Communications in Physics, Vol. 21, No. 3 (2011), pp. 272-276

THE THEORETICAL MAGNETIZATION HYSTERESIS CURVE OF Nd-Fe-B ANISOTROPIC BONDED MAGNETS

NGUYEN VAN KHANH
Faculty of Physics, Hanoi National University of Education
NGUYEN VAN VUONG
Institute of Materials Science, VAST

Abstract. *The theoretical magnetization hysteresis curve of Nd-Fe-B anisotropic bonded magnets is simulated using Jiles-Atherton model and random number generation technique. Gaussian statistics was used to assign magnetic particles to random values of magnetic field* (H_{ai}) *and effective interaction* (α) *parameters. The prospect of anisotropic bonded magnet is evaluated and discussed.*

I. INTRODUCTION

Originating from ideas of seeking a magnetic phase of Nd-Fe-B material at the stable and quasi-stable states [1–3], up to now, permanent magnets Nd-Fe-B have been fabricated by using the powder metallurgy [4] (for sintered magnets) and rapid solidification technique (for bonded ones). Recently, the energy product $(BH)_{max}$ of sintered magnets is about 30 - 35 MG.Oe commonly, and can reach 45 - 50 MG.Oe by finely controlling the processing [5]. Sintered magnet is applied for high power applications such as generator, motor, magnetic resonant amplifier, and magnetic equipments for cruel oil exploitation. On the contrary, bonded magnet is always used for small power application, small dimension devices with multi - polar magnetic structure. Bonded magnet is almost fabricated by MQ1 process [6], with energy product of ˜10 MG.Oe. Usually, due to the rapid solidification process, bonded magnet is isotropic. Besides the two above kinds of magnets, there is an intermediate magnet, called anisotropic bonded magnet. They are synthesized by bonded technique using anisotropic powder which is dominant by $Nd_2Fe_{14}B$ phase. The powder is made by general ground technique or ground in H_2 by HDDR (Hydrogenation Disproportionation Desorption and Recombination) technique [7]. This kind of magnet takes a full advantage of a hard magnetic quality of anisotropic ferromagnetic particles and the flexibility of bonded technique. This allows us to fabricate a magnet which has energy product of 15-20 MG.Oe, applying for medium power devices.

In principle, anisotropic bonded magnets have better magnetic quality than isotropic bonded ones because they are constructed by anisotropic magnetic particles. However, this is much depended on the microstructure of magnetic particles and the process to form the magnetic orientation using external magnetic field.

In aim of optimizing the fabrication conditions to produce high quality anisotropic bonded magnets, the modeling based on Jiles - Atherton model [8] and the random number generation technique [9] has been established. The details of modeling are described in

Sec. II, its results are presented in Sec. III, and conclusions of the oriented fabrication are summarized in Sec. IV.

II. MODELING THE MAGNETIZATION HYSTERESIS CURVE OF ANISOTROPIC BONDED MAGNETS

The anisotropic bonded magnet is reputed to be a group of ferromagnetic particles which are separated in a nonmagnetic adhesive medium. In general, the particles have difference size, difference sharp and are specific by difference demagnetization coefficient (N_i). The anisotropy of particles depends on the intrinsic properties of materials (the anisotropic field K_α), and the microstructure of grain (the effective interaction coefficient between particles).

The magnetization hysteresis curve $M(H_{ext})$ (M is magnetization, H_{ext} is external magnetic field) of anisotropic bonded magnets is modeled by the sum of magnetic curves contributed by all of the ferromagnetic particles in magnets. The modeling is based on the following suggests:

1. The magnet consists of ferromagnetic particles which have similar size and sharp. From this assumption, instead of the random parameter, the particles demagnetization coefficient N_i is chosen. The realization of random parameters N_i was performed by using random number generation technique [9]. However, for the hard magnet $Nd_2Fe_{14}B$ with tetragonal structure, it is assumed that the grain with long sharp, therefore, N_i is ignored.
2. To model the magnetic hysteresis of individual particle, we can choose one of four macroscopic models which were described in [8]. However, for the anisotropic magnetic particle which has multi-domain structure, the Jiles-Atherton model is more useful. In this model, the magnetization M_i can be expressed as:

$$M_i = M_s \cdot f_i(H_{eff}) \tag{1}$$

The f_i function is of Langevin form:

$$f_i(H_{eff}) = \coth\left(\frac{H_{eff}}{H_{ai}}\right) - \frac{H_{ai}}{H_{eff}}. \tag{2}$$

The field H_{ai} is relative with external magnetic field at which the magnetization M_i of i-particle reaches to saturated value. For $Nd_2Fe_{14}B$ the maximum value of H_{ai} is about 7.6 T [10]. The real value of H_{ai} is determined by the influence of external magnetic field during the bonding process. H_{ai} is a random parameter and its distribution follows the Gaussian statistic function in the range of 0-7.6 T corresponding to the direction of external magnetic field that particles oriented to.

