Zero-field energy minimization principle to control the domains size by lines scribed with a laser on surface oriented magnetic structures.

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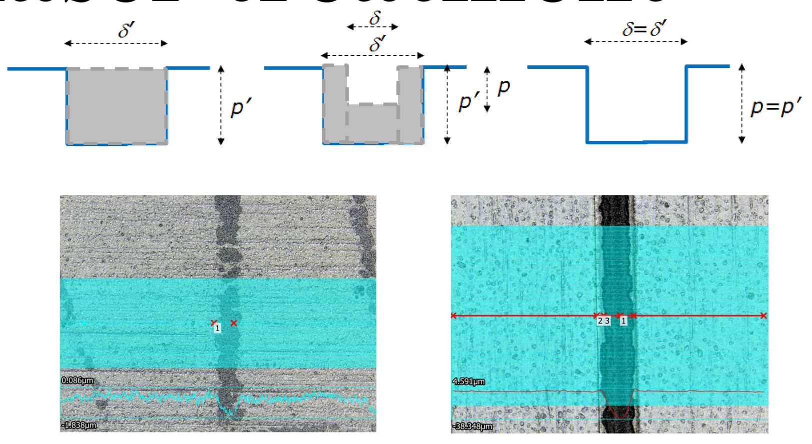
Introduction: This work focuses on a method to help the specification of the most adequate laser patterns to optimize the performance (magnetic permeability, coercive force, losses) of a soft magnetic material. To do so, we investigate a theoretical tool to estimate statistically the impact of both a pattern (such as the **scribing** or **irradiation "lines"** geometry, **spacing**, **depth**, width …) and some material properties (sheet **thickness**, magnetic **exchange** and **anisotropy**) onto the main parameters that define a magnetic structure at zero external magnetic field, especially the **domain wall spacing**.

Role of the laser treatment[a]

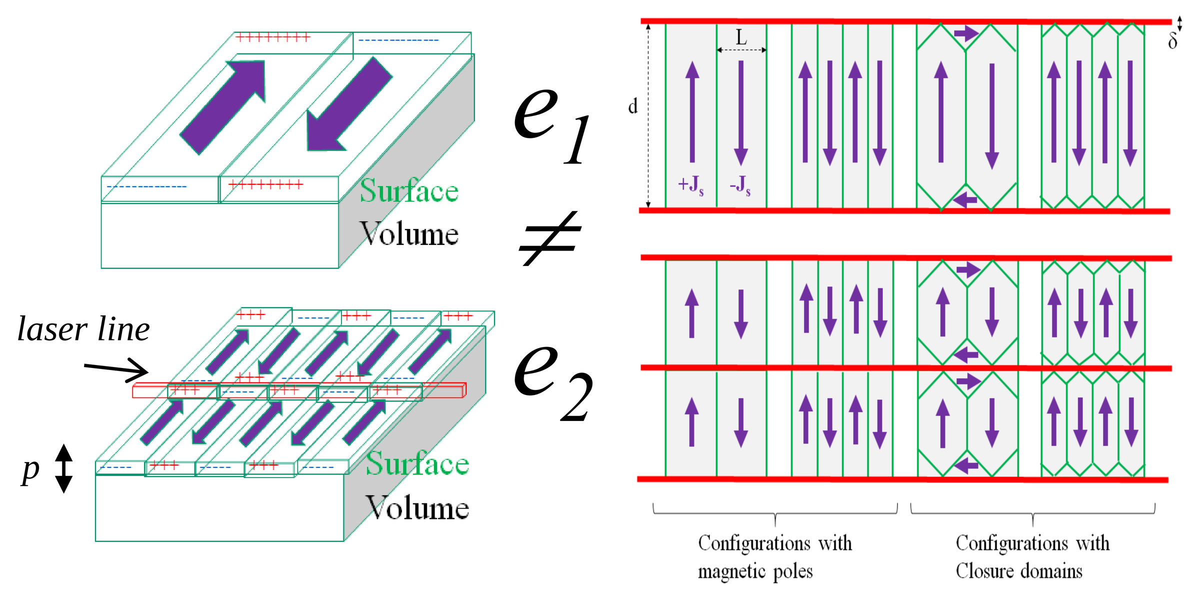
Scribing modes and depth:



width and depth of Heat Affected Zone (p', δ') ? (HAZ)

width and depth of Material Removal Zone (p, δ) ? (MRZ)

