

Review

Advanced Manufacturability of Electrical Machine Architecture through 3D Printing Technology

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Abstract: The rapid evolution of electric machines requires innovative approaches to boost performance, efficiency, and sustainability. Additive Manufacturing (AM) has emerged as a transformative technique, reshaping the landscape of electric machine components, ranging from magnetic materials to windings and extending to thermal management. In the area of magnetic materials, AM's capacity to fabricate intricate structures optimizes magnetic flux dynamics, yielding advanced shape-profile cores and self-coating laminations for superior performance. In windings, AM's prowess is evident through innovative concepts, effectively mitigating AC conduction effects while reducing weight. Furthermore, AM revolutionizes thermal management, as exemplified by 3D-printed ceramic heat exchangers, intricate cooling channels, and novel housing designs, all contributing to enhanced thermal efficiency and power density. The integration of AM not only transcends conventional manufacturing constraints but also promises to usher in an era of unprecedented electric machine innovation, addressing the intricate interplay of magnetic, winding, and thermal dynamics.

Keywords: additive manufacturing; electrical machines; 3D-printed windings; magnetic materials



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1. Introduction

In the realm of electrical engineering, the continuous quest for innovation has led to remarkable advancements in the design and manufacture of electrical machines. These machines, which serve as the backbone of modern industrial, commercial, and residential systems, are essential components of our technological landscape. As demands for enhanced performance, energy efficiency, and cost-effectiveness persist, researchers and engineers are driven to explore novel approaches that redefine traditional manufacturing paradigms. One such paradigm-shifting technology that has gained significant traction in recent years is 3D printing [1–3]. Originally developed for rapid prototyping, 3D printing has now evolved into a transformative tool capable of fabricating complex and intricate structures with unprecedented precision. This technology's potential to revolutionize the manufacturing landscape has propelled it into diverse industries, including aerospace [4], automotive [5], renewable energy [6,7], and naval applications [8]. In a broader context, Additive Manufacturing (AM) offers a multitude of industrial advantages, encompassing:

- (i) **Efficient Low-Volume Production:** AM emerges as a cost-effective solution for manufacturing low volumes of intricately designed parts, seamlessly accommodating unique and complex geometries. This versatility is particularly beneficial in scenarios requiring tailored components with minimized production runs.
- (ii) **Optimized Design and Weight Efficiency:** This facet holds substantial promise, particularly within aviation and space sectors, where refined designs and reduced weight translate directly to substantial fuel economies and diminished carbon emissions. AM

- empowers the realization of such optimization by enabling intricate structures that were previously unattainable through conventional techniques.
- (iii) Sustainable Technological Approach: Diverging from traditional subtractive manufacturing methods, AM stands out as a champion of sustainability with its near-zero waste generation. This ecological disposition aligns AM with other green energy technologies, contributing to a more environmentally conscious industrial landscape.
 - (iv) Streamlined Component Integration: The concept of part consolidation underscores the capacity to merge disparate components into a singular unified part. This consolidation not only simplifies manufacturing but also drastically curtails assembly and repair durations. By eliminating intricate interconnections, AM-driven consolidation expedites processes while enhancing overall operational efficiency.
 - (v) In summary, the industrial implications of AM span a spectrum of advantages. These include economical low-volume production, profound design optimization fostering weight reduction and efficiency gains, alignment with environmentally friendly practices due to minimal waste generation, and the transformational potential of part consolidation for augmented assembly and repair workflows. Each of these dimensions amplifies the significance of AM as a disruptive force that is reshaping manufacturing paradigms across various sectors.

In the context of electrical machines, the fusion of 3D printing technology with machine design presents an intriguing opportunity to reimagine the architecture, performance, and manufacturability of these vital devices. This paper delves into the realm of 3D-printed electrical machines, aiming to uncover the uncharted territories where innovation and engineering excellence intersect. Through this paper, we endeavor to explore the symbiotic relationship between electrical machine architecture and 3D printing technology. By harnessing the design freedom and material versatility offered by 3D printing, engineers can push the boundaries of conventional manufacturing processes, enabling the creation of highly customized, efficient, and optimized electrical machine designs. This paradigm shift not only promises breakthroughs in terms of performance metrics such as power density, efficiency, and thermal management but also introduces a level of agility in the design iteration process that was previously unattainable. As we embark on this journey into the realm of advanced manufacturability, we will unravel the intricacies of integrating 3D printing technology into the electrical machine design workflow. We will delve into the challenges and opportunities that emerge, from material selection and electromagnetic considerations to thermal management and mechanical integrity. Moreover, by examining case studies and real-world applications, we will illustrate the tangible impact that this fusion of technologies can have on the electrical engineering landscape.

In conclusion, the integration of advanced manufacturability and 3D printing technology presents a transformative avenue for reshaping the way we conceive, design, and fabricate electrical machines. By bridging the gap between cutting-edge manufacturing techniques and the demands of modern electrical engineering, this paper envisions a future where customization, efficiency, and innovation converge to define the next generation of electrical machines.

This paper provides an insightful exploration into the diverse methodologies encompassing metal additive manufacturing (AM). Furthermore, it presents an all-encompassing examination of the extensive utilization of metal AM within electrical machines. This inclusive review extends to the forefront of progress in the creation of varied machine components, spanning cores, windings, and thermal management elements. The unique contributions of this work are outlined as follows.

- Comprehensive Integration of AM and Electrical Machines: While existing review articles focus on specific aspects, such as the construction of electrical machines or metal additive manufacturing, this review uniquely integrates both Additive Manufacturing (AM) techniques and their applications in various components of electrical machines. This work provides a holistic perspective that covers magnetic materials, windings, thermal management, and the intricate interplay of these aspects.

- **Advanced Manufacturability Emphasis:** This review article specifically centers on the concept of “advanced manufacturability” through AM techniques. It delves into how AM can optimize manufacturing processes, facilitate the creation of intricate designs, and ultimately enhance the overall performance, efficiency, and sustainability of electrical machines.
- **Focus on Emerging Trends and up-to-date Innovations:** This work aims to provide readers with insights into the latest advancements and trends in AM for electrical machines. By doing so, it highlights cutting-edge research and sheds light on the evolving landscape of AM techniques, enabling researchers and practitioners to stay up-to-date with the rapidly developing field.
- **Thermal Management Emphasis:** This review explores the significant role of AM in revolutionizing thermal management strategies for electrical machines. It delves into the intricate cooling channel designs, 3D-printed ceramic heat exchangers, and novel housing designs that contribute to enhanced thermal efficiency and power density.
- **Interdisciplinary Perspective:** While existing reviews focus on specific components or technologies, this work takes an interdisciplinary approach by addressing the interplay between magnetic materials, windings, and thermal dynamics in electrical machines. It highlights how AM impacts all these aspects collectively.

2. Various 3D Printing Techniques

The landscape of metal additive manufacturing (AM) technologies is in a constant state of expansion. Presently, there exist 18 distinct operational principles, with an impressive network of nearly 150 suppliers contributing to this evolution [9–11]. These methodologies are classified according to the nature of their feedstock materials, and this categorization is visually represented in Figure 1a. Despite the ongoing refinement of techniques, the foundational physical concept remains fundamentally unaltered, as succinctly depicted in Figure 1b. At its core, the creation of the final metal component arises from the fusion of both raw material and energy, intricately intertwined with the synchronized behavior of the molten material. However, it is important to acknowledge that these diverse methods exhibit varying degrees of maturity, as visually outlined in Figure 1c. Each approach is situated along a continuum of development, marked by its unique progression towards technological maturity. The chart illustrates the evolution of several additive manufacturing (AM) technologies based on their respective technology maturity index, timeline until industrial utilization, and index achievement milestones. The AM technologies include Laser Beam Powder Bed Fusion (LB-PBF) [12,13], Wire Electric/Plasma Arc Deposition, Electron Beam Powder Bed Fusion (EB-PBF), Powder Laser Deposition [14], and Fused Filament Deposition [15]. The chart also includes additional technologies with their corresponding timelines and index achievements, such as Wire Electron Beam Deposition, Binder Jetting [16], Cold Spray (CS) [17], Wire Laser Deposition, Pellet FDM (Fused Deposition Modeling), Mold Slurry Deposition, Liquid Metal Printing, Resistance Welding, Ultrasonic Welding, Powder Metallurgy Jetting, Metal Nano Particle Jetting [18], and Metal Lithography. The index provides a visual representation of the advancement and adoption stages for each AM technology. It is apparent that the timeline to reach industrial utilization varies among these technologies, with some achieving widespread use within a shorter timeframe compared to others that require more time for development and implementation.

