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Research articles

3D printed magnetic polymer composite transformers

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ABSTRACT

The possibility of 3D printing a transformer core using fused deposition modeling methods is explored. With the use of additive manufacturing, ideal transformer core geometries can be achieved in order to produce a more efficient transformer. In this work, different 3D printed settings and toroidal geometries are tested using a custom integrated magnetic circuit capable of measuring the hysteresis loop of a transformer. These different properties are then characterized, and it was determined the most effective 3D printed transformer core requires a high fill factor along with a high concentration of magnetic particulate.

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1. Introduction

Transformers are omnipresent today due to their essential role in the transmission, distribution, and utilization of AC electrical energy. Specifically, they execute the important task of increasing or decreasing alternating voltages in electric power applications. They are found in our power transmission and distribution systems, as well as radios, TVs, computers and audio systems. Typically, transformers consist of a magnetic core wrapped with two coils of electrically conducting wire, termed the primary and secondary windings.

A number of factors determine the efficiency of a transformer, including the core material, the core geometry, and the windings [1]. The design goals of the core material include high magnetic permeability to maximize conversion output, low magnetic coercivity to minimize hysteresis losses, and high electrical resistivity to minimize eddy current losses [1]. To achieve these goals, the cores are commonly constructed by stacking laminated sheets of silicon steel or amorphous metal, die-pressing iron or metal powder, or sintering ceramic ferrite powders [2].

A donut-like toroidal geometry theoretically makes the most efficient transformer due to its ability to maximize the enclosed magnetic flux. However, less-efficient shapes with rectangular cross-sections and right angles are often used in practice due to restrictive manufacturing costs [1]. Developing enhanced manufacturing processes that are able to easily create transformer cores with toroidal geometry could lead to transformers that are both efficient and low in cost.

Additive manufacturing refers to the process of building a part up with a material, layer by layer. This allows for the manufacture of complex geometries without being limited by the abilities of tools or molds, like in other types of manufacturing. While there are many different types, one of the most common and readily available types of additive manufacturing is fused deposition modeling (FDM) [3]. FDM, often generally referred to as 3D printing, is a process that involves heating a material (most commonly a thermoplastic polymer) in a nozzle and continuously extruding the viscous material onto a print bed to create a layer. When one layer of the part is complete, the printer head moves up a fraction of a millimeter, so a subsequent layer can be extruded and deposited [4]. This process is repeated until each layer of the part is extruded.

Combining FDM equipment with an appropriate software package allows for a fully customizable printed part geometry. In particular, the flexible nature of the printed design necessitates that a number of external and internal structural parameters be specified in the printing of a part. These features include the fill factor (percent density or concentration of the extruded lines), the outer layer (shell) thickness, and the fill pattern. The selection of such features can readily influence the properties of the final printed part [5].

Here, we explore the construction and performance of magnetic transformers printed with a magnetic thermoplastic polymer composite material via FDM. First, we demonstrate the successful printing of a toroidal core geometry via FDM. We then compare the performance of identically-shaped printed and standard cores, and explore how the internal geometry (fill factor and fill pattern) of the printed cores affects the core performance. We find that, while the fill pattern does not appreciably change the core

