J Electr Eng Technol.2016; 11(5): 1316-1322
http://dx.doi.org/10.5370/JEET.2016.11.5.1316

ISSN(Print) 1975-0102
ISSN(Online) 2093-7423

Residual Magnetic Flux Density Distribution Calculation Considering Effect of Aligning Field for Anisotropic Bonded NdFeB Magnets

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Abstract – This paper presents a calculation method of residual magnetic flux density distribution for a four-pole anisotropic bonded NdFeB permanent magnet (PM) considering the effect of aligning magnetic field during the forming process. To manufacture the anisotropic bonded NdFeB magnet, the magnet powder needs to be aligned with a proper aligning field before magnetizing. Therefore, it is necessary to analyze the magnetizing process based on the aligning field analysis to determine accurate distribution of residual magnetic flux density (B_r) for the anisotropic bonded NdFeB PM. In order to estimate the B_r distribution of the anisotropic bonded NdFeB magnet, an analysis method by combining the external electric circuit equation coupled with the transient finite element method and the scalar Jiles-Atherton hysteresis model is proposed.

Keywords: Aligning magnetic field, Anisotropic bonded NdFeB magnet, Finite element method, Forming process, Magnetizing analysis

1. Introduction

In order to design high performance permanent magnet (PM) machine, the PM type selection is essential. Nowadays, the PM machine utilizing NdFeB magnet is popular due to its high efficiency, high power density, and simple structure [1, 2]. On one hand, according to the manufacturing process, the NdFeB magnet can be classified into sintered and bonded types. On the other hand, according to the characteristics of magnet powders, it can be classified into isotropic and anisotropic ones [3-5]. Among different types of PMs, the anisotropic bonded NdFeB magnets are more attractive to the low power applications. The main reason is that they have lower cost around 150 \$/kg and higher structure flexibility than the sintered ones (200 \$/kg). Furthermore, they have relatively higher B_r (~0.98 T) and maximum magnetic energy product $(BH)_{max}$ (~175 kJ/m^3) than the conventional isotropic bonded NdFeB magnets with B_r of 0.71 T and $(BH)_{max}$ of 80 kJ/m^3 [6, 7].

To align the anisotropic magnet powders, the manufacture of the anisotropic bonded NdFeB magnet requires a proper and enough strong magnetic fields which is named aligning magnetic field. The aligning magnetic field, which is generated by a four-pole electromagnet, can be either a radial pattern or a polar pattern [8, 9]. Following the molding process, the magnet powder, which is uniformly distributed and fixed with the resin in the PM, is aligned with the aligning magnetic field. However, it is not fully magnetized and has to be magnetized by impulse magnetization at a considerably high field level [10].

Although the magnetic property of the anisotropic bonded NdFeB magnet such as B_r, mainly depends on the orientation ratio of particles decided by the aligning magnetic field, there does not exist any general guidance for magnetizing the anisotropic bonded NdFeB magnet.

In the forgoing researches, there are some contributions that investigate the effect of aligning magnetic field for the anisotropic bonded NdFeB magnet. However, in [8], [9], and [11], authors only explained the effect of aligning magnetic field on the magnet itself, the effect on the magnetizing process was not mentioned. In [12], authors described the effect of aligning magnetic field on the magnetizing process for the anisotropic bonded NdFeB magnet. However, the detailed description was not given in their papers. Furthermore, in all of these contributions, the hysteresis property of magnet was not considered.

In this paper, a numerical method which combines the finite element method (FEM) is proposed to predict B_r distribution of the anisotropic bonded NdFeB magnet. Before magnetizing analysis, the aligning field analysis is carried out and the local magnetic property of the PM determined by the aligning magnetic field is calculated.

