3D MAGNETIC MICROACTUATOR MADE OF NEWLY DEVELOPED MAGNETICALLY MODIFIED PHOTOCURABLE POLYMER AND APPLICATION TO SWIMMING MICROMACHINE AND MICROSCREWPUMP

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ABSTRACT

This paper describes a newly developed photocurable polymer with ferromagnetic property for microstereolithography to fabricate magnetic microactuators with three dimensional (3D) structures and its application to a wirelessly controllable swimming micromachine and microscrewpump. This polymer was prepared by mixing a photocurable polymer with magnetic particles, together a viscosity-increasing agent to maintain the particle dispersion. It was demonstrated that this polymer were rapidly fabricated into various complicated 3D magnetic microstructures using microstereolithography. Finally, a swimming micromachine and microscrewpump driven by magnetic force wirelessly were developed using screw-type microactuators made of the polymer with a diameter of submillimeter order.

INTRODUCTION

Magnetic microactuators can generate large force and large displacement compared with electrostatic and piezoelectric ones. In addition, it can be driven by energy supplies without physical contact with components such as tethers. Because of this, they can be remotely controlled in closed spaces and in liquid. These advantages can be put to effective use in microactuators and micromachines for microelectromechanical systems (MEMS), microfluidic devices and minimally invasive surgery in the human body. Various microactuators and micromachines have already been developed [1]-[3].

Structure is a very important factor for machines because it decides functions and performance of them. For example, a fan has blades with 3D structure, and they convert rotational motion into force to pump fluid. Moreover, its pumping efficiency is dependant on the blade's structure. In microscale, the importance of structure is also same, and therefore appearance of microactuators and micromachines with arbitrary 3D structures is desired.

In the previous researches, the magnetic materials can be fabricated into microstructures using techniques such as electroplating, micromolding, and screen printing, but the magnetic microstructures fabricated by these techniques are generally only two dimensional [1],[2]. It is needed to assemble 3D magnetic microstructures from simply structured microparts such as a wire and cylinder [3]. Microassembly techniques, however, still lack the precision required for the dexterous handling and bonding of the microparts of miniaturized and complexly structured micromachines.

Microstereolithography, a technique based on rapid prototyping, can fabricate complex 3D microstructures within short process periods [4]-[6]. 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 new materials with specific functions [7],[8]. None of the materials developed, however, have had magnetic properties.

To overcome the structural limitation of magnetic microactuators and micromachines, we developed a magnetically modified photocurable (MPC) polymer for microstereolithography, and demonstrated the feasibility of 3D magnetic microstructures arbitrarily using this polymer [9]. For its application, we developed a wirelessly controllable swimming micromachine and microscrewpump using screw-type microactuators made of the MPC polymer.

DEVELOPMENT OF MPC POLYMER

Photocurable polymer has no ferromagnetic property, because its primary components are organic. A material with both ferromagnetic and photocurable properties can be produced by mixing magnetic particles into photocurable polymer.

As it turned out, we were unable to obtain an MPC polymer with good dispersion of the magnetic particles merely by mixing the particles into the photocurable polymer. Figure 1 shows the dispersion of ferrite particles (mean particle size: 1.3 µm) of 10 wt% added into liquid photocurable polymer. 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.

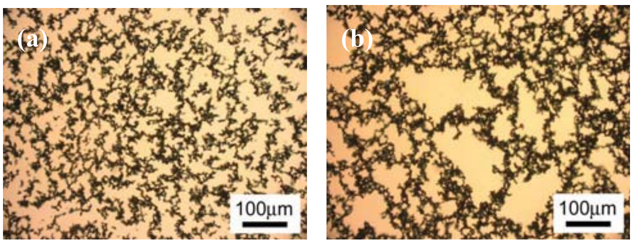

Figure 1: Aggregation of the magnetic particles in the liquid photocurable polymer matrix without additives (a) immediately after mixing and (b) 1 h later.

