

Development of Rare Earth-saving Magnet Using Localized Diffusion Method

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ABSTRACT

A magnet in which rare earth content is reduced by means of a localized diffusion method has been developed in order to reduce the volume of dysprosium used in $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets employed in the drive motors of hybrid, electric and other vehicles.

Based on the fact that the distribution of the demagnetization fields to which the magnets in a motor are subject is not uniform, but rather concentrated at the corners of the magnets, the necessary coercivity distribution for the magnets was quantified using CAE, and a magnet with localized Dy diffusion was developed in order to realize this coercivity distribution. Evaluation of motor characteristics showed the developed magnet to possess identical demagnetization characteristics to a conventional magnet.

Dysprosium resources represent a particular issue among the rare earths more generally, and the technology developed in this project is able to reduce dysprosium use in magnets by 30% or more while maintaining motor performance.

1. Introduction

$\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets possess high magnetic flux density, and contribute to the realization of high torque and reduced size in motors. However, when used at high temperatures, the flux density of the magnets drops, resulting in a decline in motor torque. To compensate for this characteristic, dysprosium (Dy) is substituted for part of the neodymium (Nd) content of the magnets to produce Dy-containing $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets. The highly anisotropic magnetic field of the Dy makes it possible to use the magnets at high temperatures.

These Dy-containing $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets are used in the drive motors of hybrid and electric vehicles. This accounts for a high volume of Dy use among the substance's applications in magnets, with between 5 and 15wt% being added.

The electrification of automobiles is accelerating today as a measure to reduce CO_2 emissions, and as Fig. 1 shows, it is predicted that the demand for magnets will increase with increases in the number of electric vehicles and other vehicles fitted with motors⁽¹⁾. However, rare earths such as Dy are found only in a limited range of areas, and at present China holds a more than 90% share of their production. As a result of the limited areas of production against the

background of increasing demand, the price of Dy increased significantly in fiscal 2011. Figure 2 shows trends in rare earth prices⁽²⁾. While prices have most recently displayed a tendency to decline, they remain more than 20 times higher than they were five years previously. It is predicted that in future the gap between demand and supply for Dy will not be closed, and that resources will become depleted⁽³⁾, making the reduction of Dy use while maintaining current levels of demagnetization performance in magnets used in automotive motors an urgent issue.

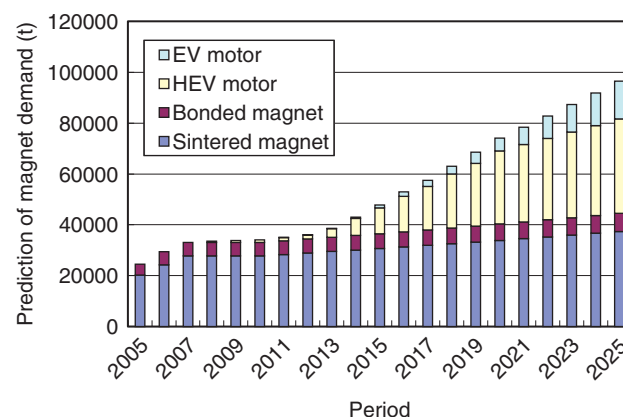


Fig. 1 Prediction of magnet demand

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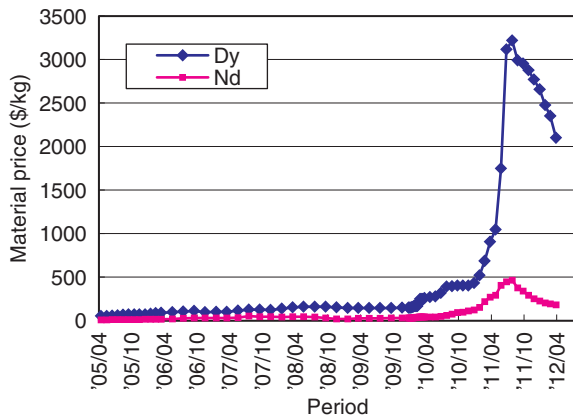


