Additive Manufacturing of Magnetic Materials

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Abstract

This module introduces students to the additive manufacturing (AM) methods used in fabricating magnetic materials. The module briefly introduces magnetic properties, types of magnetic materials, AM technologies used to produce these magnets, and application areas.

Objectives

Students will gain understanding of the working principle of different AM manufacturing methods and be able to:

- define the types of materials used in AM
- provide fundamental knowledge on magnetic properties
- describe AM processing techniques
- understand how AM-made magnets are used in real applications and the advantages and disadvantages of AM methods.

Keywords: Additive manufacturing, soft magnets, hard magnets, composite magnets.

Grade level: High school students and introductory college courses.

Type of module: Presentation.

Time Required: 45 min.

Introduction (slides 3-8)

Additive manufacturing (AM) allows arbitrarily shaped parts to be produced with minimum material waste, offering an effective technique for fabricating magnetic components. An advantage of the AM approach is that it enables the fabrication of physical parts directly from the computerized design (CAD) models, with no tooling required for fabricating magnets.

AM plays an important role in reducing the magnet cost and eliminating the associated manufacturing (i.e., cutting, machining, etc.) waste that cannot be readily reused. Unlike conventional techniques, metal and polymer additive techniques make highly efficient use of energy and raw materials because materials are deposited only where they are needed. State-of-the-art AM technology is well-suited to fabricate magnets, which frequently are made of expensive and critical rear-earth (RE) elements.

Magnetic composite materials have gained more attention in recent years. Composite magnetic materials are especially attractive to manufacturers of small motors and actuators for household and automotive use as well as to the audio, video, and computer industries. These magnets fall into two categories such as soft and hard composites.

- Soft magnetic composites usually iron-based, are obtained by pressing soft magnetic powder with a dielectric binder.
- Hard magnetic composites usually Nd-Fe-B, are obtained by bonding hard magnetic powder with a dielectric binder (nylon).

It's important to note that the term "soft" refers to materials that are soft in the magnetic sense, not the hardness of the material. Soft magnetic materials easily magnetize and demagnetize where as permanent, or "hard", magnetic material maintains its magnetization. This makes soft magnetic material very useful in situations where you want to switch the magnetic field quickly and easily such as in motors. Hard magnets require too much current to do that. Instructor should refer the details about the magnetic composites in "Magnetic Composites" module in www.materialseducation.org.

Magnetic composites are an essential technology for energy conversion and are desirable to be obtained from AM processes. These magnets must be pre-charged prior to their use in an application and must maintain this magnetization during an intended operation. Additionally, permanent magnets must generate the required magnetic flux for a given application. Therefore, understanding the magnetic properties of AM-fabricated magnets is essential. Generally, the four main properties of magnets are coercivity, remanence, maximum energy product, and the Curie temperature, which are briefly explained below.

Coercivity

Coercivity is the magnetic field required to reduce the magnetization of a material from a saturation level down to zero. In other words, it is a measure of the ability of a magnet to resist demagnetization.

Magnetic materials are categorized as either hard or soft based on coercivity. Hard magnetic materials, such as permanent magnets, have high coercivity while soft magnetic materials, such as electrical steel, have low coercivity. Coercivity is a structure-sensitive extrinsic magnetic property affected by temperature, crystal anisotropy, stress-state, and microstructural impurities [1]. Figure 1 gives an overview of characteristic magnetic materials fabricated by different manufacturing processes [2].

Remanence

Remanence is the residual magnetization that remains when no magnetic field is applied to a magnetic material that was previously magnetized to saturation. Remanence is directly related to the amount of magnetic flux that can be generated with a permanent magnet. Figure 1 indicates the remanence values of various magnetic materials. Here, it can be seen that soft magnetic Fe-Co alloys have significantly higher remanence than permanent magnetic materials.

