

# Magnetic Paste as Feedstock for Additive Manufacturing of Power Magnetics

Chao Ding<sup>1</sup>, Lanbing Liu<sup>1</sup>, Yunhui Mei<sup>2</sup>, Khai D. T. Ngo<sup>3,4</sup>, and Guo-Quan Lu<sup>1,2,3,4</sup>

<sup>1</sup>Department of Materials Science and Engineering, Virginia Tech, Blacksburg, VA 24061 USA

<sup>2</sup>School of Materials Science and Engineering, Tianjin University, Tianjin, 300072 China

<sup>3</sup>Center for Power Electronics Systems, Virginia Tech, Blacksburg, VA 24061 USA

<sup>4</sup>The Bradley Department of Electrical and Computer Engineering, Virginia Tech, Blacksburg, VA 24061 USA

E-mail address: gqlu@vt.edu

**Abstract**—Inductors and transformers are ubiquitous in switch-mode power converters. Additive manufacturing or 3D printing of these components has the potential to drastically accelerate their design and prototyping. However, there are very few reported activities claiming successful fabrication of power magnetics by 3D printing. One of the main reasons is the lack of suitable feedstock materials for printing platforms. In this effort, we developed two types of magnetic paste material as the feedstock for a commercial paste-extrusion 3D printer: (1) a low-temperature (< 200°C) pressure-less curable powder-iron paste; and (2) a high-temperature (> 900°C) pressure-less sinterable NiZn ferrite paste. Of each type, the magnetic properties (relative permeability and core-loss density) after heat treatment were found to be comparable or better than its corresponding commercial products, which often require pressure for fabrication. The powder-iron material had a relative permeability of 35 and a core-loss density of 110 mW/cm<sup>3</sup> at  $B_{\text{peak}}$  of 10 mT and 1 MHz. The core-loss density was 33% lower than that of a commercial powder-iron core from Micrometals with the same relative permeability. The ferrite material had a relative permeability of 72 and a core-loss density of 200 mW/cm<sup>3</sup> at  $B_{\text{peak}}$  of 10 mT and 5 MHz. The loss density is almost 50% lower than that of a commercial 4F1 core with a relative permeability of 80. With these feedstock materials, one can start taking full advantage of the flexibility of the 3D printing platform to design and prototype high-performance, unique-shaped magnetic cores.

**Keywords**—additive manufacturing; feedstock materials for paste-extrusion 3D printer; magnetic components; powder-iron and ferrite

## I. INTRODUCTION

Magnetic components, such as inductors and transformers, are bulky and heavy, but necessary elements to store and convert electric and magnetic energies in switch-mode power electronics (PE) converters [1, 2]. To achieve higher conversion efficiency and power density, PE engineers can design novel structures of magnetic components [3-10] to shrink their sizes and improve material usage; however, they are frustrated by the availability of limited sets of core geometries and materials. The conventional fabrication processes of soft-magnetic cores, either powder-iron or ferrite, require pressure to shape core geometries, thus are expensive to make custom parts and difficult or impossible to make complex, intricate structures. Additive manufacturing or 3D printing, proven in other industries as an innovative manufacturing tool for rapid

prototyping and fabrication of complex structures, has potential in power electronics for making custom-designed magnetic components to improve converter efficiency and power density [11, 12].

There are only a few studies reporting on the application of additive manufacturing for fabricating soft magnetic components. In [13], it was shown that an ABS polymer filament with NiZn-ferrite fillers can be used in a Fused Deposition Modeling (FDM) 3D printer to make magnetic cores; but the relative permeability of the printed material was less than 2. A group in Oak Ridge National Laboratory (ORNL) [14] reported a 3D-printed ferrite E-core with relative permeability of also about 2. Proto-pasta [15] markets a polylactic acid (PLA)-Rustable magnetic iron composite with relative permeability up to 8 for a FDM 3D printer. Bollig et al. [16] utilized filaments consisting of a PLA polymer matrix and a particulate phase of only 40 wt% iron to print a transformer core. Recently we demonstrated [17-20] 3D-printing of planar inductors, toroid inductors, and constant-flux inductors by developing a powder-iron paste for a paste-extrusion 3D printer. The paste consisted of a mixture of magnetic particles and Benzocyclobutene (BCB); and after curing at 250°C, the 3D-printed powder-iron cores had relative permeabilities as high as 30 depending on the powder composition; however, the core-loss densities were significantly higher than those of commercial powder-iron cores with similar permeabilities. Thus, before the advantages of 3D printing can be fully realized to make high-performance power magnetics, feedstock materials that are specifically suited to a given printer platform and can be heat-treated without pressure to give high relative permeability and low core-loss density have to be developed.

