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EFFECT OF Ga ADDITION ON Nd-Dy-Fe-Co-B SINTERED MAGNETS

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To elucidate the effects of Ga addition on Nd-Dy-Fe-Co-B sintered magnets, the temperature dependence of coercivity and changes in the Nd rich phase were studied. The 2nd ferrromagnetic phase was observed in Co substituted sintered magnets. The Co containing Nd rich phase, $(Nd,Dy)_3(Co,Fe)$, is changed to $(Nd,Dy)_5(Fe,Co,Ga)_3$ by the Ga addition. iHc and Tc increase and σ_s decreases with increasing Ga content for synthetic $(Nd_{0.9}Dy_{0.1})_5(Fe_{0.2}Co_{0.8-u}Ga_u)_3(0\leq u\leq 0.6)$ alloys. This change of magnetic properties of $(Nd,Dy)_5(Fe,Co,Ga)_3$ seems to be the reason for coercivity enhancement.

1. INTRODUCTION

Coercivity enhancement by Ga addition for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08})_{5.5}$ sintered magnets was studied and a 2nd ferromagnetic phase was observed in the temperature dependence of iHc and AC permeability near Tc[1,2]. Room temperatue iHc increases by 25% from about 22kOe with Ga addition up to u=0.015 for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$ sintered magnets. However, room temperature anisotropy field (H_A) does not increase enough to explain the iHc enhancement by Ga addition, even though 70% of added Ga was found in the 2/14/1 matrix.

In this paper, to understand why Ga addition enhances coercivity, temperature dependence of iHc near Tc and magnetic properties of the 2nd ferromagnetic phase were investigated.

2. EXPERIMENTAL

Sintered magnets were prepared by the conventinal powder metallurgy process and heat treated according to the pattern described previously[3]. The iHc near Tc was measured with a Vibrating Sample Magnetometer (VSM) after magnetization in a 14kOe applied field. For determining the temperature coefficient of iHc between 25 and 120℃, magnetic properties at 25 and 120℃ were measured with a Recording Fluxmeter and VSM, respectively, after magnetization in a 25kOe applied field. EDX/SEM analysis was carried out for a polished surface perpendicular to the alignment direction.

3. RESULTS

Variation of iHc at 25 and 120℃ and the temperature coefficient of iHc(β, in the temperature range of 25～120℃) with Ga content for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}(0\leq u\leq 0.030)$ sintered magnet is shown in Fig. 1. The T_2 temperature for each alloy was determined to achieve the lowest irreversible loss(Pc=2) at elevated temperatures. iHc increases up to 0.015 and decreases with increasing Ga content. β decreased with

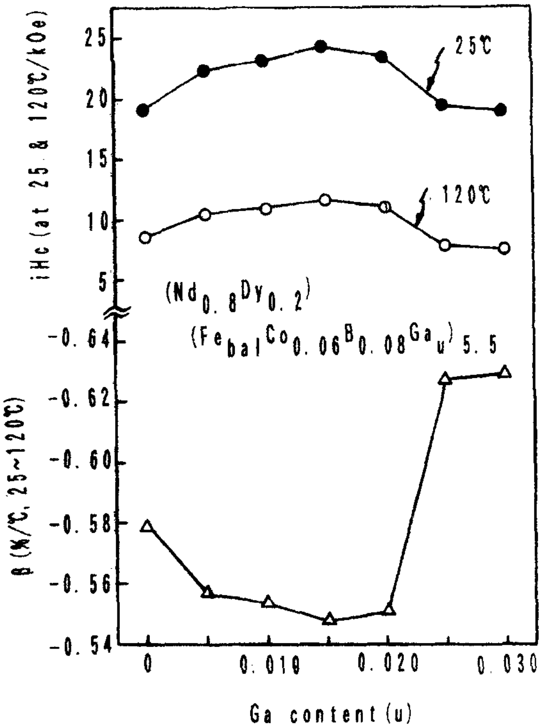

Fig. 1. Variation of iHc(at 25 and 120℃) and temperature coefficient(β) with Ga content for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$ $(0 \leq u \leq 0.030)$ sintered magnets.

