STRAIN ENGINEERED 3D MAGNETIC MICRO ACTUATORS WITH PROGRAMMED MAGNETIC ANISOTROPY

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ABSTRACT

This work combines programmed magnetic anisotropy and strain engineering in superparamagnetic polymer composites. The proposed approach enables tailored deformation of planar strips into three-dimensional (3D) micro actuators with shape-independent magnetic properties in a single wafer-scale fabrication step. The developed process allows for pattern feature sizes below five μm using a superparamagnetic polymer composite with a particle content of 10 %vol. The feasibility of this approach is demonstrated by fabricating helically shaped swimming microrobots, also known as Artificial Bacterial Flagella (ABF), with shape-independent magnetic properties and diameters as small as 100 μm. The necessity of decoupling the magnetic properties from the shape was confirmed by demonstrating that only ABFs with programmed anisotropy, i.e. shape-independent magnetic properties, are capable of performing desirable locomotion patterns.

INTRODUCTION

3D magnetic micro actuators are regarded as potential key instruments in revolutionizing the field of minimally and non-invasive medicine [1]. These actuators combine two inherent advantages: 1) The application of magnetic fields and materials enables untethered actuation in any magnetically transparent environment including the human body [2] and 2) The 3D shape enables complex actuation schemes such as the well-known cork-screw propulsion in the low Reynolds regime [3].

State-of-the art fabrication approaches for 3D actuators rely on rather complex fabrication tools like Molecular Beam Epitaxy [4] or fabrication schemes such as Two-Photon-Polymerization (TPP) [5, 6], which are generally not considered low cost and may not be found in most cleanrooms. Subsequently, several approaches have been proposed to fabricate 3D microstructures by self-assembly. Self-folding of polymer bilayers has been demonstrated by Luchnikov *et al.* and Guan *et al.*. While self-folding was initiated by isotropic swelling of bilayer arrangements, folding occurred only along the length axis of the presented sub-mm structures and was thus shape dependent [7-9]. In contrast, Lee *et al.* demonstrated shape-independent, direction controlled self-assembly based on volume shrinking of SU-8 during post-exposure bake. However, shrinking is limited to about 3% and allows for comparably high radii of curvature in the mm range [10]. More recently, Erb *et al.* suggested the fabrication of helical configurations through structural reinforcement by aligning magnetic particles inside a swollen hydrogel polymer matrix. However, the particle alignment, which also implies the orientation of the magnetic properties, solely serves structural properties and the magnetic properties are coupled to the shape [11].

While the batch fabrication of 3D micro structures in general and helical configurations in particular represents a challenge in itself, 3D soft-magnetic micro structures further suffer from the adverse effect of magnetic shape anisotropy. This effect ties the preferred direction of magnetization, also referred to as magnetic easy axis, to the longest expansion of an object. As magnetic torque can only be applied perpendicular to the magnetic easy axis, the object's shape implicitly restricts certain actuation patterns or makes them highly ineffective. However, decoupling magnetic properties from the shape of TPP-fabricated micro actuators has been shown to greatly enhance actuation efficiency and to enable specific actuation patterns [12, 13].

To overcome the aforementioned issues concerning the batch fabrication of helical micro actuators as well as decoupling of magnetic properties from the actuator shape, this work combines strain engineering in highly absorbent liquid polymers and the concept of a programmed magnetic anisotropy to fabricate 3D helical micro actuators with tailored magnetic properties in a single wafer-scale fabrication step.

MATERIALS AND METHODS

A superparamagnetic FerroFluid (FF) (iron oxide nanoparticles dissolved in γ-Butyrolactone, particle concentration 265 mg/ml) was obtained from ChemiCell GmbH Berlin, Germany. Further details about the FF can be found in [14]. Poly (ethylene glycol) diacrylate (PEG-DA) 575 was obtained from Sigma Aldrich Switzerland. Irgacure photo initiator (PI) was donated by BASF AG Basel, Switzerland. For the preparation of superparamagnetic PEG-DA, the FF was reduced to increase the particle content and PEG-DA was added to yield the following volumetric composition: 10 %vol nanoparticles, 45 %vol PEG-DA, and 45 %vol GBL. PI and a photo sensitizer were added to achieve concentrations of 50 and 10 mg/ml with respect to the PEG-DA volume, respectively. All components were mixed using a Hauschild DAC planetary mixer for 10 minutes. The obtained mixture is referred to as superparamagnetic polymer composite (SPMPC) and is crosslinked using an exposure dose of 2500 mJ / cm^2 at 365 nm wavelength. Particle alignment was carried out using a custom Helmholtz coil with a field strength of 10 mT.

