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Magnetic Field Influence on the Mechanical Properties of 3D-Printed Magnetorheological Composites

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Abstract — Magnetorheological (MR) materials, such as ferromagnetic particle-reinforced composites, exhibit tunable mechanical properties under magnetic fields, which are crucial for innovative applications in automotive, aerospace, and medical devices. However, accurately modeling their behavior remains challenging due to the intricate interactions between the magnetic particles and the matrix. This research explores how applying a magnetic field during additive manufacturing, also known as 3D printing, can affect the alignment and distribution of magnetic particles, influencing the material's mechanical properties. Preliminary results show that magnetic fields significantly alter mechanical properties, including toughness and Young's modulus, suggesting the potential for real-time control during fabrication. Iron-reinforced polylactic acid (PLA) filament is magnetized during the fused filament fabrication (FFF). ASTM D638 Type IV specimens are printed under three conditions: without a magnetic field, above a single samarium cobalt magnet, and between two samarium cobalt magnets. All samples were printed using 0- and 90-degree raster for anisotropic behavior evaluation. The effects of these different orientations on the material's mechanical properties and microstructure are examined using tensile testing and optical microscopy. The findings provide valuable insights into the influence of magnetic field direction and field strength on MR materials, which contribute to developing these materials for enhanced and tunable structural integrity.

Keywords - magnetorheological materials; magnetic field; additive manufacturing; Young's modulus; toughness; ultimate tensile strength; polylactic acid.

I. Introduction

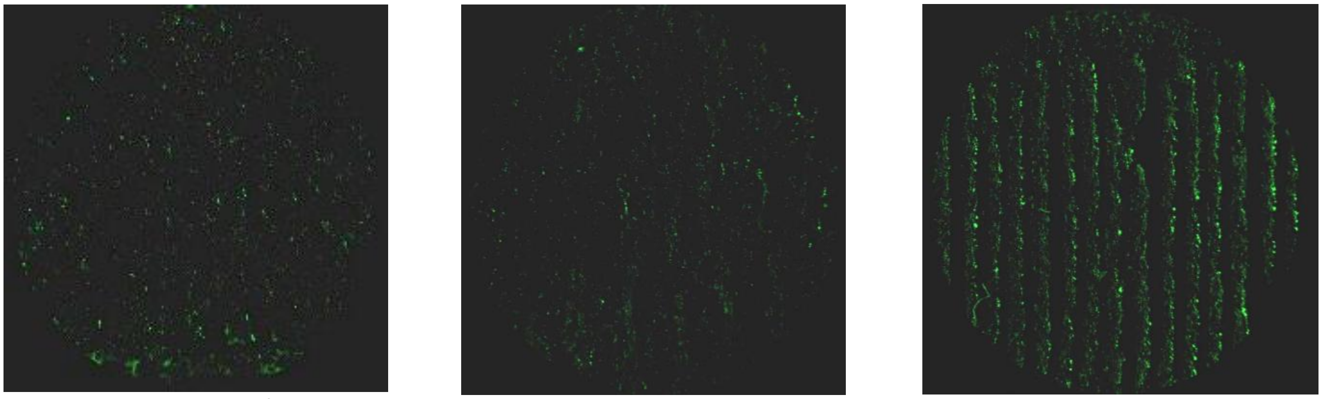
Additive manufacturing (AM) has revolutionized modern fabrication by enabling the rapid production of complex structures with high precision, reduced material waste, and customizable properties. Fused filament fabrication (FFF) is widely adopted for its cost efficiency, ease of implementation, and compatibility with various thermoplastics, including composites [1]. By integrating functional additives into polymer matrices, FFF has expanded beyond conventional applications, allowing the development of smart materials that respond to external stimuli paper such as heat, light, electricity, and magnetic fields [2][3].

One emerging class of such materials is magnetorheological (MR) composites with a polymer matrix embedded with magnetically responsive particles. When exposed to an external magnetic field, these composites can dynamically alter their mechanical and physical properties [4]. This makes them valuable for applications in automotive (e.g., vibration-damping components [1][5]), aerospace [5](e.g., morphing structures [6]), soft robotics [7], and biomedical devices (e.g., implants, prosthetics).