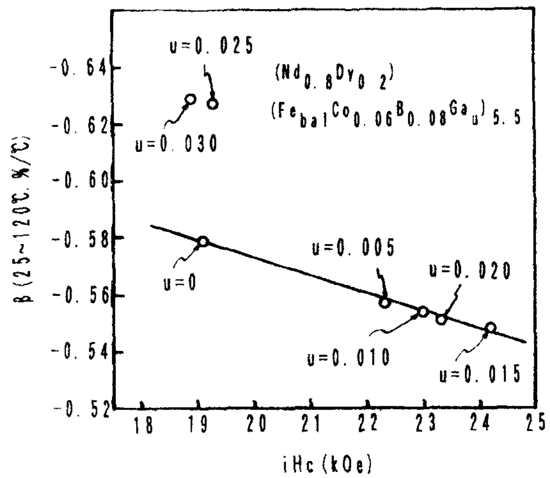

Fig. 2. Variation of β with iHc for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$ $(0 \leq u \leq 0.030)$ sintered magnets.

increasing iHc up to u=0.015. The lower β is obtained in the specimen with higher iHc which is attributed to Ga addition as shown in Fig. 2. However, too much Ga addition decreases iHc and increases β, for example, u=0.025 and 0.030(see Fig. 2). Already, it was observed that the room temperature H_A was not enhanced by Ga addition as was iHc[4). However, there is a possibility that Ga addition changes the temperature dependence of H_A. The temperature dependence of H_A for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$(u=0 and 0.015) is shown in Fig. 3. No clear difference in the temperature dependence of H_A for sintered magnets with and without Ga addition is observed. There is also no difference in the grain size of the 2/14/1 matrix which

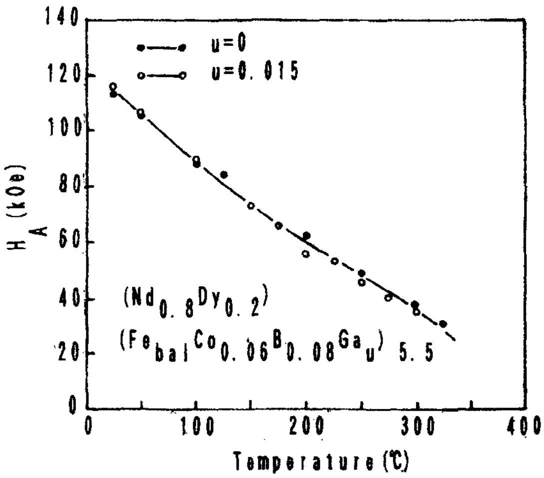

Fig. 3. Temperature dependence of H_A for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$(u=0 and 0.015) sintered magnets.

contains 70% of the added Ga[4).

Fig. 4 shows the variation of iHc near Tc for(1)$Nd(Fe_{0.92}B_{0.08})_{5.4}$, (2)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08})_{5.5}$, (3)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08})_{6.2}$ and(4)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_{0.015})_{5.5}$ sintered magnets. For Nd-Fe-B ternary sintered magnet, Tc of the matrix is 310℃ and no 2nd ferromagnetic phase was observed. Also, for high z magnet, alloy (3)(z=TM/RE, TM:Fe+Co+B+Ga, RE:Nd+Dy), Tc of the matrix is 380℃

