3MA Finite Element Modeling of 3MA NDT Devices in Different Inspection Situation

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Currently, the nondestructive characterization of materials with electromagnetic NDT methods requires a huge amount of experiments and establishments of complex formulas to recover the magnetic and mechanical behavior of the material. All these measurements are very costly in terms of money and time, which is why the use of such NDT techniques often remains limited today. In order to speed up the characterization process, analytical and numerical simulations are run in order to predict the a priori magnetic behavior of the material in different inspection situations and to reduce the measurement series. Therefore, Fraunhofer IZFP has focused his efforts to develop an electromagnetic FEM tool using Flux Software (developed by CEDRAT) which is able to reproduce the inspection situation with 3MA device and to simulate the magnetic signatures.

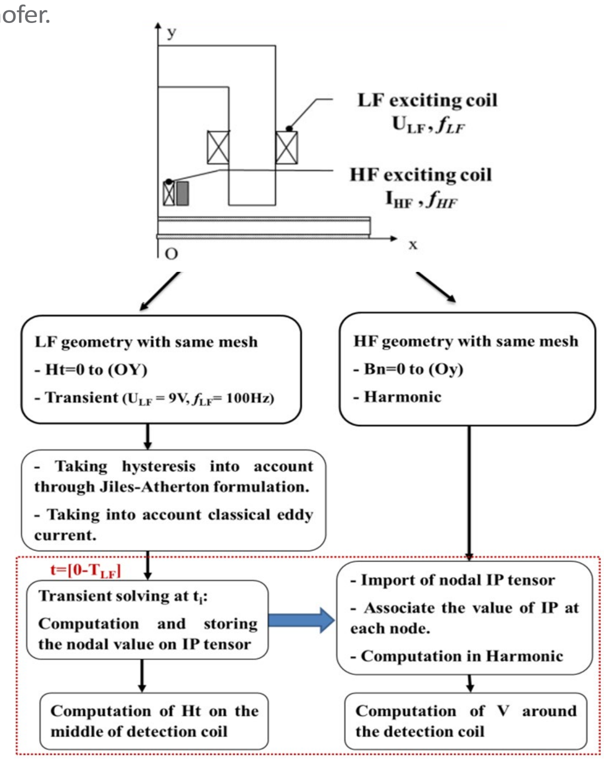

Figure 2: Diagram of computation strategy.

3MA devices

The 3MA is the acronym of micro-magnetic multi-parameter microstructure and stress analysis. This technic is used for non-destructive characterization of ferromagnetic materials properties base on magnetic effect at the microscopic level. Fraunhofer IZFP has developed a large panel of 3MA which is adaptable for different inspection situation, which is linked to the geometry (ring, strip, tooth,..), position (inclination, lift off,..) and size of the sample (figure 1).

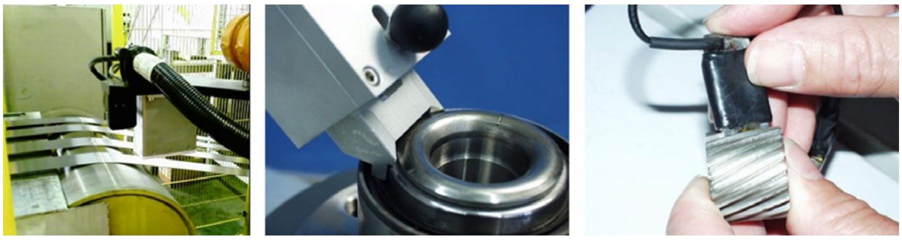

Figure 1: Different 3MA devices designed for different application.

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3MA combines four different micro-magnetic measurement procedures, namely Barkhausen Noise (BN), incremental permeability (μ_Δ), harmonic analysis of the tangential magnetic field strength (Ht) and multi-frequency eddy current analysis. Several test statistics are evaluated for every procedure, adding up to a total of 41 micro-magnetic output quantities. The advantages of combining test statistics in a multi-parameter procedure are manifold, especially when the target values (e.g. hardness, case depth) and the disturbance variables (temperature, residual stress, etc.) are subject to concurrent variations.

Challenge of 3MA FEM simulation

The most challenging simulation is the case of the incremental permeability (IP) method, because it consists in magnetizing the specimen at a low frequency (f_{LF} = 50- 200 Hz) hysteresis cycle and simultaneously measuring the materials impedance at each point of the cycle, with an eddy current pickup coil operating at a higher frequency (f_{LF} = 20- 250 kHz). The measurement is performed with the direct field determination to accurately control the local magnetization condition. The measured impedance is to be related to the incremental permeability, allowing to the estimation of several parameters such as the coercive field of the material.

The main challenge was to overcome the combination of the system's multi-scale geometry and multi-scale time signals, with the implementation of the hysteresis model. Then, a new computation strategy was developed and validated in 2D, separating HF and LF computation. This method allows performing faster computations with less memory space (see figure 2).

