

Review

Additive Manufacturing and Topology Optimization of Magnetic Materials for Electrical Machines—A Review

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Abstract: Additive manufacturing has many advantages over traditional manufacturing methods and has been increasingly used in medical, aerospace, and automotive applications. The flexibility of additive manufacturing technologies to fabricate complex geometries from copper, polymer, and ferrous materials presents unique opportunities for new design concepts and improved machine power density without significantly increasing production and prototyping cost. Topology optimization investigates the optimal distribution of single or multiple materials within a defined design space, and can lead to unique geometries not realizable with conventional optimization techniques. As an enabling technology, additive manufacturing provides an opportunity for machine designers to overcome the current manufacturing limitation that inhibit adoption of topology optimization. Successful integration of additive manufacturing and topology optimization for fabricating magnetic components for electrical machines can enable new tools for electrical machine designers. This article presents a comprehensive review of the latest achievements in the application of additive manufacturing, topology optimization, and their integration for electrical machines and their magnetic components.



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1. Introduction

The electrical machine is considered a key part in electric drives, which account for approximately 50% to 70% of electricity usage in the EU and the United States [1]. Its applications include, but are not limited to, compressors, HVAC systems, power tools, generators, electric and hybrid vehicles, elevators, and MAGLEV trains. In the last decade, there have been consistent efforts from both the US Department of Energy and the EU to advance the design and development of future generations of electrical machines that positively impact the environment and reduce greenhouse gas emissions [1,2]. The next generation electrical machines include designs with high efficiency and power density; however, another important aspect is their environmentally friendly construction, including aspects such as minimal material waste and recyclability.

Additive manufacturing (AM), also known as 3D printing, is an emerging manufacturing technology that can potentially enable and facilitate development toward the next generation electrical machines. AM provides key advantages over traditional manufacturing methods. AM can reduce material waste and scrap parts associated with many traditional manufacturing processes. The 3D printing process, in general, recycles unused raw materials such as powder and wire filament [3], potentially achieving full use of the raw material. Recycling and reusing the raw material are critical to reduce cost, especially for high-cost raw materials such as permanent magnets. Also, recent technological

advancements in AM allow the use of a wide range of materials, including copper [4,5], ceramics, and magnetic materials [6]. These materials are key for manufacturing electrical machine components.

One of the most important advantages is that AM requires minimal tooling and additional processing techniques to fabricate complex topologies. For very complex shapes, AM technologies may provide the most economical and expedited means for fabrication of small quantities. Topology optimization (TO) has been used in many application areas to identify novel designs that reduce weight without compromising mechanical integrity. TO determines the optimal way of distributing a single or multiple materials in a defined design space. Complex designs often result from TO. Application of TO is seen in the design of the rotor core of a switched reluctance machine [7]. TO is also used to find the optimal distribution of the permanent magnet and the iron rotor core in permanent magnet machines [8,9].

One drawback of TO designs is the manufacturability of the optimized solutions. This has hindered the adoption of TO toward electrical machine design. However, recent applications of AM toward electrical machine components, especially in ferromagnetic materials and permanent magnet, have revitalized the adoption of topology optimization. As AM can manufacture almost any complex topology, it has become clear that TO and AM have high levels of synergy and can be used in parallel to facilitate the development of next generation electrical machines.

There is limited literature on the integration between AM and TO for magnetic components in electrical machines. In [10], a combined magnetic-structural TO is applied for the design of a rotor core of a surface mount permanent magnet machine. The optimized rotor core is then 3D printed using high silicon steel. In [11], permanent magnets with multiple magnet grades are proposed for a surface mounted machine to reduce manufacturing cost without penalizing machine performance. Though AM was proposed for fabrication, TO was not applied; however, it could be used to identify optimal distribution of magnet grades.

There are works discussing the current state of additive manufacturing for electrical machines and their components, including magnetic materials and windings [12]. In [13], applications of AM technologies are broadly discussed for components of electrical machines, including iron cores, windings and insulation systems, magnets, and heat management/exchanger systems. For each component, ref. [13] provides a broad view around the performance of the 3D printed components and where they are compared to traditionally manufactured components. In [14], the advantages of AM technologies are discussed toward the construction and assembly side of the electrical machines.

In this paper, applications of additive manufacturing and topology optimization toward magnetic components for electrical machines are reviewed. Fundamental concepts regarding AM, especially for magnetic materials, are mentioned first to set the stage for discussing the integration of topology optimization in the later part of the paper. Also featured in more detail is the current state of the art in integration of additive manufacturing and topology optimization, especially toward iron cores and permanent magnets in electrical machines. These case studies highlight the novel integration between these emerging technologies and show their potential in future design of electrical machines.

2. Additive Manufacturing of Soft Magnetic Materials

Soft magnetic materials are characterized with low intrinsic coercivity, typically below 1000 A/m, and can be easily magnetized or demagnetized [15]. As the iron cores are responsible for the guidance and improvement of the main flux created by the continuously moving magnetic field, there are some criteria in the selection of soft magnetic materials during the design phase. The following characteristics are considered to be key for the iron cores: magnetic saturation J_s , intrinsic coercivity H_c , relative permeability μ_r , hysteresis loss density p_h , dynamic loss p_e , and yield strength [16]. For electrical machines, the iron cores are traditionally made of either steel laminations or soft magnetic composites (SMCs).

Steel laminations are typically formed from iron alloyed with silicon, nickel, cobalt, and other additives. To form the desired stator and rotor geometry, steel laminations are usually punched, either with mechanical or laser cutting technique. They are then stacked, welded, or bolted together to form the iron cores. It is well recognized that degradation of the magnetic properties can occur with mechanically handling techniques [17]. Thus, the magnetic properties of the stacked iron core may be very different from the properties of the mother coil. Another concern with stacked iron cores is waste of materials associated with the traditional manufacturing process. For segmented or complete laminated cores, the amount of steel waste due to cutting and punching of laminations can range between 50% to 80% [18]. This low use ratio signals a waste in producing iron cores. Additionally, forming the iron cores for machine topologies that require a 3D flux path can become a challenge with laminations. Thus, laminations are typically seen in iron cores where the preferred flux paths are parallel with the in-plane lamination directions.

In contrast to stacked iron cores, SMCs are selected for machine topologies where easy flux flow in three directions is preferred [19]. These machine topologies can include axial flux machines, tubular linear machines, or claw pole machines. Since iron cores made from SMCs are produced by compacting and molding iron particles into desired shapes, it may require less mechanical handling and post-processing steps. Thus, mechanical processing steps such as stamping and welding may not be required. Another advantage of SMCs in comparison with laminated steel is that it has lower eddy current loss at high excitation frequencies. At excitation frequency of 1000 Hz and above, the eddy current loss of SMC core is much lower compared to laminated steel core. This benefits SMCs for electrical machine designs where high speed operation is a requirement. There are, however, notable challenges regarding application of SMCs. They are subjected to high hysteresis loss, high intrinsic coercivity, low relative permeability, and low yield strength. Typical yield strength value of SMCs is below 20 MPa, while for lamination steel the typical value is around 350 MPa. For high speed electrical machines, rotor cores made from SMCs can be subjected to high von Mises stress, which is undesirable.

The recent proliferation in studies regarding AM for soft magnetic materials aim at providing alternative materials for fabricating the iron cores. In general, these studies try to exploit key features of AM, at the same time improving the performance of the printed soft magnetic materials that can be potentially used in the cores. Some of the early work in application of AM for fabricating iron cores focus on demonstration of AM as an easy mean of manufacturing complex geometries, Figure 1. Multiple demonstrations of additive manufacturing for a rotor core of a synchronous reluctance motor is shown in [20,21]. Here, the fabrication of the prototype rotor cores is achieved with two 3D printing techniques, fused deposition modeling (FDM) and selective laser melting (SLM) without any use of molding or tooling. In [22], the surface of the rotor core of a switched reluctance machine that resembles the structure of a honeycomb is analyzed. The use of the honeycomb structure was shown numerically to improve both the torque ripple and the leakage flux associated with the machine.

In electrical machines, the three commonly seen soft magnetic materials are iron-cobalt (FeCo), iron-nickel (FeNi), and iron-silicon (FeSi) alloys. As previous studies highlighted AM capability in fast prototyping of complex iron core geometries, other research in AM of soft magnetic materials focus on laying foundations for printing these iron alloys. These foundations include magnetic, mechanical, and microstructural characterization of the printed iron alloys, as well as their relationships to the printing parameters.



Figure 1. Additive manufactured rotor cores. These structures were fabricated without molding and tooling. (a) Printed rotor core for a synchronous reluctance machine [21]; (b) Printed rotor core for a switched reluctance machine [22].

