Development and Testing of Soft Magnetic Rotor for a Switched Reluctance Motor Built Through Additive Manufacturing Technology

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Abstract – **Additive manufacturing, commonly known as 3D printing, is an emerging technology that is gaining considerable research interest in recent years. In particular, metal printing methodologies might be successfully employed in developing lightweight and complex geometry components for electrical machines. In this paper, a soft magnetic material with a high content of silicon (i.e. ≈5%w.t.) has been characterized and its properties have been determined. The obtained material has been then used for 3D printing a salient, 8 pole rotor through selective laser melting. Finally, the manufactured rotor has been placed inside the laminated stator of a switched reluctance machine and its performance has been assessed comprehensive experimental tests. The collected results confirmed the viability of additive manufacturing technology in the electrical machine field.**

Index Terms—**Additive Manufacturing, 3D Printing, SLM, Electrification, Electrical Machines, Switched Reluctance**

I. Introduction

Future electrification roadmaps [1, 2], leading to the progressive de-carbonization of transportation platforms, can only be met through the introduction and exploration of game-changing technologies and unconventional design methodologies [3] for drive-train components [4, 5]. The Electrical Machine (EM) represents the key element in both hybrid / electric road vehicles as well as aircraft [6]. Whilst recent innovations in terms of materials optimization [7] and sizing tools have brought to considerable advancements in terms of efficiency, there is still a long way to go for meeting challenging power density targets [8, 9]. The potential for improvement lies on each and every component within a machine, although it is perceived that key enablers will be the clear understanding of aging phenomenology in insulating materials and systems [10-13] and the efficient utilization of advanced manufacturing techniques [14, 15].

In conventional manufacturing, a component is built by a material removing process, which is contrary to Additive Manufacturing (AM) technologies, where a data Computer Aided Design (CAD) is utilized to precisely create geometric structures via layer-by-layer material deposition. AM allows the development of net-shape parts and components featuring complex geometrical features at no extra cost, minimizing the wasted material. The only limits are represented by the resolution of the 3D printing process and the maximum build volume, which is directly related with the printer size.

AM through non-metallic materials (e.g. plastics) is nowadays a well-assessed technique in various branches of engineering. As opposed to traditional manufacturing methods, AM enables the rapid prototyping of newly-designed elements, thus shortening the overall development time-frame of new products. This because the use of pressing / stamping dies, cutting tools, etc., for manufacturing new components is not a requirement in AM processes.

In recent years, AM is progressively gaining popularity within the EM community. Various examples, where AM is employed for the construction of both active and non-active parts for EMs, have been reported in specialized literature [16-22]. A comprehensive and detailed review on the topic is represented by [23].

For what concerns AM of metallic elements, a technique known as Selective Laser Melting (SLM) has the potential to be employed for EM's magnetic parts manufacturing [24, 25]. Whilst SLM-manufactured parts are relatively mature from the structural point of view, new growing research is recently focusing on the optimization of magnetic properties, so that the potential of this technique can be fully exploited in EM design [16, 24].

This work represents a comprehensive study, where a rotor for a Switched Reluctance Machine (SRM) is 3D printed through SLM and fully tested. The presented analysis covers both the physical characterization of the additively-manufactured material, as well as the actual manufacturing of the rotor. The electro-mechanical performance of the SRM employing the 3D printed rotor is then experimentally verified, and the complete torque-speed envelope of the machine is extracted.

II. SLM of Soft Magnetic Material

The stator and rotor cores of industrial EMs are typically manufactured by axially stacking thin sheets (generally < 0.5 mm thickness) of soft silicon-steel alloys (Fe-Si). The silicon content within the alloy has a direct influence on the machine's efficiency, as its addition helps in cutting down eddy current losses, by directly acting on the lamination's

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electrical resistivity. The silicon content, for industrial-grade non-grain oriented electrical steel, lies around 3 to 3.5% w.t., although for high performance applications it can go up-to ≈ 6%. Carbon content in all silicon steels is considerably low, approximately 0.003% w.t., which makes rolling and other fabrication processes easier.