2. Molding Process Analysis of Anisotropic Bonded NdFeB PM with Aligning Magnetic Field

The anisotropic bonded NdFeB magnets are developed with anisotropic magnet powders, which are manufactured through the dynamic hydrogenation decomposition, desorption recombination (d-HDDR) treatment, and the

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Received: January 19, 2016; Accepted: May 9, 2016

resin compound. The mixture, and then, is filled with 2500-4000kg/m^3 filling density in the molding tool. As the temperature of the molding tool increases around 100-150°C under the pressure of 0.4 GPa, the compound melts and the magnet powders suspend in the semi-liquid. Meanwhile, surrounding the molding tool, a four-pole DC electromagnet is assembled to generate a strong magnetic field so that the magnet particles can be enforced to rotate and attempt to align the direction of the magnetic field vector. This DC magnetic field is called aligning magnetic field. The aligning mechanism of the magnet powder is sketched in Fig. 1. After that, the semi-liquid component is cooled until room temperature and the prepared magnet is manufactured.

Fig. 2 shows a quarter of the designed powder aligning fixture, which consists of a four-pole DC electromagnet and a molding tool. The inner side of the molding tool cavity is a solid cylinder made of low carbon steel while the outer side is a non-magnetic hard alloy ring. Between the molding tool and the electromagnet, the magnetic and non-magnetic alloys are arranged across each other to concentrate the magnetic flux, which is generated by the electromagnet.

To investigate the effect of the aligning magnetic field on magnetic properties of the anisotropic bonded NdFeB magnet, the anisotropic bonded NdFeB magnet samples with different aligning fields are prepared. The magnetic properties are measured by using the PM hysteresis loop measurement instrument. From Fig. 3, it can be seen that with increasing the aligning magnetic field, the residual magnetic flux density B_r and maximum magnetic energy product $(BH)_{max}$ are enhanced, especially at the region of a low aligning field. Even though the intrinsic coercive force $({}_iH_c)$ of the magnet is slightly reduced, it can be said that the increasing aligning field can improve the magnetic properties of the magnet. Moreover, the orientation of the anisotropic bonded NdFeB magnet is determined by the aligning magnetic field. It should be noted that the prepared anisotropic bonded NdFeB magnet does not have magnetism after forming process. Therefore, before using, the magnet has to be magnetized by applying an enough strong impulse magnetic field. This impulse magnetic field is called magnetizing field. Before the magnetizing process analysis, the aligning magnetic field based on the magneto-static FEM is analyzed firstly. In this analysis, the PM region is taken as air and the permeability of this region equals to the permeability of vacuum μ_0.

After above analysis, the magnetic flux density B vector in the cavity of the molding tool is determined and based on vectors of the aligning magnetic field and the magnetizing field at the specific element, the effective magnetic flux density component is determined as shown in Fig. 4. The component of B can be calculated as follows:

