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Electromagnetic Examination of Hardened Depth of Steel Using 2D Nonlinear Hysteresis FEM Analysis

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Abstract

The inspection of the hardened depth on surface carbon hardening steel is an important quality parameter in maintenance and for the other applications as well. For this purpose, two kinds of samples with different hardening depth are studied. The flux density in the surface hardening steel is examined using 2D finite element code taking into account the hysteretic and eddy current behaviour. The simulation results are compared to Experimental signals.

Keywords: Non-destructive testing, 2D FEM modelling, hardening depth, incremental permeability, hysteresis characteristics

1. Introduction

In industrial application, the induction hardening is commonly used for improving wear and fatigue in steel components. The estimation of hardening depth is an important parameter for accurate process control quality factor. A lot of methods are used for the measurement of hardening depth thickness. Micrographic observation based on optical microscopic analysis which makes the determination of the transition area between martensite and ferrite-perlite is the main weakness. The micro-hardness profile studied at the material cross section gives more precise depth of the case hardening. Nevertheless, both methods are time consuming and expensive. The growing demands of quality control and process monitoring of steel parts in mass production line requires fast and more economical examination, which leaves no chance for destructive tests.

Non-destructive testing (NDT) is not only limited for the application of defect detection or cracks but furthermore it is extended to the characterization of mechanical and metallurgical properties. Magnetic measurements are frequently used for the characterization of change in the structure of the ferrous material, because their magnetization processes are closely linked to microstructure. This fact makes magnetic measurement technics an evident candidate for non-destructive testing, for detection and characterization.

Previously, it has been shown that is possible to determine the hardness profile using an electromagnet multi-frequency eddy current [1], and Zergoug and al. investigated the relation between micro-hardness and changes in the impedance plane [2].

In this paper, the hardened depth of surface hardening carbon steel (SAE1070) using 3MA Incremental Permeability (IP) method is investigated by experiments and numerical FEM calculation. The hysteresis properties of different layers of the non-hardened and hardened part of SAE1070 are measured. The magnetic behaviour of the layers is represented by hysteresis Jiles Atherton model and it is implemented in the Flux FEM code. The comparison of the IP simulated signal to the experimental one show good accuracy.

2. Experiments

2.1 Destructive tests

2.2.1 Surface hardening carbon steel of two samples

Two steels are proposed, SAE1070 and 50CrMo4. The steels have a similar chemical composition with the main difference is the lower 0.5% carbon content for 50CrMo4 compared to 0.7% for SAE1070. The surface hardening process will result in a martensitic hardened case and an unaffected softer core material as described in figure 1. Therefore, two different materials need to be described for each steel grade. The core material is fine lamellar and spheroidized pearlite, while the case is martensitic.

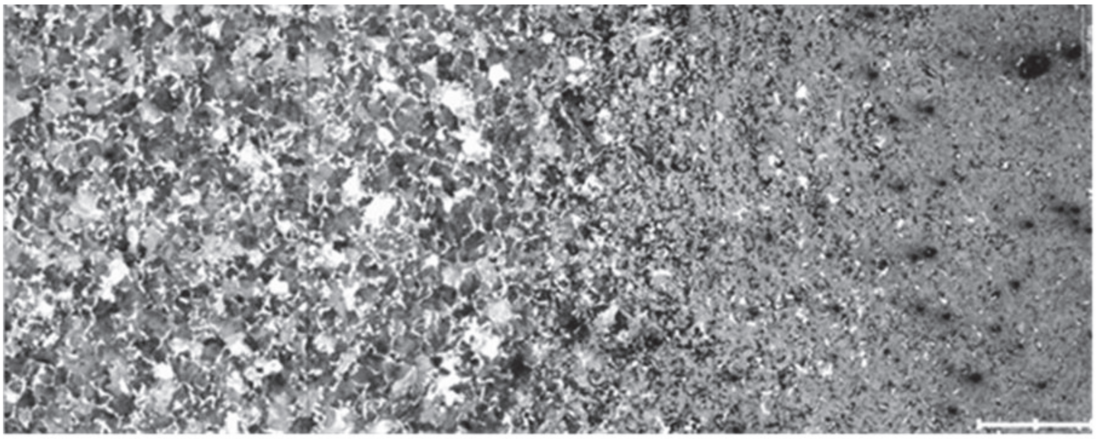


Figure 1:Microstructure of the case (martensite) and the core (pearlites)

The surface hardening process applied for these steel grades are different, where the main difference is the width of the transition zone which also can be described as the slope of the hardness profile for both samples shown in figure 2.

