Micromagnetics Numerical Method for Rotational Magnetization of SMC Material Considering Magnetoelastic Effect

Changgeng Zhang[1], Qingxin Yang[1,2], Yongjian Li[1], and Erping Li[1]
[1]Province-Ministry Joint Key Laboratory of Electromagnetic Field and Electrical Apparatus Reliability,
Hebei University of Technology Tianjin 300130, China
[2]Tianjin Key Laboratory of AEEET Tianjin Polytechnic University Tianjin 300387, China

This paper analyzes the magnetic anisotropy of the soft magnetic composite (SMC) material which is observed in rotational magnetic properties measurement. It proves that magneto-elastic effect brings out magnetic anisotropy for pure iron particle with a single domain. And then a new micromagnetics numerical method is developed to consider magneto-elastic effect for polycrystalline iron particle under the framework of OOMMF. The simulation shows that magnetoelastic energy may cause magnetic anisotropy characteristic in the SMC material.

***Index Terms*—polycrystalline, magneto-elastic, magnetic anisotropy, micromagnetics**

I. INTRODUCTION

The theory of micro-magnetism developed by Landau and Lifshitz and Brown is a rather effective tool to describe magnetization process. The Landau-Lifshitz-Gilbert (LLG) equation for the magnetization can be solved for a time varying external field by finite element method (FEM) or finite difference method (FDM). The FEM can be used in complicated object with irregular mesh, while the FDM is easier to be implemented only for simple shape object with regular mesh [1]. Crystalline soft magnetic materials as permalloy, sendust, silicon steel and soft magnetic composite (SMC) are characterized by a low magneto-crystalline anisotropy and a low magnetostriction. It has been shown experimentally that the exact nature of grain orientation and distribution plays a crucial role in magnetization reversal behavior [2]. In the macro electromagnetism simulation, LLG equation is not possible in practice because of huge computational time. Therefore, several phenomenological hysteresis models, such as Mayergoyz hysteresis model, Preisach-Stoner-Wohlfarth (PSW) model are developed [3]. Moreover, the parameters of a phenomenological model are identified by computing LLG equation [4]. This paper proposed and implemented a new numerical method considering magneto-elastic effect in LLG equation for SMC material. The simulation results show that magnetoelastic energy is one reason causing magnetic anisotropy characteristic of the SMC material.

II. THEORY OF SINGLE DOMAIN MAGNETIZATION CONSIDERING MAGNETO-ELASTIC EFFECT

A small magnetic particle with uniaxial anisotropy and coherent magnetization without domain structure is considered. The total energy including the magneto-crystalline anisotropy energy U_{ani} , magneto-elastic energy U_{me} and the energy associated with the field also called Zeeman energy U_H is a minimum . Then

$$d(U_{ani}+U_{me}+U_H)/d\theta=0 \tag{1}$$

When the alternating field is applied on X axis with easy axis along x axis , and the tensile force being applied along the x axis, the deformation is computed $e_{xx}=\sigma/E, e_{yy}=-\nu e_{xx}$, where σ is pressure and E is Young modulus. And the magnetization is expressed as

$$m=\frac{M_s H}{2(K_u+B_1\sigma(1+\nu)/E)} \tag{2}$$

where B_1 is a coefficient of magneto-elastic and K_u is the coefficient of uniaxial anisotropy. When the alternating field is applied on 45^{o} axis and easy axis is along 45^{o} axis and the tensile force being applied along X axis and Y axis $\sigma_x = \sigma_y$. The magnetization response becomes

$$m=\frac{M_s H}{2(K_u)} \tag{3}$$

For pure iron crystal, B_1 = -2.9×106(J/m^3), the susceptibility along X axis is bigger than that in 45^{o} direction. The derivation procedure will be shown in the full paper.

III. NUMERICAL METHOD FOR POLYCRYSTALLINE CONSIDERING MAGNETO-ELASTIC EFFECT

SMC material is composed of 0.1mm pure iron particle which is polycrystalline material. The bulk of SMC material is magnetic isotropic because both the crystallites and iron particles are randomly oriented. Within a pure iron grain, the magnetic moments are not uniform. The interplay among exchange interactions, the magnetocrystalline cubic anisotropy and demagnetization effect cause a non-uniform magnetization distribution.

