Coupling the domains structure and **T**ensor **M**agnetic **P**hases with AC/DC fields in soft magnetic materials

O. Maloberti[1,2], E. Salloum[2], M. Nesser[2], P. Dassonvalle[1,3], S. Panier[2], J. Fortin[2], J. Dupuy[4], C. Pineau[5], J-P. Birat[6]

[1]*ESIEE Amiens, 14 quai de la Somme, 80080 Amiens, France.*
[2]*LTI Laboratory, IUT d'Amiens, Avenue des Facultés - Le Bailly 80 025 Amiens, France.*
[3]*MIS Laboratory, UPJV, 14 Quai de la Somme - EPI 3 (2eme et 3eme étage) – 80080 Amiens, France*
[4]*MULTITEL, 2 rue Pierre et Marie Curie, 7000 Mons, Belgique.*
[5]*IRT-M2P, 4 rue Augustin Fresnel, 57070 Metz, France.*
[6]*IF-Steelman, 5 rue du Gate Chaux, 57280 Semecourt, France*

Local and microscopic non-uniformities within the magnetic structure (domains and walls [1]), mainly due to surface effects, anisotropy and exchange energies [2, 3], express itself with space variations of domains geometry and properties from the bulk towards the surface. A first work [5] proposed to cope with the problem of soft magnetic materials heterogeneity in terms of domains structure at a static equilibrium. For this purpose, it is proposed to describe a magnetic structure from a mesoscopic point of view thanks to one tensor variable **[Lambda²]**, statistically gathering main topological and dynamic properties of the magnetic domains and walls [5, 7]. Typical subdivisions were introduced by defining a tensor state variable **[V²]**=**[Lambda²]⁻¹** with 6 unknowns. In reference [6], a way is initiated to couple static and dynamic relationships between the magnetic field and the magnetic polarisation to domains and walls structuring. The latter method, called the Tensor Magnetic Phase theory (TMP) [8], is supposed to provide a deterministic method that predicts the geometry dependent vector behaviour, including static and dynamic hysteresis and iron losses, of every soft materials. The material structuring can be explained thanks to energy tendencies, for a given value of the tensor components of $\mathbf{[Lambda^2]_0}$=$\mathbf{[Lambda^2]_{surf}}$ at the surface of a sample. Therefore, in addition to a material parameter κ, related to a ratio between the total anisotropy (magneto-crystalline or induced by magnetostriction and stress) and the exchange energy density of walls, and a volume diffusion time constant τ; it is necessary to know the surface magnetic properties of the material, i.e. the walls surface, density and mobility, including the closure domains. The main challenge is thus to be able to infer these latter properties from boundary conditions that can be calculated through classical formulations in neighbouring regions (magnetic vector **A** or electric vector **T** potential, *i.e.* induction **B** or field **H**) and identified material properties (induction-field static and dynamic relationship). We investigate a way to make a link/coupling between the classical state variables used in electromagnetic FEM formulations (**A** and **B** or **T** and **H**) and the tensor state variable ($\mathbf{[V^2]_0}$=$\mathbf{[V^2]_{surf}}$) through first an energy balance and secondly the fields' boundary conditions, taking the dynamic magnetic behaviour [4] into account, at the surface of the material.

The aim of this paper is to define, implement and put to the test (Figure 1) the physical equations that should be used in the bulk and at the surface of a soft magnetic material to make an efficient coupling between classical formulations used in electromagnetism for non-magnetic materials and the Tensor Magnetic Phase formulation proposed by [8] inside the magnetic material. Adequate boundary conditions for the Tensor state variable $\mathbf{[V^2]_{surf}}$ and the magnetic induction **B** and applied field **H** will be derived first from a surface energy balance and secondly from the boundary conditions on **B** and **H**, taking the dynamic magnetic behaviour of the material into account, expressed thanks to either a weak formulation or an Ordinary Differential Equation (ODE). This model provides a way to either identify or analyse and quantify the impact of a surface magnetic structure modification induced by various treatments (irradiation, scribing, ablation …) onto the volume magnetic structure and consequently onto the global magnetic behaviour.