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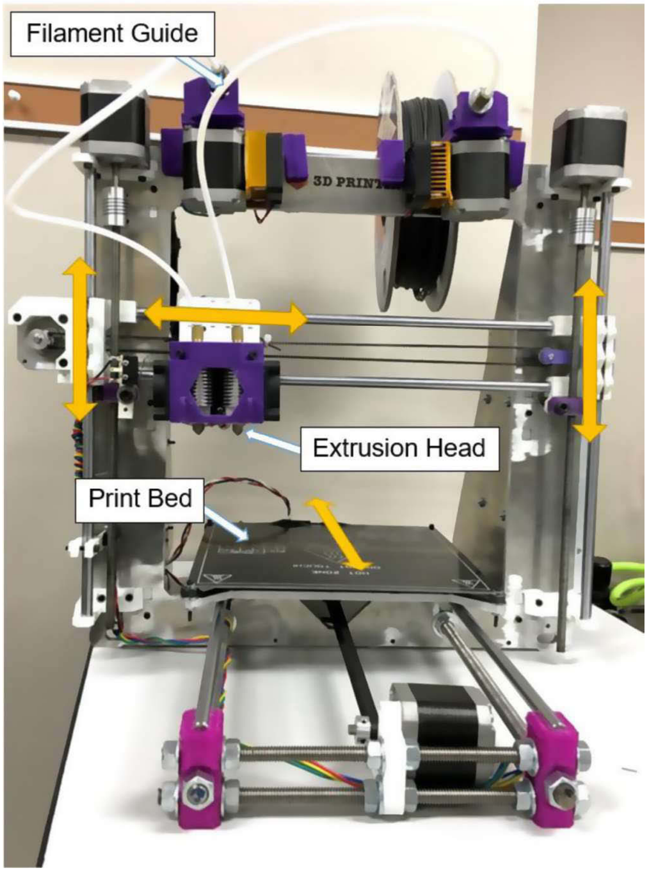

Fig. 1. Customized gMax 3D printer that is utilized to 3D print the transformer cores. Various components of the printer are shown; including the filament guide, extrusion head, print bed, and the x-y-z axes of motion of the stepper motors.

performance, the largest fill factors give the greatest printed core performance. We also characterize the structural and magnetic properties of the composite filament material, which gives insight into future opportunities to improve the performance of the printed cores.

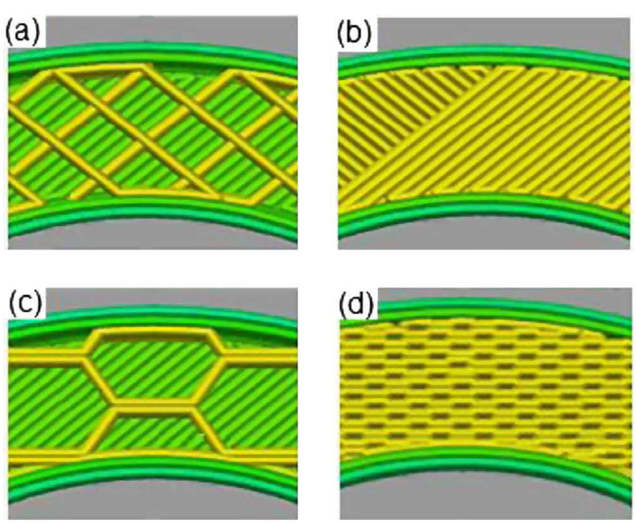

Fig. 2. Horizontal cross-sections of transformer cores modeled on Simplify3D with different fill patterns and percent fill. (a) Rectangular fill pattern with 20% fill, (b) rectangular fill pattern 100% fill, (c) honeycomb fill pattern with 20% fill, and (d) honeycomb fill pattern with 100% fill.

2. Methods

2.1. Transformer core preparation

The transformer cores were printed with Proto-Pasta's Composite PLA – Rustable Magnetic Iron filament (1.75 mm diameter) consisting of a polylactic acid (PLA) polymer matrix and a particulate phase of 40 wt% iron. The PLA was NatureWork's 4043D Ingeo Biopolymer. The combination of these two materials makes it possible for the filament to be printed by a thermoplastic 3D printer and to display ferromagnetic properties.

A custom 3D printer based on the gMax printer made by gCreate was used to print the transformer cores (Fig. 1). The filament extrusion temperature was 210 °C, and an extrusion nozzle width of 0.4 mm was used. A wear resistant brass nozzle plated with nickel was necessary to withstand the abrasion from the iron particulate within the filament as it was extruded.

