Additive Manufacturing of Magnetic Components for Heterogeneous Integration

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Abstract—In an effort to simplify the process of integrating magnetic components to power electronics circuits, an additive manufacturing (AM) process, or commonly known as 3D-printing, for fabricating magnetic components is studied in this work. A commercial multi-extruder paste-extrusion 3D printer was evaluated for making magnetic components. We developed two material systems for printing magnetic cores: (1) curable powdered iron paste system; and (2) sinterable ferrite system. We used commercial nanosilver paste for the conductive winding. A half piece of constant-flux inductor (CFI) and a planar inductor were fabricated in this study.

For the half piece CFI, 3D-printing was used with nanosilver paste and low-temperature curable powdered iron paste. The printed winding was sintered at 250°C for 30 minutes firstly and then magnetic paste was printed to cover the sintered winding. The magnetic paste was cured at 230°C for one hour without any external pressure to form the structure. Two printed pieces were connected to form the full size CFI. Inductance of the CFI was measured to be about 3.5 µH. The DC resistance of the winding was 59 mΩ.

For the planar inductor, 3D printing was used with nanosilver paste and high-temperature sinterable ferrite paste. It was sintered at 920°C for 14 hours without any external pressure to form the structure. The inductance of the planar inductor was measured to be about 792 nH. The DC resistance of the winding was 15 mΩ.

Microstructures of the printed inductors were examined by scanning electron microscopy (SEM). Both the winding and core magnetic properties can be improved by adjusting the feed paste formulations and their flow characteristics and fine-tuning the printer parameters.

Keywords: additive manufacturing; power electronics integration; magnetic components; magnetic pastes; heterogeneous integration

I. INTRODUCTION

Today’s power electronics (PE) circuits are custom-designed and fabricated by interconnecting discrete components of power semiconductor devices (silicon or future WBG), capacitors, inductors, and transformers [1-3]. Among all of these components, magnetic components (inductors and transformers) are usually the heaviest and largest ones [4]. As shown in Fig. 1, magnetic components can take up 50% of the circuit surface area. Nowadays, magnetic cores and electrical conductor windings that make up magnetic components are fabricated separately in multiple, complex steps [5-7]. For example, to make a soft ferrite inductor, the core is firstly formed by a high-pressure powder-compaction process followed by sintering at high temperatures (typically > 900°C), and then copper wires are “hand-wound” around the core. This method of fabrication results in bulky parts, limits the better design of the magnetic components, and is incompatible with other processes used in assembly of the circuits, which leaves magnetics integration to remain as a challenge in the field of PE.

Heterogeneous integration of separately manufactured components into a higher level assembly enables enhanced functionality and improved operating characteristics. Therefore, heterogeneous integration of magnetic components has the potential to further increase power density and efficiency in power electronic converters [8]. One possible way to fabricate the inductor/transformer into package level for ease of integration of the components into a module integration process is to use an additive manufacturing (AM) process for fabricating the magnets. AM is a layer-by-layer process of making products and components from a digital model. Its potential has been demonstrated for applications in various industries. Some key benefits of AM are shorter lead times, mass customization, reduced parts count, more complex shapes, less material waste, and lower life-cycle energy use [9]. Recently, some research groups explored application of AM in power electronics. For example, Oak Ridge National Laboratory (ORNL) researchers [10, 11] reported in 2014 a 3D-printed aluminum heat sink and a plastic lead frame for a 10-kW power inverter and then in 2016 a ferrite E-core with relative permeability of about 2; Wei Liang et al. [12] 3D-
printed a plastic structure as a mold for making a unique sterling-silver inductor; Proto-pasta [13] introduced an iron-powder filled polylactic-acid (PLA) filament for use with a fused-deposition-model (FDM) 3D printer to make magnetic cores with relative permeability of about 1.5; and Yunqi Wang et al. [14] developed a NiZn-ferrite-filled ABS filament for the FDM printer with relative permeability of about 2. In 2016, our research group firstly demonstrated the feasibility of using a multi-extruder paste-extrusion 3D printer for processing a self-formulated low-temperature curable (< 250°C) magnetic paste and a commercial low-temperature (< 250°C) sinterable nanosilver paste invented in our laboratory to fabricate a planar inductor and a toroid inductor. However, the performance of the printed components was limited by the formulation of the magnetic paste and the post-curing process. The relative permeability of the low-temperature curable magnetic paste was about 10 [15, 16].

