Magnetization Modeling of SMC Material with Rotating Fluxes

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This paper investigates a modified Stoner-Wahlfarth model, and a truncated asteroid is employed to model the magnetic characteristics of the SMC material under rotating field excitation. Through adjusting the truncation factor the correct angles between rotating field **H** and magnetization **M** can be evaluated, however this model still needs studying and improving more in future.

Key Words: Soft magnetic composite (SMC) material, Magnetization modeling, Rotating flux, Stoner-Wohlfarth (S-W) model.

1. Introduction

In the past years, a lot of research, both theoretical and experimental, has been conducted to explain the magnetization process in magnetic materials [1]-[11]. However, most of the work focused on scalar magnetic hysteresis models with the applied field constrained to a specified axis, such as the Preisach model. It is criticized on the grounds that the models fail to properly describe the rotational properties of magnetic materials in the engineering application. This is partly because of the questionable assumptions used in coupling vector hysteresis components, and the fact that the Preisach model does not include reversible magnetization.

In general, the magnetic field strength in engineering application is vectorial, and the magnetization process in magnetic materials has to be considered using vector magnetization. Thus, the vector magnetization **M** of materials must be treated as a vector with both magnitude and direction.

This paper presents a method to model the process of magnetization for the soft magnetic composite (SMC) materials under a rotating field excitation. It incorporates the Stoner-Wohlfarth (S-W) elemental operator, an inherent vector physical model into engineering. The rotational mechanism of the magnetic moment $\mathbf{m}_s$ and its reversible and irreversible processes are illustrated graphically. Finally, the numerical simulation results of the magnetization of SOMALOY™ 500 [12], an SMC material, are compared with the measured ones by using a single sheet square specimen tester.

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The presented method is useful to simulate the magnetic characteristics of electromagnetic devices with complex topology and rotating magnetic flux in practical engineering.

2. Stoner-Wohlfarth Model

2.1 Stoner-Wohlfarth coherent rotation model

The Stoner-Wohlfarth (S-W) model has been studied and used for many years [1]-[10], because of its intrinsic vector nature. It has several advantages: a single mechanism generating both reversible and irreversible changes in magnetization, naturally three dimensional, and easy to account for the anisotropy of particles.

This model assumes that a magnetic material consists of a collection of pseudo-particles, each with uniaxial anisotropy due to stress and crystal structure, or particle shape. Each particle is uniformly magnetized to saturation in the direction of its easy axis, giving a single magnetic domain with magnetic moment $\mathbf{m}_s$ which is free to rotate in any direction. Such a particle is called the S-W particle.

With an applied magnetic field, the magnetic moment $\mathbf{m}_s$ of S-W particle rotates to the orientation, resulting in the minimum energy. It can be determined in three dimensions by the well-known Stoner-Wohlfarth asteroid rule, which indicates that for the external field **H**, the equilibrium directions of $\mathbf{m}_s$ correspond to minima of E are parallel to the tangent line to the asteroid which pass the tip of the field **H.** When **H** is applied inside the asteroid, four tangent lines can be drawn and the possible equilibrium orientations of $\mathbf{m}_s$ are parallel to two lines of them that make the smallest angles with the easy axis or anti-easy axis respectively. When **H** is outside the asteroid, two such tangent lines can be drawn, and the possible equilibrium orientations of $\mathbf{m}_s$ are parallel to the line which makes the smallest angle with the easy axis. An irreversible jump of the magnetic moment from one direction to another must occur, when **H** exceeds and crosses the asteroid boundary. However, the direction of magnetic moment $\mathbf{m}_s$ is dependent on its previous history. Fig. 1 illustrates a graphical solution for the asteroid rule in 2D and 3D, respectively.

