Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

Deposition Controlled Magnetic Alignment in Iron-PLA Composites

Nathan D. Watson, and Paris Von Lockette

Department of Mechanical and Nuclear Engineering,
The Pennsylvania State University, University Park, PA, 16802

Abstract

By manipulating the print plane, infill direction, and geometry of Fused Filament Fabricated (FFF) iron-PLA composite parts, the alignment of their magnetic axes can be influenced. FFF printing allows control of deposition direction, which affects the arrangement of the iron within the composite part in ways that induce preferred magnetic orientation, the so-called easy axis. Qualitative results show the direction of deposition of the composite iron-PLA filament has significant effects on the response of the printed parts to an external magnetic field. Results further show that across different geometries, the easy axis of a printed part can be prescribed by setting the print plane and infill direction parallel to the desired orientation. Expected part geometry effects, along with the print plane and infill influences, suggest the phenomenon can be modeled using multi-scale demagnetizing field theories to print magneto-sensitive devices that can perform localized, controlled actuation in a uniform magnetic field.

Introduction

Additive manufacturing (AM) is a process used to create 3D parts by depositing material layer by layer. Fused Filament Fabrication (FFF) uses a heated extruder to melt and deposit material in a 2D pattern to create each layer. AM offers advantages over other manufacturing techniques by providing free complexity and a unique control over how the material is structured in a 3D part. This allows the fabrication of relatively inexpensive, highly customized low volume production. This allows for specific customization for individual applications or people.

Recent advances have led to the development of 3D printed structures with embedded electromagnetically sensitive inclusions for a range of applications including communications, locomotion, actuation, and control[1,2,3,4]. In these works, the inclusions were biased toward a preferential direction using an external, controlled, electromagnetic field generator that physically reorients the inclusions either before, during, or after deposition of the initial feed stock. The processing therefore necessarily requires additional equipment, complexity and ultimately expense beyond simple deposition of the existing stock material.

Previous work has shown that direction of deposition can affect a printed part's mechanical response to loading[5]. By controlling the direction of deposition, the extruded filament which make up a printed part can have a major axis on which the fibers lay. In magnetism the concept of a major axis plays an important role in how a part responds in a magnetic field. Magnetic materials may develop a so-called easy axis along which they are more susceptible to external fields, e.g. along the length of a nail or from the south to the north poles in a bar magnet. This work seeks to examine this phenomenon.

C. Huber, C. Abert, F. Brucknet et al. imbedded NdFeB particles in extrudable plastic filament and were able to use a dual feed extruder to mix NdFeB composite with a base plastic to vary the weight percentage throughout a printed part[6]. By changing the weight fraction at different parts of the geometry, they were able to design the remanence field around the part. While they mainly realized the effects of the weight fraction in the part they didn't research how other printing parameters effected the magnetic properties of the parts.

L. Bollig, M.Patton, G.Mowry et al. looked at how certain print parameters changed the magnetic properties of printed parts using Proto-Pasta Iron PLA composite[7]. They measured the response of test samples in the VSM after changing the infill percentage, angle of infill pattern, and number of parameter walls. While they were able to find differences based on how the part was oriented in the VSM, they didn't find how infill can play a major role in the magnetic properties of a part.

By manipulating some of the printing parameters of a printed part, the structure of the deposited fibers can be arranged in a way to make an easy axis for the part which causes the part to physically align with a uniform magnetic field. Both infill direction and print orientation create strong effects on the easy axis and by manipulating each, two constraining moments can be applied on a part to align a part in a particular orientation in a magnetic field. By setting a particular print orientation, an easy plane is created. The part orients itself in a way that makes the print plane parallel to the field. This allows the part to rotate freely on that plane with no opposing magnetic moment. By adding an infill direction perpendicular to the print plane, a second easy plane is created, and where those planes intersect is the easy axis, or the orientation the part takes in a uniform magnetic field.

Just as fibers want to align in a magnetic field in a part, the same principal can be used, but instead of moving the fibers in the part to align with the field, the 3D printer easily allows for the arrangement of fibers and lets the user define the orientation of the fibers before the print. As magnetic fibers are placed in a magnetic field; a magnetic moment is created in order to reduce the demagnetizing field and in turn reduce the Zeeman energy of the system.

Methods

When placed into a uniform magnetic field, the parts printed would align to the predefined easy axis. This meant that depending on the print parameters and print orientation set for printing a particular item like a cylinder, defined how the cylinder would align in the magnetic field. Cylinder A from figure 1 was printed on its side making the print plane along the axis of the cylinder. This allows the cylinder align itself parallel with the field. Cylinder B from figure 1 was printed vertically on the print bed making the print plane perpendicular to the cylinder. This makes the cylinder orient itself horizontally in the magnetic field.

