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A 2D finite element study on the role of material properties on eddy current losses in soft magnetic composites*

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Abstract. The use of soft magnetic composites (SMCs) in electrical engineering applications is growing. SMCs provide an effective alternative to laminated steels because they exhibit a high permeability with low eddy current losses. Losses are a critical feature in the design of electrical machines, and it is necessary to evaluate the role of microstructure and constitutive properties of SMCs during the predesign stage. In this paper we propose a simplified finite element approach to compute eddy current losses in these materials. The computations allow to quantify the role of exciting source and material properties on eddy current losses. This analysis can later be used in the development of homogenization models for SMC.

1 Introduction

Soft magnetic composites (SMCs) can be portrayed as ferromagnetic inclusions surrounded by a dielectric insulating matrix, which considerably cuts down the Joule losses arising from eddy currents (EC) [1]. The characteristics of low EC losses make SMC a prominent alternative to laminated steels, used for instance in motors [2,3]. In order to design electrical machines with SMC as magnetic material, it is essential to have an accurate prediction of losses in these materials. The total losses consist of hysteresis, eddy current and excess losses. We focus on eddy current losses in order to determine the overall conductive behavior of SMC, without considering the hysteresis and excess losses which are related to microscopic detail of magnetization process [4,5]. Several models have been developed to predict the behaviour of such composites [6–8], usually relying on simplifying assumptions or methods since the SMC microstructure is very complex to model. Nevertheless, there is no clear and thorough examination of the relationship between constituent material parameters and effective macroscopic properties of SMC.

Computational electromagnetism has become popular with the emergence of powerful computers and has been developed gradually and steadily with the development of new numerical strategies such as FDTD, finite element method (FEM) is able to solve complex electromagnetic problems provided that the microstructure of the material is fully described. Thus EC losses can be determined. Nevertheless, meshing and calculation on fine granular microstructures, with a typical size much smaller than the device size, bring tremendous numerical difficulties. That is the reason why SMC are often modelled as homogeneous material in a device study.

In this paper, in order to obtain a more simple analysis of the key parameters involved in the EC losses, SMC with fibre inclusion is employed, which can be considered as 2D case by studying a cut plane perpendicular to the fiber length. A perfect insulation between fibres is considered in this study. Therefore, SMC microstructure is studied numerically on a plate structure. Such a simple structure brings symmetries involving a huge simplification in the modelling, leading to a model with reasonable computation cost.

In a first part, the FEM model is described with the geometry simplifications and associated boundary conditions. In a second part, the effect of the magnetic loading on the EC losses is studied. Thirdly, the effect of constitutive properties of the constituents is examined. In the last part, the most influential parameters for SMC behaviour are identified and discussed.

2 Finite element models for SMC

The granular microstructure of SMC usually requires a very fine mesh when FEM is used to model these materials since the grain size (typically 50 μm) is very small compared to the device size (on the order of cm or dm). Various evolutions from standard FEM have been introduced to describe SMC microstructure. Bottauscio and Manzin

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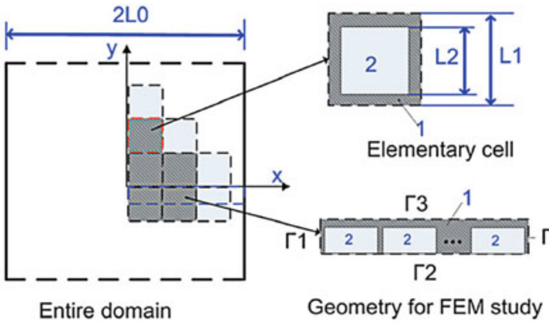

Fig. 1. Periodic microstructure of the composite with two materials 1 (matrix) and 2 (ferromagnetic inclusions) and the geometry used for numerical computation.

exploit MsFEM (Multiscale FEM) and VMS (variational multiscale method) for the eddy current computation [9]. Niyonzima et al. focus on HMM (heterogeneous multiscale method) strategy [10]. These multiscale models, which take advantage of the scale separation, reduce time and memory usage for FEM while maintaining a certain accuracy. However, the computational cost is still high and the transition between fine and coarse scales needs to be handled carefully. Besides, their effects are mainly dedicated to composites exhibiting global eddy currents and usually use constituents with property contrast much lower than realistic SMC in order to maintain numerical stability. In our study, we lay emphasis on realistic SMC with Iron inclusions embedded in an epoxy matrixby extracting the most influential factors on EC losses.