Fig. 2 Material prices for Nd and Dy

2. Issues of Reducing Dy Use

When the demagnetizing fields that magnets in motors are exposed to exceed the magnets' coercivity, the magnetic flux produced by the magnets declines, and the magnetic flux level does not return to normal despite the weakening of the demagnetizing field, resulting in a decline in torque. This phenomenon is termed demagnetization. Because $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets display low coercivity at high temperatures (Fig. 3), demagnetization occurs when a specific limit temperature is exceeded. The anisotropic magnetic field strength of Dy is approximately twice that of Nd, and the addition of Dy to the magnets therefore increases coercivity and raises the temperature at which demagnetization occurs. In an automotive environment, conditions such as hill climbing and continuous high-speed driving can increase the magnet temperature from 160°C to 200°C. A decline in coercivity at high temperatures due to a reduction in the use of Dy would therefore render a magnet unsuitable for automotive use. This necessitates the development of a technology able to maintain the demagnetization characteristic of a magnet despite a reduction in Dy.

A technology for the diffusion of Dy at the grain boundary has been proposed as a means of reducing the

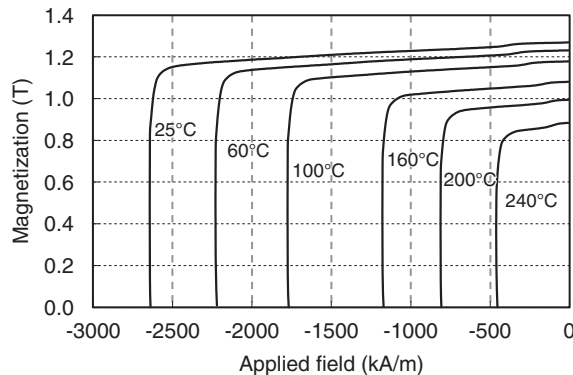


Fig. 3 Temperature-dependence of magnet property

volume of use of Dy in $\text{Nd}_2\text{Fe}_{14}\text{B}$ sintered magnets^{(4), (5)}. This grain boundary diffusion technology is a method of promoting internal diffusion of Dy coated on the surface of the magnet. However, the technology is only able to boost the demagnetization characteristic close to the surface of the magnet, and only reduces Dy use by approximately 10% to 15%. In addition, while magnets with a uniform coercivity throughout the magnet have long been in use, there are no examples of the use of magnets with differing characteristics in specific areas.

The development concept behind the research discussed in this paper was to employ the minimum amounts of Dy in only the necessary areas of the magnet in order to further reduce its use, even if only marginally. It was considered that the realization of increased coercivity only in the corner sections of the magnet, which are prone to demagnetization, using the grain boundary diffusion technology discussed above would make it possible to obtain a demagnetization characteristic equivalent to that of a conventional magnet. Figure 4 shows an image of this concept. In order to maintain the demagnetization characteristic while reducing Dy content, the issue was the realization of a technology able to locally diffuse Dy.

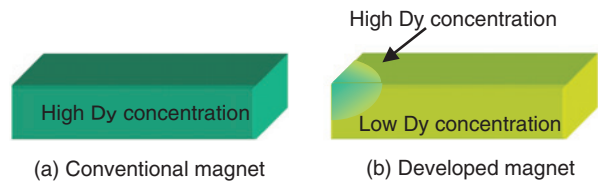


Fig. 4 Concept of reduction of Dy through localized diffusion

3. Study towards Reduction of Dy

Using the electromagnetic field analysis software JMAG, manufactured by JSOL, the demagnetization behavior of an interior permanent magnet (IPM) motor was computed, and the necessary amount of Dy for each area of the magnet was quantified.

The motor's electromagnetic field was analyzed under demagnetizing conditions, and the areas in which demagnetization occurred were identified. The results are shown in Fig. 5. Demagnetization does not occur uniformly

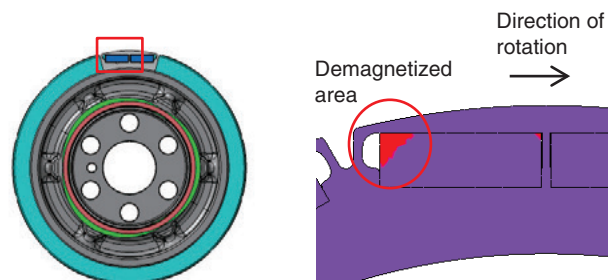


Fig. 5 Motor demagnetization area

throughout the magnet, but rather occurs from the tip of the magnetic pole on the rotor outer circumference side. This is thought to be due to the fact that the demagnetizing field to which a magnet is exposed in a motor is stronger at the corners of the magnet.