In this work we propose to:

- Sum up the basic principles of the TMP theory

- Introduce the two main coupling equations to be implemented at borders
  - Coupled Degrees of Freedom (6+3=9 DoF): $[\mathbf{V^2}]_{surf}$ and $\mathbf{B}=\nabla\times\mathbf{A}$ or $\mathbf{H}=\mathbf{T}$
  - Surface governing equations on $[\mathbf{V^2}]_{surf}$ and weak formulation on the surface
  - Boundary field **B** and **H** conditions and magnetic dynamic behavioral equation
  - Discussions: Contribution of the Zeeman energy on the surface ? In the volume ?

- Develop and Implement the formulation for a 1D test case with Non Grain Oriented (NGO) and Grain Oriented (GO) materials. Analysis inside the thickness e of $[\mathbf{V^2}](x)$ (Figure 2) of an electrical steel sheet submitted to a uniform magnetic field applied $\mathbf{H}_{surf}=\mathbf{H}(x=\pm e/2)$ at the surface along the z axis (Figure 2).
  - Definition of the 1D Test case (4 DoF for GO and 7 DoF for NGO)
  - Magneto-harmonic solution(s) ($[\mathbf{Lambda^2}](x)$ and $\mathbf{B}(x)$)
  - Discussions: Description of main domains (space variations and refinement), closure domains (orientation and space variations) and magnetic polarization.

- Investigate the coupling formulation for a 2D test case with NGO and GO materials
  Analysis inside the cross section $[\mathbf{V^2}](x,y)$ (Figure 3) of an electrical steel sheet submitted to a uniform magnetic field applied $\mathbf{H}_{surf}$ at the surface along the z axis.

References

[1] A. Hubert, R. Schafer, *Magnetic Domains*, Springer Verlag, 2000.

[2] H.A.M. Van Den Berg, A.H.J.V.D. Brandt, "Self-Consistent Domain Theory in Soft Ferromagnetic Media II: Basic domains structures in thin film objects", *Journal of Applied Physics*, 1986, vol. 60, n°3, pp. 1105-1113.

[3] L. Landau, E. Lifshitz, "On the theory of the dispersion of magnetic permeability in ferromagnetic bodies", Reprinted from Phys. Zeitsch. der Sow. 8, pp. 153–169 (1935).

[4] O. Maloberti et al., "Hysteresis of Soft Materials Inside Formulations: Delayed Diffusion Equations, Fields Coupling, and Nonlinear Properties", IEEE Transactions on Magnetics, Volume: 44 , Issue: 6 , June 2008.

[5] O. Maloberti, G. Meunier, A. Kedous-Lebouc, V. Mazauric, "How to Formulate Soft Materials Heterogeneity? *1. Quasi-Static Equilibrium and Structuring*", *submitted to J.M.M.M.*, conference SMM'18 in Cardiff 2007.

[6] O. Maloberti, A. Kedous-Lebouc, G. Meunier, V. Mazauric, "How to Formulate Soft Materials Heterogeneity? 2. Hysteresis, Dynamic Motions and Diffusion", *submitted to J.M.M.M.*, conference SMM'18 in Cardiff 2007.

[7] O. Maloberti et al., "Investigating a Tensor Formulation to describe the Magnetic Structure of Soft Magnetic Materials", COMSOL conference 2018 in Lausanne, 2018.

[8] O. Maloberti et al., "The tensor magnetic phase theory for mesoscopic volume structures of soft magnetic materials – Quasi-static and dynamic vector polarization, apparent permeability and losses – Experimental identifications of GO steel at low induction levels", Journal of Magnetism and Magnetic Materials, Volume 502, 15 May 2020, 166403.

