A Modeling Approach for the Characterization of Stress in Magnetic Materials using Eddy Current Non-Destructive Evaluation

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Abstract — There are several non-destructive techniques for the evaluation of stress in materials. The aim of this research is to develop a non-destructive method based on eddy current to evaluate stress in magnetic materials. It is based on the significant effect of stress on the magnetic behavior of magnetic materials. This effect can be detected using eddy current technique. In this work, an experimental approach is used to evaluate the elaborated modeling which combines a multiscale material model and a 3-D finite element approach.

***Index Terms*—Eddy current probe, impedance measurement, mechanical stress, residual stress, magnetostriction.**

I. Introduction

Stress in magnetic materials can deteriorate the properties of electromagnetic devices. The characterization of the mechanical stress in magnetic materials is then an important issue. There are several destructive and non-destructive methods available for the evaluation of stress. The most commonly used non-destructive evaluation (NDE) technique is based on X-ray diffraction [1]. Since the magnetic permeability of magnetic materials significantly depends on stress, a stress evaluation method based on eddy currents (EC) - themselves highly dependent on permeability - can be a convenient alternative [2]. The EC technique has many advantages: it is simple to implement, easily automatable and cheap. Efficient modeling tools are needed in order to design EC probes as well as to analyze the EC signals issued from inspections. The purpose of this work is to develop a numerical tool to model the EC signal provided by an EC probe inspecting a material subjected to stress. The modeling is done in two-steps. First, the effect of stress on the permeability is predicted using a multi-scale model. Then the EC probe signal is determined as a function of the permeability using the finite element method (FEM). The results are compared to an experimental NDE performed on an Iron-Cobalt alloy.

II. Material modeling

The material magnetic behavior under stress is modeled using a multiscale magneto-elastic model previously published [3,4].This multi-scale model is based on an energetic description of the magneto-elastic equilibrium at the magnetic domain scale. Scale transition rules allow to link the macroscopic scale - at which an average constitutive law is defined - to the local scale - at which the relevant physical mechanisms can be described. This multi-scale model allows the prediction of the response of a magnetic material subjected to multiaxial magneto-mechanical loadings. Only the reversible (anhysteretic) part of the magneto-elastic behavior is modeled. In this paper, only uniaxial tensile stress is considered. Fig. 1 shows the two in-plane components of the relative permeability tensor of an initially isotropic Iron-Cobalt alloy as a function of the uniaxial stress applied along x-axis. As observed experimentally [5], it can be noticed that the effect of stress is non linear and non symmetric between tension and compression. The multiscale model also predicts the stress induced anisotropy.

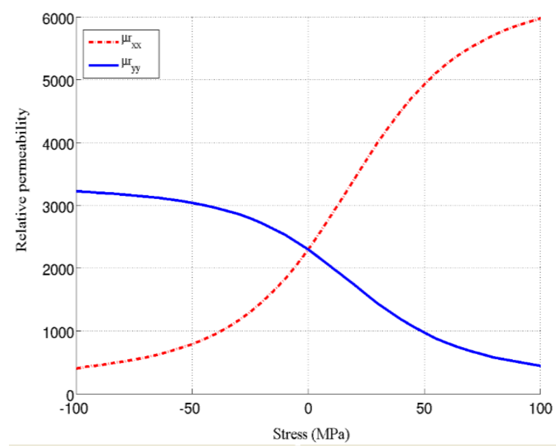

Fig. 1. In-plane components of the relative permeability tensor as a function of stress for an Iron-Cobalt- alloy (tension/compression stress along x-axis).

III. Eddy current modeling

For the EC modeling, the FEM is used with the magnetic vector potential and the electric scalar potential as degrees of freedom. The considered EC configuration consists in an eddy current probe (coil) positioned close to the ferromagnetic material on which the uniaxial stress Txx is applied (see Fig. 2). Considering the small excitation field used in EC NDE, a linear FEM calculation is implemented using the magnetic material permeability obtained from the multiscale model. Only a quarter of the 3-D problem is studied due to the physical symmetries. Regarding the mesh, two kinds of elements are used: hexahedral and tetrahedral elements depending on the considered physical region. In the considered application the mesh is constituted of approximately 230000 elements.

The observed probe signal is the coil impedance which is determined for its real part from the power losses in the conducting domain (magnetic material) and for its imaginary part from the stored magnetic energy in the whole meshed domain.