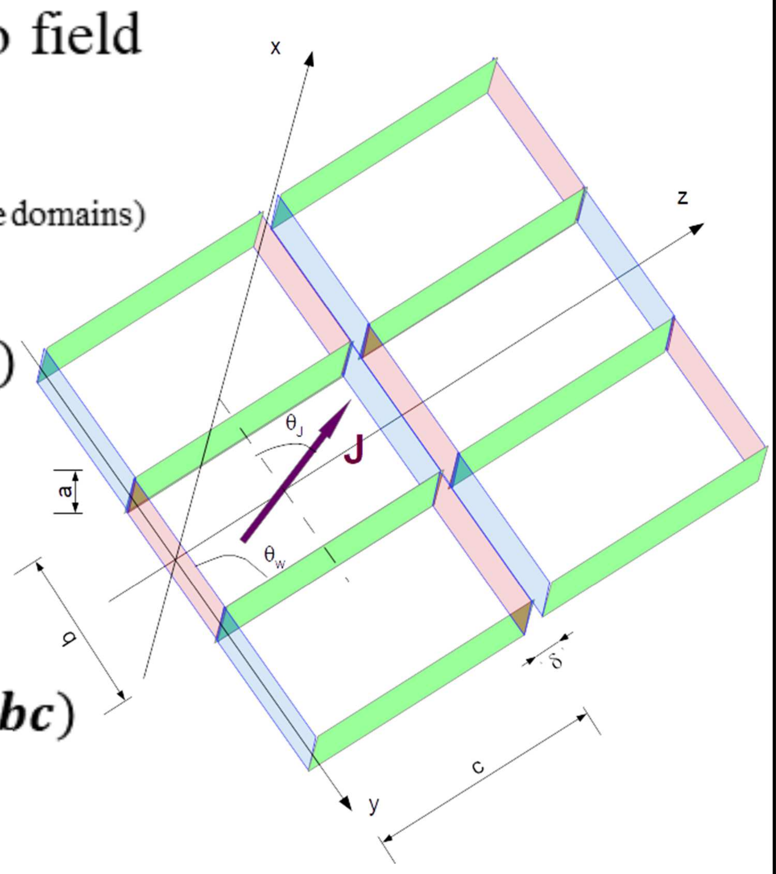
- Located modification of magnetic properties, reduction of polarization inside the affected zone (stress, ablation, damage …)
- Located closure domains or magnetic poles that define typical size of magnetic domains due to an energy minimization principle.



Surface magnetic domains refinement. Interactions between the surface and the bulk magnetic structure have to be described elsewhere.

Min{domains+walls+poles} energy Test-Case studied

Energy of M*N domains at zero field



Domains energy density
(magnetocrystalline anisotropy energy, only for closure domains)
- Case of one easy axis along z

$$e_a \approx \sum_{closure\ m} (K_{an} a b_m^2/4)/(MNbc)$$

Walls energy
(magnetic exchange + anisotropy energy)
- Case of Bloch walls at 180°

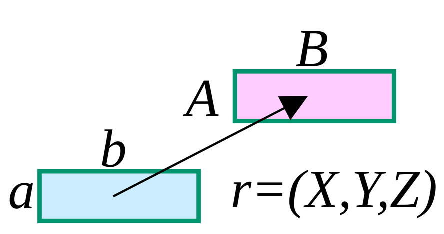
$$e_w \approx \sum_m \sum_n 2(ca)\sqrt{A_{ex}K_{an}}/(MNbc)$$

Poles' energy
(magnetostatic demagnetizing energy)
- Contribution of surface magnetic poles only

$$e_d \approx \frac{1}{2}\sum_{m1}\sum_{n1}\sum_{m2}\sum_{n2} N_d(a,(m2-m1)b,(n2-n1)c)J^2/(MNbc)$$

Demagnetization coefficient N_d:

$$\left\{\begin{matrix} U = X + (-1)^i \frac{A}{2} - (-1)^j \frac{a}{2} \\ V = Y + (-1)^k \frac{B}{2} - (-1)^l \frac{b}{2} \\ W = Z \\ R = \sqrt{U^2+V^2+W^2} \end{matrix}\right\} \quad N_d \approx \frac{1}{2\pi\mu_0}\sum_{i=0}^{1}\sum_{j=0}^{1}\sum_{k=0}^{1}\sum_{l=0}^{1}(-1)^{i+j+k+l}\begin{pmatrix} \frac{1}{2}U(V^2-W^2)\ln(R-U) \\ \frac{1}{2}V(U^2-W^2)\ln(R-V) \\ UVW\tan^{-1}\left(\frac{UV}{RW}\right) \\ \left(\frac{15}{4}UV - \frac{1}{2}(U^2+V^2)\right)R \end{pmatrix}$$



