Manufacturing of Soft Magnets using the Fused Filament Fabrication Process

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Abstract

Rare-earth (RE) materials are currently used to fabricate permanent magnets through various additive manufacturing (AM) methods. Fused filament fabrication (FFF) is one of the most commonly used polymer-based AM methods and has recently been used to produce metal-matrix composites, known as "green parts," using a metal powder-infused filament[1]. The FFF method has gained much attention in various industries including the automotive, aerospace, and medical fields. Therefore, involving RE in the FFF process using magnetic powder-infused filaments promises to result in the fabrication of low-cost, efficient, and complex magnetic components based on application areas. This module introduces the FFF process and provides a case study for high school and technical college students to gain a fundamental understanding of how magnetic powders are infused and how parts are fabricated using this method.

Objectives: Students will learn how feedstock material is manufactured using FFF technology and how to fabricate magnetic parts using this method. The case study will be conducted on the production of soft composite magnets. Students will fabricate the soft magnetic parts with different process parameters and conduct an experiment to characterize the differences in magnetic properties of various samples.

Keywords: Additive manufacturing, fused filament fabrication, magnetic parts, soft composite magnets.

Activity: Multi-day classroom experiment, including the sample manufacturing and testing.

Manufacturing of Soft Magnets using the Fused Filament Fabrication Process

Time Required: One or more 45-min. class periods (or lab periods), depending on level of the class.

Grade Level: Secondary or post-secondary.

Equipment and Supplies Needed

- ✓ Fused filament fabrication 3D printer
- ✓ Chosen iron PLA composite filament from Proto Pasta Company (see reference list)
- ✓ Simple CAD software or STL file provided
- ✓ 3D printing/slicer software appropriate to the printer
- ✓ Commercially available NdFeB magnet or equivalent
  - o Any size could be used
- ✓ Ruler to measure distance
  - o Ruler app could be installed and used in smart phones

Instructor Background and Notes (slide 3)

Hi-tech, miniaturized green products have become essential to everyday life, and as consumer preferences continue to shift in this direction, the supply of RE elements becomes a significant concern. The FFF method is known as an efficient, low-cost manufacturing process and could be used to produce permanent magnets while limiting waste and without the necessary tooling of conventional processes.

In this module, the FFF process is used to demonstrate magnet fabrication using an iron-reinforced polymer matrix filament to demonstrate the process without actually using REs. The preparation of filament material is also demonstrated in the following section. CAD software is used to design the simple shapes in the class. Free online software (including Tinker CAD and AutoCAD) should be available for simple designs and designing these models will only require a 2D sketch and one extrusion.

The goal of this module is to show students how the magnetic filament material is fabricated using the extrusion process and how this filament material could be used to fabricate soft magnetic parts using the FFF process. Here, we are essentially testing the difference between magnetic properties of 3D printed magnets and how different process parameters, such as infill density, affect the magnetic properties. While other process parameters could be changed, such as different layer heights, layer widths, printing temperature, and printing speed, this module only focuses on the difference in magnetic properties with respect to the infill percentages.

General concept of feedstock filament preparation (slide 4-5)

This aim of this section is to provide an overview of the filament extrusion process, which will help students to understand the filament making process. This is for illustration only, as the module experiment uses purchases filament material.

To make the metal matrix composite infused with iron particles, an extrusion of the filament process was introduced, and the single-nozzle 3D printer (ZMorph VX) was utilized to fabricate the net-shaped magnetic material. The workflow from raw material to finished product (filament feedstock) is schematically shown in Figure 1 [2]. The setup includes a low-temperature furnace; filament extruder with 1.75 mm diameter hardened

