Development of Vector Hysteresis Model using a Magnetic Flip Model

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***Abstract*— This paper presents a "magnetic flip model" based on micromagnetics hysteresis model. In this model, magnetic domain wall displacement is approximated as a microscopic magnetic flip and its energy barrier. This hysteresis model is applied to a grain-oriented electrical steel sheet and non-oriented electrical steel sheet. The calculation results show that the vector hysteresis properties can be modeled by modeling the effects of 3-dimensional domain wall motion and related magnetization dynamics.**

***Index Terms*—Vector hysteresis, micromagnetics**

I. INTRODUCTION

The enhancement of the computing power and the development of simulation technology have combined to enable us to accurately design electrical machines with magnetic materials, such as motors and transformers, by utilizing electromagnetic simulators mostly based on finite element method. Since the higher efficiency, smaller dimensions, and lower energy consumption have become increasingly important in the design of these machines, a further accurate method for analyses of magnetic hysteresis.

Especially it is important for the accurate iron loss analysis of the motor to establish the model of vector hysteresis properties of the electrical steel sheet. Some approaches are done based on the extension of the scalar hysteresis model [1], [2]. However, these models can describe the vector hysteresis property due to the mathematical operation. On the other hand, it is reported that the crystalline orientation affects the vector hysteresis loops [3].

In this study, we focused on the development of the vector hysteresis model based on micromagnetics [4], [5]. In contrast with JA model [6] and Preisach model [7], it easily takes account anisotropies. In this paper, the extension of the micromagnetics hysteresis model is discussed. The crystal anisotropy and the magnetic energy of domains are considered and the magnetic domain wall motion is approximated as the flip of the magnetization vector. This model is applied to the grain-oriented (GO) electrical steel and non-oriented (NO) electrical steel.

II. HYSTERESIS MODEL

To describe the vector hysteresis properties, we consider that the magnetization of the electrical steel is modeled as a collection of single domain particles [5]. The magnetic state of single domain particles is determined by the magnetic energy,

$$E_{tot}(\boldsymbol{M}) = E_{ext} + E_{ani} + E_{\sigma} \tag{1}$$

where, E_{ani}, E_{ext}, and $E_{\lambda\sigma}$ are magnetic anisotropy energy, Zeeman energy, and magnetoelastic energy, respectively. Each term is expressed as following forms,

$$E_{ext} = -\boldsymbol{M} \cdot \boldsymbol{H}_{\boldsymbol{ext}} \tag{2}$$

$$E_{ani} = K_1\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2\right) \tag{3}$$

$$E_{\sigma} = -\frac{3}{2}\lambda\sigma(\alpha_1\gamma_1 + \alpha_2\gamma_2 + \alpha_3\gamma_3)^2 \tag{4}$$

where, K_1 is the anisotropy constant and λ is a magnetostriction. The α_1, α_2, and α_3 are the direction cosines of magnetization vectors with respect to x, y, and z axes (easy axes) of each grains, respectively. The cubic anisotropy energy is employed, because the Si-Fe steel may have the grain of the cubic crystal.

In the micromagnetics hysteresis model, the hysteresis property is reproduced by the local energy minimum state [5]. On the other hand, magnetization process in electrical steel can be classified to two processes. One is the domain wall motion and another is the magnetization rotation. Therefore, two magnetization processes are considered as follows. The domain wall motion is treated as the flip of a single domain particle. The schematic illustration is shown as Fig.1.In the case of cubic crystal anisotropy, the 90 degree domain wall and 180 degree domain wall exist. The each domain particle is considered to have the pinning site of the domain wall, and

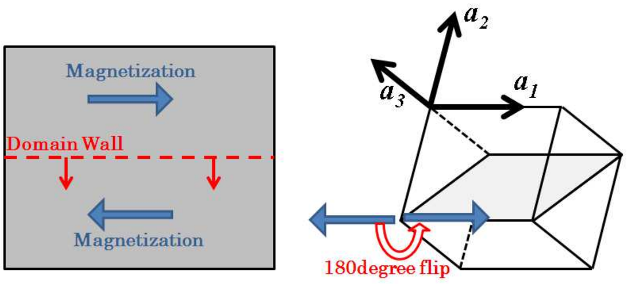

Fig. 1. Magnetic Wall Motion and Magnetic flip (180degree)

the flip is assumed to occur when satisfying the following equation,

$$E_{tot}(\boldsymbol{M}_i) > E_{tot}(-\boldsymbol{M}_i) + \Delta E_i^{180} \tag{5}$$

In a similar way, the 90 degree domain wall is treated as the 90 degree flip.