One key challenge is controlling the distribution and alignment of magnetic particles during fabrication. In traditional FFF, particles distribute randomly due to extrusion dynamics, leading to mechanical performance and anisotropy inconsistencies. The lack of control over particle orientation can limit the performance of MR composites in applications that require directional mechanical strength or controlled magnetic responsiveness [8].

An external magnetic field is proposed to address the challenge of manipulating particle alignment and optimizing material properties during the FFF printing process. Research indicates that orienting magnetic particles during fabrication can enhance tensile strength, stiffness, and mechanical stability, particularly for load-bearing applications [4][9]. However, there is still limited research quantifying how different magnetic field conditions—such as field strength, field direction, and particle orientation—affect the mechanical performance and microstructural characteristics of printed MR composites.

This study explores the potential of magnetic field-assisted 3D printing as a novel method to enhance and dynamically control the mechanical properties of iron-filled polylactic acid (PLA) composites. By investigating how different magnetic field configurations influence particle alignment, anisotropic behavior, and mechanical properties, this research contributes to developing advanced functional materials with tunable structural integrity. These findings could pave the way for customized smart materials that adapt to specific engineering



A) No magnetic field B) Above one magnet C) Between two magnets

FIGURE 1: OPTICAL MICROSCOPY IMAGES

demands improving the efficiency and performance of MR composites in various technological domains.

II. Materials and Methods

A. *Materials*

Iron-filled PLA filament from PROTOPASTA, a commercially available magnetically responsive polymer composite, was used in this study. This filament contains approximately 45 wt% iron particles dispersed within a PLA matrix, providing ferromagnetic particle behavior while maintaining printability. The iron content in the filament enables interaction with external magnetic fields, making it suitable for the study.

Samarium cobalt (SmCo) permanent magnets from Jobmaster Magnets Canada Inc. were used to introduce an external magnetic field during printing. These magnets have high coercivity, excellent thermal stability, and strong magnetic flux density, making them ideal for maintaining a consistent magnetic influence on the printed material. The magnets have a diameter of 2.54 cm and 0.635 cm of width.

B. *Experimental Setup*

Dog-bone samples were printed using a Prusa MK4 FFF 3D printer, which was modified to accommodate magnet-assisted printing. The printing parameters were carefully optimized to prevent interference between the heated print bed and the magnetic field, ensuring uniform extrusion and minimal thermal effects on particle alignment. The final printing settings are shown in Table 1.

TABLE I: PRINTING SETTINGS

Parameter	Value
Printer Model	Prusa MK4
Nozzle Diameter	0.4 mm
Extrusion Temperature	230°C
Print Bed Temperature	30°C
Layer Thickness	0.2 mm
Raster orientations	0° and 90

To analyze the effect of magnetic fields on mechanical properties, specimens were printed under three distinct magnetic field conditions:

1. Without a magnetic field (control condition)
2. Above a single SmCo magnet
3. Between two SmCo magnets

To investigate anisotropic mechanical behavior, each condition was printed with two raster orientations:

- 0° raster – Print lines aligned with the tensile loading direction.
- 90° raster – Print lines perpendicular to the tensile loading direction.

Each sample set was printed three times to ensure statistical accuracy.

C. *Characterization Methods*

a) *Mechanical Testing*

Tensile testing was performed using a universal testing machine (UTM) following the ASTM D638-14 standard for tensile properties of plastics [10]. ASTM D638 Type IV specimens were tested under controlled environmental conditions at approximately 23°C. The mechanical properties analyzed included ultimate tensile strength (UTS), Young's modulus, and toughness.

