Analysis of physical and magnetic properties of composite NdFeB bind with polyvinyl alcohol

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Abstract. The composite magnet NdFeB has been made using magnetic powder MQP-B and polyvinyl alcohol (PVA) as the binder. The mixing compositions of raw materials used are: 95 wt\% NdFeB - 5 wt\% PVA, 92.5 wt\% NdFeB - 7.5 wt\% PVA, 90 wt\% NdFeB - 10 wt\% PVA, and 87.5 wt\% NdFeB - 12.5 wt\% PVA. Both raw materials are weighed according to the composition, and then mixed until homogeneous. Furthermore, pellet forming was made using dry pressing at 50 kgf/cm\(^2\) pressures and continued with drying at 100 °C and 10 mmbar for 4 hours. The characterization includes bulk density, hardness, compressive strength measurements, and magnetic properties testing. The characterization results show that the optimal composition of binder PVA is achieved at 5–7.5 wt\% NdFeB composite magnet with following properties: bulk density = 5.21–5.25 g/cm\(^3\), hardness = 302.17 - 304.32 H\textsubscript{v}, compressive strength = 25.17–3.17 kgf/cm\(^2\), magnetic flux = 1150 -1170 Gauss, remanence = 70.90–74.97 emu/g or 4.7–5.0 kGauss, coercivity = 8.68–8.76 kOe, and energy product = 2.89–3.04 MgOe.

1. Introduction

The bonded or composite permanent magnets are technical products whose properties can be produced to suit a very wide variety of requirements. These materials have very important role as functional components within the wider spectra of contemporary devices in different industrial branches, as well as in the wider consumption. One of the most important applications of the permanent magnets are: parts in AC and DC engines production as well as synchronized motors, transformers, actuators, magnetic buffers, stationary fields [1, 2]. The most important advantages of polymer bonded magnets are low weight, can be produced in any shapes and high dimensional accuracy, i.e. near-net shape manufacture, good fracture toughness and corrosion resistance as well as isotropic magnetization [3]. Bonded magnets are produced by mixing a magnetic material with a binder and processed the mixture into a finished product. Magnets based on rare-earth-transition metal alloys like NdFeB alloy have excellent magnetic properties with high performance and maximum energy product value among other hard magnets [4, 5]. Nd-Fe-B magnets can be produced by sintering or bonding; in contrast to sintered magnets, bonded Nd-Fe-B magnets are produced by blending various polymer binders, such as epoxy or nylon, where melt-spun ribbons play the role of raw material. However, the magnetic properties of bonded magnets are inferior to those of sintered magnets. Commercial bonded magnets have a remanence \((B_r)\) up to 0.7 T and an coercivity \((H_{c1})\) up to 1400 kA/m but sintered magnets possess magnetic properties as high as with a \(B_r\) up to 1.4 T and an \(H_{c1}\) up to 2500 kA/m\(^3\) [6, 7]. The magnetic
properties of bonded magnets have been previously studied and reviewed by many researchers. In addition to magnetic properties, mechanical properties of bonded magnets also play critical roles for many advanced applications. However, the temperature-dependent mechanical strengths of bonded magnets are not readily available in open literature for magnet designers [9].

The type of binders and composition of binders are parameters which are important in making bonded permanent magnet. One would expect the remanence and energy product of a bonded magnet to be directly linked to the amount of binder used, typically 2 wt% in compression molded magnets and 8–15 wt% in injection molded magnets [9]. The purpose of this research is to make bonded magnetic NdFeB type MQP-B and adhesive polyvinyl alcohol with various composition. This research is expected to produce optimal composition for bonded permanent magnets.

2. Experiments

Synthesis of composite magnet NdFeB was carried out using magnetic powder NdFeB type MQP-B and polyvinyl alcohol (PVA) as binder. The mixing compositions of the raw materials used are: 95 wt% NdFeB - 5 wt% PVA, 92.5 wt% NdFeB - 7.5 wt% PVA, 90 wt% NdFeB - 10 wt% PVA, and 87.5 wt% NdFeB - 12.5 wt% PVA. Both raw materials are weighed according to the composition, and then mixed until homogeneous. Furthermore, pellet forming was made using dry pressing at 50 kgf/cm² pressure. Then the pellets were dried at 100 °C and 10 mmbar for 4 hours. The characterization includes bulk density using Archimedes method, vickers hardness using Microhardness Tester, compressive strength measurements using Universal Testing Machine (UTM), and magnetic properties testing measurement by using Gauss meter and Vibration Sample Magnetometer (VSM).

