Demagnetization Analysis Method using Dy Diffused Magnets and the Most Suitable Dy Diffusion Methods and their Effects for Motor Applications

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Abstract :
Dy diffused magnets which could reduce Dy content of Nd-Fe-B sintered magnets are well known as one of the method achieving high performance magnet. We have developed the demagnetization analysis method using Dy diffused magnets which have graded coercive force distribution from surface to inside of magnet. In this paper, it is discussed about the most suitable Dy diffusion methods and magnets using newly developed demagnetization analysis method and also reports their effects for motor applications.

JMAG Users Conference 2011

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Demagnetization Analysis Methods Using Dy Diffused Magnets, The Most Suitable Dy Diffusion Methods, and Their Effects for Motor Applications

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NEOMAX Company
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Shifts In the Rare Earth Metal Prices of Rare Earth Magnet Materials

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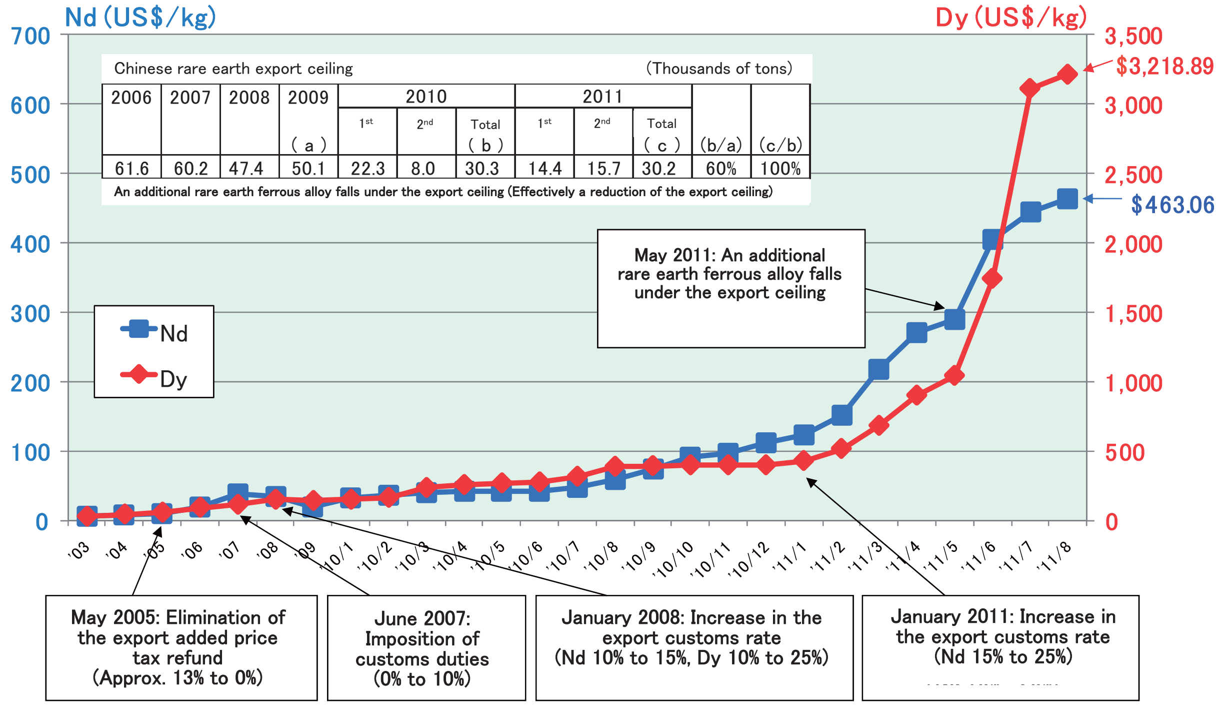
2003 – August 2011



Chinese rare earth export ceiling (Thousands of tons)

2006	2007	2008	2009	2010			2011				
			(a)	1st	2nd	Total (b)	1st	2nd	Total (c)	(b/a)	(c/b)
61.6	60.2	47.4	50.1	22.3	8.0	30.3	14.4	15.7	30.2	60%	100%

An additional rare earth ferrous alloy falls under the export ceiling (Effectively a reduction of the export ceiling)

Source: Metal-Pages

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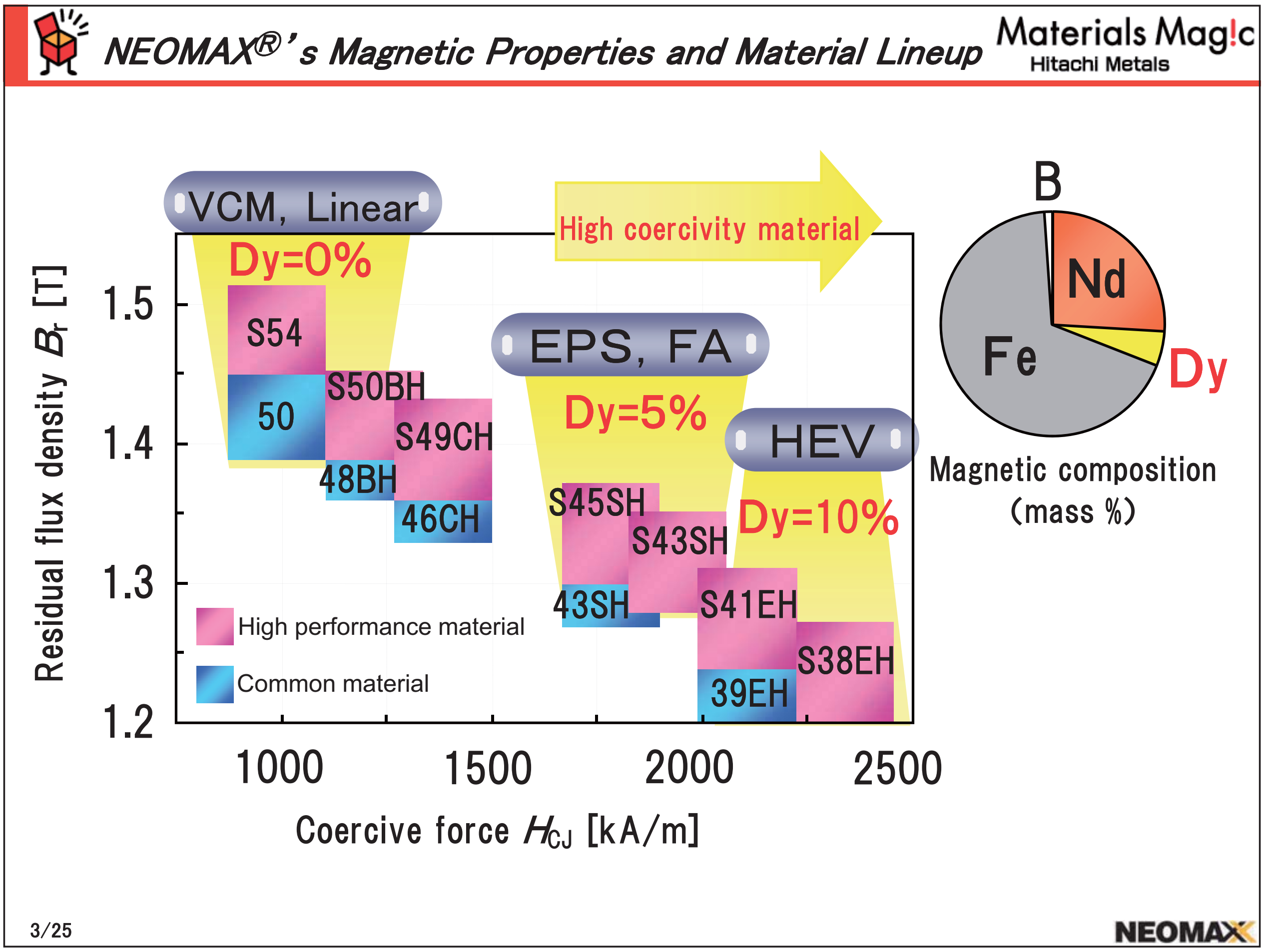

