Paper

Reduction in Current Consumption of Small DC Motor with Rare-Earth Flexible Bonded Magnets Prepared by Powder Compacting Press and Hot Rolling

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The usage of high-performance rare-earth magnets is one of the key technologies in the development of efficient small motors. Ring-shaped melt-spun Nd-Fe-B bonded magnets, prepared using a powder compacting press and/or injection molding, are generally used in typical applications to small efficient motors. For exploiting the maximum characteristics according to the variety of magnetic powder, however, the preparation method of the magnet, the magnet form, and the motor design needs to be changed for high-productivity as well as for improving total performance, including the magnetic properties of bonded magnets. This paper reports recent achievements in new preparation processes for rare-earth bonded magnets and small motors using new materials other than Nd-Fe-B melt-spun powder. This paper especially focuses on the method for maximally exploiting certain rare-earth magnetic powders . Furthermore, reduction in the current consumption of the small DC motor using the developed technique is reported.

Keywords : small motor, Nd-Fe-B bonded magnet, HDDR and atomized powder, powder compacting press and hot rolling method

1. Introduction

The total number of production of the small motor during the period from 1992 to 2000 has increased from 2.4 billion pieces to 4.7 billion pieces. The production of the DC motor accounts for 70% of the total production. Significant increases are seen for four kinds of motor, the DC motor, the brush-less motor, the stepping motor, and the core-less motor. The total production of these four kinds of motors increased by 2.6 billion units from 1992 to 2000. Furthermore, an annual growth-rate of 9% can be expected on average in the future [1][2]. These tendencies suggest that the development of efficient small motors using high-performance magnets and their utilization have been advanced in the small motor industry. Thus, the ferrite-rubber magnets and melt-spun Nd-Fe-B rigid epoxy bonded magnets used in small motors will be replaced by other high-performance magnets in the future.

In the past, isotropic Nd-Fe-B-based resin-bonded magnets with a ring-form were generally applied to small efficient motors and the actuators used for PC's and peripherals [3]. For further size reduction of such motors, however, development of a new type of magnet with superior magnetic properties is needed. Fig. 1 shows the relationship among the constituent technologies relevant to the fabrication of the bonded magnet [3] including the new technique. As shown in the figure, it is necessary to change the preparation method of the magnet, the magnet form, and the motor design for high-productivity as well as for improving total performance including the magnetic properties of bonded magnets. Anisotropic Nd-Fe-B-based HDDR powder [4] and isotropic Nd-Fe-B-based powder atomized with a spinning-cup [5] have not been mainly applied to ring-shaped magnets for small motors up to now.

To apply them to small motors, a new technique has been developed, which has enabled the preparation of a new form of magnet, a highly dense flexible bonded magnet. This developed technique consists of the preparation of a powdery compound using new materials followed by the preparation of a highly dense green compact, using the powder compacting press and curing followed by rolling the green compact to form a ring. Both isotropic and axially oriented magnets can be prepared using this technique, and the prepared magnets are suitable for efficient small motors such as small DC motors and small brush-less motors. As mentioned above, this paper describes the method of preparing highly-dense rare-earth flexible bonded magnets from anisotropic Nd-Fe-B- based HDDR powder and isotropic Nd-Fe-B-based powder atomized with a spinning-cup, and compares the magnetic properties of developed magnets with conventional $Nd_2Fe_{14}B$ rigid epoxy bonded magnets and ferrite rubber magnets. Furthermore, a reduction in the current consumption of the small

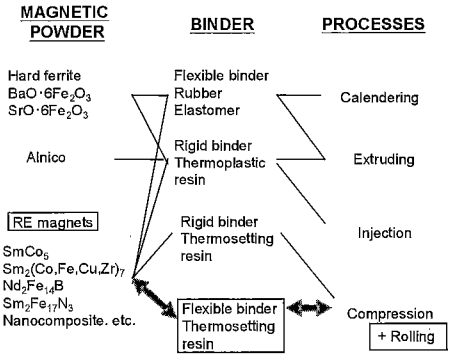

Fig. 1. Relation among constituent technologies relevant to the fabrication of a bonded magnet including the new technique