In this work, we modified our previous powder-iron paste by changing the organic chemistry and the magnetic filler particles to reduce the curing temperature below 200°C and lower the core-loss density. We also formulated a NiZn ferrite paste that can be sintered without pressure at temperatures greater than 900°C. Different organic chemistries were used in the two pastes to get the desired flow and thermal characteristics for printing and subsequent heat treatment. Magnetic properties of the printed cores using each paste type were compared with those of corresponding commercial cores.

---

This work is supported by National Science Foundation (Grant No.1507314), Texas Instrument.

## II. EXPERIMENT

### A. Material formulations

#### 1) Powder-iron paste

The low-temperature curable powder-iron paste consisted of Trimethylolpropane triacrylate (TMPTA) (from SigmaAldrich Co. LLC) monomer solution and two kinds of magnetic fillers. One of the magnetic fillers was a round-shaped permalloy powder (from ESPI Metals) with an average particle size of 12  $\mu\text{m}$ ; and the other filler was flake-shaped sintered NiZn ferrite powder (from 3M) with an average particle size of 500  $\mu\text{m}$ . Organic substances (surfactant, solvent, etc.) were added into the paste to achieve desired particle dispersion, flowability, and thermal properties.

#### 2) NiZn ferrite paste

The ferrite paste consisted of 80 wt.% NiZn ferrite powder LSF 50 (from Powder Processing & Technology, LLC) in an aqueous solution of Methacrylamide and N,N'-methylenebisacrylamide (both from SigmaAldrich Co. LLC). Small amounts of Darvan 821A (from Vanderbilt Minerals, LLC) and Polyethylene glycol 400 (from Alfa Aesar) were added as dispersant and plasticizer respectively to achieve desired particle dispersion and flowability.

### B. Characterization of magnetic properties

To characterize the magnetic properties of the feedstock materials, toroid cores were fabricated by pouring the pastes into toroid-shaped molds followed by heat treatment. The powder-iron paste was heated to 200°C for one hour without external pressure to polymerize the monomer and solidify the structure. If lower curing temperature is desired, one can extend the curing time, e.g. to cure at 140°C, use two hours. The ferrite paste was heated to 950°C and held there for two hours under ambient pressure to burn out the organic compounds and densify or sinter. For all the cores, measurements of the relative permeability versus frequency were taken using a precision impedance analyzer (4294A; Agilent, Santa Clara, CA). Their core-loss densities were measured using a custom-designed setup described in [21, 22].

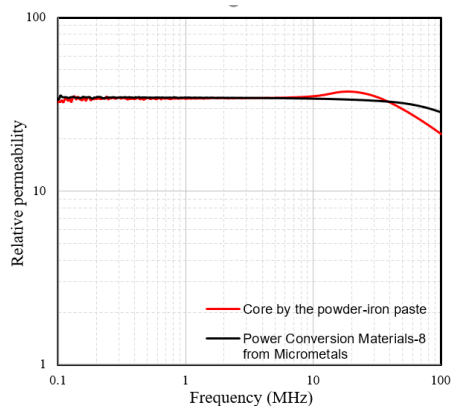


Fig. 1. Plots of relative permeability versus frequency of our powder-iron core and that of a Power Conversion Material-8 core from Micrometals.

## III. RESULTS AND DISCUSSION

### A. Relative permeability and Core-loss density

#### 1) Powder-iron

Shown in Fig. 1. are plots of relative permeability versus frequency of a powder-iron core and a commercial core (Power Conversion Materials-8) from Micrometals. Both have a similar relative permeability of 35 until 10 MHz. Fig. 2. shows their core-loss densities measured at 1MHz and room temperature. The core made by our powder-iron paste has a core-loss density of 110  $\text{mW}/\text{cm}^3$  at 10 mT excitation, which is 33% lower than that of the commercial core from Micrometals. It is worth pointing out that the commercial core requires pressure to make.

#### 2) NiZn ferrite

Shown in Fig. 3. are plots of relative permeability versus frequency of a core made by our NiZn ferrite paste and a commercial 4F1 core from Ferroxcube. Our ferrite core has a relative permeability of 72 versus 80 of the 4F1 core. The magnetic resonance frequency of our ferrite core is around 50 MHz versus that of the 4F1 core at around 30 MHz. Fig. 4. shows the core-loss densities measured at 5 MHz and room temperature. The core-loss density of our ferrite core is around 200  $\text{mW}/\text{cm}^3$  at 10 mT excitation, which is 50% lower than that of the commercial 4F1 core. Again, we point out that the commercial ferrite core requires pressure to compact the powder prior to sintering.