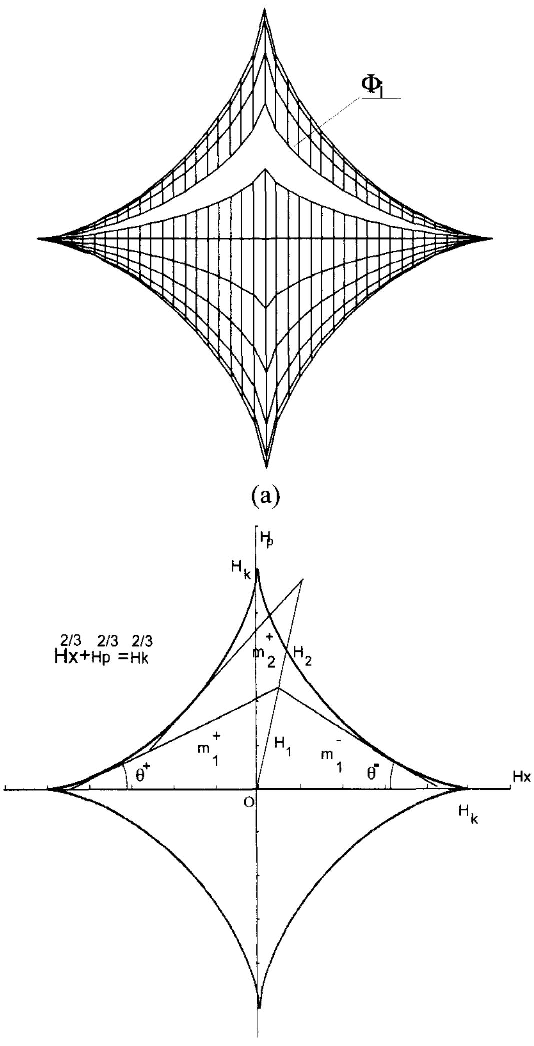


Fig. 1. (a) An astroidal plane Φ_i in spatial astroid, (b) astroid rule in Φ_i

The critical field sets can be evaluated by the following equation as

$$H_x^{2/3}+(H_y\sin\phi+H_z\cos\phi)^{2/3}=H_k^{2/3} \quad (1)$$

where $H_k=2K/\mu_0 m_s$ is the crystal anisotropy field, ϕ is the angle between the plane XOZ and the plane XOH that contains the magnetic field **H** and the easy axis of particle, and ϕ varies over 360 degrees.

2.2 Modification of the switching criterion

However, the S-W model does not describe very well the hysteresis loops of real ferromagnetic materials [9]. One problem is related to the fact that the coherent rotation is not giving the correct dependence of the critical field on the angle between the easy axis and the applied field direction. In order to solve this discrepancy a modification of the switching criterion is used.

It is known that the coherent rotation model predicts coercive fields that are roughly five times those observed for typical recording media. In addition, the switching filed H_c has a minimum at 45° that is also not observed [3].

The critical field, H_c, as a function of its anisotropy field H_k and the orientation δ in the literature [10] is given by

$$H_c=H_k/[(\sin\delta)^{2/3}+\xi(\cos(\delta)^{2/3}]^{3/2} \quad (2)$$

or in [9] is given by

$$H_c=((1-q^{1/3})/(1-q))^{3/2}H_k \quad (3)$$

where ξ and q are the truncation factors. Fig. 2 illustrates an asteroid and a truncated asteroid with a specific truncation factor $\xi=1.5$.

