A Homogenization Model for Soft Magnetic Composites Considering the Effect of Mechanical Stress

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Soft magnetic composites (SMC) are an alternative to laminated steels for the design of smaller and lighter electromagnetic devices. Such electromagnetic devices might be subjected to significant mechanical stresses that can alter their electromagnetic properties. This article presents a homogenization model that provides estimates for both the nonlinear magnetic response and the eddy current (EC) losses of SMC subjected to a stress state.

***Index Terms*—Eddy current (EC) losses, effective permeability, multiphysics, multi-scale model, nonlinear magnetization.**

I. INTRODUCTION

SOFT magnetic composites (SMC) are designed in such a way that they exhibit low eddy current (EC) losses compared to laminated or bulk ferromagnetic materials. Indeed, EC losses of SMC are cut down because of their particular microstructure, which consists of small ferromagnetic particles (typical size: 10–100 μm) insulated in a dielectric matrix.

During the design stage of electromagnetic devices based on SMC, their behavior is described by the macroscopic model because it is too computationally expensive to consider its heterogeneous nature (the scale separation is large: device size ~10 cm). Several approaches have been developed recently in order to predict the macroscopic magnetic response (linear or nonlinear) of SMC and their EC losses [1]–[3].

However, some devices may be subjected to harsh environments, such as high temperatures and high mechanical stress (for example, inertial stress due to high-speed rotation in electrical machines). Macroscopic models for SMC usually neglect the effect of mechanical stress, but it is necessary to consider it for some applications.

In this article, a homogenization model that can consider the effect of stress on SMC is presented. The model is based on a simplified multi-scale model (SMSM) [4] for representing the magnetoelastic behavior of ferromagnetic particles. The effect of stress on both the macroscopic magnetic response and the EC losses is investigated.

II. HOMOGENIZATION MODEL

A. Ferromagnetic Particles

The model describing the behavior of ferromagnetic particles is an SMSM, which considers the static and lossless magnetoelastic behavior of multiple domains with different magnetization directions [4]. This approach can predict the effect of stress on magnetization and magnetostriction.

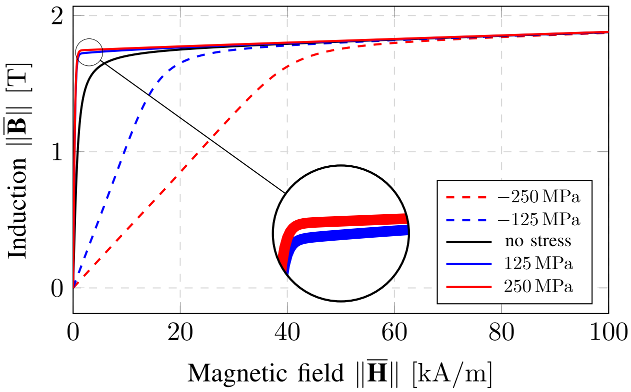

Fig. 1. Iron magnetization curves predicted by the SMSM for different levels of stress (uniaxial aligned with the magnetic field).

Fig. 1 shows the magnetization response predicted by this SMSM for different uniaxial tension-compression stress. The parameters used in the SMSM have been chosen to correspond to iron alloy behavior. This figure shows that stress has a strong influence on the magnetic behavior of ferromagnetic particles.

In this study, the domains in the SMSM are isotropically distributed. The parameters of the SMSM are [5], [6]: initial magnetic susceptibility: 1200, saturation magnetization: 1.4×10^6 A/m, saturation magnetostriction: 1×10^{-5}, Young modulus: 110 GPa, and Poisson ratio: 0.23.

B. Composite Behavior

When applying a macroscopic loading (stress and magnetic field) to the composite, the fields will distribute differently among the different constituents due to the heterogeneity of properties. However, the considered microstructure for SMC

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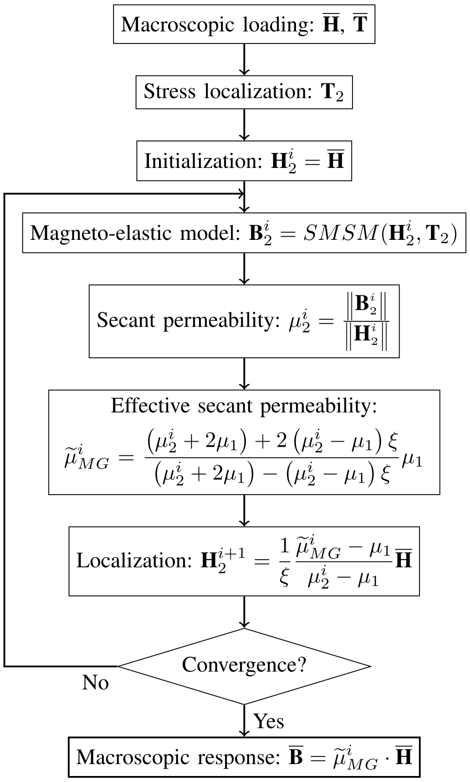


Fig. 2. Algorithm for the nonlinear magnetic homogenization using an uncoupled elastic localization of stress.

