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Toward Additively Manufactured Electrical Machines: Opportunities and Challenges

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Abstract:

With the growing interest in electrification and as hybrid and pure electric powertrains are adopted in more applications, electrical machine design is facing challenges in terms of meeting very demanding performance metrics, for example, high specific power, and harsh environments. This provides clear motivation to explore the impact of advanced materials and manufacturing on the performance of electrical machines. This article provides an overview of additive manufacturing (AM) approaches that can be used for constructing electrical machines, with a specific focus on additively manufactured iron core, winding, insulation, and permanent magnet, as well as cooling systems. Since there has only been a few attempts so far to explore AM in electrical machines (especially when it comes to fully additively manufactured machines), the benefits and challenges of AM have not been comprehensively understood. In this regard, this article offers a detailed comparison of

multiple multimaterial AM methods, showing not only the possibility of fully additively manufactured electrical machines but also the potential significant improvements in their mechanical, electromagnetic, and thermal properties. The articles will provide a comprehensive discussion of opportunities and challenges of AM in the context of electrical machines.

SECTION I. Introduction

Additive manufacturing (AM), which refers to building up a three-dimensional (3-D) component in layers by depositing material, has been highlighted/adopted in a wide range of applications due to its ability to make complex parts that would be very difficult or impossible to make using conventional subtractive methods. The major categories of AM methods include the following.

1. *Fuse filament fabrication (FFF)/fused deposition modeling (FDM)*: Extrusion-based method using thermoplastic materials.
2. *Stereolithography (SLA)*: Photopolymerization method using liquid.
3. *Selective laser sintering/melting (SLS/SLM)*: Powder bed fusion approach using metal powder.

The major advantages/benefits of AM include [1]

1. fast prototyping;
2. complex geometries and hard-to-reach areas;
3. building different components simultaneously;
4. mix of multiple materials;
5. improved properties/enhanced performance.

A. Additive Manufacturing

Despite the fact that AM is currently intended for low-volume manufacturing due to low manufacturing rate (0.01–1 kg/h) and high cost (\$0.1–10 per gram), it can be envisioned based on its fast growth in terms of availability of materials and quality of processes that the depth and scope of its application will be exponentially expanded.

There has been great progress in the area of AM over the past few years regarding the following two aspects.

1. *Materials*:
 1. increasing no. of available materials that can be additively manufactured;
 2. complex structures can be additively manufactured out of multiple materials for significant weight savings;
 3. controllability of material properties, for example, orientation.
2. *Processes*:
 1. more processing methods other than the three mainstream methods (extrusion, photopolymerization, and powder bed fusion);
 2. thinner layer thickness and higher resolution for each method.

Table I provides a brief comparison of the three AM approaches mentioned above. FFF/FDM and SLA can be used to build insulating components, whereas SLS/SLM is generally utilized to manufacture conductive parts. The 3-D printer price climbs from FFF/FDM, SLA, to SLS/SLM, whereas the maximum build area goes down. SLA has the highest accuracy as well as manufacturing rate among the three approaches. It should be noted that the

price and accuracy keep changing with advancing AM technologies. Although the values used in Table I is based on the state of the art, they are more appropriate on relative basis.

TABLE I Key Features of Three Major Methods of AM

AM Methods	Material	Price of Pinter	Accuracy and Maximum Build Area	Applications
FFF/FDM	<ul style="list-style-type: none"> Thermoplastic polymers (eg. ABS, PLA, ASA, nylon, etc) Metal powder and binder mixture (eg. steel power mixed with polymer) 	Low (\$100 to \$2 k depending on performances)	Layer thickness: 0.127-0.254 mm; X/Y resolution: 0.607 mm 914.4 x 609.6 x 914.4 mm ³ (F900)	Concept modeling; Insulating parts; Light structural parts; Magnets and iron cores.
SLA	Clear, ABS-like, Polypropylene-like, heat resistant, ceramic reinforced resins (viscosity: 150-2000 cps)	Medium \$500~\$3 k: consumer \$3 k- \$ 200 k: industry	0.025-0.05 mm per inch of part dimension 1500 x 750 x 550 mm ³ (Prox950)	Fast concept modeling; Light structural parts.
SLS/SLM	Metal alloy in powder form (size: 10-100 um) (eg. copper, aluminium, stainless steel, cobalt chrome, titan i um , etc)	High (\$ 5k~\$600 k depending on performances)	<ul style="list-style-type: none"> SLS: Layer thickness: 0.1~0.15 mm; X/Y resolution: 0.76~ 1.27 mm. SLM: Layer thickness: 0.02-0.038 mm; X/Y resolution: 0.30~0.41 mm. 500 x 280 x 850 mm³ (SLM 800) 	Dense metal parts (eg. iron cores, magnets , structural parts, cooling jackets)

Note: price, accuracy, and maximum build area are based on market prices and specifications of printers made by major vendors—Stratasys (FFF/FDM), 3-D systems (SLA), SLM solutions (SLS/SLM).

Several technical fields, such as aerospace and transportation, have significantly benefited from this progress and widely adopted AM. According to General Electric (GE) additive, hundreds of assemblies in turbo engines are made by AM, achieving ~80% lead time reduction, complex and lighter structures, as well as significantly less waste of expensive material, such as titanium, compared with subtractive manufacturing [2]. AM's beauty of fast prototyping and complex geometries has been shown in making customized tooling, cooling vents, as well as improving aerodynamic design of vehicles.

B. AM of Electrical Machines

However, when it comes to the area of electrical machines and drives, there have been few sporadic attempts to explore the potential of AM. So far, these attempts were limited to either analysis or fairly small hardware demonstration [3].

In the following, a review of technical attempts to utilize AM to build some of the assemblies in a variety of electrical machines is presented.

1) *Electrostatic Machine*

Stereolithographic (SLA) 3-D printing, casting, and injection molding have been adopted in building an electrostatic machine that is made of plastic (stator, rotor) and nickel (dowel pins) [4]. Compared with subtractive manufacturing, SLA successfully addresses the geometric complexity of the stator and rotor and thus reduces the cost and time required during fabrication processes. In order to reduce cost and weight, only selective surfaces are plated with nickel.