The effective field H_{eff} describes the net field influence on each particle, including the external magnetic field H_{ext} and the effective field cause by surrounded particles. The expression of H_{eff} is indicated by:

$$H_{eff} = H_{ext} + \alpha_i \cdot M_i + H_{dip}. \tag{3}$$

The coefficient α_i is directly proportional to the interaction of magnetic domains between particles. The value of α_i is very small ($\alpha_i \ll 1$) for the soft magnetic particles;

the large value of α_i the harder magnetic behavior is. The dipole magnetic field H_{dip} characterizes for the interactions between magnetic particles in nonmagnetic adhesive medium. After [11], the interaction coefficient between particles is one order smaller than α_i and thus, H_{dip} can be eliminated in expression (3).

Based on the phase diagram of Nd-Fe-B, one can see that the particles which are fabricated by two above methods are not identical in microstructures. Co-exists with $Nd_2Fe_{14}B$ phase are $NdFe_4B_4$ phase and Nd-rich phase. Hence, the coefficient α_i of particles must be random parameter in the range $\alpha_{i\,\min} - \alpha_{i\,\max}$ which depends on the microstructure of particles.

By using two above mentioned suppositions and the random number generation program with an assigned statistic function [9], the magnetic hysteresis curve of anisotropic bonded magnet is modeled and computed in Pascal programming language.

III. MODELING RESULTS AND DISCUSSION

In the case of isotropic bonded magnet by using rapid solidification technique for example, the two parameters H_{ai} and α_i could be counted as constants for all particles, the value of H_{ai} is about $H_{a\max}/3 \simeq 2.5$ T, and $\alpha_i \simeq 5$. As described in [12] the magnetic hysteresis curve of the magnet proved the good agreement between modeling and experimental results.

In this study, anisotropic bonded magnet consists of anisotropic particles. Therefore, this technology focuses on the effect of external magnetic field (H_{emo}) on the magnetic orientation of magnet during bonding process. The magnetic orientation is determined by the half-width of maximum σ_{Ha} of Gaussian distribution of particles number N_{sh} versus H_{ai} parameter. With the suitable bonding technique, for the distribution of a given particles size, the larger H_{emo} value leads to better magnetic orientation and smaller σ_{Ha}. On the fact, σ_{Ha} value could be changed from 0.5 T to 7.6 T. Figure 1 shows the considerable effect of magnetic orientation to magnetic hysteresis curve (Fig. 1a) and energy product $(BH)_{\max}$ (Fig. 1b) of the anisotropic bonded magnet. In this work, we use $H_{a\max} = 7.6$ T, $H_{a\min} = 0.5$ T, $\alpha_{\max} = \alpha_{\min} = 3$ for calculation and σ_{Ha} parameter changes from 0.6 to 3 T.

In practice, the maximum density of anisotropic bonded magnet normally reached about 85% of ρ_R then $(BH)_{\max}$ value is only about 20 MG.Oe. However, this value could be increased by a improvement of α_I coefficient, in principle, the α_I depends the particles size and can be increased to 3 as the size of particles reduces to the size of single domain. In the critical case, assuming that α_i of particles in anisotropic bonded magnet is equal to 5 [12], $\sigma_{Ha} = 0.6$, $\rho_R = 7.62$ g/cm^3, $(BH)_{\max}$ may reach to 30 MG.Oe. In the practice, density is about 85% of idea value, therefore $(BH)_{\max}$ of anisotropic bonded magnet only reach to 25 MG.Oe. Experiment results indicated that anisotropic bonded magnet fabricated using HDDR powder almost reaches this one [12].

