

5-1-2019

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Towards Fully Additively-Manufactured Permanent Magnet Synchronous 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, harsh environments, etc. This provides clear motivation to explore the impact of advanced materials and manufacturing on the performance of electrical machines. This paper provides an overview of additive manufacturing (AM) approaches that can be used for constructing permanent magnet (PM) machines, with a specific focus on additively-manufactured iron core, winding, insulation, PM 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 paper offers a detailed comparison of multiple multi-material AM methods, showing not only the possibility of fully additively-manufactured PM machines but also the potential significant improvements in their mechanical, electromagnetic and thermal properties. The paper will provide a comprehensive discussion of opportunities and challenges of AM in the context of electrical machines.

Author Keywords

Additive manufacturing (AM), electrical machine, permanent magnet machine, three-dimensional (3D) printing

SECTION I. Introduction

ADDITIVE manufacturing (AM), which refers to building up a three-dimensional (3D) 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:

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

The major advantages/benefits of AM include [1],

- Fast prototyping
- Complex geometries and hard-to-reach areas
- Building different components simultaneously
- Mix of multiple materials
- Improved properties/enhanced performance

A. Additively Manufacturing (AM)

Despite the fact that AM is currently intended for low- volume manufacturing due to low manufacturing rate (0.01~1 kg/hr)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,

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

Several technical fields like aerospace and transportation have significantly benefited from this progress and widely adopted AM. According to 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 like Titanium, compared to 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 Used in 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. 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)three-dimensional (3D) printing, casting and injection molding have been adopted in building an electrostatic machine that is made of plastic (stator, rotor)and nickel (dowel pins)[3]. 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 additive manufacturing 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 like flux-modulation machines, transverse flux machines, claw pole machines, etc. Those machines either have complex mechanical structure or flux path. They highly yield to manufacturing constraints if built with regular subtractive approaches.

In [4], ferromagnetic flux-modulation rings with cavities are built by 3D printing (SLM) for reducing core losses. In [5] 3D-printed (FFF /FAM) plastic stator cases that are used to hold stator U-cores of a 2-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, etc.

In [6], additively-manufactured electrical machines potentially used for more electric aircrafts (MEA) have been discussed. Key insights include the following:

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

3) Rotor Core

The mechanical performance and reliability of the rotor core of an interior permanent magnet (IPM) synchronous machine (Geometry: Prius 2010 motor) that is made by laser beam melting (LBM, layer thickness: 100µm, material: M15 steel), has been studied through numerical modeling [7]. The results show that the 3D-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 [8]. 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 [9], 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. A saturation flux density value of 2.3 T has been achieved.

4) Copper Winding

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

- Screen printed airgap-winding for 3-phase PM machines;
- Temperature-resistant materials like ceramics (in form of powder) in replacement of regular lacquer coat (enamel, synthetic resin, waxed paper, polymer, etc.) for higher operating temperatures;

- 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 [11]. In [12], 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 [13]. 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 is 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 (i) Rapid growth of electrified aircraft industry; (ii) Very demanding machine performance required in such application especially specific power; (iii) Relative maturity of AM in several areas of the aerospace industry.

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

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

This paper is organized as follows: Section II discusses

AM of iron core. Section III investigates the feasibility of AM of copper wires/ coils/ windings as well as their insulations while Section IV discusses how to additively manufacture PMs and get them magnetized. Section V covers the role of AM in the integration of electrical machine and power electronics. Conclusions are included in Section VI.

SECTION II. Iron Core

Nowadays, non-grain 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:

- AM allows a mix of different types of metal powders, which helps in making alloys like Co-Fe in an easy way;
- The iron core can be made of plastic and ferromagnetic materials, so that the cost/weight can be greatly reduced;
- Complex core structure/design can be realized by AM, for example continuous skewing, complex flux path, and complex cooling channels.

A. Sheet Lamination 3D Printing

Sheet lamination 3D printing, which is eccentrically based on laminated object manufacturing (LOM), can be adopted to build laminated iron core [14], [15]. According to the Helisys Inc., the pioneer of LOM, paper, copper and steel sheet can be used for sheet lamination 3D printing.

Fig. 1 shows some fundamentals of the sheet lamination 3D printing. The major processing procedures are as follows [16]:

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.