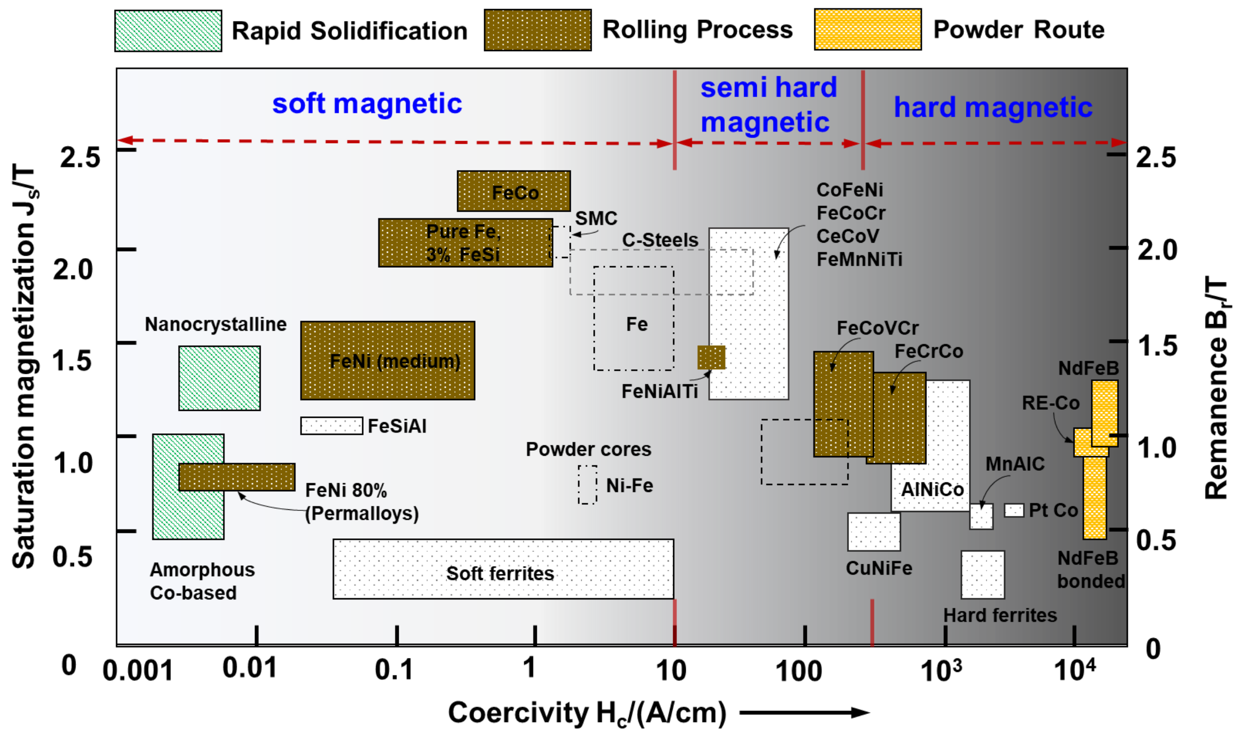

Fig. 1. Coercivity, saturation magnetization, and remanence of various magnetic materials [2].

Curie Temperature

The Curie temperature is a structure-insensitive magnetic property. Ferromagnets change their magnetic property to a paramagnetic state above their Curie temperature. A high Curie temperature is desired when using permanent magnets at elevated temperatures.

Permanent magnets perform best at their working temperatures, which are below the Curie temperature. This temperature is called the maximum operating temperature (MOT). For instance, NdFeB magnets have Curie temperatures in the range of 300 to 120˚C, and the MOTs are between 80 and 120˚C.

Detailed information regarding magnetic composites is found in the “Magnetic Composites” module in www.materialseducation.org.

Maximum Energy Product

The maximum energy product (BH_{max}) has gained wide acceptance as a property to qualify the performance of permanent magnets. It is the maximum value of the product *BH* obtained in the second quadrant of the demagnetization plot and represents the maximum energy a permanent magnet can generate outside the magnet, measured in MGOe (cgs) or kJ/m^3.

