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Printing of hard ferromagnetic materials for remote magnetic actuation

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Abstract: The remote magnetic actuation of untethered devices has great potential for many clinical applications such as drug targeting and precision surgery. 3D printing offers great flexibility in the manufacturing process of these milli- and micro-scale devices. To achieve better functionalization of these devices it is beneficial to directly integrate the desired properties into the printing process. This work focuses on the development and analysis of a magnetic print material. NdFeB microparticles of different concentrations were incorporated into a liquid polymer resin for LCD-based 3D printing. The print quality is investigated and the resulting magnetic properties are analyzed for their suitability to be used for remote magnetic actuation.

I. Introduction

Applications such as targeted drug delivery and precision surgery are important aspects of personalized medicine. In the future, these procedures could be realized by remote steering of small devices or robots that perform specific tasks [1]. One very flexible way to achieve the controlled movement of these devices is by using magnetic fields. Such fields can be applied from outside the patient to steer the magnetic device with controlled forces and torques depending on the used field geometry. To perform propulsion by rotation of a helical swimmer, a homogeneous rotating magnetic field is applied. If the device has a magnetic moment, a torque will act on it resulting in a rotation of the device. While it has been shown that also soft-magnetic materials can be used for these types of rotating devices due to magnetic anisotropies [4], the remanent magnetic moment of hard ferromagnetic materials results in a more efficient generation of torque which enables higher rotation frequencies and therefore higher speeds.

In the construction of milli-scale swimmers, additive manufacturing is a useful method since it enables the creation of functional structures that would be difficult to achieve with subtractive manufacturing. To functionalize the printed objects and to give them their desired magnetic properties, different approaches have been pursued. For example, the magnetic properties were added after the printing in the form of a coating [2], or a standard sintered neodymium magnet was integrated into the device [3]. By integrating the magnetic properties directly into the printed material two main benefits arise: First, the removal of the additional step will simplify the manufacturing of the device. And second, the whole volume of the device can contribute to the magnetic properties to achieve strong magnetic moments, which is especially important when miniaturizing the design. Since the maximum achievable torque depends on the magnetic moment of the swimmer, the maximum swimming speed can be increased with a larger magnetic moment.

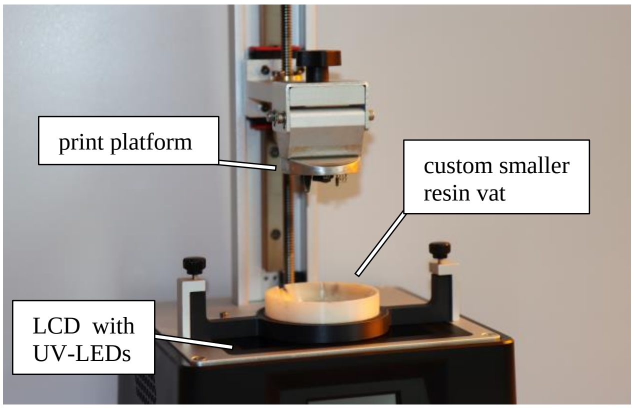

Figure 1: Printing setup with the modified resin vat and a finished print on the modified print platform.

Previous work has shown that the integration of neodymium-iron-boron (NdFeB) powder into a filament provides a suitable way to print custom-shaped magnets [5]. This work presents a procedure to print these types of polymer-based magnets using a higher-resolution resin 3D printer to create functionalized materials and to print magnetic swimmers.

II. Material and methods

To print the magnetic material a resin 3D printer (Photon Mono, Anycubic, Shenzhen, China) was used. It uses an LCD screen as a mask to selectively cure a single layer of UV-sensitive resin using UV-LEDs. Due to its simple printing principle, it is one of the cheapest options for resin 3D printers. To produce parts with the desired magnetic

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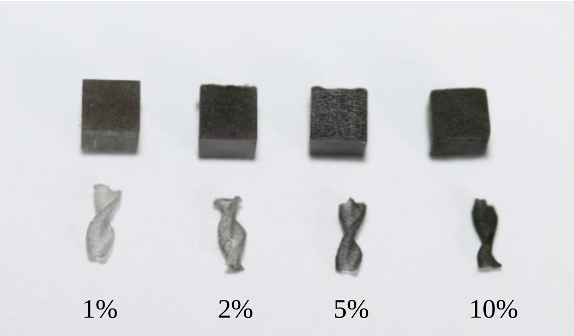

