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Characteristic Analysis and Finite Element Simulation of Rare Earth Permanent Magnet Materials

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Abstract

The important function of rare earth permanent magnet materials is to produce magnetic flux and provide magnetic adsorption force to the outside world. According to the characteristics of rare earth permanent magnet materials, the mathematical model of permanent magnet materials is established by using Kirchhoff's law of magnetic circuit, and the qualitative analysis of magnetic adsorption force is carried out. The static magnetic field characteristics and magnetic adsorption force of permanent magnet are analyzed by ANSYS Maxwell finite element simulation software. Through the actual measurement of the magnetic adsorption force of permanent magnet, the error causes between the actual measurement and theoretical calculation and finite element simulation are analyzed.

Keywords

Rare earth permanent magnet materials; Magnetic field characteristics; Finite element simulation.

1. INTRODUCTION

The reuse function of rare earth permanent magnet materials is to generate magnetic flux and provide magnetic adsorption force to the outside world [1]. Magnetic materials usually contain two parts, one is the permanent magnetic material that generates magnetic flux, and the other is the soft magnetic material that guides magnetic flux. Permanent magnet materials can still maintain strong remanence after magnetization [2].

At present, the common permanent magnet materials on the market include neodymium iron boron, rare earth cobalt, aluminum nickel cobalt alloy, ferrite, etc. among the above permanent magnet materials, neodymium iron boron permanent magnet material is the permanent magnet material with the best magnetic performance at present [3]. Neodymium iron boron magnetic steel is a tetragonal structure formed by neodymium, iron and boron rare earth materials, which has good anti-magnetic aging characteristics. Neodymium iron boron magnetic steel can still maintain good magnetic adsorption capacity at 150 °C, that is, good stability. Figure 1 shows the characteristic curve of NdFeB material. In the figure, the AC line is the demagnetization curve, which is almost a straight line, and the recovery curve and demagnetization curve almost coincide. After applying the interfering magnetic field, the magnetic energy product of NdFeB with the magnetic field removed will hardly change.

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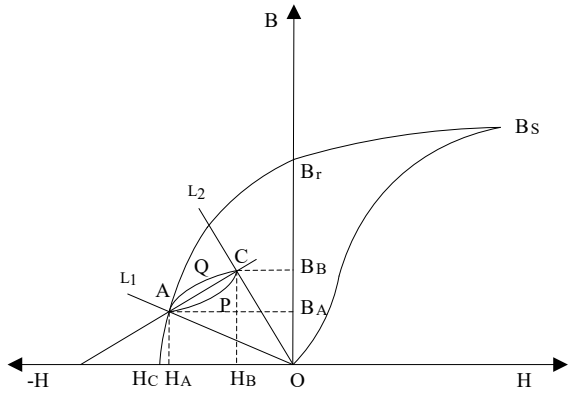

Figure 1. Magnetization, demagnetization curve and recovery curve of Nd-Fe-B material

The permanent magnet material selected this time is N35 Nd-Fe-B, and its main performance parameters are shown in Table 1. Due to the complexity of the actual production of permanent magnet materials, it can be properly simplified in the finite element simulation.

Table 1. Performance parameters of NdFeB N35

Performance Parameter	Unit	Numerical Value	Permanent Magnet Parameters	Numerical Value
Remanence Br	T	1.17~1.23	Length	40mm
Coercivity Hcb	KA/m	851~955	Wide	10mm
Intrinsic Coercivity Hcj	KA/m	>955	Height	5mm
Maximum Magnetic Energy Product BH	KJ/m³	264~288	Magnetization Direction	40*10
Maximum Operating Temperature T	°C	150		

2. ADSORPTION MATERIAL

The adsorption material is of great significance to the adsorption force of magnetic steel. Different materials have different hysteresis curves. Q235 steel is used in this experiment, and its hysteresis curve (B-H curve) is shown in Figure 2.