However, this fluid-filled electrostatic machine is only for low-speed direct drive applications. The potential of AM has not been maximized yet in fabricating mainstream electro-magnetic rotating machines.

2) *AM Assemblies in Unconventional Electrical Machines*

Unconventional electrical machines refer to electrical machines with unusual complex structures, such as flux-modulation machines, transverse flux machines, and claw pole machines. Those machines either have complex mechanical structure or flux path. They highly yield to manufacturing constraints if built with regular subtractive approaches.

In [5], ferromagnetic flux-modulation rings with cavities are built by 3-D printing (SLM) for reducing core losses. In [6], 3D-printed (FFF/FAM) plastic stator cases that are used to hold stator U-cores of a two-phase transverse flux machine were reported.

For regular electrical machines, i.e., radial flux electrical machines, AM technology has been discussed for fabricating different parts of the machine, including rotor core, stator core, copper winding. In [7], additively manufactured electrical machines potentially used for more electric aircrafts (MEA) have been discussed. Key insights include the following.

1. Availability and properties of soft magnetic materials, such as Co–Fe and 6.5% Si steels.
2. AM opens up the design space for topology optimization with little manufacturing constraints. Thus, higher machine performance can be achieved.
3. Other potential benefits include continuous skewed rotors, unconventional saliencies/flux barrier designs, control of magnetic properties, for example, orientation.

3) *Rotor Iron Core*

The mechanical performance and reliability of the rotor core of an interior permanent magnet (PM) synchronous machine (Geometry: Prius 2010 motor), which is made by laser beam melting (LBM, layer

thickness: 100 μm , material: M15 steel), has been studied through numerical modeling [8]. The results show that the 3-D-printed rotor is mechanically vulnerable under high-speed operation due to complex microstructure between layers that might lead to crack initiation and propagation.

AM also shows its value in manufacturing the multilayer rotor core of synchronous reluctance machines [9]. On one hand, AM can simultaneously build magnetic and nonmagnetic parts of the rotor for better mechanical strength. On the other hand, AM can support the manufacturing of the complex shape of cavities enabling a real geometrical optimization with little manufacturing constraints.

In [10], the adoption of Fe–Co powder (<63 μm) in SLM (machine model: SLM 125HL) has been reported. An optimized rotor of a reluctance machine (6S/4P) with complex cavities has been manufactured with the mentioned material and approach, as shown in Fig. 1. A saturation flux density value of 2.3 T has been achieved.

Fig. 1. SLM-based Fe–Co rotor of switch reluctance motor with complex cavities and high saturation flux density by VTT technical research center of Finland [10].

4) Copper Winding

In [11], the possibility of 3-D screen printing in opening up the design space for machine design and manufacturing is discussed. Mentioned benefits include higher achievable torque densities, higher operating temperatures, higher efficiencies, and smaller as well as more dedicated machine designs. The focus is placed on winding design. Key insights developed include the following.

1. Screen-printed airgap winding for three-phase PM machines.
2. Temperature-resistant materials, such as ceramics (in form of powder) in replacement of regular lacquer coat (enamel, synthetic resin, waxed paper, polymer, etc.) for higher operating temperatures.
3. Flexibility in wire cross-sections (hollow, polygon, etc.) that yield to higher slot fill factor as well as better thermal behavior (heat dissipation up to 200 W/mk).

United Technologies Research Center has also pushed the application of AM in design and manufacturing of high-power vehicle traction induction machines [12]. In [13], thermal and stress analyses have been performed to demonstrate the improvement of thermal performance due to AM (8 A/mm² with forced air cooling; >20 A/mm² with liquid cooling). In addition, customized end winding geometry has been investigated to reduce end winding length (50% reduction), volume, and mass [14]. Again, AM is the key enabling technology for this improvement.

C. Summary and Objective

As a summary, key takeaways include the following,

1. It can be predicted that AM will become more popular in the construction of electrical machines through the devolvement of manufacturing technologies (rate, cost, quality, materials, and

manufacturability) as well as design concepts that can benefit from such advanced manufacturing technologies.

2. Currently, state-of-the-art technologies regarding AM for electrical machines are separately realized in each individual machine assemblies or parts. Some of the examples shown above are even peripheral for machine design. An electrical machine that is fully/completely manufactured by AM has not been realized yet.
3. In terms of application, additively manufactured electric machines might take place first in the area of aerospace. This is mainly due to
 1. rapid growth of electrified aircraft industry;
 2. very demanding machine performance required in such application, especially specific power;
 3. relative maturity of AM in several areas of the aerospace industry.

Basically, the design of electrical machines is supposed to consider electromagnetic, thermal, mechanical, and electric issues simultaneously. It is the introduction of AM that can gradually open up the design space for such complexities.

The objective of this article is to investigate the role of AM in the area of electrical machines. The focus of this study is twofold 1) investigate the know-how of AM approaches that can replace conventional methods; 2) explore the potential changes and benefits that can be introduced by AM in terms of building electrical machines. PM machines are the main focus of in-depth discussions included in this article.

This article is organized as follows. Section II discusses approaches to additively manufactured iron cores. Section III investigates the feasibility of additively manufactured wires/coils/windings as well as their insulations. Section IV discusses how to additively manufacture PMs and get them magnetized. Section V covers advanced thermal management designs enabled by AM. Finally, Section VI concludes this article.

SECTION II. Iron Core

Nowadays, nongrain silicon steel laminations, which are usually punched and stacked together, are widely used for manufacturing iron cores in electrical machines. In contrast, potential advantages of additively manufactured iron cores include the following.

1. AM allows a mix of different types of metal powders, which helps in making alloys, such as Co-Fe, in an easy way.
2. The iron core can be made of plastic and ferromagnetic materials, so that the cost/weight can be greatly reduced.
3. Complex core structure/design can be realized by AM, for example, continuous skewing, complex flux path, and complex cooling channels.
4. Material microstructure like crystallographic texture/direction can be purposely controlled to introduce the desired magnetization direction.

