iron (Fe), magnetite (Fe₃O₄), strontium-ferrite (SrFe₁₂O₁₉) and also NdFeB, are embedded into printed soft matrix to fabricate self-fold origami structures under an applied magnetic field. In the process of printing, a composite filament is fed through a heated apparatus and then becomes molten or semi-molten. The viscous filament (termed “infill”) is pushed through a nozzle by the solid filament and is deposited onto the target deployable model. The FDM parts cool to solidify without the need to be cured, making it easier to manufacture untraditional structures, including magneto-origami models.

FDM gained the most attention among active manufacture methods because it costs less and is timesaving. Its capability to produce complex objects provide the possibility to realize the fabrication of magnetoactive structures [18]. Moreover, polylactic acid (PLA) is the most common components of printing materials for FDM because it is non-poisonous, recyclable, biodegradable and biocompatible [19], enabling printed magnetoactive models to be used in medical areas. Additionally, the inherent properties of the magnetic particulate have large effects on the magnetic response [20], which is one of the main reasons for the little use of FDM in the manufacture of magnetoactive deployable structures.

2.4 Other Manufacture Approaches

Though printing methods have been widely used, other fabrication methods of magnetoactive stretchable structures are also considered because some special mechanisms, e.g., origami film of nanoscale cannot be easily printed. Spin coating is an approach to producing thin films with thickness of micrometers or nanometers and most of raw materials for MSMs and M-SMPs meet its demands for high percentage elongation and large tensile strength [21]. Similar to 3D printing, spin coating may also be adapted to produce origami films. Though the complex responsive structures cannot be made through usual spin coating method, dividing substrate according to the aimed deployable pattern and applying corresponding external magnetic fields in different stages may help create magnetic anisotropy on the stretchable membrane. Moreover, when fabricating simple magnetoactive deployable models, printing may not be necessary because traditional investment casting methods still adapt to this process when targeted scale of the model is relatively large [22]. During the process of casting magnetoactive
composites in the mold, an external magnetic field can also be applied to arrange magnetic domains on the model. Though it is more complicated than direct printing method, cost will be saved with investment casting.

3. Conclusion
In summary, the manufacture technologies for magnetoactive deployable structures and their corresponding processes are reviewed. The emergence of 4D printing simplifies fabrication of complicated deployable mechanisms and expands application fields of magnetoactive stretchable structures. Meanwhile, features of 4D printing like predetermining properties of printed objects, can also adapted to other techniques. However, challenges still exist in printed magnetoactive structures. For instance, they cannot be reprogrammed once printed and can only realize one morphing form. To make more flexible self-foldable magnetoactive structures, materials like magnetic fluidic metals can be incorporated into the composite polymer and besides using external magnetic fields to control transformation, temperature can also help rearrange magnetic domains on the printed mechanisms. With more smart materials being utilized, the applications of magnetoactive deployable structures can be extended into more prospective areas.

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