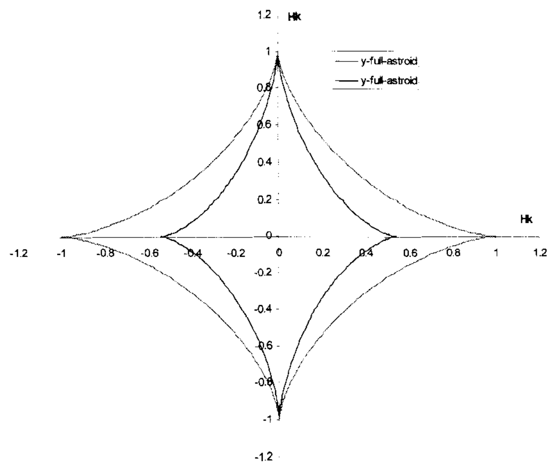
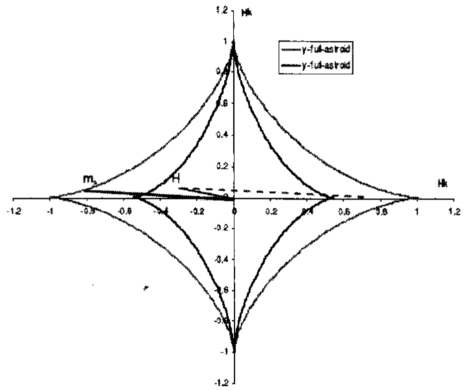


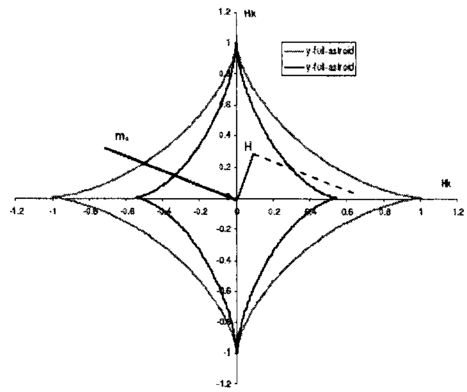
Fig. 2. Truncated asteroid in the modified model

The modification is easily implemented in the computer program by substituting a different switching threshold for that in (2). However, the orientation of magnetic moment $\mathbf{m}_s$ is still determined by the full asteroid tangency condition.

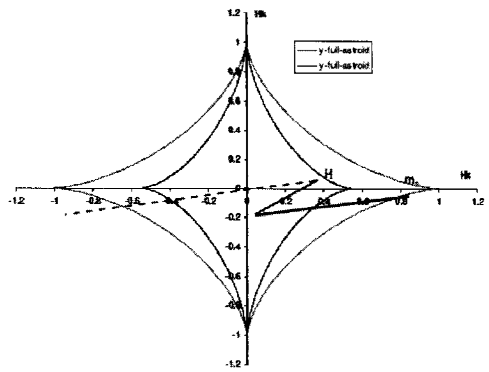
Fig. 3 illustrates the rotation of magnetic moment of a single particle with a rotating field that the magnitude of the magnetic field strength does not change, while the direction of the field rotates. The magnetization process corresponding to the field rotation from (a) to (b) is reversible, and it is irreversible from (b) to (c).



(a) $\mathbf{m_s}$ orientation corresponds to field



(b) $\mathbf{m_s}$ rotates with a rotating field



(c) $\mathbf{m_s}$ jumps with a rotating field

Fig. 3. Magnetization process for a rotating **H**

3. Modeling of SMC Materials and Discussion

3.1. Numerical method of S-W model

The magnetization **M** for bulk materials is the vector sum of contributions of all the constituent particles, and can be mathematically expressed as

$$\mathbf{M} = S(\mathbf{H}_a + \alpha\mathbf{M}) \tag{4}$$

where *S*() stands for the S-W model.

In numerical implementation, the magnetization is obtained by the vector sum of the magnetic moments $\mathbf{m}_s$ of an assembly of N_p magnetic particles, as expressed below

$$\mathbf{M} = \sum_{i=1}^{N_p} \mathbf{m}_{si}(\mathbf{H}_a + \alpha\mathbf{M}) \tag{5}$$

The simulations for the magnetization processes of an isotropic magnetic material under both alternating and rotating magnetic fields have been carried out. It is implemented by numerical algorithm in Matlab. Here, 3600 pseudo particles are uniformly distributed on a plane. With the AC current excitations the hysteresis loops can be computed. Fig. 4 shows the M-H loops with different truncation factors for ξ = 1, 3, and 6, respectively.