The SLM process produces near-net-shape parts, with densities comparable to the bulk material, by applying a high power laser beam to a layer of metallic powder according to the data contained inside the CAD file of the part to be manufactured. The laser energy fully melts the powder, layer by layer, effectively creating the desired metal parts upon cooling.

Despite its great potential, Fe-Si was not processed via SLM until recently [24, 26] . In these pioneering papers, the authors proved the feasibility of such a powder bed AM process on a high silicon steel, using a substrate plate kept at 200 °C. The samples featured a favorable crystallographic texture and quasi-static magnetic properties very close to those encountered in commercial Fe-Si laminations, after annealing.

Similar work, for iron based soft magnetic materials manufactured via SLM was also presented on Fe-Co alloys. The latter are well known for possessing the highest saturation magnetization among all magnetic materials, making them suitable for a wide range of high performance applications.

In this work, it has been decided to adopt a blend in which pure Fe powder is mixed with a pre-alloyed high silicon steel, for creating a Fe-5w.t.%Si composition. A microscopy enlargement of the resulting powder blend is shown in Fig. 1. The average particle size, measured through laser diffraction, is 36 μm as can be observed in the particle size distribution shown in Fig. 2, while the measured apparent powder density is equal to 7.665 g/cm^3.

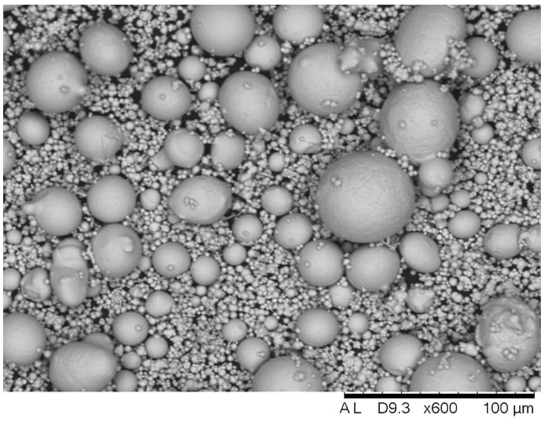

Fig. 1. Morphology of the metallic powder blend obtained through scanning electron microscope.

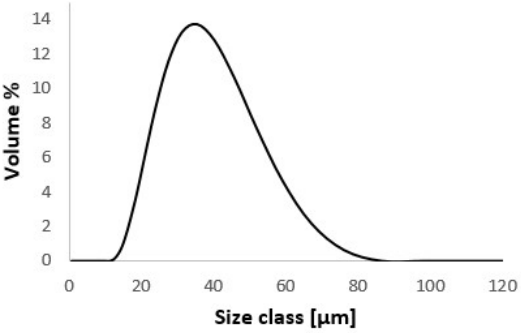

Fig. 2. Particle size distribution of the metallic powder blend.

The SLM process was carried out in argon atmosphere using a Renishaw 3D printing system. In order to minimize the residual stress of the printed parts, the base plate was pre-heated. Fig. 3 shows the build chamber configuration.

A traditional Taguchi approach was applied and the design of experiments (DOE) was used to assess the impact of various processing parameters. After single scan tracks, thin walls, and single layers were built, an optimum processing parameter window was identified, that maximized the density of cube samples. The optimum laser power, resulting from the DOE was found to be 200 W with a spot diameter of 35 μm.

The density was measured on cross-sectioned cubic samples, which are shown in Fig. 4. The samples were processed in order to carry out optical density measurements, which showed a structure with 99.9% density.

Suitable specimens, as those shown in Fig. 5, where used for measuring the material's tensile strength, whose result is reported in Fig. 6.

The electrical resistivity was measured on rectangular bars, using a 4 wire Kelvin testing setup. This test arrangements is generally used when measuring relatively low electrical resistances, and allows to automatically compensate for the testing instruments cables and terminals resistances. The average value of the (bulk) resistivity for the tested material was 104 μΩ·cm.

