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Experimental Measurements and Numerical Simulation of ID and OD Signals in Plate Ferromagnetic Materials Using Magnetic Flux Leakage

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Abstract- In this paper, magnetic methods are used to detect inner and outer defect in plate ferromagnetic materials. A new magnetic yoke is introduced. A numerical analysis, based on FEM-BEM code is performed. The nonlinearity of the problem is treated by using a fixed point procedure. An experiment is set-up and the sensitivity of the method is analyzed for both inner and outer defects. The effectiveness of the method is discussed.

1. INTRODUCTION

Magnetic Flux Leakage (MFL) has been established as an effective method in the detection of inner (ID) and sub-surface defects in ferromagnetic structures [1]. Recently, the degradation of the low alloy stainless steel welds has been reported in PWRS in USA and France [2]. The defects usually appeare on the outside surface (OD) due to the high stresses and the presence of contaminants from the insulation and protective materials or atmospheric corrosion. The necessity to detect and improve the sensitivity of signals from both OD and ID requires new enhancements of the detection and analysis in MFL.

In the paper, a new magnetic yoke is used to magnetize plate ferromagnetic sample. Also, a nonlinear analysis based on FEM-BEM code is performed, and the signal is calculated for both ID and OD in the remanent state.

An experiment is set-up and magnetic measurements are done in both active and passive field. Magnetic field is measured by using Hall sensors. Variation of the field due to various air gap distance between yoke and sample, and yoke movement above the crack area is studied. The effectiveness of the method is discussed for both ID and OD in remanent and active field.

2. NUMERICAL FORMULATION OF FEM-BEM CODE

A new code based on FEM-BEM for treatment of the ferromagnetic materials was developed [3]. Using Maxwell equation and Coulomb gauge the governing equations are obtained:

$$\frac{1}{\mu_0}\nabla x(\nabla x\vec{A}) = \vec{J}_S + \vec{J}_M = \vec{J}_S + \nabla x\vec{M}, \quad \text{in} \quad \Omega_m \tag{1}$$

$$\frac{1}{\mu_0}\nabla x(\nabla x\vec{A}) = \vec{J}_S, \quad \text{in} \quad \Omega_0 \tag{2}$$

where Ω_m is the magnetic material, Ω_0 is the air region, $\vec{J}_S$ is the external currents sources, $\vec{M}$ is the magnetization of the material and μ_0 is the magnetic permeability of the air. External current source are supposed to exist only in the non–magnetic region. On the interface between FEM and BEM domains the following condition assures the continuity of the tangential component of $\vec{H}$:

$$\left.\frac{\partial\vec{A}}{\partial\vec{n}}\right|_{BEM} = \left.\frac{\partial\vec{A}}{\partial\vec{n}}\right|_{FEM} - \vec{M}x\vec{n}\ . \tag{3}$$

Applying Galerkin procedure, the above equations are discretized using shape functions approximation. Integrating on the problem volume, the following equations systems are obtained:

$$[P]\{\vec{A}\} = [K]\{\vec{F}_0\} + [S]\{\vec{M}\} \tag{4}$$

where [P], [K] and [S] are matrix. The source term { $\vec{M}$ } is used to correct the nonlinearity characteristics of the magnetic field. In the present implementation a fixed point procedure was adopted [4]. Starting from an initial zero value of magnetization, magnetic field is calculated and next value of magnetization is computed, based on a hysteresis model, which is input for the next iterative step.

3. EXPERIMENTAL MEASUREMENTS

In a 14 mm thick plate sample made of F82H ferromagnetic material three cracks with semi-elliptical shape were machined. The crack width is 0.5 mm, length is 15 mm and depth is 3, 6 and 9 mm respectively. Position of defects on the plate is indicated in Fig. 1. The dashed line represents a imaginary crack shape with zero volume. Plate is magnetized with the use of the yoke, shown in Fig. 2. On the left and right arm of the yoke, two exciting coils with 35x35 mm cross section are used to generate magnetic field. In all experimental measurements the yoke is centered above the defect area in that way that the direction of crack is perpendicular to the imaginary line connecting the polar pieces of the yoke. Magnetic flux is measured using BH 200 Hall sensors located between yoke legs or in the air gap between yoke and sample. The active surface is 1.77x5.33 mm. Experimental measurement of the magnetic field is associated with the central point of sensor.

