3D Printing Magnetic Material with Arbitrary Anisotropy

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Abstract

A process for 3D printing of magnetic materials with programmatically controlled anisotropy is presented. Using an experimental thermal inkjet printer magnetic structures with and without anisotropy are printed and characterized to demonstrate the unique advantage afforded by inkjet printing – that of arbitrarily controlling the anisotropy orientation within the structure during printing. The technique will make possible 3D printed inductor and transformer cores with low losses, antenna loading materials and graded index lenses for processing microwave signals, and magnetic field sensors to name a few applications.

In the inkjet printing technique presented here, a magnetic ink composed of magnetic nanoparticles in a UV curable resin is jetted on the substrate. The nanoparticles are then aligned in a magnetic field generated using a two-axis electromagnet and the ink cured to obtain a composite with the desired magnetic anisotropy. The process is repeated to fabricate a 3D structure of the desired shape and dimensions.

Introduction

Advances in 3D printing technology have made it an economically viable, highly customizable form of manufacturing that minimizes waste of materials. As manufacturing need progresses from fabricating mere *parts* to intrinsically "smart" *products* capable of actuation, sensing, computation and communication, the winning 3D printing technology will be one with the ability to deposit a wide range of materials as well as vary the composition and physical properties (e.g. Young's modulus, thermal or electrical conductivity, magnetic permeability, etc.) of the component materials *during* manufacturing. Structures not possible to fabricate by conventional machining techniques have already been demonstrated with 3D printing [1]. With the addition of digital control of materials and properties, new devices presently not manufacturable or even imaginable will become feasible.

Inkjet printheads, originally developed for printing text and graphics, have now been adapted to 3D print a wide range of structural and functional materials: virtually any material that can be processed into a nanopowder and suspended in a carrier fluid can be printed [2-4]. Inexpensive integration of multiple ink sources (as developed for color printing) allows for multiple materials to be deposited simultaneously, and with excellent registration, during each pass of the printhead. Such inkjet-based systems have been used to manufacture devices, such as, inductors [5-9], electrostatic-drive motors [6], capacitors [7,8], conductive circuits [7-11], sensors [9,10] and antennae [10]. Figure 1 shows an example of an inductor fabricated by ink-jet printing.

A particular advantage of inkjet-based 3D manufacturing is that control of material composition and properties *within* a printed object or device may be achieved by programmatically mixing different proportions of source material during printing. For instance, variation in electromagnetic properties can be realized by changing the ratio of the constituent high-permeability or high-permittivity materials. Such control of electromagnetic characteristics is of interest for application in antennae loading materials and graded index RF lenses [12-14] to enable small but efficient communications antennae with custom-designed beam patterns.

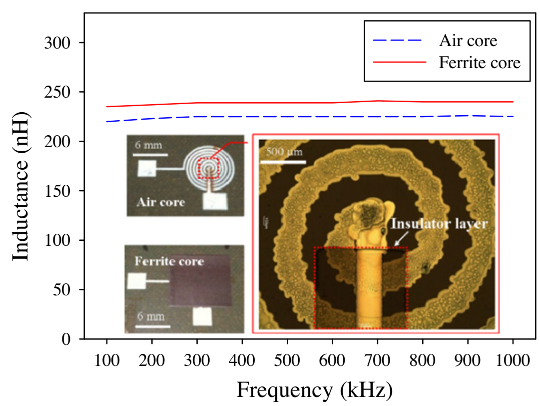

Figure 1. *Printed flat spiral inductor with air and ferrite core. Reprinted from All-Inkjet-Printed Electrical Components and Circuit Fabrication on a Plastic Substrate, vol. 97, no. 4023, pp. 251-254, Copyright 2012, with permission from Elsevier.*

Material properties can also be varied by changing the ambient conditions (e.g., temperature, illumination and electromagnetic field) during deposition of each ink droplet. In this paper, arbitrary magnetic anisotropy in printed materials, achieved by applying a magnetic field during printing, is demonstrated. It is well known that the performance of soft magnetic materials, as used for example in motors and inductor cores, can be improved and losses reduced by aligning the anisotropy axis of the material orthogonal to the magnetic flux lines. Digital control of anisotropy orientation during printing of a part offers the unique capability to align the constituent magnetic particles along *any* arbitrary flux path within a device. Such arbitrary alignment of anisotropy is impossible to achieve with conventional manufacturing processes. The printing techniques and the results obtained thereof are discussed next.

Experimental Techniques and Results

The printer platform is implemented with a thermal inkjet printhead and controller designed by Hewlett-Packard Company for experimental use (Fig. 2). The Thermal Inkjet Picofluidic System (TIPS) controller, as it is known, allows for inks to be tested in small volumes. A universal serial bus (USB) interface facilitates computer control of the droplet ejection parameters, e.g., amplitude, rise time, duration and frequency of the voltage pulse to nucleate the vapor bubble in the ink chamber. The controller is compatible with multiple printheads, with varying number of nozzles and orifice diameters – to optimally print a wide variety of inks. The disposable printheads (see Fig. 2c) can be easily installed and uninstalled, lending to the versatility of the controller.

