TOPOLOGY OPTIMIZATION OF NON-LINEAR FERRITE CORE FOR INDUCTION HEATING IN INJECTION MOLDING

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Abstract - **Recent progress in additive manufacturing methods has alleviated manufacturing constraints on devices, enabling the fabrication of components that were previously challenging to produce. Topology optimization techniques can leverage these reduced limitations, allowing for an automated design of components. In this article, topology optimization techniques are applied to design an injection molding tool heated by an induction coil. The optimized design shows a better thermal behaviour for the process, compared to the original.**

I. INTRODUCTION

Topology Optimization (TO), originally developed and applied in solid mechanics problems, has been recently taken a growing interest also in many electromagnetic applications, mainly due to the 3D printing advancements and novel additive manufacturing techniques [1, 2]. Since TO deals with the optimal distribution of material in a certain domain, the application of this technique for designing electromagnetic components results in reducing the volume of material used while achieving performances comparable, or even better, than the full volume case.

In this paper TO has been applied to optimize the ferrite surrounding the coil in an induction heated injection molding tool. The key aspect of this optimization is achieving a configuration in which the material placed in the mold cavity reaches the target temperature faster, reducing the cycle time and the overall cost of the process.

II. ELECTRO-THERMAL MODELING

Induction heating occurs through the application of a high-frequency electric current to an inductor, inducing eddy currents within conductive media, thereby resulting in joule losses. The heat generated from these losses is then uniformly distributed throughout the material, following its inherent thermal properties. To perform induction heating studies, two different physics must be coupled: one for the magnetic and one for the thermal problem [3]. The effect of the AC current flowing in the inductor coil can be evaluated through the following equation:

$$\nabla \times [\nu(\nabla \times \boldsymbol{A})] + j\omega\sigma\boldsymbol{A} = -\boldsymbol{J_S}, \qquad (1)$$

where $\boldsymbol{J_S}$ is the electric current density of the inductor coil, $\boldsymbol{A}$ is the magnetic vector potential generated by this current, σ is the electric conductivity of the material, and $\nu(\boldsymbol{B})$ is the magnetic reluctivity. The thermal power related to joule losses produced by eddy currents can be then evaluated as:

$$Q = \rho_e ||J||^2, \qquad (3)$$

where ρ_e is the electric resistivity.

These Joule losses, act as heat sources in the domain Ω, where the heat conduction problem is solved, coupled with heat convection on the boundary as per:

In Ω
$$\rho c \frac{\partial T}{\partial t} = \nabla \cdot (k\nabla T) + Q \qquad (4)$$

On ∂Ω
$$-k\frac{\partial T}{\partial n} = h(T - T_{amb}), \qquad (5)$$

where ρ is the density, c the specific heat and k the thermal conductivity. The coupling between the two physics is performed by using (3) as an input for (4), and then using the temperature distribution obtained in (4) to update the temperature dependent parameters in (1).

III. TOPOLOGY OPTIMIZATION

Topology Optimization (TO) represents an effective technique to find out the optimal distribution of a given amount of material within a given design domain (D), with the purpose of maximising or minimizing a given objective function f.

In this section the Solid Isotropic Material with Penalization (SIMP) approach [2,4] is used to find the optimal distribution of $\nu(\boldsymbol{B})$ within D. Given a partition of D into N_v finite elements (e.g., triangles in 2D or hexahedra in 3D), the TO process assign to each element of the mesh the density ϑ_i, $i = 1, \cdots, N_v$, in such a way that $\nu(\boldsymbol{B})_i$, to be assigned at i^{th} element, is reconstructed as:

$$\nu(\vartheta_i, \boldsymbol{B})_i = \nu_{air} + (\nu(\boldsymbol{B}) - \nu_{air})\vartheta_i^{\alpha} \qquad (6)$$

where, ν_{air} and $\nu(\boldsymbol{B})$ are the reluctivities of air and material respectively. During the TO process, the value of ϑ_i is modified to reach the desired objective and satisfy additional constraints, e.g., on the maximum amount of material.

It is worth mentioning that in the SIMP approach the design variables ϑ_i prior to be used in the Material Interpolation Scheme (MIS) (6) are filtered and projected. Indeed being $0 \leq \vartheta_i \leq 1$, "gray-scales" are generated resulting in unspecified material property values. Filtering and projection are performed to mitigate the "gray-scale" phenomenon [5]. Being the TO solved with a gradient-based approach the Adjoint Variable Method (AVM) as described in [6] is used.

IV. NUMERICAL EXAMPLE

The methodology described in the previous sections has been used for the TO of the ferrite core of an inductor heater for the injection molding process of ABS. The analyzed configuration of the inductor heater is given in Fig. 1, with dimensions specified in mm. The geometry is inspired by those seen in [7].