A. Sheet Lamination 3-D Printing

Sheet lamination 3-D printing, which is eccentrically based on laminated object manufacturing (LOM), can be adopted to build laminated iron core [15], [16]. According to the Helisis Inc., the pioneer of LOM, paper, copper, and steel sheet can be used for sheet lamination 3-D printing.

Fig. 2 shows some fundamentals of the sheet lamination 3-D printing. The major processing procedures are as follows.

1. Material that comes in sheet form is positioned in place on the cutting bed.
2. Material is bonded by pressure and heat application, over the previous layer, using a thermal adhesive coating, which can provide insulation between layers.
3. Required shape for each layer is cut from the sheet, by carbon dioxide laser.

Fig. 2. Sheet lamination 3-D printing [17].

The advantages of LOM include low cost, no postprocessing and supporting structures required, no deformation or phase change during process, and the possibility of building large parts [18].

In terms of building iron cores for electrical machines, concerns about sheet lamination 3-D printing include the following.

1. In terms of material utilization, sheet lamination 3-D printing is equivalent to regular processing of cold-rolled silicon steel sheet.
2. Smallest adhesive thickness has not been specified, which is important for iron loss reduction as well as stacking factor control.
3. Currently, copper and limited types of stainless steel are available, which still limits design options.

B. Soft Magnetic Composites

Soft magnetic composites (SMC, small isolated iron particles) and corresponding powder metal processing (compacting, curing, etc.) have been proposed for building iron cores of electrical machines that feature complex structure and 3-D magnetic flux paths [19], [20]. Compared with conventional silicon steel sheet and corresponding processes, such as punching, stacking, riveting, and welding, the appealing features of SMC-based iron core include the following.

1. Reduction of eddy losses in 3-D magnetizing directions due to its magnetically isotropic property as well as coating of iron particles, which is desired for a variety of machine topologies, such as transverse flux machines, claw pole PM machines, and axial-flux machines [21], [22].
2. Low specific core losses at electrical frequency values higher than 500 Hz due to very high specific electric resistivity [23].
3. With well-established powder metal processing technics, net-shape low-cost components with complex structure can be built.
4. Using material processing, such as compacting and curing, there are no magnetic/mechanical property deteriorations due to manufacturing process.

Although the mechanical strength and permeability of SMC are lower than laminated silicon steel sheet, with years of efforts in research and development, SMC-based manufacturing and application have grown with leaps.

Hoganas has developed a series of SMC materials for electromagnetic applications. With compacting pressure of 600–800 MPa as well as heat treatment of 650 °C, the tensile strength/yield strength can be 15–25 MPa [24]. Fig. 3 shows an example of axial flux PM machines with SMC iron cores. Also, there have been ongoing efforts to improve the magnetic properties of SMC, especially saturation magnetization and permeability.

Fig. 3. Axial flux PM machine with SMC iron cores by Hoganas [24].

C. Solid Iron Core

If eddy current losses are low and/or the mechanical integrity of rotor is of significance (especially in some high-speed SPM rotors), a solid iron core can be built layer by layer by means of LBM, which allows a mix of different types of metal powders, such as cobalt–iron (Co–Fe, with high saturation magnetization) and nickel–iron (Ni–Fe, with low iron losses) [25]. Like any other AM parts, appealing features, including light weight, complicated structure, complex flux path, can be realized compared with conventional stacked silicon steel lamination [26].

However, since the cohesive bond between layers is based on remelting of previous layers, the finished alloy is asymmetric and nonuniform on a microscopic level. This concerns the mechanical strength and reliability of the iron core when shear stress is applied on the iron core. The impact of nonuniformity and heterogeneous nature of additively manufactured rotor cores have been studied using simplified 3-D finite-element analysis [8]. It was shown that as the angular velocity increases, the bonding interfaces begin to suffer damage more easily versus stacked laminated core. This is one of the areas that require further development especially for high-speed rotors.

Other than the mechanical properties, the magnetic properties of additively manufactured materials can be potentially improved compared with conventional materials. Some studies show that crystallographic texture can be created in anisotropic stainless steel by the SLM process. The crystallographic texture can be purposely controlled by the power and scan path of a laser [27], [28]. Fully dense grain-oriented high-silicon steel shape is manufactured using SLM [29], [30]. It has been found that the fiber texture along the build direction can be changed into a cube texture by increasing the energy of the laser beam. Besides, annealing has been explored to improve the microstructure and magnetic properties in further [31]. Increasing evidence and understanding in this area is leading toward the wide adoption of LBM-based iron core.

Another important factor is that currently the resolution of LBM is not good enough for building high-precision iron cores. Typically, the layer thickness can be as low as 0.02–0.038 mm, whereas the x/y plane resolution is 0.3–0.4 mm. In contrast, the resolution of a laser cutter can be 0.025 mm or even lower with a typical surface finish of 0.003–0.006 mm. This tradeoff will remain until high-precision positioning is developed in LBM machines.

D. Ferromagnetic Helix or Spiral

In [32], ferromagnetic helix (for radial-flux machines) or spiral (for axial-flux machines) shapes can be formed by means of LBM with ferromagnetic material particles. Then, the surfaces are coated with an insulating material by spray coating, submerging coating, or vacuum impregnation. Finally, the ferromagnetic helix or spiral is compressed to form the final laminated iron core. Fig. 4 shows the processing procedures of coating and compression.

(a)

(b)

Fig. 4. AM of iron cores by coating and compression of LBM-based ferromagnetic helix [32]. (a) Coating. (b) Compression.

The advantages, key features, as well as limitations of this method include the following.

1. Since all laminas are in connection with each other, clamping or attachment of laminas can be reduced or even unnecessary.
2. It can also enable cooling channels, structural parts, and other conformational characteristics to be integrated and built simultaneously.
3. Thickness of an insulating layer on the lamina is on the order of 10, 20 μm , or less. Achievable stacking factor is round 97% or 98%.
4. Postprocessing, including coating and compression, are still required.