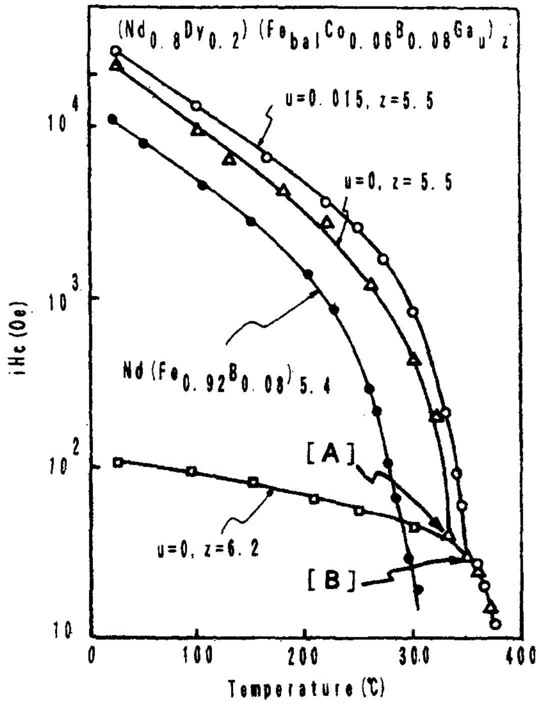

Fig. 4. Variation of iHc near Tc for (1)$Nd(Fe_{0.92}B_{0.08})_{5.4}$, (2)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08})_{5.5}$, (3)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08})_{6.2}$ and (4)$(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_{0.015})_{5.5}$ sintered magnets.

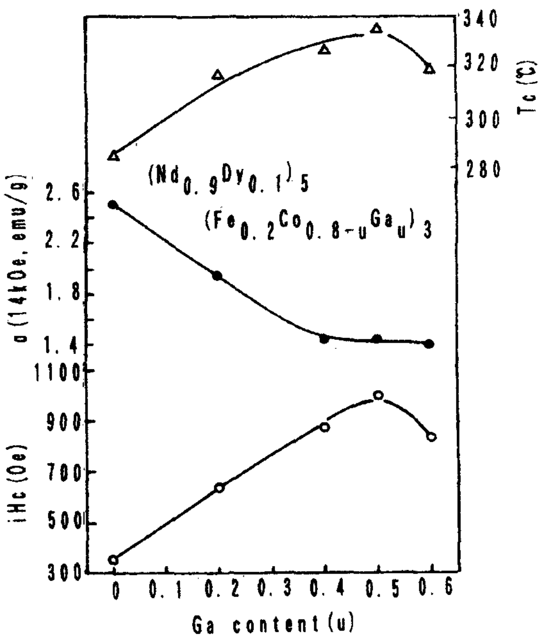

Fig. 5. Variation of σ_s, iHc and Tc with Ga content for $(Nd_{0.9}Dy_{0.1})_5(Fe_{0.2}Co_{0.8-u}Ga_u)_3$ ($0 \leq u \leq 0.6$) alloys.

and no 2nd ferromagnetic phase is observed. For the Co substituted sintered magnets with high iHc, alloys (2) and (4), Tc of the matrix and 2nd ferromagnetic phase are observed. The point of intersection of two iHc vs T curves for alloys (2) and (3), which is 330℃ (point [A] in Fig.4), is thought to be the Tc of the 2nd ferromagnetic phase. Tc's of the matrix are 380 and 385℃ for alloys (2) and (4), respectively. Tc's of the 2nd magnetic phase are 330 and 350℃ (point [B] in Fig. 4) for alloys (2) and (4), respectively.

Ga also exists in the boundary phases, namely Nd rich phases. The results of EDX/SEM analysis is shown in Table 1. There are 2 kinds of Nd rich phases, Co free and Co containing Nd rich phase. The Co containing Nd rich phases is $(Nd,Dy)_3(Co,Fe)$. This phase