NEOMAX®'s Magnetic Properties and Material Lineup
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VCM, Linear
Dy=0%
High coercivity material
EPS, FA
Dy=5%
HEV
Dy=10%
S54
50
S50BH
48BH
S49CH
46CH
S45SH
43SH
S43SH
S41EH
39EH
S38EH
High performance material
Common material
Residual flux density Br [T]
1.5
1.4
1.3
1.2
1000
1500
2000
2500
Coercive force HcJ [kA/m]
B
Nd
Fe
Dy
Magnetic composition (mass %)
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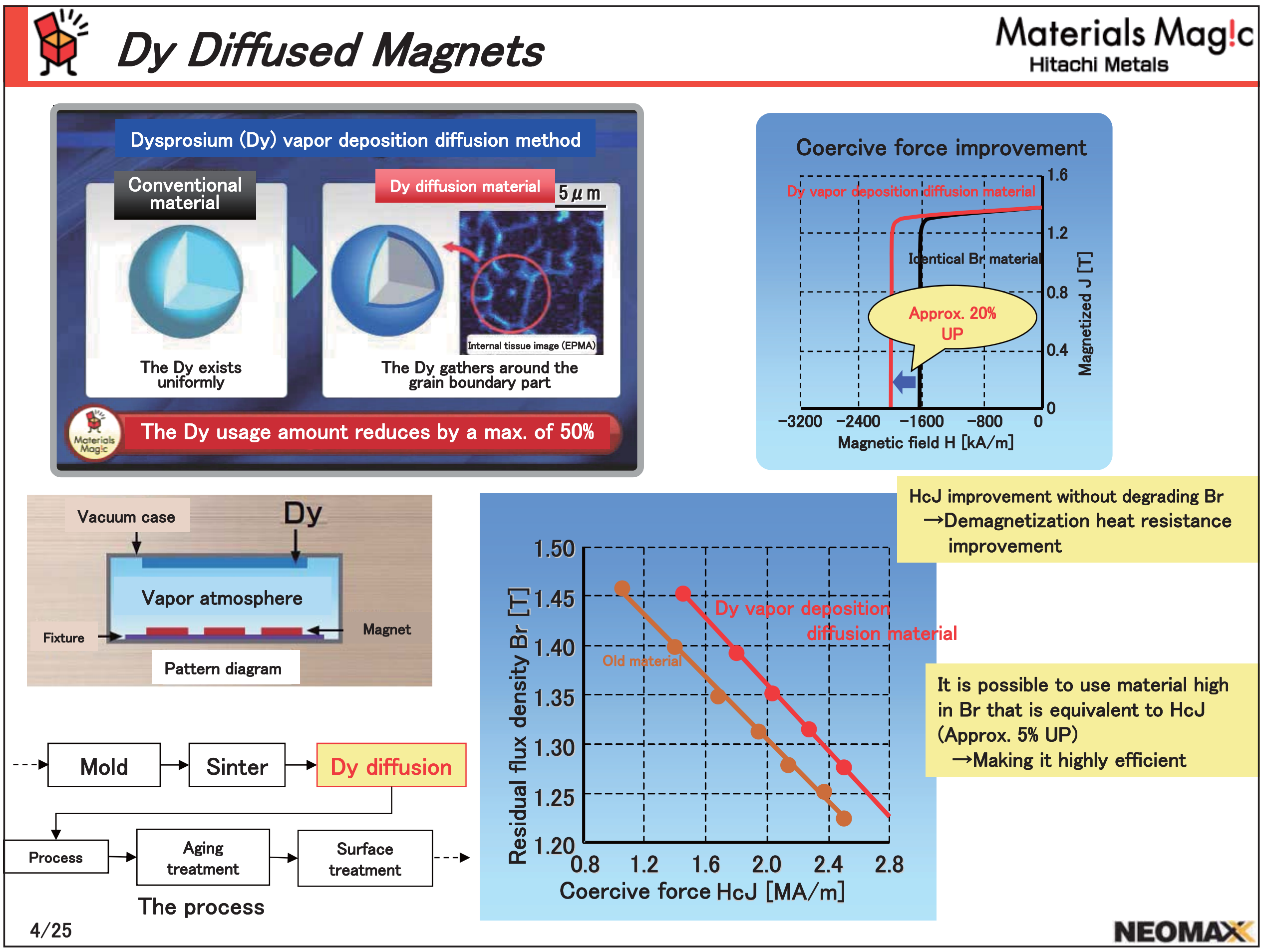