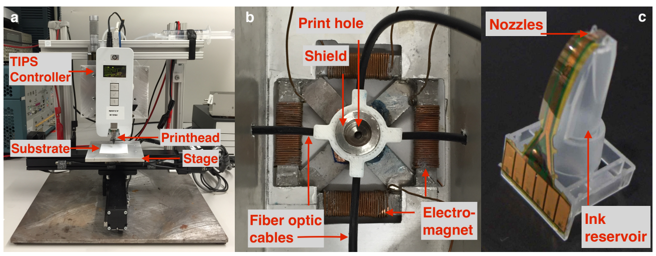

Figure 2a. *Experimental printer platform showing the TIPS controller, the printhead and substrate on a micropositioning stage.* ***b.*** *Top view of the substrate stage. The printhead sits directly over the print hole and inside the mu-metal shield. The four windings of the two-axis electromagnet can also be seen.* ***c.*** *Picture of the interchangeable printhead.*

A two-axis electromagnet is integrated on the platform just below the printhead to provide a magnetic field arbitrarily controllable in strength and direction, for precisely aligning the anisotropy as each droplet of magnetic nanoparticle containing ink is printed. The nozzle is kept from clogging by magnetically shielding the printhead with mu-metal (a high permeability Ni-Fe alloy). Micropositioning or rotation stages allow the substrate to be translated relative to the printing nozzle, for 3D fabrication.

In the work presented here, a nozzle with a 60 µm orifice diameter is used. The nozzle to substrate distance is 4 mm. The ink is composed of a low viscosity (~6 cP) aqueous solution of cobalt-based ferromagnetic nanoparticles with an average diameter of 40 nm. Ring shaped samples are printed on commercial inkjet paper by rotating the substrate at 2 rpm while applying a 10 mT field so as to obtain radial alignment of nanoparticle anisotropy. The ring is one layer thick with a printing dot pitch of 100 µm. The inner and outer diameters of the ring are 4 mm and 7 mm respectively. The samples are air-dried and their magnetic hysteresis in the radial and circumferential directions subsequently characterized by vibrating sample magnetometry. The data, shown in Figure 3, are compared with the hysteresis loops of a control sample fabricated without field applied during printing. As expected the control sample exhibits no anisotropy – that is, hysteresis loops measured in the radial and circumferential directions show no difference. In contrast, samples with induced anisotropy show a squarer hysteresis response (lower permeability) enclosing a larger area (higher losses) in the radial direction than in the circumferential direction. These results suggest that the performance of 3D magnetic material and devices can be tailored to be application-specific via control of magnetic anisotropy [5]. Inkjet printing affords the unique ability to optimize anisotropy arbitrarily within a 3D structure: as each drop of magnetic particle containing ink is printed, a field can be applied to align the anisotropy of the particles in the required direction. No conventional deposition or lithographic technique allows such tunability or control in magnetic material and device fabrication.

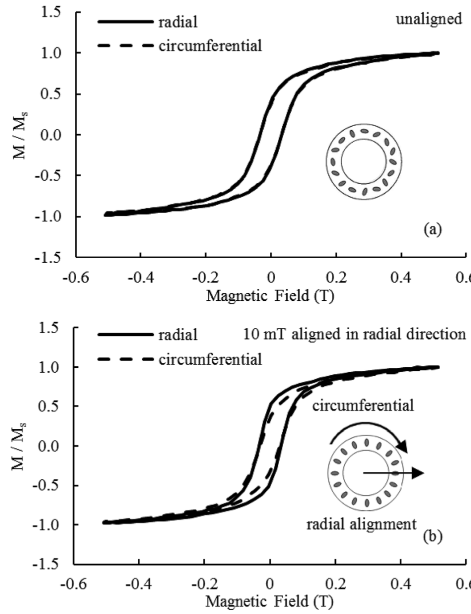

Figure 3. *Normalized hysteresis curves measured in radial and circumferential directions for* ***a.*** *an unaligned, and* ***b.*** *a radially aligned ring shaped sample.*

As noted, the ring shaped samples for demonstrating anisotropy control during printing were air-dried single layers. For fabricating 3D magnetic structures multiple layers must be printed. The ink is hence reformulated to be UV curable to allow each layer to be hardened prior to printing the next. Cobalt-based magnetic nanoparticles are obtained from the ink used earlier by heating 13 µL of the ink solution for 30 minutes at 80 °C. Upon solvent evaporation, approximately 5 µL of the nanoparticles remain and are added to a mixture of 800 µL of ethanol and 200 µL of a UV curable resin. To get a uniform dispersion of the 0.5 volume percent cobalt nanoparticles, the mixture is then sonicated for 5 minutes. The resulting UV curable "ink" has an amenable viscosity of approximately 2 cP for jetting.

