Rare Metal Materials and Engineering
Volume 51, Issue 8, August 2022
Available online at www.rmme.ac.cn

Science Press

Cite this article as: Yang Youwen, Wang Yongle, Yang Lei, et al. Influence of Binder Content on Mechanical and Magnetic Properties of Bonded NdFeB Magnets[J]. Rare Metal Materials and Engineering, 2022, 51(08): 2727-2731.

LETTER

Influence of Binder Content on Mechanical and Magnetic Properties of Bonded NdFeB Magnets

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Abstract: As an essential component in the preparation of bonded NdFeB magnets, the function of binder is to improve the fluidity of magnetic powder particles and the bonding strength, ensuring the mechanical and magnetic stability of products. The selection of binder content and its effects on the mechanical and magnetic properties of bonded NdFeB magnets were studied by combining theory with experiment. On this basis, high performance bonded NdFeB magnets were prepared. The structure and morphology of the magnet were characterized by the scanning electron microscope (SEM). The magnetic and mechanical properties of ring-shaped bonded NdFeB magnet (RSM) were measured under conditions of NIM-200C hysteresigraph and electro-mechanical universal testing machines (AG-X plus), respectively. The results demonstrate that bonded NdFeB magnet with 3wt% binder is able to achieve the highest density of 5.59 g/cm^3 and the highest compressive strength of 159 MPa with the optimum value of magnetic properties.

Key words: bonded NdFeB magnets; magnetic ring; binder content; mechanical properties; magnetic properties

As the third-generation of rare earth permanent magnet materials developed in 1980s, NdFeB permanent magnets have excellent magnetic properties and high cost performance, and they have been momentous material foundation of new technology[1]. Besides, the efficient utilization of electric energy is often inseparable from NdFeB magnets[2]. According to the fabrication process, NdFeB magnets are usually classified into the sintered and the bonded ones. The sintered NdFeB magnets have excellent magnetic properties[3], and show a broad application prospect in the fields of nuclear industry, electric vehicles and aeroengines[4]. And the excellent magnetic properties are closely related to the number of $Nd_2Fe_{14}B$ magnetic phases, as well as the synergistic effect of B-rich and Nd-rich nonmagnetic phases[5]. But at the same time, they are prone to intergranular brittle fracture under load, due to the strong uniaxial magnetocrystalline anisotropy, few slip system and relatively weak Nd-rich grain boundaries[6]. Therefore, their toughness is very poor, which severely limits their further application in many bearing fields[7]. Bonded NdFeB magnets are characterized not only by their wide range of magnetic adjustment, but also by the ease of material preparation into products with high dimensional accuracy[8]. Bonded NdFeB magnets generally have a relatively high resistivity, making them more widely applied in electronic equipment and other alternating current (AC) and high frequency environment[9]. Furthermore, the bonded NdFeB magnet also has the stable magnetic properties and multipolarization magnetization[10].

The excellent properties of bonded NdFeB permanent magnet materials make them applicable to a wide range of applications. Though the discovery and mass production are relatively late, they are still recognized and supported by some industries which need such excellent performance, such as high-precision machinery and automation equipment for industrial production[11]. Nevertheless, consuming electronic products among them are developing towards smaller size and lighter weight[12], which forces us to prepare more precise bonded NdFeB magnets. This is because the manufacturing

Received date: August 02, 2021
Foundation item: Major R&D Projects of Hefei Key Technologies (J2020G20); Anhui Province 2020 Quality Engineering Project of Higher Education Institutions (2020jyxm1514)
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accuracy deviation of magnets will not only cause the waste of rare earth resources[13], but also affect the surrounding magnetic field[14], which may affect the magnetic properties of magnets. In the preparation of high-precision bonded NdFeB magnets, the process and composition are crucial factors, in which the role of binder is to combine the dispersed NdFeB magnetic particles into a whole framework and to raise the fluidity of magnetic powder particles and the bond strength between them[15]. Rusnaeni et al[16] investigated the effects of different epoxy resin contents on microstructure and physical properties, and the experiment showed that the magnetic properties of bonded $Nd_2Fe_{14}B$ magnet made of 2wt% epoxy resin were the highest. Xi et al[17] studied the effects of epoxy resin and phenol formaldehyde resin on the compressive strength and microstructure of magnets. And it is demonstrated that the compressive strength of NdFeB magnet prepared with phenolic resin as binder was much higher than that of epoxy resin. Therefore, it is of great significance to select the optimal proportion of binder with high strength, low water absorption and excellent thermal stability for the preparation of bonded NdFeB magnets with high precision and performance.