$$B_{comp} = \vec{B}_{mag} \cdot \vec{d}_{align} \tag{1}$$

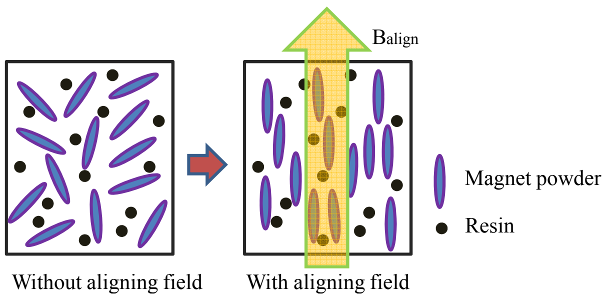

Fig. 1. Aligning mechanism of magnet powder

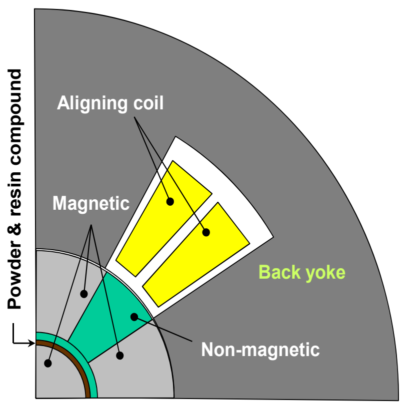

Fig. 2. Topology of the powder aligning fixture

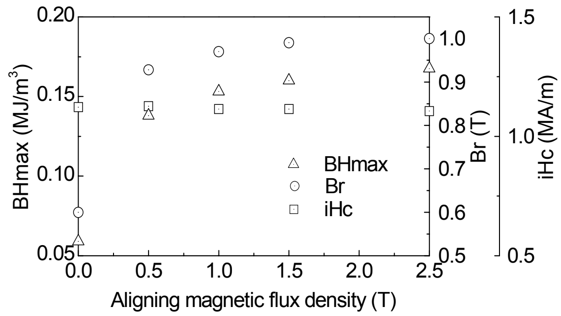

Fig. 3. Magnetic properties of PM with different aligning magnetic fields

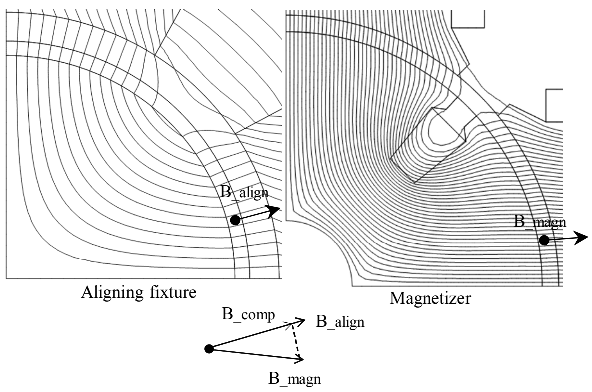

Fig. 4. Effective magnetic field component determined from aligning field and magnetizing field

where the B_{comp} and the B_{mag} are magnitudes of effective components of B and magnetizing field, respectively, and d_{align} is the direction vector of the aligning magnetic field.

Not only the direction but also the magnitude of the aligning magnetic field has effect on the magnetic properties of the magnet. Therefore, it is necessary to distinguish magnetic properties based on the magnitude of the aligning magnetic field. In this article, four different cases are considered, as shown in Fig. 5. For example, for case IV, there is the largest aligning magnetic field around 2.5 T, so the corresponding measured initial magnetization curve and demagnetization curves are selected and applied. For case I, in the transition region of PM, the aligning magnetic field is almost zero, so the initial magnetization curve and demagnetization curves which are measured according to this case, is selected. Apart from case I and IV, the magnetic properties named case II with aligning magnetic field of 0.5 T and case III with the aligning magnetic field of 1.5 T are also applied. In order to combine the analysis of aligning field with magnetizing analysis, the post process of the aligning magnetic field analysis is applied and the flow chart of this process is shown in Fig. 6.