Figure 6 shows the results of quantification of the necessary coercivity in each area of the magnet by means of electromagnetic field analysis. Figure 7 shows the concept of magnet specifications. When a low-coercivity (low-Dy) magnet is used as the base magnet prior to the diffusion process, it is necessary to increase coercivity in the corner sections in order to maintain the same demagnetization characteristic as a conventional magnet, necessitating localized diffusion of Dy. Because the amount of Dy necessary at the corner sections of the magnet increases when the coercivity of the base magnet is further reduced, the total amount of Dy used takes on an extreme value. In the case of the motor studied in this project, using a magnet of 550 kA/m lower coercivity than a conventional magnet, it would be possible to reduce the amount of Dy used if coercivity was increased in areas of approximately 3 mm around the corners, realizing the same level of coercivity in the corner sections as a conventional magnet. In this case, it was estimated that Dy could be reduced by 30%.

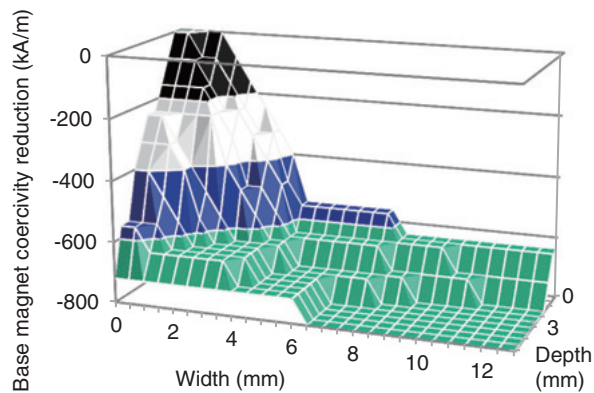


Fig. 6 Minimum Dy distribution

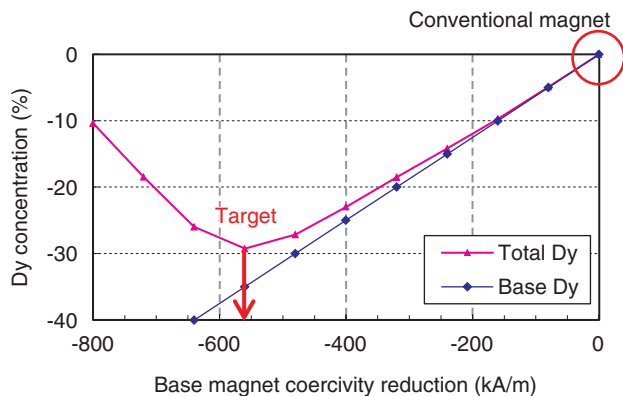


Fig. 7 Concept of base magnet

4. Manufacture of Magnet and Methods of Evaluation

4.1. Manufacture of Magnet with Localized Dy Diffusion

Diffusion conditions were set so as to diffuse Dy locally only in the areas of the magnet in which it was necessary to increase coercivity. Figure 8 illustrates the differences between the conventional magnet manufacturing process and the concept employed here. In order to diffuse Dy, the developed process adds procedures for the application of a Dy paste to the surface of the magnet and for its thermal diffusion. Figure 9 shows a model of standard diffusion⁽⁶⁾. The governing factors in the diffusion of Dy were studied

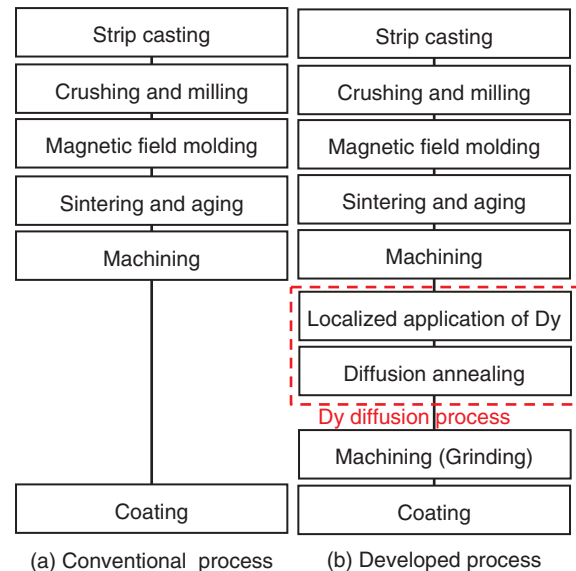
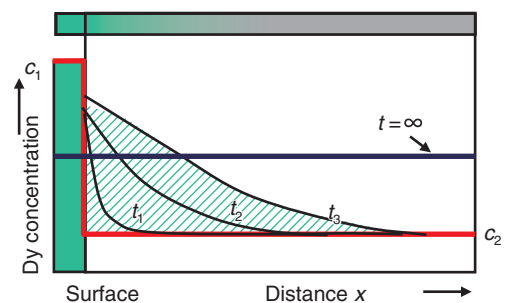