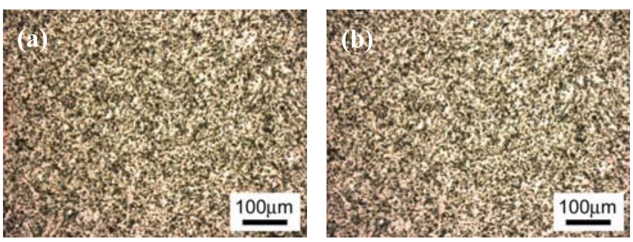

Figure 2: Dispersion of the magnetic particles in the liquid photocurable polymer matrix with the viscosity-increasing agent (a) immediately after mixing and (b) 1 h later.

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As shown in Fig. 1, the magnetic particles gradually started to aggregate just after the mixing, and by 1 hour had thoroughly aggregated into a network-like structure. This was presumably caused by the magnetic attraction intrinsic to the individual particles. Aggregation such as this degrades the fabrication accuracy, while imparting an uneven magnetism in a structure. While a surfactant has proved to be effective for dispersing ceramic and metal particles [7],[8], the magnetic force of the particles used in our experiment countered the dispersive effect of the surfactant.

To stop 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 the ferrite particles of 10 wt% in the liquid photocurable polymer with the viscosity-increasing agent of 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 dispersed uniformly after the mixing, and the dispersion was maintained for more than 1 hour. 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 fluid property of the polymer matrix with the viscosity-increasing agent ensures that the good dispersion of the magnetic particles can be sustained for a long period. According to our experiments, the dispersion of the magnetic particles was sustained for more than 10 days.

3D MAGNETIC MICROSTRUCTURE

For the demonstration of 3D magnetic micro-structures, we fabricated many kinds of magnetic microstructures using MPC polymers and microstereo-lithography. Figure 3 shows microscrews with different diameters of 0.5 mm and 0.1 mm, and Fig. 4 shows a micro sirocco fan and a microsculpture of a beetle. The MPC polymer with 50 wt% magnetic particles was used to fabricate the microstructures in Figs. 3 and 4(a), and the MPC polymer with 30wt% magnetic particles was used for the microstructure in Fig. 4(b).

All of these microstructures were fabricated within 30 min. Figures 3 and 4 confirm that complex microstructures having high aspect ratios, overhangs, 3D curved surfaces, and ceilings can be easily fabricated using microstereo-lithography. Structures like these cannot be fabricated by conventional microfabrication techniques such as electroplating or micromolding.

SWIMMING MICROMACHINE

For an application of the magnetic microactuator fabricated by microstereolithography, we developed a wirelessly controllable swimming micromachine with the same size as a human hair.

Figure 5 shows the schematic diagram of the wirelessly controllable swimming micromachine. This micromachine consists of a magnetically driven screw-type microactuator as a locomotive part and two orthogonal Helmholtz coils to control the microactuator.

Driving mechanism of the screw-type microactuator as a swimming micromachine is as follows. The microactuator is magnetized in the radial direction, and then inserted into a capillary filled with water. The capillary is located at the center of orthogonal Helmholtz coils which generate rotational magnetic field around the longitudinal axis of it. The microactuator is rotated by the rotainal magnetic field wirelessly, and its screw structure converts the rotational motion into the force to propel itself. Hence, the microactuator can swim in the capillary.

In our experiment, the screw-type microactuator made of the MPC polymer with a diameter of 0.1 mm shown in Fig. 3(b) was used as the locomotive part of the swimming micromachine, and glass tube with an inner diameter of 0.2 mm was used as the capillary. The rotational magnetic field of 1mT induced by the orthogonal Helmholtz coils was applied to the microactuator, and the relationship between the swimming velocity and the rotational frequency of magnetic field was measured.

Figure 6 shows time-series photographs where the screw-type microactuator was driven at a rotational frequency of 500 Hz. From these photographs, it was verified that the screw-type microactuator made of the MPC polymer can be wirelessly controlled by applying the external magnetic field to it and swim along the capillary. If the rotational direction of the magnetic field is reversed, the microactuator can swim in the opposite direction.