In order to obtain a high quality anisotropic bonded magnet, besides the good magnetic orientation, the main phase in the sample is $Nd_2Fe_{14}B$, and the amount of non-magnetic $NdFe_4B_4$ phase is ignored. In addition, Nd-rich boundary region between micro-particles need minimize. These all conditions aim to increase the coefficient α_i. Of course, due to the dependence of quality of sample on many parameters, therefore, we

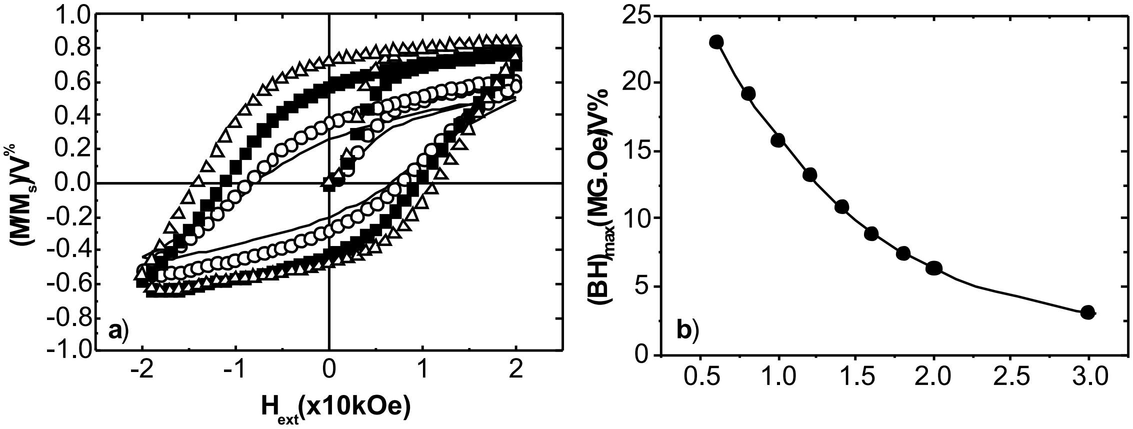

Fig. 1. The effect of magnetic orientation to (a) magnetization hysteresis curve (σ_{Ha}= 3T(–), 2T(○), 1T(■), 0.6 T(△)) and (b) energy product (BH)$_{\max}$ of anisotropic bonded magnets.

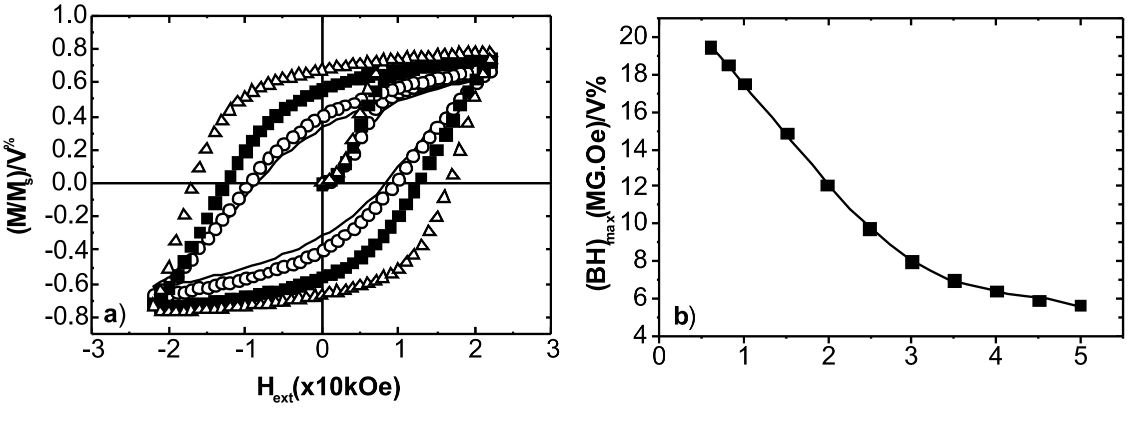

Fig. 2. The influence of σ_α on (a) the magnetization hysteresis curve (σ_α= 5(–), 3(○), 1.5(■), 0.6 (△)) and (b) energy product (BH)$_{\max}$.

must consider coefficient α_i as a random parameter which has probability density obey on Gaussian distribution with full wide half maximum α_i. In case of $Nd_2Fe_{14}B$ materials, α_i value is about $0\div6$ [12]. The influence of this distribution to magnetic hysteresis curve and energy product $(BH)_{\max}$ of anisotropic bonded magnet is shown in Fig. 2. Parameters used for calculation are $H_{a\max} = H_{a\min} = 2$ T, $\alpha_{\max} = 6$, $\alpha_{\min} = 0$ and the variable σ_α value changes between $0.6 \div 5$.

