

Topological Optimization for Loss Reduction in Additively Manufactured Soft Magnetic Materials

Jan Kaska¹, David Pánek¹

¹Department of Electrical and Computational Engineering, University of West Bohemia, Pilsen, Czech Republic, kaskaj@fel.zcu.cz

Although metal additive manufacturing has matured into a technology that offers significant design freedom, it is still finding its place in the field of electrical machines. Its great potential lies in printing atypical electrical machines, such as transverse flux motors. Numerous successful attempts to print various soft magnetic materials can be found in the literature; however, high eddy current iron losses remain challenging. While there are several methods to reduce the losses, they often do not respect the shape of the part or the operating frequencies. To address this, we propose using topological optimization methods commonly used together with additive manufacturing in mechanical engineering to find new structures that effectively reduce losses. The resulting designs must then be evaluated not only in terms of specific loss but also with respect to the input power required to achieve the desired magnetic flux density.

Index Terms—Eddy currents, optimization, soft magnetic materials, three-dimensional printing

I. INTRODUCTION

ADDITIVE MANUFACTURING (AM) of metals, especially the laser powder bed fusion (LPBF) method, has already reached a high level of technological maturity. The freedom of additive manufacturing, combined with the power of topological optimization, has been extensively used in mechanical engineering applications. It can also be of great interest in electrical machines, particularly atypical electric motors such as axial or transverse flux machines.

There are many studies where soft magnetic materials are printed, including silicon steels such as FeSi3 or brittle FeSi9 [1], permalloys [2], and amorphous materials [3]. Although these printed materials exhibit good quasi-stationary magnetic properties comparable to conventional materials, the problem is the eddy current iron losses. While it is possible to print thin sheets similar to conventional electrical steels, there is a risk of bending, and the benefits of AM are mostly lost.

II. IRON LOSS REDUCTION METHODS

The simplest methods of reducing losses, such as [4], [5], are based on the concept of electrically insulated sheets, used in conventional electrical machines. While these methods are effective, the minimal technological distance between the individual walls (sheets) results in a low fill factor, i.e., the ratio of magnetic to non-magnetic material in the part's volume. Another issue is the required mechanical connection of the walls, which reduces efficiency.

Another approach is to create porous structures, using, for example, Hilbert curves [6], honeycombs, or deliberate cracking [7]. The problem here is often the inability to remove the remaining powder from the voids. Multimaterial LPBF printers are not widely available, and it is often difficult to combine magnetic and electrical insulating materials due to differing melting temperatures. However, successful attempts can be found [8].

III. TOPOLOGY OPTIMIZATION FOR LOSS REDUCTION

The aim of this paper is to use a topological optimization method to identify suitable topologies that reduce eddy current iron losses. Such topologies could theoretically be more efficient than the shapes used in some studies, as they are tailored specifically to the problem geometry.

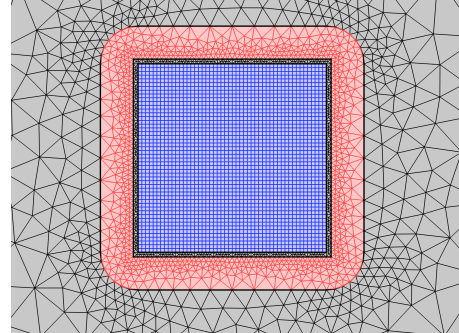


Fig. 1: Toroidal coil geometry with meshed domains.

The toroidal coil core, depicted with a computational mesh in Figure 1, was chosen as the test scenario. The red domain represents the coil, the blue domain represents the optimized iron core, and the grey regions represent air. The optimization task is defined as

$$\arg \min_{\theta} \sum_f w_1 P - w_2 \phi, \quad \text{s.t.} \int \theta dV < c, \quad (1)$$

where f are the considered frequencies, P is the eddy current loss, and ϕ is the magnetic flux through the surface (both scaled to their initial values). The constants w_1 and w_2 set the importance of each goal, so setting $w_1 = 1$ and $w_2 = 0$ means only the losses are minimized, and vice versa, only the flux is maximized. The variable θ is the control parameter of the topology, which ranges from 0 (air) to 1 (iron). The parameter c represents the constraint for the volume fraction

of iron. The finite element model and topological optimization were implemented using COMSOL Multiphysics software.

TABLE I: Experimental setup

Setup	Linearity	Frequency (Hz)	Goal	Constraint
1	Linear	25, 50, 100, 250	P	0.9
2	Linear	25	P	0.9
3	Linear	50	P	0.9
4	Linear	250	P	0.9
5	Linear	25, 50, 100, 250	P	0.8
6	Linear	25, 50, 100, 250	P	0.95
7	Linear	25, 50, 100, 250	$P - \phi$	-
8	Linear	25, 50, 100, 250	$P - 2\phi$	-
9	Linear	25, 50, 100, 250	$P - 4\phi$	-
10	Linear	25, 50, 100, 250	P	0.5
11	Nonlinear 1*	25, 50, 100, 250	P	0.9
12	Nonlinear 2**	25, 50, 100, 250	P	0.9

* Maraging steel BH curve, ** FeSi BH curve

Table I shows 13 experimental setups, which differ in terms of the material's linearity, the frequencies considered, the w_1 and w_2 constants, and the volume fraction constraint. Setup 10 uses vertical stripes as the initial condition for the material distribution, while the initial condition for all other setups is full iron. Two different magnetization curves were used for the nonlinear materials.

IV. RESULTS

The resulting topologies are shown in Figure 2. For all setups, the loss-limiting structures expand from the surface to the center, as the majority of the loss occurs near the surface, due to both the proximity of the coil and the penetration depth. All the results are symmetrical and can be tiled to create larger loss-limiting structures.

