

An Improved Multi-scale Energy Model Based on Parallel Computing and Magnetic Property Modeling in the Electrical Steel Sheet

Xin Wu, Yanli Zhang, Zhen Wang and Dianhai Zhang

School of Electrical Engineering, Shenyang University of Technology, Shenyang, 110870 China, ylzhang@sut.edu.cn

Multi-scale Energy Model (MSEM) is commonly utilized in the magnetic properties modeling of polycrystalline materials. To improve the computational efficiency of MSEM, this paper investigates a parallel computing method to obtain the demagnetization coefficient and to carry out the minimization of magnetic domain energy. In this study, a grain-oriented electrical steel is discretized into many single crystal elements in accordance with the actual size of the sample. The magnetic properties of electrical steel sheets under different numbers of discrete elements are explored. The computing results indicate that the proposed model can improve computational efficiency as well as good agreement with the experimentally measured values.

Index Terms—Magnetic properties, magnetic domains, parallel computation, demagnetization.

I. INTRODUCTION

ELECTRICAL STEEL, as a high-performance soft magnetic polycrystalline material, is widely used in electromagnetic conversion devices. The accurate prediction of the macroscopic magnetic properties in the electrical steel is of crucial importance for the optimal design of electrical equipment. Recently, the MSEM has attracted more and more attention, which estimates the magnetic hysteresis and loss from the point of magnetic domain scale to the grain scale and then to polycrystalline scale [1].

For the MSEM, the demagnetizing field within one element composed of six magnetic domains needs to be calculated by employing the micromagnetic simulation approach, which takes the interact of magnetic moment among different domains and elements into account [2]. Also, to obtain the magnetic moment direction of each domain, the minimization of local magnetic domain energy may be carried out by solving an artificial state equation. As a result, these two above aspects increase the computational complexity of the MSEM, lows its estimation efficiency compared with some classical models such as Jiles-Atherton model, and limits its engineering application.

To improve the computational efficiency of MSEM, this study proposes a Parallel MSEM (hereinafter called P-MSEM), in which the parallel computation is employed to solve the demagnetization coefficient tensor and to perform the minimization of magnetic domain energy. Meanwhile, the optimal number of discretized elements is discussed by considering both the computation time and accuracy. Finally, the improved MSEM is verified with experimental test data from a grain-oriented electrical steel sheet.

II. APPROACH AND FORMULATION OF P-MSEM

A. Magnetic Domain Energy and its Minimization within Single Crystal

The polycrystal of the electrical steel belongs to cubic crystals, and there are six easy magnetization axes within the crystals. Therefore, in the MSEM, a single crystal is defined as the combination of six magnetic domains along the six easy

magnetization directions. The energy within a single crystal mainly includes: magneto-crystalline anisotropy energy E_{an} , Zeeman energy E_{ap} , exchange energy E_{ex} and demagnetization energy E_{deg} . Among them, E_{an} , E_{ap} and E_{ex} are local energies, which exists inside the magnetic domains and can be obtained simply by integration. However, the E_{deg} is non-local energy, which is affected not long by the interact among magnetic domains the within a single crystal, but also by the interact from different single crystals [1]. Thus, these energies except the exchange energy, which can be ignored due to relatively small value compared to other energy, can be given as

$$E_{an} = \sum_{i=1}^6 r_i (\alpha_{1,i}^2 \alpha_{2,i}^2 + \alpha_{2,i}^2 \alpha_{3,i}^2 + \alpha_{1,i}^2 \alpha_{3,i}^2) \quad (1)$$

$$E_{ap} = \frac{-\mu_0 M_s \mathbf{H}}{K_1} \cdot \sum_{i=1}^6 r_i \mathbf{m}_i \quad (2)$$

$$E_{deg} = \frac{\mu_0 M_s}{2K_1} (H_{deg-x} m_x + H_{deg-y} m_y + H_{deg-z} m_z) \quad (3)$$