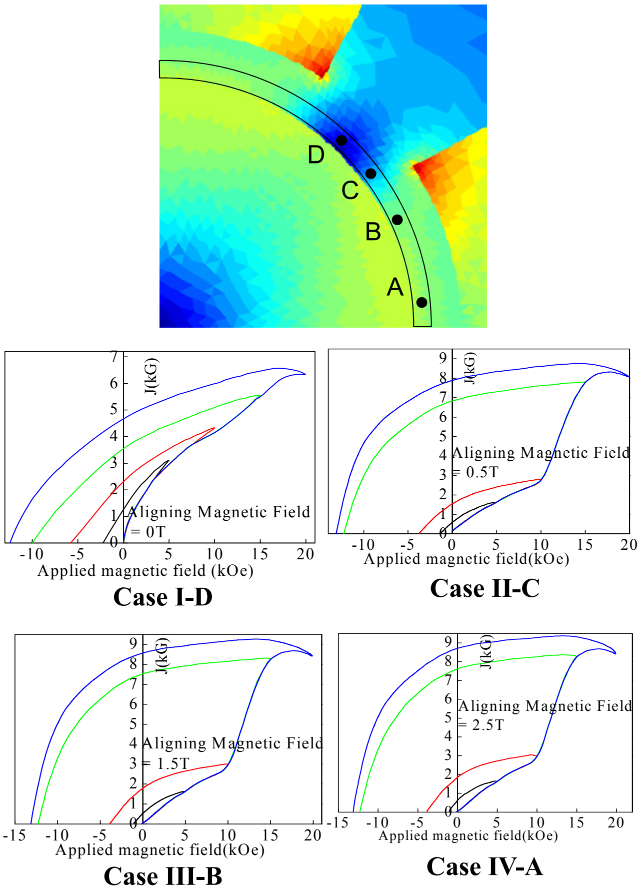

Fig. 5. Selection of initial and hysteresis properties according to the aligning magnetic field

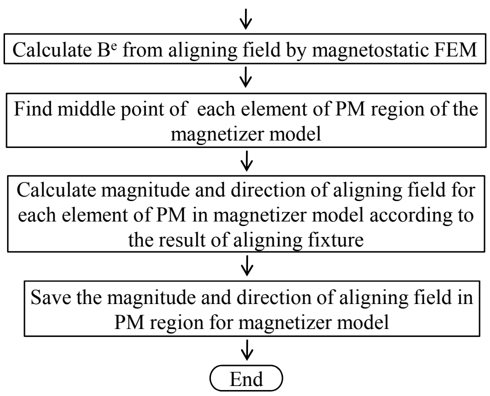

Fig. 6. Flow chart of aligning magnetic field analysis

3. Calculation of B_r Distribution Considering Effect of Forming Process

After forming process, the prepared magnet is required to be fully magnetized by a considerably strong magnetizing field which is generated by a capacitor discharge impulse magnetizer. The fundamental equation for magnetizing analysis of PM is treated as an unknown voltage source initial value problem coupled with an external electric circuit equation. Due to the relatively low conductivity of the prepared bonded magnet material around 2.9×10^3 S/m and the laminated back yoke for the magnetizer, the effects of eddy current in the analysis are ignored without loss of accuracy. The field governing equation in the FEM is written as follows:

$$\mathrm{rot}\left(\nu\,\mathrm{rot}\vec{A}\right)=\vec{J}_0+\mathrm{rot}\vec{M} \tag{2}$$

where υ is the medium reluctivity, $\boldsymbol{A}$ is the magnetic vector potential, $\boldsymbol{J}_0$ is the applied current density determined by the external electric circuit equation, and $\boldsymbol{M}$ is the magnetization of the magnet.

When the transient FEM coupling with external electric circuit is applied, the current is unknown. The voltage equation of the equivalent electric circuit shown in Fig. 7 derived from Kirchhoff's voltage law is shown as follows:

$$\frac{d\psi(t)}{dt}+Ri(t)+L_0\frac{di(t)}{dt}-\frac{q(t)}{C}=0 \tag{3}$$

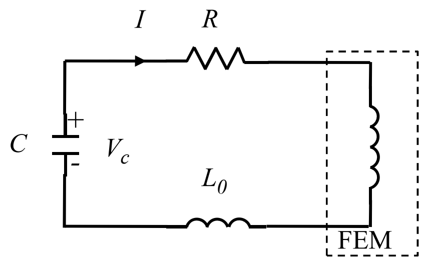

Fig. 7. Equivalent circuit of magnetizing fixture

where ψ is the flux linkage of the exciting winding, q is the instantaneous charge of the capacitor, R is the resistance of total winding for one pole, and L_0 is the leakage inductance of the winding. The relationship between the discharge current $i(t)$ and the discharge voltage $v_c(t)$ on the capacitor C is shown as follows:

$$i(t) = -C\frac{dv_c(t)}{dt}. \tag{4}$$

In order to simplify the analysis process, after achieving the maximum B for each element, the magnetization in the PM is assumed to increase or decrease monotonically. The overall algorithm can be summarized as follows:

Step 1. Analyze magnetization during the ascent stage of magnetic field according to initial magnetization curves;
Step 2. After achieving maximum B in Step 1, the magnetization is calculated from the hysteresis loops modeled by the Jiles-Atherton (J-A) hysteresis model.