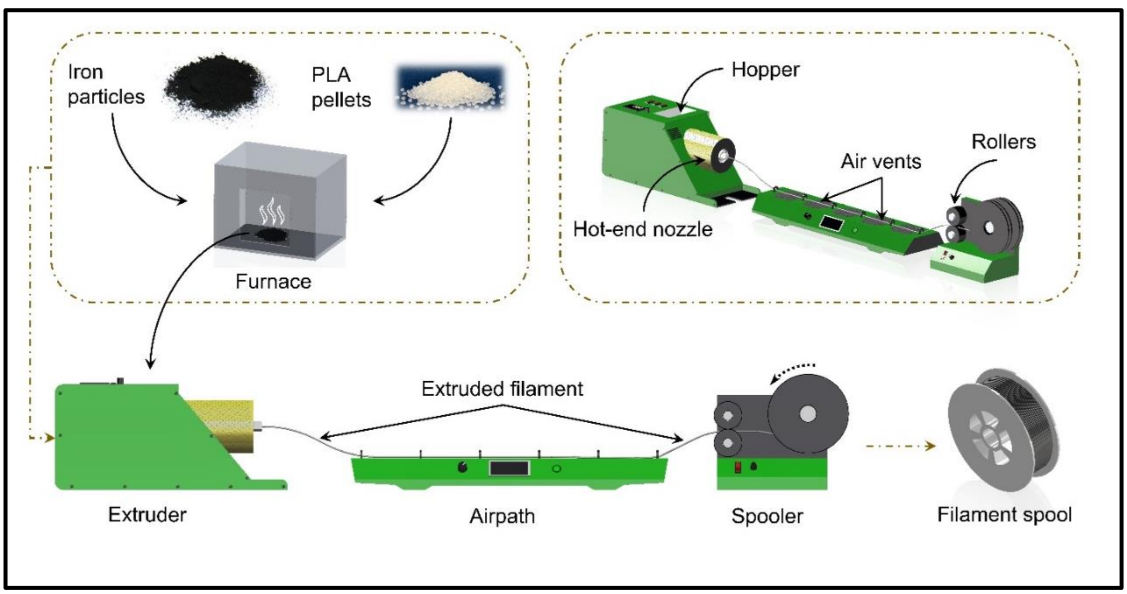

Fig. 1. Preparation of feedstock material using filament extrusion process.

steel nozzle head; air path; filament spooler; and finally, the extruded filament. The low-temperature furnace was utilized to dry the polylactic acid (PLA) pellets and iron powders before using them for filament manufacturing. This reduces the formation of bubbles during extrusion due to the absorbed moisture inside the powder and PLA pellets. Here, a uniform diameter of the extruded filament is achieved by adjusting the extruder parameters such as extrusion temperature, speed, and the air path fan speed. Dried raw materials are stirred together to obtain a uniform distribution of iron particles and PLA pellets. The materials are then poured into the hopper, which melts the polymer with the iron particles, and mixes them properly to obtain a homogeneous distribution of particles at the hot end of the nozzle. After that, the air path is used to cool the filament before spooling it.

This process is provided to the students to demonstrate how the filaments are made and how one can alter the material properties of polymers by adding the different reinforcements/particles. This allows RE magnets to be fabricated using NdFeB powders for actual permanent magnet production.

In this module, the goal is to provide a general knowledge base for students to understand the phenomena behind the filament preparation process. The process will follow the magnetic part fabrication using commercially available 1.75mm iron PLA filaments, from Proto Pasta company. These filaments can also be purchased and printed in any desktop 3D printers and are composed of 40 wt.% iron powders. The iron particulate is roughly isotropic with a diameter of ≈ 40 micrometers [3].

Fused Filament Fabrication of Magnetic Specimens (slide 6-9)

For this module, a ZMorph VX high precision multi-material FFF machine was utilized. However, any other commercially available 3D printer with 1.75mm extrusion system could be used. Since the iron PLA filament is slightly brittle, it needs special attention before it is put into the printer. Generally, the direct filament feed FFF machine is desirable because it works better with brittle filaments. Figure 2 shows the general FFF process using a metal powder-infused filament. The process is known as the “layer-by-layer” fabrication method in which the build platform moves down after depositing each cross section of a part based on the 3D computer aided design (CAD) model. Extrusion temperature was set between 195°C and 215°C, and adhesive was used on a glass-type print bed to ensure proper adhesion of the first layer. Printing speed was set to 25 mm/s, and the speed for the first layer was adjusted to 40% of the main printing speed. First

