

High performance HREE-free hot-deformed Nd-Fe-B magnets by Nd-Cu grain boundary diffusion

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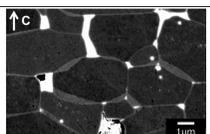
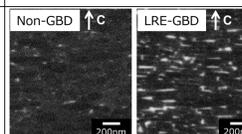
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Introduction

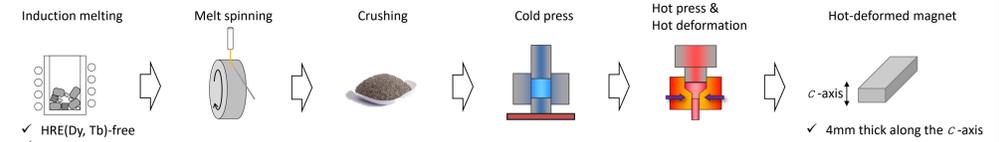
Nd-Fe-B magnets used in EVs require high coercivity to withstand high temperatures and high antimagnetic fields. One of the methods to improve the coercivity of hot-deformed Nd-Fe-B magnets without using heavy rare earth elements such as Dy and Tb is the grain boundary diffusion (GBD) process using light rare earth elements. In this study, we fabricated high-performance HREE-free Nd-Fe-B hot deformed magnet which is adequate for usage of EVs by diffusing Nd-Cu alloy into a hot-deformed magnet with low rare earth content.

Comparison between heavy rare-earth and light rare-earth grain boundary diffusion processes

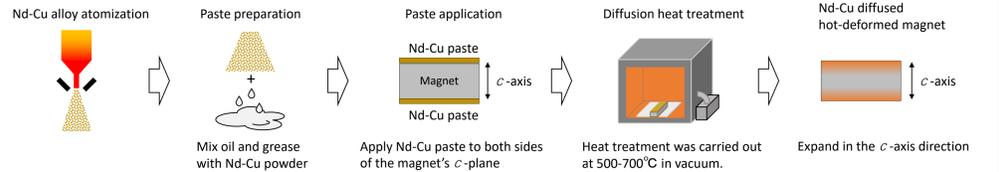
	HRE-GBD	LRE-GBD
Microstructure		
Mainly Applied Magnet Type	Sintered magnet	Hot-deformed magnet
Mechanism of Coercivity Enhancement	Formation of Dy/Tb-rich shells on the surface of Nd ₂ Fe ₁₄ B grains	The infiltrated eutectic alloy such as Nd-Cu widening the grain boundary phase, weakening the magnetic interaction between the Nd ₂ Fe ₁₄ B grains
Key Features	<ul style="list-style-type: none"> Excellent high-temperature stability Heat treatment at 800-1000°C 	<ul style="list-style-type: none"> HRE(Dy, Tb)-free Low cost Heat treatment at 500-700°C

Experimental Details

Fabrication of Nd-Fe-B hot-deformed magnets



Nd-Cu grain boundary diffusion process



Evaluation methods

Magnetic property evaluation : DC fluxmeter, Pulsed high-field magnetometer
Microstructural analysis : FE-SEM
Analysis of Nd and Cu concentration profile in the diffusion direction : EPMA

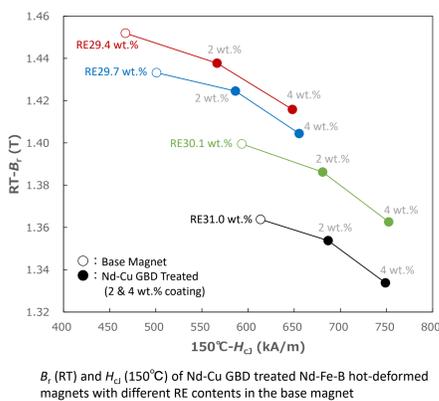
Effect of RE Content of Base Magnet on Magnetic Properties after GBD

Heavy-rare-earth-free hot-deformed magnets with various RE contents were fabricated followed by Nd-Cu GBD. Magnets with lower RE content in the base magnet exhibited a more favorable balance between remanence (B_r) and coercivity (H_{cJ}) after GBD. This is attributed to the following two reasons:

