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Hysteresis Loss Evaluation of Additively Manufactured Soft Magnetic Core

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Abstract – Magnetic properties of additively manufactured soft ferromagnetic nonlaminated material is investigated and its DC magnetic losses determined. Ring samples from 4% silicon content electrical steel powder are prepared with a selective laser melting system. Sample hysteresis losses are determined experimentally with quasi-static measurements at 25 mHz magnetization frequency. Material hysteresis power losses ranged from 0.925 W/kg (1 T, 50 Hz) and 2.85 W/kg (1.5 T, 50 Hz) W/kg. Additionally, the results are compared with hysteresis losses obtained through the extrapolation of losses data measured at higher frequencies of 1, 10, 30 and 50 Hz. Correlation between the quasi-static and extrapolated results is obtained below the knee-point of the material, at 0.8 T and 1 T. The results are compared to other conventional electrical steel and 3D printed materials.

Index Terms-- Electric machines, Manufacturing processes, Magnetic materials, Three-dimensional printing, Iron losses, Annealing

I. INTRODUCTION

DYNAMIC advancements in the additive manufacturing (AM) technologies have stimulated the recent development of novel 3D printed electrical machine (EM) components. Presently, full 3D printing of EM is yet to be achieved, however all the necessary components have successfully been individually fabricated: soft magnetic rotor [1], [2] and stator designs [3], gapped [4] and insulated [5] coils and metal bearings [6]. Majority of the printed soft ferromagnetic components have been fabricated with Selective Laser Melting (SLM) systems in the literature, with the exception of [7] binder jetting (BJ) and [8] Laser Engineered Net Shaping (LENS) technologies. In the case of printed electromechanical devices, the magnetic flux guides are expected to exhibit high saturation magnetization for amplifying the magnetic interactions in the machine air gap and low coercivity, i.e. low induced iron losses induced by the rotating magnetic field. For this reason, electrical steel, Fe-Si, has been selected for study in the paper, as the addition of silicon to iron has been shown to reduce its magnetostriction, magnetic anisotropy and electrical conductivity. In standard electrical machine applications, the soft magnetic guide structures are also segregated into thin laminations, separated by layers of non-conductive varnish, as all metallic soft

magnetic guides are capable electrical conductors, despite the addition of silicon. In SLM prepared soft ferromagnetic components, considerable eddy current losses are present, as the technology is not suitable for the concurrent printing of insulating and magnetic materials, i.e. the realization of laminated internal structure. Several studies do however show the potential of geometrical manipulation and the printing of airgaps into the printed parts for eddy current loss reduction. [9], [10]. In this study, hysteresis loss component of the fully-dense printed sample is determined separately from excess and classical eddy current losses induced in the material. Printed sample material hysteresis curves are determined, and its DC magnetic losses are compared with other commercial and 3D printed soft magnetic materials.

II. SELECTIVE LASER MELTING

SLM is a widely employed powder-bed based additive manufacturing process for rapid prototyping and the fabrication of highly specialized metal parts. The process involves the melting of thin metal powder layers with a focused laser beam. The layer thickness is usually within the range of 20–60 μm and the maximum laser power in the range of 100 – 1000 W. After melting each cross-sectional layer of the printed part, the build platform is lowered, additional powder is supplied on the platform, which then again is melted with the laser beam. The schematic of the printing system is presented on Fig. 1. The technology allows for the realization of three-dimensionally topology optimized parts with simplified logistics and smart material utilization, however its industrial scale application in the future would require considerably faster and more competitively priced SLM systems [11].

Fig. 1. SLM printing system: laser (a), scanning mirrors (b), protective glass (c), re-coater arm (d), build platform with the printed part (e), powder supply opening (f), powder coating (g)

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III. METHODS.

Toroidal samples with a cross-section of 5x5 mm and an outer diameter of 60 mm were printed with a SLM printing system Realizer SLM-50. The gas-atomized powder employed consisted of 4 % Silicon, 1.4 % of Chrome and 94.6% of Iron, exhibiting a mean particle size of 33.5 μm . Printing parameters employed are summarized in Table I.