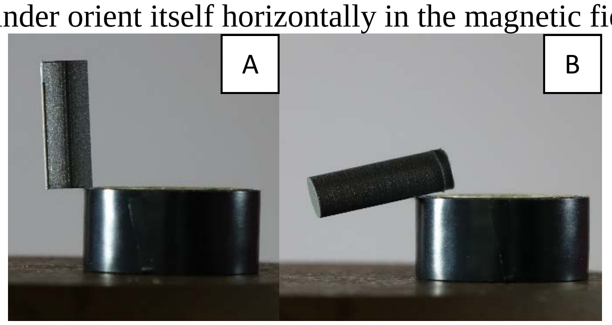

Figure 1: Cylinder [A] printed horizontally cylinder [B] printed vertically in a uniform magnetic field, being held in position by the magnetic moment on the print.

In order to test the magnetic response to the effects of infill direction and print plane orientation, samples were made to isolate each. By printing flat cylinders and rotating the cylinders along its axis, the geometry of the part was taken out of the test because the sample maintains its geometry at each angle the sample is tested at. To isolate the infill of the sample, the cylinder was printed flat on the print bed so that the print plane would be at the same orientation relative to the field as the cylinder is rotated. The infill direction in the sample was printed so that each deposited fiber was parallel and as seen in figure 3A. The sample designed to isolate the print plane was printed on its edge with the infill running from the base of the cylinder to the top. This way as the cylinder rotates about its axis the print plane changes while the infill stays perpendicular to the field as seen in figure 3B. A control was also printed, but instead the infill is comprised of concentric circles which makes the sample axially symmetric. The samples were tested in a vibrating sample magnetometer (VSM) as seen in figure 2. The samples were 8mm in diameter and 2mm tall.

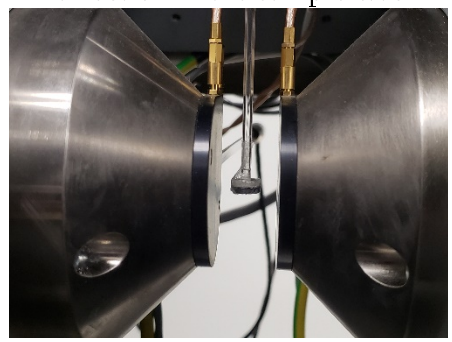

Figure 2: VSM machine testing a sample in the transverse position

The samples were printed on an Ultimaker 3 using Proto-Pasta iron PLA which is 45% iron by weight. [Proto-Pasta] The samples were then testing on a two tesla VSM in the transverse direction, rotating the parts on the axis of the cylinder. The samples were tested at 5 different angles, 0 degrees being where the field lines produced by the VSM is parallel to either the print plane or infill direction and 90 degrees being perpendicular. At each angle the samples were tested from -18900 Oe to 18900 Oe. The VSM is able to find at what field the sample saturates at each angle.

Results

When tested in the VSM machine, the samples showed that 3D printed parts can exhibit anisotropic properties by manipulating the printing parameters. For both the parallel infill sample and the print plane sample, the linear portion of the curve approached saturation faster in the orientation with the infill or print plane parallel to the field as seen in figure 3. Figure 4 shows the slope of the curves of the samples at each angle at 1000 Oe, which is at a linear portion of the curve. The sample with concentric circle infill did not show significant changes in the magnetization based on the angle of the sample in the VSM machine.

The saturation of the samples at each angle were normalized to 1 in order to account for the slight variations from the slight change in position in the VSM as the angle changes as well as the differences in mass of the samples. As the sample in the VSM machine rotated, the position between the magnetic pick up coils would change causing a difference in measured saturation while the saturation is not dependent on the position or angle of the magnetic material in the VSM machine[7]. The inconsistencies of the printing process also caused the samples to have different masses despite having an identical bulk shape. The more magnetic material in the VSM machine would raise the saturation of the sample. By normalizing the saturation to one, it also corrects for the inconsistencies of the mass and the possible slight inconsistencies in the weight fraction of the Proto-Pasta iron PLA.