3. Results and discussion

Bulk density of the dried pellets were measured to evaluate densification results as a function of binder composition (PVA). The results of bulk density measurement is shown at figure 1. Figure 1 shows that changes in bulk density values from composition of binder (PVA) of 5 wt% to 7.5 wt% is relatively small and constant. Nevertheless, density values tend to decrease sharply from 7.5 wt% PVA to 12.5 wt% PVA. The decreasing of bulk density value is due to the density value difference of NdFeB and polymer (PVA). PVA has density value of about 1.2–1.5 g/cm³, but density value of NdFeB is higher, i.e. 6–7 g/cm³ [9]. If the amount of polymer material is higher, the bulk density of mixed materials tends to decrease. Based on the reference, a commercial bonded magnet NdFeB has bulk density of about 5.6-6.8 g/cm³ [10, 11]. Meanwhile, the results achieved from this research obtained the highest bulk density value of about 5.21-5.25 g/cm³ on samples with 5% and 7.5% PVA. According to the result of bulk density measurement, the achieved densification is about 83.87 %. Figure 2 shows vicker hardness curve as a function of binder composition (PVA). The profile curve of vickers hardness is similar with profile curve of bulk density, where the highest value of hardness is about 304.32 Hv and 302.17 Hv for samples with 5 wt% PVA and 7.5 wt% PVA, respectively. The hardness value for sample with binder composition (PVA) of more than 7.5 wt% tends to decrease. The decreasing value of hardness value is due to the amount of PVA composition. It has similar correlation with the density.

Based on the results in figures 1 and 2, it is found that samples with 5% and 7.5% binder (PVA) have the highest bulk density and vickers hardness values. This is because the amount of PVA binder that it serves to fill the pores and binds NdFeB magnetic particles perfectly, so that it can obtain the maximum density. If the material has high bulk density value then the value of hardness will also increase as well. When the amount of PVA binder is more than 7.5%, the bulk density and hardness value drops sharply. This is because the density value of PVA material is much lower than that of the NdFeB particle. Therefore, with the addition of adhesive over the optimal limit there will be a decline in the value of bulk density and hardness. Compressive strength is one of many mechanical properties of a material and it is measured to determine the ability of PVA binder to bind magnetic particles.
Figure 1. Bulk density curves as function of composition of binder (PVA).

Figure 2. Vickers hardness curve as function of binder composition (PVA).

Figure 3 shows that compressive strength value tends to increase from 25.17 kgf/cm² to 33.75 kgf/cm² with increasing PVA binder composition from 5 % to 12.5 wt% PVA. Because of the higher volume fraction of binder, the sample exhibits higher compressive strength. It indicates that higher composition of PVA binder gives greater adhesion forces between powder particles. The highest compressive strength value of bonded magnet NdFeB using PVA adhesive is 33.75 kg/cm² whereas based on reference [10] bonded magnet NdFeB using epoxy resin adhesive has compressive strength value of about 55 kg/cm². The results achieved in this study indeed produced lower compressive strength, because different type of adhesive material can provide different mechanical strength. Therefore, the PVA adhesive produces lower adhesion when compared to the epoxy resin adhesive. More adhesive material will result in increasing compressive strength. However, it should also be considered that increasing amount of non-magnetic adhesive material will decrease its magnetic properties.

Magnetic properties of pellet samples were measured using Gaussmeter to obtain magnetic flux value. The result of magnetic flux measurement is shown in figure 4. Magnetic flux decreases slightly (1170 Gauss to 1150 Gauss) at samples with 5 wt% PVA to 7.5 wt% PVA and decreases sharply (1150 gauss to 810 Gauss) at samples with 7.5 wt% PVA to 12.5 wt% PVA. The decreasing of flux magnetic value is due to the increasing of binder composition and also the fact that the binder material (PVA) is a non magnetic materials. The optimum value of PVA composition is 5 wt% to 7.5 wt%.