TABLE I
SUMMARY OF PRINTING PARAMETERS

Parameter	Value
Layer Thickness	35 μm
Hatch Distance	60 μm
Laser Re-Melting	Yes
Laser Power	50 W / 75 W
Scanning Velocity	1 m/s / 0.75 m/s
Energy input	50 J/m / 100 J/m
Laser Lens Focus	12.5
Pre-Heating	200°C
Environment	Argon

The finished printed toroid is shown on Fig. 2 (a), exhibiting approximately 98% relative density, measured by threshold processing of the microscope images. Absolute density of the material was measured 7340 kg/m^3 by Archimedes scale method. Before the magnetic measurements, the toroid was then annealed at 1150° C for one hour after printing for material recrystallization. The post annealed granular structure is shown on Fig. 2 (b). Ring method [12], [13] was used in this study for the measuring the magnetic material properties. Measurements were conducted in the range of 0.4 to 1.5 T, at frequencies of 25 mHz, 1, 10, 30 and 50 Hz. Quasi-static measurements at 25 mHz agree with the European standard EN 60404-4 [14] and higher frequency measurements were completed in accordance to EN 60404-6 [12]. Specific iron losses of the investigated toroid were calculated from the area of the measured hysteresis curves with (1), where T denotes the period of each

magnetization cycle, ρ the material density, B the magnetic flux density in the material and H the magnetic field strength.

$$P_s = \frac{1}{T\rho} \left(\int_0^T H_1 dB_1 - \int_0^T H_2 dB_2 \right) \quad (1)$$

At quasi-static conditions, the total core loss of each magnetization cycle is approximately equal to the hysteresis losses of the material, as the classical eddy current losses are near decayed due to low rate of change of magnetic flux in the material. Classical and excess eddy current losses are present at higher material magnetization frequencies however, where classically the total iron losses are divided into three frequency proportional components of: hysteresis, classical and excess eddy current losses (2) [15].

$$P_s = P_h + P_{ec} + P_{exc} = \quad (2)$$

$$= C_{hys} \hat{B} f + C_{ec} \hat{B}^2 f^2 + C_{exc} \hat{B}^{1.5} f^{1.5}$$

Material hysteresis losses can be separated from classical and excess eddy current losses at higher frequency measurement results by the extrapolation method. [16], [17]. The calculated losses at specific flux density in the material are divided by frequency (3) and plotted in the frequency domain.

$$\frac{P_s}{f} = C_{hyst} \hat{B} + C_{ec} \hat{B}^2 f + C_{exc} \hat{B}^{1.5} f^{0.5} \quad (3)$$

$$\frac{P_s}{f} = a + bf + cf^{0.5}$$

In the work of Plotkowski [10], the effect of the excess losses in 3D printed samples on the data extrapolation was shown to be negligible. When discarding the excess losses term in (3), the fitting of the extrapolation becomes linear (4).

$$\frac{P_s}{f} = af + b \quad (4)$$

The intercept of the linear data fit denotes the specific core losses divided by frequency, representing the losses at 0 Hz – the quasi-static case, which remains constant throughout the frequency domain. Segregated hysteresis losses calculated by the extrapolation method are shown on Fig. 4.

Fig. 2. (a) Printed toroid, (b) Micrograph of the post-annealed printed material grain structure

Fig. 4. Separation of hysteresis losses and eddy current loss.

IV. RESULTS AND DISCUSSION

A. Hysteresis measurements summary

Main challenges and the summary of the data obtained through hysteresis measurements is presented at Fig. 5. First, as seen on Fig. 5 (a), the area and the total core losses of the measured material are strongly dependent on the maximum magnetization of the material, whereas the losses increase in particular beyond the knee-point (approximately 1.1 T in our sample) of the material, which can most likely be contribute to saturation losses. The relatively low saturation magnetization of the sample can most likely be contributed to the pinning effect of intragranular porosities [18], [19] on the large recrystallized (growth from approximately 5 to 500 μm) grains (Fig. 2. b). Main challenges met at quasi-static measurements are shown on Fig. 5 (b-e).

At quasi-static conditions, due to the low voltage induced on the sensing coil, spline fitting and drift correction was applied to current the measurements noise and DC drift. Measured hysteresis loops at 25 mHz, 1 T and 1.5 T are presented on Fig. 5. before and after DC drift correction and spline fitting. At higher frequencies the effect of DC drift and measurement noise were negligible. Magnetization of 1 T in the sample was achieved at magnetic field strength of approximately 200 A/m, whereas 1.5 T was achieved at 16000 A/m, indicating heavy saturation of the material. The coercivity of the sample ranged from 31 A/m (1 T) to 76 A/m (1.5 T) for the quasi-static measurements and 260 A/m (1 T) to 1810 A/m (1.5 T) at 30 Hz. The high coercivity and losses measured at can 30 Hz can be attributed to the excessive eddy currents induced in the nonlaminated bulk toroidal sample.

