A STUDY ON THE MODELING OF THE OPTIMAL CONFIGURATION OF FERROMAGNETIC MATERIALS

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Abstract - The most distinctive property of ferromagnetism is the observation of hysteresis loops. It is the feature showing the fact that ferromagnetism can remain as a nonzero magnetization after applying an external field and then removing it. The natural domain theory is about one of the physical mechanisms influencing the observed phenomenon. According to this, “Ferromagnetic material is subdivided into regions, called magnetic domains” [1]. In each domain, the magnetic moments are aligned via the molecular field, but the orientation of spontaneous magnetization can vary from domain to domain. When the magnetization is averaged over volumes large enough to contain many domains, magnetization may be close to zero. It turns out to be the minimalenergy state. This sounds reasonable to the thermodynamic balance principle. By using the finite element analyst method, we have figured out the origin domain configuration of the sustainable energy state of ferromagnetic material and the rearrangement to a new structure under an external field.

Key words - magnetic domain; domain wall; spin; closure domain; magnetostatic energy; spontaneous magnetization.

1. Introduction

Magnetism is one of the long-standing aspects of physics. It was originated over 3000 years ago when the Chinese invented the magnet. Since that time, magnetic studies were initiated and developed strongly. Its applications can be seen everywhere, from electric motors to transformers and permanent magnets, from various types of electronic devices to magnetic recording, …

Due to the practical and urgent demand of magnetic manufacturing and producing industries, researches on magnetism as well as its properties continue developing until today. There are many scientific projects studying magnetism, material properties, as well as how to calculate energy for the different materials, … Everyone can imagine the model by specifically magnetization characteristics and basic concepts which we are examining.

There have been many researches on the modeling of the optimal configuration of magnetic material. However, these researches face the difficulty of calculating the demagnetization energy, which depends on the size, shape and the boundary of the sample. This paper aims to introduce one method of using finite element methodology to calculate demagnetization energy, hence to obtain the optimal configuration of magnetic material.

2. Solutions

2.1. Magnetic domain

The regular configuration when observed inferromagnetic materials is magnetic domains; a material is subdivided into several uniform magnetization areas as shown in Figure 1.

A magnetic domain includes magnetic spins arranged parallel to reach spontaneous magnetization under affection of the molecular field. However, the orientation of the magnetization is different between magnetic domains.

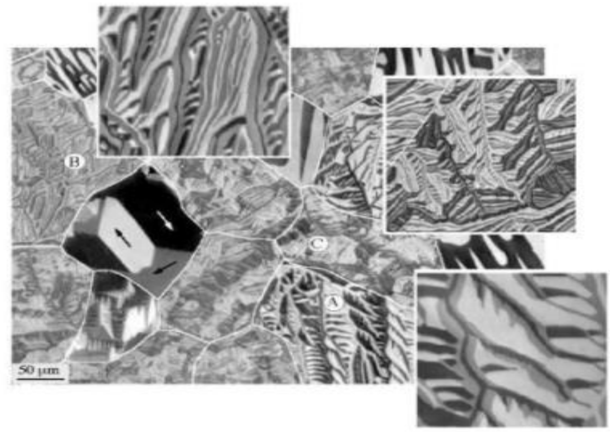


Figure 1. *Magnetic domains of FeSi alloy is thick of 0.5 mm*

The summation of magnetization of the different domains produces an approximately zero magnetization of material without applied field.

A wall domain involves spins in the interface layer among the different magnetic-oriented domains. The domain walls are classified by its spin change (Block wall and Neel wall) or the difference of magnetic domains (180^0 domain wall and 90^0 domain wall) [12].

2.2. Energy of system

We have subdivided a specimen into elementary volumes ΔV. These volumes must be small enough to assume that the physical properties of its materials is identical. In addition, these volumes must be large enough for the various materialsto be represented by assuming that these conditions are reached, we will calculate energy in these particular volumes to calculate the total energy for the whole specimen.

The energy of system is the total of particular energies: exchange energy, anisotropy magneto-crystal energy, maneto-elastic energy, magnetostatic energy (Zeeman energy and demagnetization energy) [7, 9, 10]. A system changes frequently its configuration to reach structure with total a minimal energy. This is the stable structure of system.