E. Comparison and Discussion

Table II provides a brief comparison of the four different manufacturing methods discussed in this section in terms of the key mechanical and electromagnetic properties. Specific materials are used for conventional silicon steel sheet as well as SMC, whereas little information can be found for the LOM-based laminated iron core as

well as the SLM-based solid iron core, which still need further investigation and development. Key insights are summarized as follows.

1. For a 2-D flux path design, the conventional silicon steel sheet is preferred for its best electromagnetic properties.
2. The LOM-based method can be regarded as a combination of the conventional stacked-lamination method and AM, which can enable simple 3-D structure with 2-D flux path.
3. The SMC-based approach is preferred for both 3-D flux path as well as complex 3-D structure albeit with a sacrifice in its mechanical strength and electromagnetic performance.
4. The SLM-based method has the highest mechanical strength as well as thermal conductivity, but it is only suitable for limited applications where eddy current loss does not have a major impact.
5. In terms of the utilization of material, SMC-based and SLM-based methods are the better options.

TABLE II Comparison of Different Approaches of Manufacturing Iron Core

	Density [g/cm ³]]	Tensile Strength [N/mm ²]	Maximum permeability	Saturation flux density [T]	Core losses [W/kg]	Suggested Applications	
						Flux path	Structure
Silicon Steel Sheet (eg. M235-35A)	7.60	532	6800	2.1	0.95 (50 Hz, 1T) 69.8 (1 kHz, 1T)	2D	2D
LOM-based laminated iron core	Similar mechanical, thermal and electromagnetic properties like conventional silicon steel sheet laminations					2D	simple 3D
SMC (eg. Hognas 3P Somaloy700HR)	7.51	120	760	1.9	4.53 (50 Hz, 1T) 137 (1 kHz, 1T)	3D	3D
SLM-based solid iron core	Highest mechanical strength and thermal conductivity; Unable to suppress eddy current losses				High eddy current losses	--	3D
Ferromagnetic helix/spiral	Similar mechanical, thermal and electromagnetic properties like	conventional silicon steel sheet laminations				radial, axial, transverse-flux machines	

Although high density (>99%) and low porosity (<1%) can be achieved, additively manufactured metal components typically have microstructural anisotropy features due to nonuniform thermal flows during manufacturing process. For soft magnetic materials, heat treatment, such as annealing, should be implemented during postprocessing to achieve a more uniform grain structure. Thus, the electrical conductivity, magnetic properties, and mechanical strength of additively manufactured metal parts can be greatly improved. In [33], it was shown that the saturation flux density of the heat-treated cobalt–iron component achieved is around 2.35 T, whereas that of the as-built component is only 1.6 T. Besides, the unsaturated relative permeability can be enhanced while the hysteresis loop area can be reduced. Detailed heat treatment procedures with different temperatures and time durations have been explored to achieve the desired magnetic properties and mechanical strength. In [34], it was shown that low-temperature preanneal of Fe–Co–V soft magnetic material prior to final anneal helps improve the magnetic properties as well as achieve a uniform distribution of relatively large grains. Fatigue performances of a variety of SLM metals can be improved by heat treatment as well [35].

To see the big picture, the magnetic properties and core losses of additively manufactured soft magnetic materials are usually improved through three approaches.

1. Optimum set of parameters during AM, including build bed temperature, laser power, scan velocity, orientation, etc. This is essential for having the optimized alloy compositions.
2. The use of slits, alternating layers of materials or scan patterns to reduce eddy current losses. This can help restrict the path of eddy current inside the soft magnetic components.
3. Thermal treatment, such as annealing, that can help obtain more uniform grain structure.

Table III summarizes the key magnetic properties of several commonly used soft magnetic materials as well as the methods used to obtain these properties. By scanning the parameters of SLM machines as well as heat treatment process, optimum permeability, saturation flux density, and lowest hysteresis losses can be achieved. Some of these properties are even comparable with conventional specimen provided by vendors. However, except for [33], other examples shown in Table III are based on solid iron core samples, which still cannot be widely adopted in electrical machines.

TABLE III Summary of Key Magnetic Properties of Additively Manufactured Fe–Co, Fe–Si and Fe–Ni Soft Magnetic Materials

Ref.	Material compositions	μ_{max}/M_s	He	Hysteresis losses	AM approach & parameters	Heat treatment
[33]	50Fe-49.9Co-0.1Si (gas-atomized powder, size: -53 μm +15 μm)	μ_{max} : 2600 M_s : 2.35 T	- 200 Alm	Comparable to Vacotlux 50 (sample: 5 x 5 mm, 18 layers: each 0.47 mm)	SLM (EOS machines, Citim GmbH)	Annealing@ 1100°C for 4 hr
[34]	Fe-49Co-2V (gas-atomized powder, size: - 62.7 μm)	μ_{max} : 13000	47Alm	Several times higher than laminated sample @ I .ST, 10 150 Hz (ring sample: OD 60 mm, TD 50 mm, H 5 mm)	L-PBF (GmbH 125 HL, SLM Solutions) (BPH 200°C, P_L 200W, V_L 775 mmls)	Pre-anneal @ 700°C for 2hr; Annealing@ 820°C for 10 hr.
[36]	FeSi6.7 (gas-atomized powder, size: < 45 μm)	μ_{max} : 31,000	16 Alm	0.7 W/kg at I T, 50 Hz (ring sample: OD 35 mm, TD 25mm, H 5 mm)	L-PBF (SLM 280HL , SLM Solutions) (BPH 400°C, P_L 300W, V_L 500 mm ls)	Annealing@ 1150 ° C for 1 hr
[37]	Fe-6.9%wt.Si (gas-atomized powder, size: 10-60 μm)	μ_{max} : 24,000	16 Alm	4 W/kg at IT, 50 Hz (ring sample: OD 28 mm, TD 20 mm , H 4.0 mm)	SLM (SLM-50, GmbH) (P_L 70W, V_L 250 mmls)	Annealing @ I 150 ° C for 1 hr
[38, 39]	Fe-80%Ni (gas-atomized powder: Fe: 35 μm ; Ni: 30 μm)	M_s : 550 Am ² /kg	75 Alm	Hysteresis curve available (sample: 5 x 5 x 5 mm)	SLM (MCP Realize II ^{slm} , MCP HEK Tooling GmbH) (BPH 80°C, P_L 110 W, V_L 400 mm ls)	No heat treatment applied
[40]	Ni-Fe14-Cu5-Mo4 (gas-atomized powder , size: 7.5-40.7 μm)	M_s : 0.33T	29.4 Alm	Hysteresis curve available (ring sample: OD 30 mm, TD 22 mm, H 4mm)	SLM (P_L 14 0 J/mm ³ , V_L 150-1350 mm/s)	No heat treatment applied