Dy Diffused Magnets
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Dysprosium (Dy) vapor deposition diffusion method
Conventional material
Dy diffusion material
5μm
Internal tissue image (EPMA)
The Dy exists uniformly
The Dy gathers around the grain boundary part
The Dy usage amount reduces by a max. of 50%
Coercive force improvement
Dy vapor deposition diffusion material
Identical Br material
Approx. 20% UP
1.6
1.2
0.8
0.4
0
Magnetized J [T]
−3200 −2400 −1600 −800 0
Magnetic field H [kA/m]
HcJ improvement without degrading Br
→Demagnetization heat resistance improvement
Vacuum case
Dy
Vapor atmosphere
Fixture
Magnet
Pattern diagram
Mold
Sinter
Dy diffusion
Process
Aging treatment
Surface treatment
The process
Residual flux density Br [T]
1.50
1.45
1.40
1.35
1.30
1.25
1.20
0.8 1.2 1.6 2.0 2.4 2.8
Coercive force HcJ [MA/m]
Dy vapor deposition diffusion material
Old material
It is possible to use material high in Br that is equivalent to HcJ (Approx. 5% UP)
→Making it highly efficient
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The Magnetic Properties of Dy Diffused Magnets

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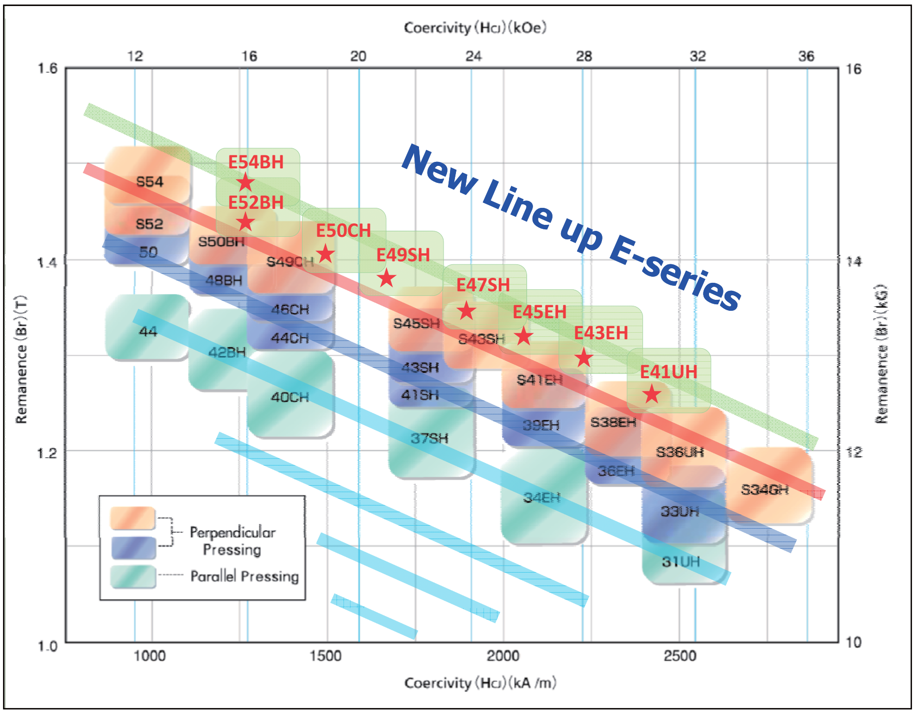

★ : Ask the sales supervisor about the quality of these materials
There are times when it is difficult to ensure the above properties due to geometry and dimensions, so we will set the warranty properties upon consultation.

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Design Challenges of Motors Using Dy Diffusion Magnets

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The key design point of motors using Dy diffusion magnets is:
Irreversible demagnetization design

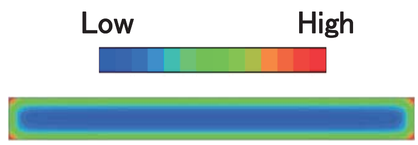
Dy diffusion magnets have coercive force (HcJ) distribution in the magnet's interior

【Design challenge】

Modelization of coercive force distribution

⇩

Demagnetization analysis of magnets that have HcJ distribution



HcJ distribution

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Modelization of Coercive Force Distribution

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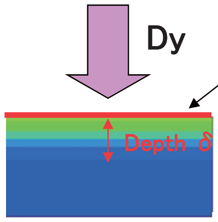
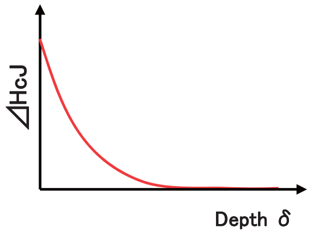
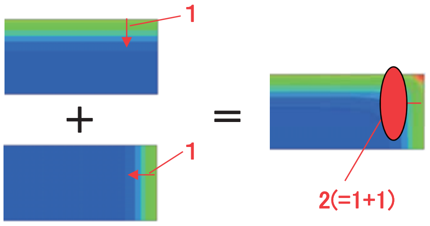
It has distribution ⊿HcJ for a depth of δ from the diffusion surface.



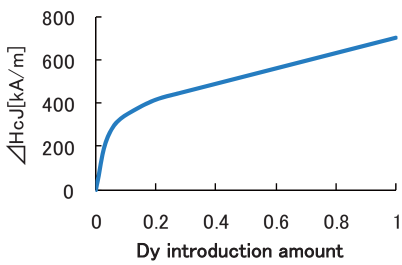


It does not turn out like:



Even if you join together ⊿HcJ for the depth δ from each diffusion surface

The reason is that ⊿HcJ for the Dy introduction amount does not have linear properties.



It is necessary to calculate the Dy introduction amount distribution and ⊿HcJ.

