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A measurement setup for acquiring the local magnetic properties of plastically deformed soft magnetic materials

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This paper introduces a new measurement setup for extraction of the local magnetic properties. With the help of finite element method simulations, modifications are made on the previous double-C-yoke method. Small dimension measuring coils are applied in the stray field produced by the magnetic circuit to evaluate the local magnetic properties of the specified part of the specimen. Through the measurements with the plastically deformed materials at different temperatures, it indicates that the magnetic properties of soft magnetic materials are quite sensitive to plastic straining. After high-temperature thermal treatment on the plastically deformed specimen, the local magnetic properties exhibit an obvious recovery. © 2011 American Institute of Physics. [doi:10.1063/1.3535549]

I. INTRODUCTION

Plastic deformation causes local magnetic degradation of the electrical steel sheets, it is attributed to the generation of dislocations acting as pinning sites for the domain walls.¹ Therefore, it is necessary to characterize the local changes of the magnetic properties in an appropriate way. The standard measurement methods in alternating magnetic fields can precisely determine the average magnetic properties of magnetic materials, e.g., the Epstein frame² and the single sheet tester³ methods. However, the local magnetic properties over certain parts of plastically deformed material cannot be measured with these methods. Presently, there are some effective methods to measure the local magnetic properties, e.g., the search coil method and the needle probe method.⁴ The search coil method is applied by drilling holes in the specimen, which has an effect on the magnetic properties. The needle probe method needs precise probes arranged along the specimen to achieve accurate results, but for the materials with isolating surface, this method cannot work properly. Therefore, we propose a new approach to measure the local magnetic properties.

The measurement setup described in this study is based on the double-C-yoke method. Compared with the single-yoke measurement, the double-C-yoke measurement shows less influence caused by the eddy currents in the specimen.⁵ By means of finite element method (FEM) simulations,⁶ the magnetic field in the material is found to be parallel with the magnetic field in the surrounding air, the amplitudes of both fields are similar to each other. To determine the local magnetic property of the specified part of the material, a small dimension H-coil is applied over the surface of the specimen to measure the magnetic field in the surrounding air. More detailed introductions of the measurement setup are described in Sec. II, the results of the measurements made over the plastically deformed materials are shown in the upcoming sections.

II. OVERVIEW AND ANALYSIS OF THE MEASUREMENT SETUP

Based on the previous double-C-yoke method, specimens are placed between two symmetrically furnished C-yokes to form two parallel closed magnetic circuits. The excitation signal is fed to two series-connected excitation coils surrounding each C-yoke. Normally, the measuring coils surround most of the specimen area to evaluate the general magnetic properties. In order to measure the local magnetic properties of the exact part, measuring coils must have properly small interfaces with the specimen. To determine an appropriate measurement method, FEM simulations are carried out here on the magnetic circuits.

As the measurement method is applied in alternating magnetic fields, the eddy current must be considered. Based on the skin effect,⁶ the penetration depth of the specimen δ can be evaluated as

$$\delta = \frac{1}{\sqrt{\pi\gamma\mu f}}, \quad (1)$$

where γ is the electric conductivity of the specimen, μ is the absolute permeability of the material, and f is the excitation current frequency.

The measurements are performed on soft magnetic material laminations with high electric and magnetic conductivity (e.g., M33035A, $\gamma \approx 10^7$ S/m, $\mu \approx 1000\mu_0$, thickness ≈ 0.35 mm), and the excitation signal is in low frequency (1–25 Hz). Hence, the penetration depth is much larger than the thickness of the specimen. It can be considered that the current induced in the alternating magnetic field can uniformly flow through the specimen, and the magnetic field in the specimen is homogeneous. Consequently, the eddy current effect can be neglected here.