2.1. Iron-Cobalt (FeCo)

One of the most attractive properties of FeCo is that it has the highest magnetic saturation compared to other soft magnetic iron alloys, with J_s value settling around 2.4 T. However, the conventional production of FeCo iron cores is subjected to the high material cost of cobalt, the low workability of the iron-cobalt alloy, and the additional requirement of heat treatment of the stacked iron core. This limits the use of FeCo iron cores, especially for cost-sensitive applications. As a result, reducing the challenges associated with the production of FeCo iron cores via additive manufacturing is of high interest among AM research groups. Efforts in printing FeCo iron cores have been shown via the applications of 3D screen printing and laser engineered net shaping technologies (LENS). It is reported in [6] that FeCo fabricated with 3D screen printing achieves magnetic induction comparable with commercial FeCo alloy with 15–20% cobalt content. Higher magnetic induction and saturation can be achieved if the porosity level in 3D screen-printed FeCo cores is reduced. Further comparison between screen-printed FeCo and commercial laminated FeCo shows that printed cores have higher iron loss, making its magnetic performance less appealing.

FeCo parts printed with LENS technology, ref. [23] show good potential, with achieved magnetic saturation settling around 2.2 to 2.3 T, within 10% in comparison to commercial FeCo alloyed with vanadium. When as-built FeCo core is heat-treated, its maximum relative permeability increases approximately three-fold, while its intrinsic coercivity drops by two thirds, as shown in Figure 2. Here, the annealing process leads to the development of a bimodal grain size characteristic, where coarse grains with average grain size around 200 to 600 μm are surrounded by finer grains (around 2 μm in size). By tuning the printing parameters or mixing additives into the iron alloy starting powder, it is possible to 3D print FeCo cores with even further attractive properties [24,25]. These explorations in AM of FeCo alloys show promise in overcoming the workability issues associated with the conventional mechanical processing of FeCo cores, while achieving DC magnetic characteristics close to commercial products.

2.2. Iron-Nickel (FeNi)

Iron-nickel alloys, in comparison to iron-cobalt alloys, have a much higher maximum relative permeability, more than 100,000, while saturates at a much lower J_s value, usually between 0.7 and 1.6 T, depending on the nickel wt.% content. Two laser-based AM processes, SLM and LENS, are typically seen in 3D printing of iron-nickel alloys. Reported results on fabricated Fe–30%Ni and Fe–80%Ni showed great potential in achieving magnetic saturation M_s comparable to commercial FeNi at the same nickel wt.% [26]. Analysis on the relationship between magnetic characteristics and 3D printing parameters found that for printed FeNi alloys, magnetic saturation is significantly influenced by the laser

power and the laser scan speed [27,28]. These printing parameters directly impact the grain size and the density of the fabricated parts, which in turn impacts the magnetic saturation. Optimization of the laser parameters, however, is required for FeNi with different percentages of Ni content to improve the magnetic saturation J_s value. As shown in [29], for Fe–30%Ni, SLM printed iron alloys show an increase of more than 20% in magnetic saturation when laser speed is increased, while for Fe–80%Ni, the magnetic saturation is slightly decreased as the laser scan speed increases [28]. Other printing parameters such as laser scan width or the number of scan passes have been found to have a low impact on magnetic saturation J_s , thus optimization of these parameters may not be necessary [30].

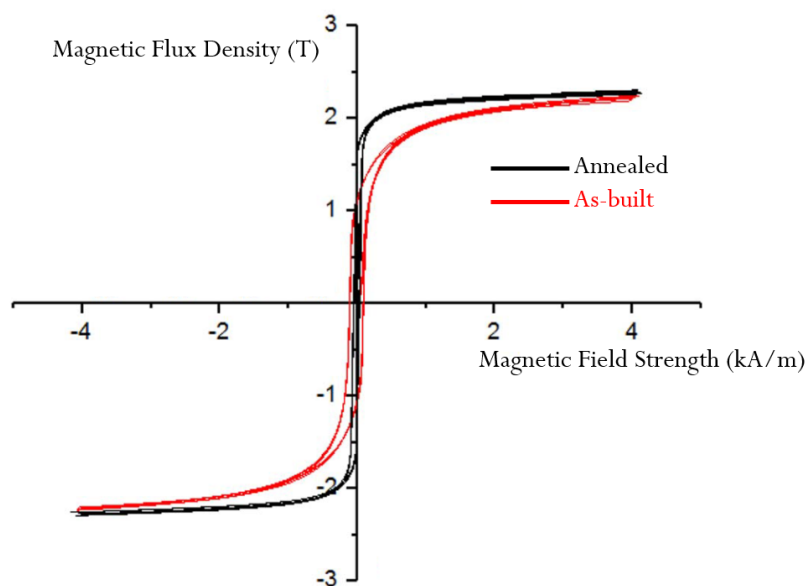


Figure 2. Comparison between quasi-static hysteresis loops of as-built FeCo and annealed FeCo. Figure is adapted from [23].

One of the major issues with the FeNi processed with either SLM or LENS is the high intrinsic coercivity H_c . The measured coercivities of the fabricated FeNi alloys range between 80 A/m to 3000 A/m [31,32], which are much higher than typical values of intrinsic coercivity found in commercial FeNi alloys. High intrinsic coercivity indicates a high hysteresis loss associated with printed FeNi alloys. Additionally, high intrinsic coercivity can have a negative impact toward maximum relative permeability, which is one of the main features of iron-nickel electrical steel. Reduction of intrinsic coercivity in printed iron-nickel is thus important. Analysis has shown that reduction in intrinsic coercivity can be achieved by reducing the porosity level as well as microstructural defects in the printed parts. This can be done by optimization of the laser power and laser scan speed as these parameters have direct influence on the cooling rate and exposure time of the molten pool. These, in turn, impact the defects, porosity, and density levels of printed parts [33]. Alternatively, the coercivity may also be reduced by blending FeNi alloys with additives such as vanadium or molybdenum as shown in [27].

2.3. Iron-Silicon (FeSi)

Considering performance per cost, iron-silicon electrical steel variants have high magnetic saturation, high maximum relative permeability, low intrinsic coercivity, low hysteresis loss, and low eddy current loss up to hundreds of Hz in excitation frequency. Variants of iron-silicon electrical steel are thus found in most iron cores used in electrical machines [16]. In pursuit of additively manufactured iron cores, most research and development activities for 3D printed ferromagnetic materials also focus on iron-silicon.

Similar to the 3D printing of iron-cobalt and iron-nickel, SLM is the most employed AM process for iron-silicon. In [34], SLM is proposed as an alternative method to produce iron-silicon with silicon content at 6.9%wt., which is brittle and challenging to produce with via conventional manufacturing method. Here, the investigation of the SLM printing parameters on the magnetic properties shows that there is a non-linear relationship between laser energy input and the relative permeability, intrinsic coercivity, and the total loss density of the printed iron-silicon. It is thus important to optimize the printing process to obtain optimal magnetic performance of printed iron-silicon. The nature of the SLM method, however, introduces defects and residual stresses on the microstructures of the printed parts, which hinders the magnetic properties of SLM iron-silicon. Compared to commercial iron-silicon lamination steel, the maximum relative permeability of as-built iron-silicon from the SLM process is lower [34,35]. Applying heat treatment to the as-built parts can help remove residual stresses and significantly improve the relative permeability as well as other magnetic properties of SLM iron-silicon [36]. In [37], the annealing process is shown to improve the maximum relative permeability of as-built parts, from an approximate value of 2000 to more than 24,000, which is on par with high performance iron-silicon steel laminations. Other magnetic properties, including total iron loss density, intrinsic coercivity, and saturation are also positively impacted via the annealing process.

Another interesting characteristic of the SLM process is that it introduces grain elongation in the build direction of the printed parts. As a result, iron-silicon fabricated using SLM can have high levels of magnetic anisotropy [38]. Additionally, higher laser energy input can even change the crystallographic texture of the printed iron-silicon, leading to the formation of Goss texture also known as cube-on-edge texture, which is seen in grain-oriented electrical steel [39]. This suggests that SLM can be potentially used as an alternative approach in producing grain-oriented iron-silicon, which in turns can be used for applications such as transformers or large electrical machines.

To avoid the effect of residual stress caused by the local melting due to the laser energy source as in SLM, other AM techniques have also been explored. In [6], FeSi sample is prepared using 3D screen printing and then compared with commercially available FeSi lamination steel. In this AM process where the powder is held together via binder, the printed part is heat-treated uniformly upon printing completion. The magnetic induction and relative permeability at low magnetic field strength are comparable to commercial FeSi steel. However, the magnetic saturation of screen-printed iron-silicon is lower than commercial lamination equivalent, owing to the low density and high porosity level of printed parts.