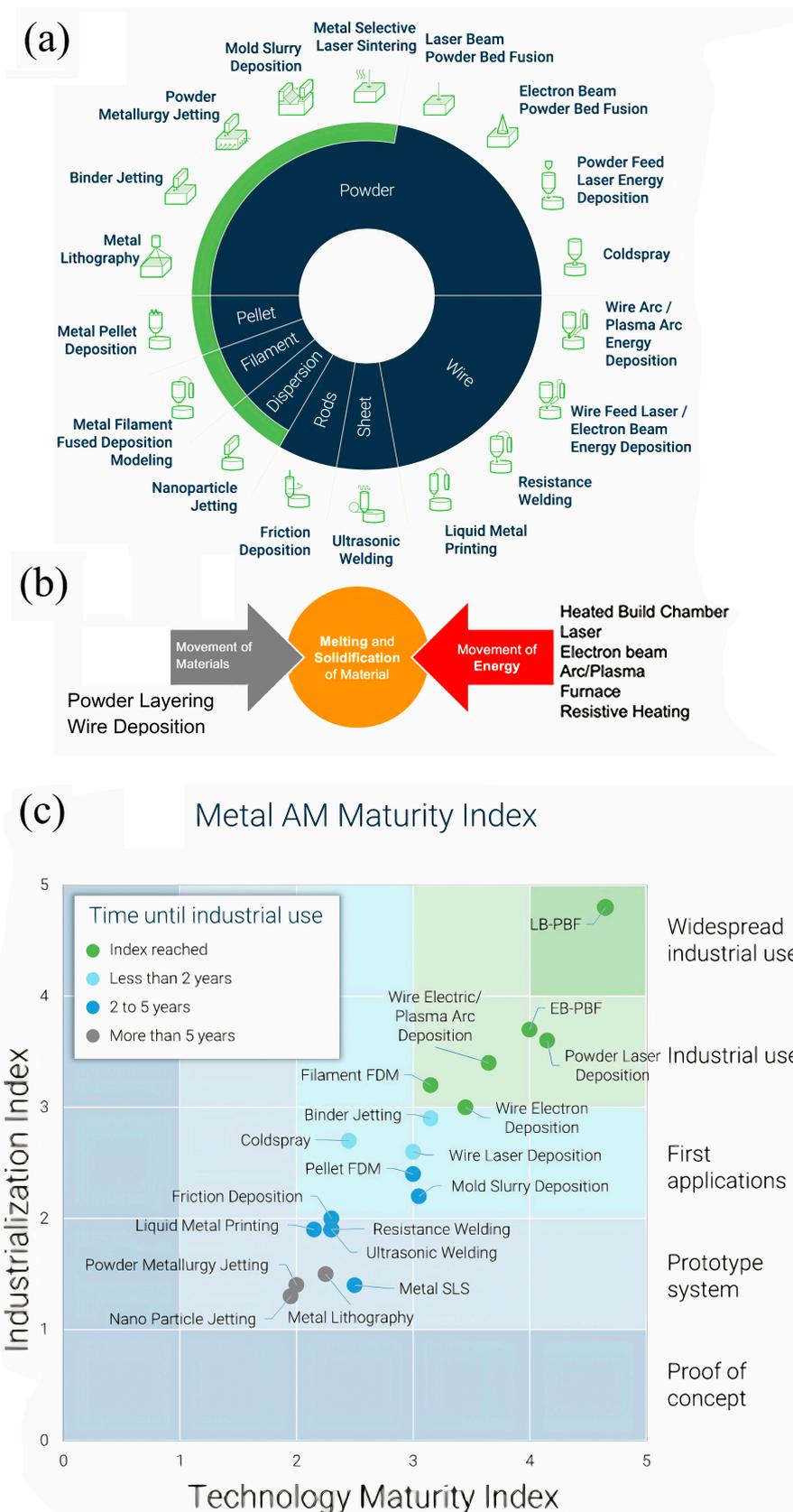


Figure 1. Additive Manufacturing Technology [9–11]. (a) Classification according to feedstock material, (b) Fundamental concept, and (c) Index gauging AM maturity.

ASTM F2792-12 provides a systematic categorization of metal additive manufacturing (AM) techniques. The standard categorizes these techniques into seven groups based on their underlying processes and methods. Here are the categories as per ASTM F2792-12:

- Powder Bed Fusion (PBF): PBF techniques use a bed of metal powder, selectively fusing or melting the powder particles with a laser or electron beam to create each layer.
- Material Extrusion (ME): This category involves the deposition of metal material through a nozzle, similar to Fused Deposition Modeling (FDM) in polymer 3D printing.
- Directed Energy Deposition (DED): DED involves the focused delivery of energy (often laser or electron beam) to fuse or deposit material as it is extruded or blown onto the work surface.
- Binder Jetting (BJ): In binder jetting, metal powder layers are selectively bound together using a liquid binder, and the excess powder is removed after each layer.
- Sheet Lamination (SL): SL techniques create metal parts by layering and bonding sheets or foils of metal material using various methods such as ultrasonic welding or adhesive bonding.
- Material Jetting (MJ): MJ operates similarly to inkjet printing, where droplets of metal material are deposited and selectively solidified by heat or light to build the part layer by layer.
- Vat Photopolymerization (VP): VP utilizes a photosensitive resin that is selectively solidified or cured using a light source, typically a laser or UV light, to build metal parts layer by layer.

These categories encompass a wide range of metal AM processes, each with its unique advantages, applications, and considerations. Researchers and manufacturers can use this standardized classification to better understand and communicate the specific metal AM technique they are using or researching.

3. Generalized Approach for 3D-Printed Coil and Cooling Designs

In this study, a generalized approach for 3D-printed coil and cooling designs is discussed, focusing on the main considerations during the design and printing process as explained in Figure 2. In this sequence, different factors should be considered during an early stage such as stator design, coil dimensions and configuration, cooling approach, and materials and printing technique.

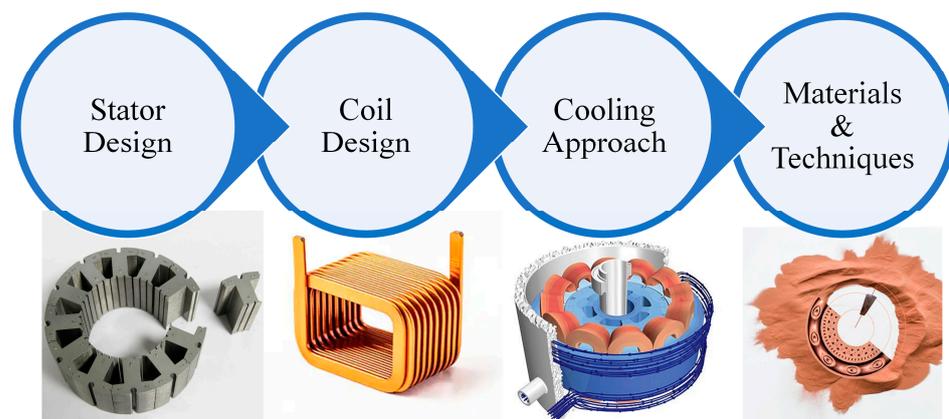


Figure 2. Design sequence and engineering of a 3D-printed coil.

3.1. Stator Design and Slot Shape

The choice of slot shape for 3D-printed coils depends on the specific requirements of the application, including magnetic performance, manufacturing complexity, and cost. The optimal slot shape must be balanced with other design parameters, such as the stator dimensions, coil configuration, and cooling system, to achieve optimal performance and

efficiency. Different slot shapes can be used as shown in Figures 3 and 4. These shapes are explained as follows.

- Round [Figure 4a]: Round slots are commonly used in electrical machines because they offer good space utilization and can provide a more uniform magnetic field distribution. However, round slots can also result in high eddy current losses in the 3D-printed coils and increased manufacturing complexity due to the need for curved walls. Typically, this design is used for stranded winding.
- Rectangular [Figure 4b]: Rectangular slots offer relatively better space utilization and better fill factors. They can also reduce eddy current losses compared to round slots. However, rectangular slots can lead to uneven magnetic flux distribution and increased leakage flux, especially near the slot opening. Typically, this design is used for hairpin winding with a single layer.
- Trapezoidal [Figure 4c,d]: Trapezoidal slots offer the best space utilization and the highest fill factor. However, they can also result in high eddy current losses and increased manufacturing complexity of the 3D-printed coils due to the angled walls. Typically, this design is more useful for double-layer windings.

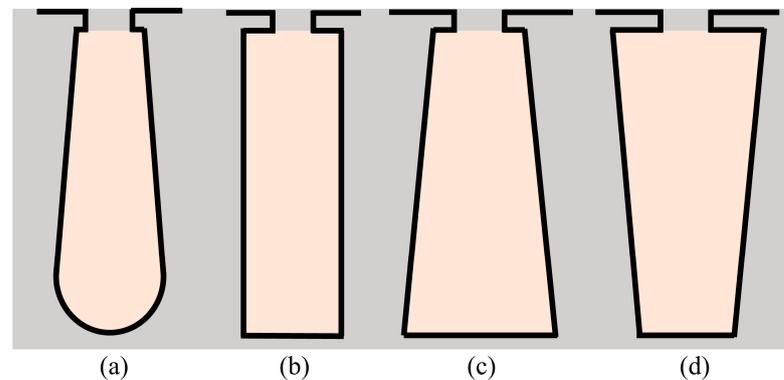


Figure 3. Different shapes of the stator slot. (a) Round, (b) Rectangular, (c) Trapezoidal, (d) Trapezoidal of inner stator.

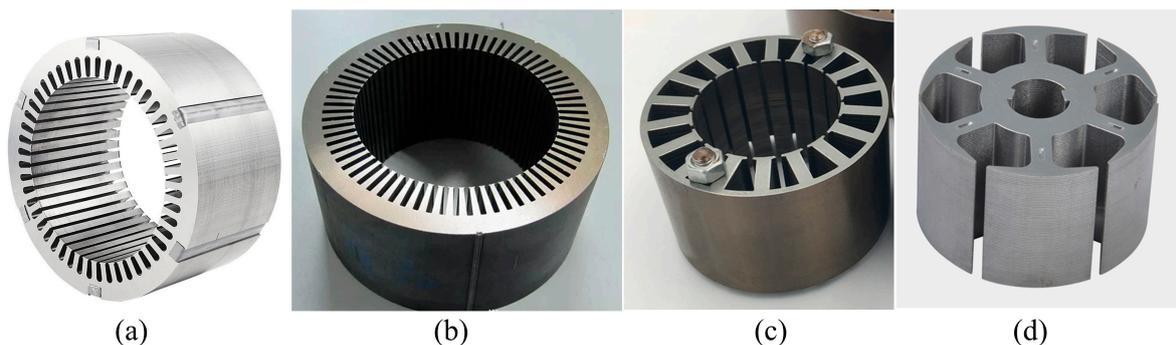


Figure 4. Different stator structures. (a) Round slot, (b) Rectangular slot, (c) Trapezoidal slot, (d) Inner stator with trapezoidal slot.