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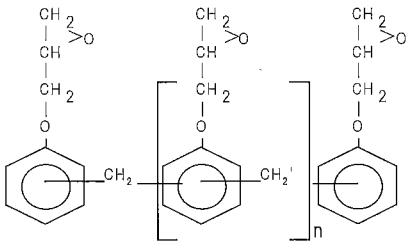
DC motor using this developed technique is reported.

2. Experiment

2.1 Materials Anisotropic HDDR powder ($Nd_{12.3}$ $Dy_{0.3}$-$Fe_{64.7}Co_{12.3}B_{6.0}$ $Ga_{0.6}$ $Zr_{0.1}$, *Powder-A*), powder atomized with a spinning-cup ($Nd_{8.1}Fe_{81.8}B_{5.4}Ti_{0.31}Zr_{0.16}$, *Powder-B*), conventional isotropic melt-spun powder ($Nd_{12}Fe_{77}Co_5B_6$, *Powder-C*) were used as starting materials. Solid epoxy oligomer, a curing agent, and polyamide fine particles including an adhesive agent were also used for the preparation of the bonded magnet. The chemical structures of the novolac-type epoxy oligomer and the powdery acid-dihydriodide are shown in Egs.(1) and (2).

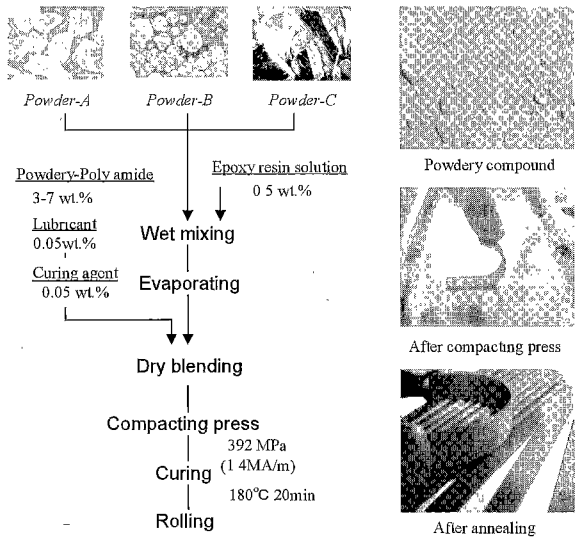


..... (1)

$$(NH_2NHCOCH_2CH_2)_2N(CH_2)_{11}CONHNH_2 \cdots\cdots (2)$$

The solid epoxy oligomer was not granulated for improving the orientation of *Powder-A*.

2.2 Preparation of Rare-Earth Bonded Magnets Flexible bonded magnets were prepared from *Powders –A*, *–B* and *–C* with the powder compacting press and by hot rolling. The process of preparation is shown in Fig. 2 as a block chart and includes photographs of the powders and the materials in the main process. After coating *Powder-A* with solid epoxy oligomer, *Powder-A* and polyamide particles from 3 to 7 wt.% including an adhesive agent, curing agent, and lubricant (slip-agent) were dry-blended and then compounded with a mortar at room temperature. The powdery compound was then filled into the cavity of the feeder cup of a powder compacting press machine, and was compressed under a pressure of 0.5 GPa in an axial direction magnetic field of 1.6 MA/m into a near-net-shape at 60-80℃. Next, the prepared green compact (flexible green sheet) was cured to a flexible sheet-shaped bonded magnet at 180℃ for 20 min. Finally, the sheet-shaped bonded magnet was rolled out at a rolling rate of approximately 2 to 80% at 60-80℃. The final thickness of the prepared flexible bonded magnet was 200 μm to 2.5mm in thickness. For obtaining axially orientated magnets, anisotropic flexible magnets were wound into a ring-form before or after magnetization. Isotropic flexible bonded magnets were also prepared from *Powder-B* without a magnetic field as well as *Powder-C*. The conventional melt-spun $Nd_2Fe_{14}B$–based rigid epoxy bonded magnet and mechanically oriented ferrite rubber-magnet were prepared for comparison.