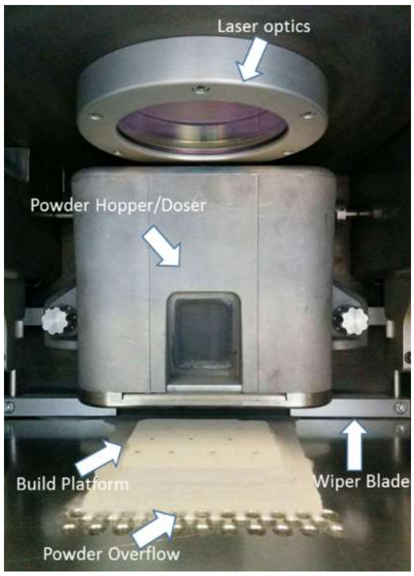

Fig. 3. Build chamber configuration.

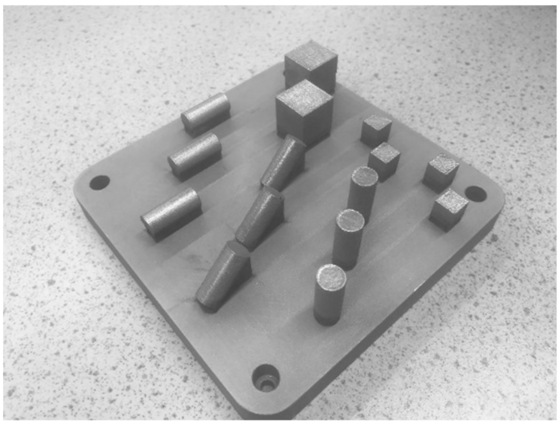

Fig. 4. Samples used for the physical characterization of the 3D printed soft magnetic material.

Fig. 5. Dog-bones-shaped samples used for the mechanical characterization of the additively manufactured soft magnetic material.

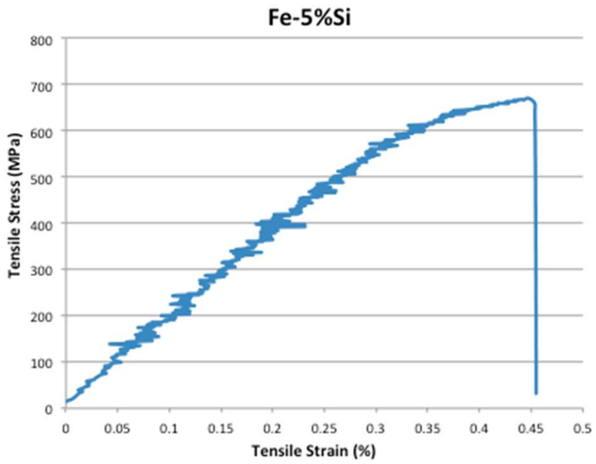

Fig. 6. Experimentally measured stress-strain curve for the additively manufactured soft magnetic material.

III. SRM Rotor Printing

A commercial SRM is used as a benchmark in this study. The machine features an 8-pole rotor and a three-phase, 12-pole stator, as depicted in Fig. 7, where the winding layout is also illustrated. The rated power is 1.25 kW at 600 rpm, whilst the maximum speed is 3500 rpm. The rotor outer diameter is 79.2 mm, and its axial length is 104 mm.

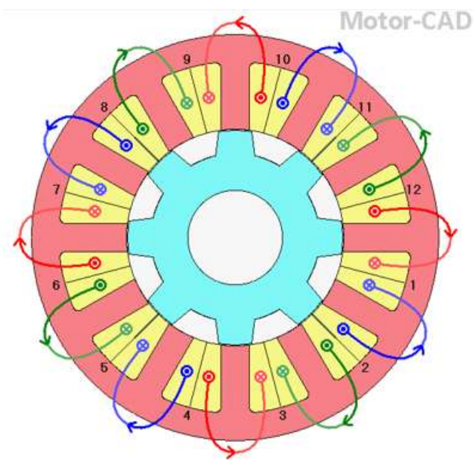

Fig. 7. Cross-sectional view and winding layout of benchmark SRM.

