Three-dimensional magnetic microstructures fabricated by microstereolithography

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Our group has developed a magnetically modified photocurable polymer for use in microstereolithography to fabricate magnetic microstructures and microactuators having three-dimensionally complex structures. This polymer is prepared by mixing a photocurable polymer with magnetic particles together with a viscosity-increasing agent for preserving the dispersion of the particles. In this study, we conducted experiments to evaluate the curing and magnetic characteristics of this magnetically modified photocurable polymer. We then rapidly fabricated truly three-dimensional magnetic microstructures by microstereolithography using this polymer. We expect that this achievement will lead to the development of magnetic microactuators. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2954011]

Magnetic microactuators can be driven by energy sources without the need for physical contact with components such as tethers. Because of this, they can be remotely controlled in closed spaces and in liquids. This remote controllability can be effectively exploited in microactuators for microelectromechanical systems and microfluidic devices and micromachines for minimally invasive surgery in the human body. Various microactuators and micromachines have already been developed.[1–6]

Magnetic materials can be fabricated into microstructures using techniques such as electroplating, micromolding, and screen printing,[1–4] but the magnetic microstructures fabricated by these techniques are generally only two dimensional. There have been cases, however, of the assembly of three-dimensional (3D) magnetic microstructures from simply structured microparts such as plates and cylinders.[5,6] Microassembly techniques, however, still lack the precision required for dexterous handling and bonding of the microparts of miniaturized and complex-structured micromachines.

Microstereolithography, a technique based on rapid prototyping, is capable of fabricating truly 3D microstructures within short process periods.[7] Yet as a process that can only be performed with photocurable polymers, microstereolithography has the drawback of poor material selectivity. Several groups have recently tried to solve this problem by developing materials with certain functions for microstereolithography.[8,9] None of the materials developed, however, have magnetic properties. To overcome the structural limitations that currently prevent the microfabrication of magnetic microstructures and microactuators, we developed a magnetically modified photocurable (MPC) polymer for microstereolithography and used it to fabricate 3D magnetic microstructures arbitrarily, without using microassembly.

Photocurable polymers have no ferromagnetic properties because their primary components are organic. A material having both ferromagnetic and photocurable properties can be produced by mixing magnetic particles into a photocurable polymer. Other groups have prepared and used a ferromagnetic photoresist composed of SU-8 and magnetic particles.[10,11] Their photoresist cannot be used for microstereolithography, however, as SU-8 contains a solvent and requires a prebake before exposure to ultraviolet (UV) light. Our group prepared a MPC polymer by mixing magnetic particles into a photocurable polymer without using any solvents or prebake processes.

As it turned out, we were unable to obtain a MPC polymer with well-dispersed magnetic particles by merely mixing the particles into the photocurable polymer. Figure 1 shows the dispersion of ferrite particles FA-700 (Toda Kogyo Corp., mean particle size: 1.3 μm) of 10 wt % added to a liquid photocurable polymer SCR770 (D-MEC Ltd.). After mixing a batch of the polymer with a mixer for 10 min, we dropped a portion onto a glass slide and observed it under an optical microscope. As seen in Fig. 1, the magnetic particles gradually started to aggregate after mixing, and after 1 h had thoroughly aggregated into a networklike structure. This was presumably caused by the magnetic attraction intrinsic to the individual particles. Aggregation such as this degrades the fabrication accuracy and reproducibility, while imparting a nonuniform magnetism to the structure. While the use of a surfactant has proved to be effective for dispersing ceramic and metal particles,[8,9] the magnetic force of the particles used in our experiment countered the dispersive effect of the surfactant.

To prevent the magnetic particles from aggregating, we tried adding an agent to increase the viscosity of the liquid photocurable polymer. Figure 2 shows the dispersion of

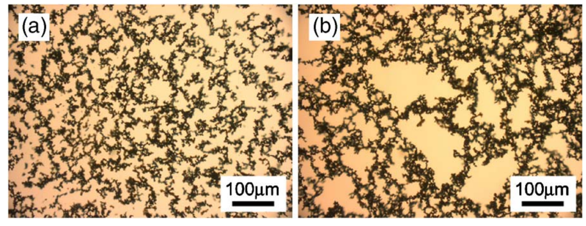

FIG. 1. (Color online) Dispersion of the magnetic particles in liquid photocurable polymer matrix without additives (a) immediately after mixing and (b) 1 h later.

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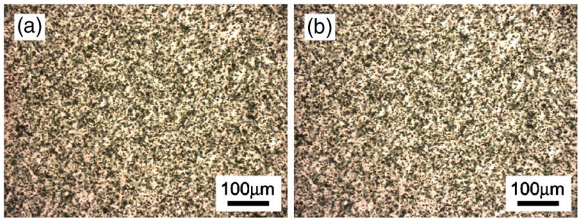

FIG. 2. (Color online) Dispersion of the magnetic particles in a liquid photocurable polymer matrix with the viscosity-increasing agent (a) immediately after mixing and (b) 1 h later.