To simplify the simulation process, the simulation is carried out with direct excitation current. Figure 1 demonstrates the magnitude of the magnetic field in the magnetic circuit. It can be seen that the magnetic field in the material

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FIG. 1. (Color online) The FEM simulation result of the magnetic field in the double-C-yoke magnetic circuit.

shares the equivalent amplitude with the magnetic field in the surrounding air. Through the simulation on the vector field, it is found that the closer the air is to the specimen, both magnetic fields in the two media are more parallel with each other.

Therefore, the magnetic field in the specimen can be determined by measuring the magnetic field in the surrounding air. To improve the measurement accuracy, the magnetic field measuring coil is wound around a $50\text{ mm} \times 15\text{ mm} \times 1.6\text{ mm}$ polyvinyl chloride core, which has the same constant permeability as the air. The H-coil is placed close to the specified part of the specimen. Through the induced voltage over the coil u_{inH} , the magnetic field in the specimen H_s can be calculated from the following expressions:

$$B_H = \mu_0 H_H, \quad (2)$$

$$u_{inH} = -N_H A_H \frac{dB_H}{dt}, \quad (3)$$

$$H_s = H_H = -\frac{1}{\mu_0 N_H A_H} \int u_{inH} dt, \quad (4)$$

FIG. 2. Overview of the measurement system.

FIG. 3. (Color online) The measurement results compared with the Epstein frame method.

where B_H and H_H are the magnetic flux and the magnetic field in the H-coil, N_H is the number of H-coil windings, and A_H is the cross section of the H-coil where the magnetic flux flows through.

Figure 2 displays the overview of the measurement setup. As can be seen from the figure, the magnetic flux coil is placed around the specimen and the H-coil. The local magnetic properties measured here are the average magnetic properties of the specified part of the specimen under the H-coil. Due to the small number of H-coil windings, an amplifier is utilized here to enlarge the voltage signal over the H-coil. Because of the low-frequency excitation signal, much effort has to be put into signal conditioning in frequency domain.

In order to validate the accuracy of the measurement results, a comparison with the Epstein frame method is made. As can be seen from Fig. 3, the double-C-yoke results show a comparative accuracy with lower excitation frequencies. For higher frequencies, the hysteresis curves change to oval form, which will affect the precision of the measurement results.

III. RESULTS AND DISCUSSION

A. Room temperature measurement

To observe the plastic deformation influence over local magnetic properties, cold plastic training is applied in the specimen. The measurements are carried out both in the deformed part and the undeformed part at room temperature (20°C). The results are displayed in Fig. 4. Compared with the results made before deformation, the magnetic property shows an obvious decrease in the deformed part, the magnetic property of the undeformed part is also influenced. Generally, the plastic deformation causes the change of the dislocation density, this change affects the pinning strength of domain walls and consequently their movement.⁷

B. High temperature measurement

Figure 5 shows the measurement results in high temperature condition between 20 and 140°C . As shown in the figure, the magnetic properties exhibit a certain decrease with an increase of the temperature, and the undeformed part shows more obvious changes compared with the deformed part.

FIG. 4. (Color online) The measurement result of material M33035A (rolling direction) with 1 Hz at room temperature.

C. Measurement after thermal treatment

For further observation, the thermal treatments in the nitrogen environment are carried out on the plastic deformed specimen. After being annealed in the nitrogen environment the magnetic permeability changes can be shown (see Fig. 6). As the comparison reveals, the local magnetic properties of

FIG. 6. (Color online) The measurement result of material M33035A (transverse direction) with 25 Hz after 800 °C thermal treatment.

the deformed part and the undeformed part both show an obvious recovery after thermal treatment.

IV. CONCLUSION

A measurement setup based on the double-C-yoke method is discussed in this paper. Accurate measurements are achieved with low-frequency excitation. The measurement results at different temperatures demonstrate the influence of the plastic deformation over local magnetic properties. The high-temperature thermal treatment promotes a clear recovery on the local magnetic properties of the plastically deformed part of the specimen.

FIG. 5. (Color online) The measurement result of material M33035A (transverse direction) with 10 Hz between 20 and 140 °C.

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