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A comprehensive review on the application of 3D-printed ferromagnetic parts in electric machines

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Abstract
Electric motors are indispensable in present times; more than half of the electricity produced worldwide is consumed in electric motors. There is a variety of configurations and applications, from small single-phase motors in household appliances to 105 MW asynchronous drives for industrial compressors. As the operation requirements of these applications are only growing, researchers continue their search to push the boundaries of the performances of electrical machines. Up until recently, the design of electric machines was bounded to the limitations of conventional manufacturing techniques. But, with the emergence of additive manufacturing of ferromagnetic materials, the design flexibility has been significantly increased. There is no longer the need to limit designs to 2-dimensional structures. This allows researchers to completely revise the design of electric machines in order to improve their performance. Different research groups are currently exploring the novel design opportunities. New ferromagnetic parts are designed, printed and submitted to a number of experimental tests. This paper aims to give a comprehensive review on the latest advancements of the application of 3D-printed ferromagnetic parts in electric machines. Novel proposed designs for the rotor and stator that benefit from additive manufacturing are compared and investigated. This paper includes a discussion of the performance and quality of the actual printed parts. The major challenge is the quality of the parts, this makes that the current generation of printed parts is not yet able to catch up with the capabilities of conventional manufactured machines. Even though there are still hurdles left to take for both the 3D-printing of ferromagnetic material, as the application of it in electrical machines, it is clear that the increased design flexibility can be a major advantage in the development of new electric machines.

Electric motors, ferromagnetic material, additive manufacturing

1. Introduction

Electric motors are a key element in modern world. Their omnipresence gets reflected by the numbers of the consumption of electricity; more than half of the produced electricity worldwide is consumed by electric motor systems. [1] Their application is also widespread, electric motors can be found in small household appliances and large industrial applications. Despite their variety in appearances, the overall tendency is that the performance requirements are becoming more stringent. For example, motors used in electrical vehicles, are targeted to increase their efficiency over a wide speed range and to limit their weight [2]. While the demands on electric motors are growing, the manufacturing techniques did not evolve with the same speed. [3] Conventionally, the rotor and stator of electric drives are made using stacks of electric steel sheets. This implies that current designs are inherently limited to 2-dimensional structures. But, with the development of additive manufacturing (AM) of ferromagnetic materials, novel design opportunities are created. Most obviously, the rotor and stator layout are no longer limited to 2-dimensional structures. Novel complex concepts of electrical machines can be created in order to increase the performance even more. This paper aims to present a comprehensive review on the latest applications of 3D-printed ferromagnetic material components in electrical machines. In the first section, different novel designs of rotor and stator, which are made available by AM, are presented. In the second section, the current hurdles of the use of printed parts in electrical machines are highlighted.

2. Novel designs enabled by additive manufacturing

The design of novel electric machines concepts knows a rather piece-wise approach. Most studies focus on single components, like rotor or stator, that are then combined with a conventional and commercially available set-up. In the following sections, a number of novel designs of rotor and stator, respectively, are listed.

2.1. Rotor

An important trend on the design of rotors, is the reduction of mass. [4] By omitting the volumes of material, that do not contribute to the output power, the weight and material cost of the motor can be reduced. On top, a lower mass of the rotor will allow a more dynamic behaviour of the motor. In [5], a lightweight rotor for a permanent magnet synchronous motor is designed (Figure 1). To reduce the mass and maintain the strength of the rotor, cavities are introduced on the inside of the rotor and filled with lattice structures. The prototype is manufactured using selective laser melting (SLM). Experimental results showed that the inertia of the rotor was drastically decreased, resulting in a 32.2% faster acceleration.

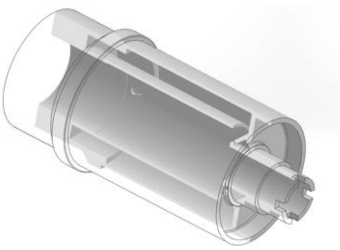

Figure 1. Lightweight rotor, the cavities are filled with lattice structures [5]

A less heuristic approach for the reduction of mass is used in [6]. A 3-dimensional topology optimization is applied on the rotor of a surface-mounted permanent magnet motor (Figure 2). The mass of the rotor could be reduced by more than 50%. The rotor was as well printed by means of SLM, using Fe-6.9%Si alloy. There are no experimental tests performed, but according to the simulations the output torque should be maintained.