Apart from radial flux machines, the coil design for axial flux machines needs to account for the axial flux path, which can result in shorter and simpler coils. The use of a concentrated coil configuration may be required for certain applications, such as in yokeless axial flux machines shown in Figure 5, which have a higher power density compared to other machine designs. However, this configuration can also result in a more complex design and manufacturing process due to the need for precise alignment between adjacent coils.

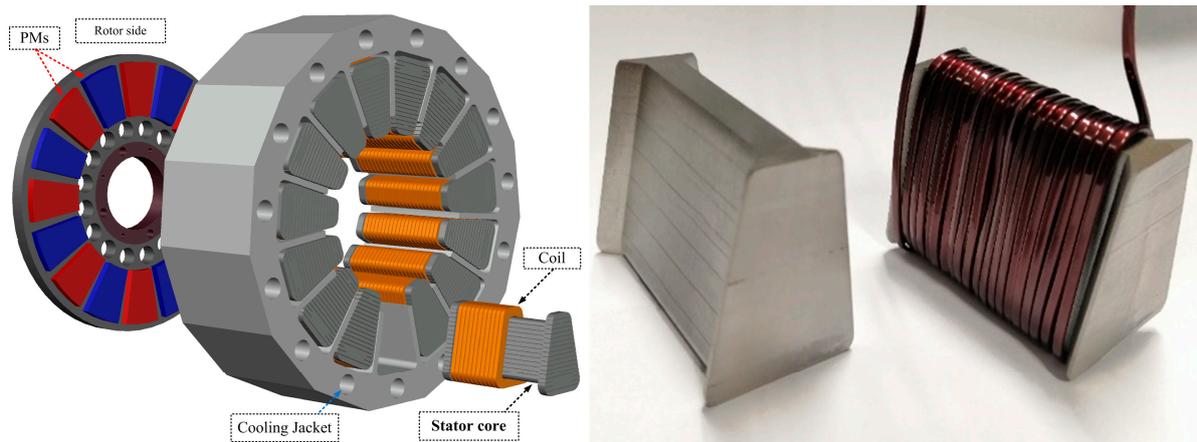


Figure 5. Yokeless axial flux machine.

3.2. Winding Configuration and Coil Dimensions

The coil configuration can be either concentrated or distributed. In concentrated windings, the entire coil is wound around a single tooth, while in distributed windings, the coil is wound around multiple teeth. Concentrated windings result in a higher power density, but distributed windings reduce magnetic leakage and improve the motor's efficiency. Printing distributed windings is only possible through limited techniques such as SLM due to its high accuracy and precision, especially for large designs with many overhanded surfaces. Concentrated windings, on the other hand, are relatively easier to print due to their compactness. Thus, most techniques can be used for their manufacturing such as SLM, FFF, or micro-extrusion.

The design of 3D-printed coils is subject to various limitations, including the layer thickness and the conductor cross-sectional area, which can affect the number of turns that can be wound around the stator. The minimum recommended layer thickness for 3D-printed parts is typically around 0.1 mm. However, this can vary depending on the printing process and material used. For example, SLM can achieve much thinner layers, down to 20 microns, allowing for more precise printing of thin walls. Additionally, sharp edges in 3D printing can cause issues such as poor surface finish, weakened mechanical properties, and poor electrical insulation between adjacent turns. To address these challenges, corner rounding is a recommended technique for smoothing the edges of the slot conductors. By doing so, the electrical performance of the coil can be improved by reducing the risk of electrical shorts and increasing insulation strength. Furthermore, corner rounding can also enhance the mechanical properties of the coil by reducing stress concentrations and improving the overall surface finish, which can improve printability.

Thin wall thickness is also a critical aspect when designing 3D-printed coils as it can affect the coil's mechanical stability and manufacturability. Thin walls are very challenging to print. Therefore, corner rounding is recommended for the slot conductors. They can affect the structural integrity of the component. The recommended minimum thickness of a thin wall is typically around 0.5 mm, but this can vary depending on the printing process, material, and geometry.

3.3. Cooling Approaches

Cooling is critical for the performance and reliability of electrical machines. Three types of cooling concepts commonly used in 3D-printed coils and cooling systems are direct cooling tubes, integrated cooling channels, and end-winding cooling.

- Direct cooling tube involves placing a tube in direct contact with the stator or winding to transfer heat away from the component. This method is simple and easy to implement but may result in uneven cooling and reduced efficiency.

- Integrated cooling channels involve embedding channels into the stator or winding to circulate a coolant through the component. This method is more complex than a direct cooling tube but can provide more efficient and uniform cooling.
- End-winding cooling involves creating a separate cooling system for the winding ends. This method can reduce the temperature rise at the end-winding and improve the component's reliability.

The ease of printing different cooling concepts for 3D-printed coils is influenced by the chosen manufacturing process. For instance, integrated cooling channels can be conveniently printed using Robocasting or Fused Filament Fabrication (FFF) due to their ability to produce inner cavities. However, the same process may pose challenges when using Selective Laser Melting (SLM) due to difficulties in extracting powder from the channels. On the other hand, end-winding cooling is less demanding to create using SLM due to its capability to produce complex geometries.

3.4. Material, Printing Technique, and Limitations

The choice of material for 3D-printed coils depends on several factors, including conductivity, weight, and cost. The commonly used materials include copper, aluminum, and their alloys. Conductivity is a key property of these materials as it directly impacts the efficiency and performance of the coil. The material used in coils must have good electrical conductivity and thermal conductivity. The typical conductivity values for some commonly used alloys are listed in Table 1 [19]. As seen, copper alloys have significantly higher conductivity than aluminum alloys. However, aluminum is lighter and more cost-effective than copper, making it a popular choice for applications where weight and cost are important considerations.

Table 1. Physical Properties of Different Conductive Materials [19].

Properties (after Heat Treatment)	Al-Si-Mg	Cu-Cr-Zr
Electrical conductivity	27.0%IACS	89.3%IACS
Thermal conductivity	173 W/(mK)	265 W/(mK)
Temperature coefficient	0.00410/K	0.00393/K
Mass Density	2670 kg/m ³	8910 kg/m ³
Yield strength	248.1 MPa	200 MPa

When it comes to the selection of the 3D printing technique, several factors must be considered as listed below.

- **Material form:** There are various options available, including metal powders, filaments, and powder pastes. The choice of material can impact the performance and cost. For example, printing with copper powder can result in higher conductivity but may be more expensive than printing with aluminum or its alloys [20,21].
- **Cost-effectiveness:** The economic feasibility of material choices is a crucial aspect. While copper and its alloys offer excellent electrical conductivity, their higher cost may lead to the consideration of alternative materials, such as aluminum and its alloys, which strike a balance between performance and cost.
- **Printing process compatibility:** Single-material printing and multi-material printing are two approaches used in 3D printing. Multi-material printing can enable the creation of more complex and optimized designs but requires a more complex manufacturing process [22,23].
- **Accuracy and precision:** Printing techniques such as Robocasting, Fused Filament Fabrication (FFF), and Selective Laser Melting (SLM) are commonly used to create 3D-printed coils and cooling systems. Robocasting is suitable for printing complex shapes and geometries, while FFF is more suitable for printing larger parts. SLM is suitable for printing metal parts with high accuracy and precision [24].

- **Reflectivity:** Highly reflective materials, such as copper and aluminum, can reflect the laser beam in SLM, resulting in poor printing quality. However, this issue can be addressed by adding anti-reflective additives or using alternative printing techniques, such as Electron Beam Melting (EBM) [25].
- **Thermal Conductivity:** In addition to electrical properties, thermal conductivity is also vital. Efficient heat dissipation is essential to ensure the coil's long-term performance and reliability. The material used in coils must possess adequate thermal conductivity to manage heat effectively.
- **Post-processing:** 3D-printed coils require post-processing steps, such as heat treatment or surface finishing, to achieve the desired mechanical and electrical properties. The choice of printing technique and material can affect the ease and cost of post-processing [26].

4. Additively Printed Electrical Machines

Metal Additive Manufacturing (AM) demonstrates a broad spectrum of applications, spanning domains such as automotive, aerospace, and even extending into the expanse of space exploration [27]. However, honing our attention toward the realm of electrical machines, we encounter a series of intricate challenges pertinent to the design and fabrication of energy-efficient electric motors. A primary instance of such challenges lies within the winding component. Here, the endeavor encompasses achieving both a flawless 100% electrical conductivity alongside a high fill factor, each demanding precision and innovation. Simultaneously, the magnetic core material introduces its own set of complexities, mandating a delicate balance between heightened permeability and minimized eddy current losses—a pursuit that holds pivotal significance for any additively manufactured part in this domain. As of now, the landscape of additive manufacturing for electrical machines is relatively uncharted, with only a handful of notable endeavors undertaken. However, the advent of AM heralds a transformative era, underpinned by its capacity for rapid prototyping and intricate geometries. This newfound potential emerges as a catalyst for innovation, permeating various facets of electrical machine construction. Notably, AM's influence extends across multiple facets, encapsulating the construction of diverse components within the electrical machine, spanning from the iron core and windings to insulation, permanent magnets, and even intricate heat exchangers and cooling systems. Moreover, the lightweight-integrated fabrication capability afforded by AM presents a unique avenue for the realization of fully additively manufactured machines. This perspective envisions a holistic transformation, encompassing not only the active components but also encompassing the incorporation of passive elements such as housing, end covers, rotor shafts, and winding frames. This promising evolution extends the potential for a paradigm shift within the industry, paving the way for comprehensive additive manufacturing applications within the realm of electrical machines. This section shall center on the central active constituents of electrical machines, notably delving into the core, windings, and the intricate landscape of thermal management components.

