SHAPE MEMORY MAGNETIC NANOCOMPOSITE ACTUATORS WITH IN-SITU PROGRAMMED MAGNETIC AXES

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ABSTRACT

Magnetic nanocomposite materials have drawn attention for the development of miniaturized devices with their improved magnetic and mechanical properties. However, few researches have been performed on the use of the polymeric nanocomposite as actuating components because it is difficult to control magnetic anisotropy of the microstructure which the actuation ability critically depends on. Here, we presents new types of magnetic nanocomposite material for the actuating component obtaining desired heterogeneous anisotropy, using magnetic nanoparticle self-assembly and simplified photopolymerization process. To show this programmable magnetic property, several types of actuators are demonstrated with theoretical modeling.

KEYWORDS: Magnetic actuator, nanocomposite, magnetic anisotropy, maskless photolithography, polymeric actuator

INTRODUCTION

Polymeric materials have received a great deal of attention for miniaturized mechanical components with their good formability, flexibility and lightness. However, the polymeric components reported so far are hardly suitable for microstructuring due to the necessity of metal electrodes for actuation or a lot of steps of lithographic process for patterning [1]. Another challenge is that existing actuation schemes, such as using thermal, ionic or electrical responses, are insufficient to achieve arbitrary motion of the component, limiting the complexity in microsystem [2]. Therefore we propose a new magnetically actuated polymeric materials with programmable heterogeneous magnetic anisotropy to overcome existing polymeric microcomponent actuating schemes. The key idea is to fabricate nanocomposite materials, which is a combination of photocurable polymer and self-assembled superparamagnetic nanoparticles, by repetitively aligning the nanoparticles and fixing nanoparticle chains via photopolymerization. This scheme greatly simplifies the manufacturing process and offers desired heterogeneous magnetic axes in a single component. Since we independently program desired magnetic anisotropy and various shapes, the fabricated polymeric component can easily obtain actuating complexity which conventional polymer manufacturing process hardly gain.

THEORY

The polymeric nanocomposite is based on a combination of photocurable polymer, which is poly ethylene glycol diacrylate (PEG-DA), and superparamagnetic nanoparticles which consists of several single-domain magnetite in the core capped with negatively charged material and silica shells. Without an applied external magnetic field, the nanoparticles are randomly dispersed in the resin. When the external magnetic field is applied, the nanoparticles are self-assembled forming chain-like structures along the magnetic field lines to minimize the magnetic dipole interaction energy of the system. Then, if the magnetic field direction is changed, the chains rapidly rotate or realign along the changed field direction. This property of magnetic nanoparticle chain is exploited to create magnetic easy axes and the cooperative response of the chains fixed in the host matrix drive the actuator.

The actuator deflection can be analyzed in terms of a simple analytical model. The prototype of polymeric microactuator consists of a narrow polymeric cantilever beam which is anchored to the substrate at one end and a free-floating polymeric plate which contains aligned superparamagnetic nanoparticles. The cooperative response of the chains enables the magnetic actuator to rotate and align the external magnetic field line. Consequently, under the uniform magnetic field, the micro-structure experiences magnetic torque on the head and mechanical restoring force owing to the thin cantilever beam deflection at the equilibrium state. The angular mechanical deflection of the micro-actuator φ at equilibrium is found

$$\varphi = \frac{K_m}{K_\varphi}\sin(\varphi_{initial} - \varphi) = K\sin(\varphi_{initial} - \varphi)$$

where φ_{initial} is the initial angle between the magnetic field line and cantilever beam before stress, K_m is the mechanical stiffness of the beam and K_φ is the magnetic factor of magnetic nanoparticle cluster. The equilibrium factor K can be rewritten as

$$K = \frac{\mu_0 \pi}{8}\frac{N_C N_P^2 d^3 l \chi^2}{w D^3 E_y} H^2 .$$

N_C and N_P are the number of chain in the head and the number of particles in a chain. d is the nanoparticle diameter, l is cantilever beam length and w and D is the thickness of the structure and the length of the head respectively. χ is the susceptibility of superparamagnetic nanoparticle and E_y is the elastic modulus of the polymer matrix. This equation implies that the actuator characteristics are easily controlled by changing actuator geometry or changing nanoparticle chain formation affected by magnetic field intensity during fabrication, in addition to the magnetic anisotropy control with chain direction.

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EXPERIMENTAL

A sequential process to manufacture miniaturized polymeric actuator is developed. The process involves magnetic field direction change and spatially modulated ultraviolet(UV) light exposure. The microfluidic channel on polydimethylsiloxane(PDMS) coated glass substrate is filled with the mixture of PEG-DA, photoinitiator and superparamagnetic nanoparticles. This resin is photopolymerized in a moment via optofluidic maskless lithography system [3] while preserving the alignments of the magnetic nanoparticles under the uniform magnetic field. Then, the magnetic field direction is changed to produce another magnetic easy axis, leading the rearrangement of the chains along the changed field line. This process is repeated until the magnetic anisotropy programming is completed. Lastly, the remaining resin is washed away and exchanged to the solution for actuating. Due to the oxygen inhibition layer created between the photocured hydrogel and PDMS surface during photopolymerization, the generated structure can be partially anchored on the glass region and partially floating on PDMS patterned region. This actuator is fabricated via a single UV exposure and a single material within a second without any additional steps such as sacrificial layer patterning and removing.