The microstructure is approximated here as a periodic pattern of square-shaped ferromagnetic inclusions embedded in a rectangular dielectric domain. The dimensions of the domain are set as $2L_0$ along x direction and infinite along y direction. Figure 1 gives the representation of this microstructure and of an elementary cell. For symmetry reasons, the FEM study is conducted only on a half-array (half width of the plate) of half cells as shown in Figure 1.

A time-harmonic magnetic field is imposed perpendicularly to the domain (**B** has z direction only). Because of symmetry, Γ_1, Γ_2 and Γ_3 are perfect electric conductor boundaries and Γ_4 belongs to the real boundary of the plate where the magnetic loading is imposed. Therefore the boundary conditions can be written as:

$$\begin{cases} n \times \boldsymbol{E} = 0 \text{ on } \Gamma_1, \Gamma_2, \Gamma_3 \\ \boldsymbol{H} = \{0, 0, H_0\} \text{ on } \Gamma_4 \end{cases}, \tag{1}$$

where H_0 is the magnitude of the exciting magnetic field.

3 Effect of magnetic loading and geometry

It is assumed that all the constitutive properties are linear. The EC losses U are defined as the Joule losses dissipated per unit volume over a wave period:

$$U = \frac{\boldsymbol{E}^* \bar{\bar{\boldsymbol{\sigma}}}\, \boldsymbol{E}}{2f}, \tag{2}$$

Table 1. Constitutive properties of the SMC constituents.

	Inclusions (iron)	Matrix (epoxy)
Conductivity (S/m)	1.12×10^7	1.7×10^{-13}
Relative permeability	4000	1
Relative permittivity	1	9

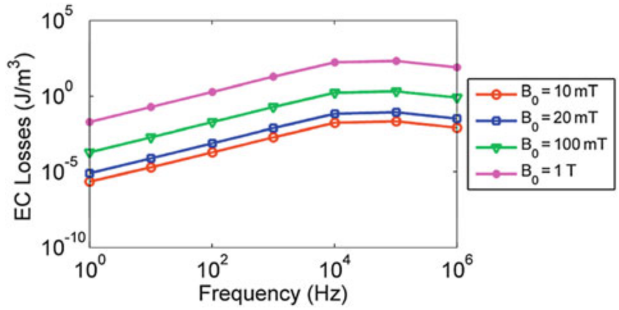

Fig. 2. EC losses along frequency range with different magnetic loadings.

where f is the frequency of the electric field $\boldsymbol{E}$ within the considered domain and $\bar{\bar{\sigma}}$ is the electric conductivity tensor. The operator $\langle\cdot\rangle$ denotes a volume average over the domain and $*$ is conjugate transpose operator over a complex vector.

We consider an SMC for which iron and epoxy are chosen respectively as the inclusion material and insulating matrix. The typical constitutive properties are listed in Table 1. The domain length is $L_0 = 1$ mm and the cell size is $L_1 = 50\ \mu$m.

3.1 Magnetic loading effect on losses

FEM simulations have been carried out to explore the effect of the magnetic loading on EC losses for a filling factor of the inclusions v_2 equal to 77.44% ($L_2 = 44\ \mu$m). We apply four sets of magnetic induction: 10 mT $\sim$ 1 T in magnitude, each with a frequency range of 1–10^6 Hz. The EC losses over the entire domain are plotted in Figure 2.

As expected (because of the assumption of linear constitutive laws), the plot shows that, for a given frequency, the ratio of EC losses for two different magnetic induction is equal to the ratio of quadratic magnitude of input flux density. We can deduce that EC losses are proportional to B_0^2 for the whole frequency range simulated.

$$U \propto B_0^2. \tag{3}$$

Another confirmation is that for low frequency (below 10 kHz here), EC losses are proportional to f. Thus, at low frequency, we obtain:

$$U \propto f. \tag{4}$$

For frequencies higher than 10 kHz, the skin effect makes the EC losses less simple to model with a basic formula.

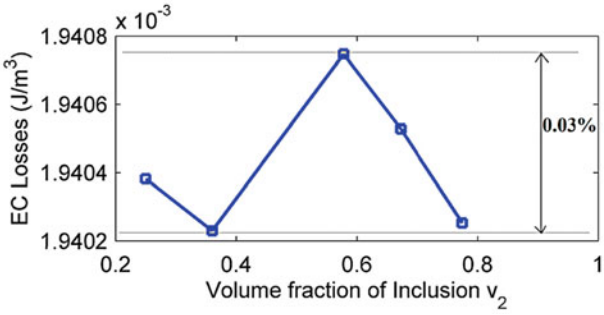

Fig. 3. EC losses for different volume fractions of the inclusions.