For any given magnetic material, the relationship between magnetizing force and magnetic flux produced can be plotted and this is known as the B-H curve of the material. The B-H curve is the curve characteristic of the magnetic powders of a material. The curve tells you how the material responds to an external field and is critical piece of information when designing magnetic circuits. Here, H is the magnetizing force (ampere turns/meter or Oersted), and B is the flux density (Tesla or Gauss). Mainly, the current creates a magnetizing force that produces the magnetic flux in the transformer core. Figure 2a shows the B-H curve which indicates as the magnetizing force is increased from zero, the flux increases up to a maximum flux value. Magnetizing force does not significantly affect the increase in flux value as shown in the graph, and it is called a saturation point [3]. Magnetic materials, once magnetized, retain some of their magnetization even when the magnetizing force is reduced to zero. However, when the material exhibiting a response to a decreasing magnetizing force that is not the same to the response to an increasing magnetizing force as it is shown in Figure 2b. The curve in the Figure 2b is called “The Magnetic Hysteresis” loop shows the behavior of a ferromagnetic core graphically as the relationship between B and H is non-linear [4].

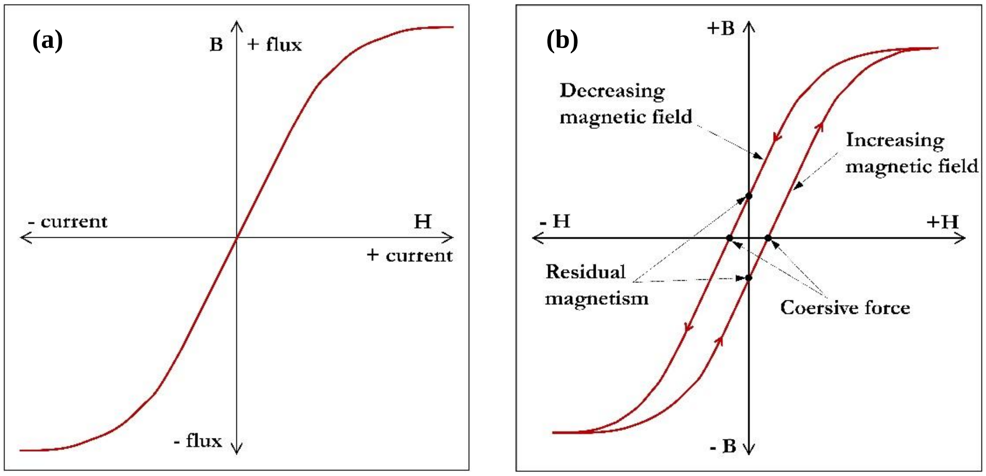

Fig. 2 Typical B-H curve shows the the increase in magnetic field results to increase in magnetix flux, (a) B-H curve, (b) the difference in B-H curve when the magnetic field is applied and removed in practice [3].

Magnetic Materials used in Additive Manufacturing (slide 9)

Permanent magnets are widely used in areas in which an energy conversion, usually from electrical to mechanical energy, is required, such as in motors and hard disk drives. These magnets consist of a large amount of RE elements such as Neodymium (Nd), Dysprosium (Dy), and Terbium (Tb).

Extrusion printing of NdFeB-bonded magnets has been reported in some recent literature. The magnetic powder loading with a 54 vol.% fraction, and the 3.6 g/cm^3 density of the printed magnet, which is lower than that of injection molded samples, indicates a higher level of porosity in the AM-fabricated samples. With the help of AM methods, bonded magnets are fabricated by mixing the magnet powder with a polymer binder (i.e., nylon, epoxy, PLA, etc.). Compared to sintered magnets, bonded magnets have enhanced freedom in terms of geometry and are more cost-effective. The drawback of this method could be related to the expense of the reduced energy product due to the incorporation of the non-ferromagnetic polymer binder. On the other hand, bonded magnets present better ductility and lower tensile strength. The shape flexibility of bonded magnets enables innovative designs for motor magnets, which can potentially increase the torque output.

The instructor could give the following example to compare the printed magnet and the injection molded one:

In a research study [11], a 3D-printed magnet was compared with the injection molded magnets. The 3D-printed sample cubes (NdFeB magnet inside a PA11 matrix material) were characterized and compared with the injection molded sample. The comparison of the results is given in Table 1. It could be stated that there was a high positive correlation between injection-molded and 3D-printed magnet properties.

