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INFLUENCE OF B AND Nd CONTENT ON THE MAGNETIC PROPERTIES OF α-Fe BASED NdFeB MAGNETS WITH ULTRAFINE GRAINS

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Abstract-The influence of Nd and B contents on the magnetic properties and structures of α-Fe based Nd-(Fe,Co)-B-Mo-Cu alloys was investigated. $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ and $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ amorphous alloys prepared by rapid solidification process were crystallized to form nanocrystalline structure. The increase of B content in $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ nanocrystalline resulted in the change of structure of soft phase in the sequence of α-Fe →α-Fe+Fe_3B→Fe_3B. The coercivitis of the alloys were increased with increasing B content and was 263 kA/m at x=18. On the contrary, the remanence has shown an opposite trends. The increase of Nd content in $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ nanocrystalline containing α-Fe as main phase had no effect on the structure and improved coercivity up to 256 kA/m. However, the remanence was decreased from 1.4 T to 1.15 T according to the increase of Nd content.

I. INTRODUCTION

Recently, it has been reported that Nd-Fe-B nanocrystallines with a low Nd content of about 4 at% have high remanence with good corrosion resistance corrosion and economical merits in comparison with $Nd_2Fe_{14}B$-based magnets[1,2]. The alloys are microstructurally composed of two phases, a magnetically soft Fe_3B as main phase and a magnetically hard $Nd_2Fe_{14}B$ as secondary phase. It is known that both Fe_3B and $Nd_2Fe_{14}B$ grains interact on the interface like a mechanical spring and this behavior plays an important role in the magnetization process to show good hard magnetic properties[3]. The improvement of magnetic properties of Nd-Fe-B alloys with low Nd content may be more effective if the remanence is increased by the replacement of soft magnetic phase with high saturation magnetization or/and the reduction of the mean grain size of both soft and hard magnetic phases. In this work, new type Nd-Fe-B magnets with low Nd content composed of both α-Fe as main phase and $Nd_2Fe_{14}B$ as secondary phase were fabricated and influence of the change of B and Nd content on the magnetic properties and structures of the alloys was investigated.

II. EXPERIMENTAL

$Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$(x=6, 10, 14, 18) and $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$(x=3, 4, 4.5, 5) and amorphous flakes were prepared by rapid quenching technique with Cu single roll. Heat treatments were carried out in the range between 600 ℃ and 720 ℃ for 10 minutes in a vacuum of 10^{-4} Torr. The microstructures and phases of the crystallized alloys were analyzed by a transmission electron microscope and a x-ray diffractometer. The magnetic properties were measured by a vibrating sample magnetometer under a magnetic field of 716 kA/m(9 kOe) after premagnetizing in a pulsed field of 8 T.

III. RESULTS AND DISCUSSION

R. Hasegawa[4] had already reported that in the crystallization of amorhpous Fe-B alloys the first crystallization phase depended on B content. For example, α-Fe and Fe_3B as the first crystallized phase in the amorphous matrix were emerged in case of the B content below 14 at.% and 25 at.%, respectively. The report suggested that the first crystallization phase of the Nd-Fe-B amorphous flakes with low Nd content might be controlled by B content if the first crystallization phase was soft magnetic phase. Fig. 1 shows the x-ray diffraction patterns for the optimally annealed $Nd_4Fe_{85.5}B_{10.5}$ and $Nd_4Fe_{77.5}B_{18.5}$ alloys. $Nd_4Fe_{77.5}B_{18.5}$

