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Surface magnetic properties of domain structure – thickness dependent behaviour of GOES* sheets

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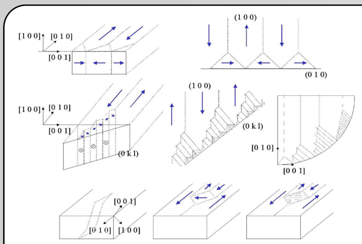
INTRODUCTION

The permeability and the losses of Grain Oriented Electrical Steels (GOES) related to its magnetic structure (topological and dynamical properties) depend on the geometry, surface quality and residual stresses. This work investigates the corresponding sensitive boundary condition with the help of the Tensor Magnetic Phase Theory (TMPT) [1].

VOLUME TENSOR MAGNETIC PHASE THEORY



$$[\Lambda^2]=\begin{bmatrix}\Lambda_{11}^2 & \Lambda_{12}^2 & \Lambda_{13}^2\\ \Lambda_{21}^2 & \Lambda_{22}^2 & \Lambda_{23}^2\\ \Lambda_{31}^2 & \Lambda_{32}^2 & \Lambda_{33}^2\end{bmatrix};\quad \begin{cases}\Lambda_{ii}^2 \propto \lambda_j\lambda_k;\ j,k\neq i \text{ and } i=1..3\\ \Lambda_{ij}^2 \propto \lambda_k^2;\ k\neq i\neq j \text{ and } i,j=1..3\end{cases}$$

$\Lambda_{ij}{}^2$ *walls density, surface, mobility, domains size, …(m²)*

γ_w: *walls energy density (J.m⁻²);* $\mathbf{K_{an}}$: *anisotropy vector (J.m⁻³)*

$[\lambda]$: *magnetostriction tensor;* $[C]$: *stiffness tensor (Pa)*

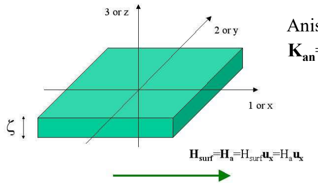
$[\sigma]$: *the stress tensor (Pa)*

τ: *time delay related to the magnetic field damping (s)*

$[V^2]=[\Lambda^2]^{-1}$

$$E_{min}\Rightarrow [\Delta]\,[V^2]-\vec{\nabla}(\vec{\nabla}.[V^2])-\frac{C_{an}}{C_{ex}}\left(\frac{K_{an}}{\gamma_w}\right)^2\left([V^2]-\left(\frac{\vec{K}_{an}([V^2]\vec{K}_{an})^T}{K_{an}^2}\right)^T\right)$$
$$+\frac{3}{2}\frac{C_\lambda}{C_{ex}}\left(\frac{K_{an}}{\gamma_w}\right)^2\left(\frac{[\lambda]\because[\sigma]}{K_{an}}\because[V^2]\right)-\frac{9}{4}\frac{C_\lambda}{C_{ex}}\left(\frac{K_{an}}{\gamma_w}\right)^2\left(\frac{[\lambda^2]\because[C]}{K_{an}}\because[V^2]\right)-\left(\frac{K_{an}}{\gamma_w}\right)^2\tau\partial_t[V^2]=[0]$$

1D solution with GO SiFe steel



Anisotropy:
$\mathbf{K_{an}}=K_{an}\mathbf{u_{an}}=K_{an}(1,0,0)^T$

$[V^2]=[\Lambda^2]^{-1}$?

thickness:
ζ=0.5 mm
or
ζ=0.23 mm

$$\left(\partial_z^2.-\kappa_{ii}(1+\tau_{ii}\partial_t.)\right)V_{ii}^2=0$$

C_{ex}, C_{an} and C_λ are dimensionless material constants.

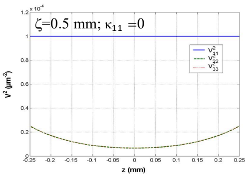
$$\kappa_{an}=\frac{C_{an}}{C_{ex}}\left(\frac{K_{an}}{\gamma_w}\right)^2\ (mm^{-2})$$

$\kappa_{11}=\kappa_{\lambda,11}$ and $\kappa_{ii}=\kappa_{an}+\kappa_{\lambda,ii}$ for i=2,3

$$\kappa_{\lambda,ii}=\frac{C_\lambda}{C_{ex}}\left(\frac{K_{an}}{\gamma_w}\right)^2\left(\frac{3\lambda_{100}}{2K_{an}}\right)\left(\frac{3}{2}\lambda_{100}-\sigma_{ii}\right),\ \sigma_{ij}=0$$

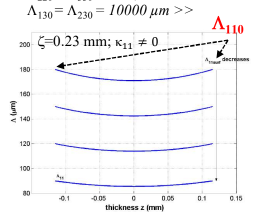
$$\tau_{ii}=\left(\frac{K_{an}}{\gamma_w}\right)^2\tau/\kappa_{ii}\ (=0)$$

Solution:



Solution depends on boundary conditions.
as an example:
Λ_{110} = *100 µm*
$\Lambda_{220}=\Lambda_{330}$ = *200 µm*
$\Lambda_{130}=\Lambda_{230}$ = *10000 µm >>*

$$V_{ii}^2(z)=V_{ii0}^2\frac{\cosh\left(\sqrt{\kappa_{ii}(1+j\tau_{ii}\omega)}z\right)}{\cosh\left(\sqrt{\kappa_{ii}(1+j\tau_{ii}\omega)}\frac{\zeta}{2}\right)}$$