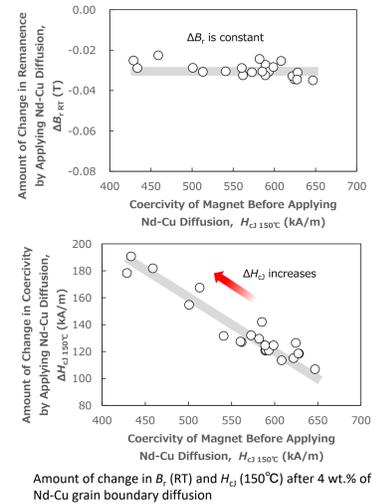
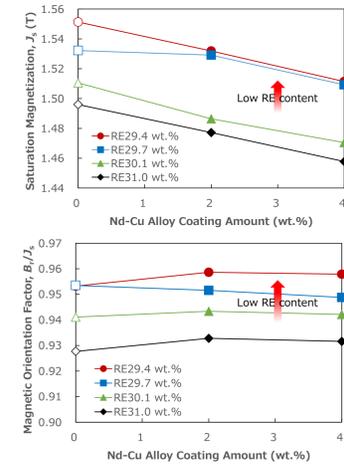
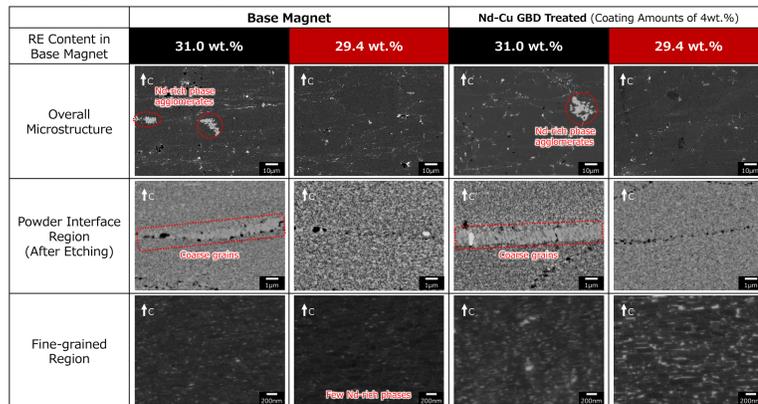
- ✓ Lower rare-earth content in the base magnet reduces the formation of agglomerated Nd-rich phases and suppresses the grain growth, thereby improving the magnetic orientation factor. This feature is maintained even after Nd-Cu GBD.

- ✓ Although the decrease in B_r due to GBD is relatively constant regardless of the initial H_{cJ} of the base magnet, the increase in coercivity is more pronounced in magnets with lower initial H_{cJ} .

These findings indicate that base magnets with lower RE content and higher B_r are advantageous for achieving better overall magnetic performance, making them well-suited for maximizing the benefits of the Nd-Cu GBD process.

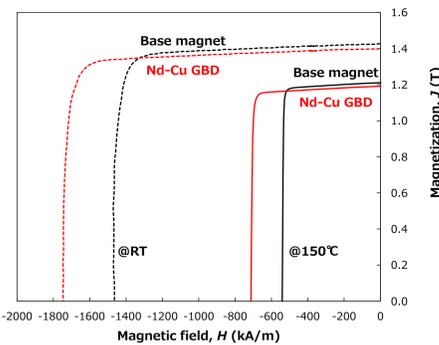


FE-SEM images of Nd-Fe-B base magnets with Initial RE contents of 31.0 wt.% and 29.4 wt.%, before and after Nd-Cu GBD treatment