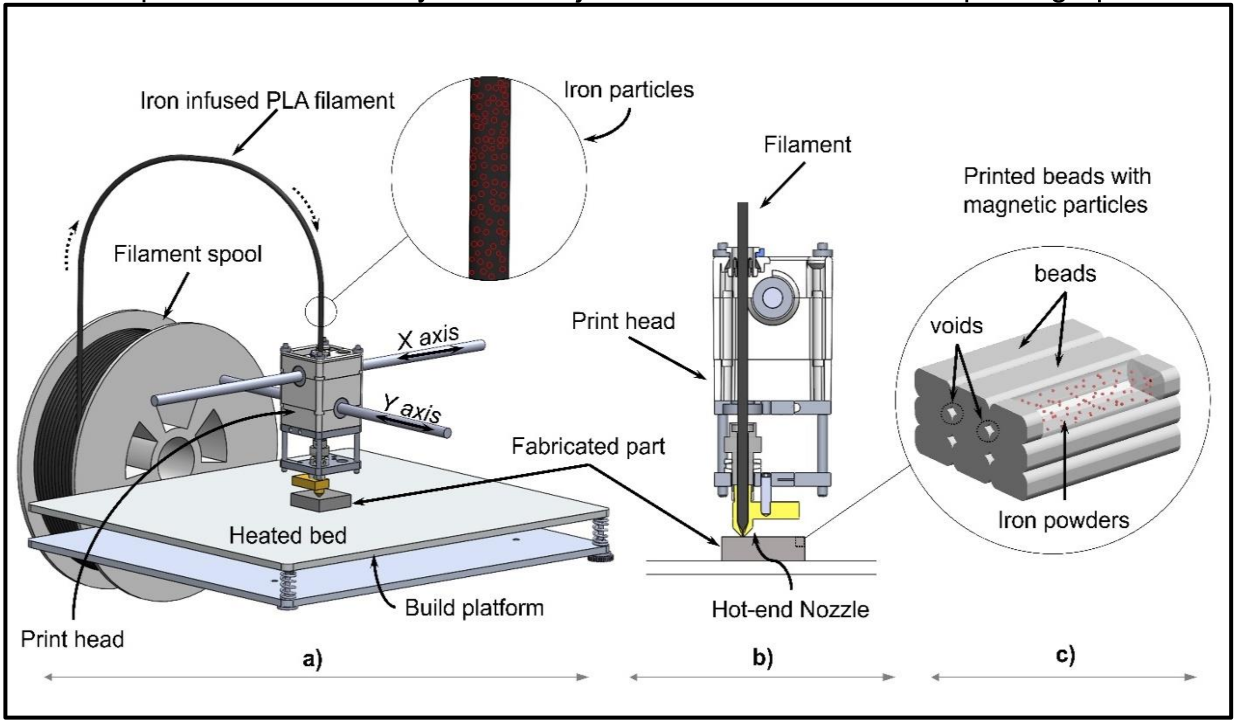

Fig. 2. Production of magnetic part using the FFF process. (a) Isometric view of the process, (b) Front sectional view of print head showing the filament deposition process at the end of the hot-end nozzle, (c) Deposited beads.

layer thickness of 0.25 mm was used to achieve a better adherence to the build platform. The heating bed was adjusted to 60°C, which is the normal printing bed temperature for PLA material. It can be seen from Figure 2 (c) that parts fabricated with the FFF process create voids between beads and layers, which might affect the magnetic properties of the final components.

These voids could be reduced by changing the process parameters such as printing temperature, printing speed, layer height, and layer width. As the filament is melted, it is extruded by the printer to build a shape layer-by-layer. This permits the production of far more complex magnets than injection molding, for example, can produce.

During the fabrication process, iron particles are in a non-magnetized state, but placing the printed magnet into a strong magnetic field converts it into a permanent magnet. This opens up new possibilities, such as using different materials within a single magnet to create areas of strong and weak magnetism. This could be useful in certain types of sensors [4].

Figure 3 shows the microstructural image of a 3D-printed part and the uniform distribution of iron granules. It can be seen that there are voids in some areas in the matrix material. These voids are the particles pulled out during the diamond saw-cutting process (during sample preparation). Overall, it is observed that iron particles are not agglomerated but are uniformly distributed over an area, which may help reduce the anisotropy in magnetic properties of FFF-made magnets.