Magnetic properties were investigated using VSM to observe the value of remanence, coercivity force, magnetic saturation, and energy product. The results are shown in figure 5. The hysteresis curve of sample bonded magnet with 5 wt% PVA and 7.5 wt% PVA is shown in figure 5, where value of magnetic properties were found: remanence, coercivity, and magnetic saturation (Ms) as shown at table 1. The hysteresis curve (figure 5) indicates that the hysteresis curve area of both samples do not look much different. The composition 5 wt% PVA and 7.5 wt% PVA do not affect significantly in the synthesis of bonded magnet NdFeB. The magnetic properties for both samples are relatively similar; the remanence value is 70.90–74.97 emu/g or 0.47–0.50 Tesla, coercivity value is 8.68–8.76 kOe and energy product 2.89–3.04 MgOe. When compared with other research, the remanence value of the results of this study (0.47-0.50 T) is still lower than that of Zhang Xiuhai and Xiong Weihao's study (0.6-0.7 T) [1, 9].
Figure 3. Compressive strength value curves as function of binder composition (PVA).

Figure 4. Magnetic flux value curves as a function of binder composition (PVA).

Figure 5. Hysteresis curve of sample bonded magnet with 5 % wt. of PVA and 7.5 % wt. of PVA.

It is possible that this difference is due to different types of different adhesive polymers, where this research used PVA adhesive while reference research using epoxy resin. Another reason regarding the low value of magnetic properties is due to the value of achieved densification. One of the most important parameters in fabrication of bonded magnet is hard and high densification [9, 12].

Table 1. Value of remanence, coercivity, magnetic saturation and energy product.

| Composition PVA (% wt) | Remanence (emu/g) | Coercivity (kOe) | Magnetic Saturation (emu/g) | Energy Product (MGOe) |
|------------------------|-------------------|------------------|-----------------------------|-----------------------|
| 5                      | 74.97 [0.5]       | 8.76             | 119                         | 3.04                  |
| 7.5                    | 70.90 [0.47]      | 8.68             | 109                         | 2.89                  |

4. Conclusions
A permanent bonded magnet NdFeB has been successfully made from raw materials NdFeB powder (MQP-B) and polyvinyl alcohol binder, with optimal composition about 5–7.5 wt% PVA. The obtained magnetic properties are bulk density = 5.21–5.25 g/cm³, hardness = 302.17-304.32 Hv.
compressive strength = 25.17–3.17 kgf/cm², magnetic flux = 1150-1170 Gauss, remanence = 70.90–74.97 emu/g (4.7–5.0 kGauss), coercivity = 8.68–8.76 kOe, and energy product = 2.89–3.04 MgOe.

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References
[1] Grujić A, Stajić-Trošić J, Stijepović M, Stevanović J and Aleksić R 2011 Magnetic and Dynamic Mechanical Properties of Nd-Fe-B Composite Materials with Polymer Matrix Metal Ceramic and Polymeric Composites for Various Uses Ed J Cuppoletti (London: InTech Open) chapter 25
[2] Haavisto M, Tuominen S, Santa-Nokki T, Kankaanpää H, Paju M and Ruuskanen P 2014 Advances in Materials Science and Engineering 760584
[3] Grujić A S, Lazić N L, Talijan N M, Spasojević V, Stajić-Trošić J T, Ćosović V R and Aleksić R 2010 Acta Physica Polonica A 117 859
[4] Abhijit P. Jadhav, Ma H, Kim D S, Baek Y K, Choi C J and Kang Y S 2014 Bull. Korean Chem. Soc 35 886
[5] Talijan N, Cosovic´ V, Grujic´ A, Stajic´-Tro´sic J and Zák T 2008 Acta Physica Polonica A 113 525
[6] Sojer D, Kulj I, Kobe S, Kova J and McGuinness P J 2013 Materials and Technology 47 223
[7] Kirchmayr H R 1996 J. Phys. D 29 2763
[8] Garrell M G, Shih A J, Ma B M, Lara-Curzio E and Scattergood R O 2003 J. Magn. Magn. Mater. 257 32
[9] Brown D, Ma B M and Chen Z 2002 J. Magn. Magn. Mater. 248 432
[10] Bonded NdFeB magnet, http://www.e-magnet.cn/productsa2.html
[11] Zhang X and Xiong W 2009 Rare Metals 28 248
[12] Paranthaman M P, Li L, Rio O, Elliott A M, Post B, Kunc V, Fredette R and Ormerod J 2016 CRADA final report NFE-15-0576.1: Additive manufacturing of isotropic NdFeB bonded permanent magnets (Oak Ridge: US Department of Energy)