Mechanical, magnetic properties and corrosion resistance of hybrid bonded magnet NdFeB - BaFe₁₂O₁₉

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Abstract. The hybrid bonded magnet NdFeB - BaFe₁₂O₁₉ has been made. The composition of BaFe₁₂O₁₉ was varied as 0, 3, 5, 8, and 10 wt%. The preparation process was started by mixing BaFe₁₂O₁₉ powder with NdFeB (MQP-B+), then mixed with exopy resin binder of 8 wt% and subsequently compacted with a pressure of 60 MPa to form a pellet. The pellet samples were heated in 10 mmbar of vacuum dryer at 90°C for 1 hour. Some parameters were measured such as mechanical properties (compressive strength), magnetic properties (magnetic flux density and hysteresis curve) and corrosion resistance. The results show that the hybrid bonded magnet NdFeB with 10 wt% BaFe₁₂O₁₉ exhibits the highest compressive strength of about 268,15 kgf/cm². While the optimum corrosion resistance of bonded magnet NdFeB - BaFe₁₂O₁₉ is obtained by 5 wt% BaFe₁₂O₁₉ addition. It has a flux magnetic density of 1340 Gauss, remanence Br of 3,827 kG and coercivity Hcj of 8,924 kOe. According to the corrosion test result, it is found that the sample with higher content of Ba-ferrite has a better corrosion resistance compare to the sample with small content of Ba-ferrite.

1. Introduction
Permanent magnet has become an important part for daily usage. Electric tools or non-electric tools use permanent magnets, for examples loudspeaker, sensor, KWH-meter, rice cooker, transformer and generator [1]. Characteristic of magnetic material is determined by its magnetic properties such as susceptibility, remanence, saturation magnetization and coercivity [1]. The development of permanent magnet currently focused on high energy permanent magnet. Permanent magnet based on NdFeB can produce energy product approximately 50 MGOe [1, 2]. Other advantages of permanent magnet based RE-Fe-B (Re = rare earth metal) are high saturation magnetic induction approximately 1,6 T or 16 kG, with the highest remanence approximately 1,53 T or 15,3 kG for sintered magnet [2]. The disadvantages of NdFeB permanent magnet are susceptible to corrosion in an acid environment. Low corrosion resistance causes the lack of passivation, mechanical destruction as a result of hydrogen and even loss of coherence and fast pulverization of magnets [2, 3]. The other type of permanent magnet is Ba-ferrite with a formula of BaFe₁₂O₁₉. It became references for magnetic material and widely used as permanent magnets, because of its high magnetocrystalline anisotropy and high curie temperature, with relatively high saturation magnetization, good chemical
stability and corrosion resistance [4]. Even the magnetic properties of BaFe$_2$O$_3$ are lower than NdFeB magnet, BaFe$_2$O$_3$ magnet is still used in many applications. For this reason, BaFe$_2$O$_3$ is mainly utilized for the production of permanent magnets. In addition, the cost of raw materials is cheaper than the raw materials based on rare earth metal [5]. Magnets are made by mixing of NdFeB and Ba-ferrite powders, called hybrid magnets [6]. They have better thermal properties and corrosion resistance than magnets produced from purely NdFeB powders [6,7]. The development and utilization of hybrid materials are economically viable due to the fact that these materials can be produced at low cost. For example, a replacement of one fraction in Nd-Fe-B with less expensive BaFe$_2$O$_3$ creates a new hybrid composite [8, 9]. This hybrid composite shows lower magnetic property compared to the original composite, but still applicable for a wide range of usages. The hybrid magnet can be used in automobiles, computers, medical devices, electrical generator, etc. [10, 11]. This paper discusses the synthesis of hybrid bonded magnet NdFeB with the addition of BaFe$_2$O$_3$ and epoxy resin as a binder. The objective of this study is to determine the effect of the composition of Ba-ferrite to the compressive strength, the magnetic properties (magnetic flux density, coercivity, remanence, energy product) and corrosion behaviour.