Table 1. The comparison of the injection molded and 3D printed magnet properties.

Procedure	ϱ (g/cm^3)	B_r (mT)	H_{cj} (kA/m)
3D printed	3.57	310	740
Injection molded	4.35	387	771

In Table 1, B_r is the measured remanence, H_{cj} is the intrinsic coercivity, and ϱ is the volumetric density of the samples.

Research studies showed that the magnet with the desired shape and magnetic properties could be printed using AM methods.

AM Techniques to produce Magnetic Materials (slides 10-15)

The advanced AM technology is well-suited to produce magnets, which frequently involve expensive and critical rare earth elements. This includes both bonded magnets or polymer-free ones, with rare-earth materials or without them. Some of the AM fabrication methods are listed below for the fabrication of net-shaped magnets.

- Material extrusion in Big Area Additive Manufacturing (BAAM)
- Fused filament fabrication (FFF)
- Binder jetting technology (BJT)
- Stereolithography (SLA)
- Selective laser melting (SLM)
- Selective laser sintering (SLS)

Material Extrusion (ME)

Material extrusion technology deposits molten thermoplastics in a layer-upon-layer fashion via a hot-end nozzle. Extruded materials solidify rapidly after each layer deposition. In this process, the chopped pellets are used directly as a feedstock material. This is the only difference from the FFF method.

Big area additive manufacturing (BAAM) is an ME process developed at Oak Ridge National Lab (ORNL) and Cincinnati Inc. and is used to fabricate large-scale parts. Recently, BAAM was used to produce NdFeB-bonded magnets at ORNL [5]. In this process, Magnequench isotropic MQP B+ powder (65 vol.%) was mixed with Nylon-12 (35 vol.%) and extruded first to yield a composite pellet, which was then used as a feedstock material in BAAM. Table 2 shows the comparison of magnetic properties of a BAAM-made bonded magnet with respect to an injection molded (IM) magnet. It can be seen that BAAM- and AM-made magnets have similar capabilities, with AM showing a slight advantage in terms of reducing material waste, the weight and production cost.

Table 2. Characteristics of the BAAM magnet vs. injection molded magnet [5].

Method	Density (g/cm^3)	H_{ci} (kOe)	H_c (kOe)	B_r (kG)	BH_{max} (MGOe)
BAAM	4.9	8.7	4.1	5.0	5.3
Injection molded	4.8	8.0	3.6	4.8	4.6

Fused Filament Fabrication

Fused filament fabrication (FFF) is a well-known, low-cost, and widely used AM method used to fabricate polymer, metal/fiber infused composite materials [6]. In the FFF method, magnetic parts could be manufactured using polymer as a binder and RE materials in a powder form as a magnetic material. FFF is a material extrusion process that utilizes thermoplastic materials in a filament form to build up an object in a layer-by-layer process.

FFF offers broader operation temperatures, which makes printed magnets suitable for specific applications. Magnetic Iron PLA is a commercially available composite filament made by the Proto Pasta company that is useful in fabricating soft composite magnetic components. This filament consists of 40 wt. % Fe particles incorporated in a polylactic acid (PLA) polymer matrix. The magnetic properties of soft magnetic compounds are mainly influenced by their filler fraction. Filling fraction of more than 65 vol. % is necessary to produce functional soft magnetic components. On the other hand, rare earth powders are used to infuse polymer matrix to manufacture hard-bonded magnets. A big disadvantage of polymer-bonded permanent magnets is the maximum energy product $(BH)_{max}$ that is lower than that of sintered magnets due to their plastic matrix material. For example, NdFeB magnets could be fabricated using the FFF method.

Magnetic properties of NdFeB powder and samples printed using the FFF method are given in Table 3.

Table 3. Magnetic properties of FFF-made magnet and pure magnetic powder.