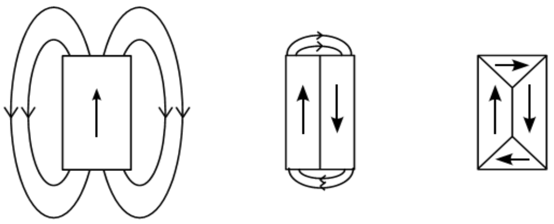
2.3. The categories of magnetic domain configuration

There are three basic categories of magnetic domains [11]:

a. Single domain: There is only one magnetic domain, it will be magnetized uniformly until the spontaneous magnetization (Figure. 2a);

b. Multi domain: The material is divided into parallel domains with opposite directions between adjacent domains (Figure. 2b);

c. Closure domain: There are two main domains and two closed domains, the orientations of the magnetization of component domains is closed inside specimen (Figure. 2c).



(a) **(b)** **(c)**

Figure 2. *Three types of magnetic domains: (a) single domain, (b) multi domain, (c) closure domain.*

Magnetostatic energy can be considered to be arising from induction loops around specimen [5, 6, 7]. It can be predicted that the magnetostatic energy of closure domain is minimal because induction loops cannot go out specimen. However, by introducing domain walls into the configuration, wall's energy must be included into the calculation of total energy. In section IIIA, we will demonstrate like that.

Let us consider the closure domain:

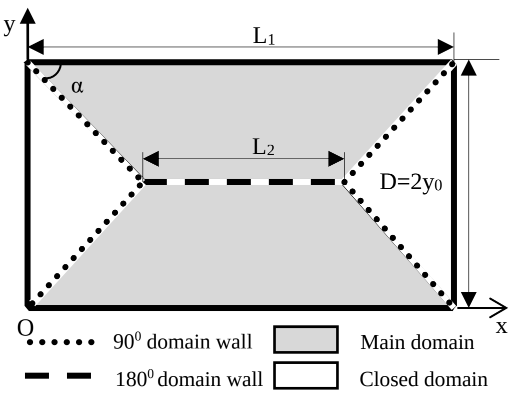


Figure 3. *Closure domain*

The relation of length L_1 and width D is calculated by the minimizing the extra energies (Block wall's energy and magneto-elastic energy).

$$D = \sqrt{\frac{2\gamma L_1}{K_1}} \qquad [4,8] \qquad (1)$$

In equation (1), γ is the energy density of 180^0domain wall, K_1 is isotropic factor of material.

The relation of length L_1, L_2, width D and α:

$$\tan\alpha = \frac{D}{L_1 - L_2} \qquad (2)$$

There is a value of α that makes system reach the minimal energy. We can calculate α by using finite element method.

2.4. The change of closure domain configuration under applied field

We have studied and determined angle α. We can change the stableness in system by adding energy. The system will reach a new balanced structure correlatively with a new minimal energy, through the motions of domain walls. If the orientation of magnetization of domain is same with applied field's orientation, that domain will be expanded and vice versa. When domain walls move, magnetization and energy of system are inversely proportional: if Zeeman energy increases, magnetostatic energy will decrease, on the contrary, a decrement in Zeeman energy lead to an increment in magnetostatic energy. Let consider two basic ways to move domain walls like Figure 4.

+ The first motion model: moving 180^0 domain walls in parallel with initial location with a change of α.

+ The second motion model: moving 180^0 domain walls in parallel with initial location while reserving α.

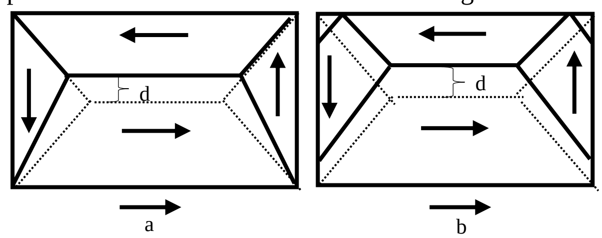


Figure 4. *The change of domain configuration under applied field. (a) The first motion configuration, (b) The second motion configuration*

By using finite element method, we can figure out the optimal motion.

2.5. Finite element method (FEM)

To resolve a magnetic problem, we have to solve the Laplace equation satisfying the certain boundary conditions:

$$\Delta\varphi_M = 0, \qquad (3)$$

Where φ_M is the magnetization of the material.

However, with the complicated boundary shapes, finding out the root of above equation is so hard, even impossible. In fact, one uses approximation methods which based on numerical technique to have solution for differential Laplace equation. The accuracy is up to how we discretize equation (3). FEM encompasses all the methods for connecting many simple element equations over many small subdomains, called finite elements to approximate a more complex equation over a larger domain. Basic idea of FEM is to know potential distribution on mesh nodes which is content with the prior conditions. First, one assumes a reasonable distribution then modifies it through repeating the same procedure after each loop until the certain precision. In summary, we can pick up an arbitrary potentialφ_i, yet the more skillful we chose, the shorter time we calculate. We also can vary differential distance from bigger to smaller to obtain results more precisely. FEM is best understood from its practical application known as finite element analysis (FEA). FEA is a computational tool to generate mesh for dividing a complex problem into small elements. Inside a scope of this paper, we use a software program named finite element method magnetics (FEMM) with the embedded FEM algorithm.