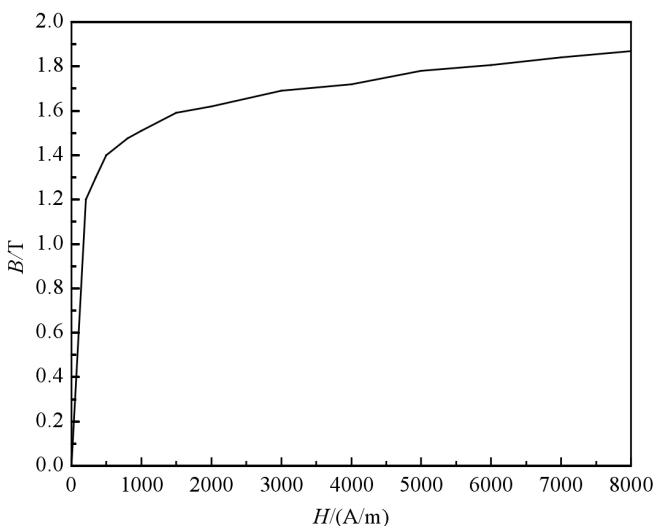

Figure 2. Hysteresis curve of Q235 adsorption material

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3. MATHEMATICAL MODELING

3.1. Theoretical Basis of Magnetic Adsorption Force Calculation

The magnetic field generated by the permanent magnet is a static magnetic field. For the static magnetic field, Kirchhoff's law of magnetic circuit can be used to analyze the magnetic field and calculate the magnetic adsorption force generated by the magnetic adsorption device.

Kirchhoff's first theorem of magnetic circuit: at the node of magnetic circuit, the algebraic sum of magnetic flux is equal to zero.

$$\sum \phi_k = 0 \tag{1}$$

The first law of magnetic circuit points out the principle of continuous magnetic flux, which indicates the magnetic flux identity at any node of the magnetic circuit.

Kirchhoff's second theorem of magnetic circuit: in any closed magnetic circuit, the algebraic sum of the magnetic potential difference of each part of the magnetic circuit is equal to the algebraic sum of the magnetic potential of the closed magnetic circuit.

$$\sum \phi_j R_{mj} = \sum \phi_{mk} \tag{2}$$

The second Kirchhoff theorem of magnetic circuit is the ampere loop theorem

$$\oint_{\Gamma} H dl = \iint_{\Omega} \left(J + \frac{\partial D}{\partial t} \right) dS \Leftrightarrow \nabla \times H = J + \frac{\partial D}{\partial t} \tag{3}$$

The second law of magnetic circuit points out that in the magnetic circuit generated by permanent magnet, the algebraic sum of magnetic potentials of two partial magnetic circuits is zero.

For permanent magnet materials, in the ideal mathematical model, the magnetic circuit is a linear magnetic circuit with no magnetic leakage, equal magnetic flux everywhere. Therefore, in the qualitative analysis and calculation of the permanent magnet according to the ideal model, the permanent magnet can be compared to the power supply. The constant magnetic potential Φ_M of permanent magnet is similar to the electromotive force E, and the linear magnetoresistance R_c is similar to the internal resistance of electromotive force. The constant magnetic potential Φ_M and linear magnetoresistive R_c are connected in series to form a magnetic flux source with Φ_m relative to the external magnetic potential, as shown by the dotted line in Figure 3. The expressions of external magnetic potential Φ_m and magnetoresistance R_c are shown in equations (4) and (5), and figure 3 shows the equivalent magnetic circuit of permanent magnet.

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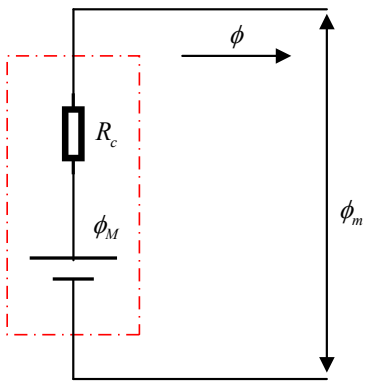

Figure 3. Equivalent magnetic circuit diagram of permanent magnet

$$\Phi_m = H_c' l_m \tag{4}$$

$$R_c = l_m / \mu_r \mu_0 S_m \tag{5}$$

In the figure:

H_c' —Equivalent coercivity;

l_m —Is the length of the permanent magnet;

S_m —Is the cross-sectional area of the permanent magnet;

μ_0 —Is the vacuum permeability, and its value is $4\pi \times 10^{-7} T \backslash m / A$;

μ_r —Is the relative permeability;

3.2. Calculation Model of Magnetic Adsorption Force

Figure 4 is a schematic diagram of a magnetic circuit composed of a magnetic steel and a steel plate wall. The magnetic flux circuit is represented by red dots and lines in the magnetic steel, steel plate wall and air gap.