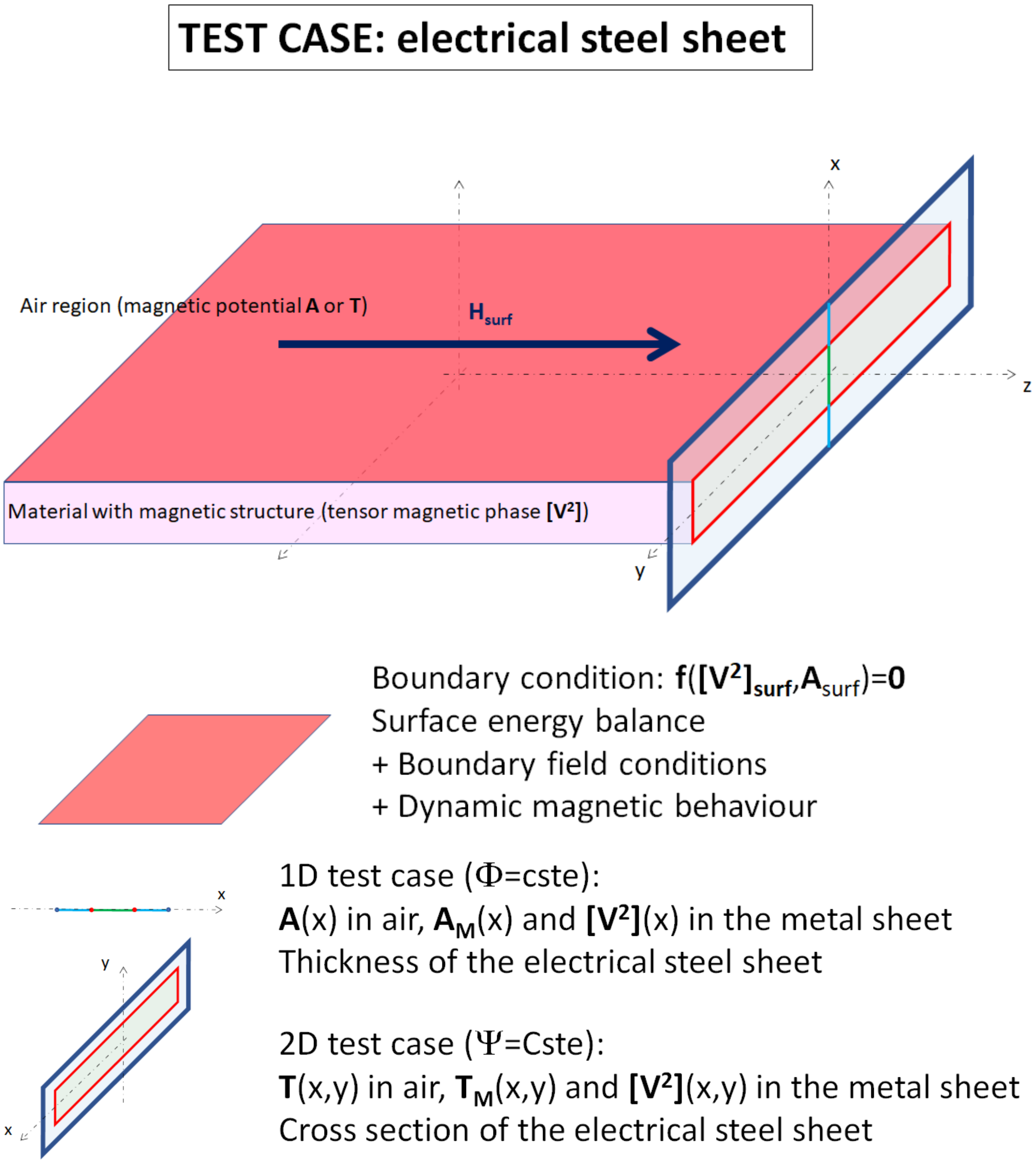

Figure 1: Test case (one magnetic sheet of thickness ζ submitted to a uniform magnetic field $\mathbf{H}_{surf}$).

