Magnetic Particles

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Fabrication and Assembly of Magneto-Responsive, Anisotropic, and Hybrid Microparticles of Variable Size and Shape**

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Magnetic particles that can be remotely manipulated by an external magnetic field have attracted a wide range of interests for applications, including bioimaging, biosensing, multiplexed detection, photonic crystals, microdisplay,[1] and separation, transport, and sorting in microfluidic devices.[2] While most studies have focused on spherical magnetic particles, it has been reported that magneto-rheological[3] and electro-rheological[4] properties can be enhanced using anisotropic particles. Meanwhile, new types of self-assembled structures (e.g. chiral cluster[5] and symmetric dimers[4]) have been created by controlling the shape and interactions between colloidal particles under a magnetic field.

Magnetic microparticles are typically synthesized by oil-in-water emulsion, seeded polymerization, and microfluidic techniques.[1e,6] Using the emulsion method, spherical magnetic microparticles of variable sizes (from tens to hundreds of micrometers in diameter) can be synthesized. Using magnetic nanoparticles as seeds and subsequent polymerization, magneto-polymer composite particles can be formed, typically also in a spherical shape. However, it is challenging to obtain uniform sized particles by these methods. In comparison, microfluidic devices have been particularly successful in producing magneto-responsive microparticles of uniform size and surface chemistry. Yin et al. have fabricated Janus supraballs from magnetic nanoparticles and quantum dots, and demonstrated a magneto-responsive fluorescent switch for flexible bead displays.[7] Kim and coworkers also prepared magnetic Janus microparticles with nanoscopic surface textures using microfluidic systems and demonstrated the remote controlled locomotion.[8] However, the microfluidic techniques impose limitations on particle size (typically several hundreds of micrometers) and shape (mostly spherical), as well as constituent materials (UV curable acrylate resins), as a result of the required complex design, fabrication process, and the preparation of materials in advance. Recently, some progress has been made in preparing magnetic particles with precisely controlled size and shape by top-down approaches, including templating, photolithographic process, and stop-flow lithography.[9] Nevertheless, questions remain in synthesizing highly responsive magnetic particles, which exploit particle size and shape, and shape anisotropy for the dynamic tuning of particle assemblies.

Herein, we present a facile and versatile method to fabricate monodispersed hybrid microparticles of variable size and shape, and investigate their magneto-responsive behaviors in aqueous dispersions with and without geometric confinement. The key feature of our method involves co-assembly of silica colloidal particles and magnetic iron oxide nanoparticles in a poly(dimethylsiloxane) (PDMS) mold with a periodic micron-sized hole array, followed by infiltration and UV curing of epoxy resin to lock the particles, and releasing the microstructures from the mold and the substrate. Compared to other methods, the replica molding method allowed us to fabricate smaller, non-spherical shaped magnetic microparticles (a few microns in diameter and aspect ratio up to 10). The fabrication was versatile and high throughput: approximately 10^6 particles/cm^2 could be prepared in a single batch and particle size and shape could be varied by simply using different molds. Importantly, the particles were highly uniform and responsive to the magnetic field: they could be rotated and flipped freely and reversibly, and assembled into one-dimensional (1D) chain structures and a two-dimensional (2D) hexagonal array. The high responsiveness was attributed to the use of silica colloids, which not only stabilized the aqueous dispersion of the magnetic microparticles, but minimized possible cancellation of the magnetic moment by sequestering the iron oxide nanoparticles to the interstitial space between highly ordered silica colloids organized within the PDMS mold. Further, we demonstrated the possibility to create isolated magnetic inclusions in the elastomeric PDMS matrix, where the motion of particles can be exquisitely controlled within the confined geometry.

First, the square-array PDMS mold with cylindrical holes (10 μm diameter, 20 μm depth, and 15 μm pitch) was prepared by replica molding from 2D SU8 micropillar arrays, which were microfabricated by photolithography. As illustrated in Figure 1, an ethanol suspension consisting of silica colloidal particles (500 nm in diameter) and iron oxide (α-Fe_2O_3) nanoparticles (under 50 nm in diameter) was dropped onto PDMS mold. Epoxy resin was then infiltrated into the PDMS mold by capillary force and cured under UV light while applying the magnetic field along the film thickness to induce the alignment of the magnetic moment of the iron oxide nanoparticles. A UV-curable epoxy resin with high elastic modulus (ca. 3 GPa) was chosen to prepare robust microparticles with the desired shape and high aspect ratio (length/