Binder jet printing (BJP) is another AM technique that does not use laser as an energy source. In [40], the BJP process is used to prepare iron-silicon samples with superior relative permeability in comparison to commercial soft magnetic composites (SMCs). Maximum relative permeability of BJP iron-silicon can be improved to more than 10,000 under post-processing heat treatment [41]. As a laser is not used to melt the powder particles together, there is no grain elongation associated with the BJP process. Thus, an advantage of the BJP process is that it can produce iron-silicon with low level of magnetic anisotropy. This is shown in [42], where the three-dimensional magnetic characterization confirms that BJP iron-silicon can achieve a low level of magnetic anisotropy, similar to SMCs. As a result, iron cores prepared with BJP process can be suitable for applications where easy flux flow in three dimensions is preferred. Hysteresis loss of BJP iron-silicon can be further reduced with the addition of boron into the starting powder [43,44]. This can be explained by the increase of 40% in average grain size of BJP iron-silicon with the addition of boron.

2.4. Performance of Additively Manufactured Soft Magnetic Materials

There are promising results at this early stage of AM for soft magnetic materials for electrical machines. AM allows freedom in design of magnetic cores, which can increase the performance of electrical machines. Additionally, magnetic properties of 3D printed

materials, especially iron-silicon, are improving and reaching the levels of many commercial electrical steel laminations as well as SMCs, see Figure 3. Maximum relative permeability of printed iron-silicon is high and comparable to iron-silicon steel lamination, especially when the printed sample is heat-treated, Table 1. As the AM iron-silicon samples undergo post-processing heat treatment steps, their grain size can significantly improve, which in turn leads to higher magnetic induction and permeability.

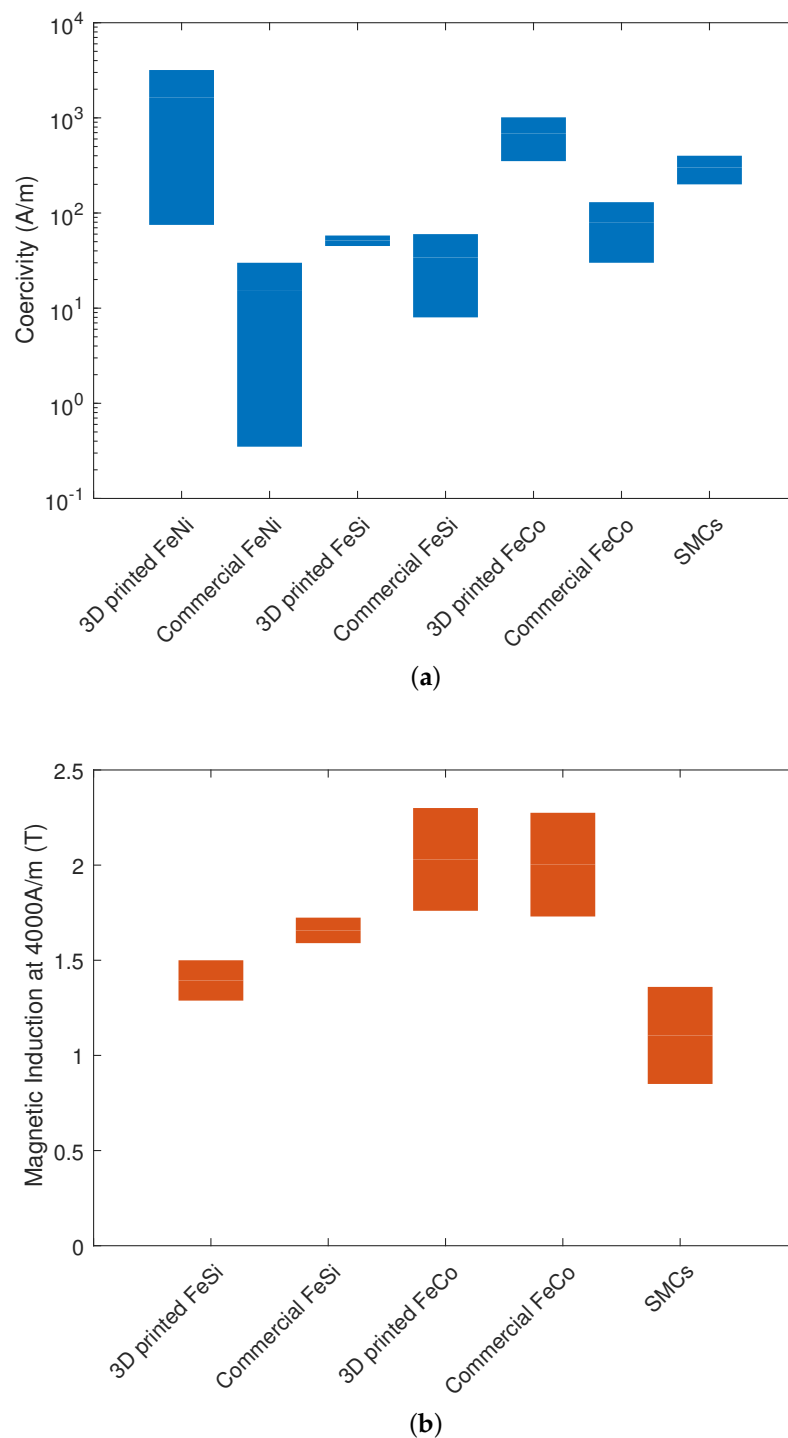
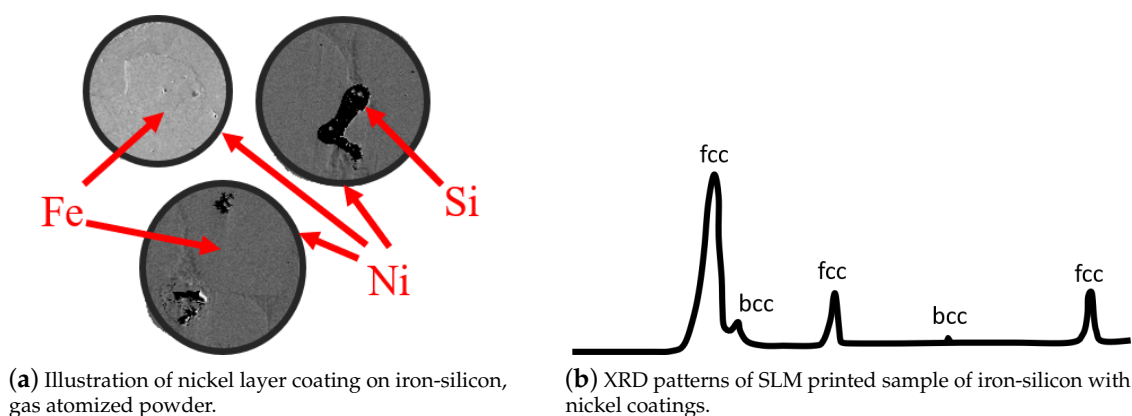


Figure 3. Comparison between additively manufactured and commercial electrical steel. (a) Comparison between reported coercivity of 3D printed electrical steels, commercial electrical steels, and SMCs; (b) Comparison between reported magnetic induction at 4 kA/m, B_{40} , of 3D printed electrical steels, commercial electrical steels, and SMCs.

Table 1. Comparison of grain size and maximum relative permeability between as-built and heat-treated printed soft magnetic materials [34,37,40,43,45].

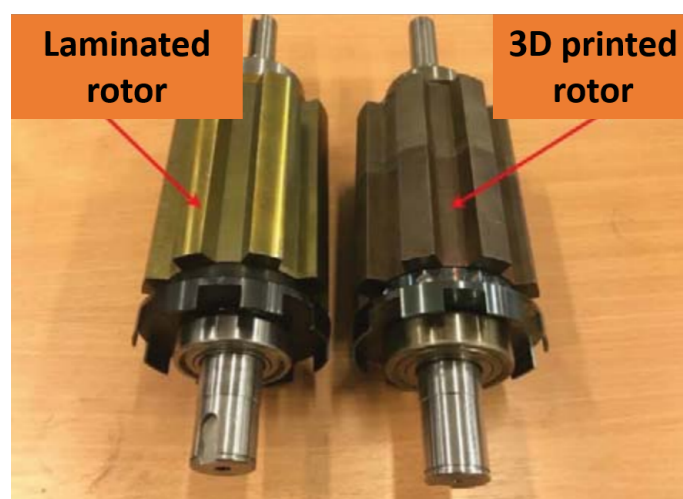
	Grain Size (μm)	Max Relative Permeability μ_{max}
As-built	10–200	1200–5500
Heat-treated	400–1000	24,000–31,000

Application of AM for soft magnetic materials can also provide the capability to manipulate the crystallography of fabricated parts on demand. As the crystal structure of the soft magnetic material changes to the desired requirements, the magnetic properties of the soft magnetic materials would also change. In [46], gas atomized silicon powder coated with nickel layer is used for printing soft magnetic cuboid sample. The SLM fabricated sample shows changes in the crystallographic structure, switching from bcc structure, which is prevalent for iron-silicon, to fcc structure, which is typically seen for iron-nickel alloy, Figure 4. Tuning the printing parameters along with customized feedstock powder can thus offer unique opportunities in achieving customized magnetic properties.

