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Modeling of dynamic hysteresis for grain-oriented laminations using a viscosity-based modified dynamic Jiles–Atherton model

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ABSTRACT

Grain-oriented (GO) materials exhibit arbitrary frequency-loss behaviors and anomalies in dynamic hysteresis loop shapes. Significant attempts have been made in the literature to approximate dynamic hysteresis loops using the dynamic Jiles–Atherton (JA) model based Bertotti's approach. Such a model is inefficient in accurate loss computation over a wide range of frequencies and in predictions of correct loop shapes. Moreover, the original static JA model also needs to be improved for accurate prediction of highly steep, gooseneck, and narrow-waist static loops of GO materials. An alternative approach based on magnetic viscosity provides flexibilities to handle indefinite frequency dependence of the losses and to control the anomalous loop shapes. This paper proposes a viscosity-based dynamic JA model which gives accurate prediction of dynamic loops of GO materials. A modified static JA model which considers crystalline and textured structures of GO materials is used to predict static hysteresis loops. The dynamic losses are included in the modified model using the field separation approach. The proposed model is validated using experimental measurements. The computed and measured dynamic loops are in close agreement in the frequency range of 1–200 Hz.

1. Introduction

GO laminations are widely used in power transformers and large rotating electrical machines due to their favorable crystallographic properties in the rolling direction. A precise model of GO laminations should consider their hysteretic, dynamic, and anisotropic behavior [1]. The dynamic hysteresis loops of these materials generally display arbitrary frequency-loss characteristics and anomalies in shapes [2]. Measured hysteresis loops of a typical GO material (Hi-B material, grade-27M-OH) at different frequencies are shown in Fig. 1. The JA model is one of the most frequently used for hysteresis description due to its relative simplicity and ease in numerical implementation [3–5]. The original JA model simulates the magnetization process using domain wall motion with pinning effects in isotropic materials [3]. Significant efforts have been made in the literature to include dynamic losses in the original JA model [6–8]. Most of the proposed dynamic JA models are based on Bertotti's approach. The models are particularly useful for non-oriented (NO) materials in a limited frequency range due to the fixed loss-frequency dependence of the approach [2]. Due to arbitrary loss-frequency behavior and anomalous shapes of dynamic loops of GO materials, these models may lead to erroneous computations [9]. An alternative approach based on magnetic viscosity has been proposed, which offers ability to predict indefinite frequency-loss characteristics and control anomalous dynamic loop shapes [10]. An attempt has been made to include the viscosity-based dynamic losses in the model using the original JA approach in [11]. The dynamic models based on the original JA approach can lead to non-physical solutions as highlighted in [9,12]. In a recently proposed dynamic JA model, the dynamic losses are calculated using Bertotti's approach and the losses are included in the original static JA model using the field separation approach [12]. The model has been applied to modeling of dynamic hysteresis loops of non-oriented materials for up to 150 Hz frequency. Moreover, the original JA model is basically proposed for isotropic materials which gives inaccurate results while predicting highly steep, gooseneck, and narrow-waist static hysteresis loops [2,13]. Also, due to the fact that the static hysteresis losses are approximately 40% of the total core losses in these materials, an accurate static hysteresis model is essential [14].

This paper presents modeling of dynamic hysteresis loops in GO laminations using the magnetic viscosity approach. The dynamic losses are included in the model using the field separation approach which avoids unrealistic features in predictions of

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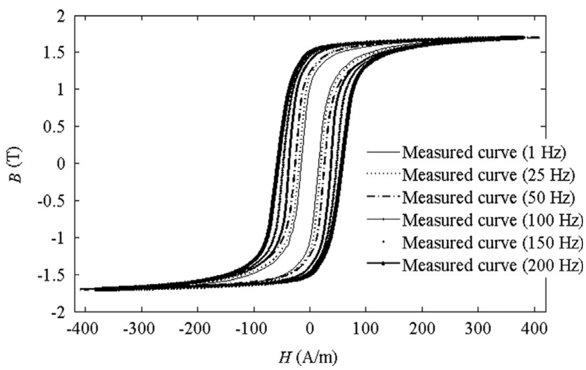

Fig. 1. Measured hysteresis loops at different frequencies (Hi-B material, 27M-OH).

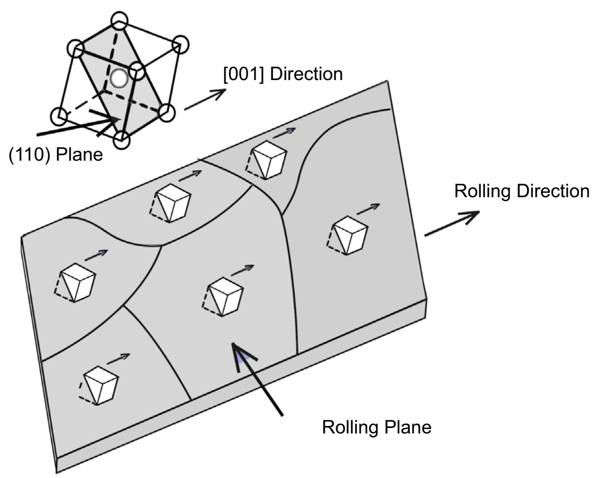

Fig. 2. Crystallites arrangement in a Fe–Si sheet (001) plane.

dynamic loops. A modified JA model which considers crystallographic features of GO laminations is used to predict static hysteresis loops in [13]. The model has been extended for inclusion of dynamic losses which are computed using Bertotti's approach [12]. However, the viscosity-based approach offers relatively much more flexibility to handle an arbitrary losses-frequency behavior, control anomalous loop shapes, and separate the static and dynamic losses [15]. Hence, the approach is also compatible to the field separation based dynamic JA models, as reported in [12]. The presented modified magnetic viscosity based dynamic JA model gives reasonably accurate predictions of dynamic loops in the range of 1–200 Hz. Measurements are carried out using a standard single sheet tester (SST) (Model: BROCKHAUS MPG 100D) on a Hi-B material (grade-27M-OH).