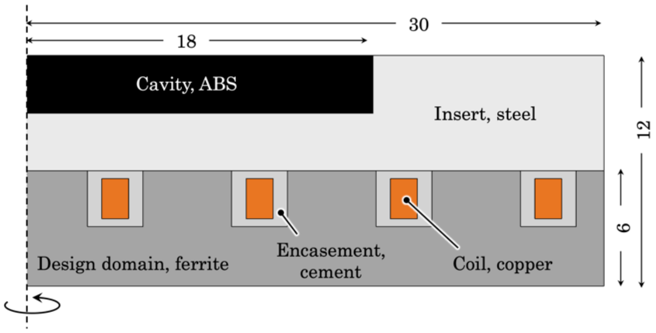

Fig.1. Test case axisymmetric geometry.

The TO aims at maximizing the power density Q within the steel insert in which the ABS is placed. The volume constraint imposed is keeping the final volume of the ferrite V, the design domain, below 70% of the initial volume. The nonlinear B-H curved of Ferrite 3C90 used in the core is shown in Fig. 2.

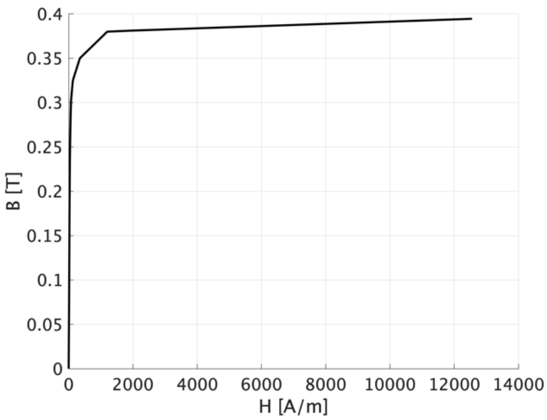

Fig.2. B-H curve of Ferrite 3C90.

The TO is solved within the commercial FEM software COMSOL® Multiphysics, which is also used for the solution of the electro-thermal problem. The magnetic analysis and the TO procedure are performed in the frequency domain at the frequency $f = 22$ kHz, where the coil is supplied with a sinusoidal current of $I = 250$ A. The final topology of the ferrite is illustrated in Fig. 3.

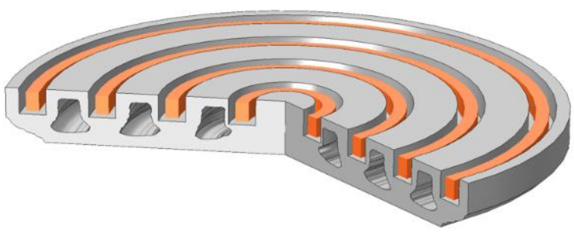

Fig.3. Final topology of the ferrite after the magnetic optimization. The trace of the coil is also reported.

Once the TO process is completed the thermal analysis is performed in transient conditions within the range $t = [0{,}40]$ s, corresponding to the heating part of the cycle process. The heat flux through the air has been considered with a heat transfer coefficient $h = 10$ W/(m^{2}K).

The results of the thermal simulation are illustrated in Fig. 4, where the average, minimum and maximum values of the temperature in the ABS placed in the cavity are reported and compared with the full ferrite volume case. It is worth noting that the optimized ferrite can increase the overall performance of the system.

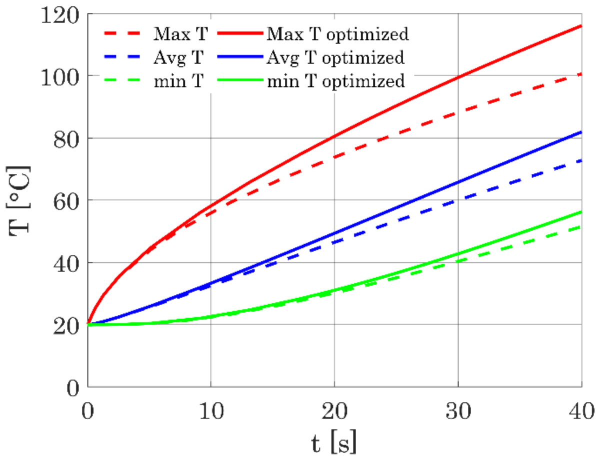

Fig.4. Comparison of temperature transients.

V. CONCLUSIONS

Topology Optimization of a non-linear ferrite core of an induction heating for ABS injection molding tool has been performed. Several advantages of this new configuration can be noticed: the temperature in the cavity increases faster than the full ferrite case. Moreover, reducing the volume of material, results in a significant decrease in material cost and weight, making these optimized tools interesting for industrial applications

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