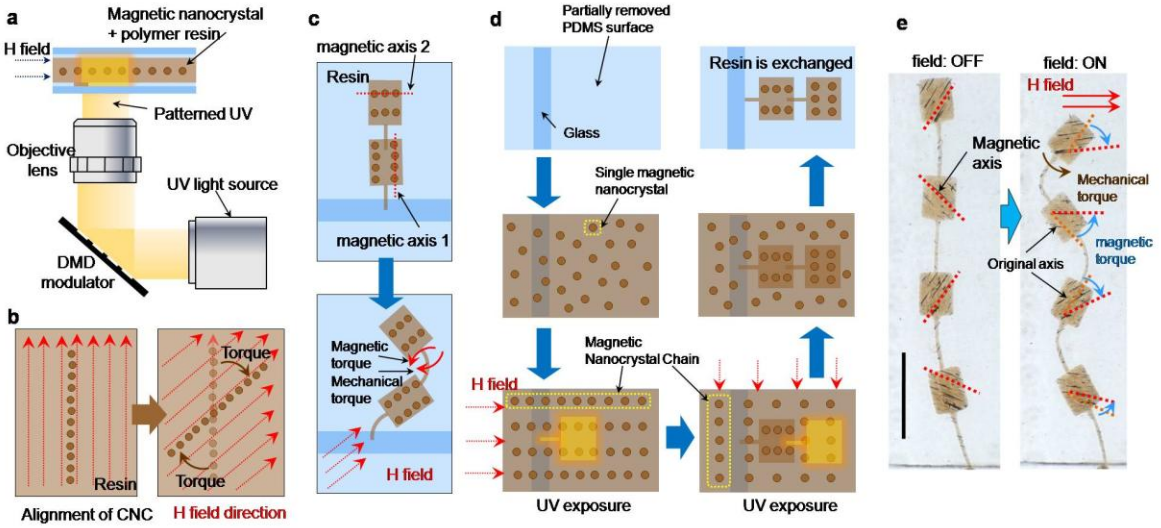

Figure 1: Schematic diagram of experimental set-up and fabrication process. (a) Set-up for optofluidic maskless lithography to modulate the UV exposure to the resin. (b) Aligned magnetic nanoparticles rotate along the changed magnetic field direction to minimize the magnetic anisotropy energy. (c) When magnetic field is applied to the structure, each plate is deformed in different direction because each has different magnetic easy axis. (d) Fabrication process of polymeric actuator with aligned nanoaprticles. (e) Snake-like actuator: each head has different magnetic easy axis, therefore the entire structure actuates like crawling snake when magnetic field is applied. (scale bar 200um)

RESULTS AND DISCUSSION

The goal of this procedure is to produce polymeric microstructure with programmed heterogeneous magnetic anisotropy regulated by magnetic field. With simple manufacturing route, as mentioned above, each part of the actuator have desired magnetic easy axes by repeatedly tuning and fixing the nanoparticle chain directions, and consequently homogeneous magnetic field independently actuate each part of actuator. In other words, the relative initial direction of the chains which we program determines the final configuration of the actuator.

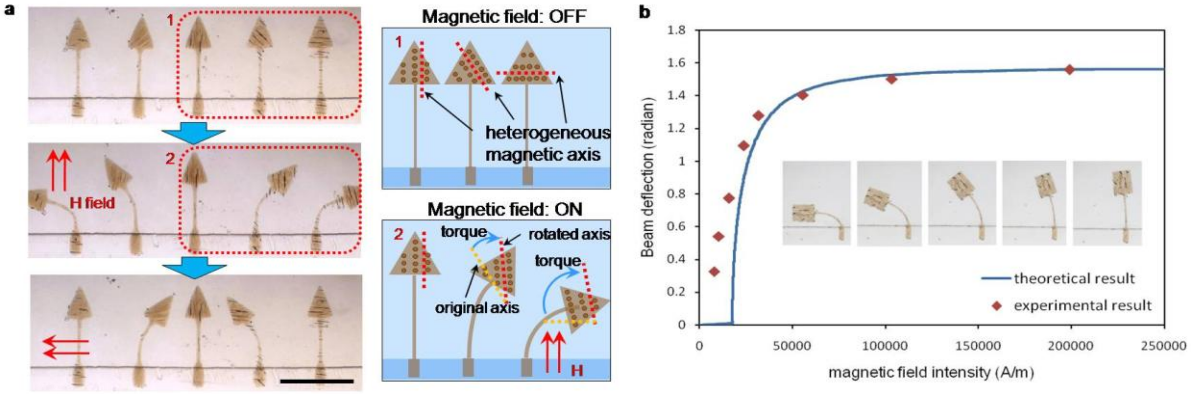

Figure 2: The programmability of actuator. (a) Five identical structures have different magnetic axes. Thus, each structure bends toward programmed directions under the uniform magnetic field. (scale bar 250um) (b) Theoretical analysis (blue line) and experimental results (red dots). We can design the actuator using this theoretical model.