SECTION III. Winding and Insulation System

There are AM processes, on a research level, that directly integrate copper wire in polymer-based AM processes, for making transformer coils, inductive sensors, and so on. However, there are few attempts to use this technology for making coils inside stator slots of an electrical machine.

A. Fiber Encapsulation AM

Fiber encapsulation AM (FEAM) enables copper wires and dielectric material to be manufactured simultaneously [41]. Fig. 5 shows the concept of FEAM, which includes extrusion of a flowable dielectric material and laying a fiber, so that the fiber can be encapsulated to form a dual-material composite.

Fig. 5. FEAM concept [33]. (a) Schematic of FEAM printhead (b) Thermoplastic and copper wire.

The advantages of FEAM include the following [42]:

1. integration of highly conductive wires inside dielectric 3-D structures;
2. the ability to incorporate wires not only on the surface of parts but also volumetrically within them;
3. isolation of wire from the environment through full encapsulation;
4. the potential to perform the entire process in a simple manner using a single, low-cost machine at speeds comparable with standard FDM.

Transformer coils, loudspeaker coils, and helical coils have been manufactured by means of FEAM, showing the potential of applying this process to the coil fabrication of electrical machines.

Key challenges of FEAM are summarized as follows.

1. The thickness of insulation should be precisely controlled for achieving effective insulation as well as high slot fill factor. There is little evidence shown so far in the research-level results regarding the precision and consistency of processing.
2. “Fiber encapsulation” is essentially FDM, whereas stator iron core is typically additively manufactured using SLS or other methods, which means that the stator armature core will be implemented using at least two different processes.

B. Ceramic-Powder-Based Insulation

With high melting point, processing of ceramics is difficult through conventional approaches. In contrast, both porous and dense ceramic shapes can be easily made by AM. Specifically, ceramic bodies can be made by the following AM technologies:

1. powder and slurry-based 3-D printing and SLS;
2. SLA;
3. LOM;
4. direct AM means, such as direct ink write, robocasting, and FFF/FDM [43].

Fully additively manufactured transformer and axial flux machine prototypes have been developed by a team at the Chemnitz University of Technology, where ceramic is used as insulation material [44]. As shown in Fig. 6, the iron core, copper winding, and insulation are made through FFF with multiple nozzles. With outstanding thermal stability of the ceramic, the coil can withstand a high temperature of more than 300 °C.

Fig. 6. Fully additively manufactured transformer and axial flux machine with ceramic insulation [45]. (a) Transformer. (b) Axial flux machine.

Challenges involving state-of-the-art additively manufactured ceramic components are summarized as follows.

1. Compared with the widely used AM metals, AM ceramics is still underdeveloped with less powder size available as well as lower powder quality. The resolution (surface finish and layer thickness) is still not good enough.
2. FDM-based ceramic body typically has residual microporosity [45]. This is an important issue for design considerations related to thermal conductivity as well as partial discharge.

C. Printed Circuit Winding

Printed circuit winding is similar to printed circuit board in which the winding wires are printed and encapsulated by nonconductive substrate. This is usually applied in slot-less machines.

A variety of slot-less PM brushless machines have been designed and produced by ThinGap Motor Technologies, in which the wire-wound armatures are replaced by precision-machined copper sheets. An example is shown in Fig. 7(a). The design merits include high thermal conduction and high copper fill factor. EmbedTec also built an axial-flux PM alternator with printed circuit winding [see Fig. 7(b)].

Fig. 7. Examples of printed stator windings. (a) ThinGap ironless motor [46]. (b) EmbedTec AFPMA [47],

In [48], planar coils are adopted for an axial-flux PM machine used for microelectro-mechanical systems. The planar coils are fabricated by multilayer UV lithography and copper electroplating.

Generally, the printed circuit winding allows predesign wire route and low-cost manufacturing. However, the printed circuit winding is only feasible for machines with low current ratings.

D. Customized Form Winding and Hollow Conductors

1) Customized Form Winding

AM opens up the design space for various customized form winding designs [49]. Without AM, special tooling is required for each individual design.

In [50], the cross section of stator winding is customized according to the distribution of slot leakage flux path shown in FEA, as shown in Fig. 8. Therefore, the well-known issue of high winding ac losses near the slot opening can be addressed. Previously, this issue is usually tackled by having enough void space between copper bar and slot opening, which sacrifice the slot fill factor.

Fig. 8. Additively manufactured shaped profile winding [50]. (a) Shaped profiled coil. (b) Stator assembly.

2) Hollow Conductors

For high-voltage or high-altitude applications, such as hybrid propulsion powertrain for aerospace, the insulation thickness could be fairly thick, which is regarded as a major challenge for heat dissipation. Hollow conductors integrated with heat pipe or cooling channel are promising solutions for such applications.