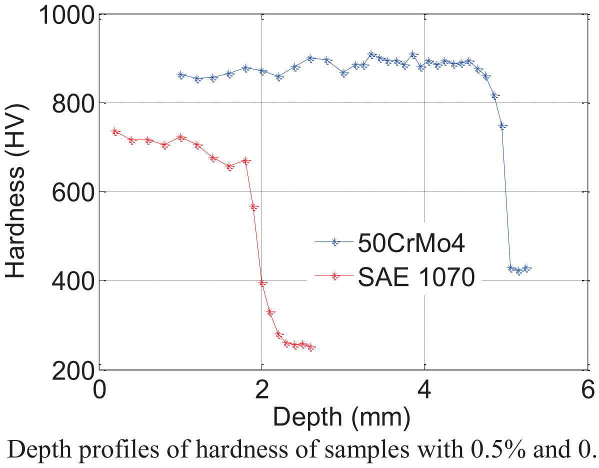


Figure 2: Depth profiles of hardness of samples with 0.5% and 0.7% of carbon

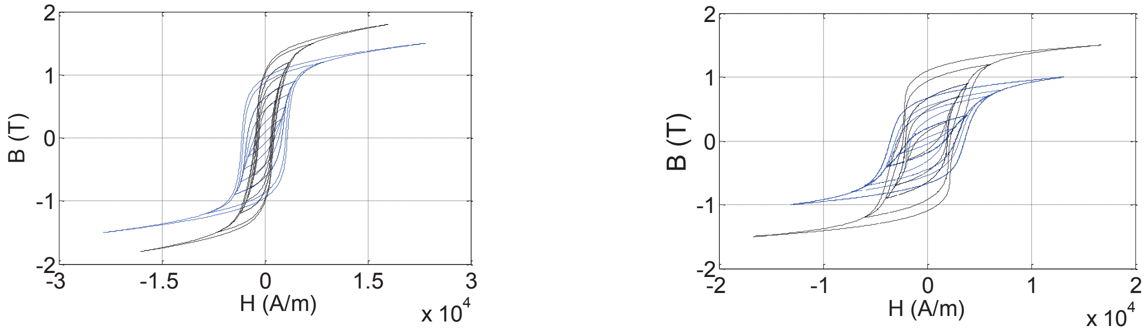
In this study, hardness in the martensite and pearlite ferrite is in the range of 864-893 and 430-426 HV, respectively for the sample of 0.5% of carbon. For the sample SAE1070, the hardness of the case layer varies between 736 -771 HV and the core is in the range of 281-252 HV.

2.2.2 Measurement of B-H curves of carbon steel SA1070

There are two standard methods for the measurement of magnetic properties, classical Epstein frame which remains the main instrument used for the electromagnetic evaluation. For testing steel strips are cut in the size of 300×30×0.25-0.5 mm in a square frame with magnetization and induction windings [3]. This method is accurate but it is expensive and time consuming. The European initiatives focused on the simplification of this method to a single sheet tester. This technique requires only one steel sheet, rounded by the magnetization coil windings and pressed by two big yokes from magnetically soft steel such as ferrite [4]. Both methods require a big section and the longer average of the field circulation. Due to the low power and hardness of the carbon steel, it is chosen to use ring shape of sample.

The magnetic properties are measured classically on magnetically closed ring-shaped specimens with driving and induction coils, uniformly wound along their perimeters. The rings are characterized at each level of induction.

The figure 3 presents the results of hysteresis measurement of the core and case area of both specimens: 0.5% and 0.7% of carbon.



(a) (b)

figure 3: Hysteresis curve of the core and the case area of both specimens (a: 0.5% C, b:0.7% C)

The measurement are realized at quasi-static low frequency magnetization f =10 Hz. The 3MA probe operates between 100Hz and 200Hz. The magnetic behaviour difference between A loop at f = 10Hz and f=100Hz is only 4%. This is due the eddy current phenomena.