3. Result and interpretation

3.1. Determine stable structure of magnetic material

3.1.1. Three basic configurations in comparison

The energy of these three configurations is shown in Table 1. From Table 1, we can conclude that the previous qualitative predictions are right. That means closure domain is the stable energy configuration.

Table 1. Comparision magnetic energy of three configurations

Configuration	Magnetic energy
Single domain	1.07 e-014J
Multidomain	1.30 e-015J
Closure domain	2.16 e-029J

3.1.2. Original configuration of system

Assume that domains structure of a symmetric crystal-material is placed in the air. Its depth is 1μm. Other required arguments are: B-H curve, coercive field H_C; and they depend on the type of material.

We use martensite whose B-H curve is demonstrated in Figure 5.

$$\alpha = \arctan\left(\frac{2y_0}{L_1 - L_2}\right) \qquad (4)$$

We chose L_1=20μm, D=$2y_0$=2μm.

When varying α, we have result as shown in Figure 6:

α is the angle between 90° wall and $0x$ axis:

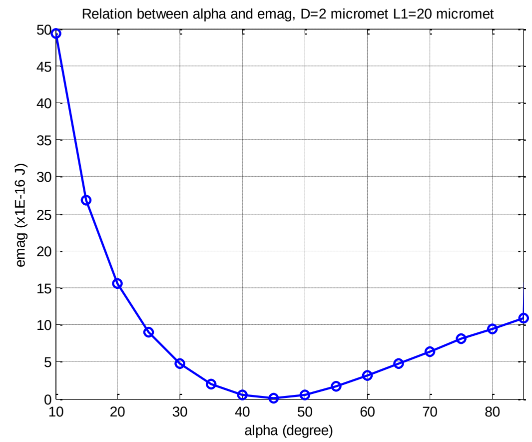


Figure 6. *System energy is in relation with α*

From Figure 6, we can see that energy is a function of α, at α = 45^0, energy is minimal or D=$2y_0$=L_1- L_2. By changing L_1 over many different values, we realize that above comment remains valid, and it is independent of specimen size.

3.2. Optimal motion model of domain walls

3.2.1. The first motion model

The walls are in the parallel-moving when compared to the original. This motion way does not reserve angles α and displacement distance d as Figure 4b. For L_1=20μm, D=$2y_0$=2μm, we obtained results as shown in Figure 7 with the different materials (martensite, alnico 5[(1)] and alnico 6[(2)])

It can be noted that:

- Magnetic energy grows up with an increment of d and take d=0 axis as a symmetric axis.
- Magnetic energy is not completely the parabolic function of d.
- The slopes of the graphs are different with the different materials because each material has its own properties.

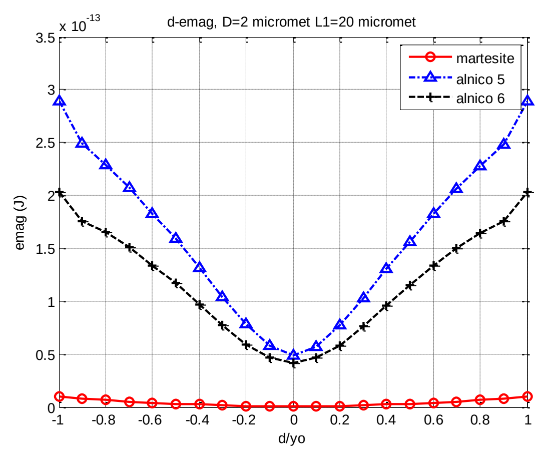
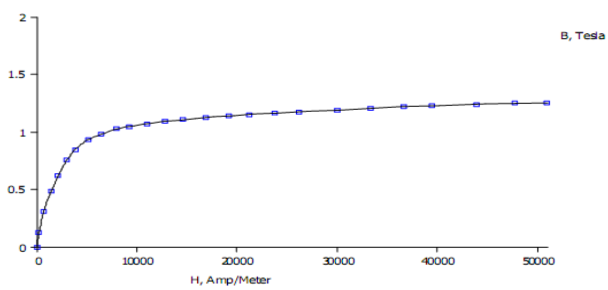