Fig. 8 Dy diffusion process



$$C = c_1 + \frac{(c_2 - c_1)}{2} \left[1 + \operatorname{erf} \left(\frac{x}{2\sqrt{D_0 \cdot t \cdot \exp(-E/k_B T)}} \right) \right]$$

C : Dy concentration

c_1 : Surface concentration

c_2 : Base concentration

x : Distance

D_0 : Vibration factor

t : Time

E : Activation energy

k_B : Boltzmann's constant

T : Temperature

Fig. 9 Basic diffusion model

based on the equation shown here, and optimal conditions were set for factors including the surface concentration of Dy, the temperature of the heat treatment applied during diffusion, time, and the dimensions of the magnet and the coated area.

4.2. Method of Evaluation of Magnet Characteristics

A vibrating sample magnetometer (VSM) was used to measure coercivity in each area of the magnet with localized Dy diffusion in order to determine the local distribution of the Dy. As Fig. 10 shows, the magnet was divided into 0.9 mm sections, and a VSM was used to measure coercivity for each section.

Total open flux was measured using a flux meter, and Dy distribution was measured using an electron probe microanalyzer (EPMA).

4.3. Method of Evaluation of Motor Characteristics

A motor was produced using magnets manufactured by means of the process discussed above, and its characteristics were evaluated. Figure 11 shows an external view of the motor evaluation system. In order to quantify the effect of local Dy diffusion, the same evaluation was conducted using a motor in which the magnets had not been subjected to the Dy diffusion process in order to provide a comparison.

For the torque characteristic, the torque produced by the motor when a predetermined current was impressed was measured. In the case of the demagnetization characteristic, a demagnetizing field of the maximum strength was induced in the magnets by impressing the maximum current in the motor at a predetermined temperature, following which the magnetic flux produced by the magnets was evaluated, and the changes before and after the current was impressed

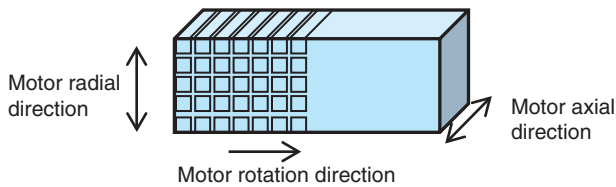


Fig. 10 Method of evaluation of coercive force distribution

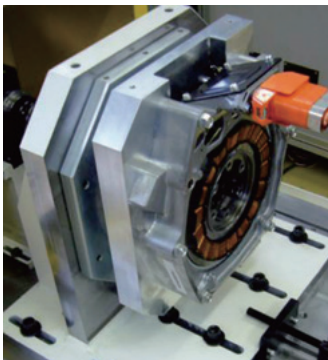


Fig. 11 Appearance of motor evaluation system

were measured. The demagnetization characteristic of the magnets was evaluated from the rate of decline in magnetic flux from the initial value.

4.4. Method of Evaluation of Characteristics following Demagnetization Test

The flux density distribution on the surfaces of the magnets was measured before and after the demagnetization tests in order to determine the demagnetized areas of the magnet. It is possible to identify demagnetized areas of a magnet by means of differences in flux density before and after demagnetization tests. A magnet analyzer was used in the measurements.