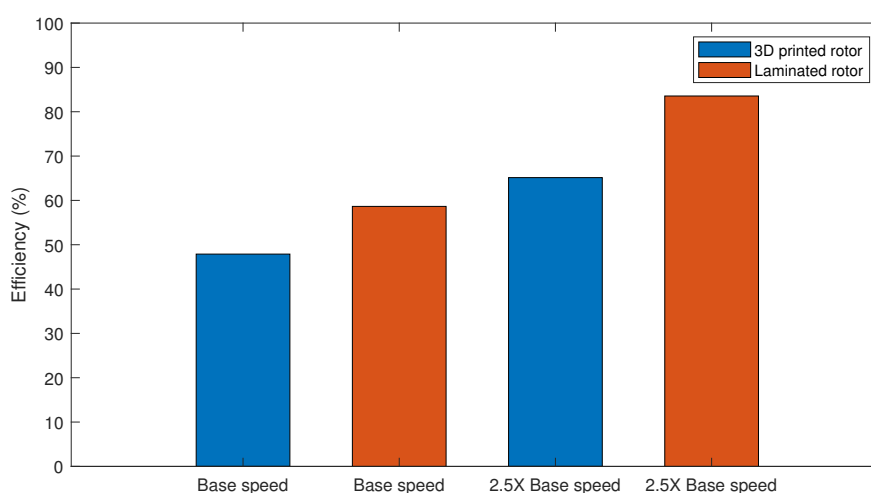
**Figure 4.** Illustration of impacts of using nickel iron silicon coated powder on the crystallographic structure of printed samples. Figures are adapted from [46].

2.5. Challenges

Iron loss characteristics of printed FeSi is still a major concern. At DC or quasi-static excitation, additive manufactured iron-silicon has been shown to achieve hysteresis loss comparable to iron-silicon laminations [43]. The intrinsic coercivity of SLM-processed and BJP-processed FeSi is nearly 4 times lower than SMCs. At low excitation frequency of 50 Hz, the total iron loss density of additively manufactured iron-silicon is between 2 and 6 W/kg at 1 T. This puts printed iron-silicon in line with SMCs in terms of total iron loss, and a bit higher in comparison to iron-silicon lamination steels. These iron loss values at low frequency range, however, are promising providing that this is still at an early stage of applying AM for soft magnetic materials. As the excitation frequency increases, however, the total iron loss of 3D printed iron-silicon increases exponentially [43]. The resistivity and eddy current loss of 3D printed iron-silicon must be reduced. In [47], a rotor core of a switched reluctance machine is printed and compared directly with a laminated rotor core, Figure 5. Experimental results show that at base speed, 3D printed machine is about 20% lower in efficiency in comparison to the benchmark laminated machine, Figure 5b. Higher operating speed leads to even higher eddy current loss and higher reduction in efficiency. Eddy current loss remains a concern with 3D printed iron core, especially when the core is printed as bulk.



(a) Laminated rotor and 3D printed rotor of a switched reluctance machine.



(b) Differences in efficiency of conventional laminated machine and electrical machine with 3D printed rotor core.

Figure 5. Illustration of eddy current loss impacts on efficiency of 3D printed electrical machine. Figures are adapted from [47].

Some strategies have been suggested for improving eddy current loss within printed ferromagnetic materials. These strategies take advantage of unique capabilities of additive manufacturing. In [45,48], AM is proposed to fabricate iron-silicon cores with complex cross-section geometries. Figure 6 shows an example of an iron-silicon rod made of multiple parallel thin plates of 400 μm thickness, where struts are added to connect the plates together. This complex cross-section geometry disrupts the paths of the eddy current, which leads to the reduction of eddy current loss when compared to the solid iron-silicon rod. Printed iron-silicon with Hilbert cross-section geometry can also result in a lower eddy current loss. Another example of complex cross-section geometries is shown in [45], where the layering technique using different materials is used to 3D print iron alloy. Here, layers of iron and iron-aluminum alloy are stacked back to back in an alternative fashion, as shown in Figure 7. Due to the differences in the resistivity between the iron alloy and the iron-aluminum alloy, the eddy current is restricted in each layer, which leads to a lower eddy current loss and total iron loss. At the excitation frequency of 100 Hz, the measured eddy current loss shows a reduction of 15 times compared to the bulk printed iron alloy. Tuning layering materials and thickness can help with further reduction in eddy

current loss, which is significant for when applying such materials for high-speed electrical machine applications.

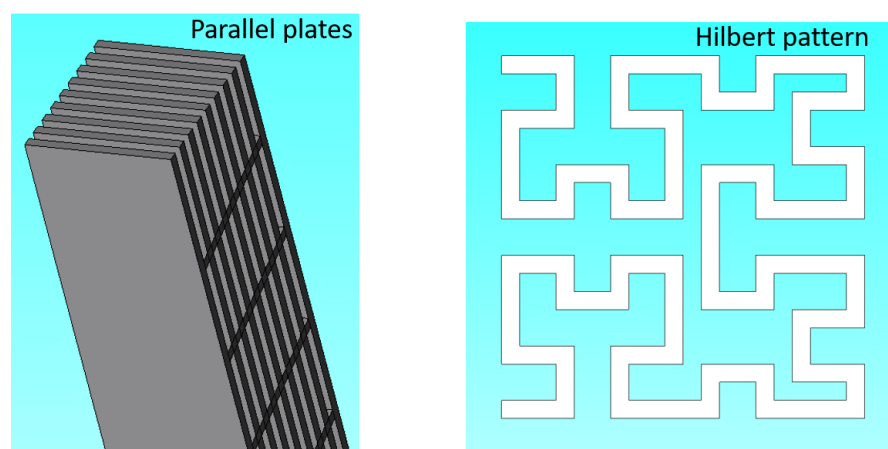


Figure 6. Examples of geometry structure in additive manufactured iron-silicon that can help with reducing eddy current loss. Printed iron-silicon with parallel plates or Hilbert cross-section can have a significant reduction in eddy current loss. Illustration adapted from [48].

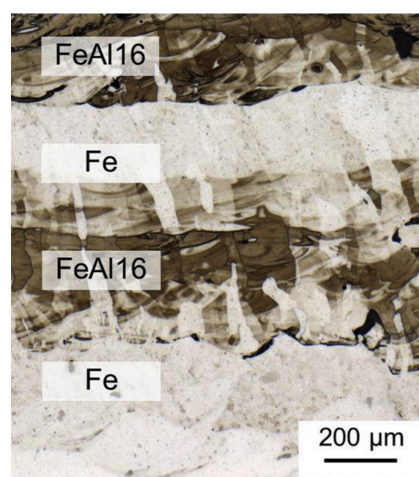


Figure 7. Optical microscopy cross-section image of printed soft magnetic sample. Here iron layer and iron-aluminum alloy layer are stacked back to back [45]. This printing strategy is implemented to reduce eddy current loss.

There are still many challenges in fabricating high performance ferromagnetic materials for electric motors and generators. The electromagnetic and mechanical properties of 3D printed materials, although advancing rapidly, still need to match or exceed the current properties of many existing commercial equivalents. Judging at the performance development of SMCs a couple of decades ago [19], and the current performance of SMCs today [49], it is encouraging knowing that the performance of additively manufactured ferromagnetic materials will continue to improve. Material characterization is thus important, especially in the development of the correlation between the 3D printing parameters, the microstructure, the crystallographic texture, and the desired properties of printed ferromagnetic parts. Other efforts in optimization of the starting powder/filament, recovery of unused material, and improvement in printing bed size, and build rate can contribute to cost reduction of the printed parts [50], furthering the application of AM beyond just prototyping. Another concern typically seen in additively manufactured parts is the surface roughness, which can potentially lead to the 3D printed iron cores with rough surface. A poor contact between the stator core and the housing of the electrical machine can change

the contact thermal resistance between the core and the housing, which in turns can lead to negative impacts in the heat transfer between them [51].

3. Additive Manufacturing of Permanent Magnets

There are three main requirements for permanent magnets used in electrical machines:

1. high functioning magnetic properties,
2. stability under high temperature and
3. corrosion resistance.