SURFACE TMPT COUPLING

Magnetic exchange — *Magnetic anisotropy* — *Self magnetostriction* — *Stress anisotropy*

$$\forall i,j:\ C_{ex}\frac{\gamma_w^3}{K_{an}^2}V_{ij}^2+C_{an}\frac{\gamma_w^3}{K_{an}^2}\left(V_{ij}^2-k_{ani}\left(\sum_k V_{jk}^2k_{ank}\right)\right)+\frac{9}{4}\lambda_{ij}^2C_{ij}V_{ij}^2C_\lambda\frac{\gamma_w^3}{K_{an}^3}-\frac{3}{2}\lambda_{ij}\sigma_{sij}V_{ij}^2C_\lambda\frac{\gamma_w^3}{K_{an}^3}$$

Dynamic field coupling — *Static and stray field coupling*

$$-\beta_z\frac{\sigma_e}{2}\frac{K_{an}}{\gamma_w}\begin{pmatrix}\mathbf{B_i}\sum_k\Lambda_{jk}^2j\omega\mathbf{B_k}\\ \mathbf{B_j}\sum_k\Lambda_{ik}^2j\omega\mathbf{B_k}\end{pmatrix}-\sqrt{\nu_{dmi}\nu_{dmj}}\frac{K_{an}}{\gamma_w}\mathbf{B_i}\mathbf{B_j}\Lambda_{jk}^2=0$$

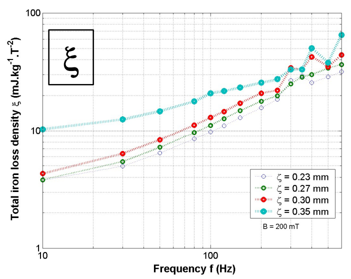
B: *flux density*, ω: *angle velocity*, σ_e: *conductivity*
β_z: *dynamic field coupling coefficient* (m²)
ν_{dm}: *static field coupling reluctivity* (m.H⁻¹)
$\kappa_{ex}=(K_{an}/\gamma_w)^2$; $\kappa_{an}=(C_{an}/C_{ex})*(K_{an}/\gamma_w)^2$
$\kappa_\lambda=(C_\lambda/C_{ex})*(K_{an}/\gamma_w)^2((9\lambda^2C/4K_{an})-(3\lambda\sigma/2K_{an}))$ (m⁻²)
⇒ *boundary condition and space variations of* $[\Lambda^2]$

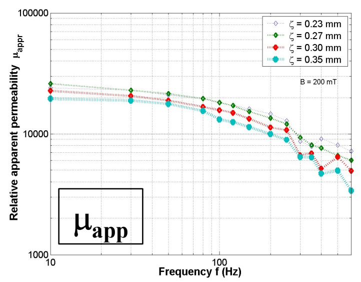
Solution for $\Lambda_{110}=\Lambda_{RD,0}$ *in GOES magnetized in RD*

$$\bar{\Lambda}_{RD,0}=\sqrt[4]{\frac{\kappa_{ex}+\kappa_\lambda}{B^2(\nu_{dm}(B,\omega)+j\beta_z(B,\omega)\sigma_e\omega)}\left(\frac{C_{an}^{5/2}}{C_{ex}^{3/2}}\frac{\gamma_w}{\kappa_{an}^{5/2}}\right)}$$

BOUNDARY PROPERTIES OF SHEETS WITH VARIOUS THICKNESSES

Magnetic measurements

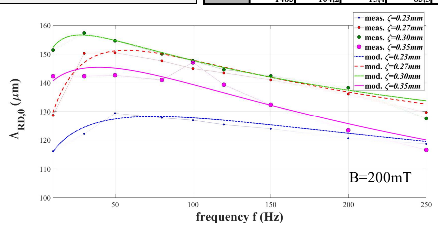


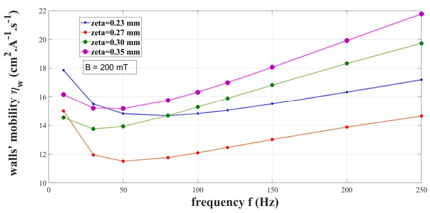


Identification of surface properties

$$\Lambda_{110}=\Lambda_{RD,0}\approx a\sqrt[4]{\frac{1}{((b)^2+(c_1f^n+c_2)^2)}}$$

	a	b	c1	c2	n
0,23	461	13,0	11,4	27,4	0,20
0,27	50	0,11	17,4	17,6	0,0031
0,3	547	12,3	4,4	13,5	0,32
0,35	1483	104,2	15,4	83,5	0,46

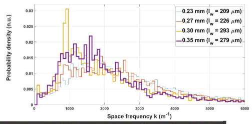


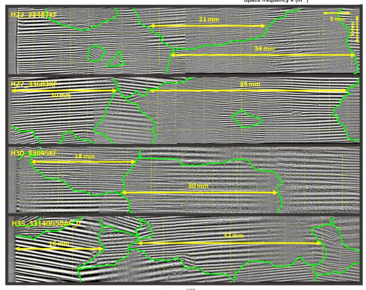


MOIF images of domains structure

FFT 2D
Spectral density
Domains' width

$$l_w=\frac{1}{2k}$$

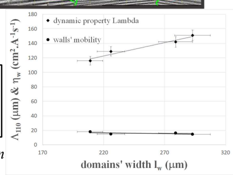




Walls' mobility

$$\eta_w=\frac{l_w}{2\sigma_eJ_s\Lambda_{110}^2}$$

J_s: *saturation polarization*



CONCLUSION

The geometry dependence of the magnetic structure is partly driven by the grains size and orientation, the residual stress and the quality of the surface (ex: laser treatment). The surface formulation required for the boundary condition used by the TMPT [1] includes these phenomena for the permeability and loss calculation in coherence with the domains size and walls' mobility.

ESSIAL

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[1] Maloberti O. et al., JMMM, vol. 502, (2020), 166403.

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