A numerical method of micro-magnetism LLG equation considering the time-varying magnetoelastic effect is proposed by means of an open source software OOMMF [5]. The effective field is computed by

$$\boldsymbol{H}_{eff}=-\frac{1}{\mu_0 \boldsymbol{M}_s}\frac{\delta E}{\delta \boldsymbol{m}} \tag{4}$$

where E is the total energy. Given a magnetization distribution $\boldsymbol{m}(r,t)=\boldsymbol{M}(r,t)/\boldsymbol{M}_s$ the magnetization equilibrium is acquired by the equation

$$\boldsymbol{m}\times\boldsymbol{H}_{eff}=0 \tag{5}$$

The energy of exchange, anisotropy, Zeeman and demagnetization are discretized in FDM. The second-order magneto-elastic energy density is

$$U_{me} = B_1(m_x^2 e_{xx} + m_y^2 e_{yy} + m_z^2 e_{zz}) + B_2(m_x m_y e_{xy} + m_y m_z e_{yz} + m_z m_x e_{zx}) \tag{6}$$

The summation of the magnetoelastic energy density is

$$E_{me} = \sum_i B_1(m_x^2(r_i)e_{xx} + m_y^2(r_i)e_{yy} + m_z^2(r_i)e_{zz}) + B_2(m_x(r_i)m_y(r_i)e_{xy} + m_y(r_i)m_z(r_i)e_{yz} + m_z(r_i)m_x(r_i)e_{zx}) \tag{7}$$

The discretized field can be derived from the discretized energies

$$H_{me} = -2\boldsymbol{D}(r_i)\boldsymbol{m}(r_i) / \mu_0 M_s \tag{8}$$

where D is the matrix

$$\boldsymbol{D} = \begin{pmatrix} B_1 e_{xx} & B_2 e_{xy} & B_2 e_{zx} \\ B_2 e_{xy} & B_1 e_{yy} & B_2 e_{zx} \\ B_2 e_{xz} & B_2 e_{xy} & B_1 e_{zz} \end{pmatrix} \tag{9}$$

IV. EXPERIMENT AND NUMERICAL SIMULATION OF ROTATIONAL MAGNETIC PROPERTY OF SMC

The SMC material specimen， SOMALOY 500， is a highly pure iron particle surface-coated to ensure low eddy current loss. A cubic SMC (22mm×22mm×22mm) sample is measured by a 3-D magnetic property testing system. The loci of magnetic field strength and flux density in *xoy*-plane are shown in Fig.1. When the flux density is reaching to the magnetic saturation, the locus of $\boldsymbol{H}$ changes to be square-like. The direction of 45° along the x axis is harder magnetized than that along x and y axes.

Supposed the grain pattern of SMC polycrystalline particle periodic, a small rectangle part (100nm×100nm) is simulated with ten grains as shown in Fig.3. The numerical parameters used in this problem are listed in Tab 1. The finite difference method has regular mesh on rectangle with $N_x = N_y = 50$ and $N_z = 1$ cells along the x, y and z direction, and the boundary condition is periodic.

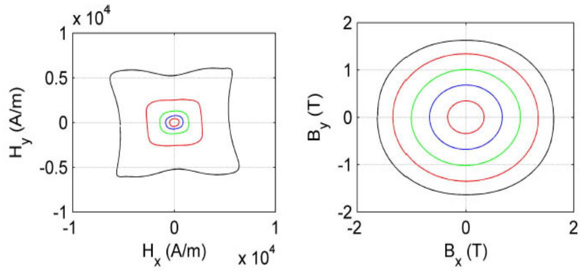

Fig. 1 The loci of magnetic field strength and flux density by experiment

According to principle of virtual work, the magnetic force applied on the magnetic measurement sample is calculated by

$$F_i = \frac{1}{2} I_i^2 \frac{dL_i}{d\delta} \qquad i = x, y \tag{10}$$

I_i being the current of winding and L_i being the inductance of winding and δ being the air gap between the sample and magnetic pole. The more accurate magnetic force could be simulated by FEM. Then the pressure σ is computed. The circular current vector (I_x, I_y) loci determine the circular loci of applied field $\boldsymbol{H_a}$. The loci of Zeeman flux density $\boldsymbol{B} = \mu_0 \boldsymbol{H_a}$ and the loci of magnetization are show in Fig.4. In the full paper, the proposed micromagnetics numerical method is compared with the electromagnetic FEM considering magnetoelastic effect .