First, toroidal cores were designed and printed. Next, in order to directly compare the printed transformer performance, transformer cores were printed with the identical external size and geometry to a control transformer core. The commercial standard Ni-Zn ferrite transformer core, Ferroxcube TN36/23/15-4A11, was used as the control. To test the effect of various structural attributes common to 3D printed objects, transformer cores were printed with a variety of fill factors (20–100%) and fill patterns (rectangular and honeycomb). The outer layer (shell) thickness for all printed cores was two layers. A typical printed transformer core and the internal fill characteristics are shown in Fig. 2 and Fig. 3.

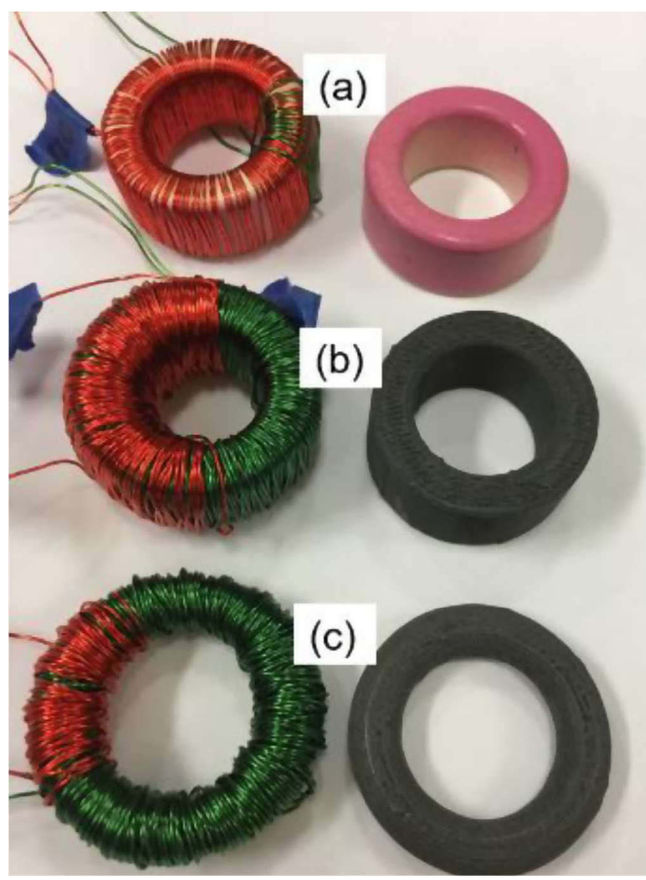

Fig. 3. Transformer cores used for testing. Left side shows wrapped cores, right side is just the core. (a) commercial core, (b) 3D printed transformer core that is the same shape as the commercial core, and (c) toroidal shaped transformer core.

2.2. Transformer core testing

To test the core performance, primary and secondary windings were wrapped around the core using magnet wire and attached to the custom integrated magnetic circuit shown in Fig. 4. A hysteresis loop for each core can be measured by graphing the output voltage versus the input current of a saturated core. This loop can be used to determine the efficiency of the core. In the circuit, a current is generated from the function generator and amplified by the power amplifier before reaching the test transformer. A hysteresis loop of interactions between the primary and secondary windings is graphed, and data is gathered from these loops.

2.3. Composite filament characterization

The structural and magnetic properties of the filament material were also investigated to shed light on the properties of the printed cores. To investigate the Fe particulate shape, orientation, and dispersion within the PLA matrix, scanning electron microscopy (SEM) was used on the pre-printed filament and a post-printed object cross-section. A Quantum Design Magnetic Property Measurement System (MPMS) SQUID magnetometer was used at measure the magnetic properties of the filament to +/-5 T at room temperature.

3. Results

3.1. Transformer cores

The standard transformer core generated a clear hysteresis loop with magnetic saturation and a coercive current of <1 A. As shown in Fig. 5a, the standard core is able to saturate much more easily than the printed core. The printed cores generated non-saturating hysteresis loops. The power amplifier is unable to saturate the printed transformer cores due to insufficient amplification of the current produced from the function generator.

While the printed transformer loops did not saturate, the fill factor did affect the response of the transformer. As shown in Fig. 5b, the larger fill factor generated a larger voltage response for a given input current. This is reasonable given that larger fill factors, results in a larger magnetic moment contained within the transformer core. With all other factors constant, the fill pattern did not appear to greatly affect the response of the printed transformer core, as shown in Fig. 5c.