Table 1. Phase analysis with EDX/SEM for $(Nd_{0.8}Dy_{0.2})(Fe_{bal}Co_{0.06}B_{0.08}Ga_u)_{5.5}$ (u=0 and 0.015) sintered magnets. (at.%)

u	Phase	Nd	Dy	Fe	Co	Ga	Remarks
0	2/14/1	8.5	2.9	81.0	7.6	---	
	1/4/4	13.6	6.2	74.6	5.6	---	
	Nd rich	74.6	14.4	11.0	---	---	Co free Nd rich
	Nd rich	71.4	2.6	5.7	20.3	---	Co containing Nd rich(3/1)
0.015	2/14/1	8.6	3.8	80.0	7.2	0.2	
	1/4/4	13.3	6.6	74.5	5.6	---	
	Nd rich	70.1	14.8	15.1	---	---	Co free Nd rich
	Nd rich	57.1	4.4	7.2	7.2	24.1	Co containing Nd rich(5/3)

Table 2. Curie temperatures(Tc) of matrix and the 2nd ferromagnetic phases for R-TM-B sintered magnets.

Composition	Matrix and its Tc	The 2nd ferromagnetic phase and its Tc
$Nd(Fe_{0.92}B_{0.08})_{5.4}$	$Nd_2Fe_{14}B$ Tc=310℃	none
$(Nd_{0.8}Dy_{0.2})(Fe_{0.86}Co_{0.06}B_{0.08})_{5.5}$	$(Nd,Dy)_2(Fe,Co)_{14}B$ Tc=380℃	$(Nd,Dy)_3(Co,Fe)$ Tc=330℃
$(Nd_{0.8}Dy_{0.2})(Fe_{0.845}Co_{0.06}B_{0.08}Ga_{0.015})_{5.5}$	$(Nd,Dy)_2(Fe,Co,Ga)_{14}B$ Tc=385℃	$(Nd,Dy)_5(Ga,Co,Fe)_3$ Tc=350℃

is changed to $(Nd,Dy)_5(Ga,Co,Fe)_3$[5] by Ga addition. The Ga is condensed in the Co containing Nd rich 5/3 phases. The Tc of the matrix and the 2nd ferromagnetic phases for R-TM-B sintered magnets are tabulated in Table 2. Using the results of EDX/SEM analysis, Co containing alloys were arc melted. The variation of magnetic properties and Tc with Ga content for $(Nd_{0.9}Dy_{0.1})_5(Fe_{0.2}Co_{0.8-u}Ga_u)_3(0 \leq u \leq 0.6)$ alloys is shown in Fig. 5. iHc and Tc increase with increasing Ga content with the maximum at u=0.5. However, σ_s(magnetization at 14kOe) decreses linearly up to u=0.4, and then keeps constant. Ga addition to the Co containing Nd rich phase decreases σ_s and increases Tc. This change of magnetic properties of the Co containing Nd rich phase seems to be the reason for coercivity enhancement of sintered magnets. The co-existing of matrix and $(Nd,Dy)_5(Ga,Co,Fe)_3$ phases and some pinning force defined at the interface of these phases seems to be the origin of the high iHc. Another possibility is that the decrease in σ_s of the 5/3 phase suppresses its behavior as nucleation sites.

4. SUMMARY

The effect of Ga addition for Nd-Dy-Fe-Co-B sintered magnets was studied to understand the coercivity enhancement. The Co containing Nd rich phase, $(Nd,Dy)_3(Co,Fe)$, is observed in the Nd-Dy-Fe-Co-B sintered magnets. This phase is changed to $(Nd,Dy)_5(Ga,Co,Fe)_3$ by Ga addition. Tc's of the 2nd ferromagnetic phases were observed at 330℃ and 350℃ in the temperature dependence of iHc near Tc for sintered magnets with and without Ga addition, respectively. So, the 2nd ferromagnetic phase should be $(Nd,Dy)_3(Co,Fe)$and $(Nd,Dy)_5(Ga,Co,Fe)_3$ for Ga free and Ga containing sintered magnets. Tc increases and σ_s decreases with increasing Ga content for the $(Nd,Dy)_5(Fe,Co,Ga)_3$. This change of the magnetic properties of the Co containing Nd rich phase seems to contribute to the coercivity enhancement of Nd-Dy-Fe-Co-B-Ga sintered magnets.

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