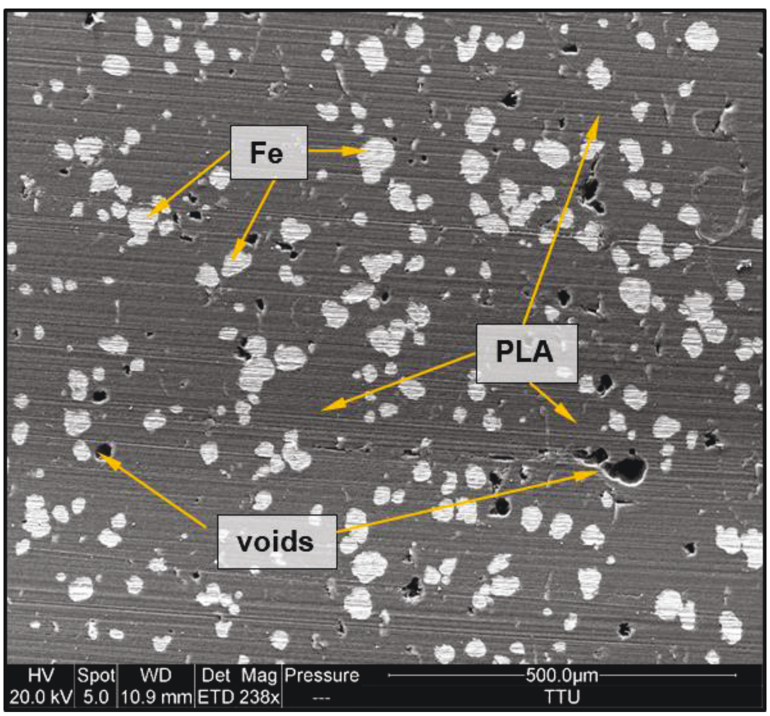

Fig. 3. Micrograph of the composite magnetic part shows the uniform distribution of iron (Fe) particles.

First, the test print is performed, and a NdFeB magnet is used to determine how it attracts the printed component. The preliminary test cube (25 x 25 x 25 mm) in Figure 4 shows the composite soft magnet attached to the permanent hard magnet.

After this, a simple experiment can be done to observe the attraction of the FFF printed product to a magnet. Here we use a cubic printed magnet sized at 10 x 10 x 10 mm for an experiment (this size could be changed depends on the time available for the class). A caliper or a simple ruler is used to measure the distance at which the printed part and NdFeB (25 x 25 x 25 mm is used in this experiment) magnet attract each other enough to overcome friction. The samples are printed with the following parameters:

- 25%, 50%, 100% infill density

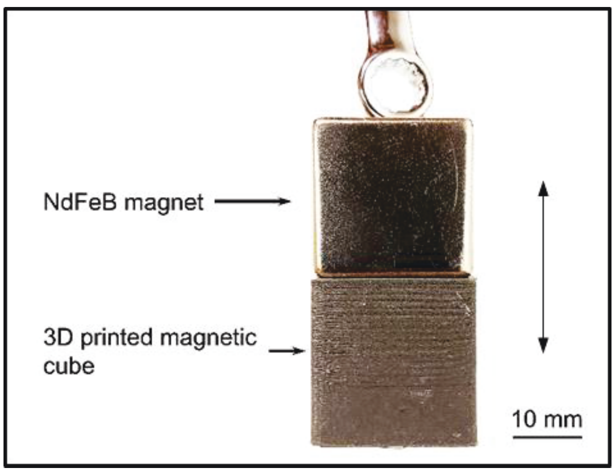

Fig. 4. Magnetic part made by FFF and attracted by the NdFeB magnet.

Classroom Experiment with NdFeB Magnet (slide 10-16)

Procedure:

Sample preparation (slide 11-12):

1) Print test samples in different infill percentages such as 25%, 50%, and 100%. To ensure that each sample is made as intended, it is best to print one at a time. Samples are small enough to print all in one class period.
   The fixed process parameters are given in table 1.