4.1. Magnetic Materials

Traditionally, electric machines rely on soft magnetic materials characterized by high magnetic permeability. Among the commonly employed magnetic materials, a prevalent choice is the assembly of stacked thin sheets, each measuring between 0.1 and 0.5 mm in thickness. These sheets, fashioned from ferrosilicon (Fe-Si) alloys, manifest as a favorable conduit for efficient energy transfer [28]. Nevertheless, in the sphere of high-power applications, these sheets must accommodate the same magnetic flux while containing less material within both the stator and rotor components. Consequently, the call for a novel approach to electric machine manufacturing emerges, and here is where Additive Manufacturing (AM) demonstrates its potential to fulfill these requisites [29]. Beyond its overarching benefits, the integration of metal AM offers supplementary advantages specifically pertinent to the core manufacturing process:

- **Magnetic Property Manipulation:** An advantage of metal AM lies in its ability to seamlessly blend diverse metal powders, allowing precise modulation of magnetic properties. This encompassing control extends to factors such as high-saturation magnetization and minimized iron losses. Examples of such amalgamations include cobalt–iron or nickel–iron alloys [30–32]. Tables 2 and 3 show the magnetic properties of different AM soft magnetic materials [33–38] and hard magnetic materials [39–47], respectively.
- **Intricate Flux Path Construction:** The versatility of metal AM substantially loosens dimensional constraints, permitting the construction of complex flux paths. This feature stands in contrast to conventional stacked silicon steel laminations [48].
- **Innovative Cooling Channel Integration:** One remarkable facet is the simplified integration of cooling channels within the machine core [49].
- **Mechanical Enhancement:** Metal AM extends its influence beyond the magnetic domain, addressing the mechanical intricacies associated with moving parts within the machine. This influence is harnessed by meticulously controlling material microstructure and fillet percentages, enabling manipulation of physical attributes such as weight and mechanical strength [50,51].

Table 2. Magnetic properties of different AM soft magnetic materials.

Material Compositions	μ_{max} & Saturation Flux Density (Ms)	Hysteresis Losses	AM Technique	Heat Treatment	Ref.
50Fe-49.9Co-0.1Si	$\mu_{max} = 2600$ Ms = 2.35 T	Comparable to Vacoflux 50	SLM	1100 °C for 4 h	[33]
Fe-49Co-2V	$\mu_{max} = 13,000$	higher than a laminated sample @ 1.5T, 10/50 Hz	L-PBF	700 °C for 2 h	[34]
FeSi6.7	$\mu_{max} = 31,000$	0.70 W/kg @ 1.0 T, 50 Hz	L-PBF	1150 °C for 1 h	[35]
Fe-6.9%wt.Si	$\mu_{max} = 24,000$	4.0 W/kg @ 1.0 T, 50 Hz	SLM	1150 °C for 1 h	[36]
Fe-80%Ni	Ms = 550 Am ² /kg	BH loop is available Losses are not calculated	SLM	non	[37]
Ni-Fe14-Cu5-Mo4	Ms = 0.33 T	BH loop is available Losses are not calculated	SLM	non	[38]

Table 3. Properties of different hard magnetic materials printed using various AM methods [39–47].

Material Compositions	AM Methods	Remanence Br (G)	Coercivity Hci (A/m)	Max. Processing Temp.	Ref.
NdFeB	BJT *1	3000	9000	150 °C	[39]
NdFeB	L-PBF	5900	8734	900 °C	[40]
NdFeB	FFF *4	690	5190	525 °C	[41]
NdFeB + SmFeN	BAAM *2	2800–11,000	10,800–11,100	204 °C	[42]
NdFeB-Al	CS *3	4900	11,000	800 °C	[43]
Ferrites	FFF	2200	3530	300 °C	[44]
SmCo5	FFF	880	8970	160 °C	[45]
AlNiCo 8	DED *5	9200	1850	1250 °C	[46]
AlNiCo 9	DED	7200	1600	1215 °C	[47]

*1 (BJT): Binder Jetting, *2 (BAAM): Big Area Additive Manufacturing, *3 (CS): Cold Spray, *4 (FFF): Fused filament fabrication *5 (DED): Directed Energy Deposition.

In [52], pioneering the realm of advanced core design, the additive printing of intricately contoured cores seeks to curtail the impact of eddy current losses as shown in Figure 6. This strategic approach aims to redefine the very shape of cores, capitalizing on additive manufacturing’s precision to optimize energy efficiency. The magnetic properties inherent to these additively printed cores undergo meticulous evaluation, with a particular focus on scrutinizing the influence of external compression. This evaluation entails subjecting the cores to mechanical stress during the magnetic measurements, unraveling the interplay between structural integrity and magnetic behavior. Additionally, a remarkable leap forward has been attained through the emergence of self-coating laminations as shown in Figure 7, marking a monumental breakthrough in the field. This innovation culminates from a controlled atmosphere heat treatment, a process that triggers surface oxidation within magnetic materials. This oxidation process inherently gives rise to the formation of a natural insulation layer. This revolutionary self-coating phenomenon represents an unprecedented achievement, underscored by its novelty as the first reported instance of such self-coating laminations. The controlled oxidation not only elevates the material’s performance but also opens a novel avenue for enhancing the protective and functional attributes of magnetic components.

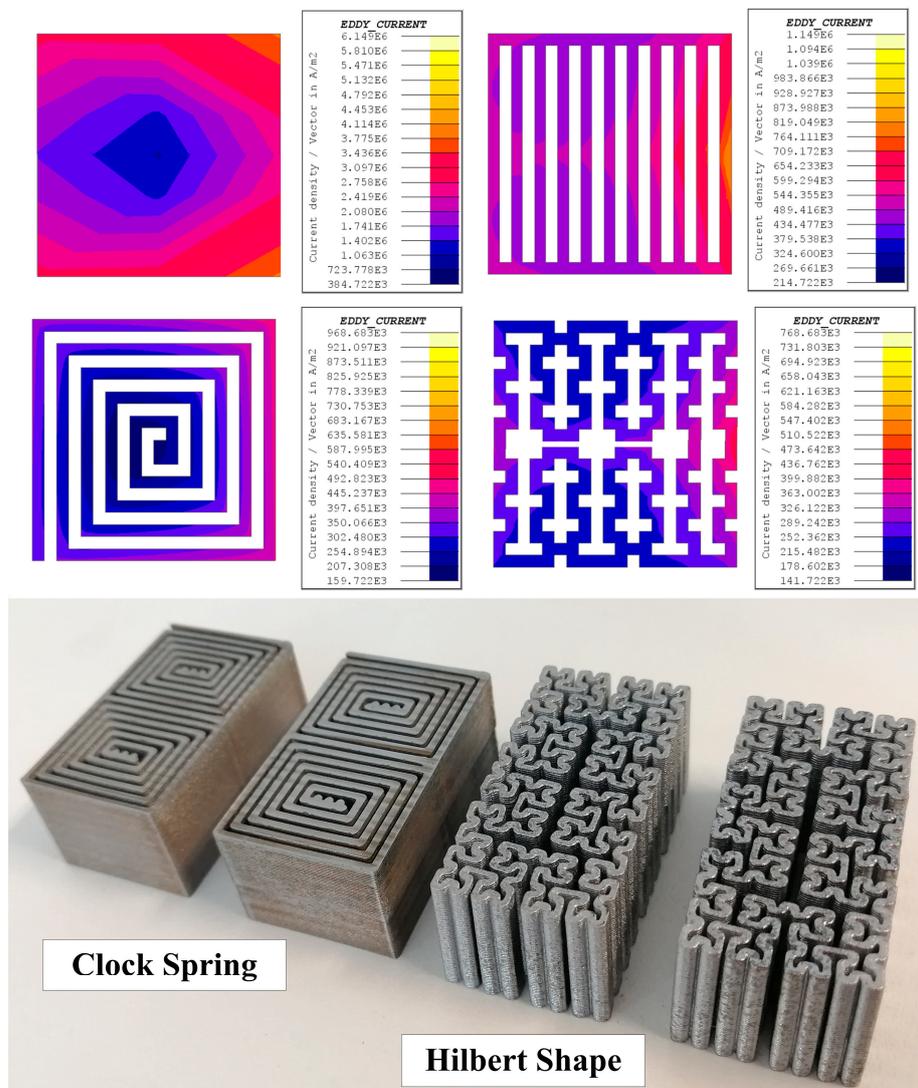


Figure 6. 3D-printed silicon steel magnetic cores using 3D micro-extrusion technology in two different shapes: clock spring and Hilbert shapes [52].

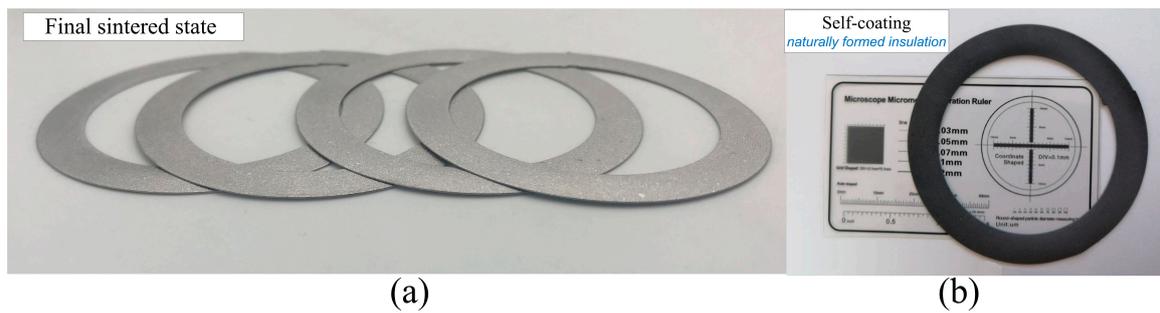


Figure 7. 3D-micro-extruded Fe–Si ring cores. (a) Final sintered state, (b) Self-coating [52].