5 mm by 5 mm samples with 1, 2 and 3 layers are printed on photo paper, found to be best suited amongst the substrates tested for adherence of the printed structures. The printing dot pitch is 50 µm. The magnetic anisotropy is not aligned *i.e.*, no field is applied during printing. Each layer is cured by exposure to 400 nm UV light for 30 s. (The selected wavelength is optimal for the UV curable resin used.) Shown in Figure 4 are pictures and hysteresis loops of the samples. The opacity of samples is seen to increase with the number of layers. Similarly, the saturation magnetic moment in the hysteresis loops increases with the number of layers and hence, magnetic nanoparticle content. Due to particle sedimentation in the ink reservoir over time, however, magnetic content in the layers printed later in a sample is higher than in the first layer printed with freshly constituted ink. As a result, the magnetic moment does not scale proportionally with the number of layers. The saturation magnetic moment is also low for practical use as a consequence of the low volume percent of cobalt

nanoparticles (5%) in the ink. Clearly, the ink must be optimized for stability and nanoparticle loading.

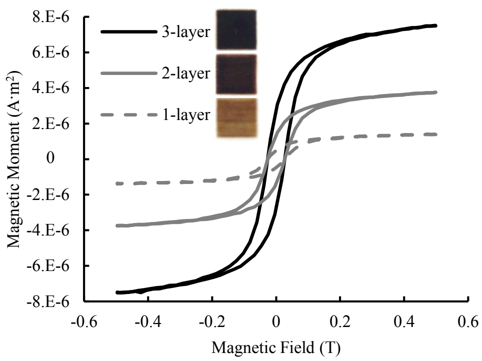

***Figure 4**. Hysteresis curves for three printed and cured unaligned samples with varying number of layers.*

Despite the shortcomings, these first experiments nevertheless demonstrate the exciting possibility of inkjet printing 3D magnetic materials and devices with custom anisotropy. Future effort will aim to investigate aligning and curing as each drop is jetted (see Fig. 5). Novel polymer cross-linking chemistries to create denser packing of magnetic nanoparticles during curing will also be explored.

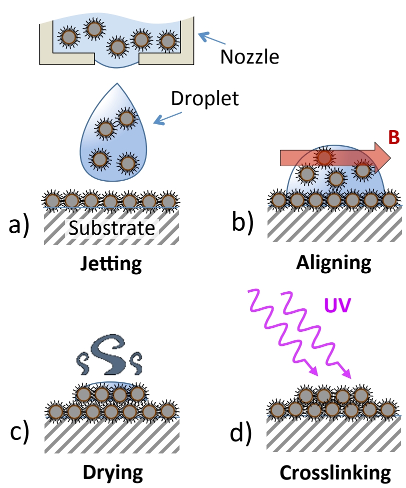

***Figure 5.** Schematic of proposed scheme for 3D printing magnetic structures with custom anisotropy **a.** drop containing magnetic nanoparticles is jetted onto the substrate; **b.** a magnetic field is applied next to align the anisotropy of the nanoparticles; **c.** and **d.** as the solution evaporates, the nanoparticles draw closer due to Van der Waals interactions and are subsequently crosslinked by photochemically activated ligands on their surface, maximizing their packing density and immobilizing them in the printed composite. The process is repeated to obtain the 3D structure of desired shape and dimensions.*

Conclusion

While 3D printing technologies for functional electronic and optical materials have advanced in recent years, very little progress has been reported in the development of viable processes for printing 3D magnetic devices. Yet the inclusion of high-permeability, low-loss magnetic materials into the toolbox of 3D printing is critical, in particular to the vision of the emerging "Internet of Things" (IoT) technology. Magnetic flux concentration using these materials will enable miniaturization of many essential components, including antennae and communications circuits; energy harvesting or remote charging devices; power management systems; and motors and actuators.

In the present effort, key steps in a process for manufacturing 3D magnetic structures with arbitrary orientation of anisotropy have been demonstrated. The steps include inkjet printing a magnetic nanoparticle bearing UV curable ink, aligning the nanoparticles with a programmable electromagnet and curing the ink with brief exposure to UV light so that the nanoparticles are pinned in their alignment. Such drop-by-drop level of control, unique to inkjet printing, has previously not been exploited and promises higher effective permeability and lower hysteresis losses in the magnetic materials and devices fabricated.

With further development, particularly in formulation of jettable and UV curable inks with high magnetic nanoparticle loading and stability, inkjet printed magnetic devices will have the potential to meet the customization and energy efficiency needs of future mobile or IoT devices.

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Author Biography

Garrett Clay received his BS in electrical engineering from Oregon State University (2014). Since then he has been working towards a MS in electrical engineering at Oregon State University where he is part of the Applied Magnetics Laboratory. His current focus is developing a 3D printer that prints magnetic material.