$$\mathbf{m} = (m_x, m_y, m_z) = \sum_{i=1}^6 r_i \mathbf{m}_i \quad (4)$$

where r_i represents the volume fraction of each magnetic domain; $\alpha_{1,i}$, $\alpha_{2,i}$, and $\alpha_{3,i}$ are three direction cosine of the magnetic moment within each magnetic domain; μ_0 is the permeability of vacuum; M_s is the saturation magnetization; $\mathbf{H}$ is the applied field; K_1 is the anisotropy constant; $\mathbf{m}_i$ is the unit magnetization vector of each magnetic domain; $\mathbf{N}$ is the demagnetization coefficient tensor; and $\mathbf{H}_{def} = (H_{deg-x}, H_{deg-y}, H_{deg-z})$ are the components of the demagnetizing field along three directions, respectively.

The process of minimizing the above magnetic domain energy within a single crystal can be referred to [1, 2].

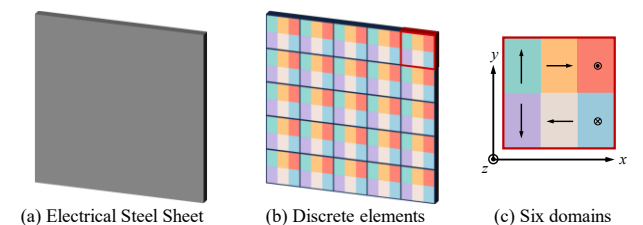


Fig. 1. Electrical steel sheet discretized into $m \times n \times l$ elements.

B. Discretization of Polycrystal Structure

In this paper, the grain-oriented electrical steel with the grade B23R080 and the size of 150mm×150mm×0.23mm in Fig.1(a) is adopted as the test sample. In order to carry out the P-MSEM, the electrical steel as a polycrystalline material firstly needs to be discretized into several single crystals in proportion. The number of discretized elements is set as $m \times n \times l$ (such as $m=5$, $n=5$, $l=1$), as shown in Fig.1(b). Each element represents a single crystal, and six magnetic domains within the single crystal are arranged along six easy magnetization directions, as shown in Fig.1(c).

C. Parallel Computation of Demagnetization Coefficient Tensor and Minimization of Magnetic Domains Energy

Fig. 2 shows two uniformly magnetized elements with same dimensions, then the demagnetizing field $\mathbf{H}_{\text{deg}}$ within the target region v can be expressed as [3]

$$\mathbf{H}_{\text{deg}} = -\frac{1}{v} \int_v \nabla \phi(\mathbf{r}) dv = -\mathbf{m} \cdot \mathbf{N} \quad (5)$$

where ϕ represents the scalar potential and the demagnetization coefficient tensor $\mathbf{N}$ can be expressed as [3]

$$\mathbf{N} = \frac{1}{4\pi v} \oint_{\partial v} d\mathbf{s} \oint_{\partial v'} d\mathbf{s}' \frac{1}{|\mathbf{r} - \mathbf{r}'|} \quad (6)$$

According to (6), $\mathbf{N}$ is related to the interaction between two rectangular surfaces s and s' , and can be written as [4]

$$\mathbf{N} = \begin{pmatrix} N_{xx} & N_{xy} & N_{xz} \\ N_{yx} & N_{yy} & N_{yz} \\ N_{zx} & N_{zy} & N_{zz} \end{pmatrix} \quad (7)$$

During the calculation of the demagnetization coefficient tensor, it is necessary to reflect the interaction between two single crystal elements, as well as to determine the minimum of the energy within each element. The traditional MSEM adopts a time-consuming sequential calculation method, which calculates this coefficient from one element to other elements step by step. In this paper, the P-MSEM calculation method shown in Fig. 3 is investigated to obtain the demagnetization coefficient tensor $\mathbf{N}$ and to perform energy minimization. The number of parallel threads is set as the maximum number of

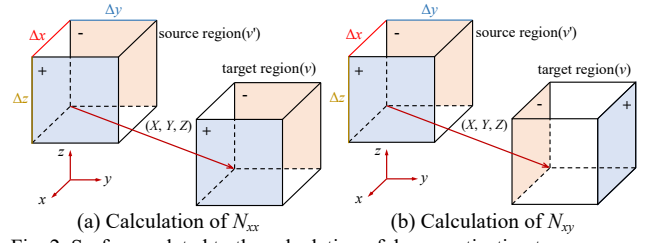


Fig. 2. Surfaces related to the calculation of demagnetization tensor.

threads of the processor minus 2, where the “2” is to escape the full load running of the computing. The parallel process will be illustrated in detail in the extended paper.