However, the fabrication of customized hollow conductors through conventional approaches can be challenging until AM has been introduced into this space [51], [52]. Even with AM, pure copper with high thermal conductivity can reflect the heat applied by a laser beam. Trumpf recently demonstrated 3-D-printed hollow copper components that can be potentially used to build hollow conductors as well as heat exchangers. This is achieved by using laser light in the green wavelength spectrum as the beam source [53]. Some samples of the 3-D-printed hollow copper components are shown in Fig. 9. Another promising method for the processing of pure copper is selective electron beam melting (SEBM) [54]. Up to 99.95% pure copper parts with 58M S/m [100% International Annealed Copper Standard (IACS)] electrical conductivity are reported in [55] and [56]. Fine processing, such as high vacuum/shielding gas conditions, constant powder bed temperature, and appropriate energy input, is required to get dense and crack-free components. Similar to soft magnetic materials, copper or aluminum components made by SLM, SLS, or SEBM should be treated with annealing to release mechanical stress and improve their electrical conductivities.

Fig. 9. Three-dimensional-printed copper components by Trumpf [53].

Different types of heat pipes, heat sinks, and heat exchangers are printed through SLM using copper powder [57], [58]. A tremendous evolution can be expected in terms of design optimization, complexity, as well as functionality. In addition, the heat pipes can be potentially integrated with winding or rotor core to effectively improve the cooling capability of electrical machines.

Table IV provides a brief comparison of the four AM methods discussed in this section. As of now, simultaneous processing of winding and insulating material can be realized only via FFF/FDM with multiple nozzles. For methods based on SLM/LBM, postprocessing of printed shapes, such as coating and drying, is still required, which makes AM less attractive in terms of its simplification. Regarding applications, all examples discussed in existing literature are for small transformers or electrical machines with fairly lower power rating, whereas its implementation on higher power electrical machines have not been explored yet.

TABLE IV Comparison of Different Approaches of Manufacturing Winding and Insulation System

Approaches	Winding and insulation system	Method	Accuracy	Applications
Fiber encapsulation AM	built separately	Wire: extrusion (FFF/FDM) Insulation: fiber encapsulation	Wire: high Insulation: unknown	Transformer coils, loudspeaker coils, helical coils
FFF-based ceramic insulation and copper winding	built simultaneously	Wire: FFF/FDM Insulation: FFF/FDM	Wire: low Insulation: low	Transformer coils, Axial flux machine coils
Printed circuit winding	built simultaneously	Manufacturing of PCB	high	Slot-less machine coils, axial flux machine coils
Customized form winding or hollow conductors	built separately	Wire: SLM/LBM Insulation: coating, drying	Wire: high Insulation: high	Concentrated coils of PM machines

SECTION IV. Magnet and Magnetization

NdFeB, Alnico, and SmCo magnets are the key materials used in high-specific-power PM synchronous machines for many applications. Conventional processing methods for the mentioned PMs typically include sintering, bonding, solidified casting, heat treatment, post processing, etc., lowering the utilization ratio of material as well as the performance of final shape.

In contrast, additively manufactured PMs can notably reduce amounts of machining, enable complex geometries, and minimize material waste. Moreover, AM can control the grain texture to create isotropic or anisotropic properties [59], [60]. Thus, better magnetic performances (high remanence, coercivity, temperature stability, etc.) can be achieved without heavy reliance on rare-earth materials, such as Dy, Tb, and Pr. Another potential benefit is to have compound magnets or a blend of different types/grades of magnets.

A. SLM-Based Magnets

1) SLM-Based NdFeB

Dense net shape NdFeB magnets can be additively manufactured by SLM according to recent research conducted by ABB Corporate Research Center at Baden-Daettwil, Switzerland [61]. A commercial powder with spherical morphology—MQP-S—has been used to avoid severe crack and pore formation [62]. Compared with conventional sintered magnets, the printed $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase has a lower grain size of $1\text{ }\mu\text{m}$, leading to good magnetic properties.

It is also found that laser parameters, such as laser velocity and laser thickness, can have a major impact on the highest energy product achievable during printing procedure. Fig. 10 shows a comparison of three manufacturing methods, i.e., 3-D printing (SLM), injection molded magnet (bonded), and spark plasma sintered. It is claimed that SLM-based NdFeB has the highest energy product peaking at 45 kJ/m^3 at $20\text{ }^\circ\text{C}$ ($H_C=695\text{ kA/m}$, $B_r=0.59\text{ T}$).

Fig. 10. Comparison of magnetic characteristics [62]. (a) BH curve (second quadrant). (b) $(BH)_{\max}$ versus temperature.

Other benefits and issues of SLM-based NdFeB are summarized as follows.

1. Complex magnet shape can be obtained, which makes rotor geometrical optimization more flexible and opens design space for interior PM machines.
2. Additively manufactured integrated magnets and cooling channels can potentially reduce the dependence on the expensive rear-earth material (Dy) for thermal stability.

Nowadays, NdFeB powder is available in a size of $35\text{--}100\text{ }\mu\text{m}$. It can be expected that smaller powder size will be available in the near future. NASA Glenn Research Center reported the nanocomposite ($<10\text{ nm}$) magnets, which is promising for further improving the magnetic performances of NdFeB magnets [63]. Bulk magnets can be printed as soon as those materials are available in powder form.

2) SLM-Based Alnico

In [64], additively manufactured net-shape Alnico magnets using high-pressure gas atomized powders and a laser engineered net shaping system (LENS) have been demonstrated.

The hysteresis loop of the additively manufactured Alnico magnet is squared, such that higher remanence and coercivity can be achieved. Compared with sintered and cast Alnico magnets, the LENS-built Alnico magnets have comparable or even higher coercivities (up to 2.03 kOe), remanences (up to 9 kG), and energy products (up to 6.0 MGOe).

B. FFF-Based Magnets

Composite pellets consist of isotropic NdFeB powder and polyamide, such as nylon and epoxy, can be mixed, melt, and supplied by the nozzle in FFF to build desired net shape NdFeB [65]. Fig. 11 shows an example of what the composite pellets can be made of. According to the Oak Ridge National Lab and Magnet Applications, the goal is to recycle neodymium magnets from used computer hard disk drives and reduce dependences on imported materials.