Aiming at flexible fabrication and heterogeneous integration of high performance magnetic components, we stick to the method of using a multi-extruder paste-extrusion 3D printer to process both magnetic paste and conductive paste into magnetic components. We developed two magnetic paste systems and applied to the 3D printer as feed materials: a modified low-temperature (< 250°C) curable iron-powder paste system as well as a high-temperature (> 900°C) sinterable ferrite paste system. For the conductive winding feed stock, we used a commercial nanosilver paste. Half piece of a constant-flux inductor (CFI) was 3D-printed by using the nanosilver paste and the modified low-temperature curable iron-powder paste. A planar inductor was 3D-printed by using the nanosilver paste and the high-temperature (> 900°C) sinterable ferrite paste. Properties of the printed inductors, both the inductance and DC winding resistance were measured. Microstructures of the inductors were also characterized by scanning electron microscopy (SEM).

II. EQUIPMENT AND MATERIALS PREPARATION

A. Commercial multi-extruder paste-extrusion 3D printer

The multi-extruder paste-extrusion 3D printer shown in Fig. 2 (a) was purchased from Hyrel 3D [17]. It has a feed-cartridge assembly with four extruders that can print four different paste materials stored in syringes. Fig. 2 (b) shows our UV curing system was affixed to the syringe extruder holder. The UV curing system has four UV LEDs (LZ1-00UV00, LedEngine, Inc.) with peak wavelength of 365 nm soldered on a customized PCB. The PCB and the heat sink are together connected to the extruder holder through a 3D-printed PLA adaptor.

B. Two magnetic paste systems

1) Low-temperature (< 250°C) curable iron-powder paste system

We developed an iron-powder paste system consisting of Trimethylolpropane triacrylate (TMPTA) (from Sigma-Aldrich Co. LLC) monomer solution and two kinds of magnetic fillers. One of the magnetic fillers is a kind of Permalloy powder (from ESPI Metals) with an average particle size of 12 μm, and the other is flake-shaped Metglas 2705M powder with an average particle size of 150 μm. The composition of the paste consists of 92 wt% of the magnetic fillers, 8 wt% of the monomer. Other organic components, such as dispersant and solvent were added to create uniform suspensions of the magnetic fillers in the organic system. Fig. 3 is demonstration of printing the iron-powder paste into a toroid shape.

To characterize magnetic properties of the iron-powder material, the toroid core was made by pouring the paste into a mold and heated to 230°C for one hour under ambient pressure to polymerize the TMPTA monomer. After demolding, the relative permeability of the core was characterized over a frequency range from 100 kHz to 110 MHz at zero dc bias by using a precision impedance analyzer (4294A; Agilent, Santa Clara, CA) with a magnetic material test fixture (16454A; Agilent, Santa Clara, CA). Then, the core-loss density was measured at 1 MHz using a setup specifically designed to measure the loss of a toroid core at high levels of magnetic field excitation [18, 19]. Fig. 4 (a) is a plot of relative permeability versus frequency of the toroid.
core, which shows that the relative permeability of the iron-powder paste is stable at 22 till one megahertz. Fig. 4 (b) shows the core-loss density plot measured at 1 MHz of the iron-powder toroid core at room temperature.

2) High-temperature (> 900°C) sinterable ferrite paste system

We also worked on a UV-curable ferrite paste system that consists of 95 wt% NiCuZn ferrite powder (Powder Processing & Technology, LL) with an average particle size of 0.5 \( \mu \)m, 4.9 wt% pentaerythritol tetraacrylate as monomer, and 0.1 wt% of phenylbis (2, 4, 6-trimethylbenzoyl) phosphine oxide as photo-initiator. Solvent was added in the mixture to obtain a ferrite paste that can be printed out smoothly by the 3D printer.

As shown in Fig. 5, a toroid-shaped structure was 3D-printed from the ferrite paste. The printed toroid core was heated to 920°C for 14 hours under ambient pressure to burn out the organic compounds and sinter. After sintering, the core was characterized. Fig. 6 (a) shows a plot of relative permeability versus frequency of the sintered core, which shows the core has a stable relative permeability value of 70 beyond 10 MHz. Fig. 6 (b) shows the core-loss density plot measured at 1 MHz of the core at room temperature.