In Figure 8a, a six-slot rotor crafted from Fe–Co powder (particle size under $63\ \mu\text{m}$) using Powder Bed Fusion (PBF) AM for a reluctance machine is showcased. Remarkably, this prototype achieves a magnetic flux density of 2.3 Tesla [53]. Turning to Figure 8b, an innovative flux barrier motor design is presented, uniting mechanical and electromagnetic aspects synergistically. Notably, this design incorporates the simultaneous creation of non-magnetic bridges alongside magnetic components, demonstrating an intricate harmony [54]. Figure 8c ushers in a new frontier, showcasing the application of AM in creating both the stator and rotor of a line start synchronous reluctance machine. This achievement underscores the transformative power of AM in redefining the construction paradigm of electrical machines [55].

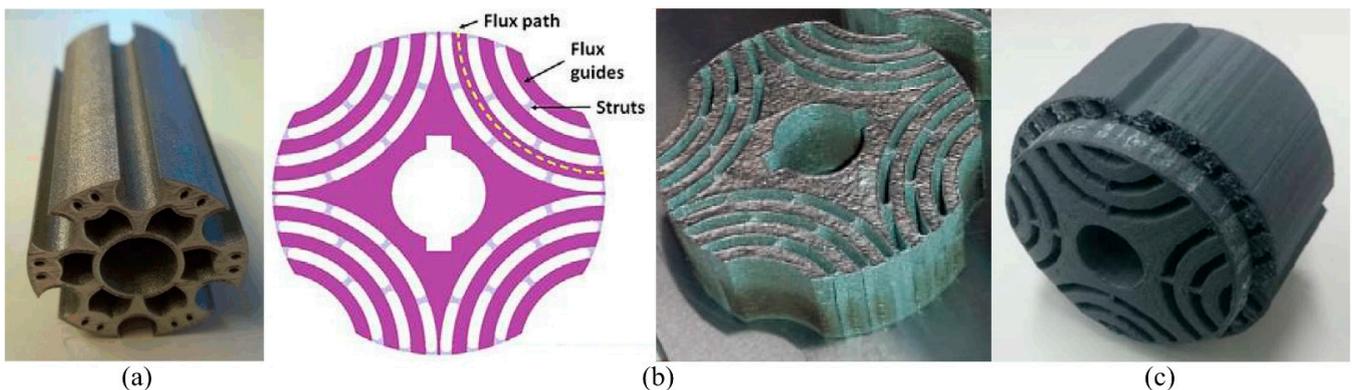


Figure 8. Additively fabricated cores for electrical machines: (a) Prototype rotor designed for a high-saturation flux density SRM [53], (b) Flux barrier rotor crafted using Selective Laser Melting (SLM) technology featuring non-magnetic bridges [54], and (c) Rotor and stator core assemblies conceived for a line start synchronous reluctance machine [55].

In reference to [56], a pioneering endeavor is documented wherein an Additive Manufacturing (AM)-fabricated interior magnets skewed rotor for a Permanent Magnet (PM) synchronous machine emerges, featuring a distinctive hollow shaft and an emphasis on lightweight construction. This innovative construction is vividly illustrated in Figure 9. The endeavor extends to the realm of rotor design, where a novel conical transition region bridges the gap between the active section and the bearings, ushering in both weight and inertia reductions. The results are noteworthy—a 53% reduction in rotor weight, thereby facilitating an impressive 9% acceleration enhancement from standstill to nominal speed. Notably, the average motor torque experiences a boost of over 5%, while the cogging torque plummets by an astounding 90%. Envisioned as a triumph of innovation, the rotor's composition entails soft-magnetic ferro-silicon alloy, fabricated using Laser Beam Melting (LBM), a powder bed-based AM technology.

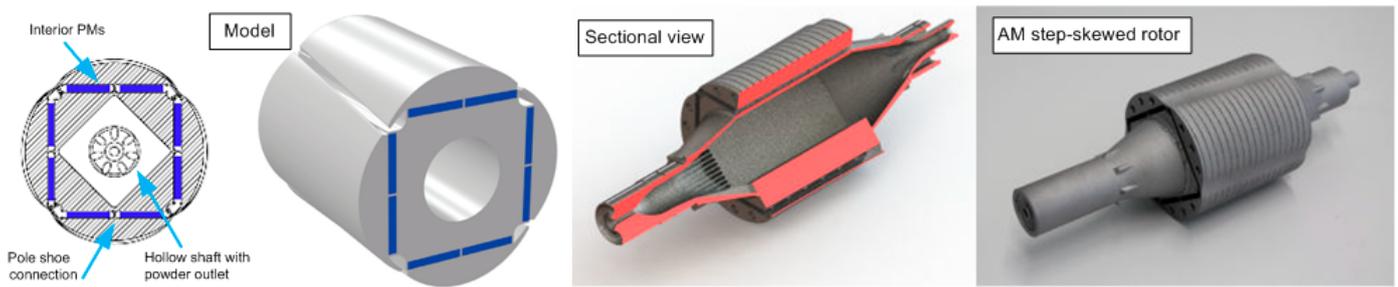


Figure 9. Skewed rotor for PM machine with lightweight hollow shaft [56].

Turning attention to [57], an entirely new breed of electric machines emerges, prominently showcased in Figure 10. Departing from conventional radial-flux or axial-flux configurations, this machine pioneers a three-dimensional magnetic flux path, distinctly setting it apart. Crafted through additive manufacturing, this machine leverages spray-formed soft magnetic material, consequently yielding compact, lighter machines that exhibit heightened power output and superior energy efficiency. Noteworthy enhancements include a remarkable 40% increase in power density and an appreciable 15% reduction in losses.

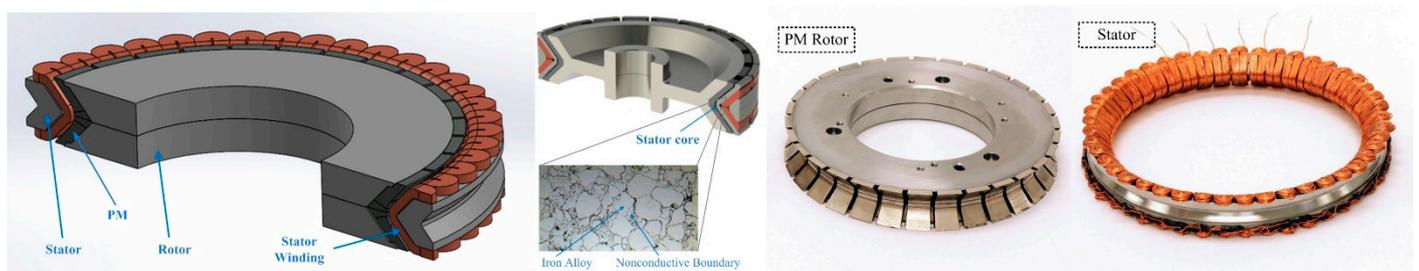


Figure 10. PM brushless machine with 3D-flux printed using spray-formed soft magnetic material core [57].

In [58], the use of 3D-micro-extrusion technologies facilitates the multi-material 3D printing of magnetic and non-magnetic material layers. This approach permits the creation of fully realized AM components that closely approximate their intended shape. A practical illustration, as seen in Figure 11a, takes form in the design of a ring core featuring a serpentine cross-sectional configuration. An insulating layer adeptly intersperses among the magnetic strata to mitigate any potential cracking during thermal treatment—a precautionary measure arising from the distinct thermal expansion coefficients of the materials. Capitalizing on the capabilities of a multi-nozzle 3D printer, the intricate structure is constructed using micro-extrusion, as showcased in Figure 11b. High-quality Fe–Si powder is employed to facilitate the deposition of wafer-thin layers, with an average thickness of 200 μm . Complementing this magnetic material, a ceramic insulator functions as an intermediary interlayer, boasting a mean thickness of 50 μm . The seamless adhesion observed between the Fe–Si and insulator layers is noteworthy. Moreover, the non-linear interface between these layers introduces an extra layer of mechanical interlocking, enhancing overall cohesion. This multi-material stratified component is anticipated to manifest improved magnetic properties, characterized by significantly reduced eddy current losses. This advantage is attributed to its near-net-shape fabrication, void of any subsequent destructive post-processing steps such as laser cutting, interlocking, welding, or stacking. The achievement lies in additive manufacturing’s capability to precisely shape intricate magnetic structures, underscoring its transformative potential within this realm. Collectively, these instances illuminate the application of metal AM in the creation of soft magnetic components for electrical machines, each representing diverse levels of technology maturity.

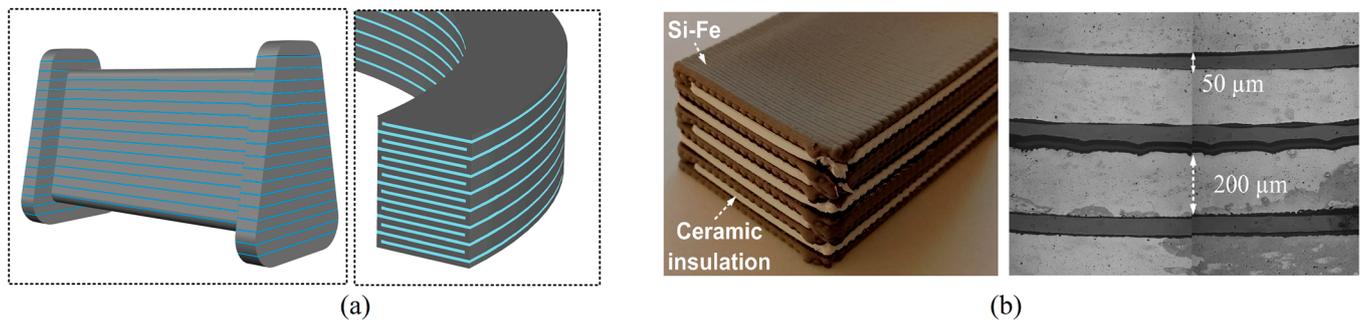


Figure 11. Multi-material 3D printing. (a) Serpentine shape. (b) Cross-section view of multi-material part [58].