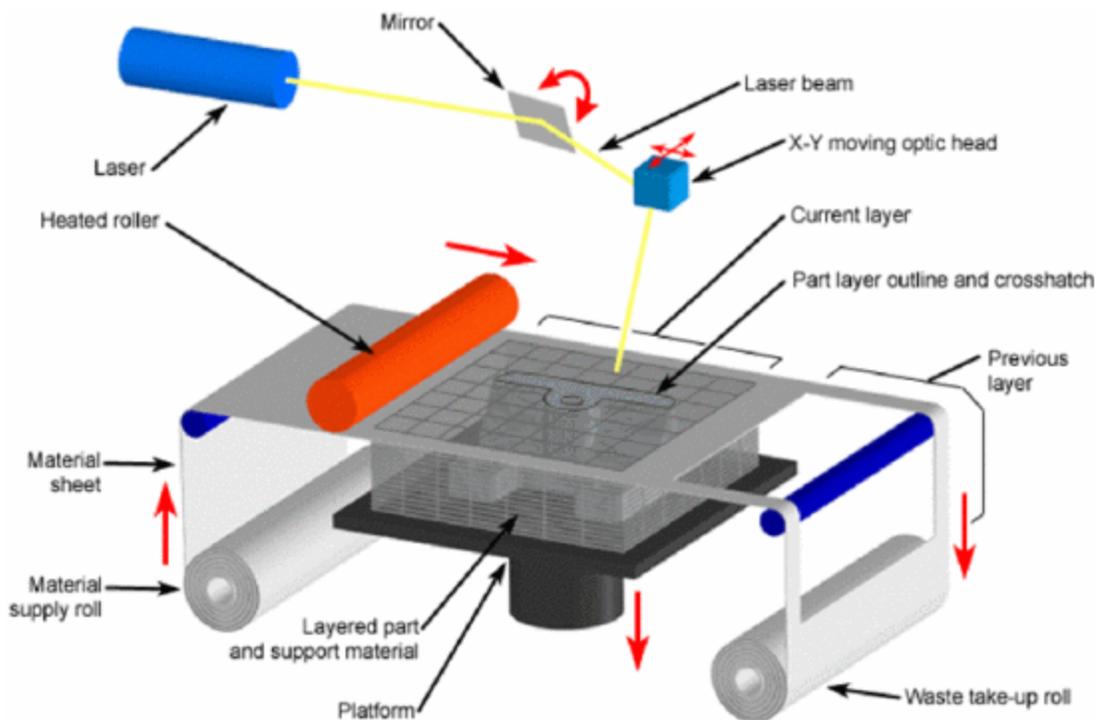


Fig. 1.
Sheet lamination 3D printing [16]

The advantages of LOM include low cost, no post processing and supporting structures required, no deformation or phase change during process and the possibility of building large parts [17].

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

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

B. Soft Magnetic Composites (SMC)

Soft magnetic composites (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 [18], [19]. Compared to conventional silicon steel sheet and corresponding processes like punching, stacking, riveting, welding, etc., the appealing features of SMC-based iron core include:

- 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 like transverse flux machines, claw pole PM machines, axial-flux machines, etc. [20], [21];
- Low specific core losses at electrical frequency values higher than 500 Hz due to very high specific electric resistivity [22];
- With well-established powder metal processing technics, net-shape low-cost components with complex structure can be built;
- Using material processing like compacting and curing, there is 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 [23]. Also, there has been ongoing efforts to improve the magnetic properties of SMC especially saturation magnetization and permeability.

C. Solid Iron Core

If eddy current losses are low and/or the mechanical integrity of rotor is of significance (especially in some highspeed SPM rotors), a solid iron core can be built layer by layer by means of laser beam melting (LBM), which allows a mix of different types of metal powders, like cobalt-iron (Co-Fe, with high saturation magnetization), nickel-iron (Ni-Fe, with low iron losses), etc [24]. Like any other AM parts, appealing features include light weight, complicated structure, complex flux path can be realized compared to conventional stacked silicon steel lamination.

However, since the cohesive bond between layers is based on re-melting of previous layers, the finished alloy is asymmetric and non-uniform 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 non-uniformity and heterogeneous nature of additively-manufactured rotor cores have been studied using simplified 3-D finite element analysis [7]. 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.