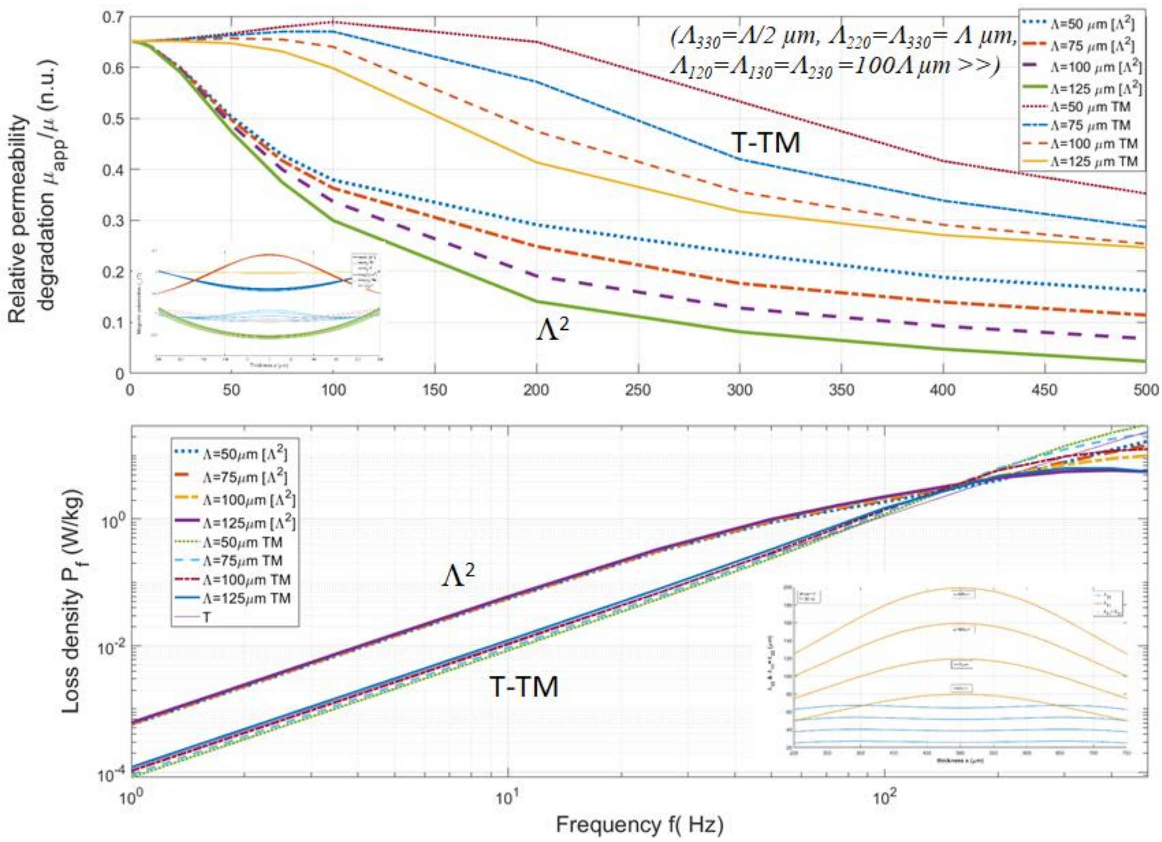

Figure 2: Apparent permeability and magnetic losses with the two coupled formulations T-TM or Λ^2 for one oriented material, as a function of frequency f and the boundary condition on Λ_0.

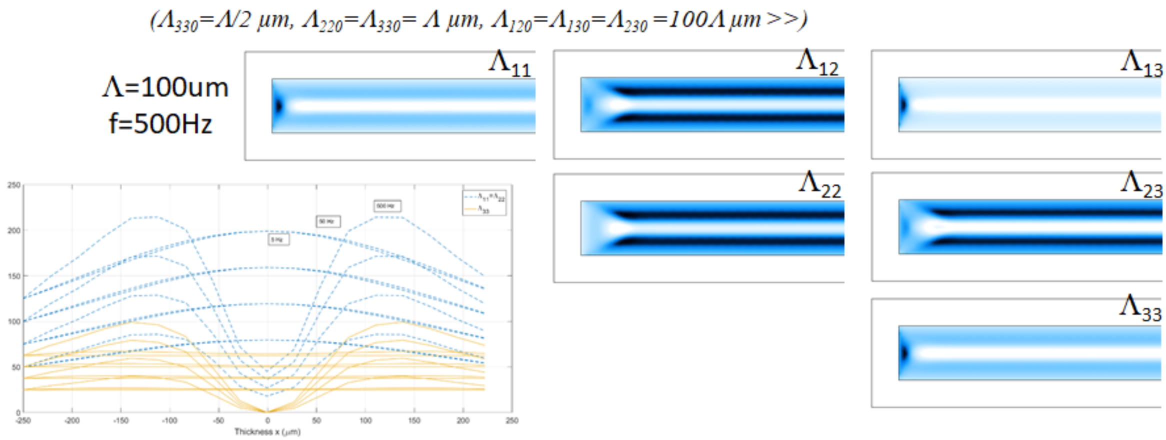

Figure 3: [V^2](x,y) components in the cross section of an electrical steel sheet made of one oriented material (ζ=0.5 mm, κ=$(4/\zeta)^2$ mm^{-2}, Λ_{330}=100μm, Λ_{220}=Λ_{110}=200μm).