(high filling factor ξ of particles perfectly insulated in a dielectric matrix) allows us to assume that the fields in the particles are uniform [2]. In other words, the behavior of the particles can be accurately described by evaluating only the average magnetic field $\mathbf{H}_2$ and the average stress $\mathbf{T}_2$ in the particles (index 1 refers to the insulating matrix, and index 2 refers to the ferromagnetic particles) localized from the macroscopic loadings $\overline{\mathbf{H}}$ and $\overline{\mathbf{T}}$. Assuming that the magnetostriction is relatively small, the problem can be simplified and treated with a weak coupling approach. First, the stress will be localized in the particles using uncoupled localization operators. Then, the magnetic problem will be treated with an iterative approach (due to the nonlinearity of magnetic behavior) in an uncoupled manner too (with constant stress in the particle).

The iterative algorithm is shown in Fig. 2.

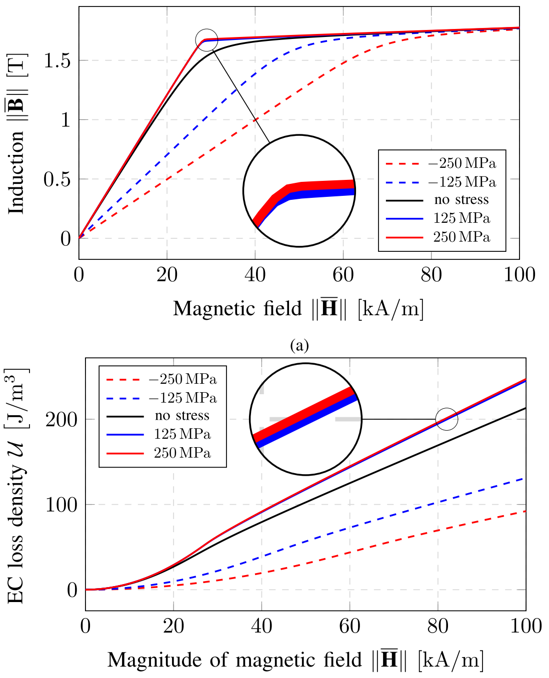
The dielectric matrix used in this study is epoxy with the corresponding properties (purely uncoupled behavior): relative permeability: 1, Young modulus: 3.5 GPa, and Poisson ratio: 0.32.

C. EC Losses Estimate

From the magnetic homogenization, the time-varying magnetic induction $\mathbf{B}_2(t)$ in the particles can be obtained when a sinusoidal magnetic field is applied to the composite.

With the simplifying assumption that the particles have cubic shapes, the EC loss density $\mathcal{U}_{\text{homog}}$ of the composite can be retrieved from $\mathbf{B}_2(t)$ with [2]

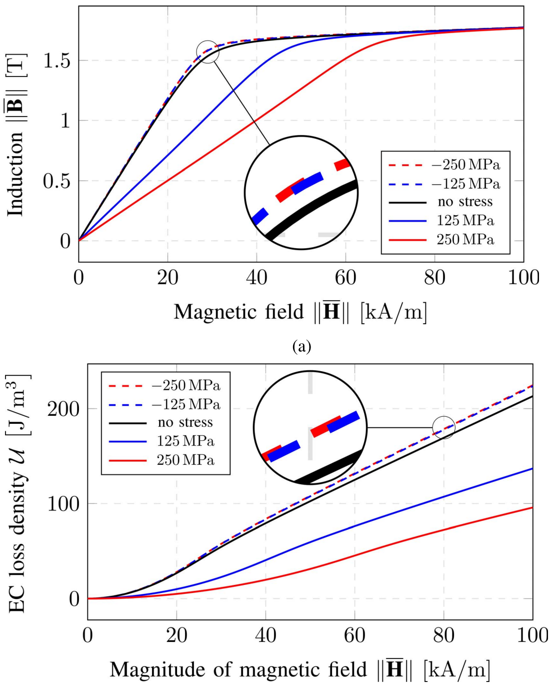
$$\mathcal{U}_{\text{homog}} = \frac{9\xi\sigma L^2}{64}\int_0^T \left(\frac{d\mathbf{B}_2}{dt}\right)^2 dt \tag{1}$$



(a)

(b)

Fig. 3. Homogenization estimates for SMC: (a) magnetization curves and (b) EC loss density. Different static uniaxial stresses aligned with the magnetic field are considered. The magnetic loading is an imposed sinusoidal magnetic field (frequency: 1 kHz and magnitude: $\|\overline{\mathbf{H}}\|$).