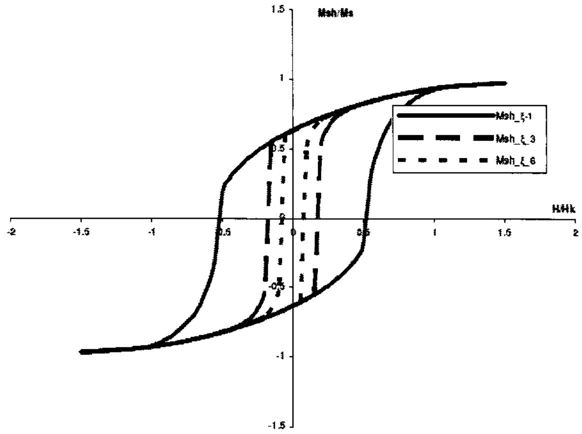


Fig. 4. Hysteresis loops with different ξ

3.2. Modeling of SMC and discussion

SMC samples were cut from available preforms of SOMALOY™ 500, which were compacted in a cylindrical die at 800 MPa and then heat treated at 500 °C. As its particles are randomly distributed, SMC can be considered as an isotropic material.

To evaluate the magnetic moment $\mathbf{m}_s$ of SMC particle, the major hysteresis loop obtained under an alternating magnetic field excitation, is used to determine the saturation magnetization $\mathbf{M}_s$ of SMC material using the relation by

$$B_{rev} = \mu_0[H + M_{anh}(H)] \tag{6}$$

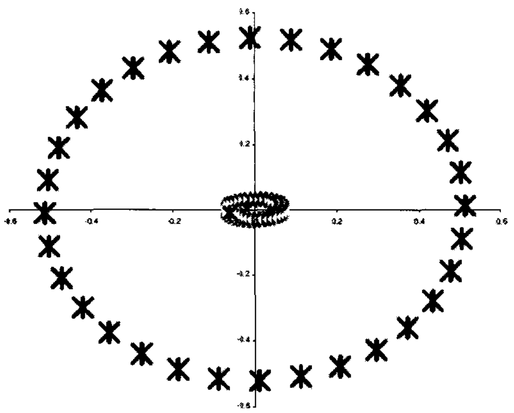
$$M_{anh}(H) = M_s\left[\coth\left(\frac{H}{a}\right) - \frac{a}{H}\right] \tag{7}$$

where (7) is an expression for the anhysteretic magnetization curve proposed in [11].

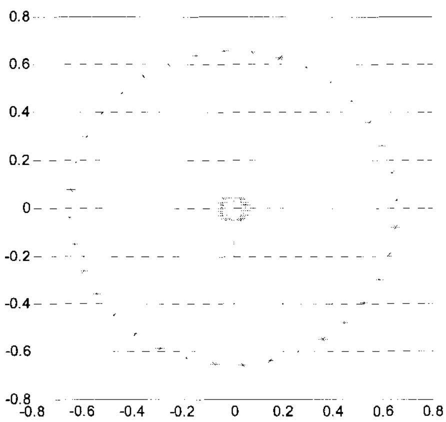
The saturation magnetization $\mathbf{M}_s$ evaluated using (6) and (7) is 1505890 A/m, subsequently, the magnetic moment $\mathbf{m}_s$ can be calculated from $\mathbf{M}_s$

using the inverse relation of (5) under the alternating excitation. In this case we assume that 720 particles are homogeneously distributed, thus, we have $\mathbf{m}_s = \mathbf{M}_s/0.9344 = 1611611$ A/m. Due to the effect of the composite insulation materials we suppose the interaction between magnetic particles is relatively small, so ignore it.

Sequentially, the loci of **H** and magnetization **M** or flux density **B** can be numerically modeled with the rotating field excitation. Fig. 5(a) plots the controlled circular **M** and its exciting field **H** of a SMC material at 1 T flux density, and (b) the modeling results. Through adjusting the truncation factors ξ of asteroid we obtain the correct average angles of SMC material between rotating magnetic field **H** vector and magnetization **M** vectors.