2. Experimental Methods

Hybrid bonded magnets were made through a solid-solid mixing method with a pressurized compact formation system, the raw materials used are NdFeB, BaFe$_2$O$_3$ magnetic powders and epoxy resin as the binder. The MQP-B+ type of NdFeB magnetic powder was from Maqne Quench China with the average particle diameter of 179.89 μm and BaFe$_2$O$_3$ type isotropic powder was from Yuxiang Magnet China with the average particle diameter of 24.89 μm. The composition of BaFe$_2$O$_3$ was varied as 0, 3, 5, 8 and 10 wt% and epoxy resin composition was 8 wt% from total weight of the mixture. Both raw materials are weighed and mixed according to the composition of Ba-ferrite. Then, the epoxy resin was added into mixed magnetic powders and homogeneously mixed. The weight for each composition is shown in table 1 and total weight of particle magnetic for each sample was 15 g. Then the powders were formed by cold press with a pressure of 60 MPa and holding time for 1 minute. The pellet-shaped samples were dried at 90°C for 1 hour using a vacuum dryer at a pressure of 10 mmbar. The samples were magnetized by using impulse magnetizer at 1.5 kV. The compressive strength of disc samples was measured by using hydraulic machine with a speed of 5mm/sec and maximum force of 20 tonf. The flux magnetic density was measured by using a Gauss meter and the measurement of hysteresis curves was done to know the remanence $B_r$, coercivity $H_c$ and energy product $BH_{max}$ by using a Vibrating Sample Magnetometer (VSM). The corrosion resistance test of hybrid bonded magnet NdFeB - BaFe$_2$O$_3$ was done by immersing in aquadest method for 96 – 400 hours at room temperature [12]. Observation of corroded magnetic material was done by observing the changes in magnetic flux density. The weakening of the magnetic flux density indicated the sample is susceptible to corrosion.

3. Results and Discussion

The results of compressive strength measurement are shown in figure 1. Figure 1 shows the correlation between compressive strength and composition of BaFe$_2$O$_3$. It can be seen that the compressive strength increases with an increasing of BaFe$_2$O$_3$ content. The lowest compressive strength is 114.69 kgf/cm$^2$ for 100 wt% NdFeB sample, but with the addition of BaFe$_2$O$_3$, the compressive strength tends to increase. The small size of BaFe$_2$O$_3$ particles (24.89 μm) fills in the pores between plate shapes of NdFeB particles having a larger particle size (179.89 μm). The smaller particles are incorporated in-between larger particles in epoxy bulk which lead to improving the mechanical properties [13]. Sample with 10 wt% BaFe$_2$O$_3$ has the highest compressive strength of about 268.15 kgf/cm$^2$.

According to the reference [14], the compressive strength of NdFeB with 10% of epoxy resin is 65.86 MPa (658.6 kgf/cm$^2$). If the results obtained are compared with the author Wei Liu, et al., the compressive strength of this research is still lower. This lies in the difference in the composition of the epoxy resin and the compressive pressure of up to 300 MPa for sample preparation. The magnetic
properties of hybrid bonded magnet NdFeB - BaFe\textsubscript{12}O\textsubscript{19} are measured by using Gaussmeter and Vibrating Sample Magnetometer (VSM). The results of gaussmeter measurement are shown at figure 2.

**Table 1.** The composition of NdFeB and BaFe\textsubscript{12}O\textsubscript{19} raw materials

| Sample (wt\%) | NdFeB (g) | BaFe\textsubscript{12}O\textsubscript{19} (g) | Epoxy Resin (g) |
|---------------|------------|----------------------------------|-----------------|
| 100 NdFeB     | 15.00      | 0                                | 1.2             |
| 97 NdFeB - 3 BaFe\textsubscript{12}O\textsubscript{19} | 14.55      | 0.45                             | 1.2             |
| 95 NdFeB - 5 BaFe\textsubscript{12}O\textsubscript{19} | 14.25      | 0.75                             | 1.2             |
| 92 NdFeB - 8 BaFe\textsubscript{12}O\textsubscript{19} | 13.80      | 1.20                             | 1.2             |
| 90 NdFeB - 10 BaFe\textsubscript{12}O\textsubscript{19} | 13.50      | 1.50                             | 1.2             |

**Figure 1.** Correlation between compressive strength and BaFe\textsubscript{12}O\textsubscript{19} concentration

**Figure 2.** Correlation between magnetic flux density and BaFe\textsubscript{12}O\textsubscript{19} concentration

**Table 2.** VSM measurement results for NdFeB and hybrid bonded magnet 95 NdFeB- 5 BaFe\textsubscript{12}O\textsubscript{19}