Figure 7 shows the relationship between the rotational frequency of the magnetic field and the swimming velocity of the screw-type microactuator. It was confirmed that the swimming velocity is linearly proportional to the rotational frequency.

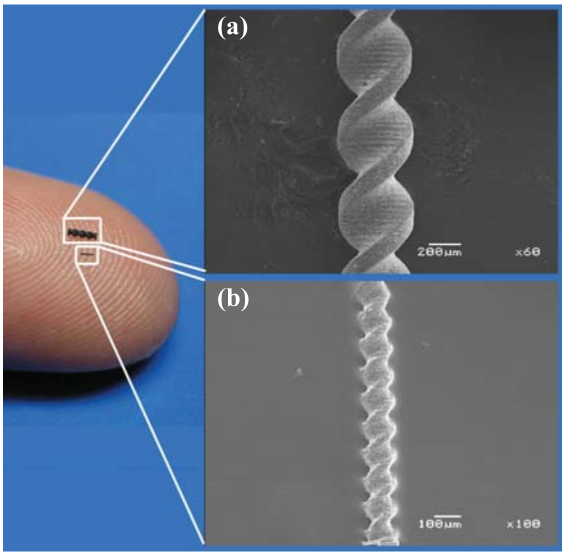

Figure 3: Magnetic microscrews fabricated by micro-stereolithography: (a) with a diameter of 0.5 mm, length of 2 mm, and spiral pitch of 1 mm and (b) with a diameter of 0.1 mm, length of 1 mm, and spiral pitch of 0.2 mm

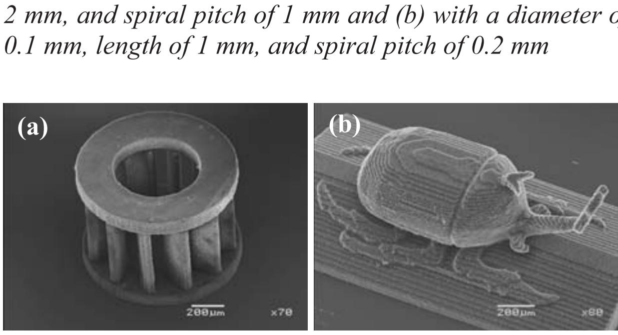

Figure 4: 3D magnetic microstructures fabricated by microstereolithography: (a) micro sirocco fan with a diameter of 1 mm and height of 0.7 mm; (b) beetle with a length of 2 mm, width of 1 mm, and height of 0.66 mm.

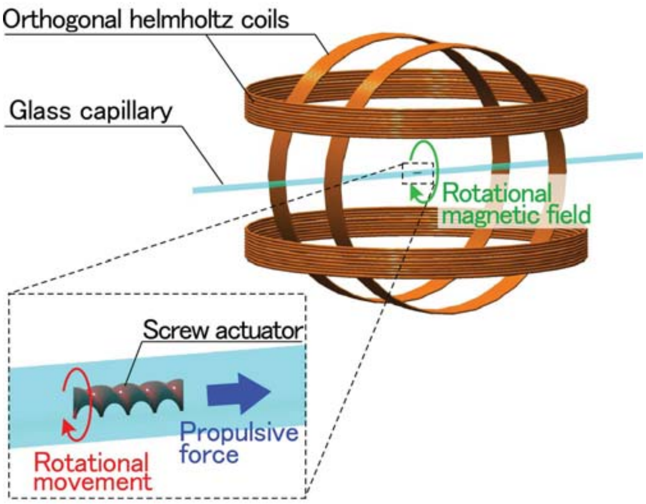

Figure 5: Schematic diagram of the wirelessly controllable swimming micromachine driven by magnetic force

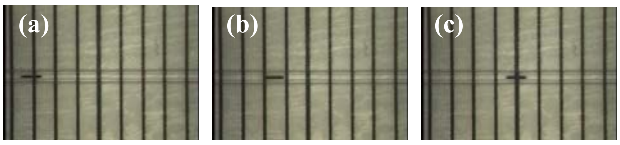

Figure 6: Photographs of the screw-type microactuator with a diameter of 0.1 mm swimming in the capillary with an inner diameter of 0.2 mm filled with water at a rotational frequency of 500Hz: (a) 0s, (b) 0.5 s and (C) 1 s later