Table I 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 (50Hz, 1T) 69.8 (1kHz, 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 (50Hz, 1T) 137 (1kHz, 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 |

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| SMC (eg. Hognas 3P Somaloy700HR) | 7.51 | 120 | 760 | 1.9 | 4.53 (50Hz, 1T) 137 (1kHz, 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 |

Other than the mechanical properties, the magnetic and thermal properties of additively-manufactured materials can be changed compared to conventional materials. As of now, the lack of evidence and understanding in this area has been an obstacle towards 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 while 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. Comparison and Discussion

Table I 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 while 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,

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

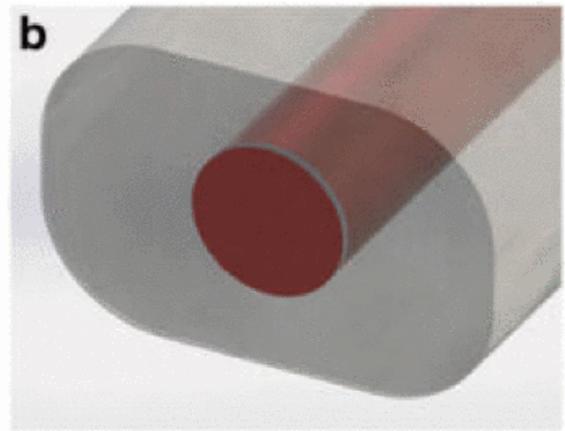
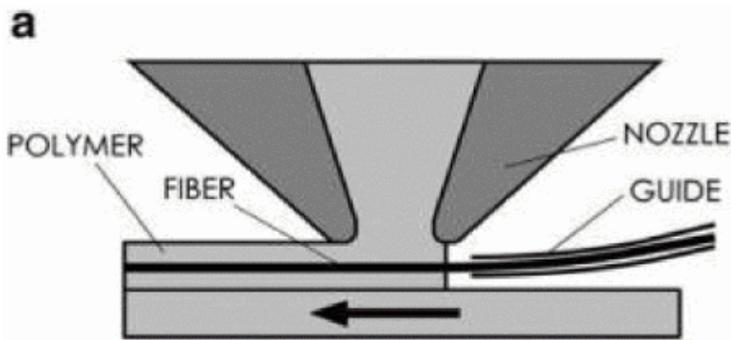
SECTION III. Winding and Insulation System

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 is few attempts to use this technology for making coils inside stator slots of an electrical machine.

A. Fiber Encapsulation Additive Manufacturing (FEAM)

FEAM enables copper wires and dielectric material to be manufactured simultaneously [25]. Fig. 2 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.

The advantages of FEAM include [26]: (i)integration of highly conductive wires inside dielectric 3D structures; (ii)the ability to incorporate wires not only on the surface of parts but also volumetrically within them; (iii)isolation of wire from the environment through full encapsulation; (iv)the potential to perform the entire process in a simple manner using a single, low-cost machine at speeds comparable to standard fused deposition modeling (FDM).



(a) schematic of FEAM printhead

(b) thermoplastic and copper wire

M. Saari, B. Cox, E. Richer, P. S. Krueger, A. L. Cohen, "Fiber encapsulation additively manufacturing: an enabling technology for 3D printing of electromechanical devices and robotic components", 3D Printing and Additive Manufacturing, vol. 2, no. 1, pp. 32-39, 2015.

Transformer coils, loudspeaker coils, 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,

- 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;
- "Fiber encapsulation" is essentially fused deposition modeling (FDM) while stator iron core is typically additively-manufactured using selective laser sintering (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 additive manufacturing. Specifically, ceramic bodies can be made by the following AM technologies: (i) Powder and slurry-based 3D printing and selective laser sintering; (ii) Stereo lithography; (iii) laminated object manufacturing; (iv) Direct AM means like direct ink write (DIW), robocasting, and FFF/FDM [27].

Fully additively-manufactured transformer and axial flux machine prototypes have been developed by a team at Chemnitz University of Technology where ceramic is used as insulation material [28]. As shown in Fig. 3, both the iron core, copper winding and insulation are made through fuse filament fabrication with multiple nozzles. With outstanding thermal stability of the ceramic, the coil can withstand a high temperature of more than 300°C.