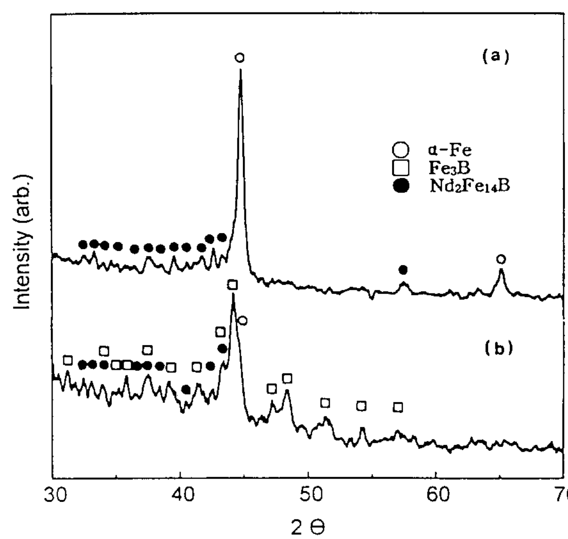

Fig. 1 X-ray diffraction patterns of the optimally annealed $Nd_4Fe_{85.5}B_{10.5}$ and $Nd_4Fe_{77.5}B_{18.5}$ alloy

alloy has shown the soft phase of Fe_3B, a small amount of α-Fe and the secondary phase of $Nd_2Fe_{14}B$ as had been already reported by R. Coehoorn[1]. On the other hand, $Nd_4Fe_{85.5}B_{10.5}$ alloy has shown only two sets of peaks, α-Fe and $Nd_2Fe_{14}B$. The x-ray analysis suggests that the decrease of B content in $Nd_4Fe_{77.5}B_{18.5}$ alloy results in the change of soft magnetic phase like a crystallization process of Fe-B amorphous alloys. On the basis of this analysis we have tried to improve the magnetic properties of the alloy by increasing the nucleation rate of α-Fe and supressing the growth rate of α-Fe. Fig. 2 shows the composition dependence of coercivities on annealing temperature for the $Nd_4Fe_{85.5}B_{10.5}$, $Nd_4Fe_{82}B_{10}Mo_3Cu_1$, and $Nd_4Fe_{74}Co_8B_{10}Mo_3Cu_1$ alloys.

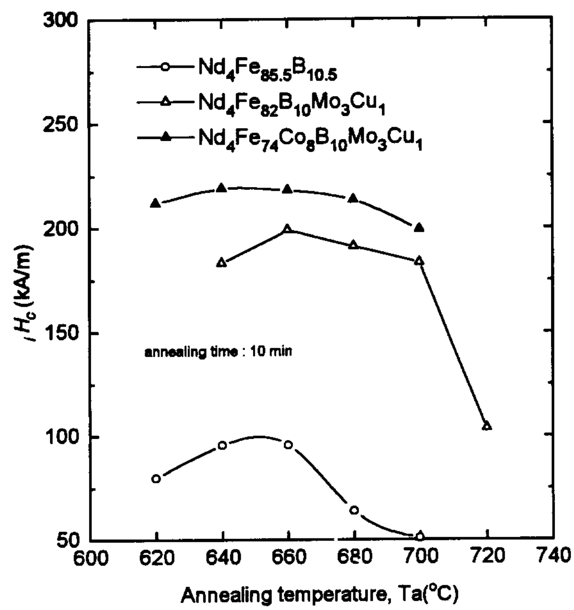

Fig. 2 Coercivities of $Nd_4Fe_{85.5}B_{10.5}$, $Nd_4Fe_{82}B_{10}Mo_3Cu_1$ and $Nd_4Fe_{74}Co_8B_{10}Mo_3Cu_1$ alloys as a function of annealing temperature

The addition of Mo and Cu to $Nd_4Fe_{85.5}B_{10.5}$ considerably increases the coercivities to 207 kA/m. It is considered that the Mo, Cu-additives strongly act on the refinement of mean grain size. The similar process to experimental trial for the nanocrystallization of magnetic materials has been already reported by Y. Yoshizawa[5]. Futhermore, the substitution of 8 at.% Co for Fe increases coercivity up to 219 kA/m at optimum annealing condition. We have confirmed that the optimally annealed $Nd_4Fe_{74}Co_8B_{10}Mo_3Cu_1$ flakes composed of only two phases, α-Fe as main phase and $Nd_2Fe_{14}B$ as secondary phase, and their mean grain size were ultrafine. The remanence, coercivity and energy product of the alloy were 1.4 T, 219 kA/m, and 104 kJ/m^3 respectively. The investigation on the change of structure and magnetic properties of $Nd_4Fe_{74}Co_8B_{10}Mo_3Cu_1$ alloy according to the increase of B content is also interesting. Fig. 3 shows the coercivity of $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ melt spun alloys as a function of annealing temperature.