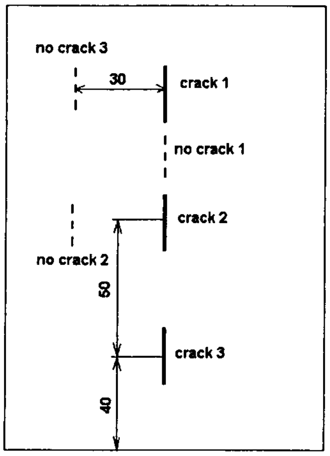


Fig. 1. *Geometry of F82H plate sample. Cracks location.*

The schematic of the experiment set-up is presented in Fig. 3. A function generator provides a sinusoidal shape form (used in demagnetization procedure) and a triangular shape form (used in attaining remanent state of sample). Current is amplified and driven to the yoke coils, which magnetize the material. The output signal from Hall sensors is filtered and recorded in the digital oscilloscope Tektronix TDS400. The movements of the yoke (for active measurements) and of Hall sensors (in passive measurements) are controlled by the XYZ stage. The exact location of the cantilever is recorded also with oscilloscope.

Three types of experimental measurements were performed. In the first one, yoke is centered above crack area and sample is magnetized and first demagnetized. After yoke is removed, remanent field is measured by scanning defect zone. During magnetization the total current in one coil was increased up to 4000 A. The air gap between yoke and sample was 0.55 mm. The current was increased and decreased in small steps to avoid eddy currents effects. The problem was numerically simulated using the FEM-BEM code. Finite element mesh during simulation is shown in Fig. 4. The yoke material is pure iron, with magnetic characteristic drawn in Fig. 5.

In Fig. 6 is presented a comparison between experimental signal and simulated one. The OD, 6 mm depth was scanned in the direction along its length. Good agreement was obtained in this case.

In Fig. 7 is shown the comparison between experimental and simulated signal for ID. During simulation, ID shape was parameterized using cell approximation. For ID the simulation results are good only in the central part of the signal. One reason for the discrepancy is the shape parameterization that increases the signal error at the edge of the crack.