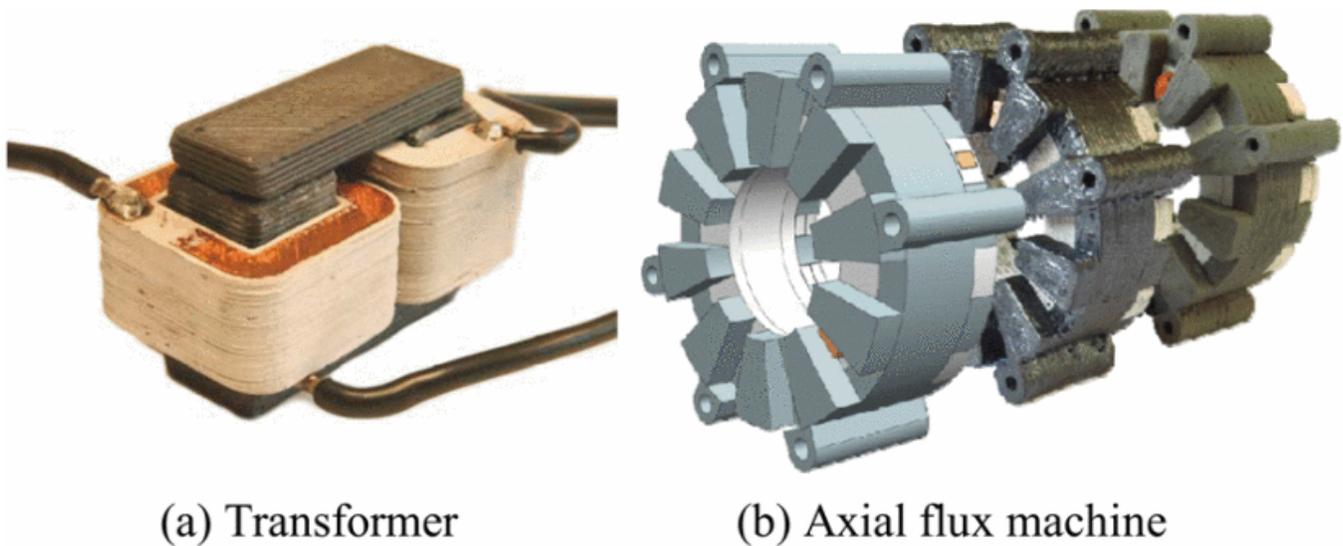


Fig. 3.

Fully additively-manufactured transformer and axial flux machine with ceramic insulation

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

- Compared to the widely-used AM metals, AM ceramics is still under-developed with less powder size available as well as lower powder quality. The resolution (surface finish and layer thickness) is still not good enough;
- FDM -based ceramic body typically has residual micro porosity [29]. 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 non-conductive 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. 4(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. 4(b)).

In [32], planer coils are adopted for an axial-flux permanent magnet machine used for micro electromechanical systems (MEMS). The planer coils are fabricated by multilayer UV lithography and copper electroplating.



(a) ThinGap ironless motor [30]



(b) EmbedTec AFPMA [31]

Fig. 4.

Examples of printed stators.

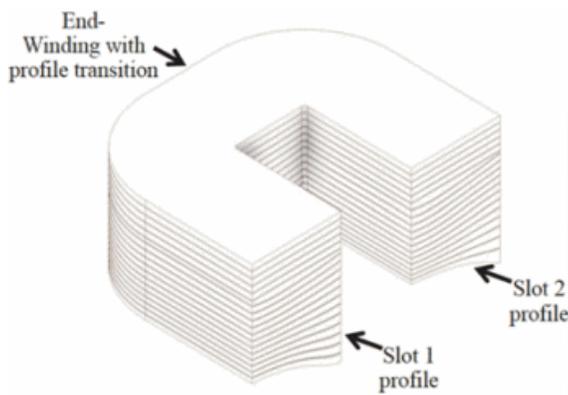
Generally, the printed circuit winding allows pre-design wire route and low-cost manufacturing. However, the printed circuit winding is only feasible for machines with low current ratings.

D. Customized Form Winding or Hollow Conductors

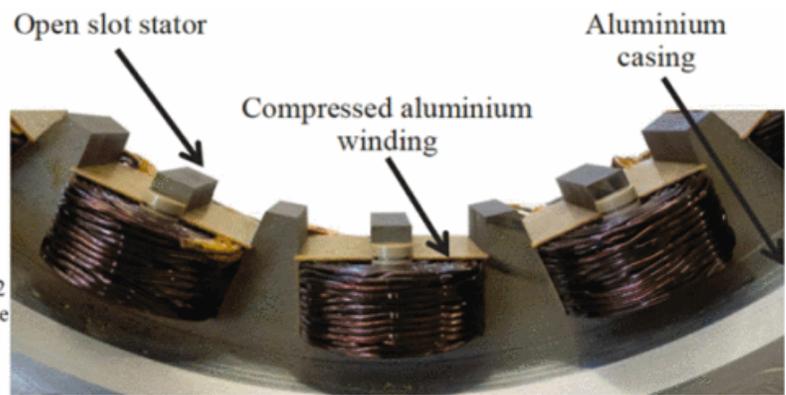
1) Customized Form Winding

AM opens up the design space for various customized form winding designs [33]. Without AM, special tooling is required for each individual design.

