

# Assessment of 3MA Technique Potentiality for Non Destructive Evaluation of Dual-Phase Steels using 2-D Nonlinear FEM and Taking Hysteretic Behavior Into Account

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**Abstract** — Modern flat carbon high strength steel strips allow reducing automotive body weight. However their properties are more exposed to process variations, therefore leading manufacturers such as ArcelorMittal to consider on-line monitoring methods for ensuring their consistency. Amongst these 3MA electromagnetic system is of particular interest, with a need to understand the link between microstructure and output signals.

Thus a modeling effort allows deriving successfully the magnetic signature of the most used so-called incremental permeability mode (IP) by FEM methods, overcoming issues with respect to multi-scale geometry & time, and the local hysteretic behavior identification at every point in the material under investigation.

## I. 3MA SYSTEM & IP METHOD

3MA is abbreviation of Micro-magnetic Multi-parameter Microstructure and stress Analysis. In its IP mode, low ( $f_{LF}$ ), and high frequency ( $f_{HF}$ ), excitation sources are combined [1], [2]. The sample is subjected to ( $f_{LF}$ ) excitation, with sufficient amplitude to reach induction levels ranging from 1 to 1.6 T in the sample. Simultaneously it is also submitted to a HF, very low amplitude (eddy current). The HF exciting coil investigates the central area of the sample along hysteresis loop created by the  $f_{LF}$  signal generated locally in the material.

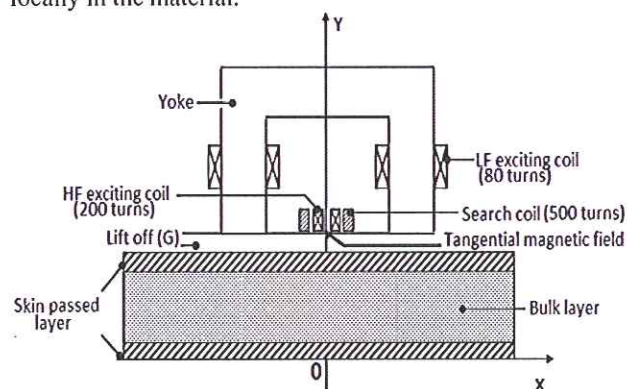


Fig. 1.3MA- specimen System

The measured signal of the pick-up coil after specific signal processing is proportional to the incremental permeability (IP). In practice, the variation of the voltage of this signal versus tangential magnetic field ( $H_t$ ) is recorded. Besides others, it allows accessing to the value of the magnetic coercive field.

## II. FEM MODELING AND CHALLENGES

The combined sample-sensor system has a multi-scale geometry (see figure 1). The sample itself is a multilayer system: the size of surface layer (skin passed layer) varies from 10 to 30  $\mu\text{m}$  and the bulk material layer is around 1 mm. The width of the yoke of the 3MA sensor is 100 mm. This scales a ratio of  $10^4$ , which requires adapted meshes depending on the area of sample-sensor system. The  $f_{LF}$  frequency varies between 50 and 1,000 Hz, whereas  $f_{HF}$  component is in the range between 10 and 100 kHz. The time scales ranges from  $10^3$  to  $10^4$ . Therefore an adapted temporal discretization is required to identify the high-frequency phenomena.

The magnetic material behavior must be locally described by a nonlinear hysteresis model. From the static hysteretic behavior, the local dynamic behavior was derived with a move-back method based algorithm.

The conventional computation results obtained by simulation of all the system step by step in time, using Flux® software [3], were encouraging. However, computation times exceeded three hour for 1/8th of the low frequency ( $f_{LF}$ ) period and 20 samples per high frequency ( $f_{HF}$ ) period. To overcome these problems of resolution and memory space, a new computational strategy was developed.

### A. Strategy computation

The strategy illustrated in Fig. 2. consists in dividing the computation in two stages, using two geometries with the same physical properties, only the limit conditions and the amplitude excitation are changing.

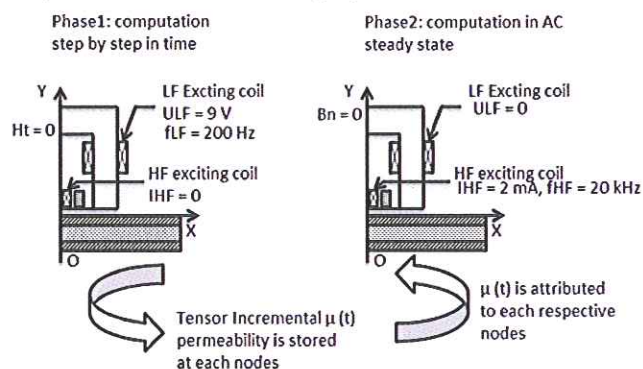


Fig. 2. Computation strategy

We start with the first phase: application of a  $f_{LF}$  transient excitation. The direction of the magnetic field should be normal with respect to the symmetry axis (OY). At each time step of this phase, the value of incremental permeability tensor (IP) is stored at each node of the sheet, and then is exported to the second phase computation ( $f_{HF}$ ), with an excitation level thousand times smaller than the first ( $f_{LF}$ ), which allows harmonic simulation. The voltage is detected around the search coil.