The photographs show the external appearance of *Powders-A*, *-B*, *-C*, the powdery compound, the green compact, and the cured flexible bonded magnets

Fig. 2. Process for producing flexible bonded magnets using a powder compacting press

In addition to the magnetic properties of the prepared magnets, the magnets were also examined for their mechanical properties, tensile strength, elongation, and windability. Furthermore, small DC motor characteristics were evaluated.

3. Results and Discussion

3.1 Optimization of Preparation Conditions Fig. 3 shows the external appearance of the powdery- compound for three kinds of flexible bonded magnets. As seen in the figure, the average particle size of *Powders-A*, *-B*, and *-C* were 55, 80, and 80 μm, respectively. In addition, it can be seen that the surfaces of the powders are coated by epoxy oligomer with the assistance of

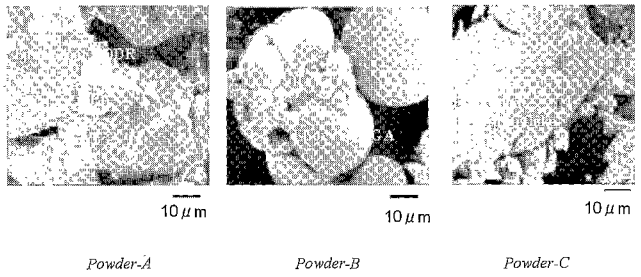
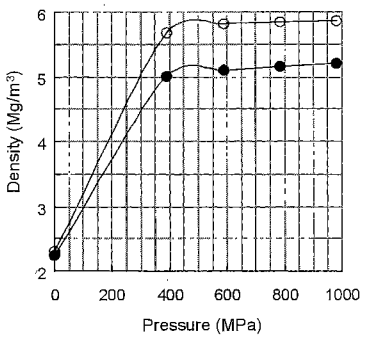
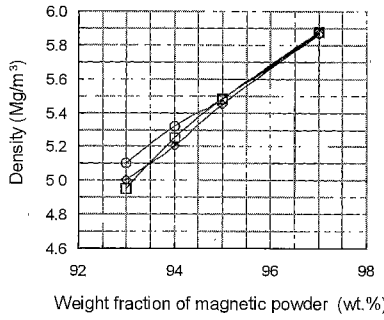


Fig. 3. External views of the three kinds of powdery compound observed with a scanning electron microscope



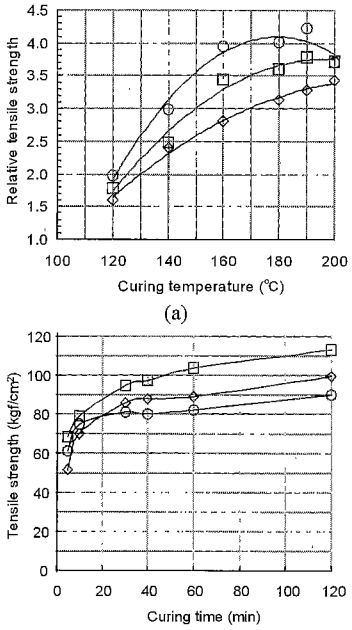
The powdery compounds made from *Powder-B* (●: 93 wt.%, ○: 97 wt.%). The temperature of the mold die was set at approximately 70℃. The green compact is 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness.

Fig. 4. Density of the green compacts as a function of compacting pressure



Three kinds of powdery compound were made from *Powders-A* : □, *-B* : ○, and *-C* : ◇. The green compact is 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness, and the com- pacting pressure is 490 MPa for 1 sec at 70℃. The curing condition is at 180℃ for 20 min.