In [34], the cross section of stator winding is customized according to the distribution of slot leakage flux path shown in FEA, as shown in Fig. 5. 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.



(a) Shaped profiled coil



(b) Stator assembly

Fig. 5.
Additively-manufactured shaped profile winding

2) Hollow Conductors

For high-voltage or high-altitude applications like 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 [35], [36]. Even with AM, pure copper with high thermal conductivity can reflect the heat applied by a laser beam (I am not sure I understand this sentence). Trumpf recently demonstrated 3D 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 [37]. Some samples of the 3D printed hollow copper components are shown in Fig. 6.

Different types of heat pipes, heat sink and heat exchanger are printed through SLM using copper powder [38], [39]. 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.

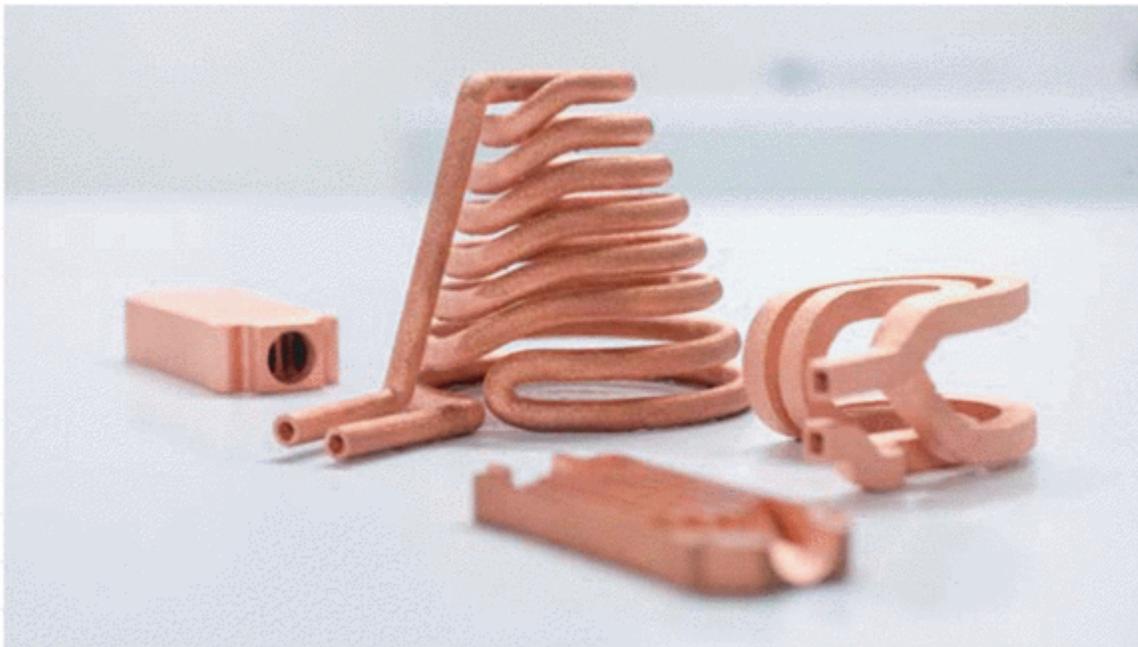


Fig. 6.
3D printed copper components by TRUMPF

SECTION IV. Magnets and Magnetization

NdFeB, Alnico, SmCo permanent magnets (PMs) 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 significantly reduce amounts of machining, enable complex geometries, and minimize material waste. Moreover, AM can control the grain texture to create isotropic or anisotropic properties [40], [41]. Thus, better magnetic performances (high remanence, coercivity, temperature stability, etc) can be achieved without heavy reliance on rare-earth materials like Dy, Tb, Pr, etc.

