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A new ferromagnetic hysteresis model for soft magnetic composite materials

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ABSTRACT

A new ferromagnetic hysteresis model for soft magnetic composite materials based on their specific properties is presented. The model relies on definition of new anhysteretic magnetization based on the Cauchy–Lorentz distribution describing the maximum energy state of magnetic moments in material. Specific properties of soft magnetic composite materials (SMC) such as the presence of the bonding material, different sizes and shapes of the Fe particles, level of homogeneity of the Fe particles at the end of the SMC product treatment, and achieved overall material density during compression, are incorporated in both the anhysteretic differential magnetization susceptibility and the irreversible differential magnetization susceptibility. Together they form the total differential magnetization susceptibility that defines the new ferromagnetic hysteresis model. Genetic algorithms are used to determine the optimal values of the proposed model parameters. The simulated results show good agreement with the measured results.

1. Introduction

The soft magnetic composite (SMC) material used in electric-machine applications is made from insulated metallic particles (Fe, Fe–Si, Fe–Si–B, etc.) pressed and bonded together. The SMC material analysis is made with a mixture named Somaloy 500™ with 0.5% (weight) lubricant processed with one-axis pressing. The Fe particles are coated by a thin oxide layer and mixed with a polymer acting as a binding material, thus creating the final compact product [1–3].

Accuracy of the ferromagnetic hysteresis model is important when using modeled hysteresis loops of various materials in order to calculate hysteresis losses taking place in electro-mechanic converters [4–7] (electric machines, actuators, etc.). In the paper [8], the authors analyze a SMC material from the perspective of the magnetic hysteresis. They find the classical Jiles–Atherton hysteresis model inappropriate since it does not respond to demands regarding characterization of the SMC magnetic hysteresis. This is mainly due to the wider and not very steep and graded hysteresis when compared to laminated silicon steel. Microscopically looking, the magnetic field in the SMC material does not have the same direction as the applied external magnetic field. Quantity of the bonding material, size and shape of the Fe particles, level of homogeneity of the Fe particles at the end of the SMC product treatment, and achieved overall material density during compression affect the microscopic distribution of the magnetic field. This is macroscopically revealed with alteration in its ferromagnetic properties mainly in the ferromagnetic hysteresis.

Speaking in terms of the above SMC properties, the new ferromagnetic hysteresis model is developed and verified through measurements.

2. Anhysteretic magnetization of the SMC material

To derive a new anhysteretic magnetization M_{an} suitable for the SMC material, we first assume that there are no interactions between material magnetic moments $\vec{m}$ [9]. Their energy E is given by

$$E=-\mu_0\vec{m}\vec{H}=-\mu_0 mH\cos\theta \quad (1)$$

and after being rearranged it takes the form

$$E=E_m\cos\theta \quad (2)$$

where θ is the angle between the direction of external magnetic field H and orientation of material magnetic moment m, and μ_0 is the permeability of free space. In this way E_m represents the maximum energy state the magnetic moment can have.

The probability that a certain magnetic moment m will occupy the maximum energy state (Eq. (2)) could be described using the Cauchy–Lorentz distribution

$$p(E)=\frac{1}{\pi k_B T}\frac{1}{1+(E/k_B T)^2} \quad (3)$$

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where k_B is the Boltzmann constant, T the temperature of the material used and E is the energy state of electrons.

The number of magnetic moments dn occupying maximum energy state E_m (meaning that they will be oriented in the direction of external magnetic field H and $\cos\theta=1$) is proportional to the number of magnetic moments on the volume unit. Their number can be defined by considering the Cauchy–Lorentz probability (Eq. (3)) and proportionality as:

$$dn = NdE_m p(E) \tag{4}$$

Magnetization M_{an} is equal to the sum of all magnetic-moment projections in the direction of the external magnetic field [9]

$$M_{an} = \int_0^N m\cos\theta \cdot dn \tag{5}$$

where N is the number of magnetic moments in the volume unit. After rearranging, magnetization becomes

$$M_{an} = \frac{2mN}{\pi}\arctan\left(\frac{\mu_0 mH}{k_B T}\right) \tag{6}$$

Product mN in (Eq. (6)) is equal to magnetization saturation M_s and the part $\frac{\mu_0 m}{k_B T}$ represents the shape parameter $1/a$ [10]. Eq. (6) now becomes

$$M_{an} = \frac{2M_s}{\pi}\arctan\left(\frac{H}{a}\right) \tag{7}$$

So far, our focus has been on magnetic moments as we deal with the paramagnetic material paying no regard to their interaction.