3.2. Composite filament

The structural characteristics of the iron particles within the PLA matrix are shown in Fig. 6. The iron particles, which appear

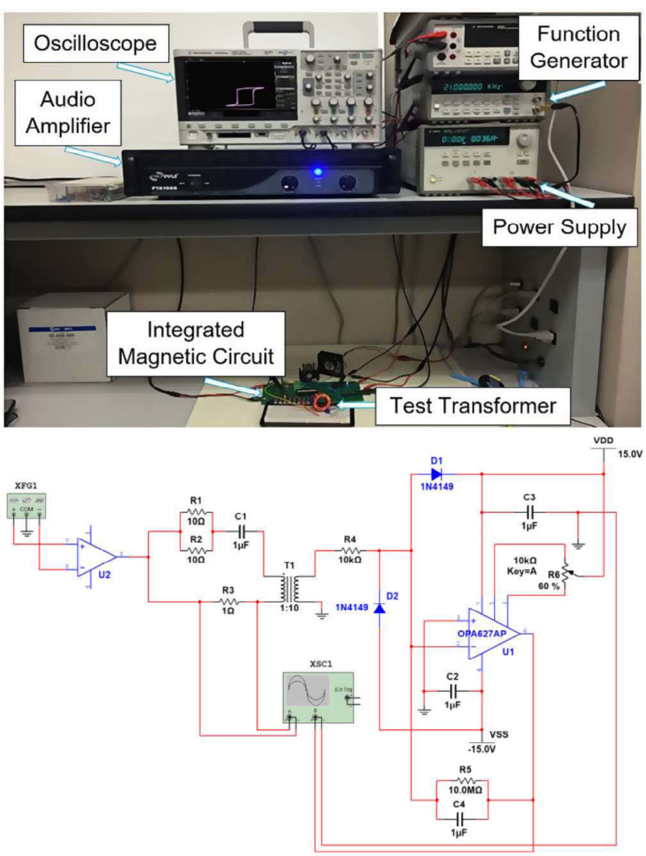

Fig. 4. Circuit setup showing (top) the equipment and (bottom) circuit used for testing the transformer cores. Oscilloscope displays hysteresis loop from standard core. The R1, R2 combination, used as a reference, is thermally stabilized in oil.