Regarding the magnetic properties, the important characteristics include remnant flux density, B_r , intrinsic coercive force, H_{ci} , and the maximum energy product $(BH)_{max}$. Permanent magnets typically seen in electrical machines are NdFeB, AlNiCo, SmCo, and ferrite magnets. For NdFeB-based magnets, rare earth element such as Dy is used to help enhancing the intrinsic coercive force of the magnets [52], especially at temperature of 180 °C and higher [53,54]. This is beneficial to permanent magnet machines operated in high temperature settings as magnet flux remnant flux density is less susceptible to thermal degradation. However, the use of critical rare earth elements such as Dy and Nd can increase the cost of NdFeB-based magnets, and constrain the supply. By reducing the use of rare earth elements, it is possible to lower the magnet cost and diversify the magnet supply [54].

The production process of sintered permanent magnets includes crushing molten or strip cast alloys into fine powder, and aligning the powder particles under strong external magnetic field. The aligned powder particles are then compacted via cold isostatic pressing or other pressing techniques. The green part is then sintered, heat-treated, and machined to desired geometries. For bonded magnets, magnetic alloy powders are mixed with polymers and then formed to desired shapes by compression or injection molding. Additive manufacturing can potentially allow both sustainability and cost reduction in manufacturing magnets as well as increasing the magnet supply chain by reducing mechanical steps, and allowing for complex geometries without use of molds. At this current stage, the magnetic properties of 3D printed NdFeB bonded magnets are highly comparable to those found in commercial bonded NdFeB magnets [55]. These commercial bonded magnets are typically manufactured with injection molded (IM) method. The magnetic properties of printed magnets, however, are dependent on the printing technology, the density of the printed parts, and the chemical composition of the filament or powder mixture used in 3D printing.

3.1. Status on Additively Manufactured NdFeB Magnets

Powder bed fusion, binder jetting, and material extrusion methods are three main technologies that have been investigated at fabricating NdFeB magnets. Big Area Additive Manufacturing (BAAM) is a special technology within the category of material extrusion, developed at Cincinnati Inc. together with ORNL's Manufacturing Demonstration Facility, has also been used to fabricate NdFeB magnets [56]. One major advantage of BAAM is that it is capable of printing large scale parts of volume up to 26 cubic meters [57].

The powder bed technology with SLM shows promise in printing magnets at above 90% density [58]. In this laser-based AM process, the laser can introduce significant cracks and residual stresses in the printed magnets which may negatively impact the magnetic and mechanical properties of the magnets. Thus, optimization of the laser parameters, such as proper selection on the scan speed and laser power, can lead to optimal performance of magnetic properties of printed magnets. Additionally, optimization of the laser scanning pattern can also help with the practical distribution of heat within the printed magnet, which can help improve its overall the performance. Here, the reported magnetic polarization of the laser-based printed magnet is around 0.55 T. Other performance characteristics of the printed magnet, however, are not included.

The material extrusion and binder jetting technologies, which do not use laser as an energy source, are widely investigated for printing NdFeB magnets. Magnetic properties of NdFeB produced via BJP have similar properties compared to NdFeB fabricated via fused

deposition modeling (FDM), a technology within material extrusion, as shown in [59]. They share similar performance in density, remnant flux density, and intrinsic coercivity [60]. Magnets fabricated via BJP have a density value around 3.5 g/cm^3 , which is approximately above 40% of the NdFeB theoretical density. One of the current challenges in fabricating magnets via BJP is to increase the volume content of NdFeB powder in the printed parts, which can help improving the magnet density and the remnant flux density. Infiltration of NdCuCo and PrCuCo alloys toward as-built BJP magnets can help improve density and mechanical integrity of the magnets and the intrinsic coercive force, as shown in [61]. However, there is a slight tradeoff of remnant flux density with the inclusion of these additives.

NdFeB magnets fabricated via BAAM, however, outperform magnets prepared with the other printing technologies [62]. Density of BAAM magnets is approximately 20% higher in comparison with BJP magnets, while remnant flux density and the maximum energy product are 20% and 40% better, respectively. The magnetic properties of BAAM magnets can further be improved with a higher volume percentage of the magnet powder used in the printing mixture [63]. A direct comparison with commercial injection molded NdFeB magnets in [56] shows competitive performance of BAAM magnets, in terms of intrinsic coercive force, remnant flux density, and magnet energy product. Thermal performance of BAAM magnets also shows similar behavior when compared to injection molded magnets, as shown in Figure 8. Here, degradation of performance of BAAM magnet as a function of temperature shows similar negative trend as ambient temperature increases. A brief comparison of the current status of magnetic properties for different additive manufacturing technologies as well as injection molded magnets is shown in Table 2.

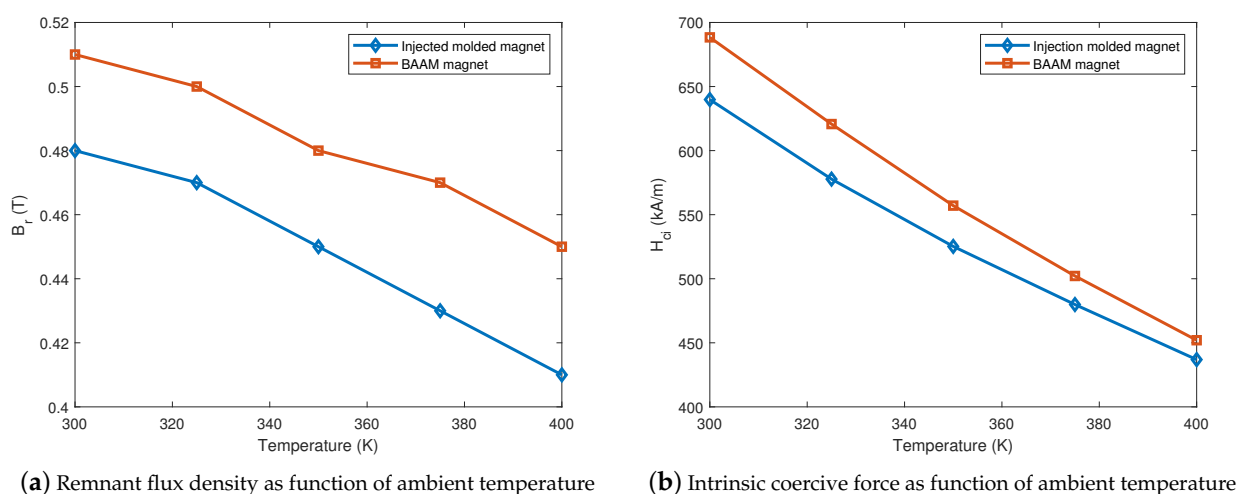


Figure 8. A comparison on thermal degradation of performance between commercial injection molded magnet and BAAM fabricated magnet. Figures are plotted using data in [56].

Table 2. Comparison of characteristics between commercial bonded magnets and additive manufactured NdFeB magnets [55,56,59,62,63].

Manufacturing Method	ρ (g/cm ³)	B_r (T)	H_{ci} (kA/m)	$(BH)_{max}$ (MGOe)
IM	3.85–5.7	0.22–0.68	135–463	3.3–9.4
BJP	3.3–3.86	0.3–0.42	700–1100	2.4–3.8
BAAM	4.9–5.2	0.51–0.58	688–708	5.3–5.47
FDM	3.53	0.3	990	NA

3.2. Status on Other Additively Manufactured Magnets

Research on additively manufactured SmCo magnets is still at the early stage, so far focusing on printing magnets made of recycled magnet powder. The authors in [64] shows the process on producing magnet filament, made of recycled SmCo magnet powder and polylactic acid (PLA) plastic, for 3D printing bonded magnet. The produced magnet filament, however, has low remanent flux density, below 0.1 T. This is due to the low volume percentage loading of the magnet powder (less than 20%), in the production of the magnet filament. Increasing the loading of the magnet powder can potentially lead to magnet filament with higher remnant flux density and maximum energy product.

On the other hand, investigation on additively manufactured AlNiCo magnets shows promising results toward application in electrical machines. The 3D printed AlNiCo magnets, via LENS technology, can achieve maximum energy product $(BH)_{max}$ with values between 48% and 66.7% in comparison to commercial sintered or cast AlNiCo magnets [65]. Regarding the intrinsic coercive force of printed AlNiCo magnets, it is equivalent to commercial AlNiCo magnets, varying between 140 kA/m to 160 kA/m. The remanent flux density, B_r , of printed AlNiCo magnets varies between 0.75 T and 0.92 T, which is approximately 10 to 15% lower than typically values found in commercial AlNiCo. These early findings show the competitiveness of 3D printing as an alternative AlNiCo permanent magnet manufacturing process. Here, optimization of the printing process, as well as further exploration in material composition can potentially produce additively manufactured AlNiCo with magnetic properties exceeding commercial equivalents. One of the key advantages of AlNiCo magnets is that the $(BH)_{max}$ value of AlNiCo can stay relatively constant at temperatures up to 300 °C. Thus, the ability to have an alternative supply chain of AlNiCo magnets is beneficial to electrical machine applications where high operating temperature is a concern.