Here it is worth noting that for this initial study it has been purposely decided to analyze a machine with a relatively simple structure. Accordingly, it is expected that the 3D printed rotor will perform poorly in terms of eddy current losses, being essentially a solid version of the original, laminated rotor. However, it should be also pointed out that AM offers the potential of "creating" virtually any desired shape. This is extremely important in EM design, as such a feature can be fully utilized for minimizing unwanted effects, such as noise, vibrations and eddy current losses through multi-objective geometrical optimization techniques. Whilst the creation of intricate geometrical features (e.g. axial slits) might result prohibitive for standard manufacturing techniques (i.e. punching lamination sheets), this does not represent an issue for AM.

The rotor is additively manufactured from the previously discussed Fe-5 wt. % Si material in three segments and assembled in one piece after machining. Such a choice is dictated by manufacturing volume constraints (i.e. build height). The shaft, keyway and two lock rings were machined from mild steel, while the bearings were commercially sourced. All the components for the assembly of the soft magnetic rotor core are shown in Fig. 8, while Fig. 9 shows the fully assembled rotor. Dynamic balancing of the 3D printed rotor was performed up-to 3500 rpm, before assembling it in the commercial stator.

Fig. 8. Main components for the assembly of the additively manufactured soft magnetic rotor core.

Fig. 9. Fully assembled 3D printed SRM rotor.

IV. Electro-Mechanical Experimental Tests

Comprehensive experimental tests have been carried out for verifying the electro-mechanical performance of the SRM with the additively manufactured rotor, in terms of its torque / speed capabilities and efficiency. These results are apprised to those obtained on the benchmark SRM, fitted with a standard, laminated rotor.

The experimental test setup is shown in Fig. 10, where the description of the main component is also illustrated. The SRM's shaft (drive-end) is mechanically coupled to a load machine – namely a high power induction motor – through a torque-meter. A power analyzer is used for measuring the a) instantaneous, b) average, c) apparent, and d) RMS electric power flowing through the SRM's terminals. The instantaneous values of current and voltage are acquired through hall-effect and differential probes respectively, connected to a wide bandwidth oscilloscope.

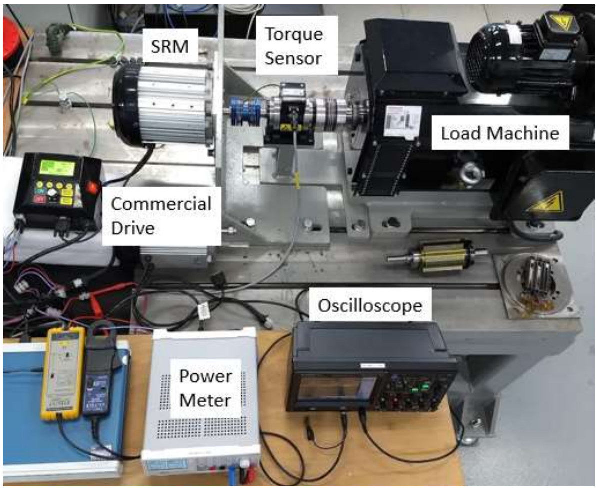

Fig. 10. Test setup for the electro-mechanical characterization of the SRM.

The machine has been tested at several operating conditions (i.e. torque / speed points), so that comprehensive characterization in the whole speed range could be achieved. The measured torque / speed envelope is shown in Fig. 11, where a comparison with the original (laminated) machine's envelope is also performed. In the low speed region (up-to ≈1500 rpm) the 3D printed machine tends to underperform (in terms of torque-producing capability) the benchmark (SRM. As the speed is increased, both configurations show similar performance. The measured electrical quantities, for both machines operating at rated speed (i.e. 600 rpm) are tabulated in Table I. It is clear that the solid, 3D printed rotor suffers from excessive eddy-current losses, causing an efficiency drop, as opposed to the standard laminated configuration.