Sample	**Wf (wt.%)**	**ϱ (g/cm^3)**	**B_r (mT)**	**H_{cj} (kA/m)**
Powder	-	7.43	746	0.880
FFF	89	3.57	344	0.918

Selective Laser Melting (SLM) and Selective Laser Sintering (SLS)

One of the frequently used AM techniques is the laser-based, layer-by-layer sintering method that involves the use of a high-power laser to melt the alloy powder. This process is called selective laser melting (SLM) and creates parts layer-by-layer by selectively melting and consolidating a thin layer of the powder with a scanning laser beam. The object is lowered by one-layer thickness after each finished layer. After the finished layer, a new layer powder is spread on the top of the object, and the defined areas are melted selectively by scanning the component’s cross-section with a laser beam. The advantage of this process is to produce dense soft magnetic objects with an arbitrary shape. The magnetic properties of the printed objects can be modified by the laser process parameters that can be used to manufacture tailored soft magnets for various applications like

- transformers
- electric motors
- and other electromagnetic devices.

The SLM can be used for producing complex-shaped parts due to the flexibility of feedstock and shapes, which cannot be realized by other conventional methods. Typically, FeNi3, or Ni-Fe-V and Ni-Fe-Mo are used as a feedstock material for the SLM process.

The selective laser sintering process is another powder-based AM method that uses localized heat sources to sinter the magnetic granules. SLS does not completely melt each powder layer but sinters the particles to retain their original microstructure. The SLS process partly melts (sinters) the powder, whereas SLM completely melts the powder.

Table 4 shows the comparison of magnetic properties of SLS-made magnets with respect to pure power magnetic properties. The coercivity of the isotropic NdFeB powder depends on the microstructure of the material. The coercivity of the SLS-made magnet is around 25% lower compared to the pure-powder magnetic properties. The lower coercivity could result from the inhomogeneous microstructure of SLS-printed magnets, in particular the grain size distribution [7].

Table 4. Properties of the isotropic NdFeB powder and the sample printed with SLS method [8].

Sample	**Wf (wt.%)**	**ϱ (g/cm^3)**	**B_r (mT)**	**H_{cj} (kA/m)**
Powder	-	7.43	746	0.880
SLS	100	4.47	436	0.653

Stereolithography (SLA)

Stereolithography (SLA) is the oldest commercially available AM method. Basically, the SLA method uses an ultraviolet (UV) light source to cure the photosensitive resin polymer selectively for each cross section and cure the entire model of every layer. In most AM methods, the part is lowered down by one-layer thickness after each cured layer. The SLA method could be used to fabricate soft and hard magnetic materials.

Table 5 shows the comparison of SLA-made NdFeB magnets with respect to the pure magnetic properties. It could be seen that SLA-made magnets have high coercivity because the microstructure is unchanged during the manufacturing process. Coercivity depends on that.

Table 5. Properties of the isotropic NdFeB powder and the sample printed with SLA method [8].

Sample	Wf (wt.%)	ϱ (g/cm^3)	B_r (mT)	H_{cj} (kA/m)
Powder	-	7.43	746	0.880
SLA	92	4.83	388	0.923

Binder Jetting Technology

BJT involves a liquid binder, which is selectively deposited into a powder bed to bind materials to form complex shaped parts. It is well-suited to manufacturing magnets as it does not use heat during the build process. After the fabrication, the magnet is then placed in an oven at 100-150°C to cure the thermoset binder. The process description of this method is given in Figure 3.