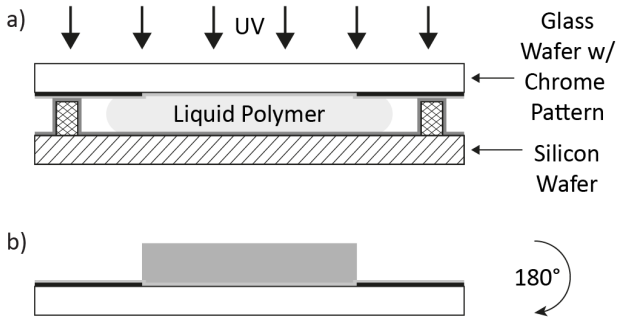

Figure 1) Liquid polymer crosslinking; a) Liquid photo-polymer is encapsulated between a chrome-patterned glass wafer and a silicon bottom wafer and subsequently exposed from the backside, film thickness is adjusted by spacers; b) Non-crosslinked polymer is removed using a solvent.

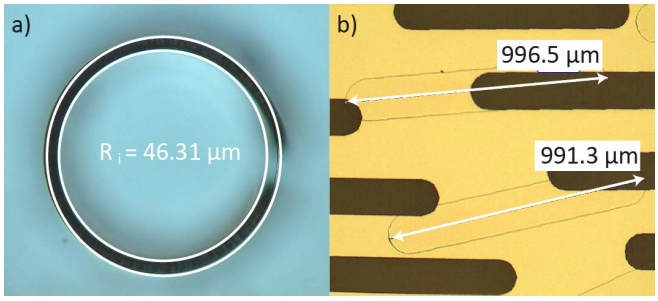

Figure 2a) Crosslinked and released polymer strips with dispersed nanoparticles curl after their release from the substrate and tumble to the side; b) Crosslinked and released polymer strips without nanoparticles remain uncurled, the chrome-patterned glass-wafer can be seen in the background.

DEFORMATION OF PLANAR STRIPS

Non-Directional Self-Scrolling

The self-scrolling of co-planar single layers relies on the encapsulation of the photo curable, liquid SPMPC between a chrome-patterned glass wafer and a silicon bottom wafer as illustrated in Figure 1 and described more thoroughly in [15]. The presence of the highly absorbent nanoparticles creates a significant intensity gradient during UV exposure. The subsequent gradient in crosslinking speed results in the formation of an intrinsic stress gradient as discussed by Basu *et al.* [16]. Upon release, the stress-gradient translates into an actuation strain curling the crosslinked beams perpendicular to their length axis. Here, the normal of the bending vector is perpendicular to the longest expansion of the strip (see Figure 2a). When this experiment is repeated with a similar photosensitive polymer free of highly absorbent particles, no bending is observed (see Figure 2b), supporting the underlying theory of Basu *et al.* [16].

Directional Self-Scrolling

In order to fabricate more complex shapes then bent strips, the normal of the scrolling vector must be decoupled

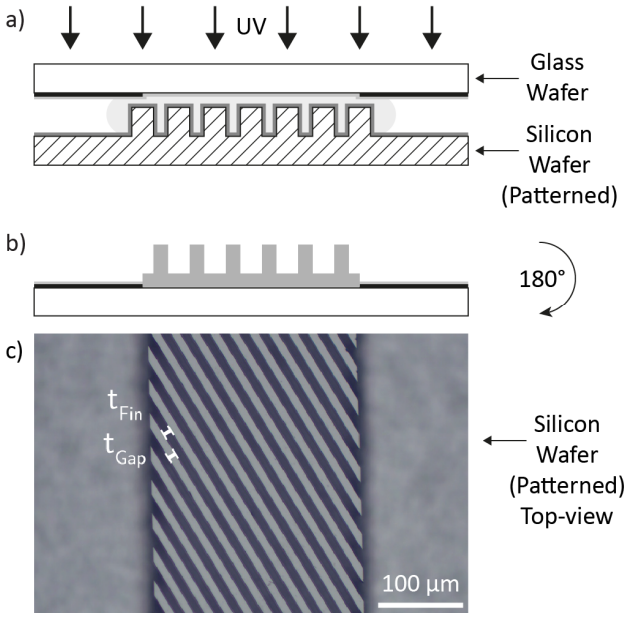

Figure 3) Crosslinking with a patterned bottom wafer: a) Liquid photo-polymer is encapsulated between a chrome-patterned glass wafer and a patterned silicon bottom wafer and subsequently exposed from the backside, film thickness is adjusted by a squeeze film between the two wafers; b) non-crosslinked polymer is removed using a solvent; c) Top view of the patterned silicon wafer.