FA-700 (10 wt %) in SCR770 with the viscosity-increasing agent (5 wt %) (identical to the mixed polymer shown in Fig. 1, but with the viscosity-increasing agent added). As shown in Fig. 2, the magnetic particles were uniformly dispersed after mixing and this dispersion was maintained for over 1 h. When a viscosity-increasing agent is added to a liquid polymer matrix, a highly viscous drag inhibits the aggregation of the magnetic particles caused by the magnetic attraction. Moreover, the plastic fluidity of the polymer matrix with the viscosity-increasing agent ensures that the good dispersion of the magnetic particles can be maintained for a long period. In our experiments, the dispersion of the magnetic particles was preserved for more than 10 days.

The photocurable polymer has two curing characteristics in microstereolithography: curing width, an index of the horizontal resolution, and curing depth, an index of the vertical resolution. We experimentally evaluated the curing width and depth of the MPC polymer.

The following procedure was used to fabricate each of a series samples for measuring the curing widths and depths of MPC polymers containing different concentrations of magnetic particles. First, the MPC polymer, SCR770 prepared with a viscosity-increasing agent (5 wt %) and FA-700 particles (0–50 wt %), was applied at a thickness of several hundreds of micrometers to the bottom surface of a glass substrate. Next, a UV laser beam (wavelength: 325 nm, power: 0.6 mW) was focused through a lens (focal length: 100 mm) and a glass substrate onto the MPC polymer and scanned in a grid pattern by galvano scanners (scan speed: 50 mm/s) [Fig. 3(a)]. Once the MPC polymer solidified, the substrate was immersed in an ultrasonic bath with ethanol to flush away the unsolidified polymer. When the sample was sufficiently dry, the curing width and depth were measured using an optical microscope and a confocal laser scanning microscope, respectively.

Figure 3(b) shows the measurement results for the curing width and depth of the MPC polymer for each concentration of magnetic particles. The curing width of the MPC polymer increased slightly when the concentration of magnetic particles was increased. When the MPC polymer was solidified in a linelike configuration, the moiety of the magnetic particles protruded from the polymer matrix line, roughening the line and increasing the curing width.

In contrast, the curing depth of the MPC polymer decreased drastically when the concentration of the magnetic particles increased. The curing depth of the MPC polymer with a 50 wt % concentration of magnetic particles was one-fifth less than that of the photocurable polymer without magnetic particles. This was due to the shallow penetration of the laser beam into the MPC polymer caused by the opaqueness of the magnetic particles. Consequently, the curing depth in

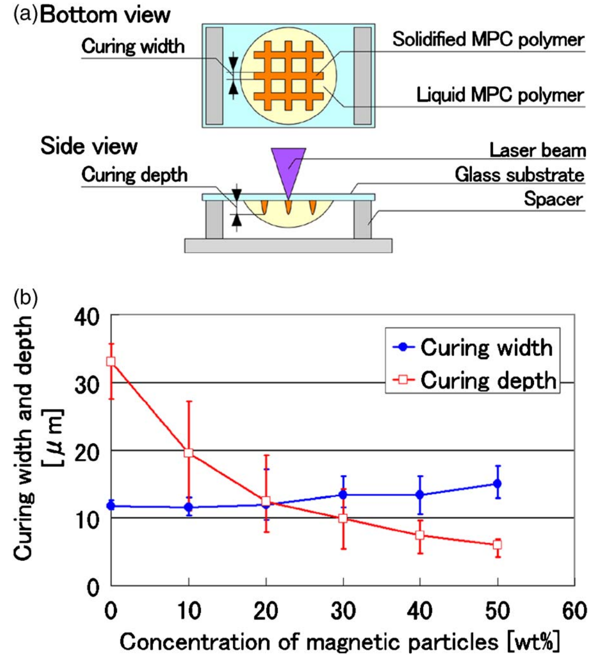

FIG. 3. (Color online) Curing characteristics of MPC polymers. (a) Schematic of sample fabrication. (b) Curing widths and depths of MPC polymers with different magnetic particle concentrations.

the photocurable polymer with the particles is shallower than that of the polymer without the particles. As the concentration of the magnetic particles is increased, the laser beam propagation is obstructed more, leading to a much shallower curing depth and a much higher vertical resolution.

It is easily conceivable that the curing width and depth could be affected by the size of magnetic particles added to the photocurable polymer. If smaller particles such as nanoparticles[12] were used, curing width would become narrower because the roughness attributed to the protrusion of the particles from the polymer matrix would be reduced. In addition, the curing depth would become shallower because smaller particles reduce the probability of the laser beam penetrating deeply into polymer matrix.

In another set of experiments, we measured the magnetic characteristics of the MPC polymers. Cube-shaped samples of 1 mm^3 were fabricated by microstereolithography using a MPC polymer, SCR770 with viscosity-increasing agent (5 wt %) and FA-700 (10–50 wt %). The magnetic characteristics of each sample were measured using a vibrating sample magnetometer.