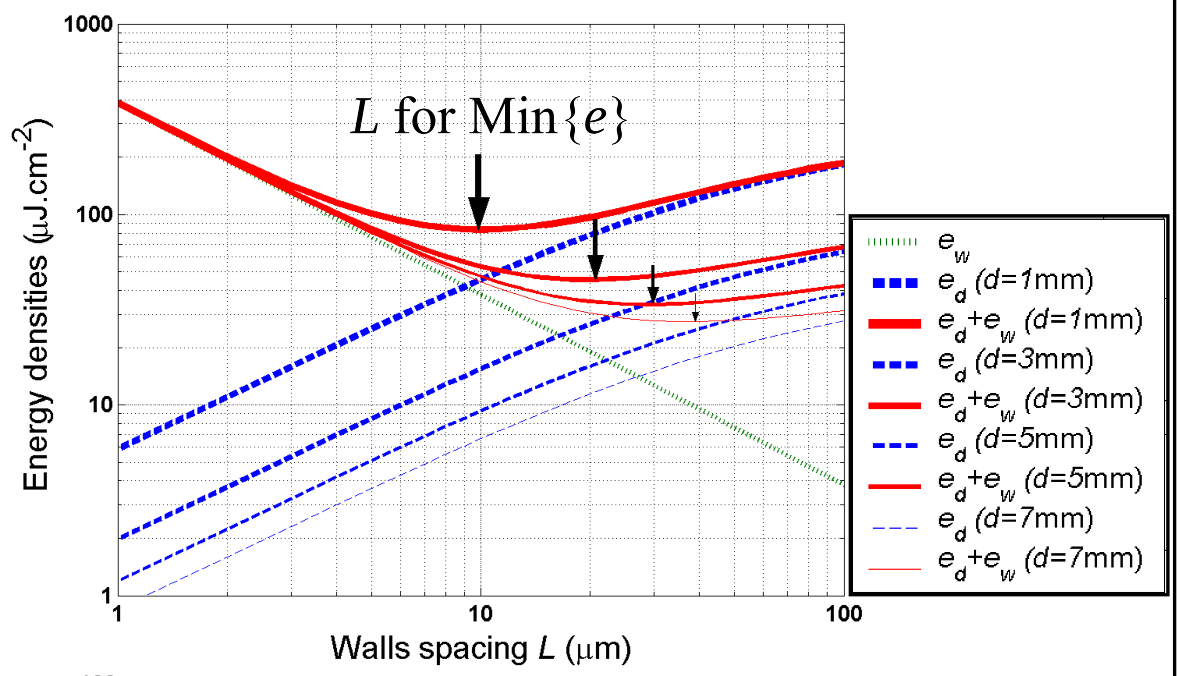
Results and sensitivity analysis[b]

Structure *(context variable)*	Laser	Description
(a) or (a')	*p or p'*	Depth of the MRZ or HAZ within the laser lines
(a)	*e or ζ*	Thickness of the sample
L	*(b)*	Width of the magnetic domains
(c)	*d*	distance between lines scribed by laser
(δ) or (δ')	*δ or δ'*	Depth of the MRZ or HAZ within the laser lines
θ_J	θ_J	angle between lines and the polarization
θ_w	θ_w	angle between lines and the walls direction
θ_{DL}	θ_{DL}	Angle between lines and the rolling direction

