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Research articles

A modified residual stress dependent Jile-Atherton hysteresis model

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ABSTRACT

Non-oriented electrical steel is widely used in the manufacturing of motor stators. The magnetic property will be influenced by the residual stress induced from manufacturing processes. The classical Jile-Atherton hysteresis model with constant parameters is widely used to describe the magnetization characteristic of ferromagnetic materials. In the model, the parameter a represents the domain density, k is the pinning factor reflecting the strength of the pinning effect, α is the domain coupling parameter affecting the slope of the mid-segment of the hysteresis loop and C is the coefficient of reversibility. However, all the four parameters are influenced by residual stress. Furthermore, the influence of magnetic peak induction on parameters can't be ignored according to our work. The classical Jile-Atherton hysteresis model cannot reflect the influence of residual stress and magnetic peak induction. In this paper, a modified residual stress dependent Jile-Atherton hysteresis model was proposed, whose parameters are extended to functions related to residual stress and magnetic peak induction. A novel device was designed to carry out magnetic property testing experiments under large stress. The parameters were identified by a MATLAB program and the influence of residual stress and magnetic peak induction was analyzed. The accuracy of parameters was validated by experiments, which showed that the modified model worked well in describing the magnetization characteristic under different stresses and magnetic peak inductions. This could provide some guidance for the manufacturing processes of motor stators.

1. Introduction

Non-oriented electrical steel is widely used in electromotor stators. However, the manufacturing of motor stators deteriorates the magnetic property, especially the hysteresis loss. The residual stress is one of the main factors. Based on the magnetostriction theory, tensile (positive) stress is applied along the magnetization axis of a specimen with positive magnetostriction, domain vectors will rotate toward the axis. If compressive (negative) stress is applied, the domain vectors rotate away from the axis [1]. In other words, the stress changes the complexity of magnetization.

A. Sipeky and Ivanyi A [2] investigated the stress dependence of an electrical steel's magnetic characteristic under different stresses. Results showed that magnetic properties were very sensitive to the applied mechanical stress. The tensile stress decreased the coercivity and the energy loss, while compressive stress does the opposite. M.F. de Campos et al. [3] studied a cold-rolled 0.5% Si electrical steel in detail, including residual stress, crystallographic texture, dc-hysteresis curves and iron loss. The significant increase of the iron loss took place due to the hysteresis loss component, even for small stress. And the texture change due to deformation also may contribute for loss increase. Yuichiro Kai et al. [4] measured the local residual stress distribution of the stator core by the X-ray stress measurement. Results showed that the magnetic property varied with the change of the principal stress' direction. K.J. Stevens [5] measured the magnetic properties (at maximum magnetization, at remanence, and at coercivity) of two grades of steel under uniaxial stress. Results showed that it was possible to use magnetic parameters to measure the uniaxial stress for the non-monotonic sensitivity of magnetic parameters to stress. And the Jile-Atherton model was used to explain the trends in the experimental data. O. Perevertov [6] carried out magnetic property testing experiments with the non-oriented electrical steel. The stress is applied by designed experimental apparatus. A so-called effective field theory based on the phenomenon logic theory was proposed and the tensile stress's non-monotonic effect on the magnetic hysteresis was investigated. The manufacturing process of motor stators usually introduces large residual stress. In spite of many experimental researches carried out, the magnetic property under large compressive stress has not been investigated enough. Because experiments under large compressive stress are difficult to be carried out. What's more, the effect of magnetic peak induction on the magnetic property is rarely to be discussed. In fact, the magnetic peak induction in the stator core is inhomogeneous. Further

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researches need to be done.

Progress to establish and improve modeling of non-oriented electrical steels has involved fundamental aspects to obtain an accurate relationship between the magnetic field and the magnetic induction that correctly accounts for hysteresis [7]. The classical Jile-Atherton hysteresis model works well in exhibiting the magnetization of ferromagnetic materials. A stress term added to the Jile-Atherton hysteresis model was used to describe the influence of residual stress on the magnetization of ferromagnetic materials [8,9]. A high order term is introduced in the denominator of the irreversible differential magnetic susceptibility equation. This leads to that the solution of the equation is complex and difficult to converge. Moreover, it describes the low field loops with large error. This model is not appropriate to be used to exhibit the magnetization of the motor stator working in low and medium field with stress, especially when the distributions of residual stress and magnetic peak induction are uneven.

In this paper, a modified residual stress dependent Jile-Atherton hysteresis model was proposed. The model parameters are extended to functions related to residual stress and magnetic peak induction. In the classic Jile-Atherton hysteresis model [8,9], the parameter a represents the domain density, which affects the magnetic peak induction of hysteresis loop. k is the pinning factor reflecting the strength of pinning effect. α is the domain coupling parameter affecting the slope of the mid-segment of the hysteresis loop and C is the coefficient of reversibility. All parameters are affected by residual stress and magnetic peak induction. So each of the parameters should be extended to the function related to residual stress and magnetic peak induction. The magnetic property testing experiments under stress in the range of −75 MPa to 100 MPa are carried out to identify the model parameter with a MATLAB program. According to the experiment results, the increasing tensile stress (less than 14 MPa) can promote the magnetization. The pinning effects are enhanced with the further increase of tensile stress. The coercivity significantly increases with the increasing compressive stress. The sensitivity of magnetic property to compressive stress was much larger than that to tensile stress. According to our research, parameters are expressed as functions related to residual stress and magnetic peak induction. And the accuracy of parameters was validated by experiments. The hysteresis loops and the hysteresis loss could be obtained according to the modified Jile-Atherton hysteresis model. This could provide some guidance for the non-oriented electrical steel manufacturing.