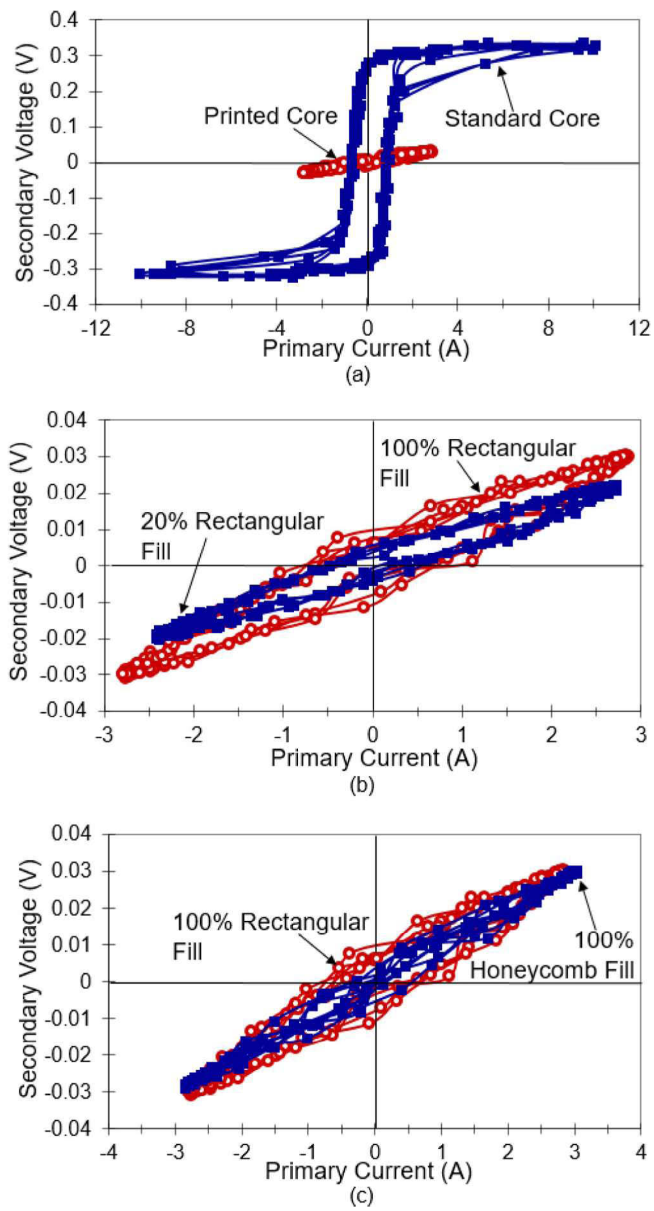

Fig. 5. Circuit hysteresis loops. (a) Control vs. printed, (b) printed 20% vs. printed 100%, and (c) rectangular vs. honeycomb.