In this study, the effects of binder content on the mechanical and magnetic properties of bonded NdFeB magnets were studied by combining experiment with theory. And the content of binder in the mixing process was determined. RSM with high precision and excellent magnetic properties was further prepared based on this research.

1 Experiment

Materials used in this study were magnetic powder with MQP10-8.5HD made by Magnequench (Tianjin) Co., Ltd, stainless steel powder (SUS) was made by Haining Feida Metallurgy Powder Co., Ltd, and W-6C binder was made by Sichuan Chenghua Adhesive Industry Co., Ltd. The magnetic powder (0.8 kg) and SUS powder (0.2 kg) were first mixed. Meanwhile, the 1wt% binder (total mass) was mixed with 7.5wt% acetone and stirred. Then, the powder, binder and 3wt% zinc stearate were mixed together. After half an hour, the magnetic powder was pressed into a standard cylindrical sample (Φ10 mm×8 mm) by a manual hydraulic press. The sample was pressed and sent to an electric constant temperature air dryer for curing. The curing temperature was 180 °C and the curing time was 30 min. As shown in Fig.1, the samples were made by varying the binder content: 1wt% (sample 1), 2wt% (sample 2), 3wt% (sample 3), 4wt% (sample 4), 5wt% (sample 5). Then, a high precision RSM with an OD×ID×H of 22 mm×19.7 mm×12.3 mm was fabricated by compression molding under the pressure of 85 kN by a powder forming machine (S-20A) according to the optimal ratio obtained from the research.

The structure and morphology of the magnet were characterized by scanning electron microscope (FESEM, HITACHISU8020). Typical remanence (B_r), intrinsic coercivity (H_{cj}), and maximum energy product $(BH)_{max}$ of the samples were measured using a NIM-10000H hysteresigraph.

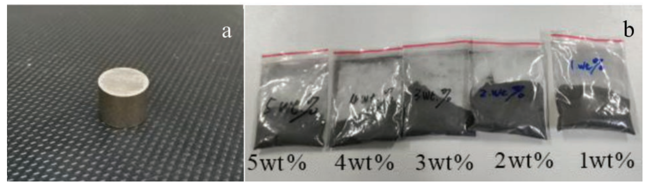

Fig.1 Bonded NdFeB standard cylindrical specimen (a) and magnetic powder after mixing (b)

The mechanical properties were determined by an electro-mechanical universal testing machine (AG-X plus).

2 Results and Discussion

2.1 Morphology feature

In order to study the distribution of binders with different contents in magnetic particles and their relationship, we carried out SEM analysis on all five groups of samples (Fig.2).

Fig. 2a shows the microscopic morphology of the bonded magnet when the mass fraction of binder is 1wt%. The binder is not enough to cover all the magnetic particles due to the low amount, leading to the failure of bonding between some powder particles, and the occurrence of delamination, cracks and other defects in the compressed magnet. It can be seen that the surface defects gradually increase and the density increases with the addition of binder content. When the binder content is 3wt% (Fig. 2c), the compactness of magnet is optimal, the binder basically covers the magnetic powder, and there are fewer delamination and cracks in the pressed magnet. It can be seen from Fig. 2e that when the mass fraction of binder is 5wt%, the magnetic powder is coated and bonded well. However, there are more binders between the magnetic particle particles and the gap increases, which greatly reduces the density of the sample and affects its magnetic and mechanical properties. This is because when the binder content is excessive, the excess binder will overflow from the magnetic powder during high temperature curing, resulting in the increase of surface voids.

2.2 Effects of binder content on magnetic properties

During the experiment, the magnetic properties of the five groups of samples were measured by magnetic measuring instrument, and the variation curve is illustrated in Fig.3. We can see that the B_r and $(BH)_{max}$ both rise at first and then descend with the gradual increase of binder content. Among them, the B_r only rises from 4.680×10^{-1} T to 4.682×10^{-1} T when the binder content is less than 3wt%. When the addition amount of the binder is 3wt%, B_r and $(BH)_{max}$ of the bonded magnet reach a maximum value of 4.682×10^{-1} T and 35.143 kJ/m^3, respectively. However, the B_r and $(BH)_{max}$ of the sample 5 are 4.372×10^{-1} T and 31.394 kJ/m^3, dropped by 7% and 11% compared with those of the sample 3, respectively.