5. Results and Discussion

5.1. Evaluation of Materials

5.1.1. Coercivity characteristic

Figure 12 shows the results of measurements of the distribution of coercivity in the magnet with localized Dy diffusion. The coercivity of the central section of the magnet is the same as for the magnet prior to the localized Dy diffusion process, but coercivity increases towards the corners, and reaches or exceeds the target level of 550 kA/m at the corners, where it is at its peak. These results conform to the results of the study using the Dy diffusion model, and confirm that differences in the concentration of diffused Dy result in different coercivity levels in different areas of the magnet.

Figure 13 shows a comparison between the distribution of coercivity in a magnet with localized Dy diffusion and target values. Coercivity distribution was evaluated from two planes, a cross-section from the corner parallel to the side and a 45° cross-section in which the diffusion distance is greatest. The necessary coercivity has been realized in both planes. The results also show that it was possible to control the allocation of coercivity by controlling the amount of Dy applied as a coating and heat treatment conditions.

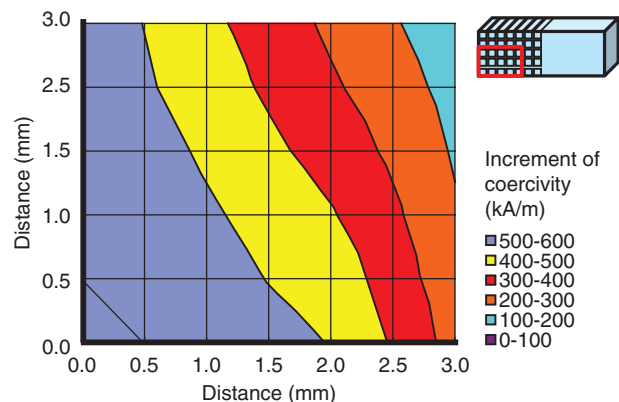


Fig. 12 Coercivity map for localized Dy diffusion process

5.1.2. Magnetic flux density

Normally, when Dy is added to a magnet to achieve high coercivity, the remanence of the magnet declines⁽⁷⁾. The magnetic flux density of the magnet produced in this research was compared with that of a conventional high-Dy magnet. No difference in remanence was observed due to the localized Dy diffusion process in the developed magnet. In a high-Dy magnet, Dy is dispersed throughout the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase. The magnetic fluxes of the Dy and Nd mutually cancel each other out, and total magnetic flux density declines. By contrast, in the magnet with localized Dy diffusion, Dy is concentrated at the grain boundary, where the melting point is low. It is believed that the decline in magnetic flux density with increased coercivity is controlled because of this fact.

Figure 14 shows EPMA images before and after localized diffusion of Dy. Figure 14(a), an image taken prior to the Dy diffusion process, shows that Dy is uniformly dispersed throughout the magnet, with no areas

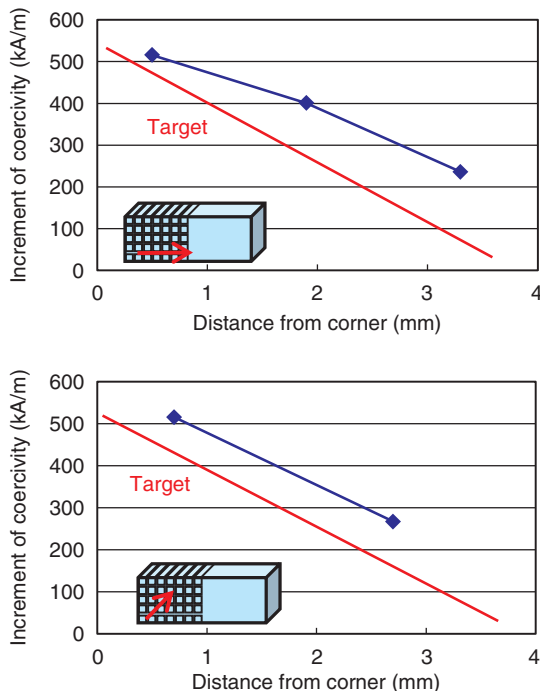
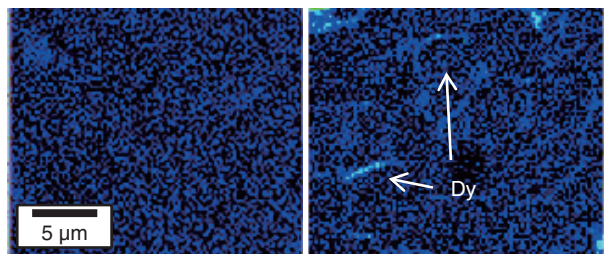


Fig. 13 Comparison of CAE analysis and magnet with localized Dy diffusion



(a) Base magnet

(b) Magnet with localized Dy diffusion

Fig. 14 Cross-sectional EPMA photographs

of conspicuous change in concentration. In Fig. 14(b), an image taken following the Dy diffusion process, the Dy (the white areas in the image) is concentrated in lines, and it is considered that there is no mutual cancelling of magnetic fluxes in the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and no decline in remanence.