Figure 7. *Magnetic energy is in relation with d (first model)*

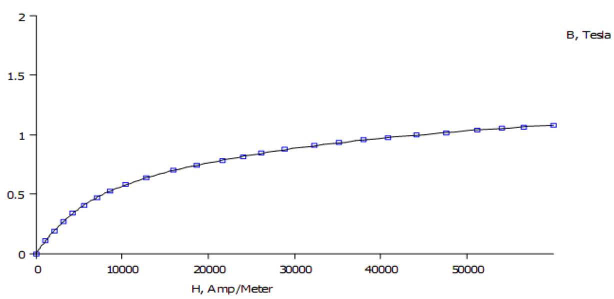
3.2.2. The second motion model

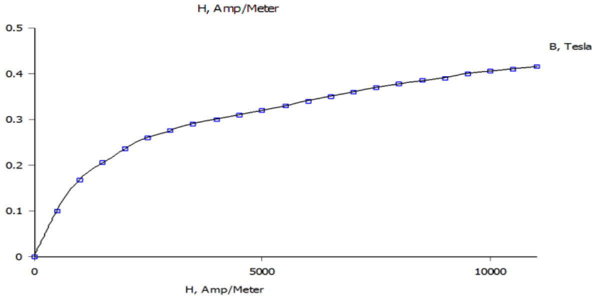
The motion is similar to the first model, but the angles α remain constant (α=45^0) (Figure 5c). From observing Figure 8, we can have the same comments as mentioned before but magnetic energy is the parabolic function of d.

[(1)]B-H curve of alnico 5



[(2)]B-H curve of alnico 6





[(3)]B-H curve of NdFeB 52 MGOe

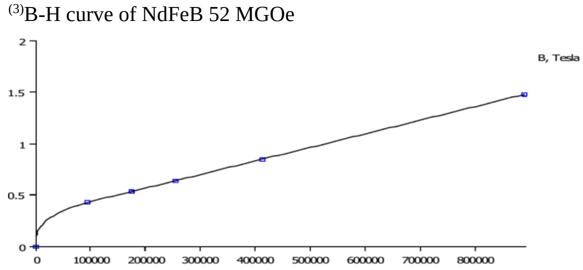


Figure 5. *B-H curve of martensite*

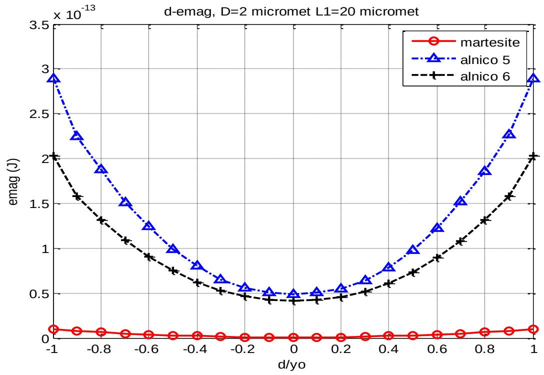


***Figure 8.** Energy is in relation with d (second model)*

3.2.3. Comparing two motion models

Simulation arguments: L_1=20µm, D=2y_0=2µm for both models with martensite material.

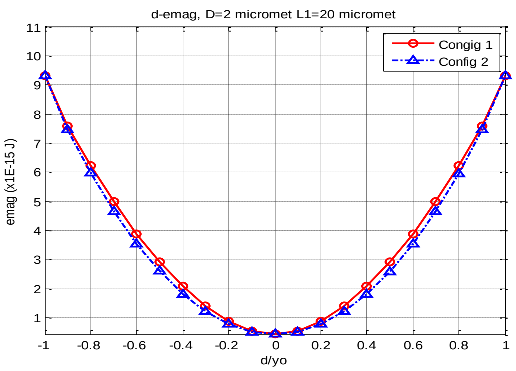


***Figure 9.** Two models in a comparison*

Comments:

- At d=0 and d=1, there is no different between two configurations, so energies are the same.
- At each value of distance d, the second motion model introduces a smaller energy than the first one.

From that, we conclude that the walls tend to move like the second model under applied field.

Magnetic energy is a second-order function of distance d as mentioned above because it is proportional to squared magnetization and magnetization is a first-order function of distance d which defined below:

Before moving:

The area of S_1 and S_2 on Figure 10 are calculated as:

$$S_1 = S_2 = y_0 L_1 - y_0^2 \quad (5)$$

$$\Delta S = S_1 - S_2 = 0 \quad (6)$$

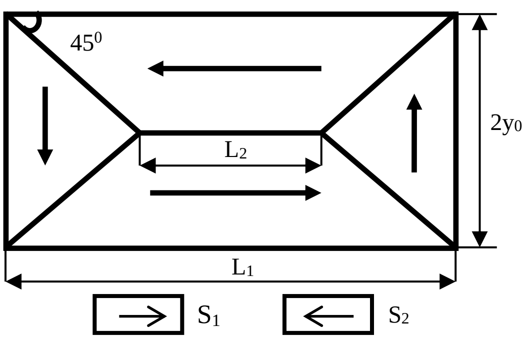


***Figure 10.** Original domain configuration*

During moving:

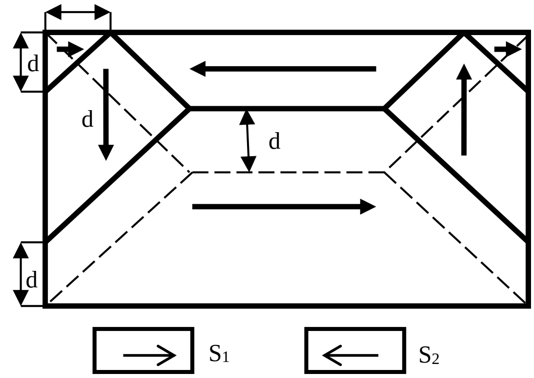


***Figure 11.** Domain configuration in the walls motions*

$$S_2 = (y_0 - d)(L_2 + y_0 - d) \quad (7)$$

$$S_1 = d^2 + y_0(L_2 + y_0) + d(L_2 + 2y_0) \quad (8)$$

$$\Delta S = S_1 - S_2 = 2dL_1 \quad (9)$$

Before moving, S_1 is equal S_2, resulting a zero magnetization. After moving, the change in S_1 and S_2 led to a nonzero average magnetization M, and it is proportional to ΔS. From that, we can figure out the magnetization along the field direction:

$$M = \frac{M_S d}{y_0} \quad (10)$$

M_s is spontaneous magnetization of material.

3.3. Movement distance d change over applied field

We havemagnetic energy density for ellipsoid specimen:

$$Emag = E_{Demag} + E_{Zeman} = \mu_0 \frac{N_d}{2} M^2 - \mu_0 HM$$

$$= \mu_0 \frac{N_d}{2} \frac{M_S^2}{y_0^2} d^2 - \mu_0 H \frac{M_S}{y_0} d \text{ [3]}$$

$$Emag' = 0 \Leftrightarrow d = \frac{H y_0}{N_d M_S} \quad (11)$$

Let $\lambda = \frac{L_1}{D} = \frac{20}{2}$ = 10>1 so

$$N_d = \frac{1}{\lambda^2 - 1}\left[\frac{\lambda}{\sqrt{\lambda^2 - 1}} \ln\left(\lambda + \sqrt{\lambda^2 - 1}\right) - 1\right] \text{[10]} \quad (12)$$

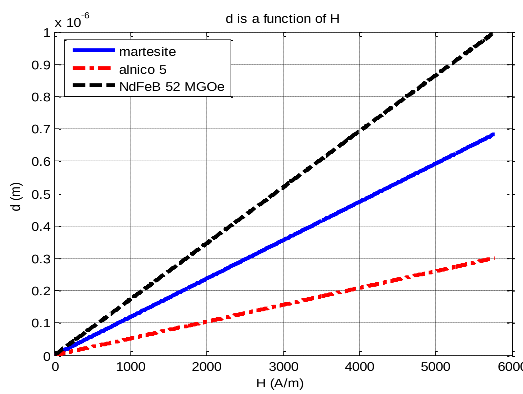


***Figure 12.** Distance d is a function of Hfor the different materials (martensite, alnico 5 and NdFeB 52 MGOe(3))*

Comments:

- d increases with the increment ofH.
- When we apply a field to the specimen, the system changes to reach the new energy minimum, and the movement distance is up to how large the field is.

- The slope of the graphs varies with the different materials.
- NdFeB 52 MGOe material's slope is biggest so that it is the easiest magnetization. On the contrary, alnico 5 material is the most difficult magnetization.

4. Conclusion

In this paper, we have concentrated on generalizing the magnetic domain model. The model we investigated is the one that has minimal magnetic energy. In particular, that is a four domain-rectangular with spontaneous magnetization in each domain but the orientation is different from domain to domain. When $\alpha = 45^0$, that model is optimal. When applied in a field, the walls will move and the system changes to reach a new stable state with new energy minimum. When the field magnitude gradually increases, the 180^0 wall tends to approach the surface of specimen in correspondence with the disappearance of the wall and the magnetic energy is proportional to the square of the movement distance. As mentioned, the motion model with remaining L_2 and all of the angles α is the best one.

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(The Board of Editorsreceived the paper on 26/10/2014, its review was completed on 28/10/2014)