2.2 Non-destructive tests

2.2.1 3MA Principal

3MA is the acronym for Micro-magnetic Multi-parametric Microstructure and stress Analysis. The 3MA device allows a nondestructive inspection of ferromagnetic materials as steels by combining four micro-magnetic measurement techniques, which are Barkhausen Noise (BN), Eddy Current analysis (EC), Harmonic Analysis of the tangential magnetic field (HA) and Incremental Permeability (IP).

In this study, we will focus on the Incremental Permeability method (IP). It combines 2 excitation sources, a first at a low frequency (LF), typically in the 50 - 200 Hz range and a second at a high frequency (HF), which is the range of 10 kHz to 150 kHz [5]. In contrast, the HA method uses LF excitation only and EC method is connected with a pure HF excitation. In more details, IP method consists in applying a low frequency (f_{LF}) excitation to the sample, with sufficient amplitude to reach induction levels up to 1.6 T in the specimen.

Simultaneously, the sample is submitted to high frequency (f_{HF}) excitation of very low amplitude. The HF excitation coil investigates the central area of the sample along hysteresis loop created by the f_{LF} signal, generated locally in the material. The processed eddy-current signal detected from a search coil is proportional to the incremental permeability (IP). In practice, the voltage of this signal is recorded and plotted against the applied tangential magnetic field (Ht). Based on such profile curves, it is possible to determine several parameters which reflect the magnetic properties of the material, like the magnetic coercive field Hcμ [6-7].

Several mock ups with different percentage of carbon and with different hardening depth are provided. The samples have cylindrical geometry with inner diameter of 36.6 mm.
The position of 3MA NDT probe is very important. In fact, for such a complex geometry, the flux surface distribution varies when the yoke is positioned on the tangential and the axial direction. The field profile is influenced by the flux leakage which is from the head leg and by the stray field from the driving coil. In order to guarantee high penetration of the field and reduce the flux leakage, we have limited our study to the tangential direction.

3. FEM modelling

3.1 Electromagnetic inspection model

The figure 4 shows the inspection 2D model of wheal bearing in the tangential direction. The inspection probe is composed of a yoke, an exciting coil (100Hz, 2V), Hall sensor, the transmitter and receiver coils. Both of these coils are set in the center of the yoke, above the sample. The magnetic field is controlled by a tangential hall sensor which is situated near the transmitter and receiver coils.

The finite element (FE) software is Flux multiphysics. The non-linear hysteretic behaviour of magnetic material is described by the inverse Jiles-Atherton hysteresis model H(B). This formula is implemented in the FEM Flux software with subroutines which is plugged to the finite element code.