Case with no closure domains, only theory & magnetic poles are considered

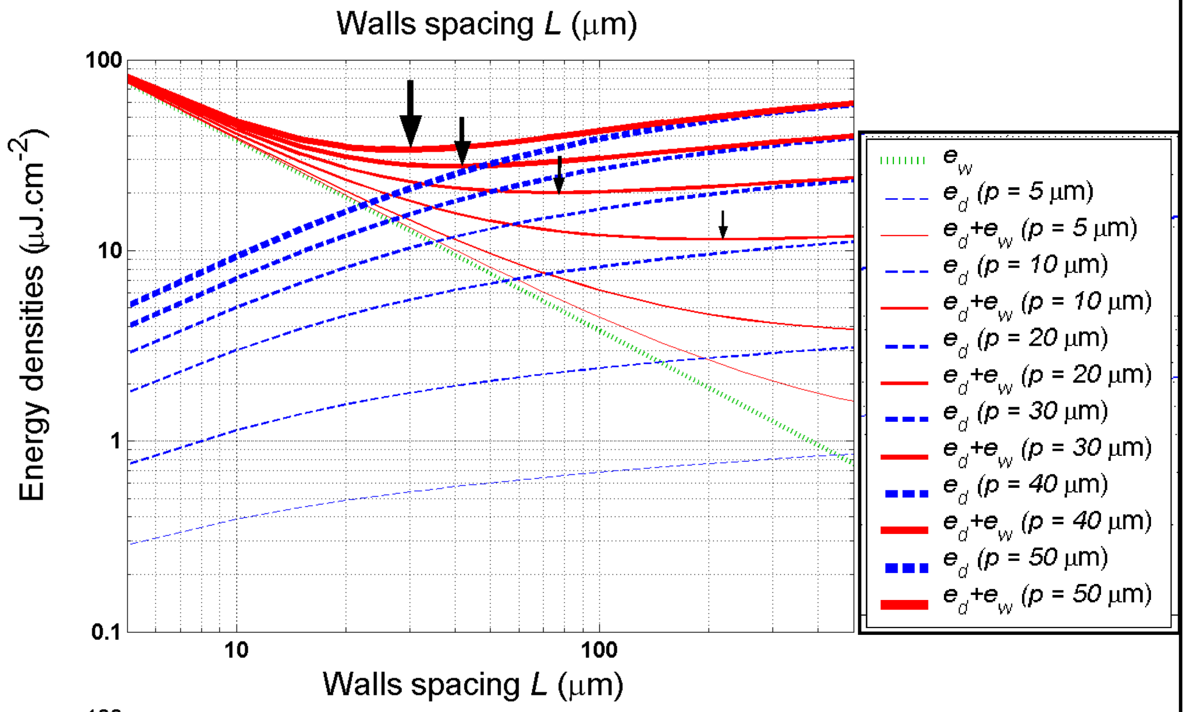
Walls spacing L vs lines spacing d

J_s = 2 T
e or ζ = 0.5 mm
p = 50 µm
$\delta \approx 0$ µm
$\theta_{DL}=\theta_J=\theta_w=90°$
$\mathbf{u}_{an}=\mathbf{u}_{DL}$



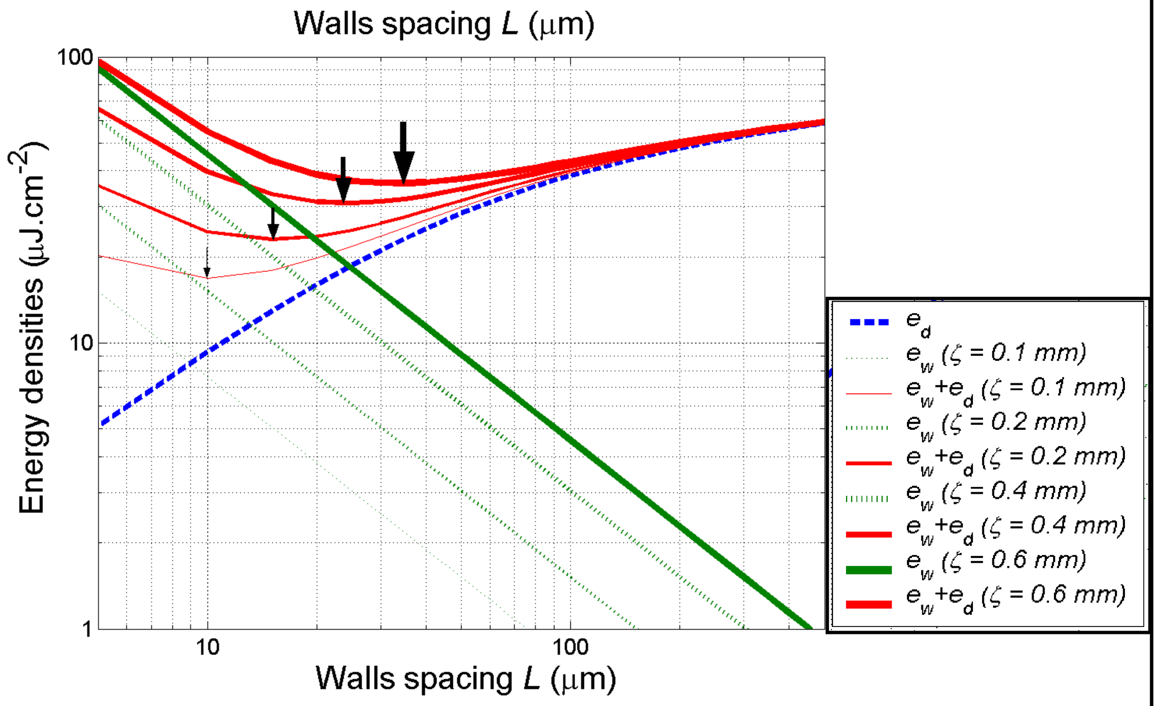
Walls spacing L vs lines depth p

J_s = 2 T
e or ζ = 0.5 mm
d = 5 mm
$\delta \approx 0$ µm
$\theta_{DL}=\theta_J=\theta_w=90°$
$\mathbf{u}_{an}=\mathbf{u}_{DL}$