Fig. 5. Density of bonded magnets as a function of the weight frac- tion of the magnetic powders



The green compact is 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness.

Fig. 6. Tensile strength as a function of heating temperature (a) and heating time of green compacts made from *Powders-A* (□), *-B* (○), and *-C* (◇)

the adhesive agent included in the polyamide particles. Therefore, the prepared powdery-compound is stable in long-term storage at room temperature.

The density of the green compact is shown in Fig. 4 as a function of the compacting pressure for *Powders-A*, *-B*, and *-C*. The green compact which is dense enough to be pressurized is obtained by a pressure exceeding 400 MPa as shown in the figure. The high density obtained at a comparatively low pressure can be attributed to the fact that the polyamide particles are softened at 60-80℃, and plastic deformation occurs. Although it is known that the magnetic properties of magnets are degraded by destroying the magnetic powder by compression, this method is expected to suppress the above-mentioned degradation. The obtained density of the magnets exceeded 5.8 Mg/m^3 when the polyamide particle concentration was 3 wt.% as shown in Fig. 4.

Fig. 5 shows the density of the rare-earth flexible bonded magnet as a function of the weight fraction of *Powders-A*, *-B*, and *-C*. *Powders-A* and *-B* have a spherical form and are suitable for this process. Consequently, the density of the magnets prepared from *Powders-A* and *-B* can be higher than that of other processes, and flexible bonded magnets whose density is higher than any flexible rubber magnets known up to now could be obtained.

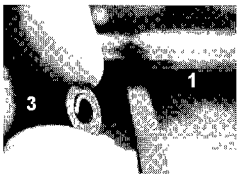
Fig. 6 (a) and (b) show the tensile strength of the rare-earth flexible bonded magnet as a function of heating temperature (a) and the heating time of the green compact. The optimum curing condition is estimated to be at 180℃ for 10-30 min as shown in Fig. 6. The tensile strength increased 2.5 - 4 times compared with that of the green compact; this can be attributed to the curing reaction between the epoxy-group and amino-group including polyamide fine particles of the powdery compounds. In addition, the addition of a curing agent resulted in a further 2 - 4 fold increase in tensile strength.

3.2 Control of Flexibility of the Magnet by Rolling Out

Controlling flexibility is an important aspect because the prepared magnet is mounted on a small motor. An effective method of giving flexibility to the prepared magnet is by hot rolling as shown in Fig. 7. To evaluate this method, the windable limit diameter was measured for the prepared magnet. The dimensional change of the magnet due to rolling was evaluated at the same time.

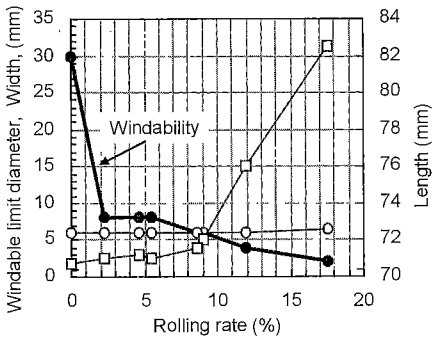
Fig. 8 shows the results of windability and the dimensional change in the magnets. The windability of the magnet improved significantly by rolling with the rolling rate of 2-10% as shown in the figure, although the dimensional change in the magnets is not significant for these rolling rates. Consequently, the magnets could be curled into a diameter of less than 8 mm. When the rolling rate exceeded 10%, remarkable increases in length were observed and the flexibility of the magnets was further improved. As a result, a magnet of 1.1 mm in thickness could be curled around a mandrel of 2 mm in diameter. In other words, a ring-shaped magnet with an outer diameter of 4 mm or less can be prepared.