The instantaneous current and voltage, measured in the time-domain, are shown in Fig. 12 and Fig. 13 for benchmark and 3D printed SRM respectively. The activation of the current hysteresis control can be easily noted for the laminated motor. In other words, the applied voltage is "chopped" with the purpose of maintaining the current within a pre-determined hysteresis band. On the contrary, such a chopping action is not detectable in the 3D SRM, where the power converter seems to have saturated.

Since a commercial drive is adopted for both machines, it was not possible to actually modify the control strategy (e.g. turn-on and turn-off angles). The latter, whilst being optimized for the benchmark, laminated SRM, is likely to be unsuitable (or not highly efficient) for the solid rotor machine.

Starting from the measured voltage and current waveforms, it is possible to compute the machines' (per-phase) instantaneous power, as done in Fig. 14 and 15 for benchmark and 3D machine respectively, where active, apparent and mechanical power are also reported for completeness. The 3D printed machine requires a larger apparent power, and shows a reduced efficiency, because of the higher rotor losses. As the machine speed is increased, the machine tends to perform better (in terms of efficiency), peaking at 65 %, as opposed to 47 % at base speed, as can be easily observed by calculating the ratio between active electric power and mechanical power in Fig. 16.

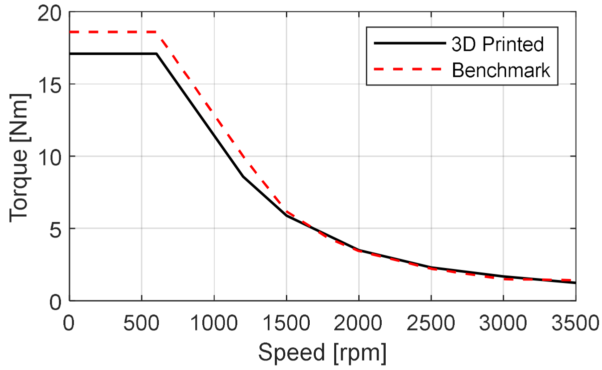

Fig. 11. Measured torque – speed envelope for the 3D printed and benchmark SRM.

TABLE I
MEASURED QUANTITIES AT BASE SPEED

Measured quantities	Benchmark SRM	3DP-SRM
Mechanical Power	1170 W	1020 W
Electric Power	1995 W	2130 W
Average phase current	3.27 A	3.31 W
RMS phase current	4.11 A	4.17 A

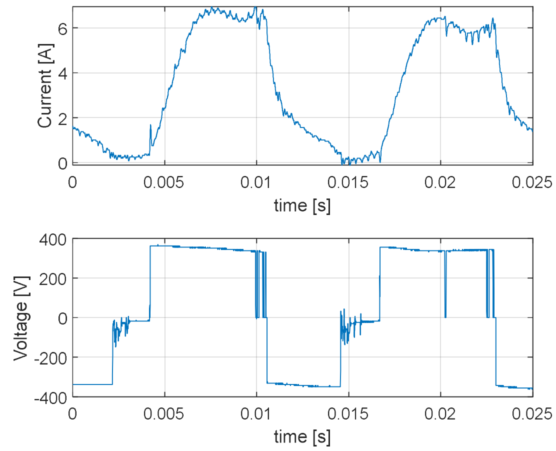

Fig. 12. Voltage and current for the benchmark SRM at base speed and rated torque.

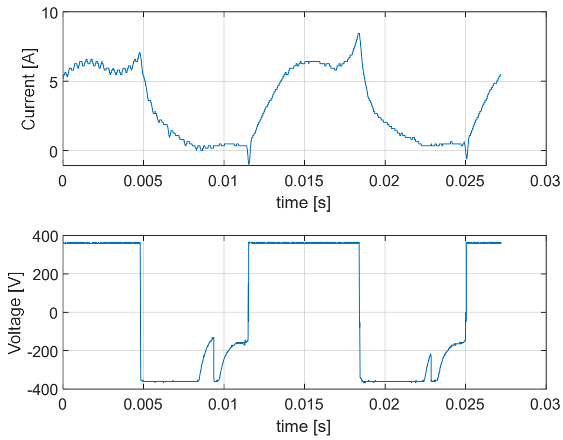

Fig. 13. Voltage and current for the 3D printed SRM at base speed and rated torque.