This strategy produced results in good agreement with the conventional computation. A maximum deviation of the detected voltage is estimated at 3%. Thus, the feasibility of the approach is validated in 2D Cartesian mode.

### B. Implementation of hysteresis model

Various models that take into account the dynamic ferromagnetic response under sinusoidal excitation have been proposed [4]-[5]. More effective representation can be provided a magnetic field models based on iron losses consideration in laminations by partitioning them into two parts [6]: Static hysteresis, eddy current. The Jiles-Atherton hysteresis model was applied for describing the static magnetic behavior of each layer of a dual phase steel. Fig.3. shows the accuracy between experiment and model result of the responses of the bulk layer in static and dynamic modes.

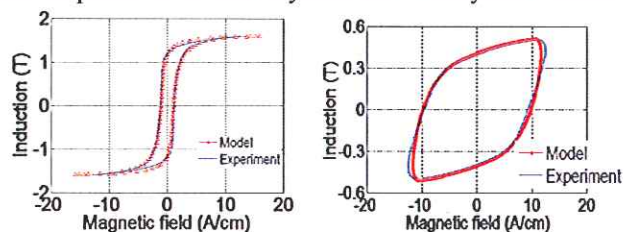


Fig. 3. Measured and simulated hysteresis loops at static  $f = 10$  Hz (left) and at dynamic level  $f = 200$  Hz (right)

The deviation between model results and experiment is estimated at less 2% for the center layer and 10% for the skin one. The deviation between model and measures for the skin passed layer is due the effect of residual stress which is neglect in this study. Only the maximum value of induction, magnetic field and specially the global slope of the hysteresis minor loop are important and taken into account.

The eddy current is taking into account by associating to the material region the property of magnetic conductor. The conductivity is defined from measurement  $\sigma = 3.56 \cdot 10^6$  S/m. The hysteresis behavior is taken into account just for the first phase of  $f_{LF}$  excitation. In order to attain the steady state results, the calculation is carried out during 3 periods ( $\approx 300$  steps). For example, the time interval  $\Delta t$  of the step by step method is chosen as  $5 \cdot 10^{-5}$  s, when the exciting  $f_{LF}$  is equal 200 Hz.

The aim of the first phase strategy simulation is to compute the incremental permeability tensor. It consists on applying a high frequency signal superimposition with a

small level signal but at high frequency. At each step of  $f_{HF}$  hysteresis loop, asymmetric minor loops are observed. The slope of these loops represents the incremental permeability.

### C. Validation

In order to assess the robustness of the strategy computation and FEM codes, experimental NDT results and FEM modeling signal are compared.

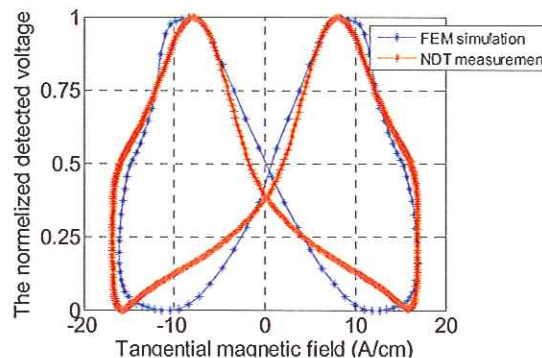


Fig. 4. Normalized voltage in a search coil when  $f_{LF} = 200$  Hz,  $f_{HF} = 20$  kHz, and  $H_{tmax} = 17$  A/cm.

The figure denotes that the measured and the simulated value of the detected voltage are almost in good agreement. The deviation of the peak which represents the coercive field is estimated at 8% (Measure: 9 A/cm, simulation: 8.3 A/cm).

## III. CONCLUSION

The results obtained are summarized as follows:

- 1) It is possible to overcome issues with memory space and computation time using the separated computation.
- 2) In order to reproduce the 3MA signature of IP method, further developments are achieved in Flux FEM software such as: Jiles –Atherton hysteresis model and analytical incremental permeability formulation.
- 3) The simulation results fit rather well with experimental data, thus reinforcing confidence in the outputs signals of the 3MA for assessing microstructure and mechanical properties of modern advanced high strength steels.

## IV. REFERENCES

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