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Electrical Resistivity of Additively Manufactured Silicon Steel for Electrical Machine Fabrication

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***Abstract*—Additive manufacturing, commonly labeled as 3D printing is an essential component of the next industrial revolution, enabling both unprecedented fabrication freedom and streamlined production and logistics. Traditionally, the electrical machine cores are stacked from varnished soft magnetic laminations, which deliver reduced eddy and hysteresis losses during machine operation. Presently, dedicated metal printing platforms can produce industrial grade homo-material metal components, promoting the fabrication of machines with highly complex topologies, but also increasing the eddy current induced in these components, due to lack of laminated structure. In this paper, we present experimental resistivity measurement results of 3% and 6.5% silicon content steel fabricated with selective laser melting.**

Keywords*—*additive manufacturing, electrical machines, electrical resistivity, selective laser melting

I. INTRODUCTION

Additive Manufacturing (AM) has been proposed to open a new epoch in the electrical machine (EM) design – as it can finally be elevated above the constraints of 2D laminations. Previously, different machines with powder metallurgy cores have been shown to benefit from three-dimensional flux paths: such as claw pole or pancake motors or designs involved in transverse flux. [1] These designs can also be realized with AM, additionally with more refined geometries. The main advantage of 3D printing lies in its capacity for realizing finite walls (up to 60 µm) and achieving partially hollow structures: improving motor cooling capacity, moment of inertia and material efficiency [2]. Coupling these possibilities with the industrial level capacity of AM platforms and topology optimization capabilities of current computational systems, we finally have a case at pushing 3D machine designs into mainstream.

Up to date, the complete fabrication of an electrical machine with AM, without any assembly or post-processing during or after printing, has been unsuccessful. Hybrid methods have been used however for prototyping different machine designs [2]–[5]. 3D printing EMs is a technically demanding procedure, due to tight tolerances for fitting moving parts and their structural makeup of multiple dissimilar materials – printing of which concurrently are not within the capabilities of current AM systems. Additively manufactured EMs require the printing of electromagnets for the controllable generation of magnetic fields, bearings for facilitating rotation of the shaft and soft ferromagnetic flux guides for the amplification of magnetic interactions inside the machine. Traditionally, these soft magnetic flux guides are composed of stacked laminations, which reduce the eddy currents in the structure by the virtue of electrical insulation between the individual laminations (Fig. 1). Despite additive manufacturing enabling the fabrication of parts with complex designs, current AM systems do not allow for parallel printing of both soft magnetic and electrical insulation materials suitable for electrical machines. Thus, for limiting the eddy currents, the geometry of the printed machine must restrict the generation of currents and its material should exhibit high electrical resistivity. This can be achieved through partially hollow layers inside the machine and employment of materials such as high-silicon steel. This paper presents the resistivity measurement results of selective laser melting (SLM) fabricated electrical steel with 3% and 6.5% silicon content.

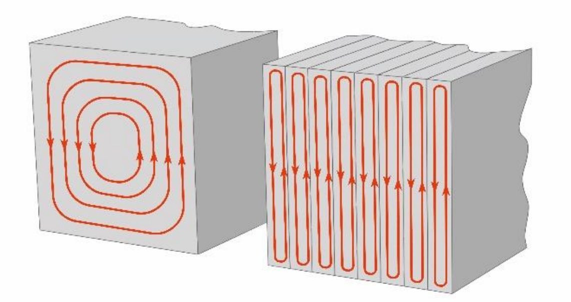

Fig. 1. Reduced eddy currents in soft magnetic flux guides in laminated constructions.

II. SELECTIVE LASER MELTING OF ELECTRICAL STEEL

SLM technology is currently the most widely used AM system to produce functional metallic parts and therefore its capabilities have also been a focal point in the research for additive manufacturing of electrical machines. SLM technology has achieved superiority to traditional production methods when fabricating high-performance parts exhibiting complex geometries. These parts are employed most prominently in automotive, aeronautic or astronautic sectors.

Due to the maturity and availability of SLM technology, it is ideal for prototype fabrication of soft magnetic components of electrical machines. It is not suitable however for multi-material printing or hybrid manufacturing methods: such as component insertion or CNC milling during printing due to its powder-bed based nature. The process of SLM involves melting thin layers of metal powders with a laser beam. After melting each cross-sectional layer, a fresh layer of powder is deposited, and the process is repeated until the 3D part is finished (Fig. 2). Microstructure and consequently the material properties of printed materials typically differ from traditionally fabricated materials. The differences, including defects, can be contributed to the high-energy density applied in the SLM building process, fast heating and cooling rates and the additive character of process [6]. The main defects observed in the SLM processed materials are porosities, cracking, anisotropy and poor surface finish [7].

These defects have been shown to have a significant effect on the mechanical [8], electrical [9] and magnetic properties [10] of the SLM fabricated material.