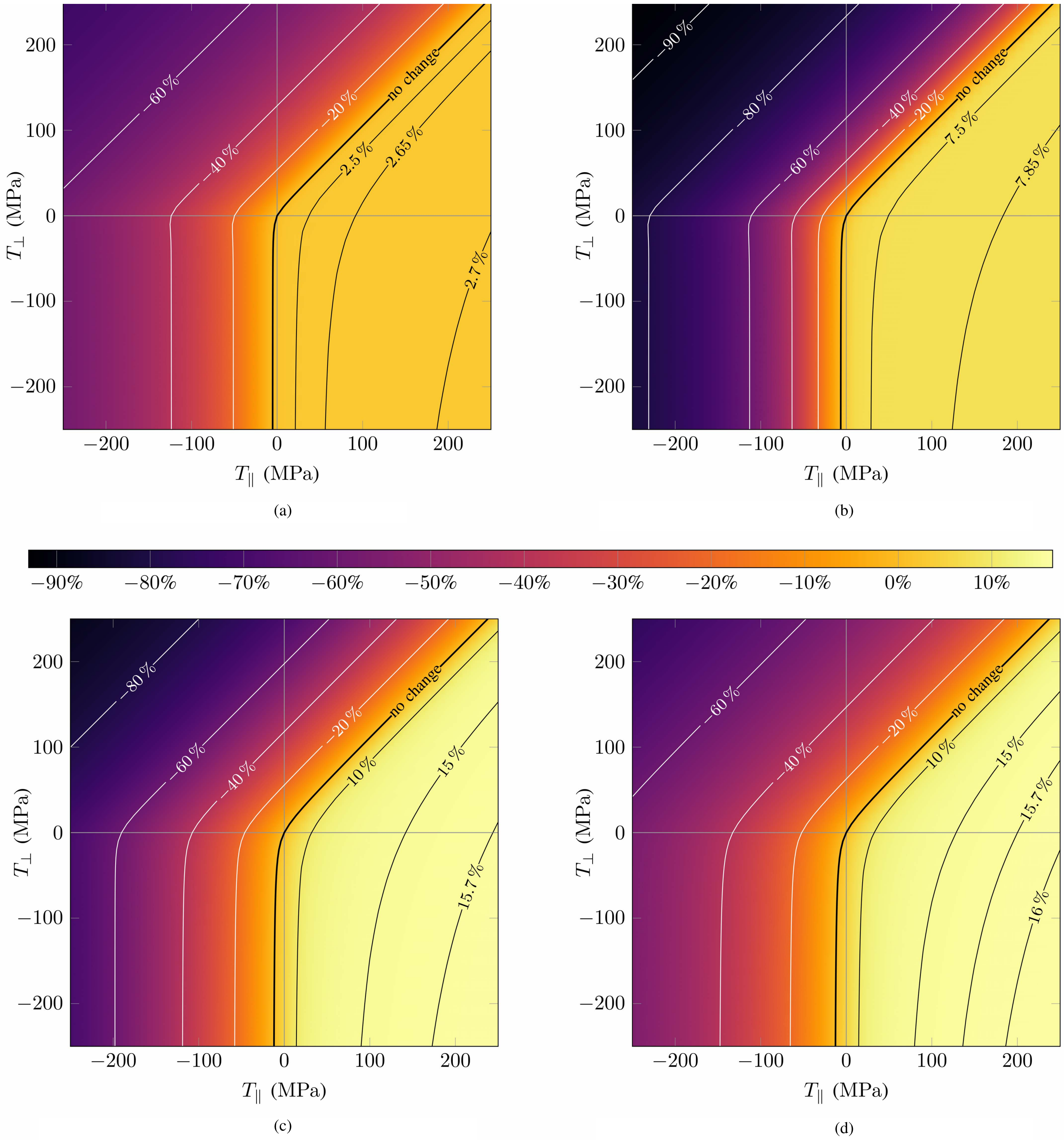


(a)

(b)

Fig. 4. Homogenization estimates for SMC: (a) magnetization curves and (b) EC loss density. Different static uniaxial stresses perpendicular to the magnetic field are considered. The magnetic loading is an imposed sinusoidal magnetic field (frequency: 1 kHz and magnitude: $\|\overline{\mathbf{H}}\|$).

with L being the size of the cubic particles and σ being the electrical conductivity of the particles. In this study, the parameters are [7]: size L is 50 μm, volume fraction ξ is 94.11%, and electrical conductivity σ is 1.12×10^7 S/m.