Figure 2: Printed 3 mm cubes and swimmers of 3 mm length [2] with different concentrations of NdFeB particles mixed in.

properties, isotropic NdFeB particles (MQFP-15-7, 5µm, Magnequench, Singapore) were added to the resin (Color Mix Resin Basic, 3DJAKE, Paldau, Austria) in exemplarily chosen mass fractions of 1, 2, 5, and 10 percent of weight (wt%). Resin and particles were mechanically mixed and then added to the printing vat.

Since the goal was to print small objects, the build platform and resin vat were rebuilt at a smaller size to reduce the amount of particle-resin mix that had to be prepared for a single experiment. The modified setup is shown in Fig. 1.

To test the printing quality a range of different geometric objects, including spheres, cubes and cylinders of different sizes were printed. The exposure times of the printed layers had to be increased from 3.5 s up to 6 s to account for the additional absorption of the added particles. In addition, the model of a helical swimmer as presented in [2] was printed in different sizes.

The magnetic properties of the prints were analyzed using a vibrating sample magnetometer (8607 VSM System, Lake Shore Cryotronics, Inc., Westerville, Ohio, USA). For the VSM measurements, 3 mm cubes with different NdFeB concentrations were used and the magnetic moment of the sample was recorded while the external field was varied in the range of $\pm 2.6\ \mathrm{T}\mu_0^{-1}$ in steps of $20\ \mathrm{mT}\mu_0^{-1}$. From these measurements, the remanent magnetization of the material at zero field amplitude was extracted.

III. Results and discussion

The print results of a subset of the test objects with different concentrations are shown in Fig. 2. The print was successful for all tested concentrations and showed no degradation of the printing quality or shrinking. However, the printing at 10 wt% required tuning of the exposure parameters and even higher concentrations started to become unreliable with print failures and no adhesion to the build plate. It is possible that the printability at these concentrations can be achieved by further tuning the exposure settings or using a different type of resin. During the printing, sedimentation of the particles in the resin caused visible concentration gradients in taller parts (>1 cm, ≥5 wt%). To increase the settling time, sonication could be used during the mixing process as shown for magnetite nanoparticles [6], however, a more detailed analysis of the sedimentation mechanics is still necessary.

The results of the measurements of the magnetic properties are shown in Fig. 3. The magnetization curves of the 3 mm cubes show a clear hysteresis resulting from the permanent magnetic material. As expected, the remanent magnetic moment increases linearly with the concentration of NdFeB particles. A larger remanent magnetic moment would allow faster rotation of a magnetically actuated swimmer.

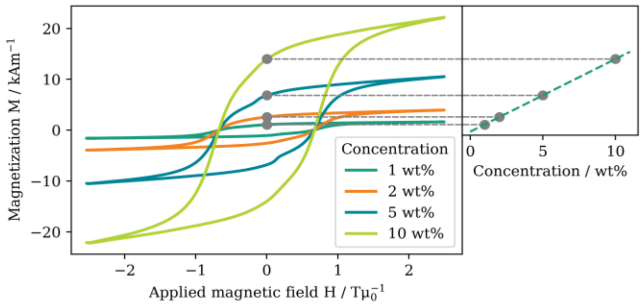

Figure 3: VSM measurements of the 3 mm cubes in different printed concentrations. A wide, hard-magnetic, hysteresis curve and a linear relationship between concentration and remanent magnetization is visible.

IV. Conclusions

In this work, we showed initial experiments to produce functionalized 3D prints with a remanent magnetic moment out of a permanent magnet material using an SLA 3D printer. The printed parts were geometrically accurate and showed the desired magnetic properties. As the next steps, different resins can be investigated to increase the maximum amount of magnetic filler material while maintaining printability. The further miniaturization of functionalized prints is an important aspect to be investigated as well [7]. The presented 3D printing process shows promising results to develop new and improved magnetic devices for remote actuation in future applications.

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Author's statement

Conflict of interest: Authors state no conflict of interest.

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