### B. Microstructure

#### 1) Powder-iron

Fig. 5. shows a SEM image of the powder-iron paste after curing. The microstructure consists of flakes of the sintered NiZn ferrite distributed in a matrix of the Permalloy powder and polymer binder. The fact that the ferrite flakes are large and aligned preferentially along the flux direction is the main reason for the high relative permeability of the composite.

#### 2) NiZn ferrite

Shown in Fig. 6. is a SEM image of the NiZn ferrite paste after sintering at 950°C for two hours. The microstructure still has about 10% porosity, which lowers relative permeability and likely increases core loss.

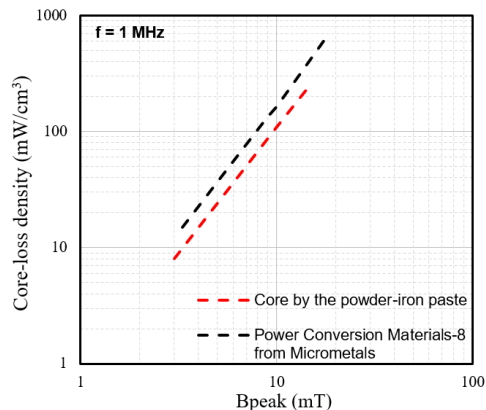


Fig. 2. Plots of core-loss density versus flux density at 1 MHz of powder-iron core and that of a Power Conversion Material-8 core from Micrometals.

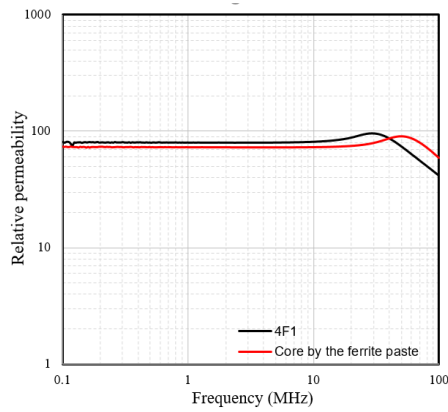


Fig. 3. Plots of relative permeability versus frequency of our NiZn ferrite core and a commercial 4F1 core.

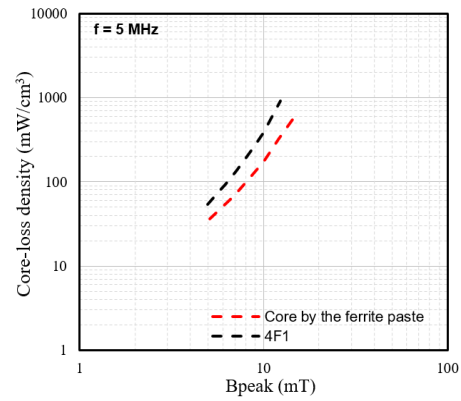


Fig. 4. Plots of core-loss density versus flux density at 5 MHz of our NiZn ferrite core and a 4F1 core.

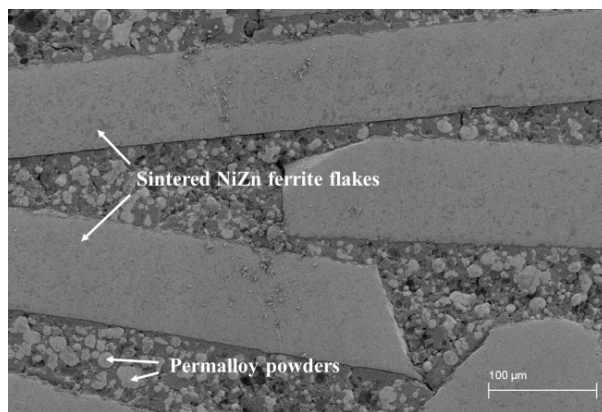


Fig. 5. SEM image of cured powder-iron paste.

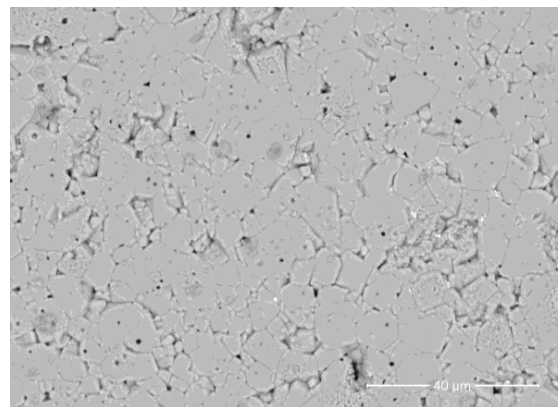


Fig. 6. SEM image of sintered NiZn ferrite paste.