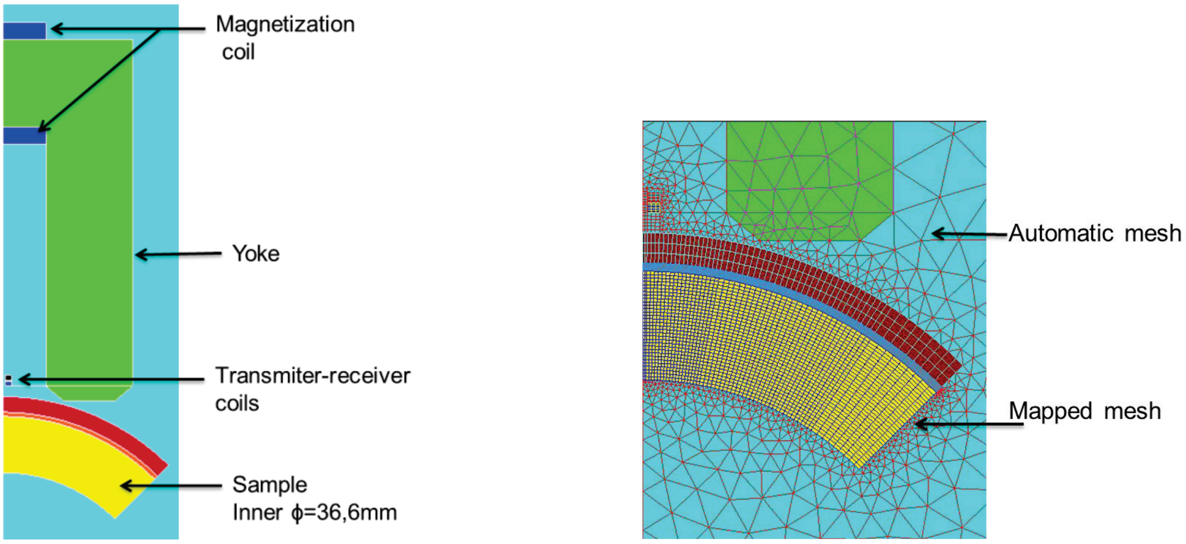


Figure 4 : 2D FEM model

The basic equation of the eddy current analysis using the A-Φ method is given by:

$$\begin{aligned} & rot\left(\nu\, rot A\right) = J_0 - \sigma\left(\frac{\partial A}{\partial t} + grad\ \Phi\right) \\ & div\left\{-\sigma\left(\frac{\partial A}{\partial t} + grad\ \Phi\right)\right\} = 0 \end{aligned} \tag{1}$$

Where A is the magnetic vector potential, Φ is the electric scalar potential; ν is the reluctivity, J_0 is the current density and σ is the conductivity. The flux and eddy current are analysed by the step by step method taking into account the nonlinearity of the material, especially the magnetic material history. Generally, such computations would be very time-consuming and require a huge memory space.

Therefore, a new computation strategy was developed in FEM Flux software code [9] and validated in 2D. This method allows performing computation in a fraction of the time and requires less memory space [10]

The strategy consists in dividing the computation in two phases. The LF and HF simulations are performed separately, but remained linked by the magnetic state of the different layers induced by the LF computation. Thus, two models are created with the same geometries and meshes and are run consecutively at each time step of the LF computation. Only the boundary conditions, the current excitations and the magnetic properties of the sample change. Moreover, this separation enables to restrict the simulations on the half of the geometry using symmetries and boundary conditions.

Phase1:

In this phase, the magnetic field distribution is represented by the Jiles-Atherton static (JA) model. The contribution of the classical eddy current is added in order to take into account the low frequency eddy current (f_{LF} = 100 Hz), by assigning magnetic-conductor property to the material. The conductivity is defined from measurement $\sigma = 3.56.10^6$ S/m. The Hall sensor is represented by a local computation of the tangential magnetic field, and is stored at each time step of the LF period.

At each time step t_i of the LF period and at each node of the sheet layers, the local incremental permeability tensor is computed using a move back method. It means that at each time step $t_{i,}$ a small signal with high frequency (same f_{HF} of the Phase 2) is applied. The JA hysteresis is called for the second time and it results on a non-centered asymmetric loop. Although the JA model is not accurate for the closure of non-centered loop but in this case only the slope (IP) is important.