The changes in the mechanical properties of the flexible bonded magnet are shown in Fig. 9 as a function of the rolling rate. The elongation in the rolling direction of the magnet increased almost proportionally to the rolling rate, and the tensile strength decreased almost linearly with the rolling rate. As the flexibility of



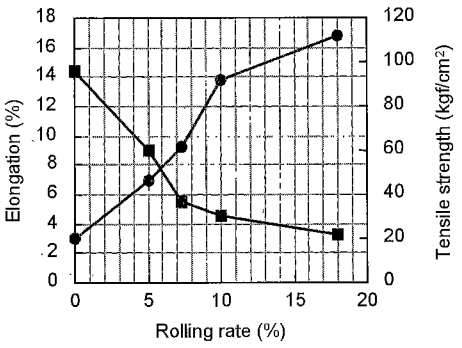
The diameter of the upper and lower rolls is 90 mm. The rolling temperature is 70℃. The objects denoted by 1, 2, and 3 are the roll, the rolled magnet, and the magnet wound after the rolling, respectively. The rolling rate is approximately 10% and the rolled magnet is 1.15 mm in thickness.

Fig. 7. The rolling process to improve flexibility of a cured bonded magnet



The windable limit diameter was defined as the diameter which was able to wind the magnet of 1.1mm in thickness of around the mandrel without the occurrence of the crack. The magnet dimensions before rolling are 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness. The rolling temperature is 70℃. The rolling rate was calculated from the ratio of thicknesses before and after rolling. (●: windability, □: length of the magnet, ○: width of the magnet). The specimens include 94 wt.% *Powder –A*.

Fig. 8. Changes in windability and dimensions of the bonded magnet as a function of rolling rate



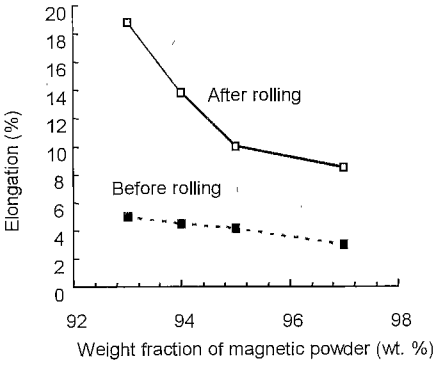
The magnet dimensions before rolling are 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness. The rolling temperature is 70℃. The rolling rate was calculated from the ratio of thickness values before and after rolling. (●: elongation, ■: tensile strength). The specimens include 94 wt.% *Powder –A*.

Fig. 9. Changes in the mechanical properties of a flexible bonded magnet as a function of the rolling rate

the prepared magnet is improved by a rolling rate of 5 - 10%, the mechanical properties for this rolling rate are important from the technical point of view. The elongation and tensile strength values observed for these rolling rate are sufficient for applications to small efficient motors.

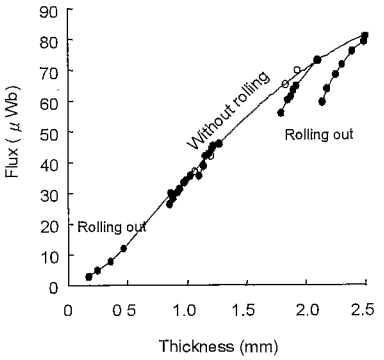
Fig. 10 shows the elongation of flexible bonded magnets as a function of the fraction of magnetic powder. The elongation decreased with the increase in the fraction of the powder. However, the elongation and the tensile strength of the developed magnets within the fraction range studied are almost the same as those of conventional ferrite-rubber magnets at room temperature, and are sufficient for applications to small motors. The highest fraction of the powder in this study, 97 wt.%, is as high as that for a conventional $Nd_2Fe_{14}B$ bonded magnet, with rigid epoxy-resin obtained using the powder compacting press.