4.2. Windings

The integration of metal Additive Manufacturing (AM) into the construction of electrical machine windings is still in its initial phases [59,60]. Nevertheless, AM emerges as a platform ripe for introducing ingenious design solutions for coils and windings, effectively heightening its competitive edge in comparison to conventional wire-based techniques. The realm of winding fabrication benefits significantly from the adoption of AM, with key contributions encompassing the following:

- **Enhanced Flexibility:** The inherent flexibility of AM empowers the design of coil cross-section areas with a heightened slot fill factor, while concurrently optimizing thermal behavior.
- **Tailored End Windings:** The customization potential extends to end windings, where a remarkable 50% of their length can be adapted [61]. This substantial tailoring translates into pronounced reductions in machine weight and volume, amplifying overall efficiency.
- **Simultaneous Winding and Insulation:** Specific methodologies enable the simultaneous printing of both the winding and insulation, streamlining the manufacturing process and enhancing efficiency.
- **Elevated Operating Temperatures:** AM facilitates the utilization of powdered temperature-resistant materials like ceramics, eliminating the need for conventional coatings such as enamel, resin, or polymers. This strategic shift opens avenues for achieving higher operational temperatures that were previously constrained by material limitations. Conventional processing techniques for materials like ceramics are hindered by their high melting points, a challenge surmounted by AM.
- **Precision Electric Property Control:** The manipulation of winding electric properties, such as conductivity, becomes a reality through the adaptation of material microstructure or the incorporation of distinct materials, illustrating the depth of control offered by AM.

In [19], a revolutionary approach unfolds as AM introduces coils with hollow conductors designed for a high-specific-power 250 kW, 5000 r/min Permanent Magnet (PM) machine. This groundbreaking concept innovatively integrates conductors with cooling channels, ushering in a direct heat exchange mechanism as vividly portrayed in Figure 12. This strategic union of conductors and cooling channels emerges as a potent solution to the heat dissipation quandary prevalent in electrical machines boasting elevated power ratings. Embodying this pioneering vision, two coils are actualized through the process of direct metal laser sintering (DMLS), employing distinct materials: copper and aluminum alloys. The chemical compositions of these materials manifest as aluminum–silicon–magnesium (AlSiMg) and copper–chromium–zirconium (Cu–Cr–Zr) alloys, respectively. These alloys, when contrasted with AM-produced pure copper or aluminum, exhibit notably enhanced mechanical properties—a favorable attribute with profound implications, particularly for aerospace applications where resilience under vibrational stress is paramount. In the context of electromagnetic prowess, meticulous evaluation reveals that the aluminum-based

design emerges as the superior choice, showcasing an innate capacity to mitigate high-frequency losses at this formidable, rated speed. This strategic advantage lends itself to the attainment of optimal electromagnetic performance, aligning seamlessly with the PM machine's demanding operational specifications.

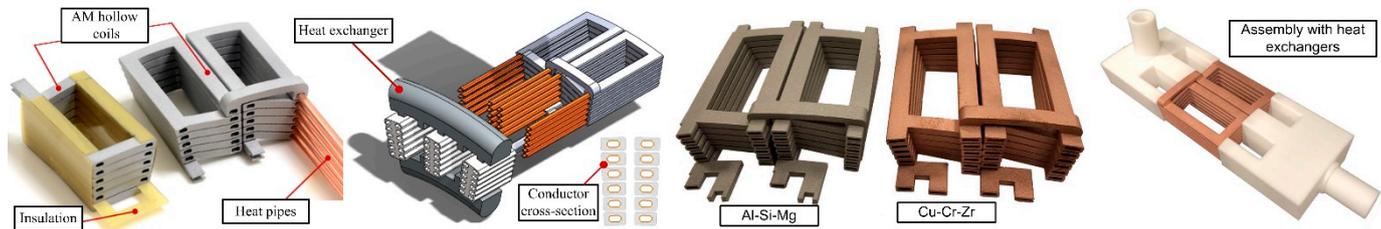


Figure 12. Hollow conductors with integrated cooling channels [19].

In [62–64], a series of pioneering strides is witnessed through the utilization of direct metal laser sintering (DMLS), effectively culminating in the creation of uniquely shaped profile coils. This transformative process unfolds using an assortment of materials, as vividly depicted in Figure 13. A strategic architectural adaptation is evident in the shaping of conductors, oriented to align parallel with magnetic flux lines, thereby mitigating AC losses. To illustrate this approach, an instance is realized where an AlSiMg alloy winding is constructed at a 45° angle to the build platform, a deliberate angle ensuring autonomous structural integrity with minimal size support requirements. The design of build supports incorporates thoughtful considerations, guaranteeing adequate clearance between the turns. In parallel, a Cu–Cr–Zr alloy coil undergoes a comparable manufacturing trajectory. The finalization of this intricate process entails the mechanical removal of support structures in a post-manufacturing phase, culminating in the application of a varnish coating. Evidencing immense potential, these shaped profile windings hold the key to augmenting efficiency across diverse applications, encompassing electric vehicle traction, aerospace propulsion fans, and generators.

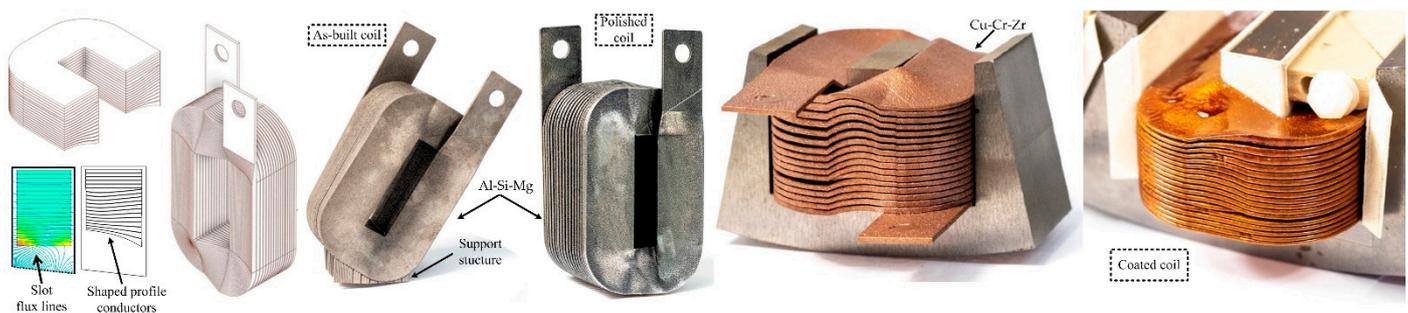


Figure 13. Profiled coils with low eddy current losses [62–64].

Embarking on further evolution of the aforementioned shaped profile coils, a novel paradigm is unveiled—a multi-material coil winding seamlessly integrated with a heat exchanger, an emblematic union brought to life in Figure 14 [65]. Employing the capabilities of multi-material Additive Manufacturing (AM), the assemblage adopts a triply periodic minimal surface heat exchanger crafted from an amalgamation of pure Cu, pure silver, and copper–silver alloys. Notably, the quest to achieve optimal thermal performance comes against the backdrop of a distinct challenge inherent to laser powder bed fusion processing (L-PBF) of pure copper. Herein, the reflective properties of infrared lasers pose a formidable obstacle, accounting for up to 98% of the laser energy. This challenge is surmounted through strategic measures, including the deployment of a high-power 400W L-PBF system featuring advanced infrared lasers with small spot sizes or distinct wavelength options. While substantial strides have been made in enhancing thermal

attributes, the electromagnetic performance of these pioneering coils awaits meticulous evaluation.

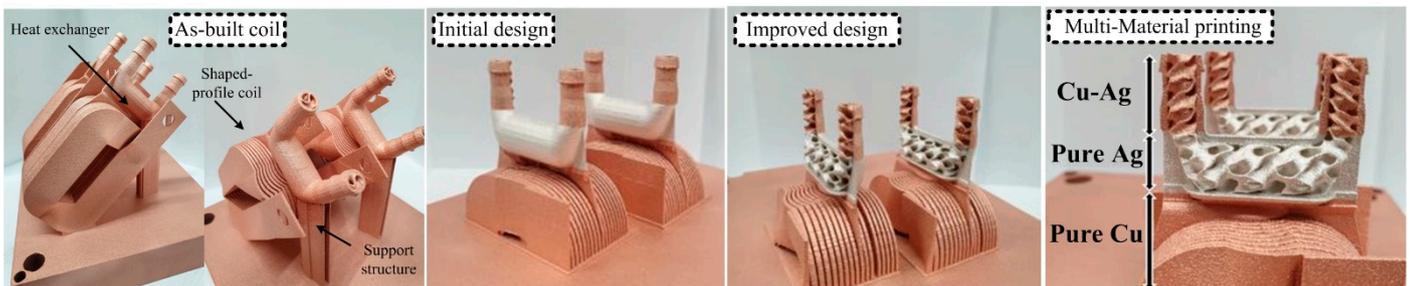


Figure 14. AM profiled coils with built-in multi-material heat exchangers [65].

In [66], a 3D-printed single coil winding is developed for a high-performance racing engine, as shown in Figure 15. With precise geometry, these coils achieve maximum copper fill factor while facilitating efficient heat transfer to the laminated core, preventing overheating. As a result, power density surges by over 45%. Turn insulation is applied in a separate step. In another stride [67], the authors introduce 3D-printed hairpin distributed windings for an E-traction motor, depicted in Figure 16. Replacing conventional copper wires with rectangular copper rods and optimizing the winding design results in a remarkable 30% increase in torque within the same slot space.