A. Selective-Laser-Melting-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 [42]. A commercial powder with spherical morphology - MQP-S - has been used to avoid severe crack and pore formation. Key takeaways are summarized as follows [43]:

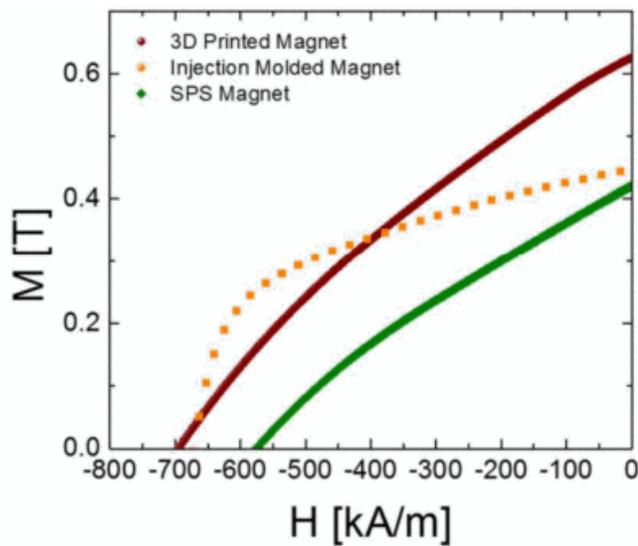
Compared to conventional sintered magnets, the printed $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase has a lower grain size of $1\mu\text{m}$, leading to good magnetic properties.

It's also found that laser parameters like laser velocity and laser thickness can have a major impact on the highest energy product achievable during printing procedure. Fig. 7 shows a comparison of three manufacturing methods, i. e. 3D printing (SLM), injection molded magnet (bonded) and spark plasma sintered (SPS). It is claimed that SLM-based NdFeB has the highest energy product peaking at $45\text{ kJ/m}^3@20^\circ\text{C}$ ($H_c=695\text{ kA/m}$, $B_r=0.59\text{ T}$).

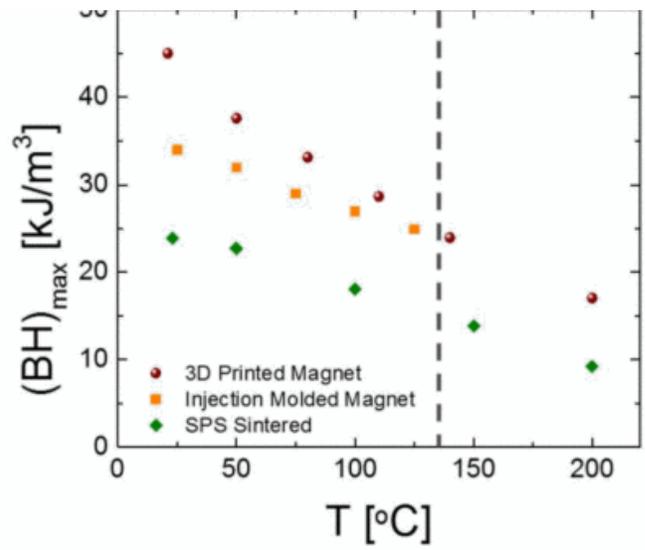
Other benefits and issues of SLM-based NdFeB are summarized as follows,

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

Nowadays, NdFeB powder is available in a size of $35\sim 100\mu\text{m}$. It can be expected that smaller powder size will be available in the near future. NASA Glenn Research Center reported the Nano-composite ($<10\text{ nm}$) magnets, which is promising for further improving the magnetic performances of NdFeB magnets [44]. Bulk magnets can be printed as soon as those materials are available in powder form.



(a) BH curve (2nd quadrant)



(b) $(BH)_{\max}$ vs. temperature

Fig. 7.

Comparison of magnetic characteristics

2) SLM-Based Alnico

In [45], 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. Fuse-Filament-Fabrication-Based Magnets

Composite pellets consist of isotropic NdFeB powder and polyamide like Nylon and Epoxy, can be mixed, melt and supplied by the nozzle in fuse filament fabrication to build desired net shape NdFeB [46]. Fig. 8 shows an example of what the composite pellets are made of.