### C. 3D-printing with the two types of feedstock

#### 1) Commercial paste-extrusion 3D printer

The paste-extrusion 3D printer (System 30M from Hyrel 3D) shown in Fig. 7. was used in this study. The printer was equipped with four feed-cartridge assemblies for extruding four different materials stored in syringes.

#### 2) Fabrication of toroid cores

Fig. 8. shows the printing of the feedstock pastes from the printer extruder head into toroid cores of each material. The printer is capable of building one layer of material to a thickness of about 100 microns. Multiple layers had to be printed to obtain the mm-thick parts shown in the figure. After printing, the cores were heat-treated, curing for the powder-iron and sintering for the ferrite respectively, to turn the materials into functional cores. We characterized the printed cores and found that their magnetic properties are similar to the corresponding molded cores described earlier.



Fig. 7. A commercial paste-extrusion 3D printer

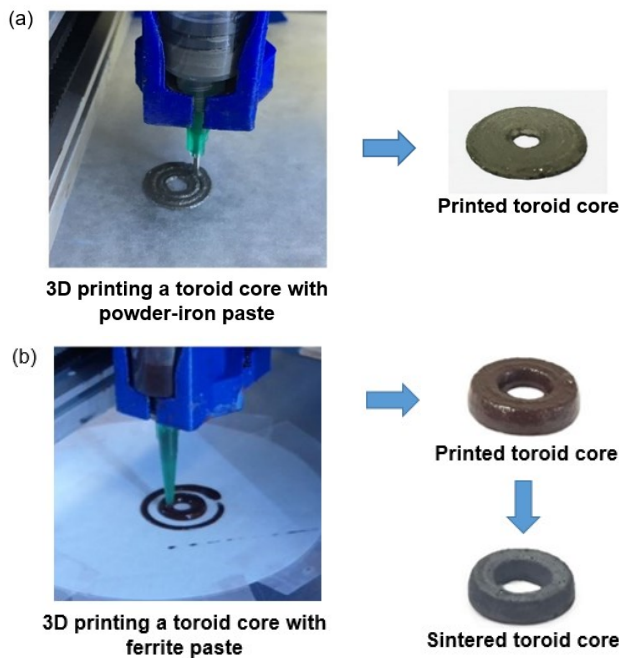


Fig. 8. (a) Printing of a toroid core using the powder-iron paste; (b) Printing of a toroid core using the ferrite paste.

#### IV. CONCLUSIONS

The field of power electronics can benefit from additive manufacturing by speeding up design and prototyping of innovative structures of power magnetics, but not before feedstock materials that are suited to individual 3D printing platforms are made available. To this effort, we formulated two types of magnetic paste as feedstock materials for a paste-extrusion 3D printer: (1) a low-temperature ( $< 200^{\circ}\text{C}$ ) pressure-less curable powder-iron paste and (2) a high-temperature ( $> 900^{\circ}\text{C}$ ) pressure-less sinterable NiZn ferrite paste. Both have desired flow characteristics to build thick structures layer-by-layer in the printer; and after their respective pressure-less heat treatments, the cores have magnetic properties that are comparable or better than their commercial counterparts. The feasibility of making high-performance magnetic components by 3D printing and pressure-less processing opens the door to power electronics researchers to explore unique core shapes, geometries, and materials to improve converter efficiency and power density.

#### ACKNOWLEDGMENT

We are grateful to National Science Foundation (Grant No.1507314) and Texas Instrument for financial support and Hyrel 3D Inc. for technical support.

#### REFERENCES

- [1] R. L. Billings, D. W. Dahringer, and A. M. Lyons, "Circuit elements dependent on core inductance and fabrication thereof," ed: Google Patents, 1993.
- [2] M. Chinthavali, C. Ayers, S. Campbell, R. Wiles, and B. Ozpineci, "A 10-kW SiC inverter with a novel printed metal power module with integrated cooling using additive manufacturing," in Wide Bandgap Power Devices and Applications (WiPDA), 2014 IEEE Workshop on, 2014, pp. 48-54: IEEE.