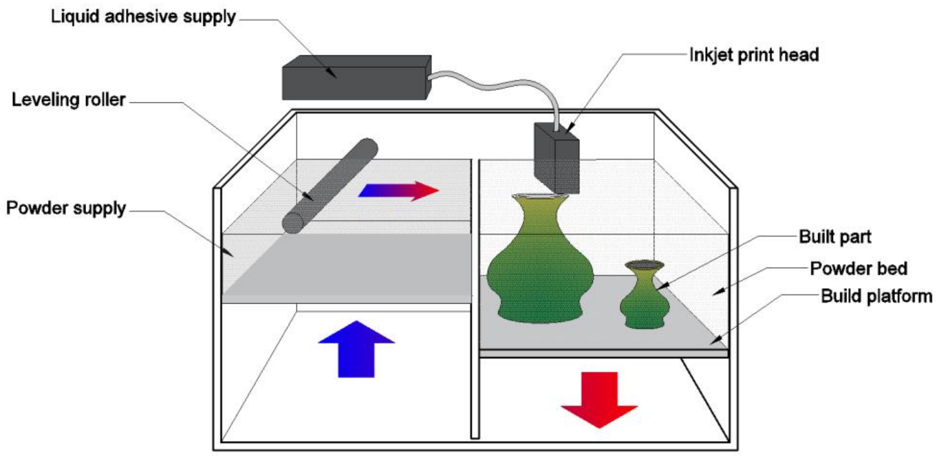

Fig. 3. Binder jetting process description.

Density of the magnetic phase is important to ensure magnet functionality as it determines the generation of magnetic flux in a given space. The density of printed magnets using BJT is around 3.3 g/cm^3, which is a nearly 43% density compared to the theoretical magnet crystal density. The low density is related to the low volume fraction of the magnet powder as well as the inter- and intra-particle porosity.

Bonded magnets with a higher energy product BH_{max} are desired for electronic applications. This can be achieved through magnetically aligning the powder material during the manufacturing process to increase the remanence *Br* as well as the density of the final part [9]. Table 6 shows the characteristics of binder jetted NdFeB bonded magnets with and without alignments. The magnetic field generated by the sintered magnet for the alignment is approximately 1 Tesla. It can be seen that the alignment enhanced the density and remanence B_r, resulting in a BH_{max} enhancement for 2.4 to 3.8 MGOe [10].

Table 6. Magnetic properties of NdFeB magnets fabricated by BJT process.

Sample	**ϱ (g/cm^3)**	**B_r (kG)**	**H_{ci} (kOe)**	**BH_{max} (MGOe)**

Without alignment	3.54	3.3	14.2	2.4
Aligned during curing	3.86	4.2	14.2	3.8

Applications (slides 16-19)

Application of advanced manufacturing methods such as AM magnets can be fabricated into unique configurations that can concentrate flux in ways not possible with conventionally processed magnets. When coupled with advanced motor or transformer design, overall performance of the motor or transformer can be improved with reduced magnet sizes and with significantly less manufacturing scrap losses. AM has proved to be a promising method for the production of net-shaped permanent magnets as it improves magnetic properties, reduces processing costs and significantly reduces the expensive rare-earth element waste.

Some of the applications of AM methods in the fabrication of magnetic components are provided in this module. The detailed information regarding the case study could be found in [12], in which the 3D-printed magnetic torus-like parts were used to make a transformer. Transformers play an important role in transmission, distribution, and utilization of AC electrical energy. They execute the important task of increasing or decreasing alternating voltages in electric power applications. This example showed the construction and performance of magnetic transformers printed with a thermoplastic polymer material using the FFF method. The core geometry was printed in a toroidal-like geometry. Then, the performance of printed and standard (commercial core) cores was compared. The effect of the process parameters such as infill density and infill pattern were also investigated in [12].

The iron powder-infused thermoplastic filament (Proto-Pasta's Composite PLA) was used in the experiment. The combination of iron and polylactic acid (PLA) filament makes it possible to fabricate magnetic parts with different process parameters.

First, the transformer core was produced with a size and geometry identical to the commercial standard Ni-Zn ferrite transformer core. Then, toroidal transformer cores with different infill patterns (rectangular and honeycomb) and infill densities (20-100%) were fabricated using a gMax 3D printer. The figure 4 below shows the rectilinear and honeycomb pattern with 20% and 100% infill densities.