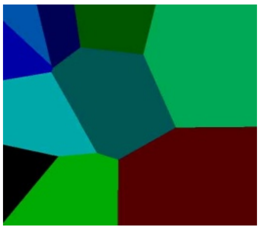

Fig. 2 Grain mosaic of SMC iron particle generated by Voronoi graph algorithm

Tab. 1 Geometrical and material parameters used for simulating SMC particle

	BCC Fe		BCC Fe
M_s	1.7189×10^{6}	$N_x = N_y$	50
K_1	4.8×10^{4}	B_2	2.9×10^{6}
K_2	-1.5×10^{4}	A(inter grain)	6.9×10^{-12}
B_1	-2.9×10^{6}	A(inside grain)	2.0×10^{-12}

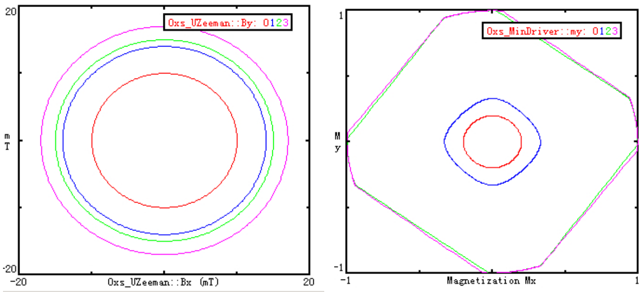

Fig. 4 The loci of applied magnetic field strength and magnetization by simulation

V. CONCLUSION

Magnetic anisotropy of the SMC material is analyzed in this paper. For pure iron particle with a single domain, the principal of energy minimization shows that magneto-elastic effect brings out magnetic anisotropy. For polycrystalline iron particle, a new micromagnetics numerical method considering magneto-elastic effect is developed and implemented. The simulation of rotational magnetization of SMC material shows that magnetoelastic energy is one reason to cause magnetic anisotropy characteristic in the SMC material.

REFERENCES

[1] B.V.Wiele, A.Manzin, O.Bottauscio, M.Chiampi, L.Dupre, and F.Olyslager, “Finite-difference and edge finite element approaches for dynamic micromagnetic modeling,” *IEEE Trans. Mag.,* vol.44 no.11,pp. 3137-3140,2008.

[2] A.W.Spargo, P.H.W.Ridley, G.W.Roberts and R.W.Chantrell, “Influences of granular microstructure on the reversal mechanism of Co nanoelements,” *J. Appl. Phys.,* vol.91,No.10,pp.6923,2002.

[3] D.D. Li, F.G. Liu, Y.J. Li, Z. Z Zhao, C.G. Zhang and Q.X. Yang, “Magnetic Properties Modeling of SMC Materials Using Two dimensional Vector Hybrid Hysteresis Model,” *J. Appl. Phys.,* vol.115,No.17,pp. 17D117, 2014.

[4] E.Cardelli, M.Carpentieri, A.Faba, G.Finocchio, “Modeling of hysteresis in magnetic multidomains,” Physica B ,vol.435,pp.62-65,2014.

[5] J. W. Lau, R. D. McMichael and M. J. Donahue, “Implementation of two-Dimensional polycrystalline grains in object oriented micromagnetic framework,” *J. RES. NATL. INST. STAN.,*vol.114,no.1,pp.57-67,2009.

[6] Y. J. Li, J.G. Zhu, Q.X. Yang, “Study on Rotational Hysteresis and Core loss under three-dimensional magnetization,” *IEEE Trans. Mag.,* vol.47,no.10,pp.3520-3523,2011.