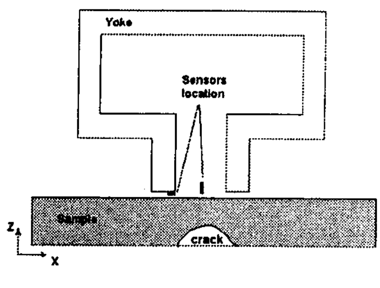


Fig. 2 *Location of Hall sensors experiment*

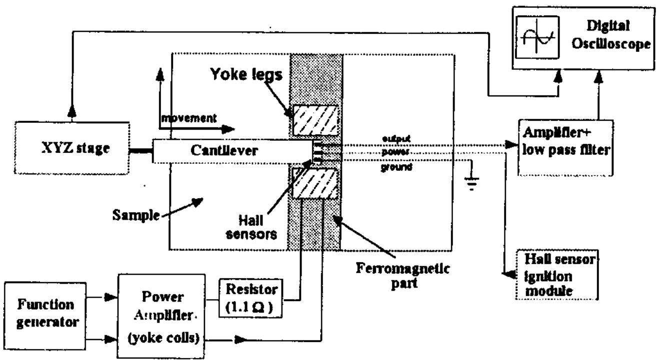


Fig. 3 *Schematic arrangement of the*

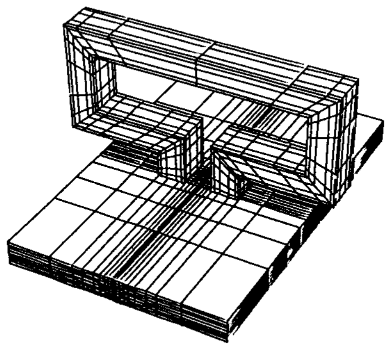


Fig. 4 *FEM mesh*

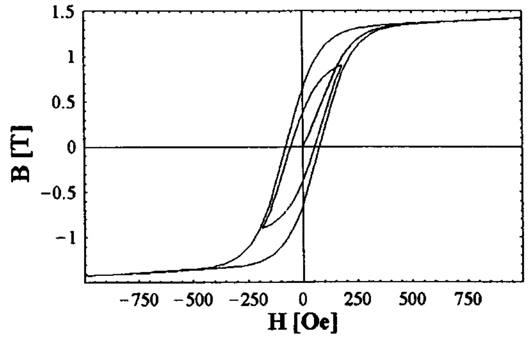


Fig. 5 *Ferromagnetic characteristic of pure iron*

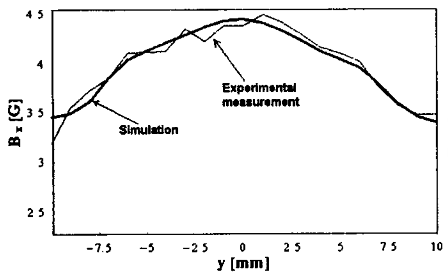


Fig.6 *Comparison between experimental and simulated result in the remanent state, for OD.*

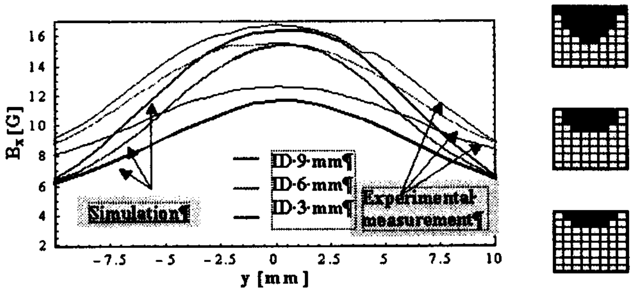
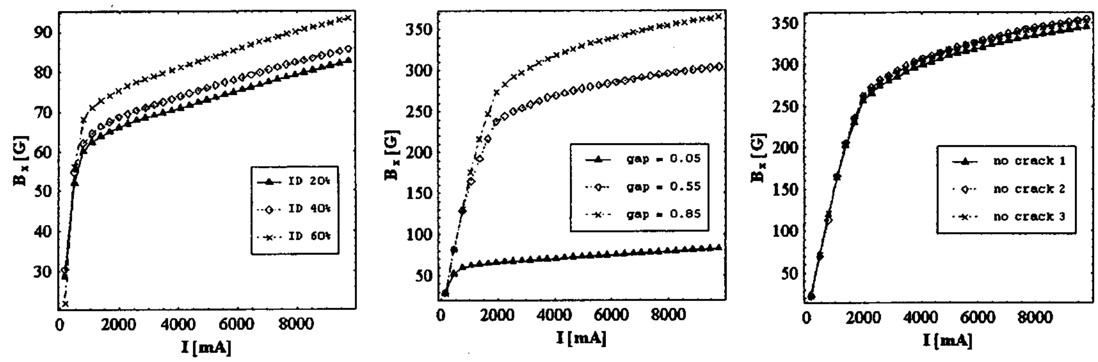


Fig. 7 *Comparison between simulation experimental Measurements for ID. Parameterization of the ID*