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Modelization of Coercive Force Distribution

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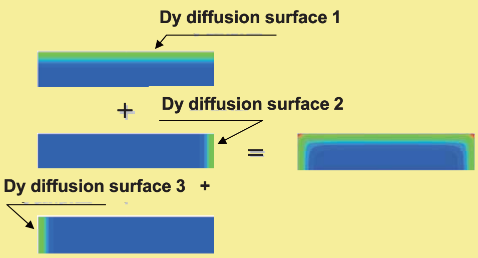
Step 1: Calculate the Dy introduction amount distribution

＜Method 1＞
Add up the Dy introduction amount distribution from each diffusion surface

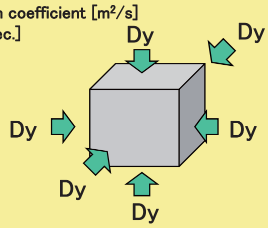


Mainly used in 2D analysis

＜Method 2＞
Calculate the Dy introduction amount distribution with Fick's diffusion equation.

$$D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}\right)=\frac{\partial C}{\partial t}$$

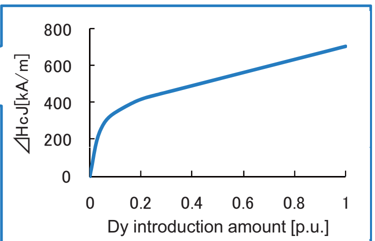
C : Concentration [mass%]
D : Diffusion coefficient [m²/s]
t : Time [sec.]



Mainly used in 3D analysis

Step 2: Convert to ⊿HcJ distribution

Step 3: Convert to HcJ distribution
(Base material HcJ+⊿HcJ)



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Modelization of the Dy Introduction Amount Distribution <Method 1>

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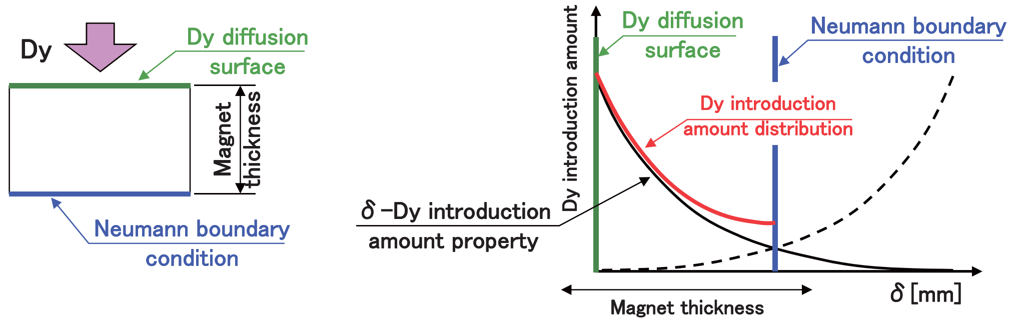
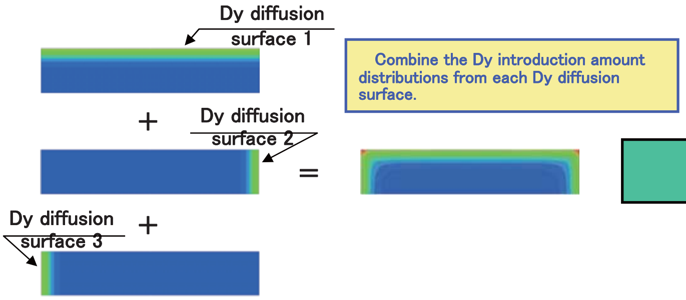
Use the depth δ – Dy introduction amount and Neumann boundary condition to modelize the Dy introduction amount distribution

【A diffusion model using the Neumann boundary condition】

Neumann boundary condition: The boundary condition where the gradient of the physical amount in the boundary plane becomes zero.





Convert the Dy introduction amount distribution from:
Dy introduction amount – ⊿HcJ properties
To: ⊿HcJ distribution

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Modelization of Dy Introduction Amount Distribution <Method 2>

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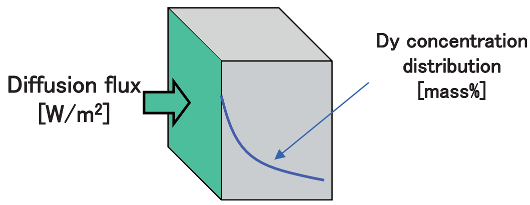
Use Fick's diffusion equation (Second law) to modelize the Dy introduction amount distribution.

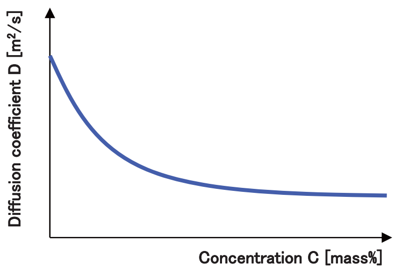
$$D\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}\right)=\frac{\partial C}{\partial t}$$

C: Concentration [mass%]
D: Diffusion coefficient [m^2/s]
t: Time [sec.]



<Analysis input>
① Time
② Diffusion flux
③ Diffusion coefficient
(Concentration dependence)

Fix the Dy diffusion conditions and identify them in advance.



The diffusion coefficient accounts for concentration dependence.

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⊿HcJ Distribution Comparison

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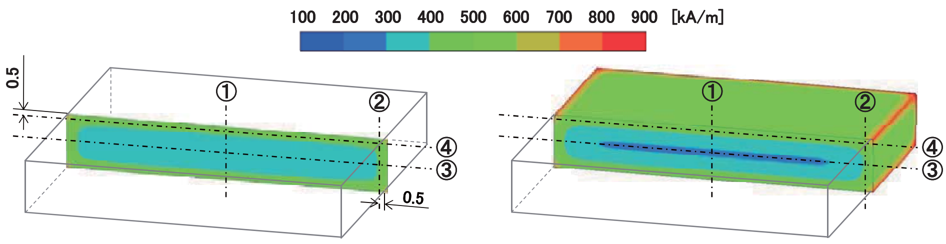
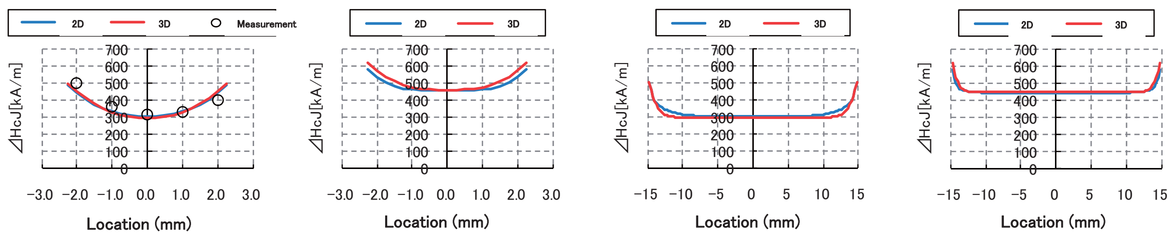
Magnet dimensions: 5(M)×30×30