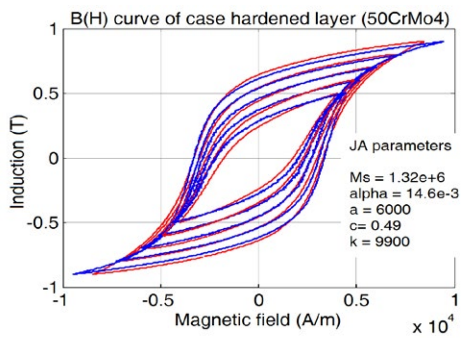

Figure 3: Hysteresis from measurement and model of the case hardened material

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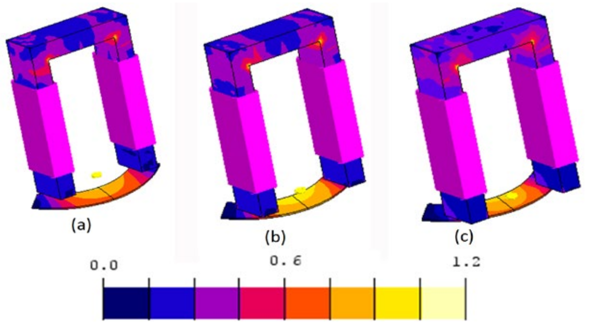

Figure 4: Flux density distribution (T) of the system Yoke -sample (a: inner side of the ring, b: center area, c: external side of the ring)

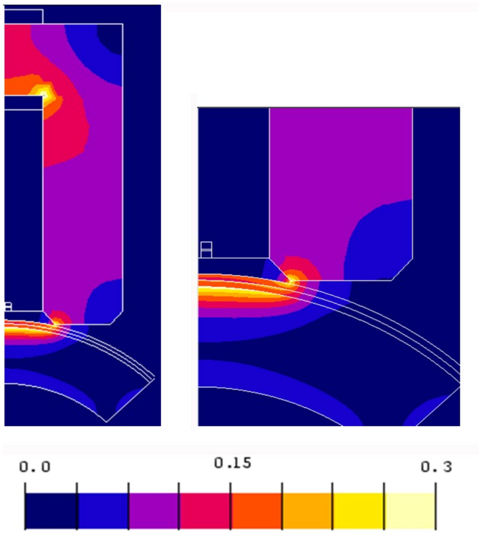

Figure 5: Flux density (T) on hardened material.

The Jiles- Atherton hysteresis model was applied for describing the static magnetic behavior of the magnetic material. The figure 3 shows an example of measured and modeled hysteresis of 22MnB5 for different induction. The coating layer is represented by the vacuum area with the electrical resistivity.

Validation

The definition of the limits of NDT investigation depth remains complex, by the multi-layer magnetic property of the material (gradient behavior) and the geometry of the sample (shape, position of the device to the sample). The conventional formula is not applicable for such applications. The FEM code offer reliable definition of skin depth. The best handling of setup parameter allows optimizing the investigated depth.

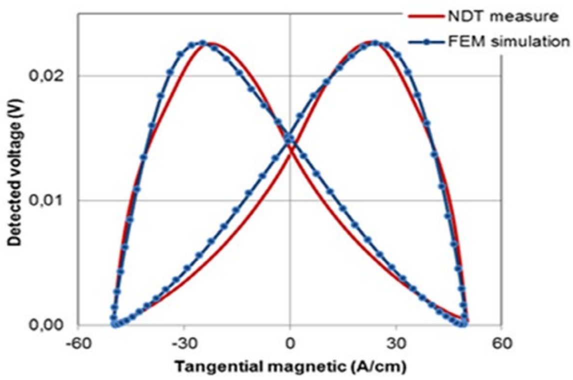

Figure 6: IP signal from measurement and simulation.

The figure 4 shows the induction distribution of the system 3MA probe –Ring of FeSi material, in three configurations: inner side, center and external side of the ring material (see figure 3), using these set up parameter: fLF = 300 Hz, Ht = 30 A/cm. the magnetic field penetrates the entire sample. The magnetic field distribution is different from one configuration to another, due the stray field and 3MA position.

The distribution of the induction is not homogeneous in case of multi-layer properties such as hardened material, the induction vary from one layer to another due to the change of permeability (see figure 5). The skin depth is estimated at 3.5 mm, using Ht = 70 A/cm and fLF = 50 Hz.

The simulation results have been validated by comparing simulated magnetic signatures and magnetic output parameters with experimental results. The figure 6 shows good agreement between results from FEM code and NDT measures..

The output parameters of IP signal are also compared. The relative error for Hcμ is less than 1% and for the other parameters is less than 10%. Linear correlation is between 3MA output signal and process parameter (hardening depth) is found (see figure 7).

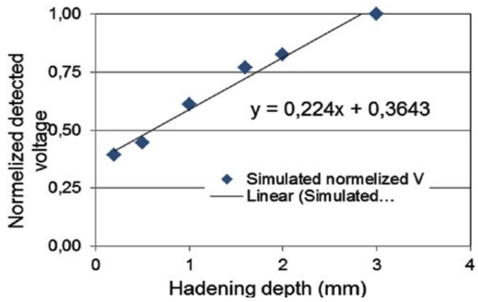

Figure 7: Correlation between hardening depth and 3MA output parameter.

Conclusion

A 3MA finite element code has been developed in order to study the magnetic response of multi-layer material. A more comfortable computation methodology is developed in order to manage the problem of memory space and computation time using separated calculation.

The 3MA simulation results prove the applicability of 3MA on a large panel of material with different geometry. Based on the simulation, optimized set-up parameters for the experiments are determined assuring best-possible penetration of field and investigation. Good correlation has been determined between 3MA measuring results and process parameter. Based on the simulation results, an “intelligent virtual” calibration could be developed, which will reduce the effort or amount of experimental calibration