2. Static hysteresis modeling for GO laminations

The original JA model can be used to describe hysteresis loops in isotropic soft magnetic materials [3]. Hence, the model needs to be modified in order to predict hysteresis loops of GO materials which display strong anisotropic behavior due to their crystalline structure. In Fe–Si GO laminations, crystals have their [001] easy axis close to RD and (110) plane almost parallel to their surface; this type of crystalline structure is called Goss texture as shown in Fig. 2.

The JA hysteresis model has been extended for inclusion of anisotropy and texture effects for fiber-textured materials via its anhysteretic magnetization in [16]. The extended model has been successfully applied for hysteresis modeling of nanocrystalline materials [17]. Recently, a modified JA model has been proposed in [13], which considers the crystalline and textured structure of these materials. The model assumes that GO Fe–Si materials maintain as a whole cubic symmetry with axes of individual crystals along the global cubic axes [18]. The magneto-crystalline anisotropy energy of a single cubic crystal can be expressed as follows [13]:

$$E_{an} = K_0 + K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 \quad (1)$$

where α_1, α_2, and α_3 are the direction cosines of the magnetization vector with respect to the three crystal axes and K_0, K_1, and K_2 are anisotropy constants. The anisotropy constants K_0 and K_2 can be neglected without affecting accuracy significantly [18]. The magnetic field in GO laminations is generally analyzed in two dimensions because of their small thicknesses. The direction cosines of the magnetization vector can be expressed in polar coordinates as given in [13]. In the presence of anisotropy, the energy equation becomes

$$E = -\mu_0 M_s \cdot (H + \alpha M) + E_{an} \quad (2)$$

where M and H are the total magnetization and the applied magnetic field, respectively. μ_0 is the magnetic permeability of free space, and M_s is the saturation magnetization. The parameter α is one of the JA model parameters and it is known as the mean field parameter [13]. Due to symmetry in the anisotropy energy, analysis of the magnetic properties needs to be done only from 0° to 180°. The anhysteretic magnetization can be expressed as a function of the magnetized direction as [16]

$$M_{an} = M_s \frac{\int_0^{\pi} \exp((E(1)+E(2))/k_B T) \sin\,\theta\, \cos\,\theta\, d\theta}{\int_0^{\pi} \exp((E(1)+E(2))/k_B T) \sin\,\theta\, d\theta} \quad (3)$$

where M_{an} is the anhysteretic magnetization, $E(1)$ and $E(2)$ are energies of two symmetrically placed magnetic moments as given in [13], and θ is the angle between the applied field and the direction of magnetic moments [13]. The hysteresis behavior can be achieved by using an offset from the anhysteretic magnetization. The offset represents irreversible domain wall motion with pinning effects [3]. The hysteresis can be represented by the following differential equation:

$$\frac{dM}{dH} = \frac{M_{an}(H) - M_{irr}(H)}{(k\delta/\mu_0) - \alpha(M_{an}(H) - M_{irr}(H))} + c\left(\frac{dM_{an}}{dH} - \frac{dM}{dH}\right) \quad (4)$$

where δ is a directional parameter with the value of $+1$ for $dH/dt > 0$ and -1 for $dH/dt < 0$. M_{irr} is irreversible magnetization. The modified model needs six parameters (M_s, a, k, c, α, and K_1), which have sound physical interpretations [13]. The model can also be expressed in its inverse form (the procedure is given in Appendix A) which is particularly useful in numerical implementation and for typical measurement systems [4]:

$$\frac{dM}{dB} = \left[\frac{\left(\frac{c}{\mu_0}\frac{dM_{an}}{dH_e}\right) + \left((1-c)\frac{dM_{irr}}{dB_e}\right)}{1 + \left((1-\alpha)c\frac{dM_{an}}{dH_e}\right) + \left(\mu_0(1-\alpha)(1-c)\frac{dM_{an}}{dH_e}\right)}\right]. \quad (5)$$

The modified inverse JA model is applied to experimental quasi-static hysteresis loops of a grain-oriented (27M-OH) material. Measurements are carried out using a standard single sheet tester for the major hysteresis loop (1.7 T) and for a minor loop (1.5 T). The thickness of samples is 0.27 mm, the length is 200 mm, and the width is 29.5 mm. The measurement frequency is set to 1 Hz. The effects of classical eddy currents and anomalous losses on the hysteresis loop can be neglected at this frequency. A hybrid optimization technique, reported in [19], is used for determining the model parameters of the major loop (1.7 T). However, for modeling of the minor loop only two parameters k and a need to be determined as these parameters obey power law reported in [20] and other parameters are the same as those of the major loop (Table 1). The computed hysteresis loops with the obtained parameters are in