(a) 2D (Method ①) (b) 3D (Method ②)

⊿HcJ distribution comparison (Contour)



(a) Line ① (b) Line ② (c) Line ③ (d) Line ④

⊿HcJ distribution comparison (Line)

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Demagnetization Analysis Method (B-H Curve Correction Method)

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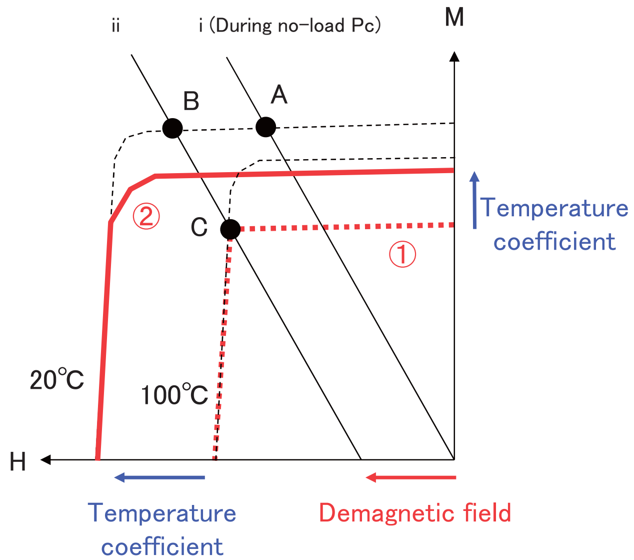
Ex.: Nd-Fe-B sintered magnet, demagnetization occurring at 100℃

Compute the post-demagnetization magnetic properties on an M-H curve, and input them by converting the analysis to a B-H curve.



1. Calculate the Pc and operating point A when there is no load (20℃)
2. Calculate the demagnetic field and operating point B when there is no load (20℃)
3. Calculate operating point C at 100℃
4. Calculate the equivalent M-H curve ① at 100℃
5. Modify M-H curve ①'s Br, HcJ with the temperature count, and calculate M-H curve ② at 20℃.

By recording the no-load Pc and the demagnetic field, it is possible to handle arbitrary magnetic properties (Br, HcJ, temperature)

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Temperature Coefficient β of the Coercive Force

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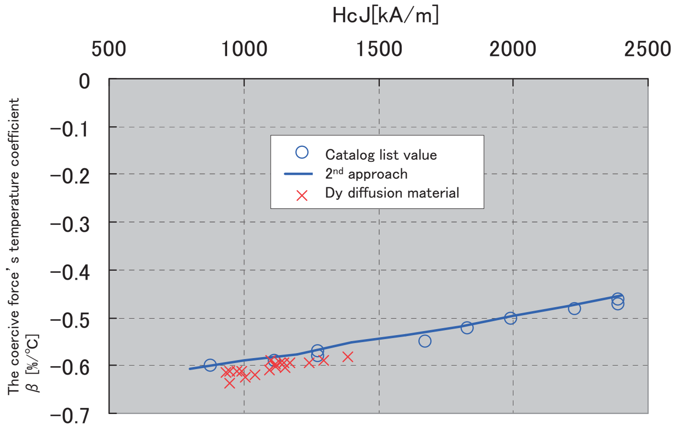
The temperature coefficient β of the coercive force is dependent on the absolute value of the coercive force.

Dy diffusion magnets have coercive force distribution in their magnets' interiors, so the coercive force's temperature coefficient β also has distribution.

Use an approximation function and calculate β for an HcJ of your choosing.



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IPM Motors for Analysis Precision Verification

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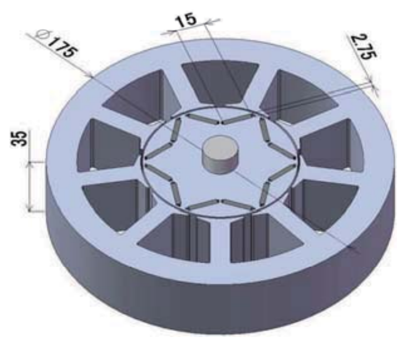
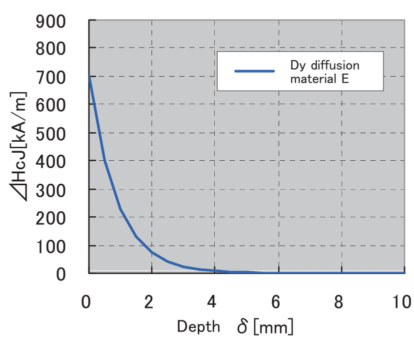


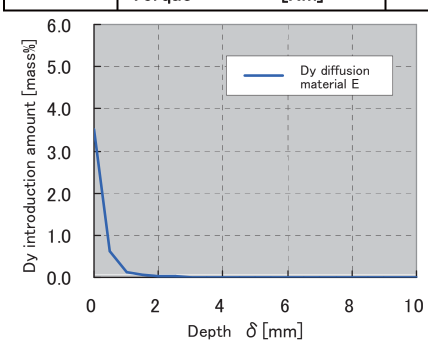
Motor dimensions

Motor Specifications

Rotor material quality		35A360
Stator material quality		35A360
Shaft material quality		S45C
Coil specs	Turns [turn/coil]	115
	Connection	3 phase Y connection 3 series/phase
Drive method		Sinusoidal current
Evaluation points	Turns [rpm]	1000
	Current [A]	8
	Current phase angle [deg.]	30
	Torque [Nm]	10.1



δ−⊿HcJ properties



δ−Dy introduction amount properties

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The ⊿HcJ Distribution of an IPM Motor For Analysis Precision Verification