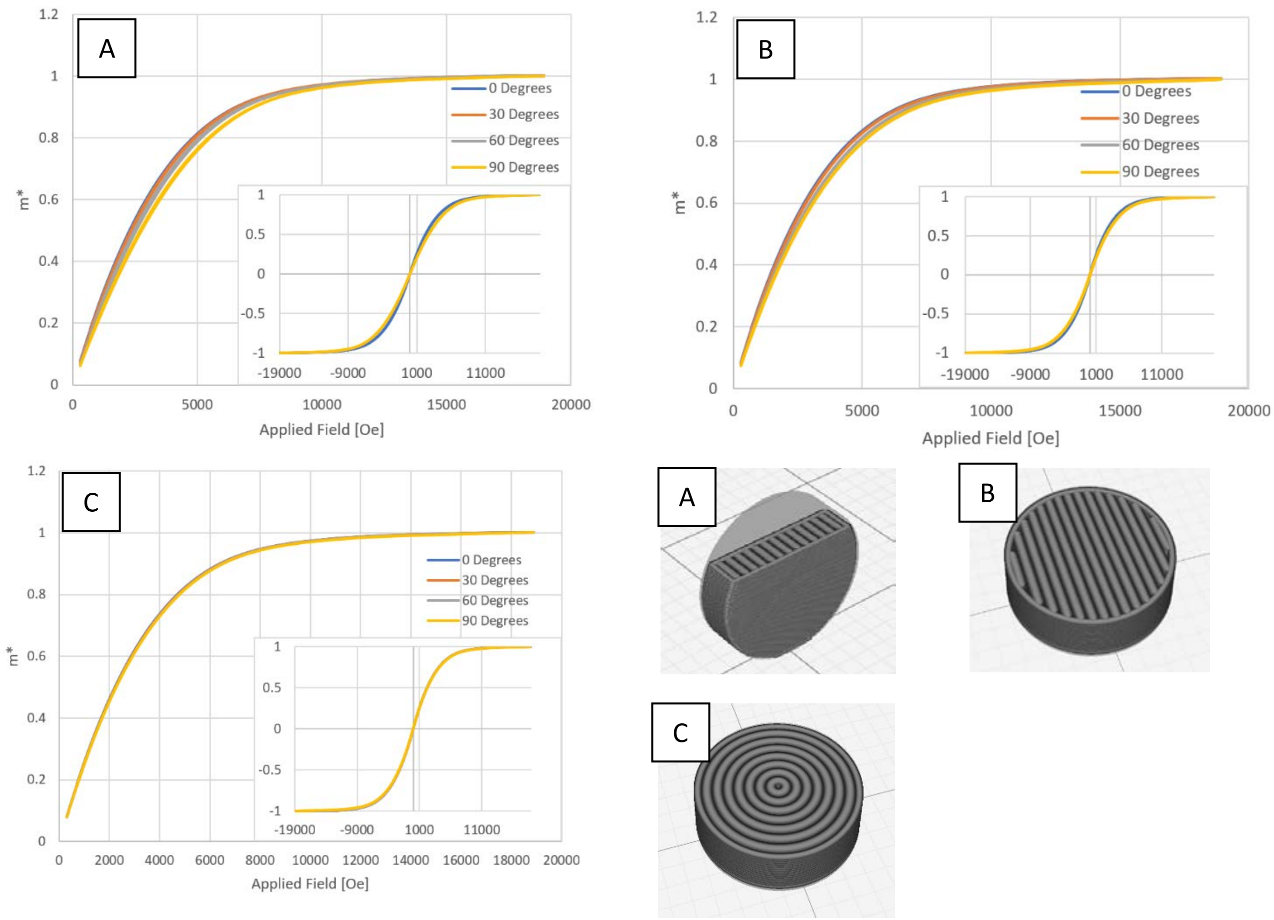

Figure 3: Hysteresis Curve of the [A] print plane, [B] infill direction, and concentric infill samples at 0, 30, 60, and 90 degrees.