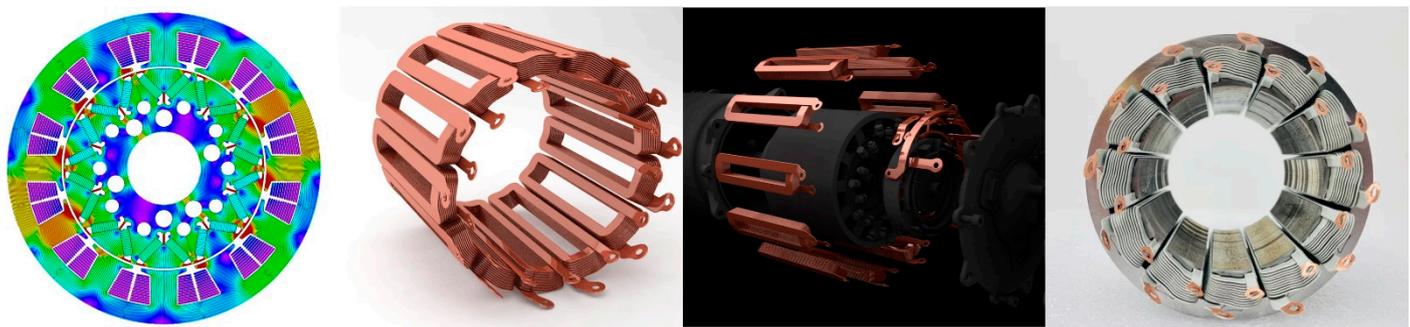


Figure 15. High-performance racing engine with 3D-printed coil winding [66].

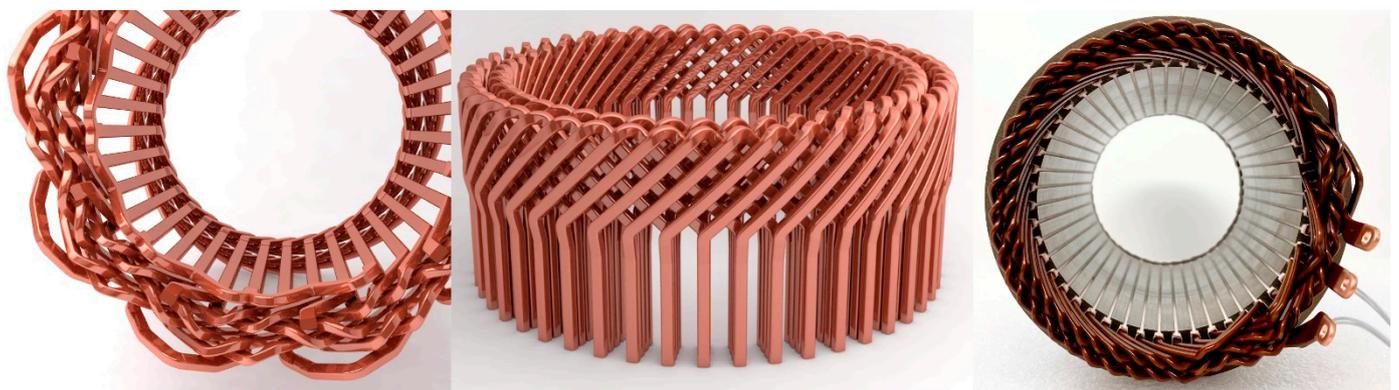


Figure 16. 3D-printed hairpin windings with distributed configuration for traction motors [67].

In [68], a novel approach emerges with the introduction of a redesigned complete coil, showcased in Figure 17, characterized by uneven layers. This ingenious configuration strategically positions turns near the slot opening with diminished height relative to those at the slot bottom. This tactical arrangement curbs the influence of cross-slot leakage flux, leading to a marked reduction in losses within the upward turns. Adding to its

multifaceted innovation, the cross-sectional area adorns a z-shaped profile, ensuring an equitable distribution of current density throughout the coil. Materializing this inventive concept, aluminum alloy is harnessed for 3D printing, imparting an additional barrier to eddy current losses during high-speed operation. Impressively, this novel coil design boasts a staggering 74% reduction in weight compared to its conventional copper counterparts. While its performance at high frequencies remains commendable, it is important to note that this coil is structured with single-strand turns.

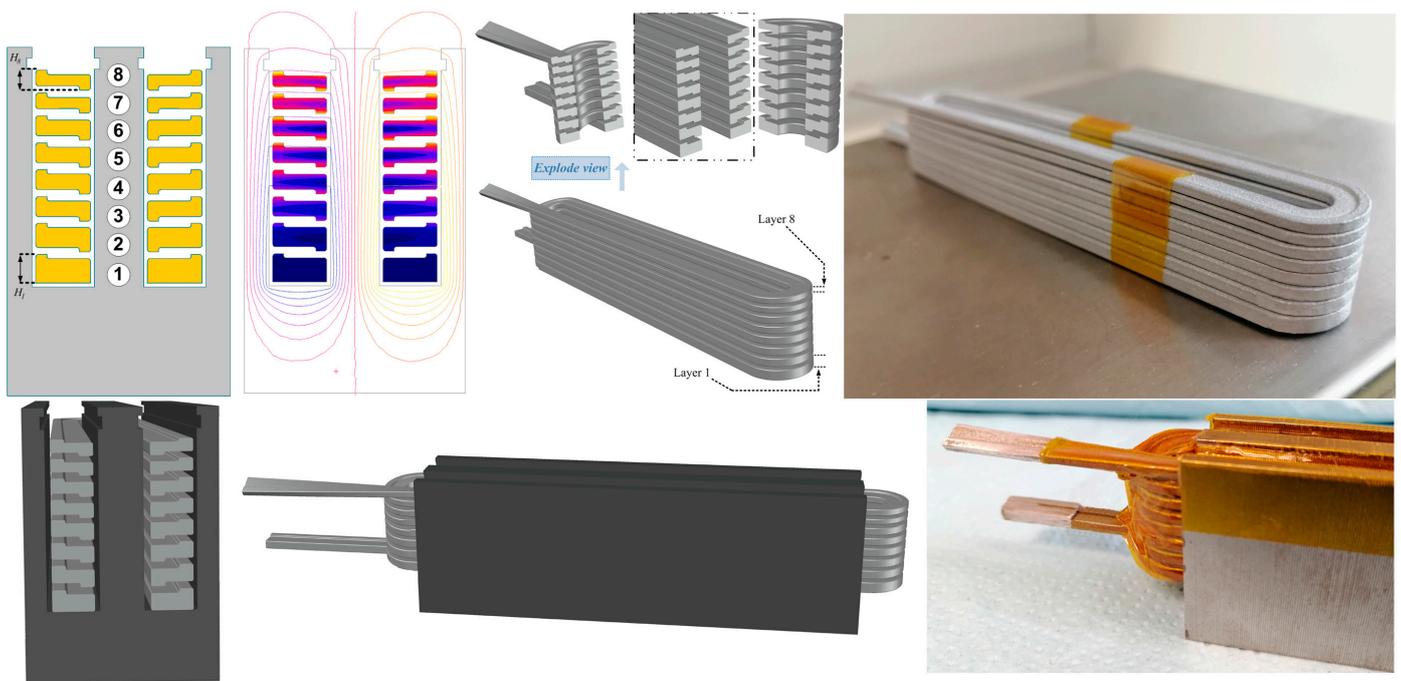


Figure 17. Shape profiled 3D-printed coil with uneven turns [68].

In [69], an innovative paradigm unfolds with the introduction of a semi-stranded winding concept, encompassing half-solid and half-stranded turns as shown in Figure 18. The focal point of this investigation revolves around mitigating adverse AC conduction effects prevalent at high frequencies in high-speed electrical machines. Employing a hybrid approach melding Finite Element Method (FEM) simulations and practical experimentation, the impact of strand transposition is scrutinized, meticulously orchestrated through controlled strand positioning. A pivotal aspect of this study lies in achieving a symbiotic equilibrium between DC and AC winding losses. This delicate balance materializes in the form of a novel semi-stranded coil, adeptly amalgamating a high fill factor with strategically transposed strand locations. This groundbreaking design is meticulously brought to life using 3D printing technology, employing ultralight aluminum alloy. Rigorous validation affirms the profound electromagnetic prowess of this novel semi-stranded coil, underscored by markedly reduced top temperatures in the high-frequency domain, all within a mere 30% of the weight of conventional counterparts. This innovative coil configuration stands resolute as a compelling contender for weight-sensitive electrical machines operating within high-power density parameters in the high-frequency realm. It encapsulates a transformative approach that aligns seamlessly with the demands of advanced electrical engineering applications.

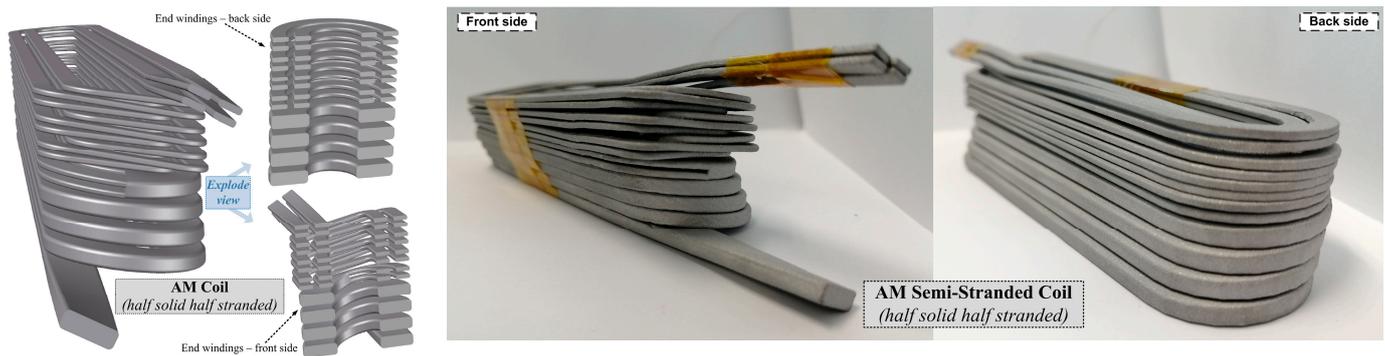


Figure 18. AM semi-stranded coil [69].