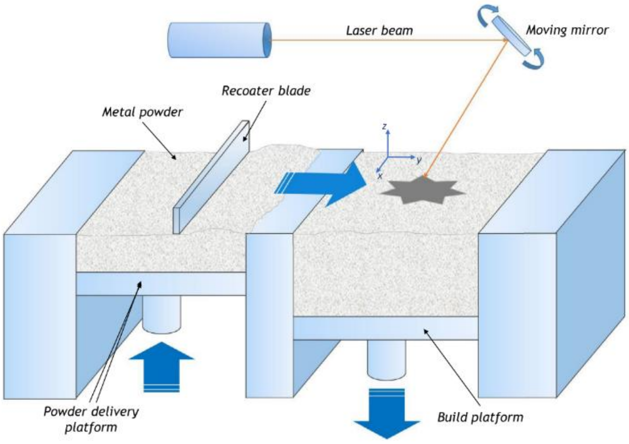

Fig. 2. Selective laser melting build process [11].

Additional silicon content in steel results in increased electrical resistivity and magnetic permeability of the material, however as a trade-off, reducing its printability due to decreased ductility and thermal conductivity. Several research groups have studied printing high-silicon steel [10], [12], [13], confirming the dependency of the printed material quality on the printing parameters employed. The experimental samples presented in this paper are printed with default parameters of the printer for steel. The main aim of the experiment was to create an entry point for further optimization of the soft magnetic component properties suitable for SLM prototyping of novel electrical machine designs. Possible design restrictions can then be determined, and simulations of new machine designs conducted.

III. EXPERIMENTAL SETUP

Industrial desktop 3D printer Realizer SLM 50 was used for printing the samples for the experiment. It is a small-scale SLM printer with a circular workspace of D70×H75 mm, capable of maximum scanning laser power of 120 W and preheating of the baseplate to a temperature of 200 °C. Powder particles size was 45 ± 10 microns for both 3% and 6.5% Si content powders. The printing was conducted in two different inert gas environments, with less than 0.4% oxygen content in the chamber.

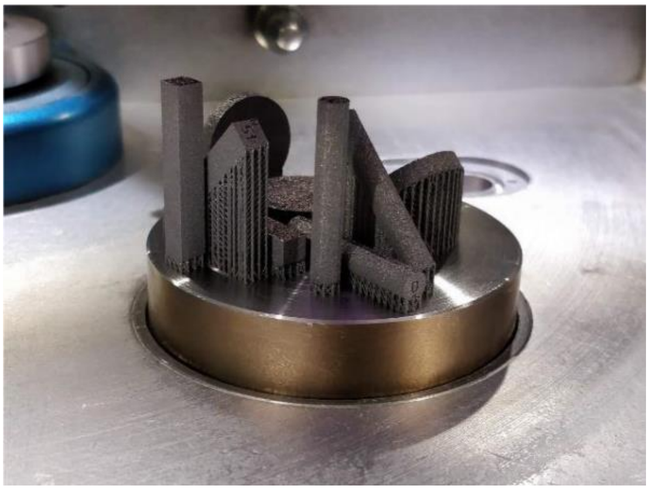

Fig. 3. First set of test samples: 3% Si to Fe printed in argon environment.

Pre-set processing parameters of the printer for steel were employed: parameters of laser power of 72 W, scanning speed of 1 m/s, layer thickness of 35 μm and no pre-heating were selected. Four sets of samples rods were printed with different silicon content and atmospheres: (I) 3% in nitrogen, (I) 3% in argon, (III) 6.5% in nitrogen, (IV) 6.5% in argon. The rods were printed with circular and rectangular cross-sections, at 0°, 45° and 90° angle relative to the printing direction. The diameter for the circular and all the side lengths of the rectangular samples were chosen 5mm and the length of all samples 3 cm. A printed sample set in the Realizer printed is shown on Fig. 3.

Electrical resistivity of a particular conductor material is a measure of how strongly the material opposes the flow of electric current through it. Electrical resistivity (ρ) is proportional to the resistance (R), the cross-sectional area (A) and the length (l) of the object, as expressed in (1).

$$\rho = R\frac{A}{l} \tag{1}$$

Four-probe Kelvin sensing was used for measuring the voltage drop on the test rods, because this technique allows the precise measurement of low resistance values. Test jig was built from 3D printed plastic parts and a set of vices to clamp the test rods between the Kelvin probes. (Fig. 4.) Before measurements the ends of the rods were polished for better contact with the probes and the dimensions of rod cross-sections and lengths were double-checked with a digital caliper. Each rod was tested a total of four times, after each measurement the sample was flipped around in the test stand to reverse the sample. Measurements were conducted with the Dewetron measurement system for its high accuracy. Resistivity was then calculated, averaged and the corresponding standard deviations determined.