(a)

(b)

(c)

(d)

Fig. 5. (a) Predicted relative effect of static biaxial stresses on the initial permeability and (b)–(d) EC losses for different magnetic field magnitudes of SMC. The plotted data are computed relative to the case when no stress is applied to the SMC (center of the figures). The magnetic loading is an imposed sinusoidal magnetic field (frequency: 1 kHz) with a magnitude $\|\overline{\mathbf{H}}\|$.

III. RESULTS

A. Uniaxial Stresses

Fig. 3 shows the macroscopic magnetization curves predicted by the homogenization model, as well as the level of EC losses, when static uniaxial stress aligned with a sinusoidal magnetic field at 1 kHz is applied to the SMC.

It can be seen that the homogenization model predicts a high sensitivity to uniaxial parallel compressive stress, while uniaxial parallel tensile stresses have much less impact. For example, a parameter of interest could be the initial permeability (linear part from the origin on magnetization curves). It appears that the initial permeability greatly decreases with compressive stresses, while tensile stresses barely modify it. The same conclusion can be drawn for the EC losses, which is expected, since decreasing the effective permeability also means a decrease of the magnetic induction in the particles, leading to EC in lower magnitudes. It must be noted here that the numerical tests are performed under sinusoidal waveform for $\overline{\mathbf{H}}$ (and not for $\overline{\mathbf{B}}$).

Fig. 4 shows the macroscopic magnetization curves predicted by the homogenization model when a static uniaxial stress perpendicular to the magnetic field is applied.

An opposite conclusion can then be drawn with uniaxial perpendicular stress since both magnetization curves and EC loss are more sensitive to a tensile configuration than to a compressive one. It appears that uniaxial perpendicular tensile stresses are almost equivalent to uniaxial parallel compressive stresses since they match both qualitatively and quantitatively. It should also be noted that uniaxial perpendicular compressive stresses appear to have even less impact than uniaxial parallel tensile stresses.

B. Biaxial Stresses

In many applications, mechanical stresses cannot be reduced to uniaxial ones. Fig. 5 shows the relative effect of biaxial stresses on the initial permeability and the level of EC losses, predicted by the homogenization model, compared to the case without any applied stress. The biaxial stress has a tensile/compressive component $T_{\parallel}$ parallel to the magnetic field and a tensile/compressive component $T_{\perp}$ perpendicular to the magnetic field.

It can be seen that the change in EC losses for different magnetic field magnitudes follows a similar pattern with the change in the initial permeability. A large range of biaxial stresses (tensile parallel stress combined with compressive perpendicular stress or with tensile perpendicular stress with a lower magnitude) exhibits a very tiny increase in the initial permeability (less than 3%), which also brings a moderate increase in EC losses. The explanation is that, even if such stress configurations lead to a significant increase in the permeability of the ferromagnetic particles, the effective permeability of the SMC tends to a maximum that only depends on the volume fraction of particles ξ. Indeed, the Maxwell–Garnett estimate (given in Fig. 2) tends to

$$\widetilde{\mu}_{\mathrm{MG}} \to \frac{1+2\xi}{1-\xi}\mu_0. \tag{2}$$

For other ranges of bi-axial stresses, the initial permeability decreases. The worst stress configuration is obtained when superimposing compressive parallel stress with tensile perpendicular stress, leading to a significant decrease of the initial permeability (the maximum decrease is close to 75% in this study).

These figures also clearly show that compressive perpendicular stresses have very little influence (if any) on both the initial permeability and the EC losses. On the contrary, an increase in tensile perpendicular stress always results in a decrease of the initial permeability, which also reduces the EC losses.

Another statement to draw from these figures is that the higher the magnitude of the magnetic field is, the worst the influence of biaxial stresses on EC losses is. Indeed, it can be seen that, for any stress configuration leading to a change of EC losses, a higher magnetic field magnitude always results in a higher increase or a lower decrease in EC losses.

IV. CONCLUSION

This homogenization model for SMC predicts both the magnetic properties and the EC losses while considering the effect of mechanical stress. It is a semi-analytical model, and it can consider any stress configuration (full stress tensor with six components).

It offers a better understanding of SMC when subjected to mechanical stress with qualitative and quantitative estimates of its electromagnetic behavior, which are very difficult to obtain experimentally in the case of multiaxial stresses.

Due to its light computational complexity, it could be implemented in a multiphysics finite element model for the study of electromagnetic devices based on SMC and subjected to stresses/forces (it could be due to pre-stress, magnetic forces, or inertial forces in moving/rotating parts).

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