4.3. Thermal Management and Cooling

The accelerating uptake of electric vehicles (EVs) is propelling the evolution of more potent and high-capacity electrical machines. For EV manufacturers, the cooling conundrum necessitates solutions that embody thermal efficiency, temperature uniformity, size, weight, and cost considerations [70]. Here, the expansive design possibilities afforded by Additive Manufacturing (AM) emerge as a critical enabler, offering innovative solutions to EV cooling challenges, as evidenced by the subsequent instances.

In [71–73], a paradigm shift is unveiled as electrical machine windings receive direct cooling via 3D-printed ceramic heat exchangers, showcased in Figure 19. This innovation leverages the unutilized space between double-layer concentrated windings, driving up electric machine power density without compromising electromagnetic design parameters. Ingeniously optimized microfeatures within inner channels through distinct shapes yield vastly improved cooling efficacy. The deployment of ceramics, renowned for their high-temperature resilience, leads to a remarkable 44% reduction in winding temperature rise. This achievement is complemented by the attainment of a continuous current density of 35.7 A/mm^2 , with the maximum winding temperature meticulously constrained under $200 \text{ }^\circ\text{C}$.

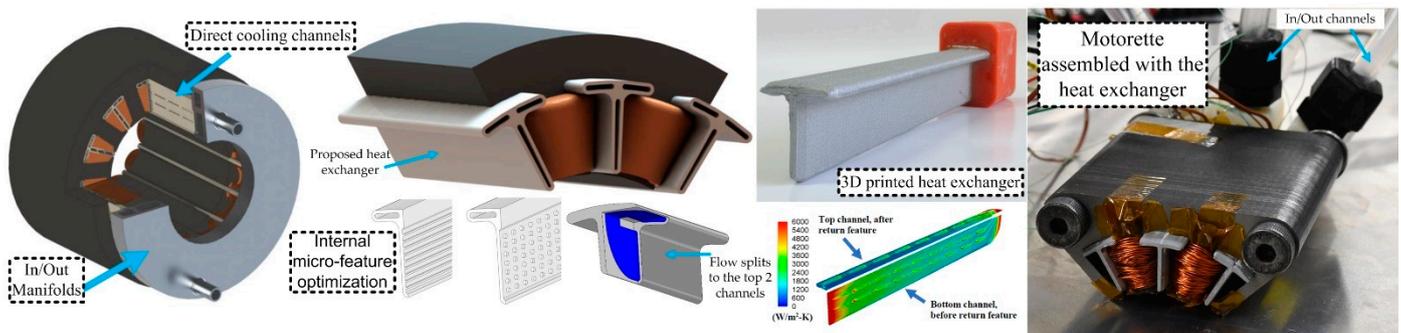


Figure 19. Enhanced Thermal Performance through 3D-Printed Ceramic Direct-Winding Heat Exchangers [51].

Figure 20 introduces a panorama of electric machine housing examples tailored for EV applications. Within [74], electric machine thermal performance ascends with the introduction of a pioneering liquid cooling integrated channel design within the housing, effortlessly realized through AM as shown in Figure 20a. Authors in [75] underscore the capabilities of metal 3D-printed heat exchangers featuring spiral fins, manufactured via SLM as shown in Figure 20b, promising heightened performance and efficiency within a remarkably brief production window. In [76], the innovation extends to a cooling jacket with an internal helix structure, forged from EOS-M-290 material as shown in Figure 20c, manifesting as a 16% lighter and 37% more efficient function-integrated cooling solution. Authors in [77] introduce a transformative free-form design (Figure 20d), straying from con-

ventional spiral-like thermal patterns. This novel configuration, enriched with artificially designed patterns, achieves a 25% reduction in thermal resistance, a 15% improvement in temperature uniformity, and a remarkable 50% enhancement in pressure drop. Notably, the free-form design redefines the cooling jacket, reducing its weight and volume by up to 40%, translating to substantial material savings, reduced weight, and enhanced affordability.

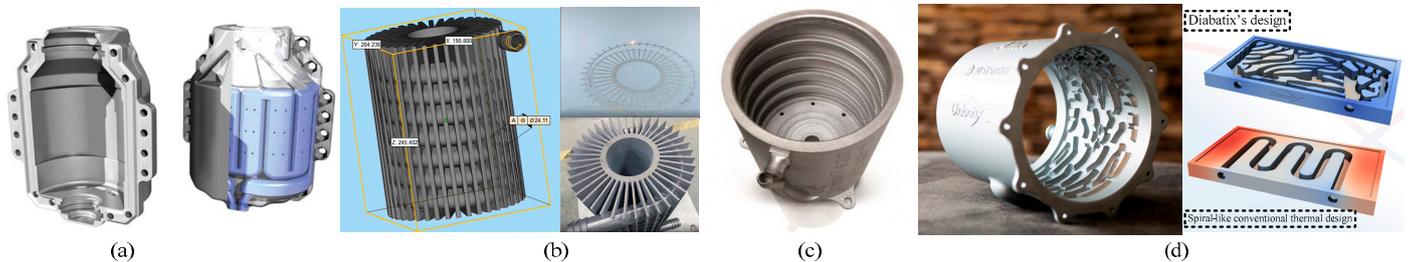


Figure 20. Instances of 3D-Printed Electric Machine Housing: (a) Motor Housing with Integrated Cooling Channels [74], (b) Selective Laser Melting (SLM) Utilized for AM Heat Exchanger with Spiral-Fins [75], (c) Internal Helix Structure Cooling Jacket [76], and (d) Diabatix's Innovative Thermal Cooling Design Featuring Artificially Crafted Patterns [77].

5. Future Research Scope and Challenges

As the field of Additive Manufacturing (AM) continues to evolve in the realm of electrical machine architecture, several intriguing research directions and challenges emerge. This section discusses key areas that present both opportunities for advancement and hurdles that necessitate careful consideration. Exploring these aspects will contribute to the refinement and expansion of AM techniques for enhanced electrical machine performance and manufacturing.

- **Material Availability and Diversity:** One of the significant limitations of metal AM lies in the availability of printable materials. While AM offers unique advantages in design flexibility and complexity, the range of materials suitable for these processes remains limited. This limitation directly impacts the variety of electrical machine components that can be effectively manufactured using AM. To address this challenge, researchers and industry professionals must collaborate to expand the selection of printable materials, enabling a broader array of applications and improved performance.
- **Post-Processing and Density Variability:** Many metal AM processes necessitate post-processing steps to achieve the desired mechanical properties and surface finish. However, the extent of post-processing required varies based on the material and process used. This variability influences the density and performance of the manufactured components. Overcoming this challenge involves developing standardized post-processing procedures and optimization techniques to ensure consistent and predictable outcomes, thus enhancing the reliability of AM-manufactured electrical machine parts.
- **Print Parameters and Component Build:** The parameters employed during the printing process—such as print speed, print resolution, print strategy, and print bed position—significantly impact the quality and properties of the resulting components. Understanding the intricate interplay between these parameters and the final component's attributes is crucial for achieving desired outcomes. Research efforts should focus on optimizing these parameters to strike a balance between precision, efficiency, and material properties, thereby refining the overall AM manufacturing process.
- **Outer Space Manufacturing:** A visionary avenue for future research involves exploring the feasibility of manufacturing electrical machine components using AM techniques in outer space environments. As space exploration and utilization expand, the demand for on-site manufacturing capabilities becomes more pronounced. Investigating the adaptability of AM to extraterrestrial conditions presents a unique set of challenges and

opportunities, with potential implications for future space missions and infrastructure development.

In conclusion, this section identifies promising research avenues and pressing challenges in the realm of AM for electrical machine architecture. Addressing these aspects will not only advance the field but also contribute to the creation of innovative manufacturing strategies and high-performance electrical machine components. By embracing these challenges and embracing collaborative efforts, researchers can usher in an era of unprecedented advancements in AM techniques and their application in electrical machine manufacturing.

6. Conclusions

This paper provides an in-depth exploration of metal additive manufacturing (AM) and its most recent breakthroughs in the production of electrical machines. In the context of electric machines, the rapidly evolving landscape has spurred the adoption of AM as a game-changing enabler. AM's multifaceted capabilities are revolutionizing the very fabric of electric machine components, spanning from magnetic materials to windings, and extending to thermal management.

In the area of core and magnetic materials, AM's impact is palpable through the creation of intricate structures that optimize magnetic flux dynamics. Innovations like 3D-printed cores with advanced shape profiles, tailored to minimize eddy current losses, underscore AM's potential to enhance efficiency while concurrently reducing weight. Moreover, the introduction of self-coating laminations, achieved through controlled atmosphere heat treatment, opens new avenues for both efficient insulation and magnetic performance. Turning our attention to windings, AM's transformative potential shines brightly as it redefines traditional design boundaries. Semi-stranded windings, a pioneering concept merging solid and half-stranded turns, epitomize AM's role in mitigating AC conduction effects at high frequencies. This approach not only addresses performance challenges but also heralds a new era of remarkable weight reduction and enhanced electromagnetic efficiency. By providing design freedom, AM charts a path towards optimized power density and thermal characteristics. In the domain of cooling and thermal management, AM emerges as an indispensable ally in tackling heat dissipation complexities inherent to high-power electric machines. The integration of 3D-printed ceramic heat exchangers directly into electrical machine windings and the creation of intricate liquid cooling channels within housings underscore AM's power to enhance thermal efficiency and power density. Innovations in cooling jacket designs, enabled by AM, usher in improved thermal performance, while simultaneously reducing weight and costs.

To sum up, the integration of Additive Manufacturing revolutionizes the landscape of electric machines and their components. AM empowers designers to transcend the limitations of traditional manufacturing methods, ushering in an era of innovative geometries, enhanced performance, and sustainability. As electric machines continue to drive the future of transportation and energy systems, AM stands as an indispensable tool, poised to shape a new era of electrification with unprecedented efficiency, reliability, and performance.

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