Table 1 Fixed process parameters

Process parameters	**Values**
Printing speed	*10-15 mm/s*
Shell/wall count	*2*
Infill orientation	*Line (0/90)*
Printing temperature	*195-200°C*
Layer height	*0.3 mm*
Layer width	*0.6 mm*

The density of each part is defined as a process parameter using slicing software. Slicing software could be different based on the 3D printer used in the fabrication of magnetic parts. Therefore, define different infill density for each part by fixing other process parameters the same as shown table 1. As the infill density decreases, the gap between beads increases. Digitally sliced files will look like the following for different infill density.

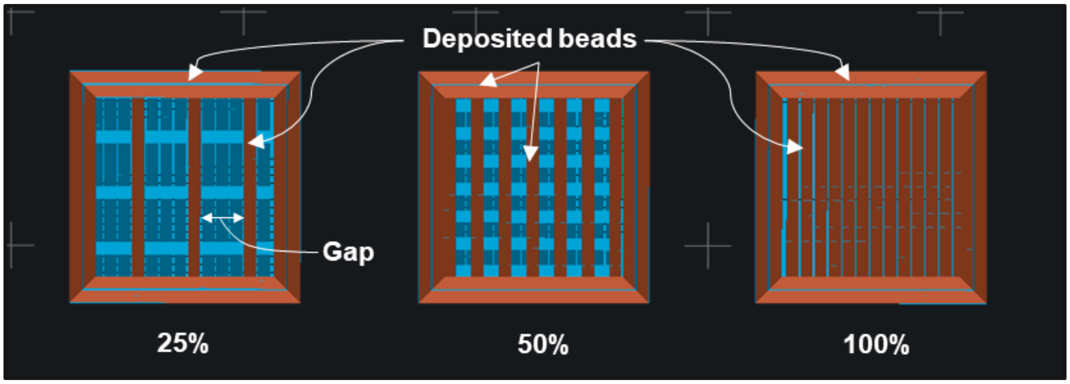

Fig.5 Cube samples with different infill densities

2) Use the samples as printed and label them as 1, 2, and 3.
3) Weigh and record the mass of each sample using the scale. The figure is shown below as a reference.

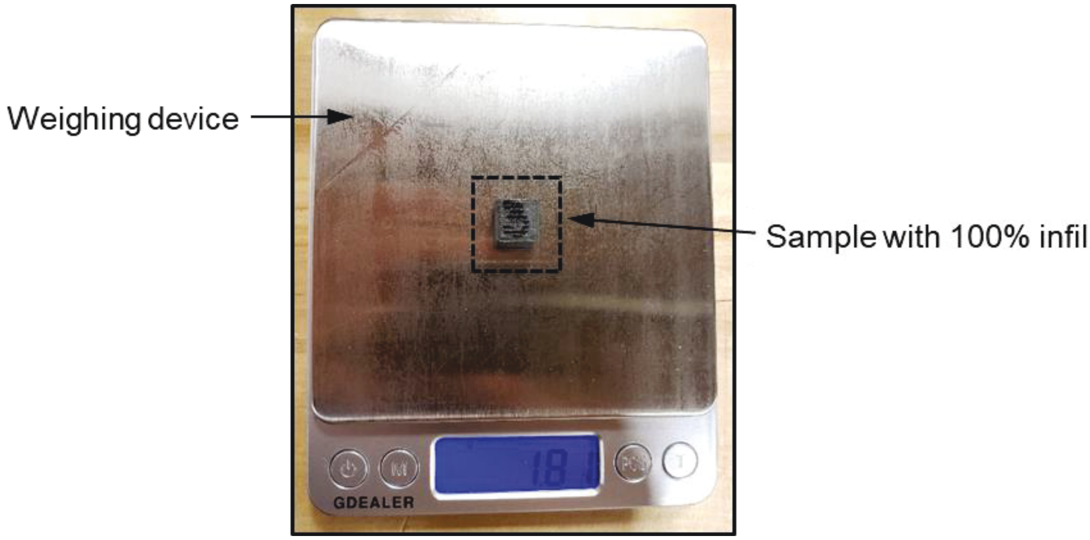

Fig.6 Weighing device measuring the sample with 100% infill

4) Create a sample matrix with columns for sample number, infill density, as-printed dimensions, mass of the sample, and the distance at which attraction to the magnet started to move the sample.