2. The Jile-Atherton hysteresis model

2.1. The classical Jile-Atherton hysteresis model

D.C. Jile and D.L. Atherton built a ferromagnetic hysteresis model based on the energy change due to the pinning effect [8,9]. The Langevin equation was used to describe the an-hysteretic magnetization.

$$M = M_S\left[\coth\left(\frac{H+\alpha M}{a}\right) - \frac{a}{H+\alpha M}\right] \equiv M_{an} \tag{1}$$

Where M_{an} is the an-hysteretic magnetization, M_S is the saturation magnetization, H is the external magnetic field.

The total work to overcome the pinning site can be expressed as Eq. (2). The change in energy of the magnetic domain caused by the rotating of magnetic moments is given by Eq. (3).

$$E = \frac{1}{\mu_0}\int BdB - \int MdB \tag{2}$$

$$E_{pin}(M) = k\int_0^M dM \tag{3}$$

Consequently, the magnetization is given by Eq. (4). If the magnetization is irreversible, the irreversible differential magnetic susceptibility can be expressed as Eq. (5).

$$M = M_{an} - \delta k\left(\frac{dM}{dBe}\right) \tag{4}$$

$$\frac{dM_{irr}}{dH} = \frac{M_{an}-M_{irr}}{\delta k - \alpha(M_{an}-M_{irr})} \tag{5}$$

Where M_{irr} is the irreversible magnetization and δ is a parameter ($\delta = 1$, when $dH/dt \geqslant 0$; $\delta = -1$,when $dH/dt < 0$). The reversible magnetization, the total magnetization and the magnetic induction can be expressed as:

$$M_{rev} = C(M_{an}-M_{irr}) \tag{6}$$

$$M = M_{rev} + M_{irr} \tag{7}$$

$$B = \mu_0(M+H) \tag{8}$$

So the total differential magnetic susceptibility can be expressed as:

$$\frac{dM}{dH} = \frac{(1-C)(M_{an}-M_{irr})}{\delta k - \alpha(M_{an}-M_{irr})} + C\frac{dM_{an}}{dH} \tag{9}$$

Combined with Eq. (8), the total differential magnetic susceptibility can be rewritten as:

$$\frac{dM}{dB} = \frac{(1-C)(M_{an}-M_{irr})}{\mu_0[\delta k + (1-C-\alpha)(M_{an}-M_{irr})]} + \frac{C[\delta k - \alpha(M_{an}-M_{irr})]}{\delta k + (1-C-\alpha)(M_{an}-M_{irr})}\frac{dM_{an}}{dB} \tag{10}$$

2.2. The Sablik-Jile-Atherton hysteresis model

M.J. Sablik modified the Jile-Atherton hysteresis model to consider the influence of residual stress on the magnetic hysteresis [1,10,11]. A stress term was added to the effective field. The revised effective field was given by [1,10,11]:

$$H_e = H + \alpha M_{irr} + \frac{3\sigma}{2\mu_0 M_S}\left\{\frac{M_{irr}}{M_S}\left[\lambda_1 + \frac{3}{2}\lambda_3\left(\frac{M_{irr}}{M_S}\right)^2\right]\right\} \tag{11}$$

Where σ is residual stress and μ_0 is the permeability of vacuum. λ_1 and λ_3 are constant. According to their researches, the irreversible differential susceptibility considering the influence of residual stress is given by [8-11]:

$$\frac{dM_{irr}}{dH} = \frac{M_{an}-M_{irr}}{\delta k - (M_{an}-M_{irr})\left[\alpha + \frac{3\sigma}{2\mu_0 M_S}\left(\lambda_1 + \frac{9\lambda_3 M_{irr}^2}{2M_S^2}\right)\right]} \tag{12}$$

Because a high order term is introduced in the denominator of the irreversible differential magnetic susceptibility equation. The order of the differential magnetic susceptibility equation increases. Furthermore, the solution is complex and difficult to converge. This model describes the low field loops with large error. So it is not suitable for exhibiting the influence of residual stress on the magnetization of the motor stator working in low and medium field.

2.3. The modified Jile-Atherton hysteresis model

There are 5 parameters in the Jile-Atherton hysteresis model. According to Khaoula Hergli [12] M_S can be calculated by:

$$M_S = \frac{B_s}{\mu_0} - H_S \tag{13}$$

Where B_S is the saturation induction and H_S is the saturation magnetic field. As shown in Fig. 1, the main magnetization curves are almost coincident when magnetic induction is over 1.75 T. Therefore, B_s and H_s are almost unchanged under different stress. Therefore, it is reasonable to assume that M_S is a constant. According to our experimental data, we take the average value: $M_S = 1.26\times10^6 A/m$. Other parameters, a, k, α, C, are affected drastically by the residual stress and magnetic peak induction (B_m) according to our research. So they should