Figure 1-(e) and Figure 2-(a) shows the programmability of our process. In figure 1-(e), the actuator have four different magnetic axes and each region bends independently. As a result, the actuator with heterogeneous magnetic axes moves like crawling snake. Five identical actuators in figure 2-(a) also have different magnetic easy axes. They are separately integrated in microfluidic channel and bend in programmed direction under the uniform magnetic field. Figure 2-(b) describes the relationship between the bending deflection and magnetic field intensity with the theoretical modeling. This results implies that we can regulate the actuation of the structure not only with the easy axis programming but also with the magnetic field intensity.

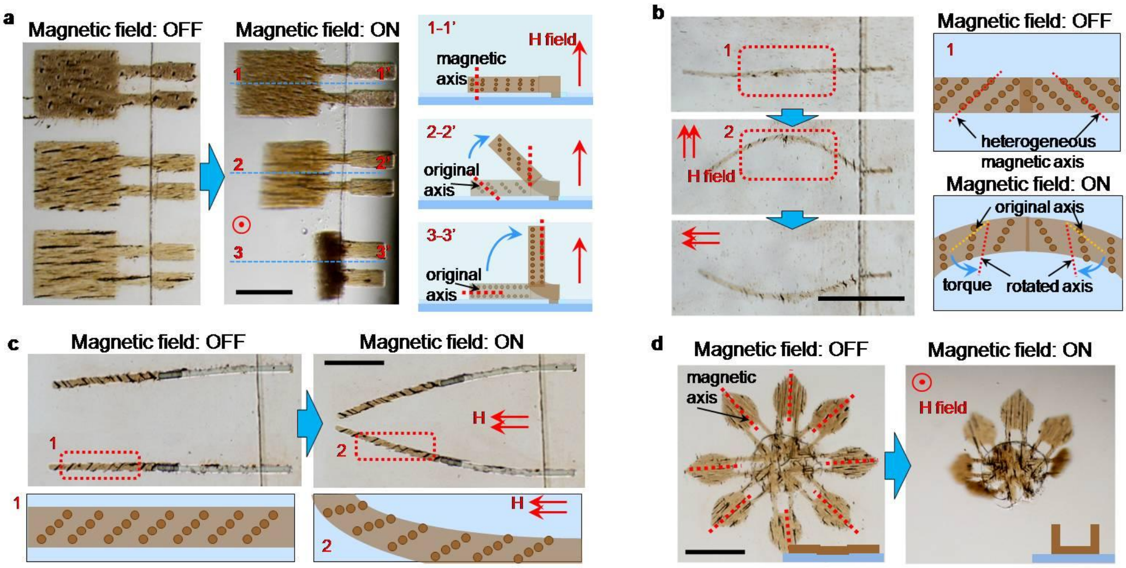

Figure 3: Various types of polymeric mechanical components with programmed heterogeneous magnetic axes. (a) Three identical cantilevers bend in different angle under the uniform perpendicular magnetic field, because each cantilever has the magnetic axis in different angle. (b) Artificial flagella: two narrow beam with different magnetic easy axis are connected and actuate like flagella because each beam is programmed to have perpendicular magnetic axis each other. (c) Magnetic tweezer: two narrow beam bend in opposite direction. (d) Reverse blooming process of flower-like actuator: PDMS surface is removed in a circle shape to fabricate the anchoring site of the component. Each petal stands up under the perpendicular magnetic field. (scale bar 200um)

To verify this concept, various types of polymeric actuators with high capability are demonstrated. The fabrication process enables in-plane movement (Figure 3-(a), (d)) as well as out-of-plane movement (Figure 3-(b), (c)). With PDMS surface patterning on the glass substrate, more diverse actuators can be fabricated, such as flower-like actuator in figure 3-(d).

CONCLUSION

In conclusion, magnetically regulated polymeric actuator using superparamagnetic nanoparticle self-assembly opens new possibilities of highly functionalized actuator. The main idea represented here is to utilize the chain forming property of the magnetic nanoparticles under the magnetic field. We fabricate microcomponent by repetitively aligning the nanoparticles and fixing the alignments in polymeric matrix via photopolymerization. With this technique, we can program the magnetic anisotropy and shape independently, achieving elaborately controlled movement of structure just by varying the magnetic field direction across the actuator. The theoretical analysis is also in agreement with the experimental results. This analysis can be applied to design the magnetic nanocomposite microactuator with programmed anisotropy.

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REFERENCES

[1] K. –J. Cho, et al., Review of manufacturing processes for soft biomimetic robots, Int. J. Precis. Eng. Manuf., Vol. 10, No. 3, pp. 171-181, (2009).
[2] E. Smela, Conjugated polymer actuators for biomedical applications, Adv. Mater., Vol. 15, pp. 481-494, (2003).
[3] S. E. Chung, et al., Optofluidic maskless lithography system for real-time synthesis of photopolymerized microstructure in microfluidic channels, Appl. Phys. Lett., 041106, (2007).

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