Fig. 11. Fabrication of net shape bonded NdFeB magnets using a mix of MQP isotropic powder (65%) and Nylon-12 (35%) [66].

The material testing results show that the magnetic and mechanical properties of the additively manufactured bonded NdFeB magnet are comparable with injection molded magnets using the same material. However, debonding of magnetic particles from the polymer binder can happen resulting in fractured surfaces [67].

Huber *et al.* [68] discussed additively manufactured polymer-bonded NdFeB magnets by the Vienna Technical University using an end-user 3-D printer. It has been found that, compared with fully dense NdFeB magnets, the polymer-bonded magnets lost 22% density, 25% remanence, and 4% coercive force. Also, its operating temperature is limited due to the use of polymer. However, it can enable the optimized magnetization by mixing extruder as well as changing the remanence as a function of printed layers.

C. Cold Spray AM

The so-called “cold spray additive manufacturing” can be used to produce high-density metallic coatings without issues associated with thermal spray [69]. Fig. 12 shows the situation when the cold spray nozzle is printing magnets inside a cylinder. The National Research Council of Canada is using this technology for fabricating magnets [70].

1. Cold spray is beneficial in applications that use heat-sensitive material (in this case, the properties of additively manufactured magnets could be similar to injection molded or sintered magnets).
2. Cold spray produces deposits that are oxide-free or with hard-to-reach areas.
3. The spot size of resolution has not been given. However, according to the state-of-the-art cold spray technology, the smallest spot size is about 4.0 mm (Year: 2014), which is much bigger than that made by SLM.

Fig. 12. PM demonstrators fabricated using cold spray AM [69], [71].

In [71], the team also explores the possibility of building the rotor of a PM-assisted synchronous reluctance motor by depositing SMC and PM on the rotor through cold spraying. With much higher mechanical strength (214 MPa tensile strength), the proposed design eliminates bridges and center posts in the rotor, making it appealing for high-speed, high-specific-power designs.

D. Discussion and Application

It should be noted that although the potential properties of AM magnets shown in the case studies mentioned above are of great interest, a solid conclusion regarding the performance merits has not been reached yet accounting for the fact that there is no comprehensive comparison between AM magnets and conventional magnets.

For any of those efforts mentioned above, the net-shape magnets need to be magnetized by external pulsed field. If magnet is made with other parts in one-time (rotor is shaped with one process), postassembly magnetization is required as well [72], [73], which has not been discussed in the existing literature.

Regarding applications, in [74], two direct current (dc) motor prototypes with identical geometry are built. One of them uses additively manufactured 70 vol.% NdFeB magnets, whereas the other one adopts conventional ferrite magnets. The measured back EMF slope of the dc motor with 3-D printed magnets is 1.91 V/p.u., whereas that of the ferrite magnet dc motor is 2.07 V/p.u. In [75], a complex shape rotor has been fabricated using cold spray AM. NdFeB-Al composite and SMC powder are adopted. Therefore, additional assembly steps are not required at all. The magnetic properties and mechanical strength of the PM rotor verifies the feasibility of the proposed method.

SECTION V. Advanced Thermal Management

Components of thermal management systems include a variety of heat exchangers, cooling jackets, heat pipes, etc. AM can be utilized to build cooling structure with porosity, complex passages/channel/duct, and extended surfaces. It can also reduce weight and lead time by optimizing geometries and minimizing tooling constraints.

A. Additively Manufactured Heat Exchangers

In [76], a 3-D-printed, direct winding heat exchanger made of dielectric polymer has been proposed, as shown in Fig. 13. The additively manufactured heat exchanger with an internal coolant return path is placed between two coils of a tooth-winding machine for direct heat removal. Carbon-fiber reinforced nylon with a glass transition temperature of 80 °C has been used to build the heat exchanger via FDM. The heat transfer testing

shows that the winding temperature rise can be reduced by 44%. AM can improve thermal conductivity in certain direction by changing material microstructure during manufacturing. However, in order to accommodate the heat exchanger, the slot fill factor is decreased. Also, imperfect contact between the heat exchanger and winding strands can offset the advantage of the design. Complementary to this research, the heat exchanger is manufactured using ceramic [see Fig. 13(c)]. A motorette (a small representative section of the stator) test shows that a continuous dc current density of 30.7 A/mm^2 has been achieved [77].

Fig. 13. Additively manufactured heat exchangers [76], [77]. (a) Heat exchanger between two coils. (b) CF-Nylon heat exchanger. (c) Ceramic heat exchanger.

In [78], a variety of heat guides with porous structure are designed and manufactured through SLM, as shown in Fig. 14. The heat guides are inserted into stator slots between two coil sides for enhancing heat removal capability. AM helps to significantly reduce the weight of the heat guides. Hence, about 40% increase in input power handling has been achieved with only 3–4% additional weight.

Fig. 14. Passive heat guides inserted in stator slots for enhanced heat transfer (approach: SLM; material: AlSi10Mg) [78].

Wrobel *et al.* [79] presented an additively manufactured air-cooled heat exchanger integrated with the stator of an outer-rotor propulsion motor for a solar aircraft. Fig. 15 shows the stator assembly of the motor in which the SLM-based AlSi10Mg heat exchanger has an extremely high active surface area to volume ratio as well as light weight.

Fig. 15. Stator assembly with integrated heat exchanger (approach: SLM; material: AlSi10Mg) [79].

B. Additively Manufactured Heat Pipes

Heat pipes can be used to greatly improve the thermal conductivity of thermal management systems. Sinter-style aluminum heat pipes built by SLM have been developed in [80]. AM can enable elaborate porous structures with different porosities, permeabilities, and pore size in the wick, which can help improve the thermal conductivity. A heat pipe grooved wick with porous structure is shown in Fig. 16. It should be noted that working fluid is injected and sealed separately after AM.

Fig. 16. SLM-based porous heat pipe grooved wick [78].