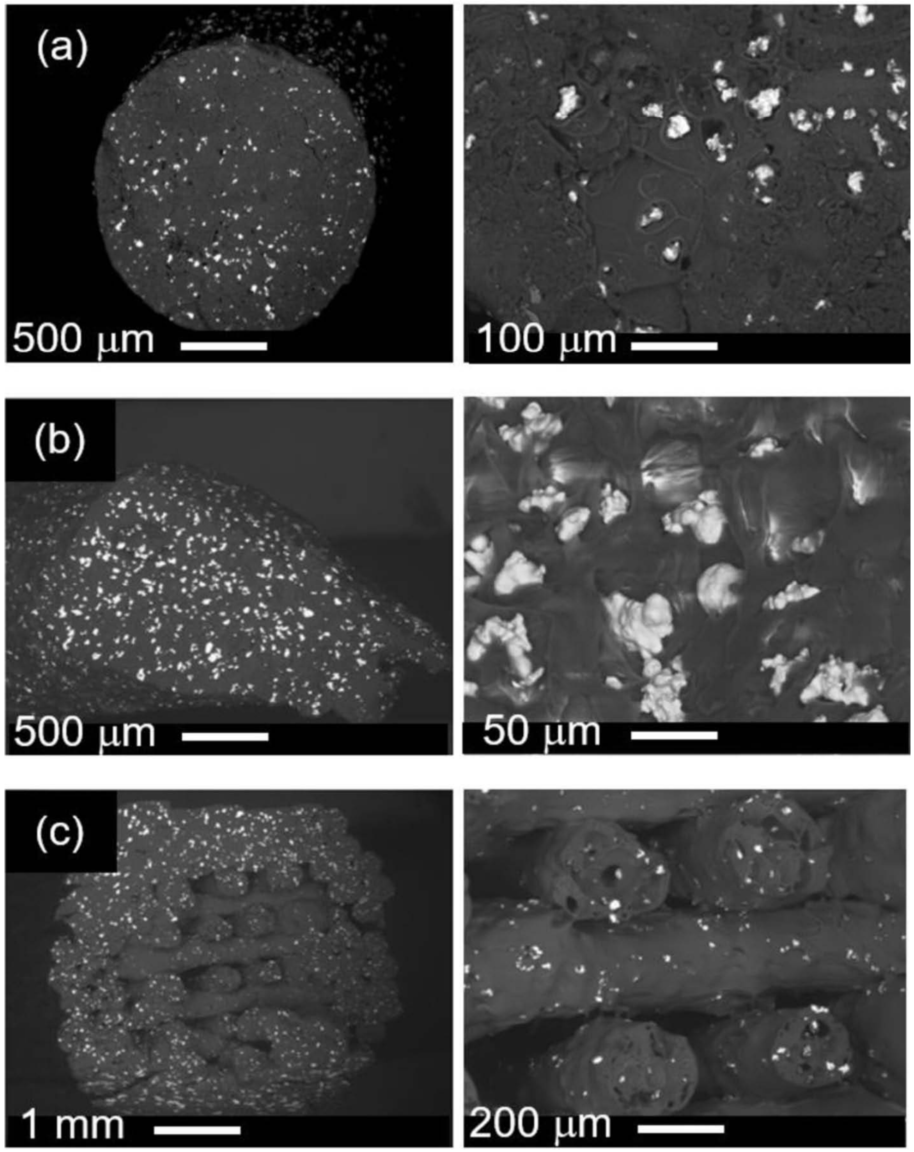

Fig. 6. SEM of (a) horizontal cross-section of filament, (b) 45° cross-section of filament, and (c) cross-section of a 3D printed transformer core. Left and right columns are zoomed out and in, respectively.

brighter in the images due to the larger electron density (Z), are both inconsistent in size and shape; however, they are roughly isotropic with a diameter of ~40 µm.

The magnetic properties of the filament were directly investigated. A magnetic hysteresis loop of the filament at 300 K with field applied parallel to the filament axis is shown in Fig. 7. The magnetic saturation of the filament was 66.69 emu/g and the coercive field was <10 Oe. As expected from the Fe contents, the material is a very soft magnet—an important feature for the application of transformer cores.

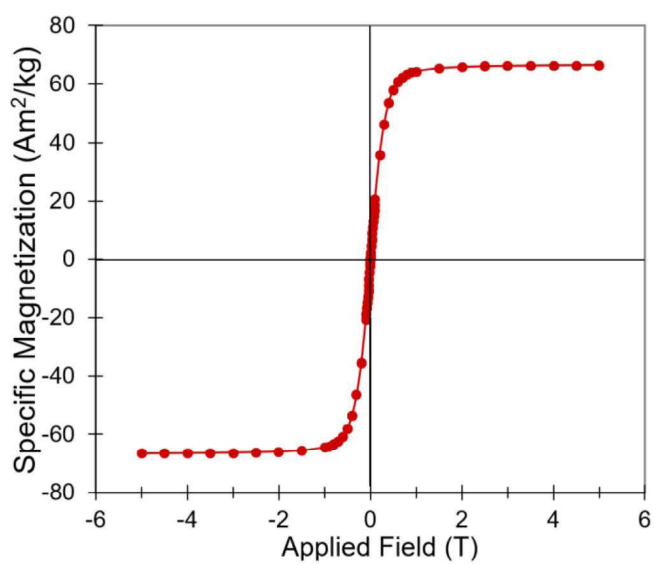

Fig. 7. SQUID hysteresis loop of magnetic composite filament (300 K).

4. Discussion

The inability for the printed core to saturate as easily as a standard ferrite is an important hurdle that will need to be overcome for this technology to be successful. To optimize the performance of a 3D printed transformer core, a number of factors can be optimized to increase the magnetic response. First, as shown above, the highest fill factors must be utilized. Second, higher Fe contents are needed; however, as one increases the percentage of Fe particulate, the extrusion processing of the composite material becomes more complicated. Third, a more magnetically responsive particulate with lower coercivity and susceptibility would also increase the performance of the printed cores. This could be tailored by a variety of particulate characteristics, such as size, shape, distribution, and magnetic annealing (either during or after deposition). Finally, the transformer geometry (diameter/radius ratio) and turn ratio could also be modified to optimize the performance.

5. Conclusion

In conclusion, a variety of 3D printed magnetic composite transformer cores have been created and tested. While the fill pattern of the printed core does not have a large impact on performance, cores printed with the highest fill factors generate a more responsive transformer. The generally small transformer response of the printed cores (compared to the standard ferrite core) originates from the sub-optimal characteristics of the Fe particulate in the PLA matrix. A variety of avenues to optimize the performance of 3D printed transformer cores have been proposed.

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