(a)



(b)

Fig. 5. Loci of (a) experiment, and (b) modeling results

Since the SMC material is not exactly uniform distributed, the **H** loci are different between experiment and modeling. This can be fixed by changing the distribution of particles. In addition, there is discrepancy of magnitudes of **M** between experiment and modeling. This shows that the switch mechanism and processing of this model need further study and improvement.

4. Conclusion

This paper investigates a modified Stoner-Wahlfarth model. A truncated asteroid is employed to model the magnetic characteristics of the SMC material under rotating field excitation. Through adjusting the truncation factor the correct angles between rotating field H and magnetization M can be evaluated. However this model still needs further study and improvement.

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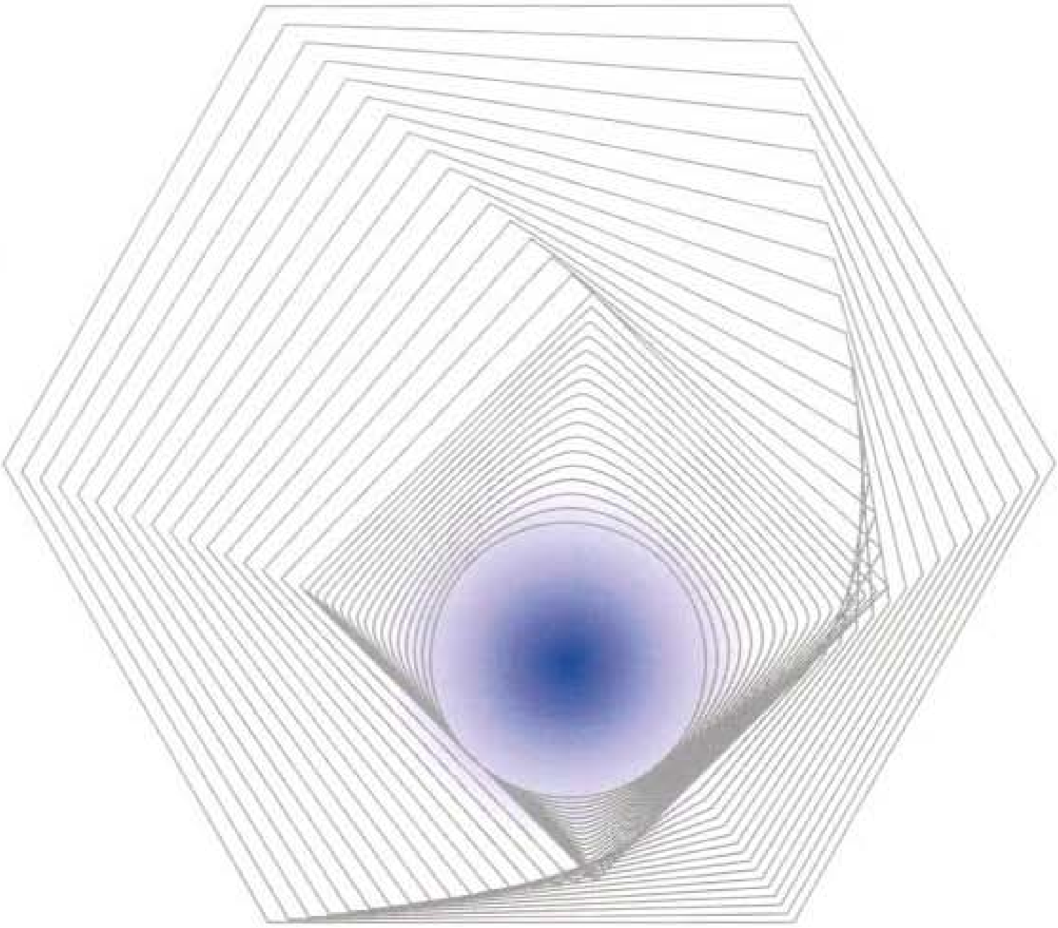

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