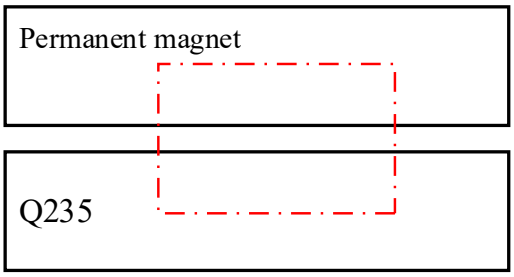

Figure 4. Schematic diagram of adsorption wall of permanent magnet unit

The magnetic circuit composed of permanent magnet, adsorption wall and air gap has uneven magnetic induction intensity and magnetic leakage. Therefore, it is very complicated to calculate the magnetic adsorption force of the permanent magnet according to the actual situation. In order to qualitatively analyze the relationship between the adsorption force of the permanent magnet and the length, width and height of the permanent magnet, the adsorption wall of the permanent magnet unit is idealized modeled. Assuming that there is no magnetic

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leakage in the magnetic circuit and the magnetic field is uniform at all places, the equivalent magnetic circuit of the permanent magnet adsorption wall unit can be represented in Figure 5.

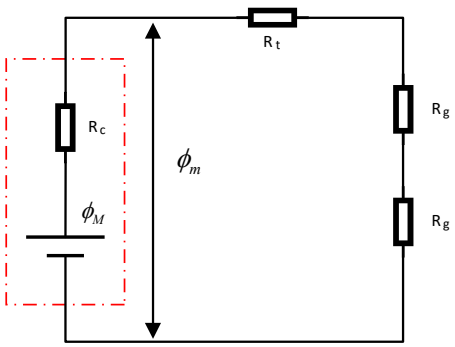

Figure 5. Equivalent magnetic circuit diagram of adsorption wall of permanent magnet unit

In the figure:

R_c —Magnetoresistance of permanent magnet in flux loop;

R_g —The magnetoresistance of the air gap in the flux loop;

R_t —The magnetic resistance of the spherical tank wall in the magnetic flux circuit;

ϕ_m —The magnetomotive force provided by the permanent magnet to the external magnetic circuit;

ϕ_M —Magnetomotive force generated by magnetic flux source;

Based on Kirchhoff's law of magnetic circuit, the mathematical model for calculating the magnetic adsorption force of permanent magnet is established, as shown in Figure 5, in which the dotted line part is the equivalent magnetic circuit of permanent magnet. It can be seen from Figure 1 that the demagnetization curve is usually linear and approximately coincides with the recovery curve, $H_C' = H_{cB}$.

Kirchhoff's second theorem based on formulas (4), (5) and magnetic circuit is as follows:

$$\left(\frac{l_m}{S\mu_m}+\frac{l}{S\mu}+\frac{2l_g}{S\mu_0}\right)\phi = H_{cB}l_m \tag{6}$$

$$\phi = \left(\frac{l_m}{S\mu_m}+\frac{l}{S\mu}+\frac{2l_g}{S\mu_0}\right)/H_{cB}l_m \tag{7}$$

The magnetic flux continuously at the air gap by the magnetic flux in the magnetic circuit

$$\Phi = B_g S = \mu_0 H_g S \tag{8}$$

The above two formulas are combined

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$$H_g = H_{cB} l_m / \mu_0 S \left(\frac{l_m}{S\mu_m} + \frac{l}{S\mu} + \frac{2l_g}{S\mu_0} \right) \tag{9}$$

The material used for the adsorption wall is Q235 steel, and its permeability is approximately infinite, which $1/\mu$ is zero, which can be eliminated S.

$$H_g = H_{cB} l_m / \mu_0 \left(\frac{l_m}{\mu_m} + \frac{2l_g}{\mu_0} \right) \tag{10}$$

$$H_g = H_{cB} l_m / \mu_0 \left(\frac{l_m}{\mu_{rm}} + 2l_g \right) \tag{11}$$

Energy storage with permanent magnet air gap

$$E = B_g H_g S x / 2 \tag{12}$$

Where x is the gap of the air gap

Using the principle of virtual work, the force F_i of a system in a certain direction i is equal to the gradient of the energy of the system in that direction.