Fig. 11 shows the thickness dependencies of the magnetic flux of anisotropic flexible bonded magnets prepared by *Powder-A* and



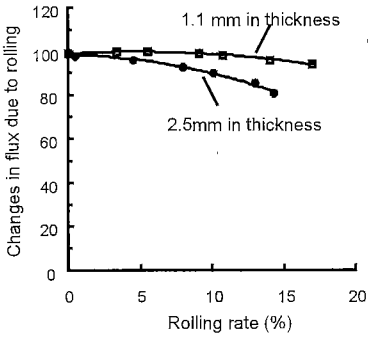
The magnet dimensions before rolling are 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness. The rolling was carried out at 70℃ with a rolling rate of approximately from 8 to 10%. The rolling rate was calculated from the ratio of thickness values before and after rolling. (□: after rolling, ■: before rolling the magnet). The specimens include 93-97 wt.% *Powder –A*.

Fig. 10. Elongation of flexible bonded magnets as a function of weight fraction of the magnetic powder



The magnet dimensions before rolling are 6.1 mm in width, 65 mm in length, and 1.1 mm in thickness. The specimens include 96 wt.% *Powder –A*.

Fig. 11. Thickness dependencies of the magnetic flux of flexible bonded magnets prepared by powder compacting and hot rolling ●: rolling-out, ○: without rolling



The specimens include 96 wt.% *Powder –A*. With thick magnets, the orientation easily falls into disorder by rolling.

Fig. 12. The relationship between rolling rate and flux decrease. The rolling rate was calculated from the ratio of thicknesses before and after rolling. ●: 2.5 mm in thickness before rolling, □: 1.1 mm in thickness before rolling

hot rolling. Here, the minimum thickness of the magnet which can be prepared by compacting is thought to be about 800 μm. However, a thick-film magnet of 200 μm in thickness can be prepared by rolling as shown in Fig. 11. Furthermore, Fig. 12 shows the results a decrease in the degree of orientation during rolling with the flux change. If the magnet of 1 mm in thickness has a rolling rate of 10 % or less, the decrease in magnetic flux by the degree of orientation can be considerably controlled as shown in Fig. 12.

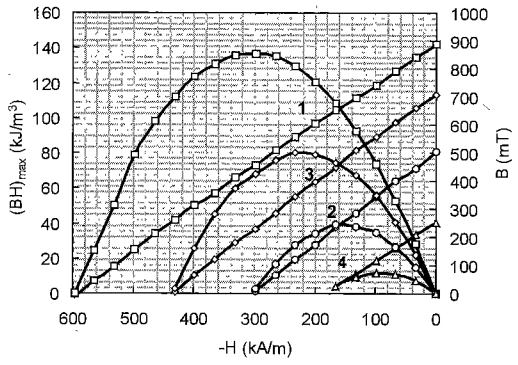
3.3 The Magnetic Properties of Flexible Bonded Magnets

Fig. 13 shows the B-H curves of typical flexible bonded magnets prepared from *Powders-A* and *–B*, together with those of a conventional $Nd_2Fe_{14}B$ rigid epoxy bonded magnet (6.0 Mg/m^3 in density) and a conventional ferrite-rubber magnet (3.7 Mg/m^3). Conventional magnets have been generally used for small DC motors and small brush-less motors. All the measurements were carried out after magnetization under a pulsed field of 4 MA/m.

The flexible bonded magnets prepared from *Powders-A*, and *-B* exhibited density values of 5.84 and 5.45 Mg/m^3, and the $(BH)_{max}$ values of 140 and 39 kJ/m^3, respectively, as shown in Fig. 13. The $(BH)_{max}$ value for the magnet prepared from *Powder-A* was more than 1.75 times as high as that of the conventional $Nd_2Fe_{14}B$ isotropic magnet, and the $(BH)_{max}$ value for the magnet prepared from *Powder-B* was more than 3 times as high as that of the conventional ferrite-rubber magnet. Therefore, the developed magnets are expected to contribute to efficient motors with ring-shaped magnets whose diameter is 10 mm or less.