The variation tendency of the B_r and $(BH)_{max}$ shown in the curve of Fig.3 may be caused by the following factors. (1) The polymer film formed by viscous resin on the surface of magnetic particles effectively prevents the contact between oxygen and magnetic particles in the molding process,

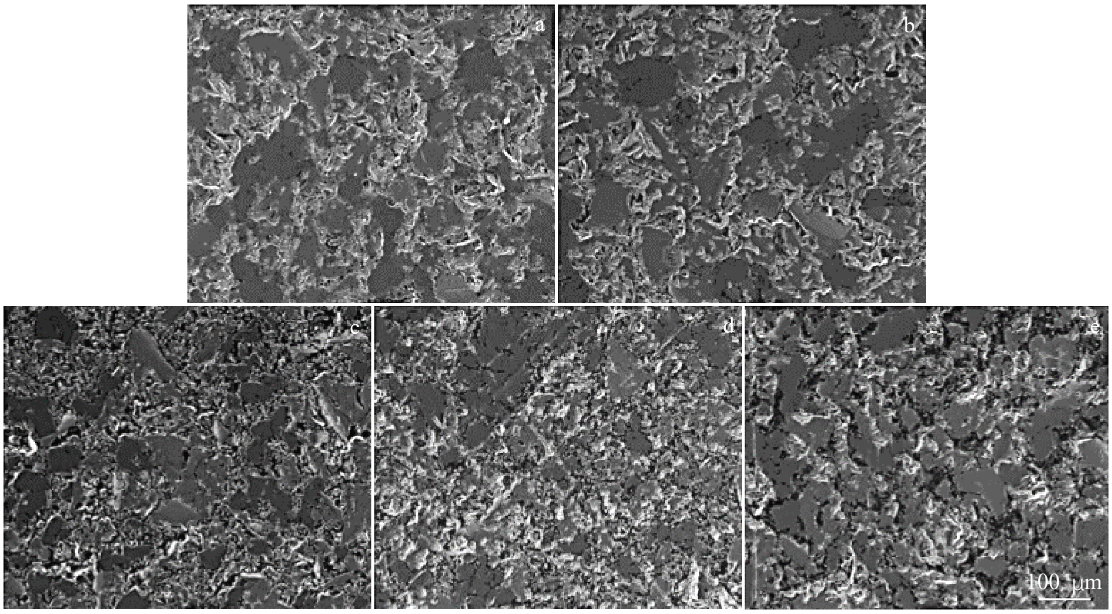

Fig.2 Surface morphologies and structures of bonded magnets with different binder contents: (a) 1wt%, (b) 2wt%, (c) 3wt%, (d) 4wt%, and (e) 5wt%

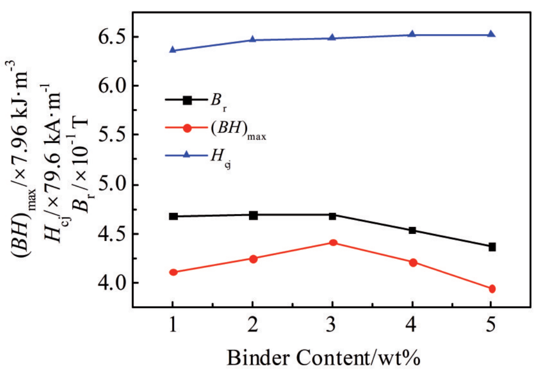

Fig.3 Curves of the magnetic properties of samples 1~5

reducing the oxidation of magnetic particles and improving the magnetic properties of magnets. (2) The excessive amount of binder will affect the magnetic properties of the magnets because the binder is a non-magnetic material. Compared with B_r and $(BH)_{max}$, the H_{cj} of the bonded NdFeB magnets remains almost unchanged with increasing the binder content. It is due to the fact that the H_{cj} in the magnet is mainly related to the crystal structure (orientation distribution and grain dimension) [18, 19]. The volume fraction of non-magnetic phase directly impacts B_r and $(BH)_{max}$ of the bonded magnets.