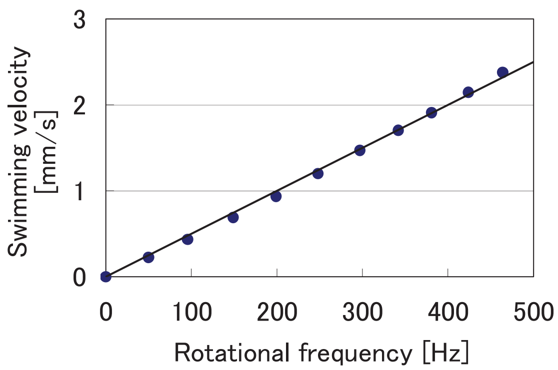

Figure 7: Relationship between the rotational frequency of the magnetic field and the swimming velocity of the screw-type microactuator with a diameter of 0.1 mm

MICROSCREWPUMP

As mentioned above, the screw structure of the microactuator converts the rotational motion into the force to thrust fluid backward, and thereby the microactuator can swim forward. On the other hand, if the microactuator are prevented from swimming and only rotated at certain place in the capillary, it serves as a microscrewpump.

Magnetic trap was employed to prevent the screw-type microactuator from swimming away. In the magnetic trap, the gradient of magnetic field in the longitudinal direction of the capillary is generated by electromagnetic coils located around it, and magnetic attraction toward the electromagnetic coils is exerted on the microactuator. The attraction counters the propulsive force of the microactuator, and prevents it from swimming away from the electromagnetic coils. When the rotational magnetic field is simultaneously generated by the electromagnetic coils, the microactuator is rotated near them, and consequently it can pump fluid (Fig. 8).

In our experiments, the screw-type mictoactuator with a diameter of 0.5 mm shown in Fig. 3(a) was magnetized in the radial direction and inserted into the capillary with an inner diameter of 0.53 mm. Silicon oils with different kinetic viscosities, 1 cSt, 10 cSt and 100 cSt, were filled in the capillary, respectively. The capillary is put horizontally and two pairs of electromagnetic coils were orthogonally located around it. These electromagnetic coils generated the gradient of the magnetic field in the longitudinal direction of the capillary and the rotational magnetic field around the axis of it. The strength of magnetic field at the center of the electromagnetic coils was 45 mT. The relationship between the flow rate and the rotational frequency was measured.

Figure 9 shows the relationships among the flow rate, the rotational frequency and the kinetic viscosity of fluid. From Fig. 9, it was found that the flow rate of the microscrewpump is linearly proportional to the rotational frequency regardless of the viscosity of fluid.

It was confirmed that the screw-type microactuator was released from the magnetic trap and swam away from the electromagnetic coils when the rotational frequency was higher than certain frequency and thereby it was not able to pump the fluids. The frequencies of swimming away were 240 Hz, 40 Hz and 4 Hz when the kinetic viscosities were 1 cSt, 10 cSt and 100 cSt, respectively.

This is because the propulsive force of the microactuator was higher than the magnetic attraction exerted on it by the electromagnetic coils. The propulsive force of the microactuator increases with increasing the rotational frequency as shown in Fig. 7. When the propulsive force is lower than the magnetic attraction, the microactuator is kept near the electromagnetic coils. On the other hand, when the propulsive force is higher than the magnetic attraction, the microactuator is released from the magnetic trap and hence it swims away from the electromagnetic coils. Moreover, because the propulsive force of the microactuator depends on the viscosity of fluid surrounding it, it swims away at lower rotational frequency when the viscosity is higher.