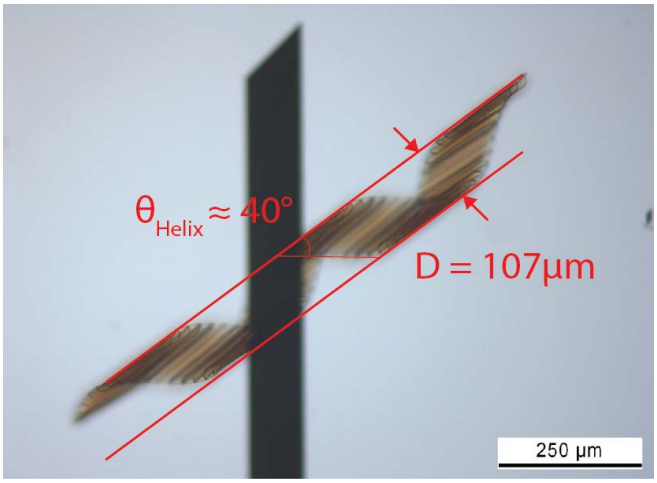

Figure 4) Light microscopy image of a curled helical structure, also known as ABF. Reinforcing fins are oriented along the length axis of the fins.

from the longest geometrical expansion of the respective strips or sheets. This decoupling is accomplished by introducing a repetitive topographical patterning to the crosslinked polymer layer. This pattern consists of parallel, elongated bars, also referred to as fins on top of the connecting base layer. It might be possible to define base layer and the fins in two separate fabrication steps. However, we propose the utilization of a lithographic nano-imprint approach where the negative of the to-be-fabricated geometries is provided by means of a topographically

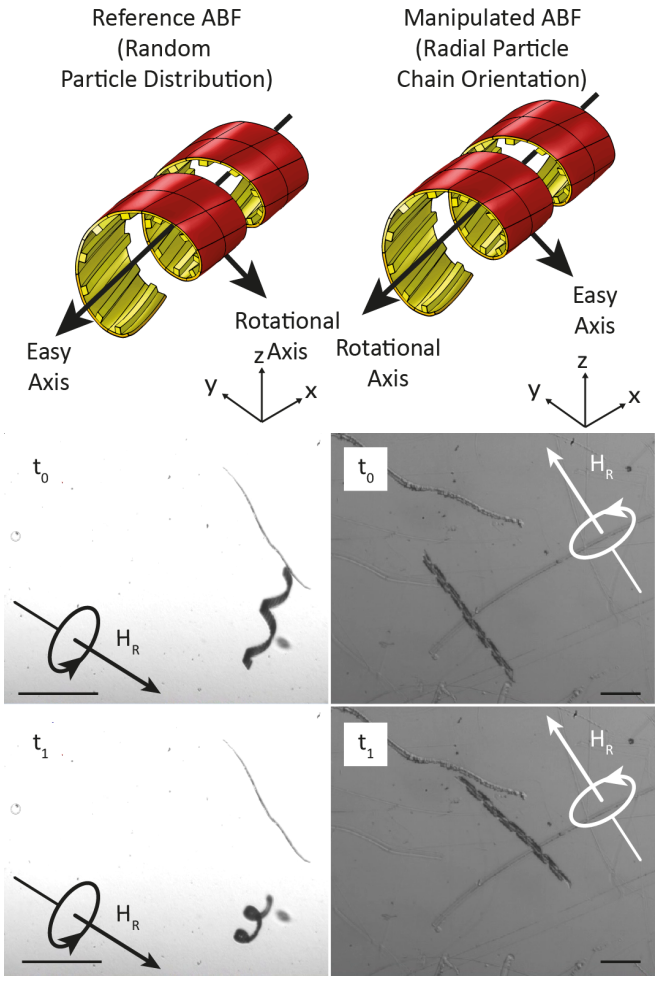

Figure 5 Left) Magnetic easy axis of reference ABFs (random particle distribution) is oriented along the helical axis; Magnetic torque is generated perpendicular to the magnetic easy axis, ABF performs a surface walk; Right) Due to the radial orientation of the embedded nanoparticle chains, the magnetic easy axis of manipulated ABFs is oriented perpendicular to the helical axis; magnetic torque is generated about the helical axis, helical propulsion is enabled; Scale bars are 300 µm.