2.3 Effects of binder content on mechanical properties

Fig.4 displays the relationship of the compressive strength and density of the magnets with the binder content. At the initial stage of the curve, the compressive strength and density of the magnet become stronger with the increase of binder content, because the thermosetting epoxy resin as binder can be firmly combined with the magnetic powder, thus improving the surface density of NdFeB magnetic powder. The hydroxyl group, ether bond and highly active epoxy group in the epoxy resin can also form a dense three-dimensional network structure of macromolecules with adjacent epoxy resin molecules and adjacent interfaces[20]. After curing, the product has high rigidity and good mechanical properties. However, when the binder content is low, it is hard to tightly cover all the magnetic particles, resulting in delamination, cracks and other defects in the blank of the pressed magnet. Besides, the low density of the bond magnet also leads to its poor mechanical properties. When the binder content is excessive, the compressive strength of the samples does not continue to rise and even begins to decline. The fluidity of the magnetic powder will become poor and local agglomeration will occur, leading to the increase of porosity[20,21]. In addition, excessive binder will reduce the density and compressive strength of the magnet due to the low density and strength of epoxy resin itself.

2.4 Theoretical analysis and calculation

The bonded magnets are composed of ferromagnetic phase NdFeB magnetic powder and non-magnetic phase epoxy resin binder. Therefore, the rational design of the magnet

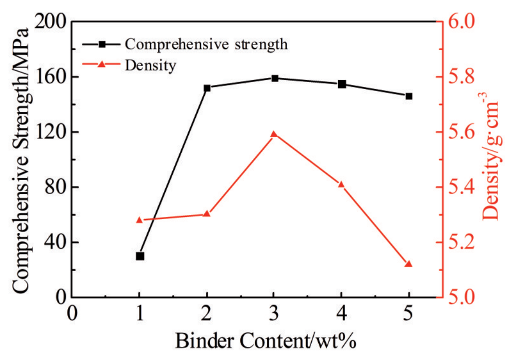

Fig.4 Curves of the mechanical properties of samples 1~5

components is directly related to the performance and application of the magnet. Lv et al [22] modeled the MQ rapid quenched NdFeB magnetic powder as a flat drum-like geometry with an elliptical cross-section and a semi-circular edge. Based on this model, the optimum addition ratio of binder can be expressed as:

$$m_{\mathrm{bp}} = \frac{\rho_{\mathrm{b}} v_{\mathrm{b}}}{\rho_{\mathrm{p}} v_{\mathrm{p}}} = \frac{\rho_{\mathrm{b}}}{\rho_{\mathrm{p}}} \cdot \left\{ \frac{4\sqrt{3}\ (a+b)(b+r)}{\pi\left[2ab + \frac{4}{3}r^2 + \frac{\pi}{2}(a+b)r\right]} - 1 \right\} \quad (1)$$

where m_{bp} is the optimum adding proportion of binder; ρ_{b} and ρ_{p} are the density of binder and magnetic powder, respectively; v_{b} and v_{p} are the volume of binder and magnetic powder, respectively; r stands for half the height of the magnetic particle; a is the semi-major axis of the ellipse on the surface of the magnetic powder; b is the short semi-axis of the ellipse on the surface of the magnetic powder.

The magnetic powder used in the experiment is MQ-C. In accordance with Eq.(1), when a=100 μm, b=60 μm, r=10 μm, ρ_{b}=1.2 g·cm^{-3}, ρ_{p}=7.72 g·cm^{-3}, the basic addition ratio of the binder calculated by the above theoretical results is 2.55wt%. In our study, MQP10-8.5HD magnetic powder was used, and its geometric dimensions were basically consistent with MQ-C. The density of the binder and the magnetic powder are 1.2 and 7.6 g·cm^{-3}, respectively, and thus the basic addition ratio of the binder calculated by the above theoretical results is 2.59wt%. In the above theoretical calculation, the binder is considered to be evenly distributed in the magnetic powder. However, in actual experiments, the magnet cannot be fully densified, more binder is needed to fill undensified void space. Therefore, the actual optimal value of the binder should be greater than the calculated value, and the optimal value obtained by our experiment is 3wt%, which exactly meets this result.