b) *Microstructural Analysis*

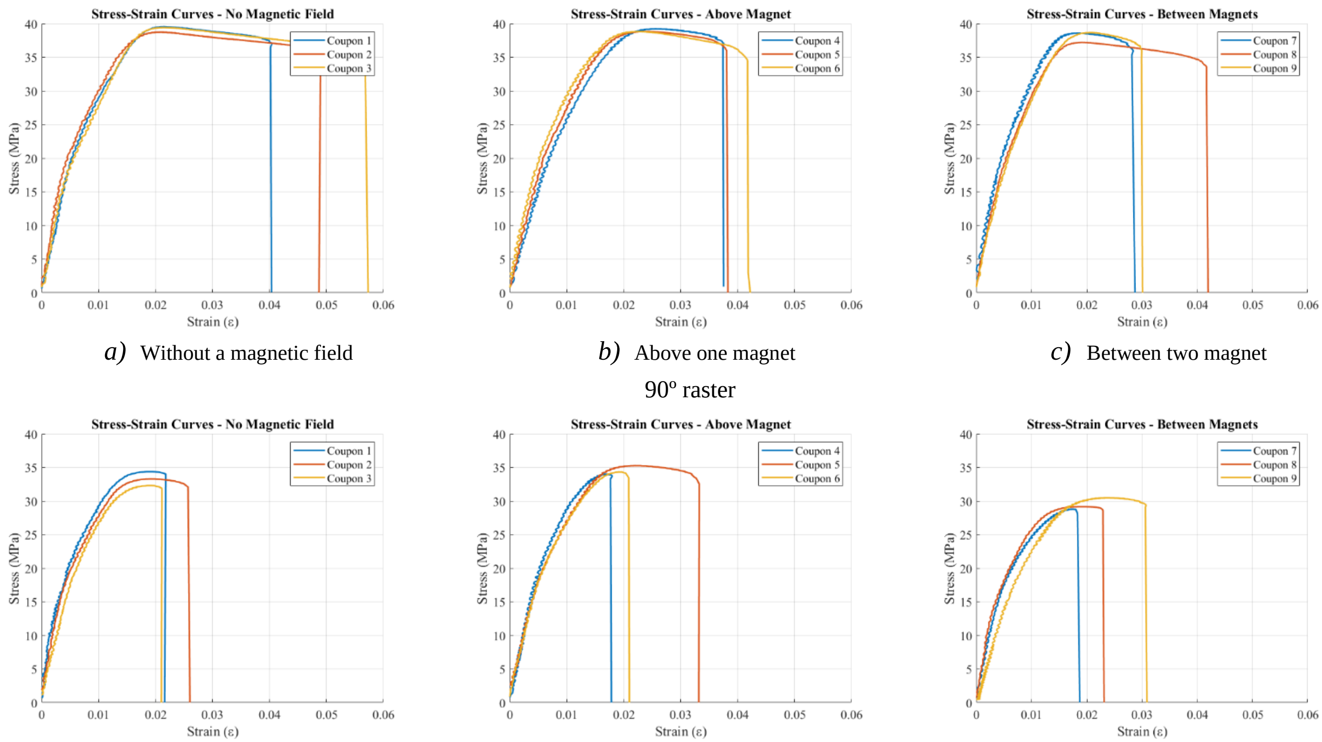
To examine the particle alignment and interfacial bonding between iron particles and the PLA matrix, optical microscopy images were taken with an ECHO Rebel Hybrid Microscope at 2.5x.

III. Results And Discussions

This section presents the mechanical characterization of iron-filled PLA composites printed under different magnetic field conditions and raster orientations. The results highlight how magnetic particle alignment influences Young's modulus, UTS, and toughness, with supporting microscopy images providing insight into particle distribution.

0º raster

90º raster



a) Without a magnetic field   *b)* Above one magnet   *c)* Between two magnet

d) Without a magnetic field   *e)* Above one magnet   *f)* Between two magnet

FIGURE 2: STRESS-STRAIN CURVES

A. *Microscopic Analysis of Particle Alignment*

Optical microscopy images from Fig. 1 were used to analyze the distribution of iron particles within the PLA matrix. The green dots in the figures represent reflections from the iron particles.

g) No Magnetic Field

Without a magnetic field, the iron particles are randomly dispersed throughout the matrix, with no precise directional alignment. This random dispersion may contribute to a higher stiffness as the isotropic particle distribution likely reinforces the structure evenly in multiple directions.