The magnetizing process is analyzed step by step until the discharge current decreasing to zero, then the magnetization of PM is recorded and treated as residual magnetization of PM (M_r). The M_r saved in each element of PM can be used to the following numerical analysis.

In order to analyze the magnetizing process of the magnet, the magnetization needs to be estimated at each time step.

At the beginning, the magnetization is determined by initial magnetization curves based on the magnitude of aligning field. Fig. 8 shows the measured initial magnetization curves under different aligning fields. According to the level of aligning field in the specific element, the magnetization is calculated by the linear interpolation or extrapolation of measured curves.

After achieving the maximum value of magnetic flux density for each element in PM region, the magnetization is determined from hysteresis loops which are modeled by the J-A hysteresis model [13].

Due to effect of aligning magnetic field during the molding process, the hysteresis characteristics need to be modeled according to different values. The identified J-A model parameters are listed in Table 1.

Table 1. Parameters of Jiles-Atherton model under different aligning magnetic fields

B	*J*	M_s	*a*	*k*	*c*	*α*
0	0.0-0.5	699890	1090993	1499974	0.6423	5.1626
	0.5-	1198775	1538301	1499990	0.3286	3.7499
0.5	0.0-0.5	531516	1627379	1499993	0.7343	9.0468
	0.5-	1564346	2048075	1426006	0.2431	4.2640
1.5	0.0-0.5	594037	1402913	1243135	0.6809	6.7241
	0.5-	1693754	2219122	1267393	0.1858	4.1449
2.5	0.0-0.5	590859	1453815	1260423	0.6899	7.1242
	0.5-	1705595	2112890	1352216	0.2180	3.9897

J: Magnetic Polarization (T), B: Aligning Magnetic Flux Density (T)

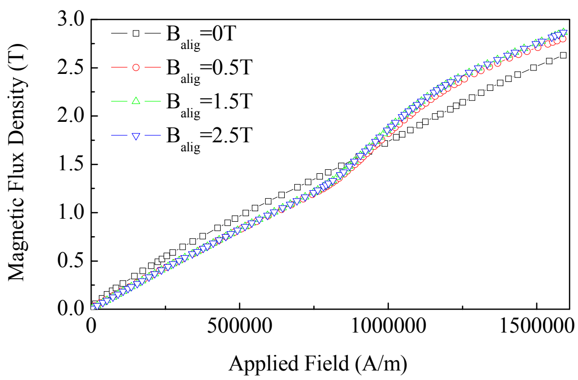

Fig. 8. Initial magnetization curves under different aligning magnetic fields

4. Numerical Results

Fig. 9 shows the analyzed model of the magnetizing fixture. Due to the symmetry of the model, the analysis region is reduced to a quarter of the whole region for saving the computing cost. The model mainly consists of outer and inner yokes, outer and inner coils, and magnet. The corresponding specification is listed in Table 2.

After analyzing the model by the aforementioned algorithm, the analysis results of the anisotropic bonded NdFeB magnet can be achieved.

The discharge current and voltage waveforms of the capacitor from 0 to 1.0 milliseconds (ms) are shown in Fig. 10. The discharge voltage decreases from initial value 1800 V to zero at 1.0 ms. And the maximum discharge current

Table 2. Specification of the magnetizing fixture

R [Ω]	*C* [μF]	V_{c0}[V]	No. of poles	No. of turns	Length [mm]
0.11	2000	1800	4	7	50.0

R: Winding resistance, *C*: Capacitance on the capacitor, V_{c0}: Initial voltage on the capacitor.