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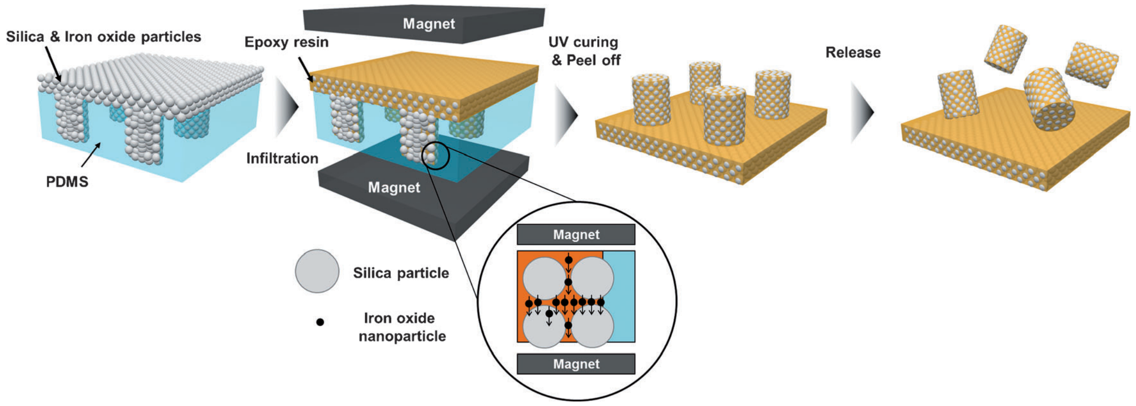

Figure 1. Schematic illustration of the fabrication of magneto-responsive, anisotropic microparticles. Silica colloids and iron oxide nanoparticles are filled into the PDMS mold with cylindrical holes. Epoxy resin is infiltrated into the cavities of the PDMS by capillary action then a magnetic field is applied to the whole system. After UV curing of the epoxy resin, the PDMS mold is peeled off, leaving an array of micropillar structures. The micropillars are released from the substrate to obtain the anisotropic, magnetic microparticles.

diameter). Previously, we showed that high-aspect-ratio (up to 18) and high-density epoxy pillar arrays were successfully replicated.[10] Because of the relatively low viscosity of the liquid epoxy resin (3400–4200 cps at 25 °C), the filling of the micropores of the PDMS mold and the nanopores between particles were achieved within a few seconds. After curing the epoxy resin, the PDMS mold was peeled off from the substrate, leaving behind a square array of micropillars over a large area (ca 3 cm^2; see Figure 2 a,b).

As seen in the SEM image, non-close packed hexagonal arrays of silica particles were formed on the outer surface of the micropillars (Figure 2 c). This is because silica colloids surface is negatively charged, the long-range repulsion between silica particles together with capillary force facilitated by ethanol,[11] drove the self-assembly of silica colloidal particles preferentially on the PDMS channel surface. Similar assemblies have been observed for microbullet particles we prepared earlier.[12] Detailed studies of the silica particle assemblies in confined channels and the effect of surface charges will be reported elsewhere. Interestingly, the iron oxide nanoparticles were found mainly trapped in the interstice between silica particles (Figure 2 d). This turned out to be critical to the magnetic responsiveness of the microparticles and will be discussed below. The alignment of magnetic moment of the nanoparticles was induced within the interstice while applying magnetic fields to whole system.

To generate magneto-responsive microparticles, the micropillars were released from the substrate by scrapping and dispersed in water containing 1 wt % Pluronic F108, a polymeric surfactant, PEO-*b*-PPO-*b*-PEO triblock copolymer (PEO = poly(ethylene oxide), PPO = poly(propylene oxide)) that is commonly used in an aqueous solution to stabilize the colloids.[13] In water containing Pluronic F108, the PEO block adsorbs on the hydrophilic silica surfaces, leaving the relatively hydrophobic block, PPO, covering the outside of the microparticles. Therefore, Pluronic F108 offers steric stabilization of magnetic microparticles in an aqueous solution. Without the Pluronic F108 surfactant, the magnetic microparticles were found to be highly aggregated to each other because of the magnetic attractive force (Figure S1a in the Supporting Information). As seen from optical microscopy (OM) and SEM images, the microparticles have uniform size (Figure 2 e and Figure S1b). In