5.2. Evaluation of Motor Characteristics

5.2.1. Torque characteristic

The torque characteristics of motors using magnets with localized Dy diffusion and conventional high-Dy magnets were compared in motor tests. The results are shown in Fig. 15. Each motor displayed identical torque characteristics, confirming that no decline in torque occurred as a result of the localized Dy diffusion process. This result accords with the fact that no decline in magnetic flux density was observed when magnets were studied in isolation.

5.2.2. Demagnetization characteristic

The demagnetization characteristics of conventional high-Dy magnets and the developed magnets with localized Dy diffusion were compared in motor tests. Figure 16 shows the results. Despite the fact that the developed magnets contain 39% less Dy, their demagnetization behavior is the same as that of the conventional magnets.

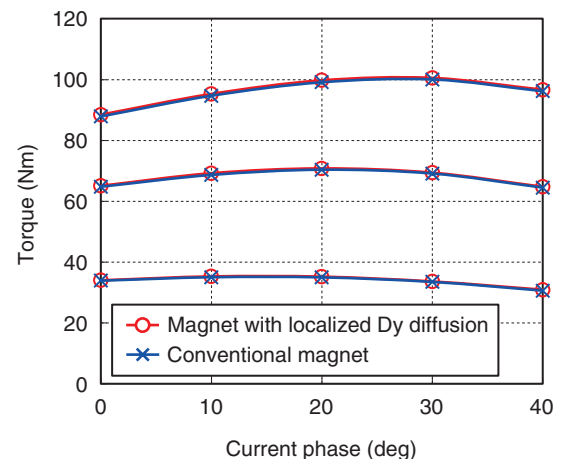


Fig. 15 Comparison of current-torque characteristics

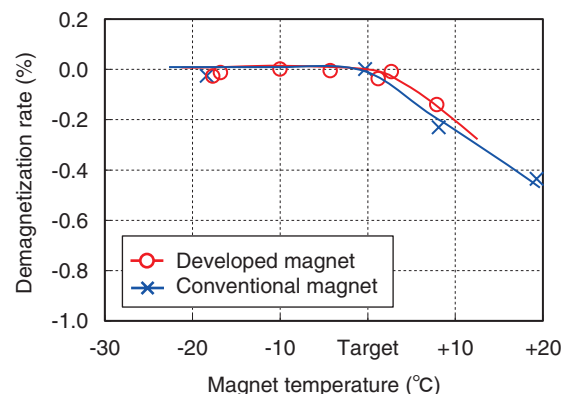


Fig. 16 Demagnetization characteristic

This is considered to be a result of the fact that the magnets with localized Dy diffusion display the same level of coercivity as the conventional magnets in their corner sections, where demagnetization commences. It is predicted that differences in demagnetization behavior would be observed at higher temperatures, when the demagnetization field acts on greater areas of the magnets, but this result indicates that in the use environment of a hybrid vehicle drive motor, the reduction in Dy content would have no effect on motor characteristics.

5.2.3. Measurement of demagnetized area

Figure 17 shows the results of measurements of the demagnetized areas of magnets following demagnetization. The results of calculations of the demagnetized areas by means of electromagnetic field analysis are also shown. The respective areas of demagnetization are shown outlined in blue. By contrast with the conventional magnet shown in Fig. 17(a), in which demagnetization commences in the corners, in the case of the magnet with localized Dy diffusion shown in Fig. 17(b), demagnetization commences in the center. This is thought to be due to the center of the magnet having become the weakest area with the realization of increased coercivity at the corners through localized Dy diffusion. In the case of the results of electromagnetic field analysis, because the calculations do not incorporate the internal temperature gradient of the magnets, there is