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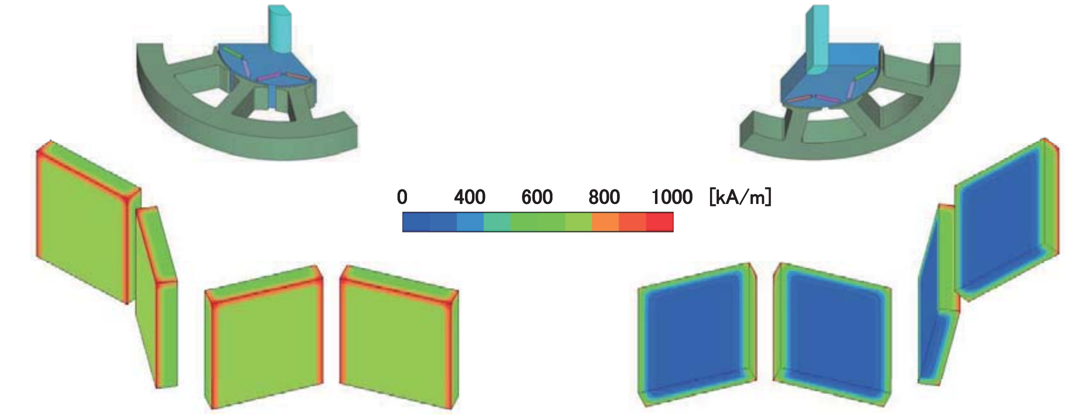
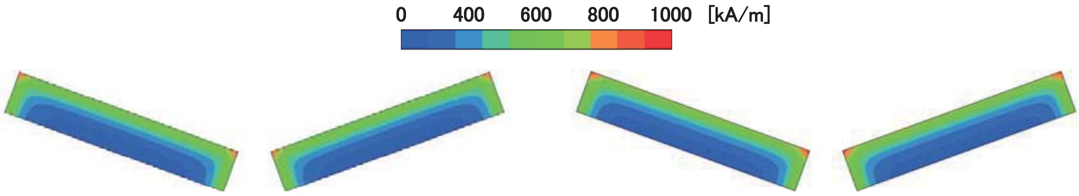


From above the external diameter   From below the internal diameter

⊿HcJ distribution



2D model   3D model (Axial direction center section)

⊿HcJ distribution comparison

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Motor Demagnetization Property Measurement Equipment

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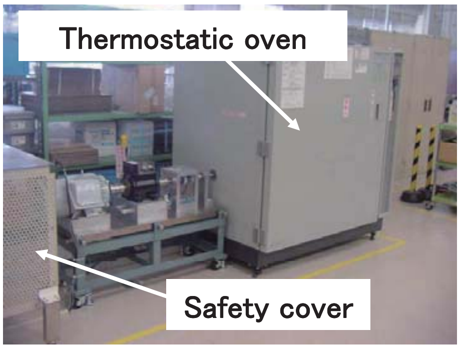

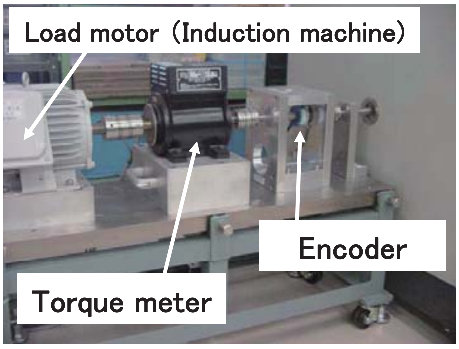

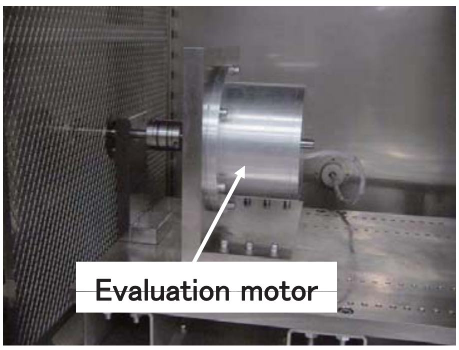

【Possible measurement range】

- Max. output : 3.7[kW]
- Max. rotation : 3000[rpm]
- Max. torque : 23[Nm]
- Temperature : Room temp–300*[°C]

* : Limited by motor parts (Coil, insulating members, adhesives)

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Demagnetization Properties of an IPM Motor For Verification

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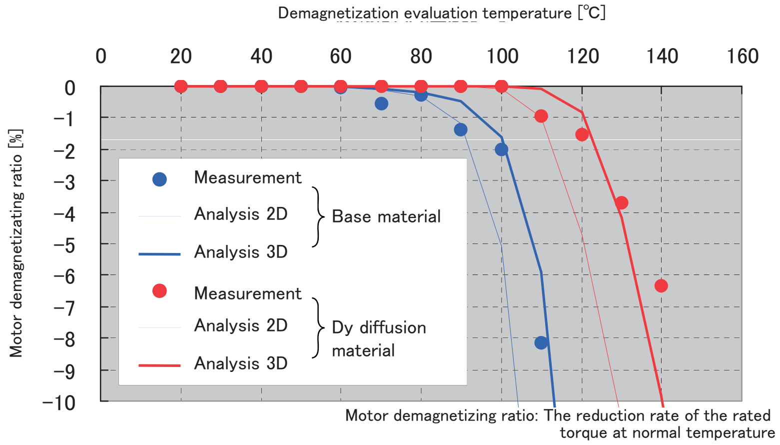

Motor demagnetization property comparison

2% demagnetization temperature comparison

	Base material			Dy diffusion material		
	Measurement	Analysis 2D	Analysis 3D	Measurement	Analysis 2D	Analysis 3D
Motor 2% demagnetization temperature [℃]	100	92	101	122	113	124
Analysis error [℃]	–	−8	+1	–	−9	+2

The error is within 10℃ in 2D analysis
Analysis precision improvement in 3D analysis

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Dy Diffusion Plane and Motor Demagnetization Properties (2D Analysis)

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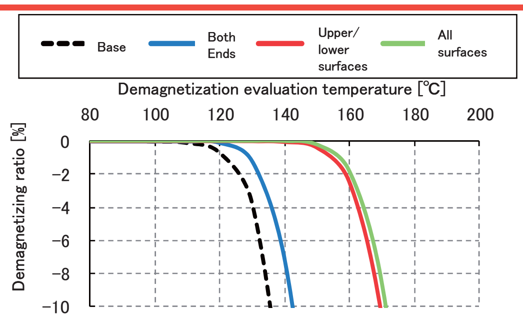