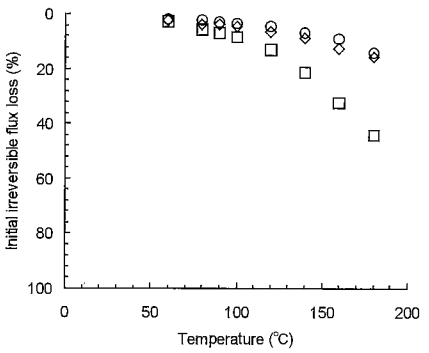
Figure 14 shows the temperature dependencies of the initial irreversible flux-loss of the flexible bonded magnet. Considering that the operating temperatures of small DC motors are generally lower than 100℃, the developed flexible bonded magnets have a sufficiently small initial irreversible flux loss.

Long-term deterioration of magnetic properties is observed for anisotropic rigid-epoxy bonded magnets prepared from *Powder-A*. Therefore, it is necessary to check the long-term flux loss



The B-H curves were measured with a VSM after magnetization under a pulsed field of 4 MA/m. The test specimens are 1.1 mm in height, 7.5 mm in width, and 7.5 mm in length. The curves denoted by 1, 2, 3, and 4 are the results for the magnets prepared from *Powders-A*, *-B*, the conventional Nd-Fe-B bonded magnet and the ferrite-rubber magnet.

Fig. 13. The B-H curves of flexible bonded magnets prepared from *Powders-A* and *–B*, together with those of conventional Nd-Fe-B rigid-epoxy bonded and ferrite-rubber magnets



The permanence coefficient (Pc) of the magnets is 0.3. Three kinds of magnet were made from *Powders-A* : □ , *-B* :○ , and *-C* : ◇ , respectively.

Fig. 14. Temperature dependencies of the initial irreversible flux-loss after 1 h exposure for flexible bonded magnets

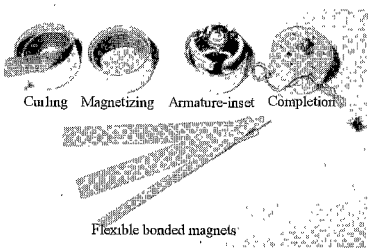
carefully for flexible bonded magnets. Recently, it has been reported that the deterioration is surmountable in the surface treatment of *Powder-A* [6]. In addition, the flexible bonded magnet has an advantage in the production process. Namely, they can be made under a low pressure and the destruction of the magnetic powder is suppressed, compared with the rigid epoxy bonded magnet. Therefore, an improvement in long-term flux loss is expected for the flexible bonded magnet prepared from *Powder-A* at 100℃ or less.

These flexible bonded magnets will be applied to the magnetic field system in an efficient small DC motor.

3.4 Application to the Small DC Motor As indicated above, the developed magnet has good windability and superior magnetic properties. Therefore, the developed magnet could be curled into a ring using an iron frame, and applied to small DC motors with a permanent magnet field system as shown in Fig. 15.

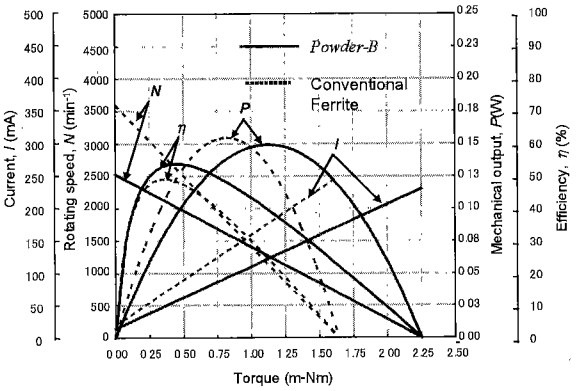
Fig. 16 shows the reduction in current consumption with the small above-mentioned DC motor which optimizes the core's design. The field system prepared from *Powder-B* can reduce current consumption of the DC motor by about 1/3 compared with the ferrite rubber magnet field system as shown in Fig. 16.