$$F_i = -\frac{\partial E}{\partial x} \tag{13}$$

In the formula:

E —System energy;

x —Coordinates in i direction;

F_i —Force in direction i;

Therefore, the partial derivative of x is calculated for the air gap energy storage E to obtain the force of the permanent magnet

$$F = -B_g H_g S / 2 = -\mu_0 H_g^2 S / 2 \tag{14}$$

Bring H_g into the above equation

$$F = -\mu_0 S \left[H_{cB} l_m / \left(\frac{l_m}{\mu_{rm}} + 2l_g \right) \right]^2 / 2 \tag{15}$$

The middle sign $-$ in formula (15) is expressed as suction, $\mu_{\mathrm{rm}} = \mu_0 / \mu_m = B_r / H_{cB}$.

The parameter is brought into formula (15), and the magnetic adsorption force of the surface composed of length and width $F = -0.5\mu_0 S B_{\mathrm{r}}^2 = 36.13N$.

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The magnetic induction intensity B of the contact part between the permanent magnet and the magnetic conducting material. Similarly, the magnetic circuit model composed of the two is simplified, that is, it is assumed that there is no magnetic leakage in the magnetic circuit and the magnetic field is uniform everywhere. The magnetic induction intensity at the center point of the permanent magnet surface can be calculated.

$$B = \frac{B_r}{\pi}\left\{\tan^{-1}\frac{LW}{2X\sqrt{L^2+W^2+4X^2}} - \tan^{-1}\frac{LW}{2(X+H)\sqrt{L^2+W^2+4X^2}}\right\} \tag{16}$$

In the formula:

B_r —Remanence;

L, W, H —Length, height and width of permanent magnet;

Matlab software can be used to explore the law of magnetic induction intensity on the surface of permanent magnet. When the length L of the permanent magnet changes from $0\sim100$mm and the width W, height H and gap X do not change, the curve shown in 6 is obtained by MATLAB simulation from equation (16).

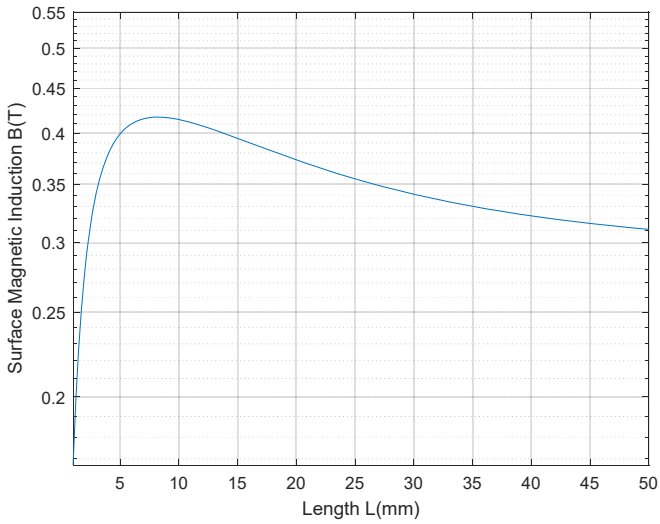

Figure 6. Curve of permanent magnet length and magnetic induction intensity at surface center

It can be seen from Figure 6 that when the length L of the permanent magnet increases from $0\sim3.7mm$, the magnetic induction intensity on the surface of the permanent magnet increases rapidly, reaches the maximum value of $0.48T$ at $3.7mm$, decreases rapidly at $3.7\sim30mm$, and decreases slowly at $30\sim50mm$. That is, the magnetic induction intensity on the surface of the permanent magnet will not increase with the increase of the length of the permanent magnet.

3.3. Influence of Parameters in Mathematical Model on Magnetic Adsorption Force

It can be seen from equation (15): when the parameters of the thickness and air gap height of the permanent magnet remain unchanged, the adsorption force of the permanent magnet is directly proportional to the area of the permanent magnet; the magnetic adsorption force is positively related to the square of the product of the coercivity of the permanent magnet and the height, and inversely related to the square of the sum of the air gap height and the thickness.