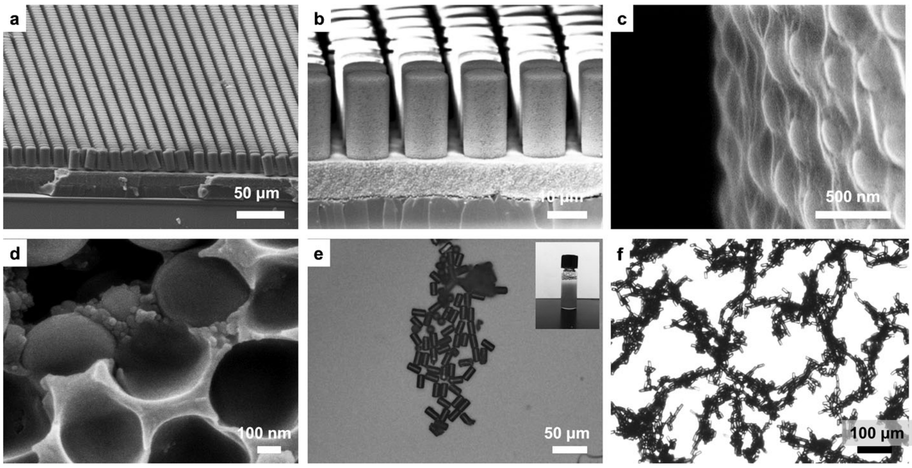

Figure 2. a,b) SEM images of micropillar arrays (10 µm diameter, 20 µm depth, and 15 µm pitch) composed of silica colloidal particles (5 wt%) and iron oxide nanoparticles (0.2 wt%) cured with epoxy resin. c) SEM image of the pillar surface, showing silica particles non-close packed at the outer surface of the pillar. d) Cross-sectional SEM image of magnetic microparticle, showing iron oxide nanoparticles assembled in the interstices of silica colloidal particles. e) Optical microscopy image of the collected microparticles with a narrow size distribution. Inset: aqueous dispersion of the magnetic microparticles in a glass vial. f) Optical microscopy image of the highly aggregated smooth magnetic particles without using silica colloids. The iron oxide nanoparticle concentration was 0.2 wt%.

our strategy, the production rate is approximately 10^6 particles/cm^2 in a single batch fabrication. The number of particles can be further increased using a larger PDMS mold.

Particles decorated with silica particles offer many advantages since silica surfaces can be easily functionalized to introduce various functionalities through silane chemistry. Previously, we functionalized the silica surface of microbullet-shaped particles with the desired anchoring chemistry and showed the reversible assembly of the particles between 1D chains and 2D hexagonal arrays in a nematic liquid-crystal liquid under an electrical field.[12] In the current case, we believe that silica particles play an important role to minimize the magnetic-moment cancellation caused by the sequestering of iron oxide nanoparticles into interstitial spaces of the close-packed silica colloids assembly. To test this hypothesis, we prepared magnetic microparticles using the same method except with no silica colloids added to the system, we refer the silica-free particles to the "smooth magnetic microparticles". As shown in Figure 2 f, the smooth magnetic particles were highly aggregated in water, even though they were treated with Pluronic F108 under the same conditions as the hybrid microparticles; they moved rather slowly under the magnetic field.

Since the hybrid microparticles were well-dispersed in water, we studied their magnetic responses under an external magnetic field. When the magnetic field (1 kG) was applied parallel to the substrate, all the particles oriented instantly in the direction of the magnetic field and formed 1D chain structures over several hundreds of micrometers in length within 5 s (see Figure 3 a). When the external magnetic field was applied perpendicular to the substrate, the magnetic particles stood up and became normal to the substrate (Figure 3 b). The homogeneous magnetic moment in each particle and the coating of Pluronic surfactants on the microparticle surface prevented the microparticles from aggregating together. We note that the amounts of silica particles and iron oxide nanoparticles were initially controlled at 5 wt % and 0.2 wt %, respectively, such that the repulsive force between surfactant molecules coated on a single magnetic particle prevailed over the magnetic attraction force. When increasing the concentration of iron oxide nanoparticles to 0.5 wt % while keep silica nanoparticle concentration unchanged, we found that the microparticles were still able to form chains under the magnetic field parallel to the substrate (Figure S2a), similar to the observation shown in Figure 3 a. However, when the external magnetic field was applied perpendicular to the substrate, some of the microparticles remained chained although at much shorter length (see Figure S2b), suggesting that magnetic attraction force began to prevail over the repulsive force between the magnetic particles.

By rotating the magnetic field (1 kG), a series of rotational and flip motions of a single microparticle were recorded at an equal angle interval of 45° (Figure 3 c,d). When the axis of magnet rotation was perpendicular to the substrate, the microparticle rotated around the same vertical axis without translation motion (see Movie S1). On the other hand, when the axis of rotation of the magnet was parallel to the substrate, the rotating magnetic field caused the microparticles to flip on the substrate (see Figure 3 d and Movie S2). Clearly, the microparticles flipped in the direction directed by the field.