In microscrewpump, although the frequency of swimming away varies with change in the viscosity of fluid as mentioned above, the relationship between the flow rate and the rotational frequency, i.e. the gradient of the graph shown in Fig. 9, does not vary with change in the viscosity. Micro diaphragm pump which is representative of mechanical micropump, in principle, nonlinearly responses to the frequency, and its flow rate varies with change in the viscosity of fluid. Thus, when a fluid with uncertain viscosity is used in this pump, it is required to measure its viscosity or calibrate the flow rate of the pump in advance. Meanwhile, microscrewpump is more convenient owing to the characteristic that its flow rate is independent of the viscosity of fluid.

Although micro diaphragm pump with check valve or diffuser/nozzle can only pump fluid unidirectionally, the microscrewpump can pump fluid reversely because it does not have structural anisotropy. In addition, compared with

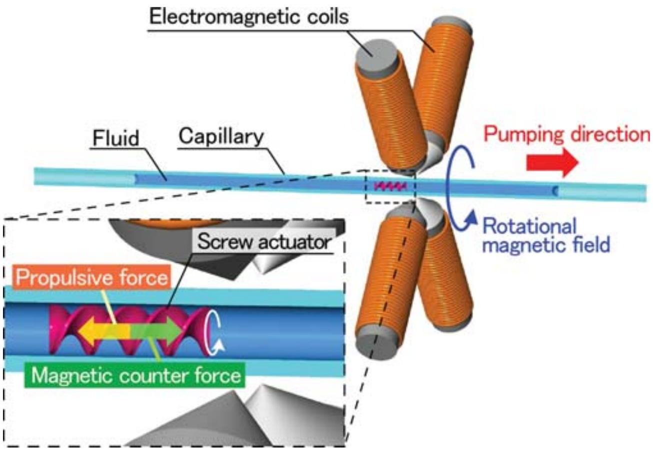

Figure 8: Schematic diagram of miroscrewpump

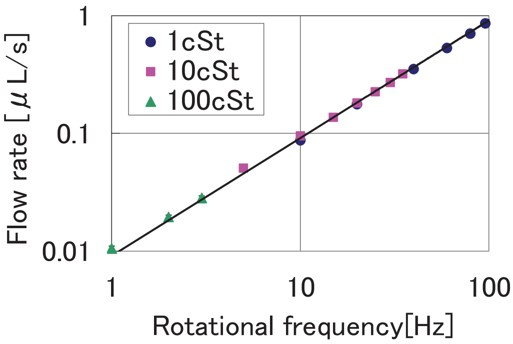

Figure 9: Relationship among the flow rate of microscrewpump, the rotational frequency of magnetic field and the kinetic viscosity of fluid

electroosmotic and electrohydrodynamic pump, many kinds of fluid are used in the microscrewpump because it pumps them mechanically.

It is not necessary for our microscrewpump to fabricate extra structures on a microfluidic chip. We have only to insert a screw-type microactuator into a microchannel on the chip and apply the magnetic field on it by electromagnetic coils located out of the chip. Thus, pump function can be arbitrarily added into microfluidic chips which do not intrinsically have it when used.

CONCLUSION

We developed special MPC polymer with well-dispersed magnetic particles and fabricated 3D magnetic microstructures using microstereolithography. As the result, it was verified that this achievement can realize a variety of 3D magnetic microactuators which are not feasible for conventional microfabrication techniques.

Using screw-type microactuators with a diameter of submillimeter order fabricated by microstereolithography, we developed a micromachine swimming in a capillary and microscrewpump. These micromachines do not need to have batteries in themselves, and external electromagnetic coils can supply energy with them and control them wirelessly. Thus, the swimming micromachine will be applicable to micro surgery microrobot driven in human body remotely.

Microscrewpump can be not only inserted into a capillary but also be implemented in a microfluidic chip. Thus, it will be applicable to implantable drug delivery systems controlled remotely in the future.

Our achievement is not limited to the feasibility of fabricating 3D magnetic microactuators. Because micro-stereolithography is based on computer-aided manufacturing, it easily cooperates with computer-aided analysis. Hence, it facilitates optimization of the design of magnetic microactuators and shortens development periods for them. It is expected that the swimming micromachine and microscrewpump will also be more efficient by optimizing their design for various applications.

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