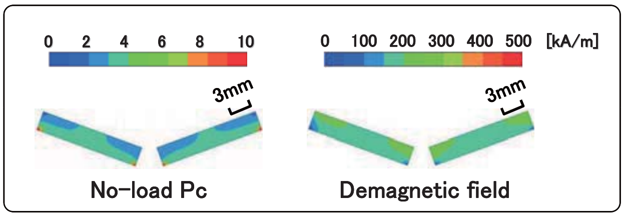

	Base material	Dy diffusion material		
		Both ends	Upper and lower planes	All surfaces
⊿HcJ distribution 0 560 [kA/m]				
Br reduction rate distribution during 2% demagnetization 0 10 [%]	(124℃)	(131℃)	(158℃)	(160℃)

( ) : 2% demagnetizing temperature

+24[℃] −3[℃]

- With Dy diffusion in only the ends, there isn't much benefit from demagnetization heat resistance improvement.
- The benefit from upper/lower plane or circumference diffusion demagnetization heat resistance is large
- The difference in demagnetization heat resistance between upper/lower plane and circumference distribution is 3℃ (2.75mm thickness)

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Effects From Magnet Thickness and the Dy Diffusion Surface

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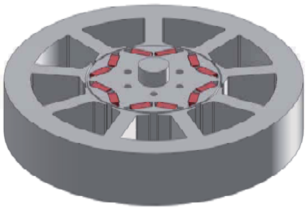
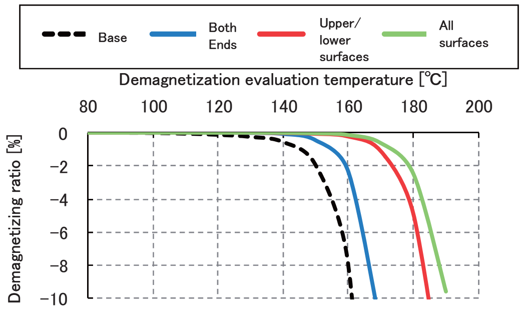
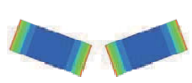
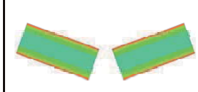
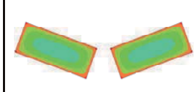
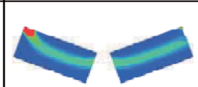
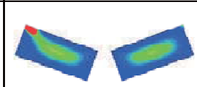
Analysis that changes the magnet thickness of an IPM motor used for analysis precision verification

Motor size: ϕ175×35
Magnet dimensions: 5.0(M)×11.8×35



Analysis model



	Base material	Dy diffusion material		
		Both ends	Upper and lower planes	All surfaces
⊿HcJ distribution 0 560 [kA/m]				
Br reduction rate distribution during 2% demagnetization 0 10 [%]	 (150℃)	 (158℃)	 (172℃)	 (177℃)

( ) : 2% demagnetization temperature

+22 [℃] −5 [℃]

■ Even if the thickness is 5mm, the difference in demagnetization heat resistance between upper/lower surfaces and all surfaces is 5℃.

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Design Example (IPM Motor)

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【Motor specs】

External diameter ϕ : 110[mm]
Rated current density : 5[A/mm^2]
torque : 2.39[Nm]
rotation : 6000[rpm] (Base rotations)

Max. current density : 10[A/mm^2]
torque : 4.53[Nm]

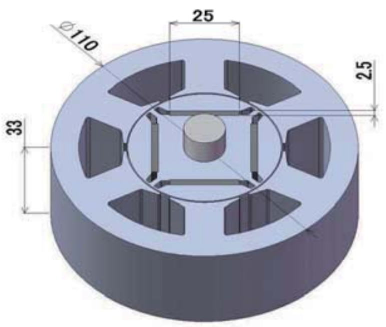
Max. line voltage : 160[V]

Demagnetizing ratio: 140℃ @ 10 [A/mm^2], β=90° with torque reduction below 1%

【A motor using normal materials】

Motor body : ϕ 110×33[mm]
Magnet material : NMX-43SH
(Br=1.305[T], HcJ=1671[kA/m])
Magnet dimensions: 2.5(M)×25×33 [mm]

Rated torque : 2.39 [Nm]
Max. torque : 4.53 [Nm]
Demagnetizing ratio: 0.0 [%]



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Design Example (IPM Motor)

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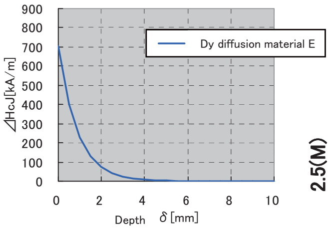
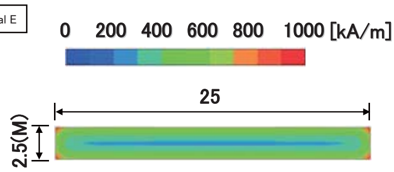
【Applied diffusion conditions】

- Calculate with Dy diffusion material E' s diffusion conditions
- Dy diffusion from all surfaces
- The magnet section geometry is the same as a normal material



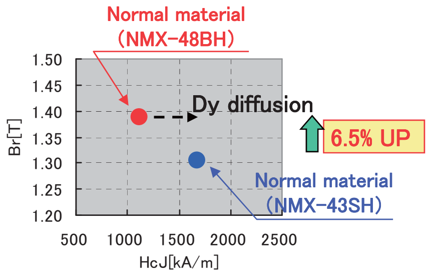
δ−⊿HcJ properties

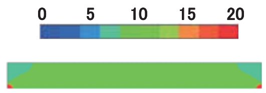


⊿HcJ distribution

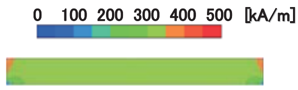
【Base material selection】

Make the base material NMX−48BH (Br=1.390[T], HcJ=1114[kA/m]) from the demagnetization specifications.

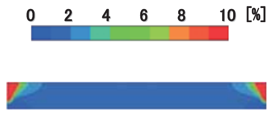




No−load Pc



Demagnetic field
(10[A/mm²], β =90[deg.])



Normal material: NMX−43SH
(160℃)

NMX−48BH+Dy diffusion
(151℃)
Br reduction rate during 2% demagnetization
(10[A/mm²], β =90[deg.])