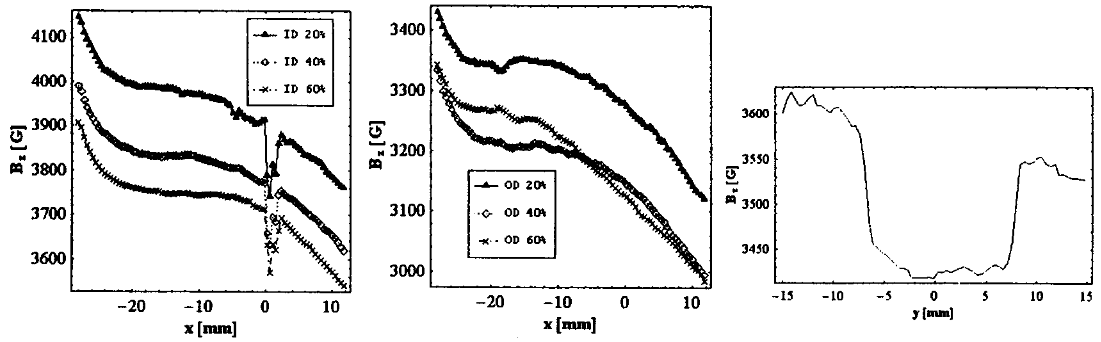


a) b) c)

Fig. 8. a) *Variation of Bx with current I when air gap is 0.05 mm; b) Bx dependency on current I for ID20% ; c) Bx dependency on current I in the no crack area.*

In the second type of experimental measurements the sample is magnetized and magnetic field is measured. During magnetization, Hall sensor is located between polar pieces of yoke in the central part, above the crack zone.

In Fig. 8a is shown variation of the Bx magnetic field for different amplitudes of exciting current. Results are available for ID. The air gap yoke-material was 0.05 mm, resulting in a small leakage field. Increasing the current (one turn) from 2A to 8A the gain in the signal amplitude is around 20%. In Fig. 8b the air gap is increased resulting in an increase of leakage field. Also, for all different air gap distance, the gain in the signal amplitude is small when the current in wire coil is more than 2 A. In Fig. 2c is presented the signal variation when the yoke was positioned above "no crack" area. For the same current, the signal is changing, showing that edge effect is important.



a) b) c)

Fig. 9. *Signal variation when yoke is moving in direction : a) transversally to ID; b) transversally to OD ; c) parallel to ID.*

In the third type of experimental measurements, yoke was used to magnetize the sample and was moved along crack area.

The constant lift-off between yoke and sample is maintained by rolling the yoke on two non-magnetic friction bearings during movement. In this experiment, sensor is located in the air gap between yoke and sample, measuring Bz component of magnetic field.

In Fig. 9a is presented the signal variation when yoke is crossing transversally the crack. During movement, the relative position of the yoke to the crack is the same like that one used in obtaining remanent magnetization. The coordinate position in the graphic corresponds to the location of Hall sensor. The ID is situated at "0" coordinate. It can be seen that there is a strong peak coming from ID when sensor is passing crack. Also, for different ID with depth variation, signal is quite different in amplitude.

In Fig. 9b is shown the signal variation when yoke is passing over OD. We notice that amplitude of signal from OD 40% is between the signal from OD 20% and OD 60%. We assumed that a large influence of edge effect is present. The OD 20% and OD 60% are located in the same relative position on the sample and OD 40% on the middle of the plate. In order to correctly extract the signal from OD edge effect must be taken into consideration.

In Fig. 9c is drawn the signal when yoke is moving longitudinally over ID. The beginning and ending of defect is easily sensed by sensor and actually the real length of the crack, 15 mm, is very well estimated.

4. CONCLUSIONS

ID and OD in ferromagnetic materials were analyzed by using magnetic flux leakage method. Numerical analysis of the crack signal in remanent state shows good agreement with experimental measurements. An experiment was set-up to analyze the crack signal in active measurements. Signal from ID has high sensitivity but edge effect should be taken into consideration in the analysis of OD signal. Also, the length of ID is very well evaluated.

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