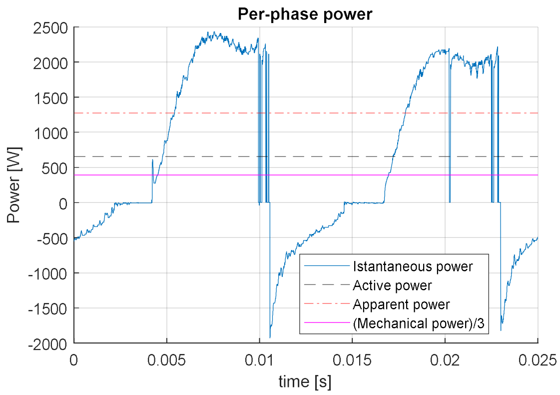

Fig. 14. Instantaneous power for the benchmark SRM at base speed and rated torque.

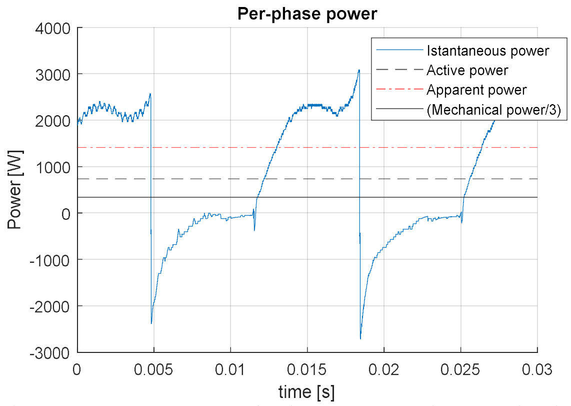

Fig. 15. Instantaneous power for the 3DP-SRM at base speed and rated torque.

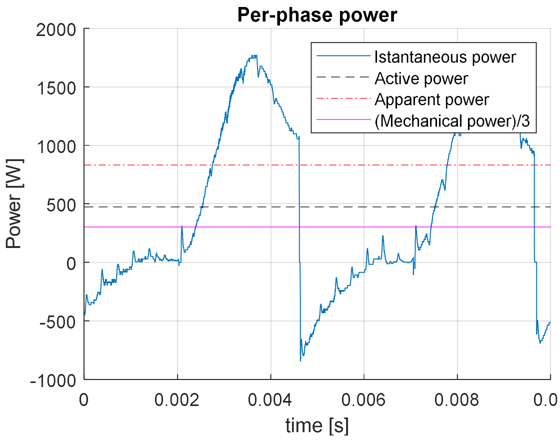

Fig. 16. Instantaneous power for the 3DP-SRM at 2.5 times the base speed.

V. Conclusions

Additive manufacturing for electrical machines' parts and components is a widely investigated topic in recent literature. Despite this popularity, only a limited number of research articles provide a comprehensive, experiment-based investigation of active, rotating parts for electric motors. This paper tries to fits within this research framework, by providing an initial investigation able to show the potentialities of additively manufactured soft magnetic elements for rotating machines.

A soft magnetic rotor core for a switched reluctance machine has been manufactured through selective laser melting, and tested by relying on a commercial platform (i.e. a standard, laminated stator core and an industrial drive).

From the obtained test results it is clear that there are wide margins for performance improvement, mainly in terms of efficiency. Thus, future work will try to address the criticality of excessive iron losses in the solid rotor structure, by including geometrical features, able to cut-down the (currently) large eddy current paths. Further research will also focus on the material development side, by investigating different metal powder mixes and processing settings, with the objective of improving the material's magnetic performance.

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