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Magnet Weight Reduction Effects

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Magnet weight reduction model

Axial length reduction from increased Br
(The magnet cross−section geometry is the same)

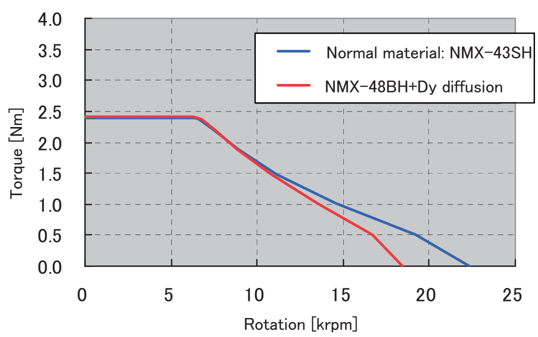
Rated current density: 5[A/mm²]

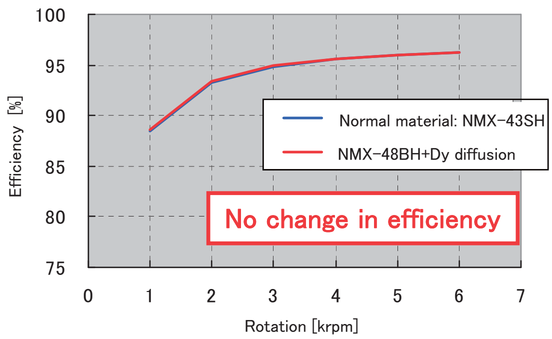
Normal material (NMX−43SH)
Axial length = 33[mm]

→

NMX−48BH+Dy diffusion
Axial length = 32[mm]

Axial length reduction amount: −3%
(= Magnet usage weight reduction amount)





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Results of Increased Efficiency

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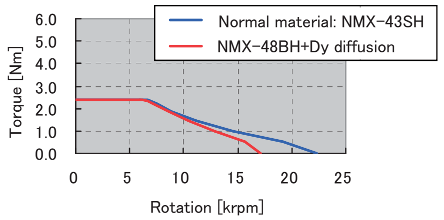
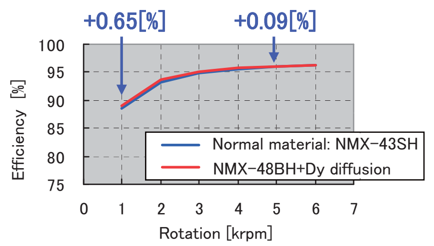
More efficient model

Current (iron loss) reduction from increased Br
(Axial length is the same)

Rated torque (2.39[Nm])

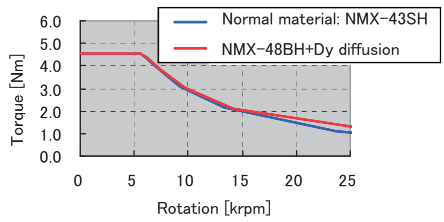
Normal material (NMX-43SH) 5[A/mm²] → NMX-48BH+Dy diffusion 4.8[A/mm²]

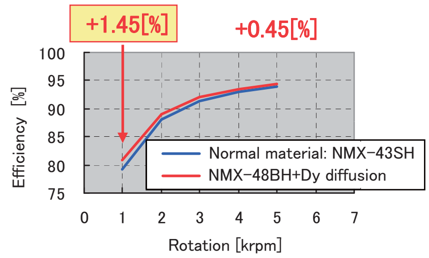




Max. torque (4.53[Nm])

Normal material (NMX-43SH) 10[A/mm²] → NMX-48BH+Dy diffusion 9.6[A/mm²]





■ Effects from increased efficiency are big in areas with low speed and large current.

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Loss Comparison, Increased Efficiency Model

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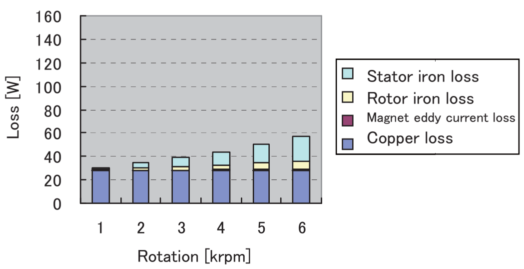
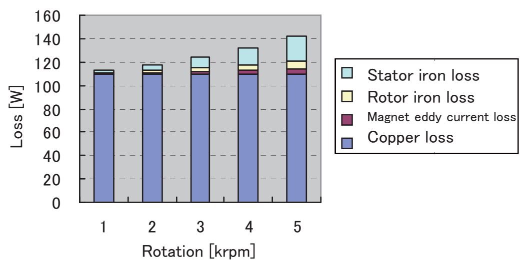
Increased efficiency model

Current (iron loss) reduction from increased Br
(Axial length is the same)

Rated torque (2.39[Nm])



Max. torque (4.53[Nm])



■ Effects are big in areas where the copper loss ratio is large compared to the total loss.

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In Conclusion

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■ Developing demagnetization analysis methods for motors that use Dy diffusion magnets

1. Calculate the Dy introduction amount distribution, and convert it to the coercive force increase amount ⊿HcJ

＜Method 1.＞

Compute the Dy introduction amount properties from each diffusion surface and add them up (Mainly used in 2D analysis)

＜Method 2.＞

Use the diffusion flux conditions and concentration dependence diffusion coefficients to calculate the Dy introduction amount distribution with Fick's diffusion equation (Mainly used in 3D analysis)

2. Demagnetization analysis that accounts for the temperature coefficient of the coercive force, and not just the coercive force distribution

Motor demagnetizing ratio analysis accuracy is within 10℃ for 2% demagnetization temperature

■ Comparing the Dy diffusion plane and the motor demagnetizing properties

- Even when using Dy diffusion to increase HcJ in places that are demagnetized with normal materials, effects from improvements in motor demagnetization heat resistance are small.
- Dy diffusion from the magnetic pole surfaces or the all surfaces produces large effects from improvements in motor demagnetization heat resistance.
(In model studies, the difference in demagnetization heat resistance between magnetic pole surfaces and all surfaces diffusion is about 5℃ in a thickness of 5mm.)

■ Studying outcomes when applied to an IPM motor

- When setting the demagnetization heat resistance, we were able to use material that was 6.5% higher in Br with Dy diffused magnets when compared to normal material.
→We were able to confirm the outcomes of reducing magnetic weight and of improving efficiency.

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