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Additive manufacturing of superparamagnetic micro-devices for magnetic actuation

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Abstract: 3D microstructures with sub-micron resolution can be manufactured in additive manner applying multi-photon laser structuring technique. This paper is focused on the incorporation of superparamagnetic iron oxide nanoparticles into the photoresist in order to manufacture micrometer-sized devices featuring a magnetic moment. The aim of the project is to achieve untethered actuation of the presented objects through externally applied magnetic fields. Future medical application scenarios such as drug delivery and tissue engineering are targeted by this research.

I. Introduction

The untethered actuation of micrometer-sized objects holds significant potential for future medical applications. A variety of locomotion techniques and manufacturing procedures have been investigated [1]. A promising method involves the steering objects through controlled application of external magnetic fields [2].

I.I. Magnetic actuation of micro-devices

An object carrying a magnetic moment $\vec{m}$ aligns with a magnetic field $\vec{B}$. The object experiences the torque

$$\vec{T} = \vec{m} \times \vec{B}\,. \qquad (1)$$

If the magnetic field vector rotates, the objects' magnetic moment and therefore the object itself could follow the rotation. A forward movement of the object can be achieved by its specific shape, which determines the swimming velocity. Most often helically shaped objects were designed [2], which can be loaded with drugs [3] or cells [4,5]. The magnetic moment can be achieved either through coating of the objects [2-5], or by incorporating superparamagnetic iron oxide nanoparticles into the material [6].

I.II. Additive manufacturing of micro-devices

Several techniques exist for manufacturing of micrometer-sized objects, including multi-photon laser structuring (MPLS) [7].

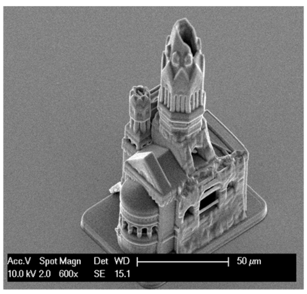

Figure 1: 10 kV SEM micrographs of Kaiser Wilhelm Memorial Church fabricated by multi-photon laser structuring.

This method does not require masks or a layer-by-layer approach: curing of the photoresist occurs only in the voxel where the photon density in the focal spot of the femto-second laser pulses exceed a power of TW/cm^2, i.e. where the photon density is sufficiently high to affect a nonlinear multiphoton absorption process leading to the polymerization of the material. By moving the focal spot, three-dimensional devices with a resolution of about 100 nm can be manufactured. An example is shown in Fig. 1.

II. Material and methods

II.I. The micro-objects

In the previous work a millimeter-sized swimmer in a shape of a Savonius rotor has been investigated (see Fig. 3 left). This swimmer was coated with magnetic nanoparticles and its steering in arbitrary directions by rotating magnetic fields could be shown [8]. The same shape was used for the micrometer-sized MPLS objects. Eleven Objects of 25-125 µm length were manufactured for each photoresist-particle composite (see next section).

II.II. Sample preparation

Superparamagnetic iron oxide nanoparticles were synthesized using the co-precipitation method. They were dried for 24 h at 60 °C. The dried particles were mechanically ground to reduce the agglomeration caused by the drying process. 10 mg of these in-house fabricated particles were mixed with 1 ml of SZ2080 photoresist [9]. The mixture was sonicated for 50 min and then deposited as a droplet onto a glass slide. The sample was baked on a heating plate for 2 hours at 60°C while it had been placed between two NdFeB permanent magnets effecting a field of about 50 mT in the center. The baking procedure increases the viscosity drastically, fixing the particles in place. The magnetic field causes the superparamagnetic particles to chain in a beads-on-a-string structure parallel to the magnetic field, which can be used to generate a magnetic moment perpendicular to the object's long-axis [10]. A second sample was prepared with the same procedure, but with commercially available (II,III) iron

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oxide powder particles (Sigma Aldrich, St. Louis, USA). In Fig. 2 light microscopy images of the polymer with incorporated magnetic nanoparticles are given.

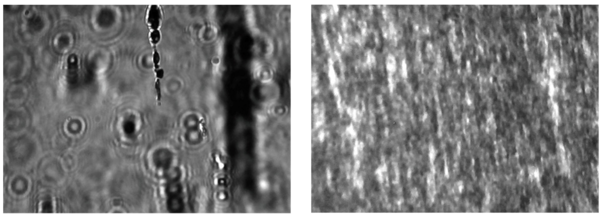

Figure 2: Light microscopy images (x63 magnification) of SZ2080 with incorporated magnetic nanoparticles. The particles show a vertical alignment due to the applied magnetic field during baking. The in-house synthesized particles (left) and (II,III) iron oxide powder particles (right) were incorporated with 1 wt.% into the resin.

II.III. Additive manufacturing

For additive manufacturing, a customized Laser Nanofactory (Femtika, Vilnius, Lithuania) with erbium-doped fiber laser was used, located at BAM. First, speed/laser power patterns were printed to find the correct fabrication window. Then the objects described in II.I. were printed, such that the alignment of the particles is perpendicular to the objects' long axis. The printing procedure took about 20 min for eleven swimmers. Afterwards the objects were developed for 60 min in methyl isobutyl ketone, removing the un-crosslinked photoresist.

II.IV. Analysis of the printed objects

The printed objects were sputtered with gold and visualized with a scanning electron microscope (Zeiss EVO MA10).

III. Results and discussion

The homogeneous mixing of dried magnetic nanoparticles with the photopolymer was feasible, although the dispersion method may require further optimization. The in-house produced particles formed larger clusters as can be seen in Fig. 2. It is expected that objects manufactured with these particles will have varying magnetic moments, due to a varying particle content in the objects and agglomeration of the particles. The opacity of the second sample might lead to a high absorption rate, which may lead to a burning during the printing process, which may be improved by careful parameter optimization. For both samples, particle alignment is induced by the applied magnetic field during the baking step, as previously described by [10]. Printing parameters could be found which allow the printing of the resin with 1 wt.% incorporated magnetic nanoparticles. Differently sized objects were manufactured, as shown in the SEM images of Fig. 4.

IV. Conclusions

It was shown that the photopolymer, which is used for MPLS can be mixed with magnetic nanoparticles. The printing of micrometer sized objects with 1 wt.% particle loading could be performed. Further investigations need to be done on the particle preparation process and mixing ratios. When a well-working protocol is defined a swarm of swimmers will be manufactured and their swimming performance in rotating magnetic fields will be investigated.

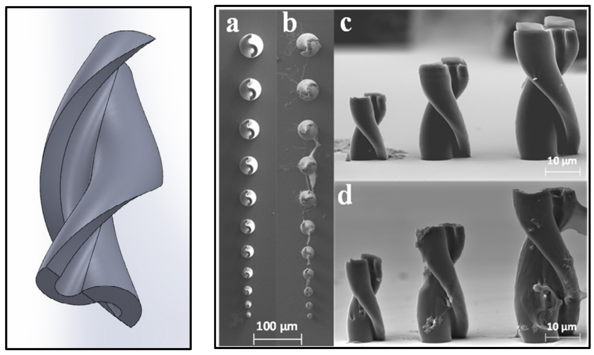

Figure 3: Left: CAD-model of the Savonius shaped object [8]. Right: 10 kV SEM micrographs of swimmers with (a,c) in-house and (b,d)commercially available iron oxide particles. Fabrication parameters: 780 nm, 15mW, 5000µm/s.

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AUTHOR'S STATEMENT

Conflict of interest: Authors state no conflict of interest. Informed consent: Informed consent has been obtained from all individuals included in this study.

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