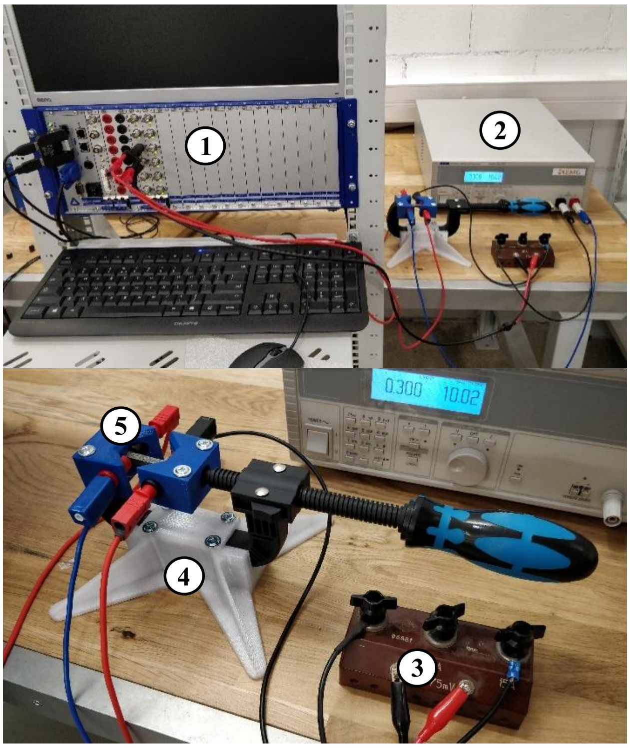

Fig. 4. Experimental setup for resistivity measurements. (1) Dewetron mesurement system, (2) DC power supply, (3) current shunt, (4) Test bench, (5) Test sample.

The calculated resistivity values for all samples are presented on Fig. 5. Because of discovered anisotropy of resistivity for the 6.5% silicone content samples, additional tests with an optical microscope were performed. It was discovered that microcracks propagated for all 6.5% silicone content samples perpendicular to the build direction (Fig. 6).

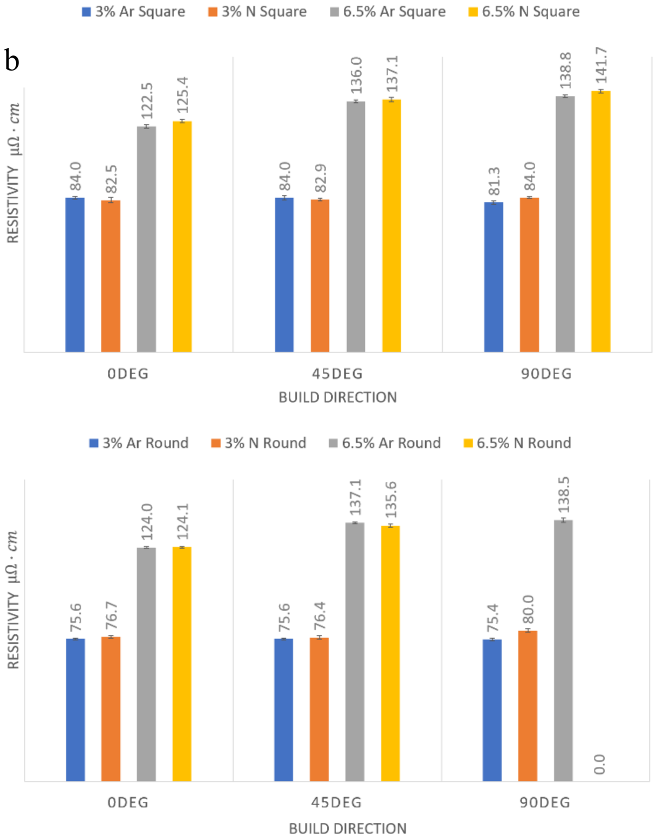

Fig. 5. Experimental results for resistivity measurements. Rectangular cross section (a), circular cross section (b).

IV. EXPERIMENTAL RESULTS AND DISCUSSION

Experimental results reveal invariancy of sample resistivity in relation to the printing environment: the difference in the resistivity of samples printed in argon or nitrogen environment in negatable. According to the literature, the resistivity for commercial 3% and 6.5% Si content electrical steel are approximately 47 and 85 µΩ·cm, respectively. [14] The measured results are in the same magnitude and exhibit similar ratio to each other. For instance, the circular samples of both materials, printed horizontally, exhibit resistivities of approximately 75 and 125 µΩ·cm. High resistivity values alongside their anisotropic nature are likely caused by the high defect content of the printed samples, especially so for 6.5% samples, which experienced extensive cracking during SLM fabrication. The discovered cracks propagated perpendicular to the build direction for all samples which indicates cracking due to high thermal gradient during printing. The cracking resulted in higher resistivity of samples printed at 45° and 90° angle relative to the printing direction compared to horizontally printed samples.