Fig. 17 shows the improvement rate of flux of field system prepared from HDDR Nd-Fe-B powder (*Powder-A*) compared with the isotropic powder atomized with a spinning-cup Nd-Fe-B powder (*Powder-B*), and the conventional rigid bonded magnet prepared from the melt-spinning Nd-Fe-B powder. The



The outer diameter and height of the motor are 24 and 12.5 mm, respectively.

Fig. 15. External appearance of a small DC motor and the flexible bonded magnets used in the motor



The broken lines indicate conventional ferrite rubber magnet field system use.

Fig. 16. Reduction in the current consumption of a small DC motor with a field system prepared from isotropic powder atomized with a spinning-cup Nd-Fe-B *powder* (*Powder-B*)

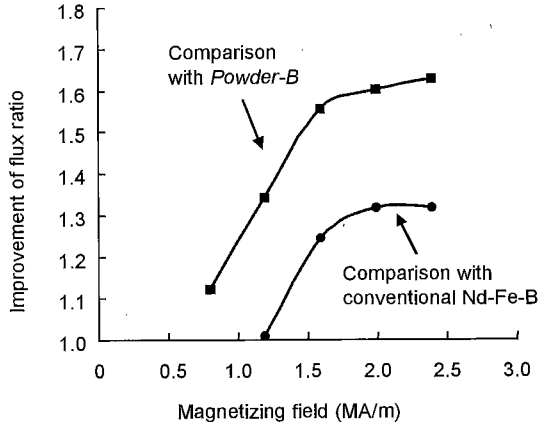


Fig. 17. Improvement rate of flux of field system prepared from HDDR Nd-Fe-B powder (*Powder-A*) compared with the isotropic powder atomized with a spinning-cup Nd-Fe-B powder (*Powder-B*), and the conventional rigid bonded magnet prepared from the melt-spinning Nd-Fe-B powder [8]

improvement of flux of the anisotropic magnet field system prepared from *Powder-A* was 1.6 times the magnet prepared from *Powder-B*. And, it was 1.3 times the conventional magnet [7][8] as shown in Fig. 17. However, the magnetization field of approximately 1.5 MA/m or more was necessary for the strong above-mentioned static magnetic field.

4. Conclusions

A method for preparing a rare-earth bonded magnet using a powder compacting press and by hot rolling, and for reducing the current consumption of the small DC motor was studied. The results are as follows:

(1) Up to now, the Nd-Fe-B-based magnet prepared from anisotropic HDDR powder and isotropic powder atomized with a spinning-cup has not generally been applied to ring-shaped magnets for small motors with a radial gap.

(2) In the past, the density of the flexible bonded magnet was poor because of its preparation process, its extrusion or calendaring processes. A highly dense, flexible bonded magnet was developed using the powder compacting press and by rolling. A density exceeding 5.8 Mg/m^3 and high productivity were achieved by the developed technique.

(3) As a result, the magnet, 0.2 to 2.5 mm in thickness and 39 to 140 kJ/m^3 in $(BH)_{max}$, could be curled around a mandrel of 1.5 mm in outer diameter after rolling with a rolling rate of about 12-15%.

(4) As indicated above, the developed magnets have good windability and superior magnetic properties. Therefore, the developed magnets could be curled into a ring with iron frame, and applied to small DC motors with a permanent magnet field system.

(5) The field system prepared from isotropic powder atomized with a spinning-cup Nd-Fe-B powder can reduce current consumption of the small DC motor by about 1/3 compared with the ferrite rubber magnet field system.

(6) Furthermore, the static magnetic field of the gap with the armature core of the anisotropic magnet field system prepared from HDDR Nd-Fe-B powder was 1.6 times the above- mentioned magnet. Moreover, it was 1.3 times the conventional magnet prepared from the melt-spinning Nd-Fe-B powder. However, a magnetizing field of 1.5 MA/m or more was necessary for the anisotropic magnet field system.

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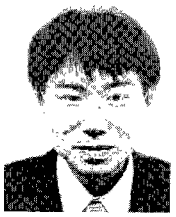

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