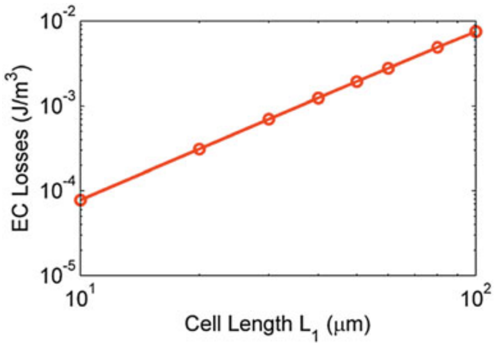

Fig. 4. EC losses with different cell sizes while keeping the volume fraction of the inclusion 77.44%.

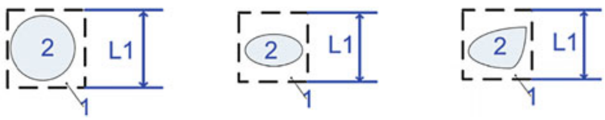

Fig. 5. Three kinds of cell configuration, circle, ellipse and arbitrary shape inclusions.

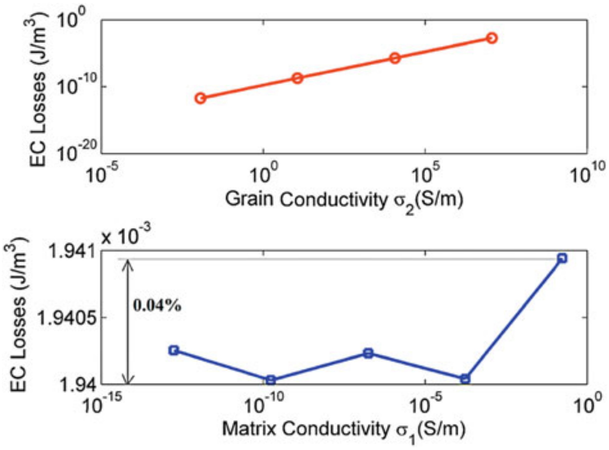

Fig. 6. EC losses as a function of electric conductivity.

3.2 Geometry effect on losses

The effect of volume fraction of the inclusions v_2 in the composite has also been studied. The loading parameters are $B_0 = 10$ mT, $f = 1$ kHz and L_2 varies to identify the effect of volume fraction. The relationship between EC losses and v_2 is shown in Figure 3.

Surprisingly, it is found that the volume fraction of inclusions does not directly impact the EC losses, with only a variation of 0.03%. However, it is noteworthy that the magnetic permeability which is another important characteristic for SMC is strongly dependent on volume fraction. The simulations are based on 2D structure (inclusions are fibres), for which the length is much bigger than the size of the cross section. In this case, the Wiener estimate [11] of magnetic permeability is relevant.

$$\widetilde{\mu} = v_1 * \mu_1 + v_2 * \mu_2. \tag{5}$$

Since $\mu_2 \gg \mu_1$, it can be approximated to $\widetilde{\mu} \approx v_2 * \mu_2$. Therefore, in order to obtain a high effective permeability, it is better to have a volume fraction of inclusions as high as possible.

Considering the cell size, the following simulations have been performed. The length L_1 changes while maintaining constant the volume fraction of the inclusions v_2. The relationship between EC losses and cell length is explored as shown in Figure 4. The losses appear to increase with the cell size in a quadratic way, so that:

$$U \propto L_1^2. \tag{6}$$

For a given shape of inclusions, the eddy current losses are only correlated with the size of the periodic cell. It steers us to design SMCs with cells as small as possible, and since the permeability should be as high as possible, it would be better to have a high filling factor v_2 for the inclusions.

Furthermore, even if the shape of the inclusions is changed into circle, ellipse or any arbitrary shape as produced during the compaction of SMC, shown in Figure 5, so long as the cell size remains the same, the final EC losses stay the same.

In next section, the role of the constitutive properties to the final EC losses is analysed in order to identify the key contributions.

4 Role of the material properties

The magnetic loading is kept unchanged: $B_0 = 10$ mT, $f = 1$ kHz and a fixed structure of cell is used: $v_2 = 77.44\%$ ($L_2 = 44$ μm). A variation of the constitutive properties around their typical values is now considered.