Figure 4 shows hysteresis curves of the MPC polymers with different magnetic particle concentrations. As the figure clearly shows, the MPC polymer was ferromagnetic and the remanent magnetization increased as the magnetic particle concentration increased. On this basis, we expect to fabricate magnetic actuators with good magnetic properties by using a MPC polymer with a high magnetic particle concentration. To do so, however, we must consider the influence of the particle concentration on the curing characteristics of the MPC polymer. The magnetic particle concentration must be appropriate for both the required structure and the desired magnetic characteristics.

In the final part of our study, we fabricated many kinds of 3D magnetic microstructures using MPC polymers and microstereolithography. Figure 5 shows a microscrew [Fig. 5(a)], a microfan [Fig. 5(b)], a microsirocco fan [Fig. 5(c)],

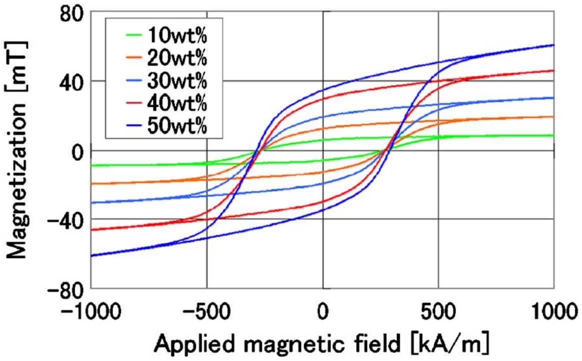

FIG. 4. (Color online) Magnetic characteristics of MPC polymers with different magnetic particle concentrations.

and a microsculpture of a beetle [Fig. 5(d)]. A MPC polymer with 50 wt % magnetic particles was used to fabricate the microstructures in Figs. 5(a) and 5(c), and the MPC polymer with 30 wt % magnetic particles was used for the microstructures in Figs. 5(b) and 5(d). The laser power, scan speed, and lamination pitch were 0.6 mW, 50 mm/s, and 7 μm in Figs. 5(a) and 5(c); 0.3 mW, 20 mm/s, and 10 μm in Fig. 5(b); and 0.6 mW, 20 mm/s, and 10 μm in Fig. 5(d), respectively. All of the microstructures were fabricated within 30 min. Figure 5 confirms that complex microstructures having high aspect ratios, overhangs, 3D curved surfaces, and ceilings can be easily fabricated using microstereolithography without using microassembly. Structures like these cannot be fabricated by pattern transfer using electroplating, screen printing, or molding.

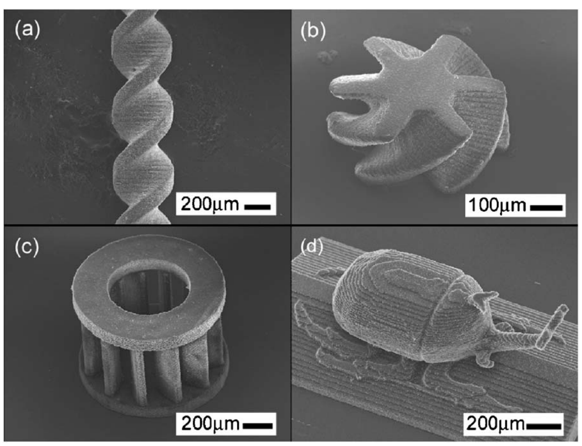

FIG. 5. 3D magnetic microstructures fabricated by microstereolithography: (a) microscrew with a diameter of 500 μm, height of 2 mm, and spiral pitch of 1 mm; (b) microfan with a diameter of 500 μm and height of 250 μm; (c) microsirocco fan with a diameter of 1 mm and height of 700 μm; (d) microsculpture (beetle) with a length of 2 mm, width of 1 mm, and height of 660 μm.

The microstructures can be magnetized in any direction and used as hard magnetic actuators. For instance, the screw actuator shown in Fig. 5(a) is magnetized in the radial direction. Subsequently, this actuator is immersed in liquid and an external rotational magnetic field is applied. Its spiral structure converts rotational motion into a thrust force, and it can thus be used as an actuator to propel itself.

In conclusion, we developed a MPC polymer that can be used for microstereolithography. We then conducted tests to evaluate the curing and magnetic characteristics of this polymer. In the current experiments, we used ferrite particles in an epoxy polymer. For MPC polymers, it will also be possible to use rare-earth magnetic particles, soft magnetic particles, and other types of photocurable polymers. Thus, we will be able to produce material properties closely suited to the desired actuators. In the final step of our study, we used microstereolithography to rapidly fabricate our MPC polymer into complex 3D magnetic microstructures of types that cannot be feasibly fabricated using conventional techniques. This achievement will allow us to manufacture a variety of magnetic microactuators.

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