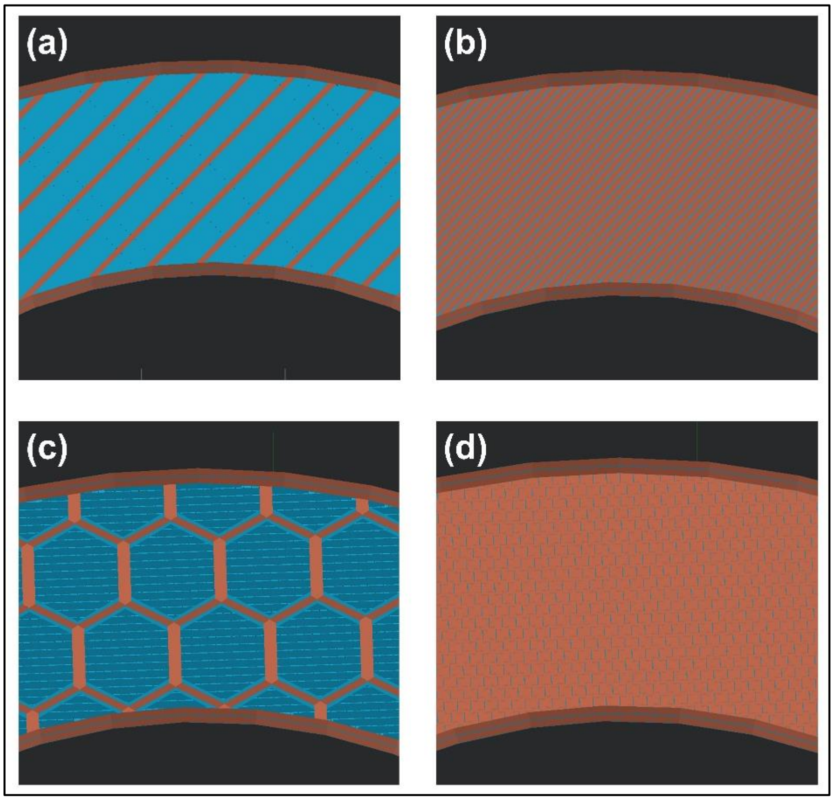

Fig. 4. Horizontal cryosections of transformer cores with different infill patterns and percent fill. (a) Rectilinear pattern with 20% infill density, (b) rectilinear pattern with 100% infill density, (c) honeycomb pattern with 20% infill density, (d) honeycomb pattern with 100% infill density.

In order to test the core performance of the transformer, the primary and secondary windings were wrapped around the core using magnet wire and attached to the custom integrated magnetic circuit. The whole procedure could be found in [12].

The results demonstrated that the standard transformer core generated a clear hysteresis loop with magnetic saturation and a coercive current of less than 1 A and showed high saturation. However, a power amplifier is unable to saturate the fabricated cores due to insufficient amplification of the current produced from the generator. On the other hand, infill density did not influence the transformer's response. Full infill density (100%) results in a larger magnetic moment contained within the transformer core. Moreover, infill pattern did not affect the response of the transformer core. The instructor is advised to refer [12] if detailed information is needed.

Conclusion (slide 20)

AM offers new opportunities in the field of magnetic field design and manipulations as it can be used to manufacture objects with the highest individual design flexibility at minimum costs. The full potential of AM comes into play in producing complex and customized parts that would otherwise be complicated to fabricate with conventional subtractive manufacturing methods.

In this education module, various types of AM methods were described. The difference in magnetic properties with respect to the injection-molded or pure-powder form magnets was shown. The areas in which the AM-made magnets can be applied were described, and an example case study was introduced.

Overall, AM of magnetic materials with different methods and materials is an active field of research. AM-made magnets with different processing methods showed that the acceptable magnetic properties depend on the application areas. This promises a huge potential for the manufacturing of complex magnetic designs with superior quality.

Student Evaluation Questions

1. What are the important properties of magnetic materials? Explain them briefly.
2. Explain the role of B, and H in the hysteresis loop?
3. What is an advantage and disadvantage of producing magnets through AM?
4. Describe the BJT process. What are the advantages and disadvantages of fabricating magnetic parts using this process? Compare the magnetic properties of AM magnets produced using the BJT process with other AM processes?

5. Which AM method could be the most cost-effective process for fabricating near net-shaped magnets?

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