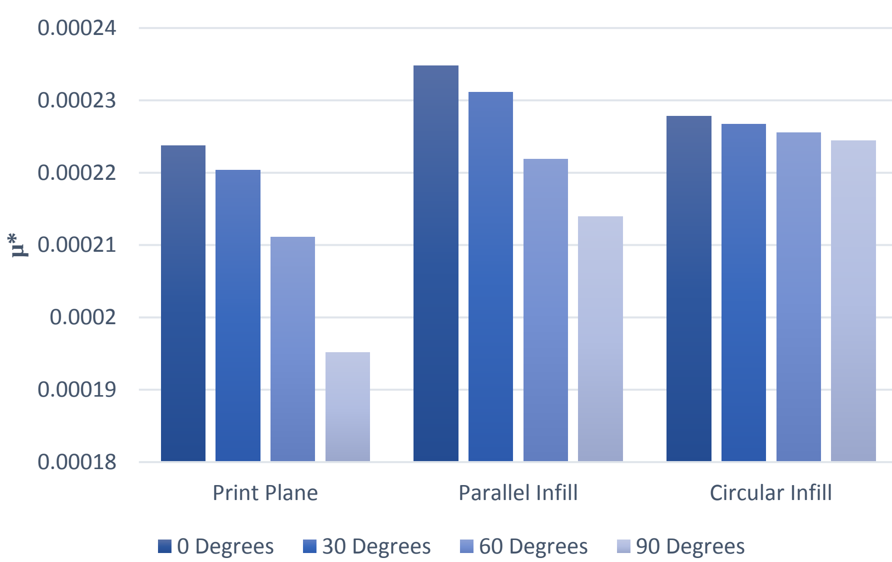

Figure 4: Slope of the normalized hysteresis curve at each angle at 1000 Oe.

Analyses and Discussion

The authors believe two factors, well known and important to magnetization response, produce the results shown in this work. First is the concept of the easy axis, a geometry-dependent direction toward which induced magnetization is biased. In this work the authors contend that the infill and print plane are able to create easy axes apart from the bulk part geometry. The orientation of the easy axis is critical to actuation, e.g. magnetic torques acting on the bulk part. When subjected to an applied magnetic field, $\boldsymbol{H}_{ext}$, a magnetic body will tend to align its easy axis with that external field direction. The underlying mechanism of alignment is minimization of the Zeeman energy[9], given as

$$U = -\mu_0 \boldsymbol{m} \cdot \boldsymbol{H}_{ext} \quad (1)$$

where $\boldsymbol{m}$ is the magnetization of the object in question and $\boldsymbol{H}_{ext}$ is the external field to which the object is exposed. While the easy axis is not necessarily collinear with $\boldsymbol{m}$, $\boldsymbol{m}$ is biased toward the easy axes direction. A thorough discussion of this phenomena is beyond the scope of this work but may be found in any text on magnetic behavior of materials[9].

From (1) it is clear that the object will tend to have its internal magnetization, and hence its easy axis, aligned with the external field. This tendency produces the well-known magnetic torque exerted on magnetic objects in an external field that has been used as an actuation mechanism in magneto-active composites[10,11,12,13]. As seen in figure 1, the bulk actuation of the printed part follows the easy axes created by preferential infill or print plane orientation, which may be in opposition to the easy axes expected from the bulk geometry.

The second important concept is that of the stray field, the external magnetic field generated by a magnetically susceptible body when the body is exposed to an external field. This stray field is important because it affects neighboring magnetic bodies by changing the external field local to them. In the case of soft magnetic material, such as the iron-PLA composites used herein, the internal magnetization can be expressed by

$$\boldsymbol{m} = \mu \boldsymbol{H}_{\boldsymbol{ext}} \quad (2)$$

where μ is the magnetic permeability of the composite. Stray fields, $\boldsymbol{H}_s$, arise from all discrete magnetic bodies surrounding the body in question such that the magnetization of the body in question can be expressed as

$$\boldsymbol{m} = \mu\left(\boldsymbol{H}_0 + \sum_i \boldsymbol{H}_{s_i}\right) \quad (3)$$

where $\boldsymbol{H}_0$ is the external field applied to the body in question and i sums the contribution of the stray fields of all discrete, magnetically susceptible bodies in the system to the external field at the body in question. From (3) it is clear that if we ignore stray fields, the magnetization of the body, in the small field region, would nominally scale linearly with $\|\boldsymbol{H}_0\|$. However, the inclusion of stray fields complicates matters, allowing the size, shape, orientation, and composition of neighboring magnetic bodies to influence magnetization response. In this work, the stray fields differentially affect the magnetization response of our printed geometries by diminishing the local field in cases where parallel planes are normal to the measurement axis and enhancing cases where parallel planes are parallel to the measurement axes, yielding the results of figure 5.