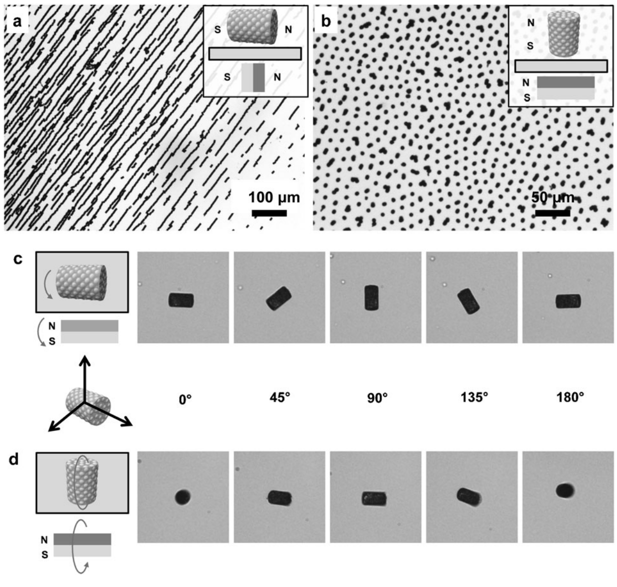

Figure 3. Optical microscopy images of magnetic microparticles dispersed in water on a planar substrate and subjected to a magnetic field a) parallel and b) perpendicular to the substrate. c,d) Schematic illustration and optical microscopy images showing c) rotational motion of the magnetic particles under an external magnetic field induced by a rotating magnet with a vertical axis and d) flip motion of the particles by a rotating magnet with a parallel axis.

The flexibility of our fabrication method offers an opportunity to tailor the size and shape of magneto-responsive microparticles simply using a PDMS mold of a variety of sizes and shapes. As seen in Figure S3, we fabricated magneto-responsive microparticles with square cross-section (10 μm in side, 10 μm in height), triangular cross-section (10 μm in side, 10 μm in height), and circular cross-section but smaller size (2 μm in diameter, 8 μm in height).

The magnetic microparticles could be separated and encapsulated in a PDMS matrix, and their motion could be exquisitely controlled in a confined geometry. To date, there have been increasing interests in magneto-rheological elastomers (MREs) or magneto-active elastomers (MAEs) as tunable stiffness elements for potential applications, including actuators and magneto-mechanical transducers.[3c,14] However, most magnetic particles embedded in an elastomer matrix are spherical or aggregates. Therefore, the force and torque generated by the magnetic field could be weak. The magnetic field could increases the effective shear modulus of the MRE composite when magnetic particles are aligned in chain structures.[14f,15] Nevertheless, most studies of the isolated inclusion of magnetic particles in elastomers have been limited to theoretical modeling.

We confined an aqueous dispersion of magnetic rod particles in PDMS microwells with well-defined hole size and spacing prepared by replica molding, followed by oxygen plasma treatment to make the surface hydrophilic. As seen in Figure 4 a, when the magnetic field was perpendicularly

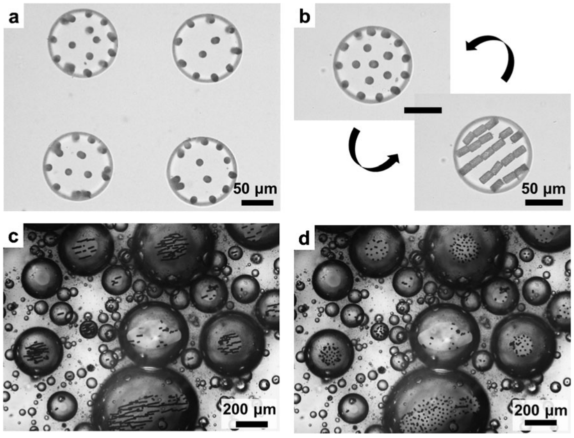

Figure 4. a,b) Optical microscopy image of the isolated magnetic microparticles within the PDMS microwell array. a) Microparticles under an external magnetic field perpendicular to the substrate. b) Reversible flip motion of the microparticles within individual microwell under a rotating magnetic field. c,d) Optical microscopy images of an aqueous suspension containing the magnetic microparticles in an elastomeric matrix when the external magnetic field was applied parallel (c) and perpendicular (d) to the substrate.

applied to the substrate, isolated magnetic microparticles were obtained within the microwells. Occasionally, a few particles stuck together at the edge of the wells due to the edge pinning effect of the water meniscus. Consistent with previous observations of microparticles dispersed in an aqueous solution without confinement (Figure 3), these particles could reversibly rotate and flip freely between the 2D hexagonal array and 1D chain structures without much resistance within individual microwells under a rotating magnetic field (Figure 4b).