A simulation was performed with a magnetization curve, two frequencies (50 and 500 Hz), and an effective magnetic flux density of 1 T to compare the resulting topologies.

The results can be seen in Figure 3, which shows the dependence of the specific loss on the power required to achieve the required flux density. Both loss and power are scaled to the initial solution (full iron). Visually similar geometries (1, 3, 12) are also close together in the plot. It can also be seen that although the optimized geometries have a smaller iron volume ratio than the initial geometry, they require less power to achieve the desired flux density due to the efficient loss reduction.

REFERENCES

- [1] C. Backes, M. Kahlert, M. Vollmer, M. Smaga, T. Niendorf, and T. Beck, "Microstructure and magnetic domain structure of additively manufactured Fe-Si soft magnetic alloys with 3 and 9 wt.-% Si," *Journal of Materials Research and Technology*, vol. 29, pp. 1691–1702, 2024.
- [2] B. Li, W. Zhang, W. Fu, and F. Xuan, "Laser powder bed fusion (L-PBF) 3D printing thin overhang walls of permalloy for a modified honeycomb magnetic-shield structure," *Thin-Walled Structures*, vol. 182, p. 110185, 2023.
- [3] L. Thorsson, M. Unosson, M. T. Pérez-Prado, X. Jin, P. Tiberto, G. Barrera, B. Adam, N. Neuber, A. Ghavimi, M. Frey, et al., "Selective laser melting of a Fe-Si-Cr-BC-based complex-shaped amorphous soft-magnetic electric motor rotor with record dimensions," *Materials & Design*, vol. 215, p. 110483, 2022.
- [4] H. Tiismus, A. Kallaste, A. Belahcen, M. Tarraste, T. Vaimann, A. Rassõlkin, B. Asad, and P. Shams Ghahfarokhi, "AC magnetic loss reduction of SLM processed Fe-Si for additive manufacturing of electrical machines," *Energies*, vol. 14, no. 5, p. 1241, 2021.

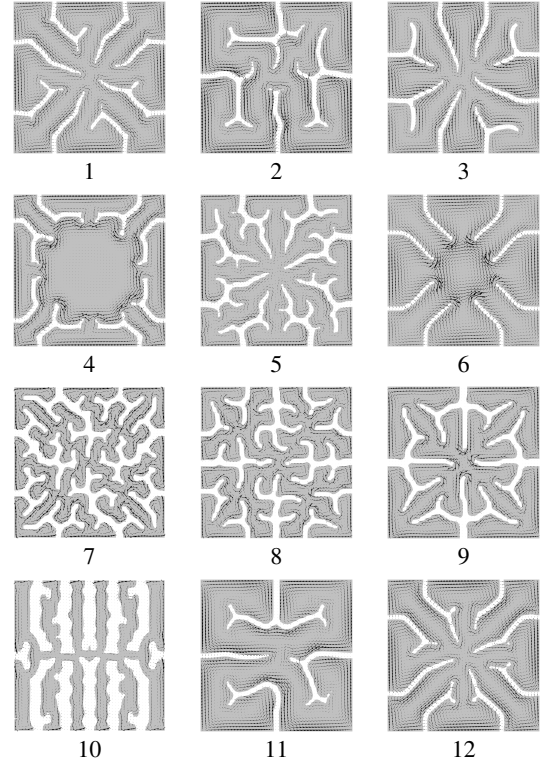


Fig. 2: Resulting topologies with vectors of current density.

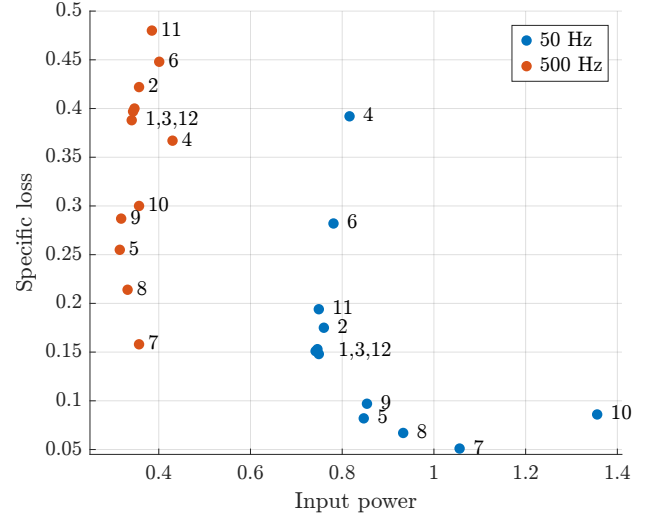


Fig. 3: Specific loss vs power input for 50 Hz and 500 Hz

- [5] G. Stornelli, A. Faba, A. Di Schino, P. Folgarait, M. R. Ridolfi, E. Cardelli, and R. Montanari, "Properties of additively manufactured electric steel powder cores with increased Si content," *Materials*, vol. 14, no. 6, p. 1489, 2021.
- [6] C. Klein, C. May, and M. Nienhaus, "Magnetic Performance of Eddy Current Suppressing Structures in Additive Manufacturing," in *Actuators*, vol. 13, no. 3, p. 94, 2024.
- [7] A. D. Goodall, L. Chechik, R. L. Mitchell, G. W. Jewell, and I. Todd, "Cracking of soft magnetic FeSi to reduce eddy current losses in stator cores," *Additive Manufacturing*, vol. 70, p. 103555, 2023.
- [8] B. Kocsis, I. Hatos, and L. K. Varga, "3D printed metal-insulator layered structure," *Journal of Magnetism and Magnetic Materials*, vol. 563, p. 169994, 2022.