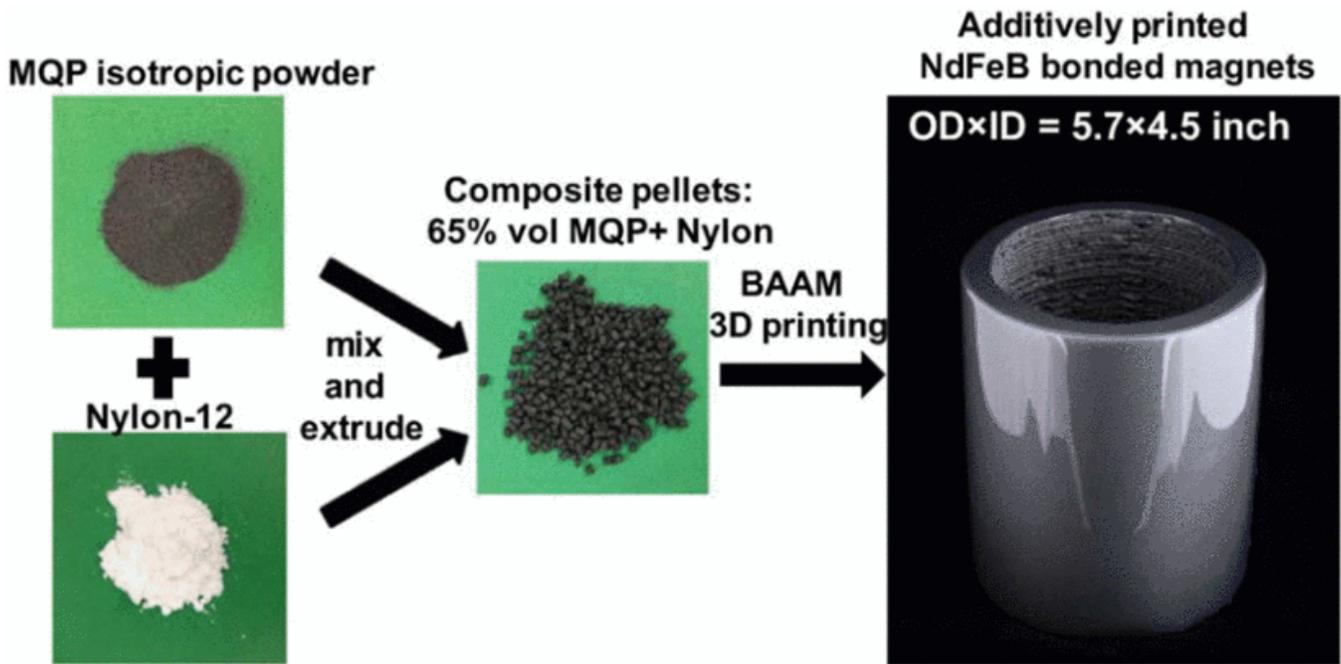


Fig. 8.

Fabrication of net shape bonded ndfeb magnets using a mix of MQP isotropic powder (65%) and nylon-12 (35%)

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

C. Cold Spray Additive Manufacturing

The so-called “cold spray additive manufacturing” can be used to produce high-density metallic coatings without issues associated with thermal spray [49]. The national Research Council of Canada (NRC) is using this technology for fabricating magnets [50]:

- 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);
- Cold spray produces deposits that are oxide-free or with hard-to-reach areas.
- 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.

D. Discussion

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), post assembly magnetization is required as well [51], [52], which has not been discussed in the existing literature.

SECTION V. Integration Between Electrical Machines and Power Electronics

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)[53].

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 [54].

Some of the underlying advantages brought by AM in the context of the IMD concept include the following,

1)

SECTION 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 copper windings can also offer form end shapes that can be encapsulated by heat exchangers with improved heat conduction condition.

2)

SECTION 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 like 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 non-conducting materials like fiber-reinforced polymer materials.

SECTION 3) Simplified Manufacturing

AM can significantly simplify the way of fabricating the cooling channels, heat exchangers as well as cooling jacket with low tooling cost and less liquid leaks.

SECTION VI. Conclusions

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

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

The trend for future AM technologies is to develop multi-material systems. This further opens opportunities for additively-manufactured electrical machines:

- A fusion of different metals: Soft magnetic material like Co-Fe, Ni-Fe; Nano-composite magnets;
- Metal with ceramic interfaces or metal with plastic: Conductors and insulation systems.

The more the multi-material AM system is developed, the more the possibility of moving towards fully additively-manufactured permanent magnet machines is significantly increased.

Other than the three key components of a PM machines, the possibility of building integrated cooling channel, heat pipe and heat sink has also been discussed. The fully AM PM machines will surpass conventional PM machines in terms of their mechanical, thermal and electromagnetic performances, which can eventually be available for extreme-environment applications that would be very challenging for conventional PM machines.

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