In the second approach, we created a randomly distributed, isolated inclusion of magnetic particles in a PDMS matrix by using oil–water emulsion droplets. An aqueous suspension containing the magnetic microparticles was emulsified in a PDMS precursor/hexane solution by shaking the water/hexane mixture. The encapsulated droplets can be fixed by curing the PDMS surrounding the droplets. As shown in Figure 4c and d, the magnetic microparticles inside the emulsion droplets embedded in PDMS matrix responded to the external magnetic field and exhibited magneto-responsive motion under a rotating magnetic field. As this experiment was only a proof-of-concept, we did not optimize the emulsion droplets size and size distribution. Submicron to micron-sized emulsions with uniform size, however, can be prepared in microfluidic devices, such as in tip-streaming mode.[16]

In conclusion, we prepared anisotropic, magneto-responsive microparticles in which silica colloids and iron oxide nanoparticles are encapsulated in a cross-linked polymer matrix. The use of silica colloidal particles was critical to create a stable magnetic particle dispersion in an aqueous solution, thus, enabling the free motion of the particles under an applied magnetic field. Our high-throughput fabrication strategy allowed unprecedented control over particle shape and size as well as aspect ratio. When an external magnetic field was applied to these particles, the magnetic microparticles showed rotational and flip motions without translation motion with a response time of less than 0.1 s. Furthermore, we highlighted two examples where the microparticles can be isolated and encapsulated randomly or in an ordered fashion in an elastomeric matrix. Within isolated inclusions (aqueous dispersion embedded in a porous membrane or oil–water emulsion droplets), the magnetic particles could rotate, flip, or be aligned into a chain structure. The highly responsive magnetic and anisotropic microparticles could enhance existing technologies, including biological sensors, actuators, field-responsive display devices (see Figure S4), and microfluidic pumps and mixers. The ability to create isolated and well-oriented magnetic inclusions in an elastomeric matrix will offer new opportunities to experimentally realize and validate the MRE theories on stress–strain response under a magnetic field, and provide new insights to design MREs with large and controlled mechanical deformation.

Experimental Section

Fabrication of magneto-responsive microparticles. 5 wt% silica particles (500 nm in diameter, Alfa Aesar) and 0.2 wt% iron oxide (α-Fe_2O_3) nanoparticles (smaller than 50 nm, Aldrich) were dispersed in ethanol. An ethanol suspension containing silica and iron oxide nanoparticles was dropped onto a PDMS mold with cylindrical holes (10 µm diameter, 20 µm depth, and 15 µm pitch) and the ethanol allowed to evaporate in a convection oven at 65 °C for 5 min. Then, the PDMS mold was placed on diglycidyl ether of bisphenol A-based epoxy resin (DER 354, Dow Chemical) containing 3 wt% photoinitiator (Cycracure UVI 6976, Dow Chemical)-coated glass substrate to infiltrate the resin into the cavities of mold by capillary force. To induce the alignment of the magnetic moment of the iron oxide nanoparticles within the cylindrical cavity, the magnetic field using two disc-type magnets was applied to whole systems for 30 min. Then, the whole system was immediately exposed to UV light to cure the epoxy resin at 365 nm at a dosage of 17 $J\,cm^{-2}$. After releasing the PDMS mold from the substrate, an epoxy micropillar array consisting of silica and iron oxide nanoparticles was obtained. Finally, the magnetic microparticles were released from the glass substrate by scraping the micropillar array with a razor blade.[12] To achieve well-dispersed microparticles in water, 1 wt% Pluronic F108 (ethylene oxide-propylene oxide-ethylene oxide triblock copolymer surfactant, BASF) was used to coat the microparticles.

Remote control of magnetic microparticles within microwell arrays and emulsion droplets. A PDMS microwell array was fabricated by replica molding from a SU-8 master, consisting of a micropost array (100 µm in diameter and 50 µm in height, 200 µm in pitch). To fill the microparticles dispersed in water into the microwells, PDMS was treated with oxygen plasma for 20 min (Harrick Expanded Plasma Cleaner & PlasmaFlo), thereby making its surface hydrophilic. Then, the magnetic microparticles dispersed in water were dropped onto the PDMS film. By gravity, the microparticles fell into the microwells. The excess particles outside of the wells were scraped off. The movement of microparticles was precisely controlled by rotating a small magnet of 1 kG at a distance of approximately 5 cm from the magnetic microparticles. For the generation of water-in-oil emulsion droplets, 30 µL aqueous magnetic microparticle suspension was added to the mixture of PDMS precursor and hexane (2:1). Then, the aqueous magnetic microparticles suspension was emulsified in hexane by shaking the water/hexane mixture for 20 s.

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