Sample testing (slide 13-15):

1) Use the ruler and a permanent magnet to identify the differences between samples based on the process parameters that they have fabricated. The figure below shows the way to position the ruler, permanent magnet, and the printed part. Make sure that the surface beneath the printed part is identical for all tests.

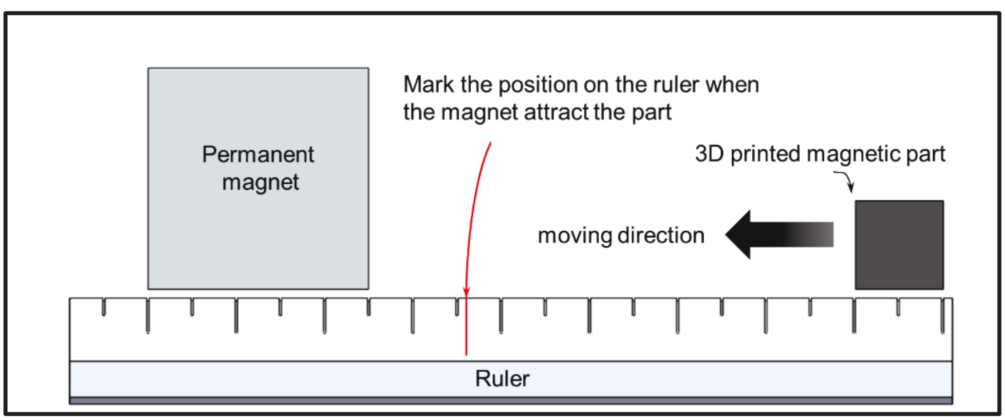

Fig.7 Representation of experimental setup

2) The ruler and the permanent magnet should be fixed in position, using adhesives or tape. After the ruler and the permanent magnet are positioned, the part should slowly be moved towards the magnet. Mark the position at which the magnet attracts the printed part. The image below shows the setup for this experiment.

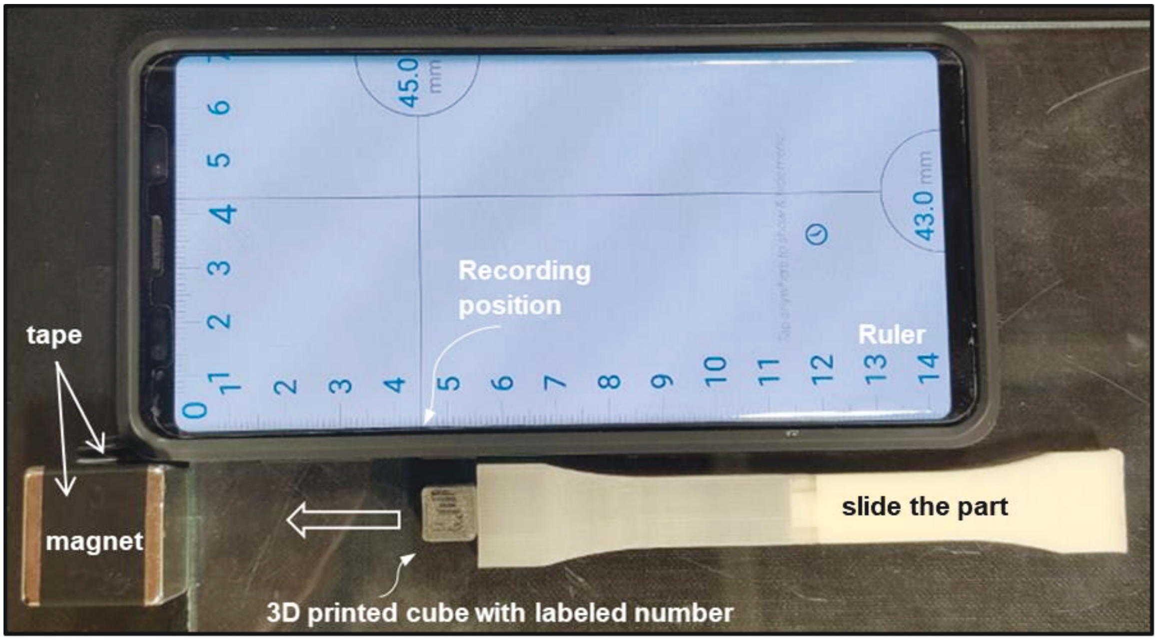

Fig.8 Sample experimental setup with magnet, printed part, and the ruler

3) Perform the same operation for all printed samples. They should have different characteristics based on their printing process parameters.