The magnetization rotation takes place so that the magnetic energy of the single domain particle may become the local minimum. The local minimum state is determined by the stationary solution of the LLG equation.

III. SIMULATION

A. Grain-Oriented electrical steel

We applied flip model to calculate the hysteresis loop of the GO electrical steel. Fig.3 shows the grain structure. We set the same grain structure in our calculation. The parameters are set as follows: Ms=1.6T, K_1=40000 N/m2, λ=2.0$\times 10^{-5}$, and σ =4.3MPa.

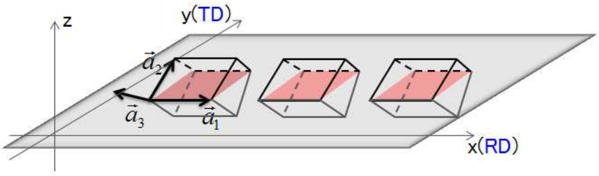

Fig. 2. Grain structure of GO electric steel and coordinate system.

Fig. 3 shows results of calculations for GO electrical steel sheet (Specimen JIS: 35P105). RD indicates the hysteresis loop of rolling direction and TD indicates the hysteresis loop of the transverse direction. The magnetic flip model reproduces both of the hysteresis loops. There is the difference of the magnetization process between RD and TD. In the case of the RD's alternating field, the 180 degree domain wall moves. On the other hand, the 90 degree domain wall is dominant in the case of the TD's alternating field.

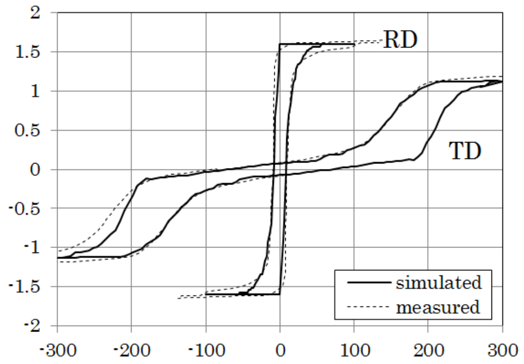

Fig. 3. Hysteresis loops of GO electrical steel

B. Non-oriented electrical steel

The magnetic flip model is applied to the NO electrical steel. The NO electrical steel has the vector hysteresis properties. The grain structure is considered to have slightly the regularity and the easy axis is set to concentrate in the rolling direction. The magnetostriction energy is set to the function of the magnetization, and is assumed as the following equation,

$$E_{\lambda\sigma} = b_2 \frac{\langle M\rangle^2}{M_s^2} + b_4 \frac{\langle M\rangle^4}{M_s^4} + b_6 \frac{\langle M\rangle^6}{M_s^6} \tag{6}$$

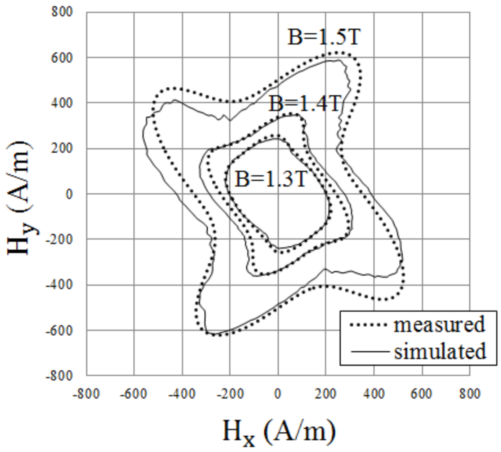

Fig. 4. Hysteresis loops of NO electrical steel at the rotational field

Fig.4 shows the vector hysteresis loops at the rotational flux. The anisotropy property due to the distribution of the crystalline orientation is well reproduced by the magnetic flip model.

Conclusion

The magnetic flip model is developed to analyze the vector hysteresis properties of the electrical steel. The simulated hysteresis loops have the anisotropic vector hysteresis properties, and is coincident with the experimental measurement.

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