| Composition (wt\%) | \(B_r\) (kG) | \(H_{cj}\) (kOe) | \(BH_{max}\) (MGOe) |
|--------------------|--------------|------------------|----------------------|
| 100 NdFeB          | 5.166        | 9.188            | 5.386                |
| 95NdFeB - 5BaFe\textsubscript{12}O\textsubscript{19} | 3.827        | 8.924            | 2.847                |
According to the results of magnetic flux density measurement, the optimum value of the hybrid bonded magnet obtained is about 1342 Gauss for 3 wt% BaFe\(_{12}\)O\(_{19}\) addition. The magnetic flux density tends to decrease with an increasing of BaFe\(_{12}\)O\(_{19}\) concentration. It is due to the magnetic properties of BaFe\(_{12}\)O\(_{19}\) that is lower than NdFeB magnet. The VSM measurement results as remanence (\(B_r\)), coercivity (\(H_c\)) and energy product (\(BH_{\text{max}}\)) of 0 % and 5 wt% BaFe\(_{12}\)O\(_{19}\) addition are shown in Table 2 and the hysteresis curves are shown in figures 3 (a) and (b).

According to results of VSM measurement as shown in table 1, 100 wt% NdFeB has higher magnetic properties than NdFeB sample with 5 wt% BaFe\(_{12}\)O\(_{19}\) addition. This is because the magnetic properties of BaFe\(_{12}\)O\(_{19}\) are lower than NdFeB.

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The hysteresis curve of figure 3 (a) shows that 100% NdFeB sample has remanence \(B_r = 96\) emu/g (6.7 kGauss) and coercivity \(H_c = 10\) kOe. But for 95 wt% NdFeB - 5 wt% BaFe\(_{12}\)O\(_{19}\) sample as seen in figure 3b, it has remanence \(B_r = 55\) emu/g (63,827 kGauss), coercivity \(H_c = 8,924\). The corrosion resistance test is carried out for the samples which have high magnetic properties as 0, 3 and 5 wt% BaFe\(_{12}\)O\(_{19}\). The measurement of corrosion resistance was done by using immersion in aquadest at room temperature. The results can be seen in figure 4.

![Figure 3. Hysteresis curve (a) 100 wt% NdFeB, and (b) 95 wt% NdFeB - 5 wt% BaFe\(_{12}\)O\(_{19}\)](image)

![Figure 4. The change in magnetic flux density as a function of immersion time in the aquadest](image)
The corrosion resistance test of the hybrid bonded magnets was observed by measuring the change in magnetic flux density of the sample as a function of immersion time in the aquadest at room temperature. The corrosion resistance is determined when the magnetic flux density starts decreasing sharply. Before immersion, the magnetic flux density of the bonded NdFeB magnet (0 wt% BaFe$_{12}$O$_{19}$) is 1400 Gauss, and the magnetic flux densities of the hybrid bonded magnet NdFeB - BaFe$_{12}$O$_{19}$ with 3 and 5 wt% BaFe$_{12}$O$_{19}$ contents are about 1342 Gauss and 1340 Gauss, respectively. Figure 4 shows that the magnetic flux density of the bonded NdFeB magnet (0 wt% Ba ferrite) tends to decrease sharply after immersion for 48 hours, but for samples with 3 wt% BaFe$_{12}$O$_{19}$ begins to decrease sharply after immersion for 96 hours and for sample with 5 wt% BaFe$_{12}$O$_{19}$, there is a sharp decline after 216 hours. The hybrid magnetic sample with greater BaFe$_{12}$O$_{19}$ content tends to have higher corrosion resistance, and the sample without the addition of BaFe$_{12}$O$_{19}$ has a lower corrosion resistance. In this case, the epoxy resin and magnetic particle of BaFe$_{12}$O$_{19}$ which have good corrosion resistance protect the NdFeB particle against corrosion.

4. Conclusions
The BaFe$_{12}$O$_{19}$ composition in the hybrid bonded magnet, NdFeB - BaFe$_{12}$O$_{19}$ significantly influence the compressive strength, magnetic properties and corrosion resistance. The increase of BaFe$_{12}$O$_{19}$ content in the hybrid bonded magnet NdFeB - BaFe$_{12}$O$_{19}$ tends to increase corrosion resistance. The optimum corrosion resistance of hybrid bonded magnet NdFeB - BaFe$_{12}$O$_{19}$ is achieved by 5 wt% BaFe$_{12}$O$_{19}$ addition. The properties of this sample have a compressive strength of 166.72 kgf/cm$^2$, a magnetic flux density of 1340 Gauss, a remanence of 3.827 kG and the coercivity 8.924 kOe.

Acknowledgments
The authors would like to thank Lukman Faris ST and VSM operator who have helped carry out this research at Research Center for Physics-LIPI.

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