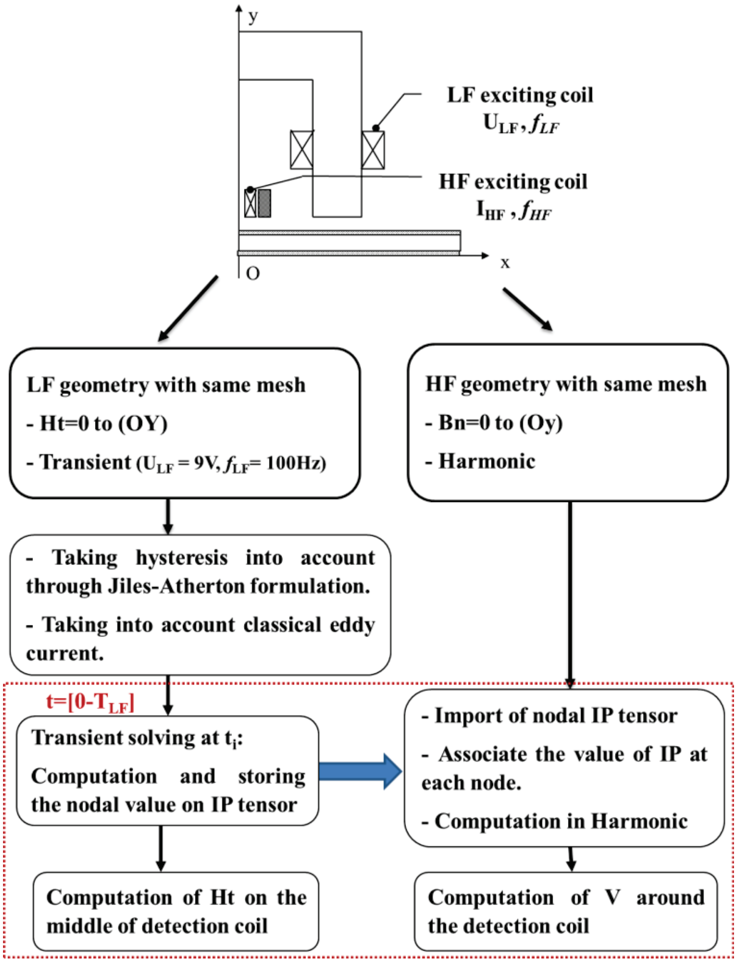


Figure 5: Diagram of strategy computation

Cedrat-Group which develops FLUX FEM software has made available a system of data exchange by exporting and importing nodal values. By this process, the nodal incremental permeability tensor is exported and stored on text file for each time ti (figure 5).

Phase2 (HF):

The nodal values of IP are imported to the second model HF and associated to their respective nodes. The HF simulation is then performed in AC steady state domain due to the low excitation level, and enables to compute the voltage around the search coil. The detected signal describes the apparent behavior of the incremental permeability of the skin depth. The process is repeated at each time step of the LF simulation.

A macro control in Python language compatible with Flux software is developed in order to implement automatically this process. The computation strategy is validated and applied on a simple case simulation [10].

4. Results and discussion

4.1 Validation

Two mock ups of 0.5% and 0.7% of carbon without any hardening are provided. The measured and the simulated signals are compared under the same condition (figure 6, 7, 8).

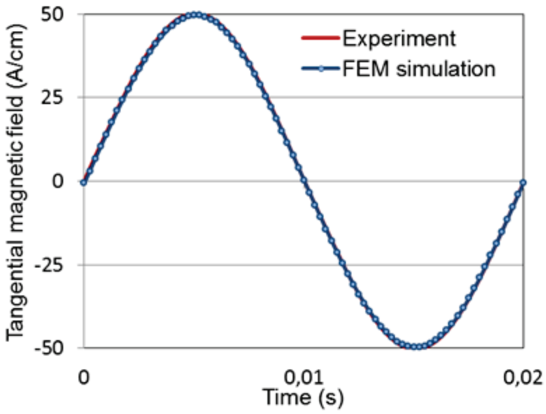


Figure 6: Measured and simulated tangential magnetic field

The incremental permeability signal for both sample are presented figure 8 and figure 9.

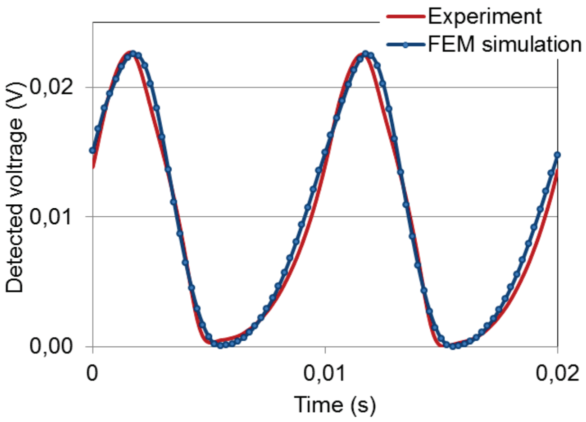


Figure 7: IP signal from simulation and measurement on 0.5% C sample

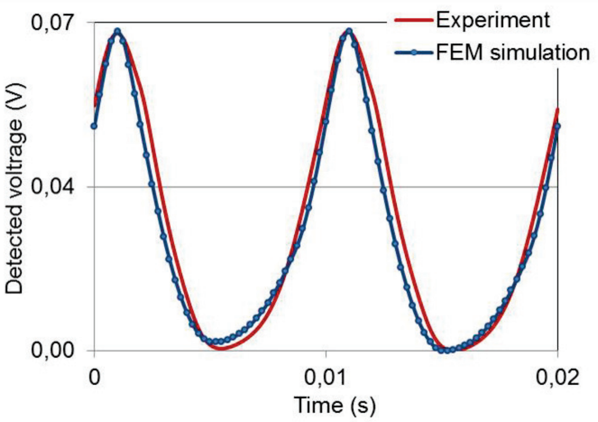


Figure 8: IP signal from simulation and measurement on 0.7% C sample

The FEM tool has successfully reproduced the 3MA signals on homogeneous material with less 10 % difference with measurements. The output parameters from simulation are quite similar to the measured one, especially the value of coercive field which is reproduced with less 4%.