- [3] D. Xu and K. Ngo, "Optimal constant-flux-inductor design for a 5 kW boost converter," in Applied Power Electronics Conference and Exposition (APEC), 2013 Twenty-Eighth Annual IEEE, 2013, pp. 2436-2443: IEEE.
- [4] J. Lu, H. Jia, X. Wang, K. Padmanabhan, W. G. Hurley, and Z. J. Shen, "Modeling, design, and characterization of multitemperature bondwire inductors with ferrite epoxy glob cores for power supply system-on-chip or system-in-package applications," IEEE Transactions on Power Electronics, vol. 25, no. 8, 2010.
- [5] M. H. F. Lim, J. D. van Wyk, and Z. Liang, "Internal geometry variation of LTCC inductors to improve light-load efficiency of DC-DC converters," IEEE Transactions on Components and Packaging Technologies, vol. 32, no. 1, pp. 3-11, 2009.
- [6] K. Shirakawa, S. Ishibashi, Y. Kobayashi, F. Takeda, and K. Murakami, "A new planar inductor with ring-connected magnetic core," IEEE Transactions on Magnetics, vol. 26, no. 5, pp. 2268-2270, 1990.
- [7] H. Matsuki, N. Fujii, K. Shirakawa, J. Toriu, and K. Murakami, "Magnetic-multi-turn planar coil inductor," IEEE transactions on magnetics, vol. 27, no. 6, pp. 5438-5440, 1991.
- [8] A. Camarda, E. Macrelli, A. Romani, and M. Tartagni, "Design optimization of integrated magnetic core inductors," IEEE Transactions on Magnetics, vol. 51, no. 7, pp. 1-10, 2015.
- [9] H. Cui, K. D. Ngo, J. Moss, M. H. F. Lim, and E. Rey, "Inductor geometry with improved energy density," IEEE Transactions on Power Electronics, vol. 29, no. 10, pp. 5446-5453, 2014.
- [10] H. Cui and K. Ngo, "Constant-flux inductor with enclosed winding for high-density energy storage," Electronics Letters, vol. 49, no. 13, pp. 841-843, 2013.
- [11] P. Industry, "The free beginner's guide to 3D printing," ed: New York, NY, 2014.
- [12] I. Gibson, D. W. Rosen, and B. Stucker, Additive manufacturing technologies. Springer, 2010.
- [13] Y. Wang, F. Castles, and P. S. Grant, "3D printing of NiZn ferrite/ABS magnetic composites for electromagnetic devices," MRS Online Proceedings Library Archive, vol. 1788, pp. 29-35, 2015.
- [14] M. Chinthavali, "Additive manufacturing technology for power electronics applications," in Applied Power Electronics Conference and Exposition (APEC), 2016.
- [15] Proto-Pasta Composite PLA - Rustable Magnetic Iron. Available: <https://www.proto-pasta.com/products/magnetic-iron-pla>
- [16] L. M. Bollig, P. J. Hilpisch, G. S. Mowry, and B. B. Nelson-Cheeseman, "3D printed magnetic polymer composite transformers," Journal of Magnetism and Magnetic Materials, vol. 442, pp. 97-101, 2017.
- [17] Y. Yan, C. Ding, K. D. Ngo, Y. Mei, and G.-Q. Lu, "Additive manufacturing of planar inductor for Power Electronics applications," in 3D Power Electronics Integration and Manufacturing (3D-PEIM), International Symposium on, 2016, pp. 1-16: IEEE.
- [18] Y. Yan et al., "Additive Manufacturing of Magnetic Components for Heterogeneous Integration," in Electronic Components and Technology Conference (ECTC), 2017 IEEE 67th, 2017, pp. 324-330: IEEE.
- [19] Y. Yan, J. Moss, K. D. Ngo, Y. Mei, and G.-Q. Lu, "Additive manufacturing of toroid inductor for power electronics applications," in Energy Conversion Congress and Exposition (ECCE), 2016 IEEE, 2016, pp. 1-6: IEEE.
- [20] J. N. Calata, G.-Q. Lu, and K. Ngo, "Soft Magnetic Alloy-Polymer Composite for High-Frequency Power Electronics Application," Journal of Electronic Materials, vol. 43, no. 1, pp. 126-131, 2013.
- [21] M. Mu, "High frequency magnetic core loss study," Virginia Polytechnic Institute and State University, 2013.
- [22] M. Mu and F. C. Lee, "A new high frequency inductor loss measurement method," in Energy Conversion Congress and Exposition (ECCE), 2011 IEEE, 2011, pp. 1801-1806: IEEE.