4. Topology Optimization for Magnetic Structures

The shaping of the magnetic structures for electrical machines can be generally categorized into two groups: (1) conventional shaping and optimization techniques, and (2) topology optimization. For the conventional shaping techniques, mathematical models and sensitivity analysis are typically used on a pre-selected machine geometry template [66,67]. The computational and analytical efforts are often intensive to improve the accuracy of the calculation of the airgap flux density, torque components, and the magnetic flux density distribution [68]. Conventional optimization, which is typically based on evolutionary multi-objective optimization algorithms, further refines the shape of the magnetic structures to improve the machine performance. As a result, the derivation of uniquely shaped magnetic structures for electrical machines can be slow.

Emerging from structural optimization, TO is increasingly applied in magnetic devices [69], and subsequently in design of electrical machines, especially at the component level such as magnetic cores [70] and permanent magnets [71]. In contrast to conventional optimization, TO can generate an initial geometry template from scratch with less analytical modeling [72]. In general, TO investigates optimal distribution of single or multiple materials within a defined design space [73]. Compared to conventional optimization shaping techniques, it offers additional flexibility in optimizing the geometry of the magnetic components for attaining the desired performance. Thus, TO can yield unique shapes that are generally not realizable with conventional optimization approach.

4.1. Topology Optimization Shaping Techniques

In seeking unique and optimal geometry either made of single or multiple materials, TO can employ approaches such as the on/off method and the density-based method. For the on/off method, the design space is typically divided into cells or put into a grid-like structure. Each cell is then represented by a variable, such as normalized density ρ_n , which can be assigned a value of zero or one, as illustrated in Figure 9a. Zero and one indicate the absence and presence of material, respectively. The pattern of the material distribution can

be determined via selection of objective functions and use of evolutionary multi-objective or gradient-based algorithm. Thus, in a finalized topology optimized design via on/off method, it typically has an unconventional geometry.

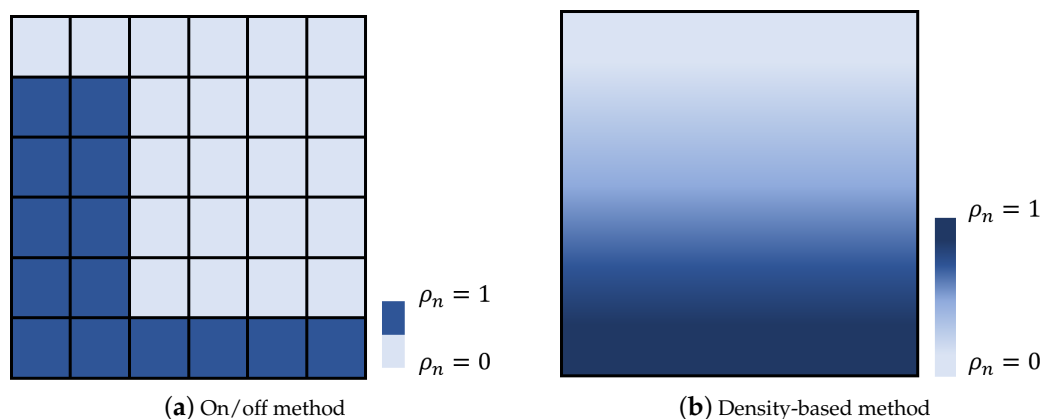


Figure 9. Illustrations of two topology optimization methods for magnetic cores. Here, ρ_n is the normalized density variable under optimization.

An on/off TO is modified to optimally distribute the soft magnetic material for a rotor core of an interior permanent magnet machine and then to smooth the shape of the design is presented as shown in Figure 10. Here, the TO algorithm in [8] first uses a genetic-based method to find an optimal solution in the global search space. The solution is then smoothed out via the use of a gradient-based method in the local search space. The illustration of the modified algorithm is shown in Figure 11.

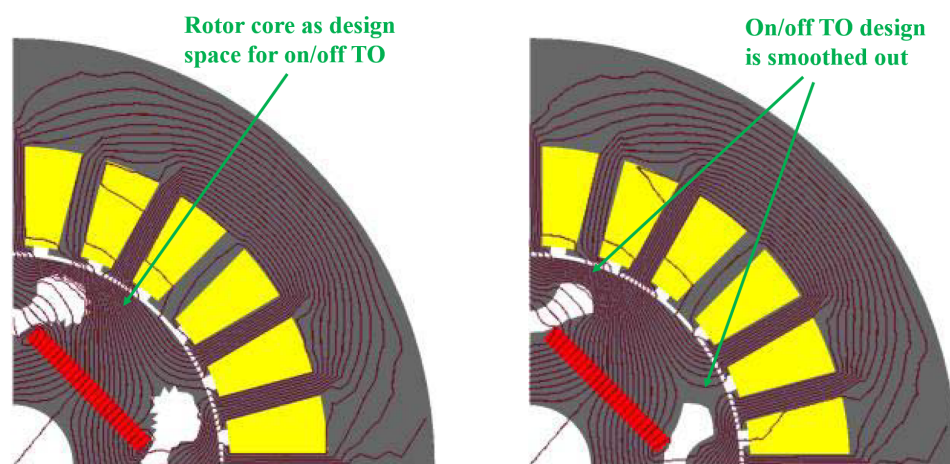


Figure 10. Example of a rotor core of a permanent magnet machine achieved via on/off TO algorithm. The TO design is smoothed out. Figure is adapted from [8].

The on/off TO method can also be applied to find the optimal distribution of multiple materials such as iron, copper, and permanent magnet. In [74], a multi-material on/off TO algorithm is used to maximize the force acted on the plunger of a permanent magnet linear actuator. The TO optimal design achieves a unique structure compared to the original design and an additional increase of 40% in average force, as shown in Figure 12.

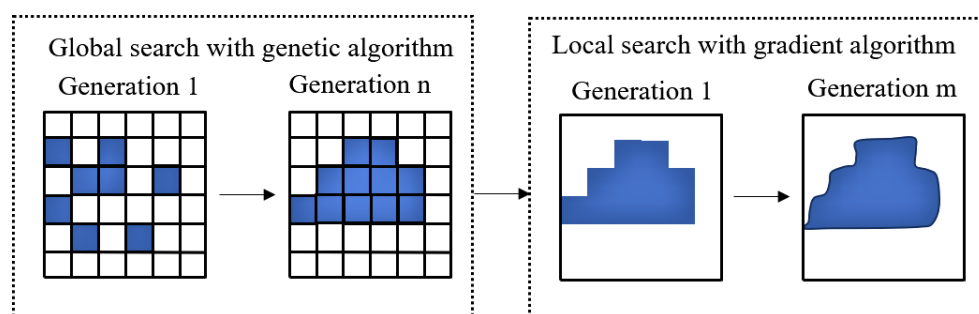


Figure 11. Example of an on/off TO algorithm where a genetic-based algorithm is combined with a gradient-based algorithm. The shape achieved with this algorithm is smoother. Figure is adapted from [8].

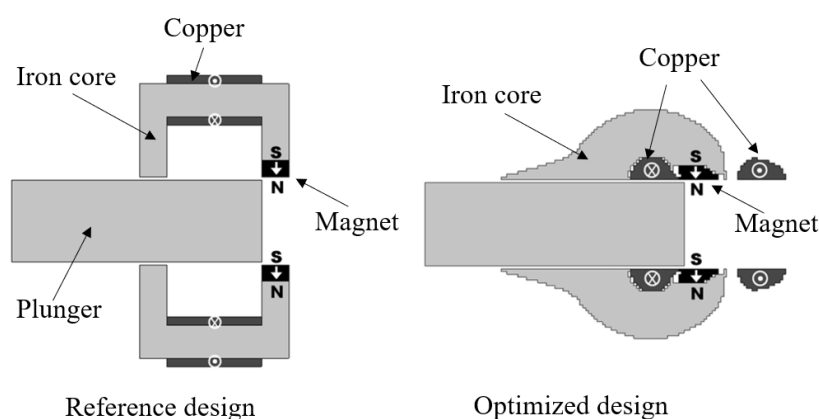


Figure 12. Illustration on the result of the on/off TO algorithm for multiple materials on a permanent magnet linear actuator. Figure is adapted from [74].