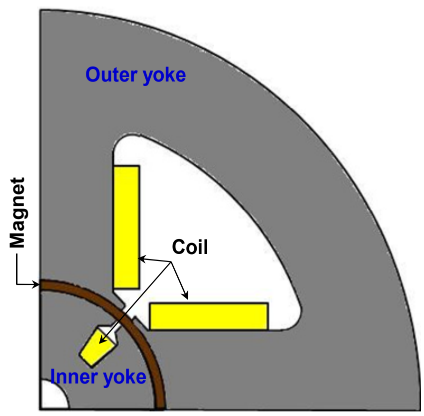

Fig. 9. Analyzed model of the magnetizer

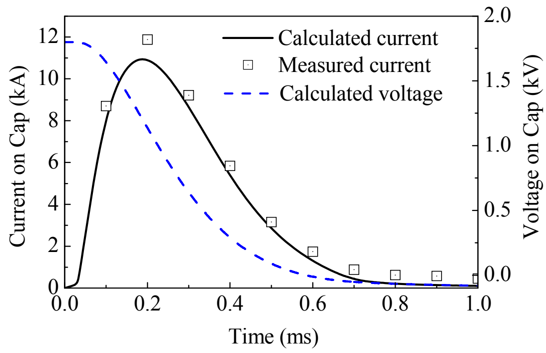

Fig. 10. Discharge current and voltage waveform on capacitor bank

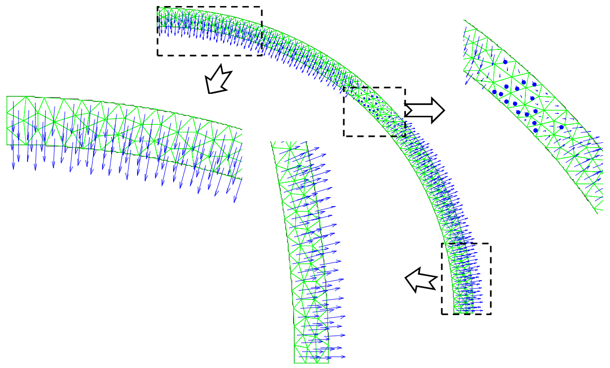

Fig. 11. B_r vector distribution of the PM after magnetizing process

increases until around 10 kA at 0.18 ms, and then it reduces to 0 at 1.0 ms. The peak current generates a considerably strong magnetic flux density to magnetize the magnet sufficiently.

Fig. 11 shows the B_r vectors distribution of each element in the PM region at the discharge voltage of 1800 V and capacitance of 2000 μF.

It is difficult to measure the B_r vector distribution for a ring magnet directly. In order to validate the analyzed B_r distribution, the experimental equipment, which consists of four-pole magnetized ring magnet and a magnetic back yoke with thickness of 1.5 mm is built. The normal component of the magnetic flux density (B_{nor}) along the inner surface of the magnet is measured by a Gauss meter. After the magnetizing analysis by using the proposed algorithm, the B_r of each element in the PM region is determined and the data is imported into the analyzed model of experimental equipment. By applying the FEA to this model, the flux line distribution is obtained as shown in Fig. 12. If the analysis results of B_r vector distribution in ring magnet are correct, the analyzed surface magnetic flux density distribution along the inner surface of the magnet, such as the testing point in Fig. 12, should be same as the measurement results. Therefore, this method can be applied to verify the accuracy of the proposed algorithm. Fig. 13 shows the comparison of measured B distribution (red square) and calculated one (black line) by the improved