patterned silicon wafer as illustrated in Figure 3a and b. Using this approach, the achievable feature size is only limited by the patterning of the silicon wafer (see Figure 3c). Although not specifically investigated, fins with a width as small as 5 µm were fabricated using the investigated SPMPC. The height of the fins is determined by the height of the topographical pattern on the silicon wafer (usually between 5 and 15 µm). The height of the base layer is resulting from squeezing both wafers together with typical thicknesses in the order of one µm. When these topographically patterned strips are released from their substrate, the fins on top of the base layer act as a reinforcement and guide the normal of the bending vector towards the length axis of the fins. If the fins are oriented away from the short axis of the polymer strips as illustrated in Figure 3c, the resulting deformation results in the formation of helical structures with diameters as small as 100 µm. A typical helical configuration after self-scrolling is illustrated in Figure 4. It can also be seen that the individual fins are oriented along the length axis of the helix.

MAGNETIC ACTUATION

Shape Anisotropic Actuators

When the magnetic particles are randomly distributed inside the crosslinked polymer matrix, the magnetic properties are shape dependent. Considering the fact that the height of the fins is one order of magnitude larger than the height of the base layer, the impact of the base on the magnetic properties can be neglected in a first approximation. Following this simplification, it is fair to assume that the scrolled helix consists only of fins with their longest expansion along the length axis of the helix. Subsequently, the preferred direction of magnetization of each fin evolves along the length axis of the helix. If we consider the relatively short range of magnetic interaction, we can further assume that magnetized fins do not interact with each other. In this case, the magnetic easy axis evolves as a direct superposition of the magnetic easy axes of all fins and the magnetic easy axis is oriented along the length axis of the helix itself.

When the released helical structures are subjected to rotating magnetic fields, they respond with a rotation perpendicular to their magnetic easy axis, i.e. they rotate perpendicular to their length axis, and perform a so-called surface walk. The orientation of the magnetic easy axis, the rotational axis as well as an image sequence of the surface walk are illustrated in Figure 5 in the left column.

Actuators with Programmed Magnetic Anisotropy

In order to translate the unwanted surface walk into the desired cork-screw propulsion, the magnetic easy axis must be decoupled from the helical shape and ideally oriented perpendicular to the helical length axis. This is accomplished by applying a homogeneous magnetic field in the thickness direction of the polymer strips during crosslinking of the SPMPC. The presence of the magnetic field aligns the dispersed nanoparticles in form of chains along the direction of the external magnetic field. During crosslinking, the particles become locked inside the polymer matrix. As the magnetic field is applied perpendicular to the thickness direction of the fins, the magnetic easy axis of each fin is rotated from the length axis towards the thickness direction. This process is also referred to as programming the magnetic anisotropy [12, 13]. After releasing the fabricated structures from their substrate, the same helical self-scrolling takes place as before and the thickness direction of the fins corresponds to the radial direction.

To explore the magnetic properties of the actuators with programmed magnetic anisotropy, similar analogies as before can be made. The impact of the base layer as well as

an interaction between individual fins can be neglected. The magnetic easy axis can again be evaluated through superposition of the magnetic easy axes of all fins and the magnetic easy axis of the fabricated helical structures must be oriented in a radial direction. The subsequent application of a rotating magnetic field leads then to a rotation about the helical length axis and subsequently to the desired cork-screw propulsion pattern. The orientation of the magnetic easy axis, the rotational axis as well as an image sequence of the surface walk is illustrated in Figure 5, right column.

CONCLUSION

In this work, we presented a simple and facile single step process that enables the tailored deformation of planar strips in to helical configurations. The application of a homogeneous magnetic field during polymer crosslinking allowed decoupling the magnetic properties of the fabricated actuators from their shape. The need of applying the principle of a programmed magnetic anisotropy was verified by demonstrating that only actuators with a programmed magnetic anisotropy were able to perform the desirable locomotion pattern.

The presented results demonstrate the potential of combining strain engineering and programmed magnetic anisotropy to be a powerful and facile, yet easily implementable tool that has the potential to enable a new class of remotely actuatable microdevices.

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