4.1 Conductivity

One parameter is examined at a time, when the conductivity of one part is varied, the conductivity of the other part is kept constant (value given in Tab. 1). First, only the conductivity of the inclusion is investigated. Its variation range is from 1.12×10^{-2} (S/m) to 1.12×10^{7} (S/m). The results are plotted in Figure 6a. Secondly, only the conductivity of matrix is examined, increasing from

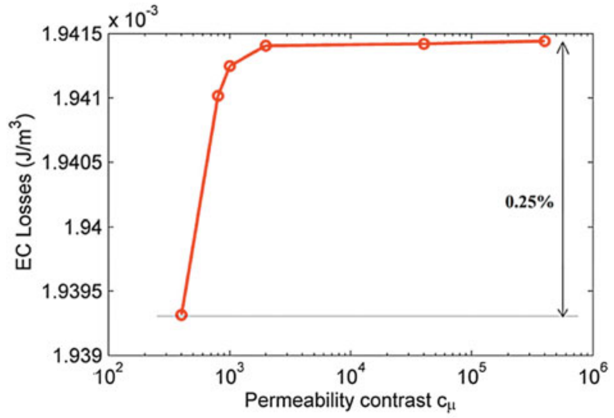

Fig. 7. Eddy current losses with the changes of permeability contrast. An average magnetic flux of 10 mT with frequency $f = 1$ Hz is imposed.

1.7×10^{-13} (S/m) to 1.7×10^{-1} (S/m). Results are given in Figure 6b.

It is found that EC losses are proportional to the conductivity of the inclusion whereas it is not affected by the conductivity of the matrix as shown in Figure 6.

$$U \propto \sigma_2. \tag{7}$$

This can be explained by the huge contrast in conductivity, leading to negligible current density in the matrix. The losses then mainly originate from the inclusions.

4.2 Permeability

In order to investigate the effect of permeability on the losses, simulations have been performed with a constant magnetic loading $B_0 = 10$ mT. The simulations show that the eddy current losses increase with the permeability contrast ($c_\mu = \mu_2/\mu_1$), rather than directly affected by the permeability of each phase (Fig. 7).

When permeability contrast increases or decreases tenfold, the final EC losses varies 0.25% maximum compared to the results retrieved with typical c_μ (4000). If $c_\mu \gg 1$, slight variations of c_μ are found to have almost no effect on the EC losses, because under such conditions, the magnetic flux is nearly totally confined inside the inclusion. From simulations, we obtain that, at low frequency:

$$\frac{B_{2,z}}{B_{1,z}} \approx c_\mu. \tag{8}$$

4.3 Permittivities

As for the dielectric permittivities, because of the low working frequency where the following condition is valid, $\omega\epsilon_2 \ll \sigma_2$, the contribution of permittivity is small in the standard frequency range for electromagnetic applications.

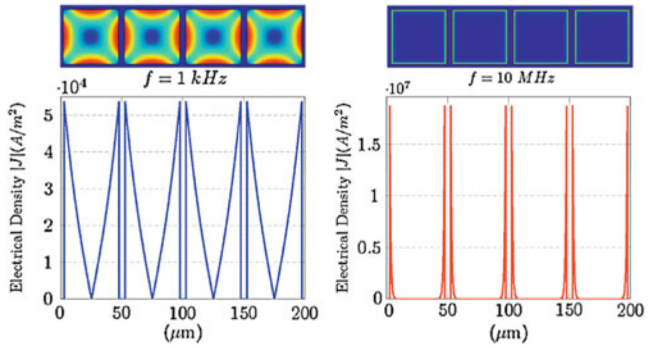

Fig. 8. EC distributions in an SMC microstructure at 1 kHz and 10 MHz.

5 Discussion

With the combination of equations (3)–(4) and (6)–(7), at low frequency (below 10 kHz) the following expression can be determined:

$$U \propto f\sigma_2 B_0^2 L_1^2. \tag{9}$$

5.1 Frequency

Actually, for standard SMC, with high conductivity contrast ($c_\sigma \equiv \sigma_2/\sigma_1 \approx 10^{20}$), EC flows only in the inclusions, as indicated by Figure 8.

And, for low frequency, the linearity between EC losses and frequency holds. However for higher frequency, because of skin effect, as shown in Figure 8, the relationship is not linear anymore. From our simulations, at high frequency where there are only currents flowing along the surface of the inclusion, the relationship between losses and frequency is:

$$U \propto \sqrt{\frac{1}{f}}. \tag{10}$$

5.2 Geometry of the structure

In the previous parts, the whole domain was a plate with an infinite y length. The domain is now a square filled with inclusions with the same inclusion-matrix configuration, except that the domain is constituted of 40×40 cells. In order to fully benefit from symmetry, an eighth of the total domain to carry out FEM calculation is sufficient, as shown in Figure 9. Besides, the eddy current results are plotted also in the same figure with a whole cell zoomed in.