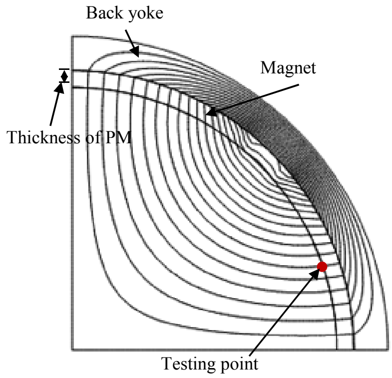

Fig. 12. The flux line distribution of the experimental equipment

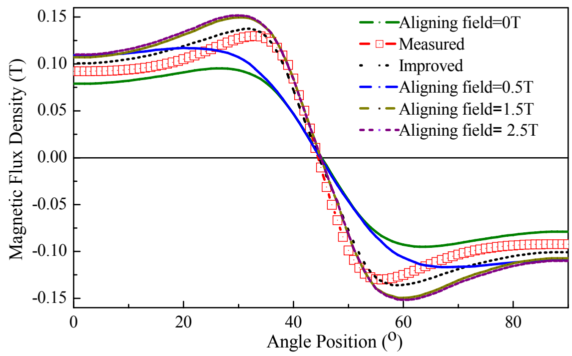

Fig. 13. Normal component of B at the inner surface of magnet with aligning condition of the PM

algorithm. It can be seen that the two results agrees well.

The hysteresis properties of anisotropic bonded NdFeB magnet depend on the aligning magnetic field. The distribution of the aligning magnetic field depends on the structure of the powder aligning fixture. Actually, in the magnet, the aligning B vectors are different everywhere. Therefore, the hysteresis properties, in the magnet, are also different everywhere. To consider the effect of the aligning magnetic field on hysteresis properties of the magnet, it is better to measure many anisotropic magnet samples at different aligning magnetic field levels. However, it is impossible to cover every aligning magnetic field cases. Therefore, in the proposed algorithm, the hysteresis properties at four different aligning magnetic field levels 0T, 0.5T, 1.5T, 2.5T are considered. In order to verify the validity of the proposed algorithm on the accuracy of B_r distribution calculation, the following four analyses are carried out: magnetizing analysis considering hysteresis characteristics only when the aligning magnetic fields are 0 T, 0.5 T, 1.5 T, and 2.5 T, respectively. Among the four analyses, the influence of aligning magnetic field direction is ignored. Fig. 13 compares the distribution of normal component of surface magnetic flux density of PM among different cases. It is obvious that, the improved algorithm can give better result than the other cases. Fig. 14 shows the surface magnetic flux density distribution with different

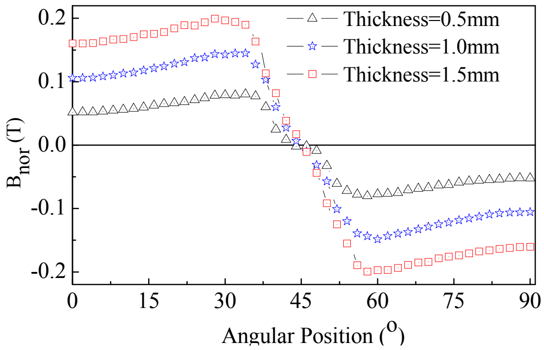

Fig. 14. Radial component of B at the inner surface of magnet with different thicknesses of the PM

thicknesses of the magnet. From the figure, the magnetic flux density of PM is approximately direct proportional to the thickness of the PM

5. Conclusion

A numerical algorithm for calculating B_r vector distribution of the anisotropic bonded NdFeB PM considering effect of the aligning magnetic field during the forming process is presented.

During the magnetizing analysis, the effective magnetic flux density is calculated according to the direction of the aligning magnetic field and magnetic properties of PM is determined element by element in the FE model based on the magnitude of aligning magnetic field.

In order to consider hysteresis characteristics of PM, the J-A hysteresis model is applied to simulate hysteresis loops of PM according to the identified parameters based on measurement results.

By applying the proposed algorithm, the accurate B_r vector distributions in PM are determined. Based on the analysis results, the surface magnetic flux density is approximately proportion to the thickness of the magnet.