As the on/off method assigns the optimizing density variable to be binary, the density-based method assigns the density variable ρ_n a continuous value between zero and one, as illustrated in Figure 9b. A version of the density-based method is applied on a rotor core of a permanent magnet synchronous machine in [9]. Here, the exclusive magnetic-based topology optimization works toward maximizing the average torque while constraining the torque ripple and cogging, and finally leads to the unique design of the rotor core as shown in Figure 13. The white areas in the rotor core represent the permanent magnet, while the dark red areas and the dark blue areas represent iron and air, respectively. In between them are regions with intermediate density values, which are represented with different shades of colors.

Magnetic-based topology optimization may result in unique designs that achieve desired electromagnetic performance. These unique designs also present challenges that must be considered. Exclusively using magnetic-based TO algorithm results in designs that are only optimized for electromagnetic performance. Since mechanical stress of the structure is not included as an objective, the mechanical integrity of the magnetic-based TO design may become a concern. A magnetic-based TO design with a unique distribution of air pockets is shown in Figure 14. Here the TO algorithm, however, does not include mechanical stress analysis in the iron regions adjacent to the air pockets. This can lead to durability performance of the design under real operating condition where the adjacent iron regions can be subjected to stress values between 240 MPa to above 450 MPa [75]. Coupled structural and electromagnetic analysis can provide tradeoff solutions to address this concern. In [76], the density-based method is applied on rotors of wound field synchronous machines. The optimized rotors are achieved via the integration of both magnetic and structural topology optimization analysis.

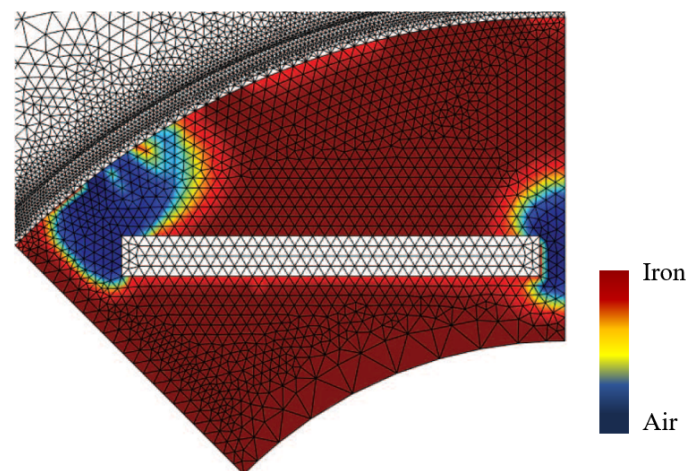


Figure 13. Illustration of density-based topology optimization for the rotor core of an interior permanent magnet synchronous machine, adapted from [9].

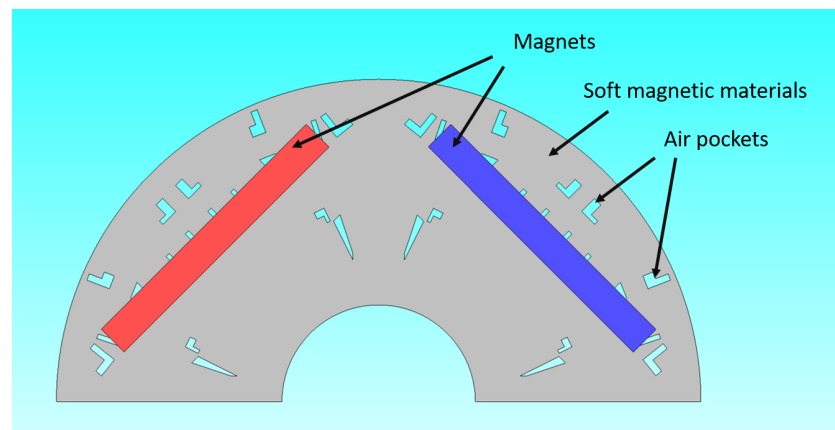


Figure 14. Example of magnetic-based topology optimization for the rotor core of an interior permanent magnet synchronous machine, adapted from [77]. Iron regions adjacent to air pockets and magnets can be subjected to high mechanical stress.

4.2. A Design Tool for Additive Manufacturing

As TO is increasingly adopted in developing unique geometries for electrical machines, manufacturability of the unique magnetic core designs is equally important. Design complexities may increase manufacturing cost for electrical steel laminations. Additionally, manufacturing methods including subtractive techniques can compromise the magnetic properties of punched laminations [17], leading to magnetic cores with inferior magnetic performance compared the mother coil. Thus, topology optimized designs in Figure 10 and Figure 14 may not be able to achieve the desired magnetic performance. Powder metallurgy can potentially be used as an alternative approach to fabricate such complex designs, as shown in Figure 15. However, the added cost of molding and tooling may become a concern.

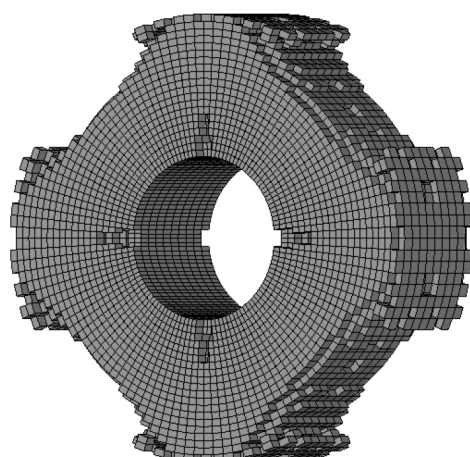


Figure 15. An example on topology optimization of a rotor core for a switched reluctance motor [78].

In application where non-homogeneous magnetic core is desired as in [79,80], powder metallurgy manufacturing approach is not a viable solution for production as it may reach the limits in fabricating such composite, non-homogenous structures. Similarly, designs of magnetic cores for electrical machines generated with the TO density-based method as in [9,76], may request material whose properties may not correspond to an available material [81]. Additive manufacturing can potentially overcome difficulties typically observed in conventional manufacturing methods, and in some cases is the only viable manufacturing solution [82].

Recent advancements in AM as well as the proliferation of its application in fabricating magnetic components for electrical machine have revitalized TO as an advanced design tool. The synergy between TO and AM can potentially lead to the development of magnetic components, whose properties and geometries are complex. Investigations in integration of TO toward AM in producing magnetic components for electrical machines have shown very promising results. In [10], a topology optimized design of a rotor core of a surface mount permanent magnet machine is additively manufactured via the SLM process, as shown in Figure 16. Here, the TO algorithm combines both the electromagnetic and structural optimization stages to achieve a rotor core geometry with 50% reduction in weight, at a tradeoff of less than 2% in average torque, while achieving maximum von Mises stress in the optimized rotor core well within the yield strength of the material. The result of this work highlights the exploitation of multi-physics TO as an advanced design tool for AM in developing new, unconventional electrical machines.

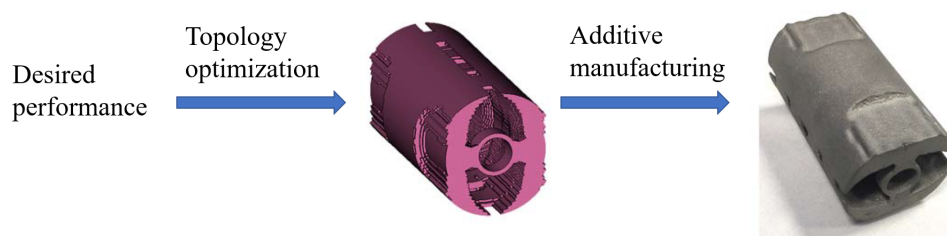


Figure 16. Optimized rotor core via coupled magnetic-structural TO. The design is then additively manufactured via SLM. Figure is modified from [10].

The integration of TO into AM is also seen in fabricating permanent magnet with unique shapes and structures. In [71], TO is implemented to generate the design of a permanent magnet such that it can provide magnetic flux density waveform close to the predefined external field. The design is then additively manufactured via the FDM process from a magnetic compound of NdFeB powder, ferrites, and polymers, Figure 17. In [11], permanent magnet made of multiple magnet grades is proposed for a surface mounted

machine to reduce manufacturing cost without penalizing machine performance. The multi-grade magnet is optimized, and investigated via finite element analysis. Although TO is not implemented, the analysis suggests the combined use of TO and AM technologies in potentially producing lower cost magnets.

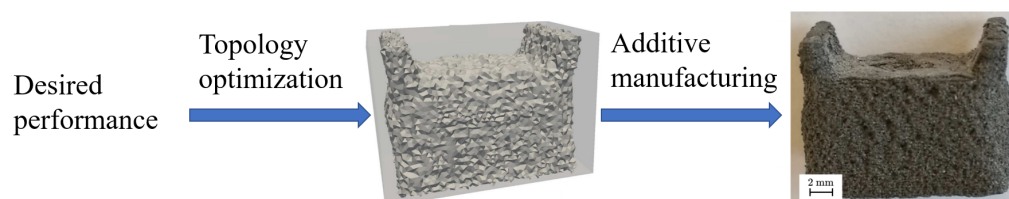


Figure 17. Topology optimized magnet. The design is then additively manufactured via fused deposition modeling. Figure is modified from [71].