C. Nanosilver paste

To print electrical winding, we tested the commercial nanosilver paste which was developed for chip bonding [20, 21]. The material can be sintered at temperatures below 250°C to result in excellent thermal and electrical properties. Fig. 7 shows that the nanosilver paste can be adapted to the 3D printing platform and extruded out to form a winding structure. The nanosilver paste can achieve a crack-free 3D printed single layer thicker than 200 \( \mu \)m. Table 1 lists the electrical resistivity of the 3D-printed winding after low-temperature and high-temperature sintering processes.
Table 1. Electrical resistivity of sintered 3D-printed silver winding and that of pure silver wire.

<table>
<thead>
<tr>
<th>Materials</th>
<th>Electrical resistivity (10⁻⁸ Ω·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250°C sintered 3D-printed silver winding</td>
<td>4.8</td>
</tr>
<tr>
<td>920°C sintered 3D-printed silver winding</td>
<td>2.4</td>
</tr>
<tr>
<td>Pure silver wire</td>
<td>1.6</td>
</tr>
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</table>

III. CONSTANT-FLUX INDUCTOR FABRICATION WITH CURABLE POWDERED IRON PASTE SYSTEM

A. Structure design

The “constant-flux” concept is leveraged to achieve high magnetic-energy density, leading to better utilize the core material and then reduce the volume of the inductor [22]. One design version of the constant-flux inductor, which is shown in Fig. 8, is configured with spiral windings embedded in the magnetic core, and requires a precise control of the different widths and same space between each turn of the spiral. The height of the designed inductor can be two times lower than that of conventional products and the target working frequency for the inductor is 1 MHz [23]. However, the intricate configurations and geometries of windings posed challenges in fabricating this inductor by using conventional fabrication method. The parameters for a half piece of the CFI are listed in Table 2.

Fig. 8. Geometry of a design version of constant-flux inductor.

Table 2. Designed dimensions of half piece CFI for printing.

<table>
<thead>
<tr>
<th>Winding number</th>
<th>Outer radius of winding</th>
<th>Inner radius of winding</th>
</tr>
</thead>
<tbody>
<tr>
<td>j = 1</td>
<td>9.2 mm</td>
<td>7.6 mm</td>
</tr>
<tr>
<td>j = 2</td>
<td>7.2 mm</td>
<td>5.8 mm</td>
</tr>
<tr>
<td>j = 3</td>
<td>5.4 mm</td>
<td>4.4 mm</td>
</tr>
<tr>
<td>j = 4</td>
<td>4 mm</td>
<td>3 mm</td>
</tr>
<tr>
<td>Winding space</td>
<td>0.4 mm</td>
<td></td>
</tr>
<tr>
<td>Winding thickness</td>
<td>0.5 mm</td>
<td></td>
</tr>
<tr>
<td>Core length</td>
<td>20 mm</td>
<td></td>
</tr>
<tr>
<td>Core thickness</td>
<td>1.5 mm</td>
<td></td>
</tr>
</tbody>
</table>

B. Fabrication procedures

Fig. 9 (a)-(f) show the 3D-printing process to form the CFI, the sintering profile used to densify the nanosilver paste, the heating profile to harden the magnetic paste, and a 3D-printed half piece CFI. The low-temperature curable iron powdered paste is the feed material for the magnetic core and the nanosilver paste for the winding. A frame for maintaining the shape of the CFI was printed by using a silicone paste. The single printing layer thickness of the nanosilver paste was 0.2 mm. Conversely, single printing layer thickness of magnetic paste was 1.6 mm.

Fig. 9. Process of 3D printing as-designed half piece constant-flux inductor.

Fig. 10. Full size constant-flux inductor.

Fig. 7. Commercial nanosilver paste for paste-extrusion 3D printer.
shown in Fig. 9 (c). Fig. 9 (d) shows the magnetic paste was filled in the frame by the printer to cover the sintered nanosilver winding and then completed half piece of CFI. The magnetic paste was heated in a programmable muffle furnace based on the curing profile shown in Fig. 9 (e). Fig. 9 (f) shows the half piece of the CFI after post polishing process. The full size CFI, shown in Fig. 10, was fabricated by connecting two printed pieces together with 60 µm thickness Kapton tape as an insulator between the windings.

C. Characterization

1) Inductance and DC winding resistance of the 3D-printed CFI

For the designed CFI, the finite element analysis (FEA) was carried out to simulate its inductance and DC winding resistance. The conductivity of the winding for simulating is three times than that of the pure silver. The relative permeability of the magnetic material for simulating is 22. The defined gap between the two windings in the model is 60 µm. The inductance and DC winding resistance of the inductor model were found to be 3.6 µH and 19.6 mΩ respectively.