Acknowledgements

This work was supported by the National Natural Science Foundation of China under Grant 51507105, and the Research Programs funded by Ministry of Education in Liaoning Province under Grants L2014045 and LZ2015056.

References

[1] D. K. Jang and J. H. Chang, "Performance comparison of PM synchronous and PM vernier machines based on equal output power per unit volume," *Journal of Electrical Engineering & Technology*, vol. 11, no. 1, pp. 150-156, Jan. 2016.

[2] W. Y. Jo, I. J. Lee, Y. H. Cho, D. H. Koo et al., "Design and analysis of axial flux permanent magnet synchronous machine," *Journal of Electrical Engineering & Technology*, vol. 2, no. 1, pp. 61-67, Mar. 2007.

[3] M. Yue, J. X. Zhang, Y. F. Xiao, G. P. Wang et al., "New kind of NdFeB magnet prepared by spark plasma sintering," *IEEE Trans. Magn.,* vol. 39, no. 6, pp. 3551-3553, Nov. 2003.

[4] C. Mishima, N. Hamada, H. Mitarai, and Y. Honkura, "Development of a Co-Free NdFeB anisotropic bonded magnet produced from the d-HDDR processed powder," *IEEE Trans. Magn*., vol. 37, no. 4, pp. 2467-2470, Jul. 2001.

[5] N. Hamada, C. Mishima, H. Mitarai, and Y. Honkura, "Development of Nd-Fe-B anisotropic bonded magnet with 27 MGOe," *IEEE Trans. Magn.*, vol. 39, no. 5, pp. 2953-2955, Sep. 2003.

[6] H. J. Kim, C. S. Koh, and P. S. Shin, "A new anisotropic bonded NdFeB permanent magnet and its application to a small DC motor," *IEEE Trans. Magn*., vol. 46, no. 6, pp. 2314-2317, Jun. 2010.

[7] H. J. Kim, D. H. Kim, C. S. Koh, and P. S. Shin, "Application of polar anisotropic NdFeB ring-type permanent magnet to brushless DC motor," *IEEE Trans. Magn*., vol. 43, no. 6, pp. 2522-2524, Jun. 2007.

[8] D. J. Kinsey, S. J. Lillywhite, G. W. Jewell, J. D. Ede et al., "Design of powder aligning systems for the compression molding of radially anisotropic permanent magnet rings," *J. Appl. Phys*., vol. 91, no. 10, pp. 8837-8839, 2002.

[9] D. J. Kinsey, G. W. Jewell, D. Howe, A. J. Williams. et al., "Electromagnetic design optimization of a powder aligning fixture for a compression-molded anisotropic NdFeB ring magnet," *IEEE Trans. Magn*., vol. 40, no. 3, pp. 1702-1707, May. 2004.

[10] Y. Kawase, T. Yamaguchi, N. Mimura, M. Igata et al., "Analysis of magnetizing process using discharge current of capacitor by 3-D finite-element method," *IEEE Trans. Magn*., vol. 38, no. 2, pp. 1145-1148, Mar. 2002.

[11] Z. Q. Zhu, Z. P. Xia, K. Atallah, G. W. Jewell et al., "Powder alignment system for anisotropic bonded NdFeB halbach cylinders" *IEEE Trans. Magn*., vol. 36, no. 5, pp. 3349-3352, Sep. 2000.

[12] C. D. Riley, G. W. Jewell, and D. Howe, "Finite element modeling of powder aligning and multi-pole magnetizing systems for anisotropic bonded permanent magnets," *J. Appl. Phys.,* vol. 79, no. 8, pp. 6342-6344, Apr. 1996.

[13] D. H. Zhang, H. J. Kim, W. Li, and C. S. Koh, "Analysis of magnetizing process of a new anisotropic bonded NdFeB permanent magnet using FEM combined with Jiles-Atherton hysteresis model," *IEEE Trans.Magn.*, vol. 49, no. 5, pp. 2221-2224, May. 2013.

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