When all the simulations based on the plate geometry are carried out with the square domain, the calculations on this structure give the same results and equation (9) is still valid.

Moreover, as for the arbitrary domain shape of realistic SMCs with inclusions periodically arranged, equation (9) is valid as long as the volume fraction error, arising along

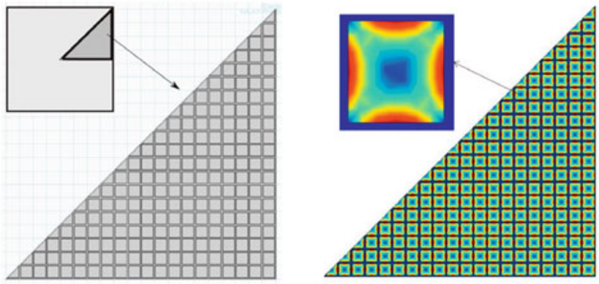

Fig. 9. The structure of a square domain calculated and the eddy current results at frequency $f = 1$ kHz.

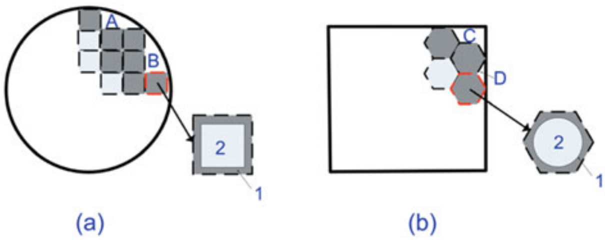

Fig. 10. The volume error arising at the domain boundary.

the domain boundary, is compensated. For example, in Figure 10, there is no enough space to contain an inclusion grain at A, B in (a) and C, D in (b), insulating material is employed to fill the space during our simulations. Thus, the real volume fraction of the whole domain is not the same as calculated from a single element cell.

5.3 Theoretical analysis

The electric field in a homogeneous square resulting from the application of a perpendicular magnetic field can be derived analytically [12]. With the assumption of low frequency ($\omega\epsilon_2 \ll \sigma_2$, below 10 kHz in this case), and because of the high conductivity contrast, the expression of the losses in the periodic cell presented in Figure 1 can be simplified into the sole evaluation of losses inside the inclusion:

$$U_{\text{cell}} = v_2 \frac{9\pi^2}{128} f \sigma_2 B_2^2 L_2^2, \tag{11}$$

where B_2 is the magnitude of the magnetic induction in the inclusion: $B_2 = B_0 \times \mu_2/\widetilde{\mu}$. Since $\mu_2 \gg \mu_1$, equation (11) can be simplified into,

$$U_{\text{cell}} = \frac{9\pi^2}{128} f \sigma_2 B_0^2 L_1^2. \tag{12}$$

Since all cell performs similarly, and since our definition of EC losses involves volume average, this indicates that $U = U_{\text{cell}}$. Thus,

$$U = \frac{9\pi^2}{128} f \sigma_2 B_0^2 L_1^2. \tag{13}$$

Equation (13) theoretically verifies the synthetic equation of (9), in great accordance with our simulations. In designing SMC, it permits us to increase the volume fraction as high as possible so as to obtain a high effective permeability while not introducing bigger EC losses.

In the case of an in-plane magnetic field, the microstructure studied here would bring a heterogeneous field distribution, which would lead to a complex EC distribution impacting the EC losses. Then, the analysis for understanding the key parameters involved in the EC losses would have been very complicated. However, the real case of 3D SMC with granular inclusions actually exhibits this complexity. This is currently a work in progress.

6 Conclusion

In this paper, a study on the influential parameters on EC losses is carried out. EC losses are shown to be proportional to the frequency and square magnitude of exciting magnetic flux density, as well as the square length of the distance between two inclusions. Simulations show that eddy currents are confined inside inclusions while negligible in the matrix. Since the working frequency is low, EC losses are only affected by the conductivity of the inclusions, the permittivity does not have any significant influence. The permeability contrast between the inclusions and the matrix slightly affects the final EC losses since this contrast has an influence on the amount of the magnetic field density flowing within the inclusion. A clear understanding of the most influential parameters on the EC losses will allow the development of efficient homogenization strategies to define the effective properties of SMCs, especially the electric conductivity.

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