h) Above One Magnet

When printed above a single magnet, the particle distribution decreases density compared to the no-field condition. This suggests that the magnetic field partially influences particle migration, potentially leading to localized clustering or slight repulsion effects during the extrusion process. This moderate alignment may be translated into some level of interlayer reinforcement without excessive anisotropy.

i) Between Two Magnets

The most significant particle alignment occurs between two magnets, where the iron particles are oriented along the raster direction. This highly structured alignment suggests the strong lateral magnetic field forces the particles into a preferred orientation during deposition. While this controlled alignment might benefit magneto-responsive applications, it also introduces weaknesses perpendicular to the alignment direction.

B. *Mechanical Properties*

Mechanical properties were analyzed based on the tensile testing data by calculating the Stress-Strain Curves shown in Fig. 2.

a) Effect of Magnetic Field on Young's Modulus

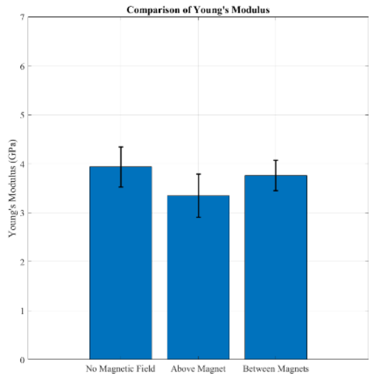
Results show that Young's modulus was higher with two magnets than printed above a single magnet in both raster conditions. This trend suggests that controlled particle alignment enhances stiffness.

At 90°, stiffness increased due to improved load distribution perpendicular to the raster direction. The intermediate stiffness in the two-magnet condition indicates that a well-aligned particle structure reinforces the material effectively, improving interlayer bonding. However, the lowest stiffness observed above a single magnet suggests that an uneven or partial alignment of particles may create microstructural discontinuities, reducing overall rigidity.

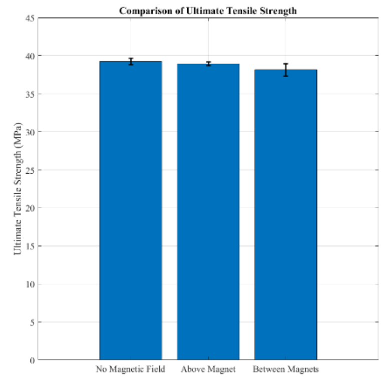
b) Effect of Magnetic Field on Ultimate Tensile Strength (UTS)

The UTS trends differ from Young's modulus, with no significant difference between the no-field and above-one magnet conditions. However, a marked decrease in UTS is observed when printed between two magnets, particularly in the