4) Record the results in a table format to compare the samples. The table for this experiment is given below. The test can be repeated to give a mean and standard deviation.

Table 2 Results with different weight and infill settings obtained experimentally

Sample number	Sample weight	Infill density	Measured distance
1	*1.10 g*	*25 %*	*38 mm*
2	*1.38 g*	*50 %*	*40 mm*

3	*1.81 g*	*100 %*	*42 mm*

Discussion

Collect the results as a class and create a table or simple plot based on the data obtained from the measurements. Find the mean and standard deviation for each sample and add these to the table or plot.

Analyze the information in the data. Which magnetic sample attracted the most? Was the difference significant?

How would you state the advantage of printing magnetic parts with less infill density? On a surface with a different coefficient of friction, how could the balance between low infill (minimizing mass) and high infill (maximizing attraction) change? Did anything about the experiment suggest there could be value in testing different infill patterns? How could different sample shapes make a difference on the magnetic properties of printed parts? Consider testing these as a class if time allows for additional experiments (see the Appendix A).

Student evaluation questions

1. Explain the filament-making process using the mix of iron powders and polymer pellets. What are the advantages and disadvantages of this process?
2. Describe the fused filament fabrication process. What are the advantages and disadvantages of fabricating magnetic parts using this process?
3. What is an effect of infill percentage on magnetic properties of FFF-made parts? Does another process parameter (layer height, layer width, printing temperature) make a difference on the magnetic properties?

Resources and references

- SketchUp free design software
  https://www.sketchup.com/plans-and-pricing/sketchup-free

- Autodesk TinkerCAD free design software
  https://www.tinkercad.com/
- Ruler application can be downloaded to mobile devices from Playstore or equivalent from Apple store.
- The feedstock filament can be found in the following link:
  https://www.proto-pasta.com/collections/metal-filled/products/magnetic-iron-pla

[1] Mohammadizadeh M, Lu H, Fidan I, Tantawi K, Gupta A, Hasanov S, et al. Mechanical and Thermal Analyses of Metal-PLA Components Fabricated by Metal Material Extrusion. Inventions 2020;5:44. https://doi.org/10.3390/inventions5030044.

[2] Gupta A, Fidan I, Hasanov S, Nasirov A. Processing, mechanical characterization, and micrography of 3D-printed short carbon fiber reinforced polycarbonate polymer matrix composite material. Int J Adv Manuf Technol 2020:1–21. https://doi.org/10.1007/s00170-020-05195-z.

[3] Patton M V., Ryan P, Calascione T, Fischer N, Morgenstern A, Stenger N, et al. Manipulating magnetic anisotropy in fused filament fabricated parts via macroscopic shape, mesoscopic infill orientation, and infill percentage. Addit Manuf 2019;27:482–8. https://doi.org/10.1016/j.addma.2019.03.026.

[4] Popov V, Koptyug A, Radulov I, Maccari F, Muller G. Prospects of additive manufacturing of rare-earth and non-rare-earth permanent magnets. Procedia Manuf 2018;21:100–8. https://doi.org/10.1016/j.promfg.2018.02.199.

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Appendix A.

Instructor could consider different printing settings to change the magnetic strength of the part. This could be achieved by changing the printing direction and the layer height in slicing software. In this case, instructor would expect different magnetic strength in different printing directions. Additionally, various layer heights (for example, 0.1mm, 0.2mm, and 0.3 mm) might affect the magnetic strength of the part, since the lower layer height would decrease the voids and porosities inside the printed object.

The figures in the text are duplicated in the accompanying PowerPoint presentation to be used by the instructor as needed.