Furthermore, good qualitative coincidence in coercive field between measurement and calculation results from hysteresis characterization and 3MA NDT investigation.

Table 1. Chemical Piece Analysis of Test Rods

	Hc from hysteresis (A/cm)		**Hc from NDT(A/cm)**	
	Measurement	**Analytical model**	**Measurement**	**FEM simulation**
SAE 1070	11,57	10,9	13,17	13,60
50CrMo4	22,02	23,27	23,1	22,6

The hardness of both 50CrMo4 and SAE1070 are respectively 250HV and 423HV. Moreover, there was additional elements which inverse the tendency and makes the steel with low content of carbon more hardness than SAE1070. The coercive field increases with the hardness, the results from NDT and hysteresis measurements match this tendency.

4.2 Correlation between magnetic and mechanical properties

The incremental permeability method is tested to estimate the hardening depth. A series of simulations is run varying the thickness of the hardened layer from 0.5 mm to 4 mm. The variations of the detected voltage are presented in figure 10 and figure11. The simulations are run under these conditions: f_{LF} = 50 Hz, Ht = 50 A/cm and f_{HF} = 150 kHz.

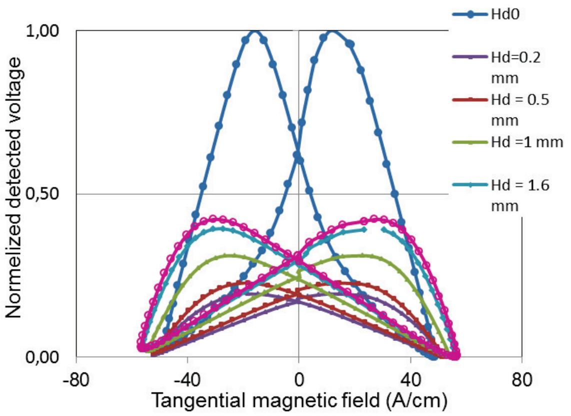


Figure 10: IP signal of multilayer sample with different hardening depth

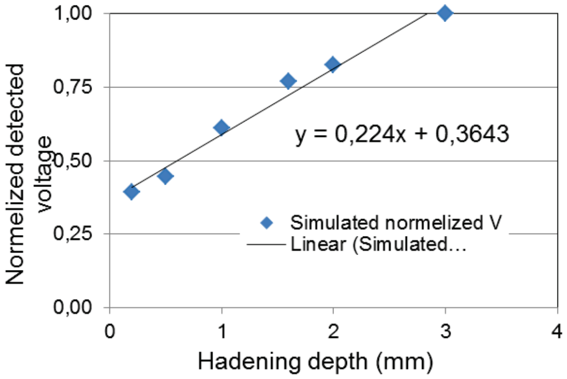


Figure 11: Correlation between Hardening depth (Hd) and 3MA output parameter

The figure 10 denotes the variation of the IP signal for different hardening depth. The figure 11 shows the IP signal amplitude with the hardening depth. The normalized value of the detected voltage Mu_{max} increases linearly in the range of Hd= [0.5-3] mm. The apparent permeability of the skin depth and conductivity increases. Since the hardened area increases, the skin depth increases, and then the flux go through the intermediate and the bulk area, and the apparent induction becomes bigger.

5. Conclusion:

A 3MA finite element code has been developed in order to study the magnetic response of hardened material. A more comfortable computation methodology is developed in order to

manage the problem of memory space and computation time using separated calculation.
In order to reproduce the 3MA signature of IP method, further developments have been achieved in Flux® FEM software such as: Jiles–Atherton hysteresis model and analytical incremental permeability formulation. The simulation results fit rather well with experimental data. Linear correlation was found between 3MA output parameter and hardening depth.

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