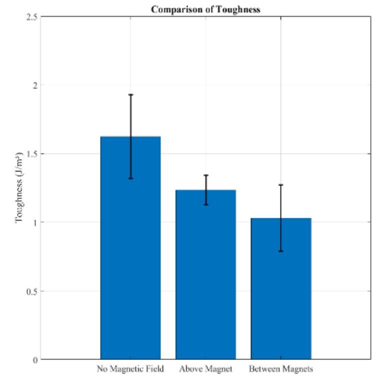
0º raster



c) Young's Modulus comparison without a magnetic field

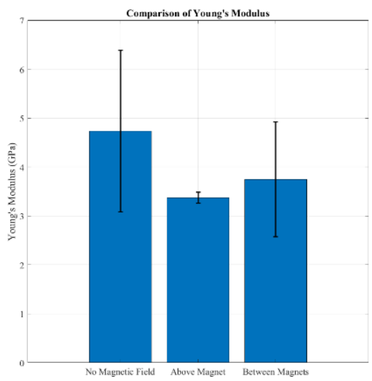


d) UTS comparison above one magnet

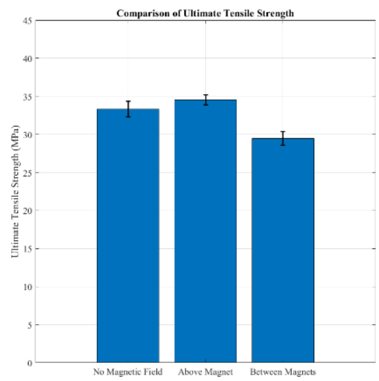


e) Toughness comparison between two magnet

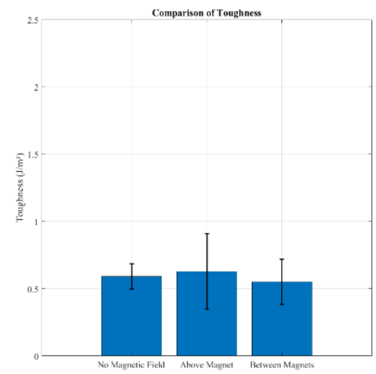
90º raster



f) Young's Modulus comparison without a magnetic field



g) UTS comparison above one magnet



h) Toughness comparison between two magnet

FIGURE 3: MECHANICAL PROPERTIES COMPARISON

90° raster orientation. This suggests that moderate particle alignment does not significantly impact tensile strength.

However, the more substantial alignment in the two-magnet condition may introduce stress concentration zones or anisotropic weaknesses, leading to reduced UTS.

i) Effect of Magnetic Field on Toughness

Toughness is the property that exhibits the most differences across magnetic field conditions with 0º raster, as shown in c) Fig. 3. Toughness was highest in the no-field condition, likely due to a more isotropic particle distribution, which minimizes stress concentration. The two-magnet condition, in contrast, may have induced localized stress zones due to strong particle alignment, reducing overall fracture resistance. The significant drop in toughness between two magnets suggests that strong particle alignment may create stress localization, leading to brittle failure. Moderate field exposure (above one magnet) helps retain better toughness, while the absence of a magnetic field provides the best overall toughness due to a more isotropic microstructure.

C. Correlation Between Microscopy and Mechanical Performance

The microscopic observations strongly correlate with the mechanical test results, supporting the hypothesis that particle alignment influences stiffness, strength, and fracture behavior. Without a magnetic field, randomly dispersed particles contribute to higher stiffness and toughness due to a more isotropic reinforcement effect. When printed above one magnet, the moderate particle alignment enhances UTS by improving interlayer bonding, though it slightly reduces stiffness. However, excessive alignment between two magnets results in the lowest UTS and toughness, as particle clustering along the raster direction introduces weak points, leading to stress localization and brittle failure.

IV. CONCLUSIONS

This study investigated the impact of magnetic field-assisted FFF on iron-filled PLA composites' mechanical properties and microstructure. The results demonstrate that magnetic fields significantly influence particle alignment, altering stiffness, tensile strength, and toughness.

Key findings indicate that printing without a magnetic field yields the highest Young's modulus (~5 GPa) and toughness (~1.5 J/m³) due to the random dispersion of iron particles, which enhances isotropic reinforcement. Moderate magnetic exposure (above a single magnet) slightly improves ultimate tensile strength (35 MPa) by promoting better interlayer bonding. Excessive alignment in two-magnet conditions reduces UTS and toughness, making the material more brittle.

Microscopy analysis confirmed these trends, showing a random particle distribution in the no-field condition, partial alignment above one magnet, and strong directional alignment between two magnets. These structural differences directly correlate with mechanical performance, underscoring the importance of optimizing magnetic field parameters for specific engineering applications.

These findings suggest that magnetic field-assisted 3D printing is a viable strategy for tailoring mechanical properties in MR composites. Printing without a magnetic field is preferable for applications prioritizing stiffness and impact resistance. For enhanced tensile strength, moderate magnetic exposure is beneficial, whereas controlled particle alignment between two magnets may be helpful for magneto-responsive applications despite the trade-off in mechanical properties.

Future work will investigate the impact of real-time magnetic field modulation during printing, explore alternative particle-matrix compositions, and conduct fatigue testing to assess long-term structural integrity in dynamic applications. Additionally, real-time magnetic field control during printing could enable dynamic material tuning, paving the way for adaptive and multifunctional 3D-printed composites with optimized performance.

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