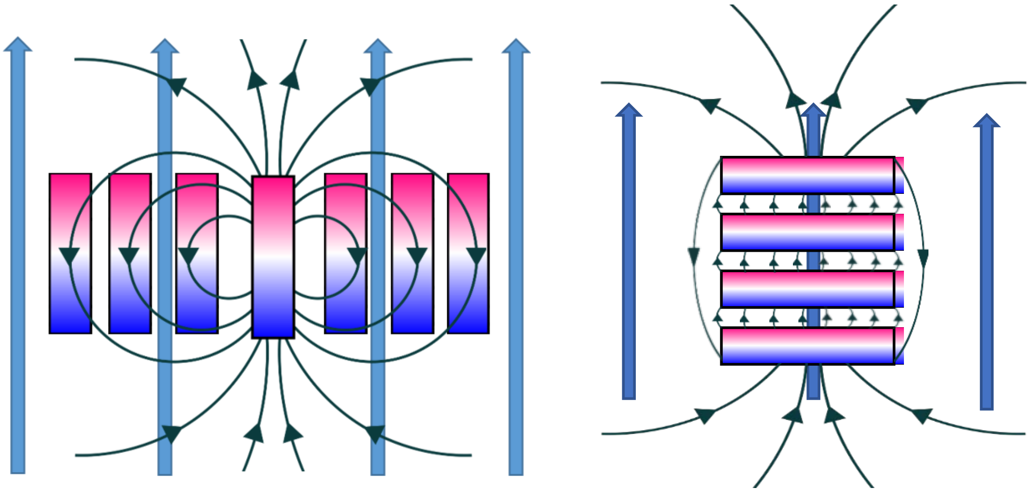

Figure 5: Iron PLA fibers in a magnetic field. Parallel to the field on the left and perpendicular to the field on the right.

Acknowledgements

The authors acknowledge Corey Breznak, Ph.D student in the Penn State MNE department, for his assistance with the VSM machine.

References

1. Pa, P., Larimoe, Z., , Parsons, P, Mirotznik, M., *Multi-material additive manufacturing of embedded low-profile antennas.* Electronics Letters, 2015. **51**(20): p. 1561-1562.

2. Kokkinis, D., M. Schaffner, and A. R. Studart. "Multimaterial Magnetically Assisted 3d Printing of Composite Materials." *NATURE COMMUNICATIONS* 6 (2015): 8643.

3. Bruyas, A., F. Geiskopf, and P. Renaud. *Toward unibody robotic structures with integrated functions using multimaterial additive manufacturing: Case study of an MRI-compatible interventional device*. IEEE.

4. Zocca, Andrea, Paolo Colombo, Cynthia M. Gomes, and Jens Günster. "Additive Manufacturing of Ceramics: Issues, Potentialities, and Opportunities." *Journal of the American Ceramic Society* 98, no. 7 (2015): 1983-2001.

5. Chakraborty, Debapriya, B. Aneesh Reddy, and A. Roy Choudhury. "Extruder Path Generation for Curved Layer Fused Deposition Modeling." *Computer-Aided Design*, vol. 40, no. 2, 2008, pp. 235-243.

6. Huber, C., et al. "3D Printing of Polymer-Bonded Rare-Earth Magnets with a Variable Magnetic Compound Fraction for a Predefined Stray Field." Scientific Reports, vol. 7, no. 1, 2017, pp. 1.

7. Bollig, Lindsey M., et al. "Effects of 3-D Printed Structural Characteristics on Magnetic Properties." IEEE Transactions on Magnetics, vol. 53, no. 11, 2017, pp. 1-6.

8. O'Handley, Robert C. Modern Magnetic Materials: Principles and Applications. Wiley, New York, 2000.

9. Cullity, B. D., and C. D. Graham. Introduction to Magnetic Materials. 2 ed. Hoboken, New Jersey: John Wiley & Sons, Inc.,, 2009.

10. vonLockette, P. von, S. E. Lofland, J. Biggs, J. Roche, J. Mineroff, and M. Babcock. "Investigating New Symmetry Classes in Magnetorheological Elastomers: Cantilever Bending Behavior." *Smart Materials and Structures* 20, no. 10 (2011): 105022.

11. Sheridan, Robert, Roche Juan, E. Lofland Samuel, and R. vonLockette Paris. "Numerical Simulation and Experimental Validation of the Large Deformation Bending and Folding Behavior of Magneto-Active Elastomer Composites." *Smart Materials and Structures* 23, no. 9 (2014): 094004.

12. Sung, Elaine, Anil Erol, Mary Frecker, and Paris von Lockette. "Characterization of Self-Folding Origami Structures Using Magneto-Active Elastomers." no. 50169 (2016): V05BT07A020.

13. Crivaro, Adrienne, Robert Sheridan, Mary Frecker, Timothy W. Simpson, and Paris Von Lockette. "Bistable Compliant Mechanism Using Magneto Active Elastomer Actuation." *Journal of Intelligent Material Systems and Structures* 27, no. 15 (2016): 2049-61.