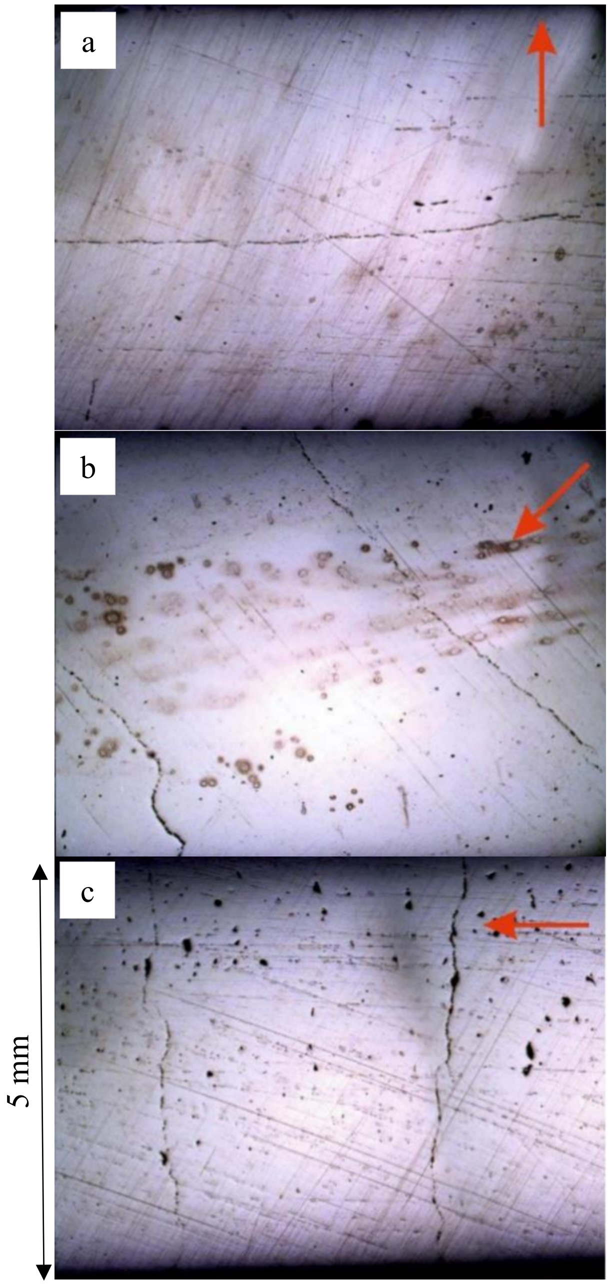

Fig. 6. Optical zoom (25×) of 6.5% silicone content test rods printed in argon environment: printed horizontally (a), at 45° angle (b), at 90° angle (c). Red arrow represents the build direction.

High thermal gradient is more dangerous for 6.5% Si content steel samples due to its inferior thermal conductivity and ductility, leading into cracking between printing layers. The measured resistivity of samples with circular and rectangular cross sections exhibited similar values, with 3% silicon steel displaying slightly lower values. This could be due to improved melting of circular cross sections during printing, resulting in a more homogenous internal structure. As the samples with 3% silicone content exhibited isotropic properties of electrical resistivity, it can be assumed that electrical steel does not experience anisotropic crystal structure during selective laser melting with employed printing parameters. Some authors [9] have experienced anisotropic electrical properties when printing samples from AlSi10Mg, which was caused due to melted microstructure of the printed samples. The authors measured lowest resistivities in the build direction, due to needle-like shapes of aluminum solidified in the build direction. The anisotropic properties were removed after heat-treating the samples, which homogenized their internal structure.

V. CONCLUSIONS

The experimentally measured resistivities for SLM processed 3% and 6.5% Si content samples coincide relatively accurately with theoretical values for the same commercial grade materials. The higher resistivity and anisotropy can be contributed to the defects in the printed material, which were especially prominent for 6.5% Si content samples. The samples with 6.5% Si content exhibited higher resistivity over all the 3% content samples, confirming reduced eddy currents for machines printed from the material.

Before SLM fabricating soft magnetic cores from 6.5% silicone steel, mechanical strength of the printed material must be measured. Mechanical integrity of the printed objects becomes particularly relevant for rotors employed in high speed electrical machines, as even relatively small structural inconsistencies are likely to lead to propagation of cracks in the rotor and fatigue failure in its integrity.

Future work of the project will consist of optimizing the printing properties to achieve the printing of near-fully dense crack-free with minimal printing duration and determining the annealing parameters for achieving the best magnetic, electrical and mechanical properties of printed material. The final goal is to achieve printed material properties suitable for 3D printing novel electrical machines.

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