C. Additively Manufactured Cooling Jackets

AM can significantly simplify the way of fabricating the cooling channels as well as cooling jackets with low tooling cost and less liquid leaks. Conventionally, a cooling jacket of an electrical machine is comprised of at least two separate parts welded together. In order to reduce the complexity of manufacturing, the cooling

channel inside the cooling jacket is usually simplified, as shown in Fig. 17(a). With SLM, cooling jackets with optimized inner helix channel can be fabricated, as shown in Fig. 17(b). Most importantly, the mechanical integrity of the cooling jacket can be greatly improved. Its application in formula electric cars shows that the cooling performance can be increased by 37%, whereas the weight is reduced by 16% by having the helix cooling channel [81], [82]. Also, AM can open the door for manufacturing a variety of cooling jackets with complicated path, such as torus, axial, helical, circumferential, serpentine water ducts [83].

Fig. 17. Additively manufactured cooling jackets with optimized helix cooling channel [81], [83]. (a) Typical cooling jacket. (b) AM cooling jacket.

In addition to machine design, at the system level, AM can open the door for more tight integration between electrical machines and power electronics, which is also known as integrated machines and drives (IMD) or integrated modular machines and drives (IMMD) [84].

For IMD/IMMD, the key to boost specific power is to have the thermal management system shared by electrical machines and power electronics. Usually, this makes thermal design fairly complicated [85].

Some of the underlying advantages brought by AM in the context of the IMD concept include the following [86].

1. *Ideal contact between components:* AM can support heat exchangers with complicated shapes and cooling pipes that can better fit between machine end windings and power electronics. Additively manufactured windings can also offer form end winding shapes that can be encapsulated by heat exchangers with improved heat conduction condition.
2. *Innovative direct cooling:* For aerospace applications, in order to avoid partial discharge at low air pressure, winding insulation is usually much thicker than conventional designs at the sea level. Conventional cooling designs, such as a cooling jacket outside the stator or spraying oil to end windings, become less effective. In this case, additively manufactured cooling channels inside slots can be very promising. The cooling channels can be built using nonconducting materials, such as fiber-reinforced polymer materials.

Other advanced thermal management systems for electrical machines and drives enabled by AM are summarized in Table V. Again, in these examples, it has been shown that AM can support optimization with less manufacturing constraints and improved heat conduction in certain direction.

TABLE V Summary of Advanced Thermal Management Systems for Electrical Machines and Drives

Advanced cooling methods	Refs.
AM heat sink based on genetic algorithm (GA) approach	[87]
Control of anisotropic thermal conductivity of AM heat sink	[88]
Optimization of additively-manufactured heat sink	[89]

Complex-structured mono lithic heat sinks enable by AM	[90]
Optimized passive heat pipes for power electronics	[91]

D. Complementary Discussions

1) AM of Structural Components

At the end of this review, it should be noted that there are also many attempts to additively manufacture structural parts of electrical machines, including stator housing, end cover, rotor shaft, ball bearings, winding frame, etc. [92]. The motivations are mainly of twofold: light weight (high specific power) and integrated/simplified fabrication. One example is a brushless dc motor manufactured by extrusion-based AM. Both the stator housing, winding frames, and rotor structural parts are made of plastic material to reduce the weight [93]. In [94], Oak Ridge National Laboratory reports additively manufactured bearing cages made of a variety of materials, including acrylonitrile butadiene styrene (ABS), titanium, 316 L and 420 stainless steel, etc. AM approaches, such as FDM, EBM and direct metal laser sintering (DMLS), are used, which enable rapid prototyping and performance evaluation of a few proof-of-concept bearings in a short period of time.

2) Technology Maturity

Fig. 18 provides a summary of the discussed AM methods in terms of their technology maturity. AM approaches with relatively good maturity are placed near the center of the radar map. Some approaches are already available now, whereas others are expected to become more mature in the future. Ture, fully additively manufactured electrical machines are unlikely to happen anytime soon as real products. Nevertheless, the feasibility of AM will be proved in more components of an electrical machine, resulting in many partially additively manufactured electrical machines. Some specific applications can even accept some current immaturity aspects of AM, such as price and material properties.

Fig. 18. Maturity of AM approaches.

3) Redesign Criteria

With more design degrees of freedom, the use of AM will certainly expand the design boundary instead of a simple one-to-one replacement of conventional machine components. The updated electrical machine design criteria/considerations can be expected in twofold.

1. *Less geometrical constraints during redesign:* For e.g.,
 1. continuous stator/rotor skewing for smoother torque;
 2. complex magnetizing direction/strength of PM for less magnetic field distortion;
 3. optimized cooling design that can support design with higher thermal loading.
2. *Redefined boundary of material properties:* Material properties can be purposely controlled by using AM. Then, more options will be available during a design, which can eventually support the optimum design that fits the cost and performance targets well.

On top of the abovementioned two points, AM can further open up design space for a tightly linked multiphysics design.

SECTION VI. Conclusion

The state-of-the-art AM technologies that are used or can be used for building the three key components of a PM machine, i. e. iron core, winding, and insulation, as well as PM, have been discussed in this article. As of now, most of the machine components are built separately while very few studies demonstrate fully additively manufactured machines.

Multiple AM technologies can be used for building iron core, winding, and insulation, as well as PM. The advantage of additively manufactured electric machines is not only enabling complex geometry and high utilization of materials but changing the microstructure and material properties as well.

The trend for future AM technologies is to develop multimaterial systems. This further opens opportunities for additively manufactured electrical machines.

1. A fusion of different metals: soft magnetic material, such as Co–Fe, Ni–Fe; nanocomposite magnets.
2. Metal with ceramic interfaces or metal with plastic: conductors and insulation systems.

The more the multimaterial AM system is developed, the more the possibility of moving toward fully additively manufactured PM machines is significantly increased.

Other than the three key components of PM machines, AM of innovative cooling channel, heat exchanger, heat pipe, and heat sink has also been discussed. With AM, it is possible to greatly improve the heat removal capability without significant penalties in additional weight/volume.

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