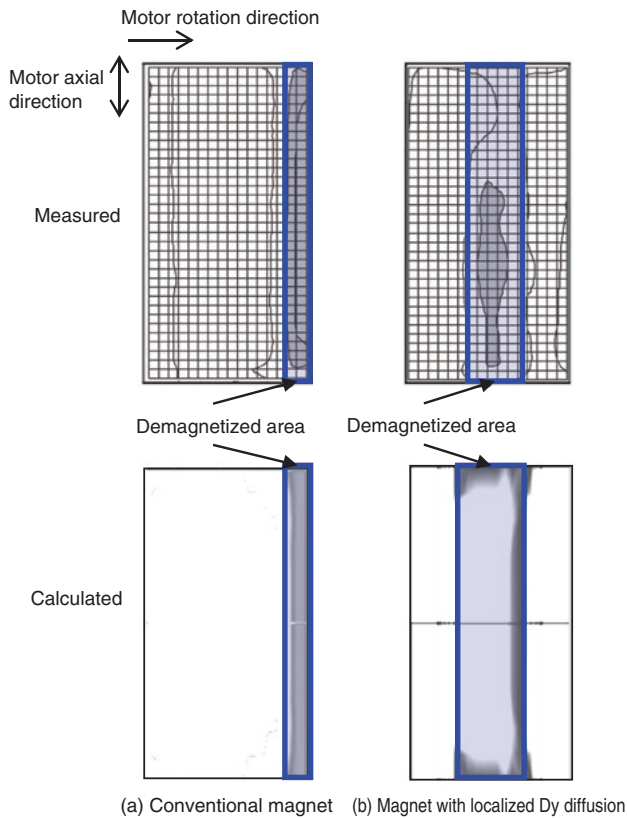


Fig. 17 Magnet flux distribution after demagnetization test

a lack of conformity between the detailed shapes of the demagnetized areas, but the tendency towards a shift from the corners to the center of the magnet is reproduced. Taken together with the demagnetization characteristics discussed in the previous section, this indicates that the project was successful in developing a magnet conforming to its initial concept.

6. Effect of Application of Technology

Magnets with localized Dy diffusion at the corner sections alone produced identical motor characteristics and displayed identical demagnetization characteristics as conventional high-Dy magnets. Figure 18 shows the effect of reduction of the amount of Dy added to the magnets. A total of 47% of the Dy concentration of a conventional magnet was reduced by not adding Dy in areas in which coercivity was unnecessary, but 8% of the Dy concentration of a conventional magnet was added in the localized diffusion process, for a final Dy reduction of 39%.

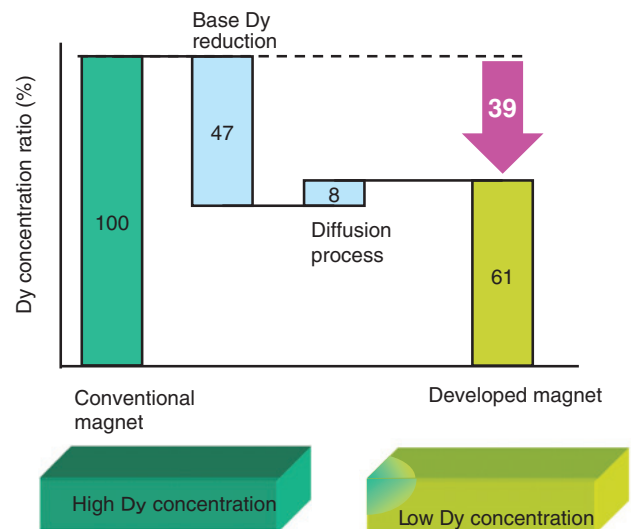


Fig. 18 Effect of application of magnet with localized Dy diffusion

7. Conclusion

Focusing on the distribution of demagnetizing fields in magnets used in automotive motors, the project discussed in this paper formulated a design concept for a magnet in which the distribution of Dy was locally varied, and established a method of manufacture for such a magnet. The developed magnet was verified as displaying identical magnetic characteristics to a conventional magnet. The reduction of the volume of use of rare earths is a long-term issue for the magnet industry, and the technology developed here was able to reduce Dy use by 39%.

The developed magnets will be employed successively

in motors used in the Integrated Motor Assist (IMA) systems of Honda hybrid vehicles.

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