Figure 2. Printed rotor, design obtained via topology optimization [6]

Next to reducing the mass of the rotor, AM is applied to increase the performance of the motor. An undesirable common phenomena of electric motors, is the fluctuation of the torque, referred to as torque ripple. Especially switched reluctance motors can experience high ripples. Skewing of the rotor is a common practice to reduce the torque ripple. But, this requires additional processing steps [7]. In [8] it is shown that continuous skewing of the rotor can be introduced using AM without increasing the complexity of the manufacturing process. Next to this, pole shoes are added to the rotor as well. To improve the performance of the rotor, windage losses are reduced by including ribs with a honeycomb structure. The results of the finite element analysis showed a torque ripple of 45%, while the conventional motor obtained 80.8%. Compared to the conventional designs, it is noted that the flux leakage via the ribs is decreased due to the use of the honeycomb structure. A prototype of the rotor is made using selective laser melting (Figure 3). The torque-speed characteristic is measured and mentioned. But there are no further details on measured torque ripples.

Figure 3. Continuously skewed rotor with pole shoes [8]

Another, and more recent, example of continuously skewing of a rotor can be found in [9]. In this paper, the rotor and shaft of the permanent magnet motor are combined in a single, light-weighting hollow part (Figure 4). The rotor is skewed, while the magnets and magnet pockets can be kept axially towards the axis. In this way, common rectangular magnets can be implemented. This part is printed using laser beam melting. Compared machines with similar rated values, the mass of the novel rotor-shaft combination was 52.7% lower, which results in 9.4% faster acceleration from standstill. The cogging torque is reduced by 90%.

Figure 4. Drawing of skewed rotor with rectangular magnet pockets [9]

In [10], a lightweight rotor with an integrated air-cooling system is designed (Figure 5). Similar to the previous mentioned example, the rotor and shaft are combined into one single part. The inner part of this component is filled with lightweight structures. A remarkable adaption of this rotor is the addition of a rotor cooling system. In permanent magnet rotors, heat will be mainly generated near the magnets due to electromagnetic losses. By the implementation of symmetric blade constructions on the inside of the rotor, air gets guided from a small diameter at the axial surface to the centre of the rotor at a larger diameter. The air will then return via the axial direction in between the magnets. A prototype of this rotor is produced using laser beam melting. It is experimentally verified that the temperature of the magnets stayed more than sufficiently below the demagnetization temperature of the magnets.

Figure 5. Lightweight rotor with integrated cooling system [10]

Up till now, the listed studies solely involve printed soft ferromagnetic materials. Nevertheless, in literature, examples of the application of printed hard ferromagnetic material in rotors are found. Ibrahim et al. [11] designed an interior permanent magnet rotor, which consist of layers of soft magnetic composite alternating with permanent magnet material. With this approach, 'islands' of soft magnetic composite can be held together by the permanent magnets. This implies that there are no bridges needed for mechanical connection. According to simulations results, this design results in 17.7% lower losses and 1.4%pt improvement in efficiency operating under the 'under city driving cycle' for hybrid electric vehicles. A prototype was constructed using cold spray additive manufacturing (Figure 6). There were no results reported on experimental verification.

Figure 6. Rotor with first layer of soft magnetic composite and hard ferromagnetic material [11]

In [12], a permanent magnet rotor with magnets mounted on the surface is designed. Three forms of magnets are compared; a conventional rectangular magnet, conventional skewed magnets and novel designed sinusoid-petal shaped magnets. All rotors are produced using cold-spray AM (Figure 7). Experimental tests showed a significant lower torque ripple for the sinusoidal-petal shape magnets, 9.31% compared to 19.27% and 18.68% for the rectangular and skewed magnets, respectively. On the other hand, the average torque of the novel design is reduced by more than 10%. It is important to note, that the simulation and experimental results do not fully match, as the edges were not fully magnetized.

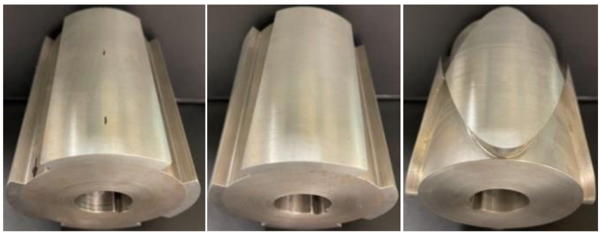

Figure 7. Rotors with printed permanent magnets. From left to right; rectangular magnets, skewed magnets and sinusoid-petal shaped magnets [12]

2.2. Stator

A remarkable novel design is the hybrid-field traction motor of Kirshnasamy et al. [13] The authors created a motor with an hour-glass shaped air gap, which maximizes the available volume for the magnetic flux flow (Figure 8). The rotor is made using solid steel with conventional magnets mounted on the surface. The stator is manufactured using spray-formed AM. According to simulations, the power density is 40% higher compared to commercial available permanent magnet motors, even when the lower magnetic permeability is taken into account. A scaled and slotless prototype of the motor is made, but no experimental results are reported.