A high precision impedance analyzer was used to measure the inductance and the DC winding resistance of the 3D-printed CFI. The measured inductance and DC winding resistance of the inductor were 3.5 µH and 59 mΩ, respectively. The measured inductance is only 3% lower than the inductance predicted by simulation. However, the measured DC winding resistance of the CFI is around three times higher than of the DC winding resistance predicted by simulation. The contact resistance came from connecting the two half CFI pieces may result in the high DC resistance of the printed CFI.

2) Microstructure

Fig. 11 is the SEM image of the 3D-printed CFI. It shows silver winding forming dense layer with some level of porosity. Voids can be found in the cured magnetic paste part. Magnetic flakes are randomly distributed in the core, which will lower the relative permeability of the core.

IV. PLANAR INDUCTOR FABRICATED WITH SINTERABLE FERRITE PASTE SYSTEM

A. Structure design

To demonstrate the feasibility of fabricating magnetic components with the as-fabricated sinterable ferrite paste and nanosilver paste, we tested it by printing a planar inductor. Fig. 12 shows the design of the planar inductor. The inductor has one turn winding embedded in the core. The designed planar inductor had the following dimensions: Core diameter = 20 mm; core thickness = 2.25 mm; winding width = 0.5 mm; winding thickness = 0.25 mm.

B. Fabrication procedures

Fig. 13 (a)-(c) show the 3D-printing process to form the planar inductor, the sintering profile used to densify the nanosilver paste and ferrite paste, and a finished planar inductor. Single printing layer thickness of both nanosilver paste and ferrite paste were 0.2 mm.

Fig. 13 (a) shows that the ferrite paste was printed layer-by-layer to form the core part and in each layer the nanosilver paste was also printed out to build the winding structure. During the layer-by-layer printing process, both the core and winding materials were dried on a 50°C -heated build-plate. Additionally, the ferrite layer was exposed to UV light to speed up its transition into a rigid layer. After 3D structure of the planar inductor was fabricated in the printer, it was heated in a programmable muffle furnace to simultaneously sintering the ferrite paste and the nanosilver winding. The sintering profile is shown in Fig. 13 (b). Fig. 13 (c) shows the finished 3D-printed planar inductor after polishing.

Fig. 11. SEM images of 3D-printed constant-flux inductor (CFI).

Fig. 12. Design of one turn embedded planar inductor for 3D-printing

Fig. 13. Process of 3D printing a one turn embedded planar inductor.
C. Characterization

1) Inductance and DC winding resistance of the 3D-printed planar inductor

For the designed planar inductor, the finite element analysis (FEA) was also carried out to simulate its inductance and DC winding resistance. The conductivity of the winding for simulating is one and a half times than that of the pure silver. The relative permeability of the ferrite for simulating is 70. The inductance and DC winding resistance of the inductor model were found to be 843 nH and 13.8 mΩ, respectively. The measured inductance and DC winding resistance of the inductor were 792 nH and 15 mΩ, respectively. The measured inductance is only 6% lower than the inductance predicted by simulation. The measured DC resistance of the planar inductor is around 8.7% higher than the DC resistance predicted by simulation.

2) Microstructure

Fig. 14 is the SEM image of the 3D-printed planar inductor. It shows that the core and silver winding are dense, but apertures can be found in the interface between the winding and the core. Also, some defects can be found in the big grain size.

Fig. 14. SEM images of 3D-printed one turn embedded planar inductor.

V. Summary

In order to realize the heterogeneous integration of the magnetic components in the future, we demonstrated the feasibility of additive manufacturing magnetic components by printing both the magnetic core and conductive winding using a commercial multi-extruder paste-extrusion 3D printer. Two paste systems were developed for the magnetic feedstock, one being a low-temperature (< 250 °C) curable iron powdered system and the other a high-temperature (> 900 °C) sinterable ferrite system. Both were shown to be compatible with the 3D printer. The commercial low-temperature sintering nanosilver paste, developed in our earlier studies, served as the feedstock for the winding. A constant-flux inductor was designed and 3D printed by using the high-temperature sinterable ferrite paste and nanosilver paste. The inductance and DC winding resistance of the printed inductors were measured and compared with those simulated by a finite-element analysis of the inductor models. The microstructures of the printed inductors were characterized, and the defects in the printed components should be eliminated to further improve the performance of the 3D-printed magnetic components.

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