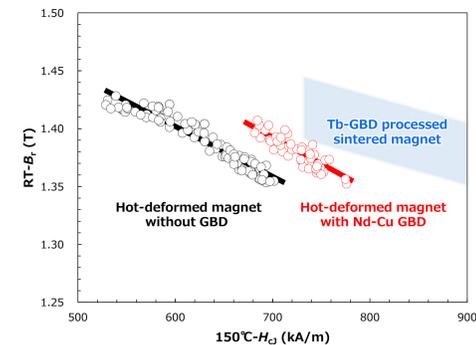


Achieved Magnetic Properties

A hot-deformed magnet with B_r of 1.42 T at room temperature, H_{cJ} of 541 kA/m at 150 °C, and H_k/H_{cJ} of 98% at 150 °C, containing 29.3 wt.% of RE elements, was used as the base magnet. After GBD with 4 wt.% of Nd-Cu alloy, the H_{cJ} of the magnet was enhanced to 713 kA/m at 150 °C while maintaining B_r of 1.40 T at room temperature without the use of HREs. The H_k/H_{cJ} maintained at 97% at 150 °C, which is adequate for usage of EVs.



Demagnetization curves of a base magnet with low rare-earth content before and after Nd-Cu grain boundary diffusion



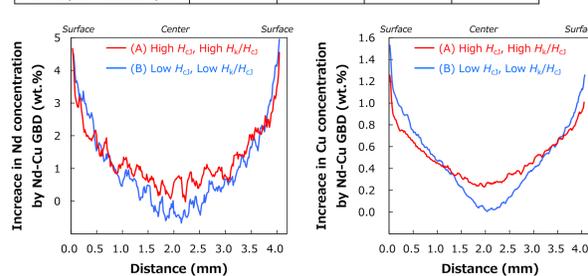
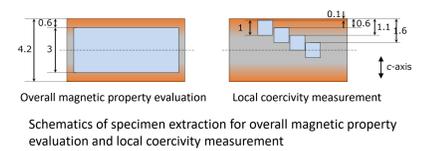
Comparison of B_r (RT) and H_{cJ} (150°C) between Nd-Cu GBD-treated and non-treated hot-deformed magnets

Coercivity Gradient of Samples

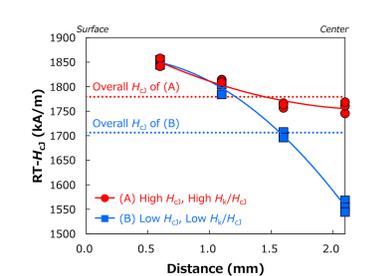
The sample exhibiting high coercivity and squareness shows a small difference in Nd and Cu concentrations between the coated surface and the center, while a small difference in local coercivity between the surface and the center. To further improve coercivity and squareness, it is essential to increase the Nd concentration at the center and to reduce the coercivity gradient.

Overall magnetic properties of samples subjected to Nd and Cu concentration profiling and partial coercivity measurements

	B_r (T)	H_{cJ} (kA/m)	$H_{cJ150°C}$ (kA/m)	$H_k/H_{cJ150°C}$ (%)
(A) High-coercivity, high-squareness sample	1.37	1780	729	97
(B) Low-coercivity, low-squareness sample	1.39	1706	688	93



Changes in Nd and Cu concentrations with distance from the coating surface in high- and low-squareness Nd-Cu GBD treated hot-deformed magnets



Local coercivity with distance from the coating surface in high- and low-squareness Nd-Cu GBD treated hot-deformed magnets

Conclusion and Outlook

Conclusion

By using a base magnet with low RE composition, we successfully fabricated a magnet with H_{cJ} of 713 kA/m (150 °C), H_k/H_{cJ} ratio of 97% (150 °C), and B_r of 1.40 T (RT), without the use of HREs.

- ✓ A base magnet with low RE exhibits high magnetic alignment and a uniform microstructure, and its degree of orientation is maintained even after Nd-Cu grain boundary diffusion.
- ✓ The enhancement in coercivity resulting from the Nd-Cu GBD becomes more pronounced as the coercivity of the base magnet decreases.

Outlook

To further enhance coercivity and squareness, it is essential to increase the concentrations of Nd and Cu in the central region of the magnet and to minimize the coercivity gradient between the region near the coated surface and the center of the magnet.

To achieve this, it is necessary to optimize the base magnet composition, the diffusion alloy composition, and the diffusion conditions.