An interaction between electromagnetic field and materials: Characterization of mechanical stress in ferromagnetic materials using eddy currents non-destructive testing

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INTRODUCTION: This application concerns the use of eddy currents (EC) in non-destructive testing (NDT) to characterize the stress state of a ferromagnetic material of gas pipelines. A « COMSOL Multiphysics » model was implemented to evaluate and to optimize the EC sensor-response (Fig.1).

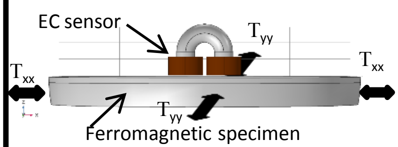

Figure 1. Problem geometry

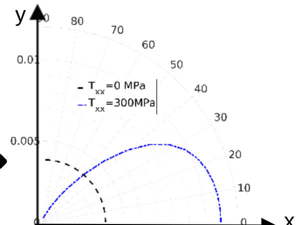

Figure 2. Magnetic permeability evolution under stress (AMSM)

COMPUTATIONAL METHODS:

To evaluate the EC NDT signal (impedance Z of the serially connected sensor coils), the magneto-dynamic equations are solved with Finite Element Method (FEM) in « COMSOL Multiphysics » using the *AC/DC module*. The response of an EC sensor is sensitive to the variation of the magnetic permeability in the tested ferromagnetic specimen. The magnetic permeability itself is sensitive to mechanical stress. Therefore, a relationship between the impedance signal of the EC sensor and the stress effect could be established by describing the magneto-elastic behavior using an Analytical Multiscale Model (AMSM) [(1)(2)]:

$$\mu(0,\boldsymbol{T}) = 1 + \frac{3\,\chi^0 A_u}{A_u + A_v + A_w} \qquad A_i = e^{\alpha T_{ii}} \qquad i\epsilon\{u,v,w\}$$

Where T_{ii} is the applied stress in the i direction, χ^0 is the initial anhysteretic susceptibility and α is material constant. These parameters are defined experimentally in the lab. Fig.2 represents the evolution of the magnetic permeability with respect to the angle $(\widehat{\boldsymbol{U}_H, \boldsymbol{F}})$, where F is the applied uniaxial force on the specimen and $\mathbf{U}_H$ is the magnetic field direction.

To implement the stress effect on the specimen into the *Magnetic and Electric Fields* (MEF) physics model in COMSOL, an external material is selected for the specimen domain to solve the Maxwell equations. *The **H(B)** general relation* of the ferromagnetic material under stress is described using the AMSM in a compiled C++ code. This solution was inspired by an example in the COMSOL Application gallery (ID: 32321). Instead of using data interpolation as in the Comsol example to calculate the magnetic field **H,** the MSM is used to calculate the magnetic permeability for each element of the mesh in order to calculate the magnetic flux density **B** with respect to the mechanical stress (Fig.3) under the hypothesis that the magnetic fields **H** and **B** are colinear for low excitations [(3)].

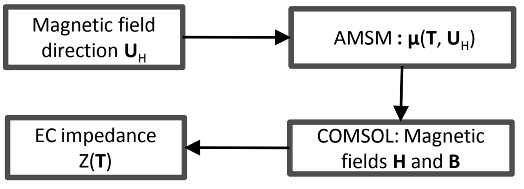

Figure 3. Direct problem modelling strategy

Because of the stress effects on the magnetic properties, the skin depth in the material changes. Therefore, the mesh is adapted to different stress states using *Boundary Layers* for a better accuracy.

The frequency domain study includes two steps, the first one solves an EC problem for a ferromagnetic material with a predefined tensor of magnetic permeability in the material properties, to initialize the second step. In the second step, the magnetic permeability of the material is corrected using the external **H**($\mathbf{B}_T$) relation, so that the effect of stress on the magnetic properties is taken into consideration, see Fig.5.

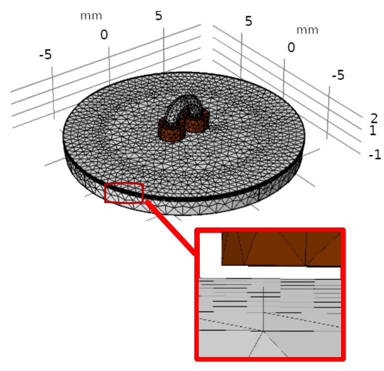

Figure 4. Boundary Layers

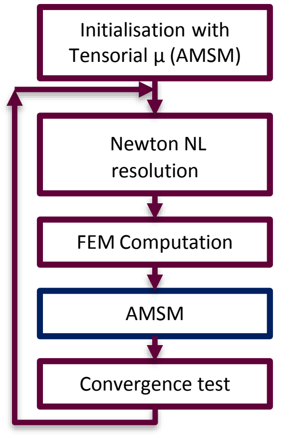

Figure 5. Algorithm

RESULTS: Fig. 6 shows the distribution of the norm of the magnetic flux density **B** at the top surface of the specimen. Under no mechanical stress the magnetic flux is distributed around the sensor (Fig. 6(a)). Under high level of uniaxial tensile stress (Fig. 6(b)) the magnetic flux is channeled along the stress direction.

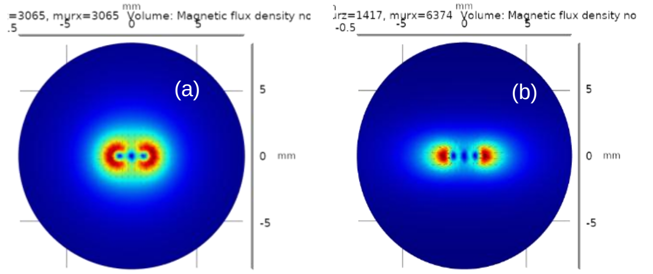

Figure 6. Magnetic density flux norm:
(a) without stress T_{xx}= 0MPa; (b) tensile stress T_{xx}= 300MPa;

CONCLUSIONS: The results obtained by this early stage model are promising because the predicted evolution of the magnetic flux density is similar to experimental data. However, the model convergence requires improvement.

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