III. RESULTS

Taking the discretized elements of $5 \times 5 \times 1$ as an example, Table I compares the computation time using the traditional MSEM and P-MSEM, respectively. It can be seen that the parallel computing method has obviously improved the calculation efficiency. The detailed comparison for other discrete elements as well as the modeling magnetic characteristic curves will be presented in the extended paper.

TABLE I
THE TIME TAKEN BY DIFFERENT COMPUTING METHODS

Demagnetization Coefficient Tensor	Element Energy Minimization	Time Consuming (s)
MSEM	MSEM	32
P-MSEM	MSEM	30
MSEM	P-MSEM	20
P-MSEM	P-MSEM	19

REFERENCES

- [1] M. Sudo, T. Mifune, T. Matsuo, and C. Kaido. “A simplified domain structure model exhibiting the pinning field,” *IEEE Trans. Magn.*, vol. 49, no. 5, pp. 1829–1832, May. 2013.
- [2] S. Ito, T. Mifune, T. Matsuo and C. Kaido. “Macroscopic magnetization modeling of silicon steel sheets using an assembly of six-domain particles,” *J. Appl. Phys.*, vol. 117, no. 17, 17D126, Mar. 2015.
- [3] C. Abert. “Micromagnetics and spintronics: models and numerical methods,” *Eur. Phys. J. B.*, vol. 92, no. 6, 120, Jun. 2019.
- [4] P. Heistracher, F. Bruckner, C. Abert, C. Vogler, and D. Suess. “Hybrid FFT algorithm for fast demagnetization field calculations on non-equidistant magnetic layers,” *J. Magn. Magn. Mater.*, vol. 503, 166592, Jun. 2020.

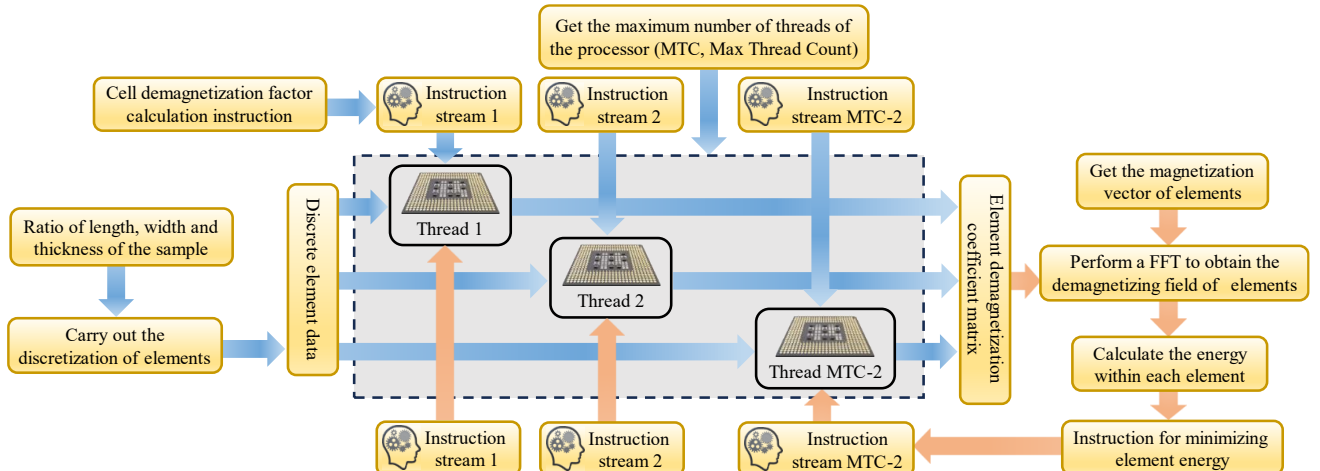


Fig. 3. P-MSEM computing flow chart.