Figure 2 clearly indicates that the smaller the contribution to α_i of particles (proportional to smaller σ_α), the larger number of large α_i particles is. Therefore, the magnetic hysteresis curve and the energy product $(BH)_{\max}$ become larger. With the medium degree of magnetic orientation, proportional to the average value of $H_{ai} = 2T$ and $\sigma_\alpha = 0.6$, the anisotropic bonded magnet which has density of $0.85\rho_R$ will achieve $(BH)_{\max} \sim 16$ MG.Oe.

In general case, both two parameters are random. With common technology, H_{ai} and α_i will change from 0 to 7.6 T and from 0 to 3, respectively. When half-widths σ_{Ha} and σ_α are 0.6 and 0.6; 1.0 and 1.0; 1.5 and 1.5, the energy product $(BH)_{\max}$ of sample which has density ρ_R will be 18.5, 10.3 and 5.5, respectively.

IV. CONCLUSION

In summary, we have used Jiles-Atherton model and the random number generation program to calculate the magnetic parameters, such as $(BH)_{\max}$ and apply them to assign the technique parameters in magnet preparation. From above presentation, we can conclude that, in order to fabricate high energy product $(BH)_{\max}$ (15-20 MG.Oe) anisotropic bonded magnet, it is required:

1. To ensure that material is dominated by $Nd_2Fe_{14}B$ phase,
2. The optimal thermal treatment process must increase α coefficient. Because of this reason, we apply hot-compacted technique to fabricate bonded magnet using only one component home-made binder with high melting temperature.
3. External magnetic field used to form magnetic orientation should be $2 \div 3$ T,
4. Density of magnet must achieve to $6.5 \div 7$ g/cm^3.

Among the four requirements, the second one is more important to improve α coefficient. Our experimental results with $(BH)_{\max} = 14$ MG.Oe confirm that the calculation is in good agreement with the condition to prepare high quality anisotropic bonded Nd-Fe-B magnet. This modeling result is an usefull assistance to improve the quality of anisotropic bonded Nd-Fe-B magnet.

REFERENCES

[1] M. Sagawa, *Proc. 16th Int. Workshop on RE Magnets & Their Applications*, Vol. 1, Sendai, Japan, 2000, Eds. H.Kaneko, M. Homma and M. Okada, pp.17-24.

[2] M. Drak, B. Ziębowicz, L.A. Dobrzański, *Journal of Achievements in Materials and Manufacturing Engineering* **31** (2008) 91-96.

[3] Huijie Wang, Minggang Zhu, Wei Li and Xin Zhang, *Rare Metals* **25** (2006) 521-525.

[4] McCallum, R. W. Kadin, A. M. Clemente, G. B. Keem, *Journal of Applied Physics*, **61** (2009) 3577 – 3579.

[5] M. Hashim *et al.*, *ASEAN-INDIA Workshop on NdFeB Magnet and Materials*, pp. 23-25 August 2000, Malaysia, pp.135-157.

[6] V. Panchanathan, *Journal of Materials Engineering and Performance* **4** (4) (1995) 423 – 429.

[7] Ed.J.M.D. Coey, *Rare-Earth Iron Permanent-Magnets*, Chapter 6, Clarendon Press. Oxford. 1996.

[8] F. Liorzou, B. Phelps and D.L. Atherton, *IEEE Trans. Mag.* **36** (2) (2000) 418-428.

[9] N. V. Khanh, N. V. Vuong, *Proc. of 5th National Workshop on Physics V*, Vol. II (2002) 748-753.

[10] Ed.J.M.D. Coey, *Rare-Earth Iron Permanent-Magnets*, Chapter 4, Clarendon Press. Oxford, 1996.

[11] N. V. Khanh, N. V. Vuong, *Proc. of 5th National Workshop on Physics V*, Vol. II (2002) 711-715.

[12] N.V. Khanh, N.V. Vuong, M.M. Tan, V.H. Ky, and N.V. Nha, *Proc. of 5th National Workshop on Physics V*, Vol. II (2002) 809-812.

Received 29 October 2010.