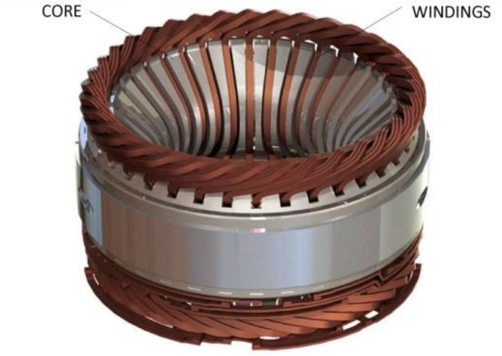

Figure 8. Drawing of stator with hour-glass shaped air gap [13]

In conventional radial electric motors, end windings, which are the part of the windings coming outside of the stator core, are mostly considered waste of space and material. These parts of the winding do not contribute to the development of the output torque, but can practically not be avoided. In [14] a 3D stator with an overhanging structure is designed so that the complete winding can be included into the stator. The performance of the fully printed 3D stator is lower compared to its conventionally made counterpart. This is caused by the lower magnetic permeability of the printed material. As a compromise, a stator is designed that combines conventional laminated steel in the middle of the stator with printed 'end-caps'. In this way, a 3D stator with improved magnetic properties can be obtained. The end-caps of this hybrid stator were printed using selective laser melting and soft magnetic composite (Figure 9). There was a deviation found between simulation and experimental results due to the tolerance during the printing process, which led to air-gaps and thus increased reluctance.

Figure 9. End-caps of SMC [14]

3. Challenges

Additive manufacturing of ferromagnetic materials is not yet a fully matured technology. Currently, ferromagnetic printed components are printed on a small scale and limited number for scientific validation and prototyping. Several authors have succeeds in effectively printing and testing various prototypes. But for the application on a larger scale, there are still opportunities left for improvement from electromagnetic point of view. Two important drawbacks for the use of printed components in electric machines are discussed below.

3.1. Magnetic properties

An important limitation of additive manufacturing of ferromagnetic materials are the current electromagnetic properties of the material. The magnetic properties of printed material are, among others, influenced by the raw materials selection and the printing process. [15] In practice, the permeability does not yet match those of the conventional steel. [16] On the other hand, the advantage of the increased manufacturability of complex structures should not be underestimated. In the earlier mentioned hybrid stator [13], the lesser magnetic properties of the material of the novel concept are taken into account. And still, the novel motor shows improved performance compared to the conventional one.

3.2. Eddy Currents

A common issue with the current generation of printed parts is the increased amount of eddy current losses. Eddy currents are circulating currents induced by the time changing magnetic field. These losses are the main reason why conventional electric machine are laminated. The insulation layer between the steel sheets disrupts, and thus minimizes, the paths for current circulation. In contrast, the current generation of printed ferromagnetic components are often solid parts made out of a single material. This means that eddy currents have free path, which will only increase the losses and deteriorate the efficiency. An evident solution for this issue, would be the application of multi-material printing, in order to mimic the conventional laminated sheets. But, multi-material printing of ferromagnetic and insulating material increases the complexity of the manufacturing process significantly, making it still a challenging task today.

Another possible solution for this increased eddy current in single material parts is the implementation of 'cuts' or 'grooves' on the surface of the component. In [17] various manners of grooving, like peripheral, axial grooving, are investigated. It was shown that iron losses can be substantially reduced, one groove per four millimetres of axial length decreased the loss energy by 25%. Nevertheless, as the grooves cannot be infinitely thin in practice, the useful rotor area is decreased, with an increasing number of cuts. This will negatively impact the performance of the motor. The principle of grooving got applied on the earlier mentioned rotor of Bieber et al. For the manufacturing of this prototype, support structures were added to avoid deformation due to residual stresses in the grooves. It is as well mentioned that bridging defects, locations where the walls of the cuts are connected, were present. The impact of these defects could not be calculated due to the small dimensions.

A reduction of eddy current losses could as well be induced by using material with a higher silicon content. This will increase the electrical resistivity of the material seriously. Material with high silicon content is often difficult to use with traditional manufacturing techniques due to its brittle nature. [6] Another type of material that will result in lower eddy current losses is soft magnetic composite. It consists of individual iron particles with an insulation layer. But, they do as well have poor mechanical properties, making processing using conventional techniques difficult. [16]

4. Conclusion

The design flexibility of electric machines is significantly increased by the introduction of additive manufacturing in the field of electric motor design. This paper aims to present a comprehensive review on how this extended design freedom is currently exploited. There is a wide variety of novel concepts. A number of them are successfully printed and experimentally validated. In other cases, experimental validation is lacking or limited results are mentioned. The second part of the paper, briefly covers two drawbacks of the application of printed ferromagnetic material, namely the inferior magnetic properties and the complex mitigation of eddy current losses for single-material printing. But even though the technique of additive manufacturing of ferromagnetic materials and its applications are not fully matured and developed yet, the new proposed concepts show promising results.

Acknowledgment

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