MAGNETOPHORETIC MANIPULATION IN MICROSYSTEM USING I-PDMS MICROSTRUCTURES

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ABSTRACT
This paper reports the use of a recent composite material, i-PDMS, made of carbonyl iron microparticles mixed in a PolyDiMethylSiloxane (PDMS) matrix, for magnetophoretic functions such as capture and separation. Indeed, we demonstrated that this composite can locally generate high magnetic field gradients when placed between two permanent magnets. We first investigated the molding resolution offered by i-PDMS to obtain microstructures of various sizes and shapes. Then, we implemented 500 m i-PDMS microstructures in a microfluidic channel and studied the influence of flow rate on the trapping and deviation of paramagnetic beads flowing at the neighborhood of the composite material.


INTRODUCTION
The objective of this paper is to evaluate a PolyDiMethylSiloxane composite - i-PDMS - to generate local gradients of magnetic field and then to carry out magnetophoresis based manipulations in a microfluidic format. This material is composed of a PDMS matrix doped with carbonyl iron microparticles that give this composite, ferromagnetic properties as already shown in previous papers [1]. In past studies, authors demonstrated that this material can form magnetically actuated membranes [2] to achieve mixing functions [1]. However, to the best of our knowledge, no study was reported on the use of this material in magnetophoresis based microfluidic functions such as trapping and separation. As previously demonstrated by our group with carbon doped PDMS [3], these composite materials present many advantages over metallic microstructures for the fabrication of active microfluidic devices. Indeed, we showed that this material, combining properties of both compounds, allows the easy and fast integration of metallic microstructures using soft-lithography approach while preserving O2 plasma bonding properties of PDMS substrate and avoiding cumbersome alignment procedure.

THEORY
A magnetic particle exposed to a magnetic field \( \vec{B} \) with a magnetic field gradient \( \vec{\nabla}\vec{B} \), undergoes a magnetic force, \( \vec{F}_{\text{mag}} \) expressed as [4]:

\[
\vec{F}_{\text{mag}} = \frac{\chi_p \chi_m}{\mu_0} \cdot \vec{v} \cdot \vec{B} \cdot \nabla B
\]

where \( \mu_0 \) is the vacuum permeability \( (\mu_0 = 4\pi \times 10^{-7} \text{H/m}) \), \( \chi_p \) and \( \chi_m \) are the magnetic susceptibility of the bead and the surrounding medium respectively and \( \vec{v} \) is the volume of the particle. Hence, in a diamagnetic medium such as water, a paramagnetic particle is attracted towards the higher magnetic field. In a microfluidic flow, this particle also experiences a viscous drag force \( \vec{F}_{\text{drag}} \) which depends on the absolute viscosity of the medium \( \eta \), the radius of the particle \( r \) and its velocity \( \vec{v} \) according to the following relationship [5]:

\[
\vec{F}_{\text{drag}} = 6\pi \eta r \vec{v}
\]

EXPERIMENTAL
i-PDMS composite was prepared by mixing thoroughly in a mortar (for 4 min) carbonyl iron microparticles (7 m diameter, 97% Fe basis) (Sigma-Aldrich) with PDMS (Sylgard from DowCorning) prior to polymer reticulation, at concentration of 83% w/w carbonyl iron. This material was processed using soft-lithography approaches [6] (Figure 1a-c) in order to integrate i-PDMS microstructures along a PDMS microchannel (Figure 1f). In the experimental configuration used, the external magnetic field was generated by two permanent magnets as presented in Figure 1g-i. The relative positions of magnets and microchannel were optimized by numerical simulations. Videomicroscopy techniques allowed us to observe the behavior of para- and diamagnetic beads in the microsystem. Before injecting the magnetic species, the microsystem was passivated with filtered 2% Bovine Serum Albumin (BSA) (Sigma-Aldrich) in Phosphate Buffered Saline (PBS) (Invitrogen) to avoid any non-specific adsorption of the particles onto the microchannel walls. The microsystem was then rinsed with filtered PBS.