5. Discussion

The implementation of AM technologies for magnetic components in electrical machines is still in its early stages. Common research themes for application of AM technologies for electrical machines focus either on understanding and improving the performance of individual components, or leveraging the freedom in design, an inherent characteristic of AM. An understanding of the characteristics of additively manufactured parts can help further the adoption of AM for electrical machines, as well as its integration with topology optimization as an enabling design tool.

5.1. Impacts of Defects Due to AM Process

Presently, there is opportunity to develop full density printed magnetic materials for electrical machines. Porosity can be observed in microstructural analysis of printed iron-silicon and printed magnets, as shown in Figure 18. Porosity, cracks, and residual stresses in the printing process typically hinder both the magnetic and mechanical properties in 3D printed parts. These defects reduce relative permeability, magnetic saturation, iron loss performance in printed soft magnetic materials, and decrease the remanent flux density and maximum energy product in printed permanent magnets. Printed iron cores and permanent magnets, if used in the rotor of electrical machines, can be susceptible to stress at high operating speed [83]. This can potentially lead to mechanical integrity issues for electrical machines. Enhancements of these magnetic and mechanical properties, however, are possible via the use of non-thermal method such as material infiltration or post-processing thermal methods [3,61].

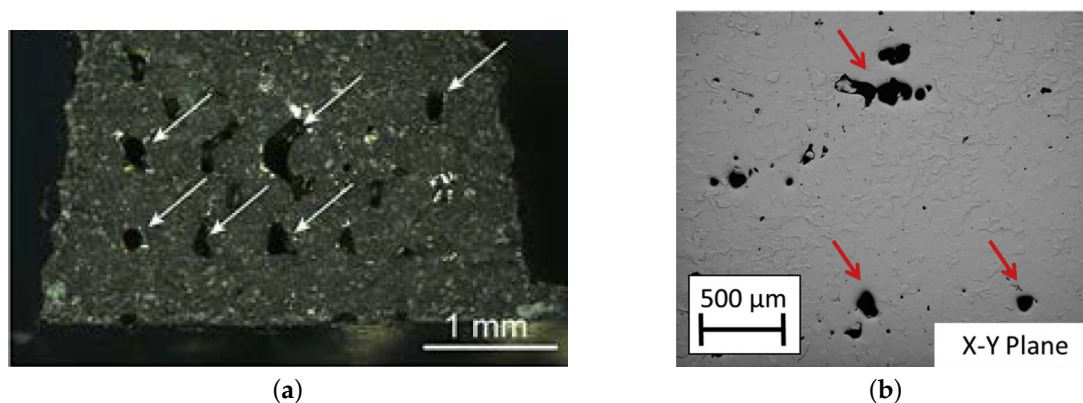


Figure 18. Images of additively manufactured NdFeB bonded magnets and iron-silicon. Here, black features indicated by the arrows in the images represent pores. (a) Cross-section of bonded NdFeB magnets fabricated with material extrusion [59]; (b) Optical micrograph of selective laser melted iron-silicon [84].

5.2. Multi-Material AM for Electrical Machines

At the current stage, the majority of AM technologies are employed for single components, using a single material for printing. The printed components are then assembled together with conventionally manufactured components to form the electrical machines [85,86]. Challenges in printing multiple materials are due to the dissimilarities in characteristics of the materials. Successful application of multi-material AM can open up opportunities for printing a complete electrical machine in a single step. Early exploration of multi-material AM for electrical machines show encouraging results, focuses on printing iron alloys, conductors, and insulation at the same time Figure 19. This proof of concept demonstrates the potential to reduce the production and assembly effort for electrical machines. The build time for the single material rotor core in Figure 16 is about 48 hours. Further research and development, however, is necessary for improving the printing process toward mass production [50].

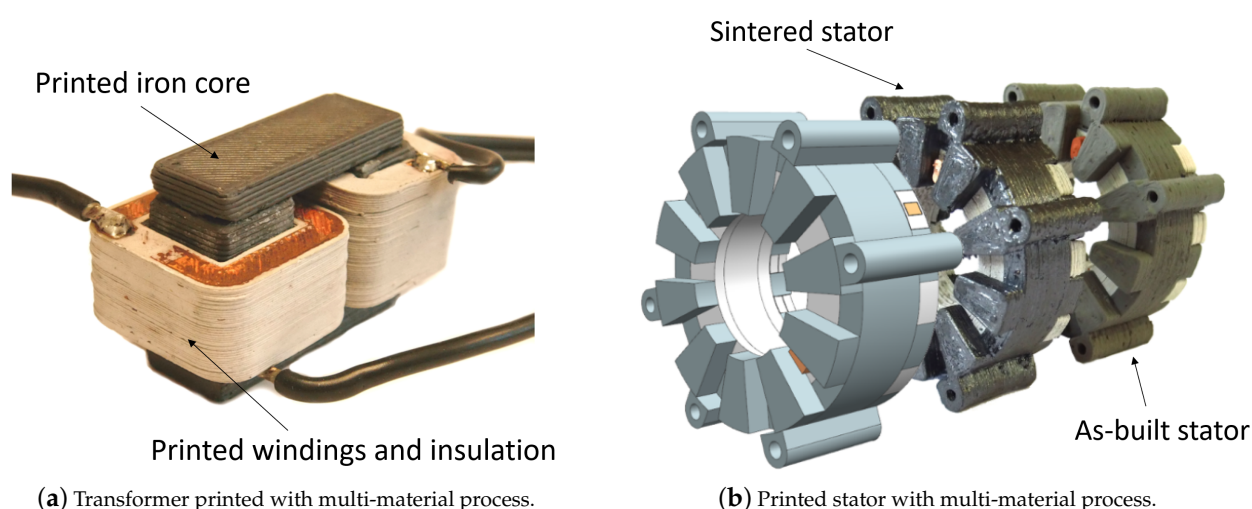


Figure 19. Examples of printing multiple key materials for electrical machines: iron core, conductors, and ceramic insulation [87].

5.3. Integration with Topology Optimization

As AM becomes a realization manufacturing method for topology optimization, there are still challenges remaining with combining these two enabling technologies. Since AM is a layer-based manufacturing technique, printed parts can suffer a degree of anisotropy. Electromagnetic properties can be slightly different in the build direction compared to the other directions. The formulation of the topology optimization algorithm has to account for the anisotropy effect when applying on a 3D optimization problem. Another concern associated with TO is the computation efforts. Optimization of just the permanent magnet rotor core in [88], via genetic algorithm, can take up to hundreds of generations to result in the Pareto front. Thus, significant computation effort would be required for of a multi-objective, multi-physics TO of multiple materials. The addition of complexities from the TO design can potentially prolong the printing time of the prototype.

6. Summary

This paper presents the current research and trends on applications of additive manufacturing, topology optimization, and their integration toward magnetic components in electrical machines. As an enabling technology, additive manufacturing provides topology optimization a method to fabricate unique 3D geometries that are challenged to be manufactured via conventional methods. Successful combinations of additive manufacturing and topology optimization on fabricating both the iron core and permanent magnet with desired performance show a great potential as a design tool for electrical machine

designers. Capability of using multiple materials within additive manufacturing is another advantage that electrical machine designers can further exploit during the early machine design process. Recent results also show that additive manufacturing technologies have great potential as an alternative approach for realizing magnetic components for electrical machines. With the advancement in printing technology and the understanding between printing process and the magnetic properties of printed parts, there have been success toward printing of magnetic components. For soft magnetic materials, the current performance of the 3D printed parts is getting close to the parts manufactured using conventional methods. As for permanent magnets, performance of additively manufactured bonded NdFeB magnets is similar to the value seen in commercial counterparts. Additionally, results on printing magnets with good thermal performance as well as using producing magnet filament from recycled materials are encouraging. This provides the possibility to drive down the future cost of manufacturing high performance permanent magnets for electrical machine applications.

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Abbreviations

The following abbreviations are used in this manuscript:

AM	Additive Manufacturing
BAAM	Big Area Additive Manufacturing
BJP	Binder Jet Printing
FDM	Fused Deposition Modeling
FFF	Fused Filament Fabrication
IM	Injection Molded
LENS	Laser Engineered Net Shaping
SLM	Selective Laser Melting
SMC	Soft Magnetic Composites
TO	Topology Optimization

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