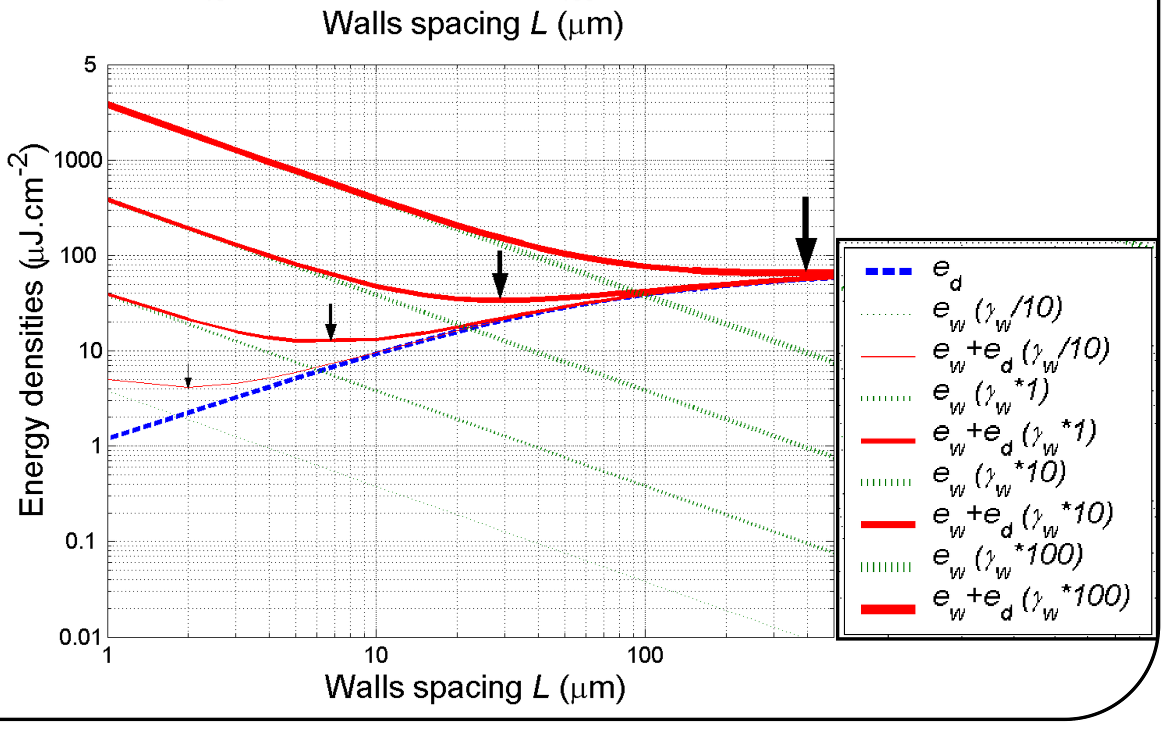
Walls spacing L vs sheet thickness ζ

J_s = 2 T
p = 50 µm
d = 5 mm
$\delta \approx 0$ µm
$\theta_{DL}=\theta_J=\theta_w=90°$
$\mathbf{u}_{an}=\mathbf{u}_{DL}$



Walls spacing L vs walls energy density $\gamma_w \propto \sqrt{A_{ex}K_{an}}$

J_s = 2 T
e or ζ = 0.5 mm
p = 50 µm
d = 5 mm
$\delta \approx 0$ µm
$\theta_{DL}=\theta_J=\theta_w=90°$
$\mathbf{u}_{an}=\mathbf{u}_{DL}$



Conclusion: The walls energy decreases when the walls spacing increases (*i.e.* the walls number or surface decreases). The demagnetizing energy increases when the walls spacing increases (*i.e.* the magnetic domains and poles become bigger or closer). We **find an optimal wall spacing which minimize the total energy** and corresponds to the best compromise, that depends on the material and laser parameters. Now, consideration of closure domains, determination of the macroscopic anisotropy, true walls energy density, observation of actual domains size and inclusion of field effects are required.

[a]Laser treatment are performed by MULTITEL and metallurgical aspect covered by the CRM and IRT-M2P. [b]Magnetic modeling and measurements are carried out by the ESIEE Amiens.

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