2.5 Preparation of RSM with high magnetic properties

Based on the above experiments, we have successfully proved that samples produced with 97wt% NdFeB powder and 3wt% binder have the maximum remanence, density and compressive strength and superior coercivity. In the previous work, we studied the effects of molding pressure on the properties of bonded NdFeB magnets, and obtained the optimal processing parameters [23]. With the development of science and technology, bonded NdFeB magnet is developed towards miniaturization, which puts forward higher requirements for magnetic properties of magnets. In this study, the thin-walled bonded NdFeB ring was processed under the optimum processing conditions of 3wt% solid epoxy with an OD×ID×H of 22 mm×19.7 mm×12.3 mm by comprehension molding technique (Fig.5a). Fig.5b depicts the demagnetizing curves of the RSM measured at room temperature. The RSM has a value of remanence B_{r}=6.718×10^{-1} T, magnetic induction coercivity H_{cb}=451.889 kA/m, intrinsic coercivity H_{cj}=933.867 kA/m, and maximum energy product $(BH)_{\mathrm{max}}$=75.748 kJ/m^3. Compared with sintered NdFeB magnets, the magnetic properties of bonded NdFeB magnets have not attracted much attention [24], but the excellent molding and processing properties of bonded magnets have always been the focus.

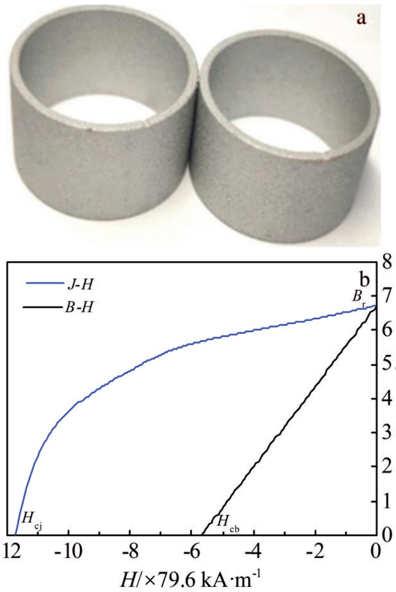

Fig.5 Optical photographs of the ring-shaped magnet (a) and magnetic properties of the RSM (b)

The bonded NdFeB magnets are more and more widely used in the sophisticated equipment, which requires superior magnetic properties. Farzam Mehr et al also prepared RSM with 8wt% epoxy resin as binder by compression molding method with magnetic properties of B_{r}=5.4×10^{-1} T, H_{cj}=732.32 kA/m and $(BH)_{\mathrm{max}}$=44.586 kJ/m^3 [25]. The RSM used in this study has better magnetic energy, making it possible to be more widely used in various fields in the future, such as automotive electronics. Consequently, it is of great significance to determine the optimal proportion of binder through experimental study to obtain high magnetic properties of bonded magnets.

3 Conclusions

1) It is necessary to adjust the binder content reasonably in the preparation process of bonded magnets. Only when the binder content is moderate and the magnetic powder is completely coated, the properties of the obtained magnetic powder particles will be consistent and stable, and the compressive strength of the prepared magnet will be better.

2) RSM can be performed with great dimensional accuracy and best magnetic properties of B_{r}=6.718×10^{-1} T, H_{cj}=933.867 kA/m and $(BH)_{\mathrm{max}}$=75.748 kJ/m^3.

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粘结剂含量对粘结NdFeB磁体力学性能和磁性能的影响

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摘　要：粘结剂作为粘结NdFeB磁体制备过程中的重要组成部分，其作用是提高磁粉颗粒的流动性和粘结强度，保证产品的力学性能和磁性能的稳定。采用理论与实验相结合的方法，研究了粘结剂含量对粘结NdFeB磁体力学性能和磁性能的影响。在此基础上，制备了高性能粘结NdFeB磁体。利用扫描电子显微镜（SEM）对磁体的结构和形貌进行了表征。在NIM-200C磁滞回线仪和电子万能试验机（AG-X plus）上分别测定了环形粘结NdFeB磁体（RSM）的磁性能和力学性能。结果表明，当粘结剂含量为3%（质量分数）时，粘结NdFeB磁体密度最高（5.59 g/cm^3），抗压强度最高（159 MPa），磁性能最佳。

关键词：粘结NdFeB磁体；磁环；粘结剂含量；力学性能；磁性能

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