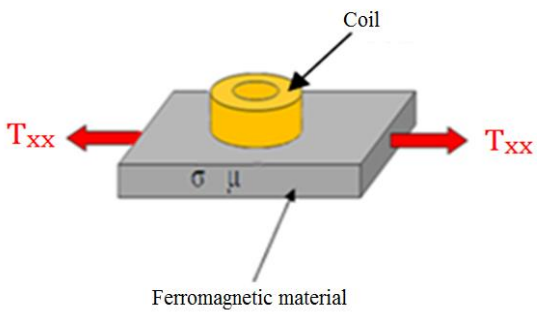

Fig. 2. Studied problem

IV. EXPERIMENTAL EVALUATION

A test-rig was designed in order to evaluate the effect of stress on the EC signals. The magnetic material sample, a commercial Iron-Cobalt alloy, is installed between the collet grips of a tension/compression electro-mechanical machine Zwick/Roell Z030. A cylindrical EC coil of rectangular cross-section (33 turns, inner radius = 2.4 mm, outer radius = 4.3 mm, coil height = 2 mm) positioned close to this sample is then used together with an impedance analyzer Agilent 4294A to collect the EC signal. The impedance analyzer allows to measure the coil impedance as a function of the stress level (see Fig. 3).

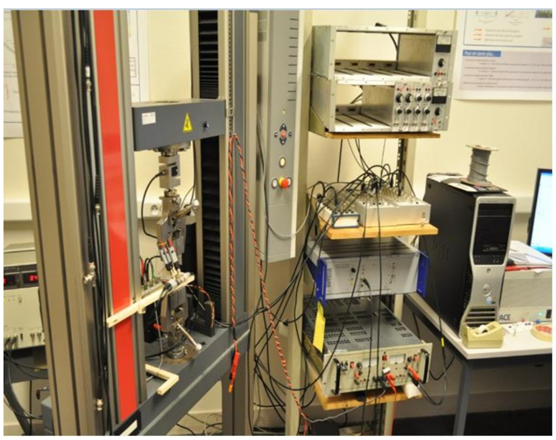

Fig. 3. Test-rig

V. RESULTS

The relative variation of impedance with respect to the unstressed case $|Z(T) - Z(0)|/|Z(0)|$ is shown on Fig.4 in the case of a T = 100 MPa tensile stress. This variation of impedance is plotted as a function the measurement frequency.

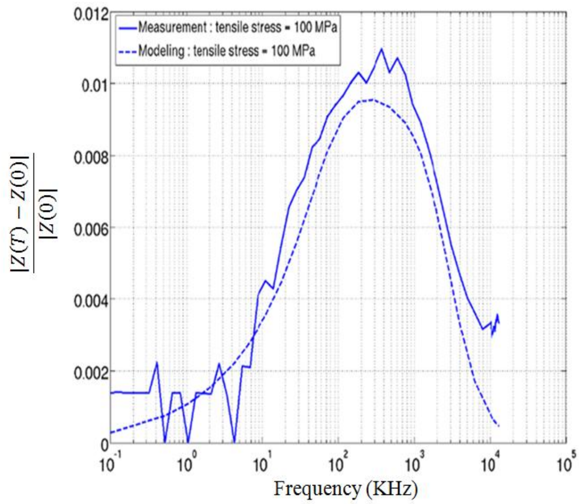

Fig. 4. Variation of impedance for 100 MPa tensile stress (relatively to the unstressed configuration) as a function of frequency.

The results obtained from numerical calculations and experimental measurements are in good accordance and show the same frequential behavior. An optimal operating frequency can be defined in order to obtain a maximum sensitivity for stress detection. Thus it suggests the possibility to use the developed modeling approach as a design tool for EC NDE of stressed magnetic materials. In the low-frequency domain the experimental signal is noised because of the low sensitivity of the EC NDE since the amplitude of the EC decreases with the frequency.

VI. CONCLUSION

The EC NDE technique is an interesting solution to evaluate stress in magnetic materials. This paper proposes a methodology for the modeling of stress detection using eddy current techniques. Such approaches allow probe design and inverse analysis. First results show the feasibility of the approach. Different EC probes could be used to have a higher sensitivity. It must be stressed that only uniaxial stress states have been considered in this paper. In practical applications, stress is usually multiaxial, and the inverse analysis can become much more difficult to perform. This multiaxiality of stress needs to be addressed, and will be the object of further research.

VII. REFERENCES

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