Fig. 5. (a) Hysteresis curves measured at 30 Hz excitation frequency, B_{max} range of 0.34 - 1.57 T. (b) DC drift present at quasi-static (25 mHz) measurements, $B_{\text{max}}=1.5$ T. (c) Corrected and spline fitted measurements, $B_{\text{max}}=1.5$ T. (d) DC drift present at quasi-static (25 mHz) measurements, $B_{\text{max}}=1$ T. (e) Corrected and spline fitted measurements, $B_{\text{max}}=1$ T

B. Hysteresis losses

Quasi-static measurement results demonstrated polynomial loss behavior in the whole experiment range. The calculated hysteresis losses are presented on Fig. 6 (a), extending from 0.0042 J/kg (0.44 T) to 0.063 J/kg (1.57 T). In practical electrical machine applications at 50 Hz field frequency, the measured quasi-static losses correspond to hysteresis losses of 0.925 W/kg at 1 T and 2.85 W/kg at 1.5 T magnetization. Calculated iron losses increased considerably with the frequency of magnetization, due to the added eddy current loss components in the sample: at 30 Hz the losses ranged from 1.4 W/kg (0.8 T) to 38.7 W/kg (1.5 T).

Fig. 6. Calculated specific core losses of quasi-static (a) and 30 Hz (b) measurements and the polynomial trends in loss behavior as a function of material magnetization.

The experimental quasi-static results were compared with the extrapolation method as shown on Fig. 7. in detail. Four sets of energy losses: at 0.8 T, 1 T, 1.25 T and 1.5 T magnetization, measured at the excitation frequency of 1, 10, 30 and 50 Hz, are presented.

Fig. 7. Energy loss at 1, 1.25 and 1.5 T magnetization and the linear trend in loss behavior as a function of magnetic field frequency.

30 and 50 Hz, are presented. The linear fit and its intercept corresponding to hysteresis losses in the printed material at each specified flux density is shown on the top left of the figure. The comparison of the quasi-static and the extrapolated results is presented in Table II. At lower material magnetization, the hysteresis losses calculated by the extrapolation method show correlation with the experimental quasi-static losses: with a difference of 22% at 0.8 T and 16% at 1 T magnetization. At higher material magnetization the results diverge considerably: 433 % at 1.25 T and 577% at 1.5 T. The considerable divergence suggests the emergence of nonlinear saturation losses component [20], [21] at deep saturation of the material, requiring higher-order fitting.

TABLE II
COMPARISON OF HYSTERESIS LOSSES

Flux Density Method	0.8 T	1 T	1.25 T	1.5 T
Quasi-Static	0.0109	0.0185	0.033	0.057
Extrapolation	0.0138	0.0218	0.143	0.329

The hysteresis power loss components of 0.925 W/kg (1 T, 50 Hz) and 2.85 W/kg (1.5 T, 50 Hz) W/kg are comparable to commercial grade materials and other 3D printed soft ferromagnetic materials from the literature. In the case of non-oriented Fe-Si sheets with 2.5-3.2% Si content, the typical total iron losses have been shown to be in the range of 2.2-2.5 W/kg (1.5 T, 50 Hz) [22]. Additively manufactured 6.9% Fe-Si has been shown to exhibit hysteresis loss of 0.7 W/kg (1 T, 50 Hz) [9]. Slightly higher hysteresis losses measured in this paper can largely contributed to the higher content of impurities in the material such as oxides, carbon, chrome, porosities and cracks, as shown by Brissonneau in 1980 [23].

V. CONCLUSIONS

Methods of quasi-static measurements and data extrapolation are presented in the study for determining the hysteresis losses of SLM fabricated ring samples. Below the knee-point of the measured material, the methods correlate with a difference of 22% (0.8 T) and 16% (1 T). In deep-saturation of the material, the linear extrapolation method was shown to be no longer applicable for the determination of the material hysteresis losses. The measured hysteresis losses are comparable to commercial grade materials and results obtained for 3D printed materials by other authors. Considerably higher eddy current loss components were observed in the 3D printed material at all frequencies other than quasi-static conditions, which can be contributed to its nonlaminated fully dense printed structure.

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VII. BIOGRAPHIES

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