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The above conclusion is based on the assumption that the magnetic circuit is ideal. There will be magnetic leakage in the actual magnetic circuit, and the permeability of the wall changes. With the increase of magnetic field strength, the permeability will decrease and the magnetic leakage in the magnetic circuit will increase.

It can be seen from equation (16): if the structural parameters of the permanent magnet are changed, the magnetic induction intensity on the surface of the permanent magnet will be changed, the magnetic leakage can be reduced and the magnetic adsorption force can be increased, but the weight of the permanent magnet will be changed.

4. FINITE ELEMENT SIMULATION ANALYSIS

The above qualitative analysis is based on the idealized model. The permanent magnet has magnetic leakage and uneven magnetic field, and the calculation of magnetic adsorption force is very complex. Using the idealized model will produce large errors. Finite element analysis is an effective calculation method to deal with these practical problems, and more accurate results can be obtained. The flow of finite element simulation is shown in Figure 7.

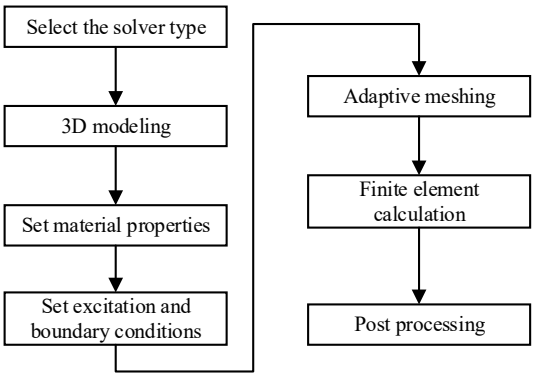

Figure 7. Finite element simulation flow

By formula (16) , the curve in Figure 8 is obtained through Matlab simulation. It can be seen from figure 8 that the magnetic induction intensity on the surface of the permanent magnet will not increase with the increase of the length of the permanent magnet, that is, the magnetic induction intensity on the surface does not change uniformly. After finite element analysis in ANSYS Maxwell software, figure 8 is the finite element simulation diagram of the middle section. It can be seen from figure 8 that the magnetic induction intensity at the edge is greater than that at the middle Magnetic induction intensity of the part. The magnetic adsorption force is 33.4N

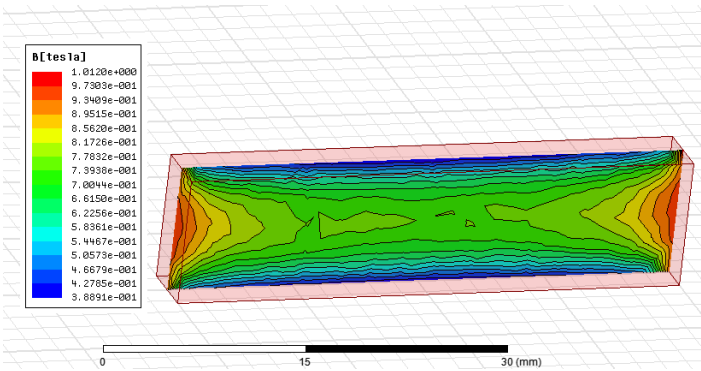

Figure 8. Cloud diagram of magnetic induction intensity in the middle section of permanent magnet

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5. MEASUREMENT TEST

In order to verify the correctness of finite element simulation, the measurement experiment of magnetic adsorption force of a single permanent magnet is designed. When the permanent magnet is separated, the readings are measured by electronic scale for many times, and the average value is 31.4N.

Figure 9. Permanent magnet adsorption experiment

6. CONCLUSION

Through comparative analysis, it can be calculated that the theoretical value of magnetic force is larger than the actual value, and the error is about 13%. The error between the magnetic force obtained by ANSYS finite element simulation analysis and the actual value is small, and the error is about 5%. The reason for this is that the edge magnetic flux density of the permanent magnet is large due to the fillet of the permanent magnet in the process of production and manufacturing, and the permanent magnet has a concentrated effect at the edges and corners. Therefore, it can be concluded that the edge magnetic induction intensity of the permanent magnet is greater than the stress intensity of the middle permanent magnet.

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