3. Total differential magnetization susceptibility for the SMC material

The bonding material between the ferromagnetic particles in the SMC material is an electric insulator, which can be magnetically treated as vacuum. To demonstrate the happenings in the material subjected to an external magnetic excitation, we set up a magnetic system (Fig. 1) based on the finite-element method. The magnetic field is excited by two permanent magnets. In the presence of external magnetic field $\vec{H}$ (Fig. 1) the magnetization process starts. The magnetic field is a normal to the boundary of each ferromagnetic particle whose shapes magnetically affect the particles in their neighbourhoods (Fig. 2). Microscopically looking, the magnetic field does not take the same direction as the applied external magnetic field (Fig. 1). Fig. 2 also shows the inhomogeneous magnetic-flux density distribution in the ferromagnetic particles. Light colours

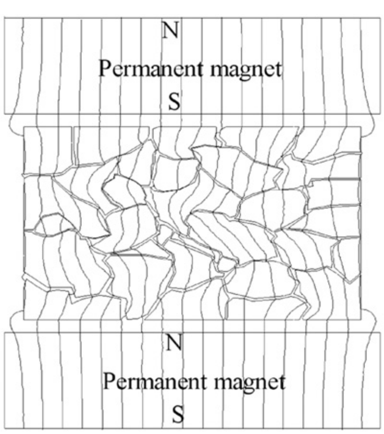

Fig. 1. Distribution of magnetic-flux lines in the ferromagnetic particles.

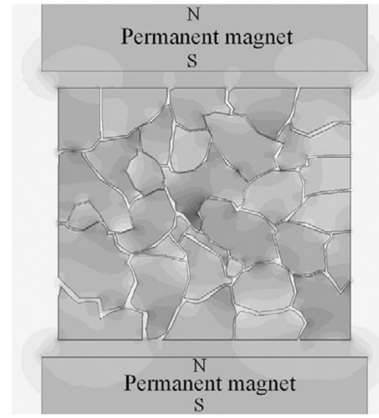

Fig. 2. Magnetic-flux density distribution in the ferromagnetic particles.

depict lower levels of the magnetic-flux density. Quantity of the bonding material affects the microscopic distribution of the magnetic field. Macroscopically this is revealed as alteration in its ferromagnetic properties. The impact of the bonding material (and all other specific properties of the analyzed material) on the SMC ferromagnetic properties can be considered with

$$B = \mu_0(H + bM) = \mu_0(H + M_b) = \mu_0 H_M \tag{8}$$

and

$$H_M = H + M_b \tag{9}$$

where parameter b determines ascendancy of the bonding material on the magnetic field distribution in the SMC material. Product $b\cdot M$ can be rewritten as M_b and it represents magnetization in the composite material.

Both irreversible M_{irr} and anhysteretic magnetization M_{an} are joined together correspondingly to (Eq. (9)) in the form of

$$H_{irr} = H + M_{b,\ irr} \tag{10}$$

and

$$H_{an} = H + M_{b,\ an} \tag{11}$$

The reversible magnetization process is represented with reversible magnetization $M_{b,rev}$

$$M_{b,\ rev} = c(M_{b,\ an} - M_{b,\ irr}) \tag{12}$$

where c presents the portion of reversible processes in ferromagnetic domains and is called the domain flexing constant [9]. In the magnetization process, there appear both reversible $M_{b,rev}$ and irreversible $M_{b,irr}$ magnetization, so

$$M_b = M_{b,\ rev} + M_{b,\ irr} \tag{13}$$

Inserting Eq. (13) into Eq. (12) yields

$$M_b = (1-c)M_{b,\ irr} + cM_{b,\ an} \tag{14}$$

Using Eqs. (9)–(11), Eq. (14) is rearranged into

$$H_M = (1-c)H_{irr} + cH_{an} \tag{15}$$

Thus, the total differential magnetization susceptibility is

$$\frac{dH_M}{dH} = (1-c)\frac{dH_{irr}}{dH} + c\frac{dH_{an}}{dH} \tag{16}$$

In Eq. (16), the only unknown is irreversible differential magnetization susceptibility dH_{irr}/dH. Anhysteretic differential magnetization susceptibility dH_{an}/dH can be found by differentiation