Different magnetic species were tested in the microsystem: 12 m paramagnetic and 10 m fluorescent diamagnetic microparticles (respectively purchased from Sigma-Aldrich and Kisker). Particles were suspended in 3.6% w/w dextran \( (M_w = 2.10^6) \) from Sigma-Aldrich in PBS in order to reduce the sedimentation of the microbeads during the time of the experiment.

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RESULTS AND DISCUSSION

Using replication strategy (Figure 1a-e), we obtained i-PDMS microstructures shaped as squares, disks and diamonds with various angles, at the surface of a pure PDMS substrate. We evaluated, by microscopic observations, that at 83% w/w doping concentration, we were able to achieve a resolution down to 50 μm. Indeed, at that characteristic dimension, microstructures still exhibited fine shapes and angle resolutions as illustrated in Figure 2. Microstructures down to 25 μm were also obtained, however their characteristics were not as sharp as for the 50 μm microstructures.

According to numerical simulations performed with Comsol Multiphysics®, diamond-like shape microstructures were more efficient than squares and disks to locally generate high gradients of magnetic field. Therefore, 500 μm i-PDMS diamond-like microstructures were implemented along a PDMS microfluidic channel to achieve magnetophoresis. The experimental configuration presented in Figure 1g-i, i.e. the relative position of the two permanent magnets compared to the microchannel, was also optimized by numerical simulations, leading to the following choices: (i) center the microstructures to the magnets height and (ii) place the magnets 10 mm away from one another. A home-made Plexiglas support was developed in order to secure this optimum configuration of the magnets and the microsystem.

With this device configuration, we first demonstrated the ability of i-PDMS microstructures to locally generate magnetic field gradient as highlighted by the behavior of paramagnetic microbeads flowing at the vicinity of a diamond-like i-PDMS microstructure. Indeed, as presented in Figure 3a representing a z-stack projection of typical videomicroscopic images, we observed both capture of the beads and deviation away from their initial position.

The study of the microbead trajectories at the neighborhood of the composite microstructure versus their initial position regarding the channel width (Figure 3b) allows the discrimination of two different areas: the capture window, where the particles tend to get trapped on the i-PDMS structure, and the influence window including the zone of the channel.
where beads undergo a magnetic force sufficient to even deviate them from their flow line and focus them towards the center of the channel. We then investigated the effect of the flow rate - ranging from 50 to 500 µL/h - on both capture and influence windows. As presented in Figure 3c, both parameters decrease with flow rate as expected according to the balance between magnetic and hydrodynamic forces. However, this trend can be counterbalanced by the addition of successive i-PDMS microstructures along the channel (results not shown here).

Finally, in a preliminary experiment, we demonstrated the potential of this composite material for applications such as the isolation and/or concentration of one magnetic species in a mixture of two populations with different magnetic properties as highlighted in Figure 4. We used here a suspension containing both non-fluorescent paramagnetic and fluorescent diamagnetic particles and Figure 4 represents a z-stack projection of the beads in bright field and fluorescence. In Figure 4a, both bead population trajectories appear. In the contrary, in Figure 4b, only the trajectories of fluorescent diamagnetic particles are present. By comparing both figures, it can clearly be seen that only paramagnetic particles were trapped during the experiment, whereas diamagnetic particles freely flowed past the i-PDMS microstructure.

![Figure 4](image-url)  
**Figure 4**: (a) bright field and (b) fluorescence z-stack projection of videomicroscopic images representing a mixture of paramagnetic and fluorescently labelled diamagnetic particles flowing at 50µL/h in the channel. Only paramagnetic beads are captured, as highlighted by the absence of fluorescent signal on the i-PDMS microstructure.

**CONCLUSION**

In conclusion we report for the first time the implementation of i-PDMS microstructures in a fluidic microsystem to perform magnetophoretic manipulations such as capture and deviation of magnetic species. We demonstrated that these abilities could be exploited in order to sort different magnetic species. Hence, we expect that this material will have broadest interests for Lab-On-a-Chip in biological and medical fields.

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