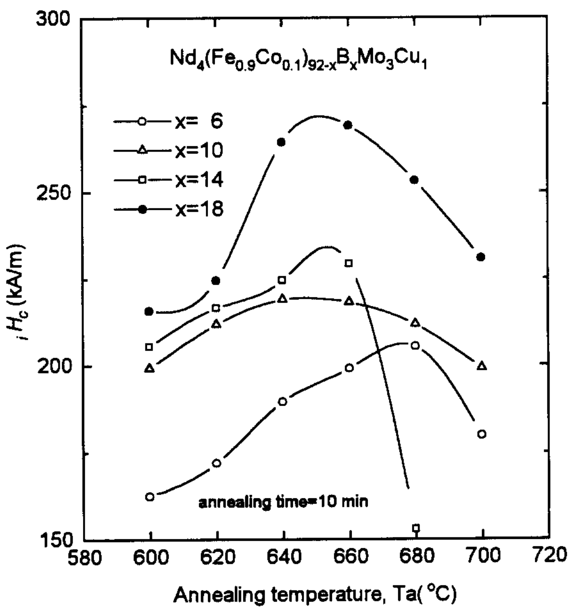

Fig. 3 Coercivities of $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ alloys as a function of annealing temperature

The coercivity of the alloy increases with the increase of B content and shows 264 kA/m at x=18. Fig. 4 is TEM micrographs of optimally annealed (a) $Nd_4(Fe_{0.9}Co_{0.1})_{82}B_{10}Mo_3Cu_1$ and (b) $Nd_4(Fe_{0.9}Co_{0.1})_{74}B_{18}$ Mo_3Cu_1 alloys. It shows that the increase of B content results in the decrease of mean grain size. Moreover, the mean grain size of $Nd_4(Fe_{0.9}Co_{0.1})_{74}B_{18}Mo_3Cu_1$ is smaller than that of $Nd_4Fe_{74}B_{18.5}$ as has been already reported[3]. It indicates that the addition of Mo and Cu results in the decrease of mean grain size of Fe_3B as well as α-Fe. The increase of coercivity is due to the

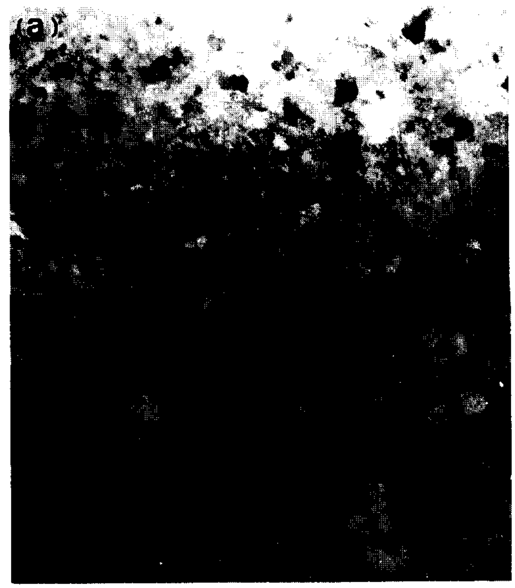

Fig. 4 TEM bright field micrographs of optimally annealed (a) $Nd_4(Fe_{0.9}Co_{0.1})_{74}B_{18}Mo_3Cu_1$ and (b)$Nd_4(Fe_{0.9}Co_{0.1})_{82}B_{10}Mo_3Cu_1$ alloys

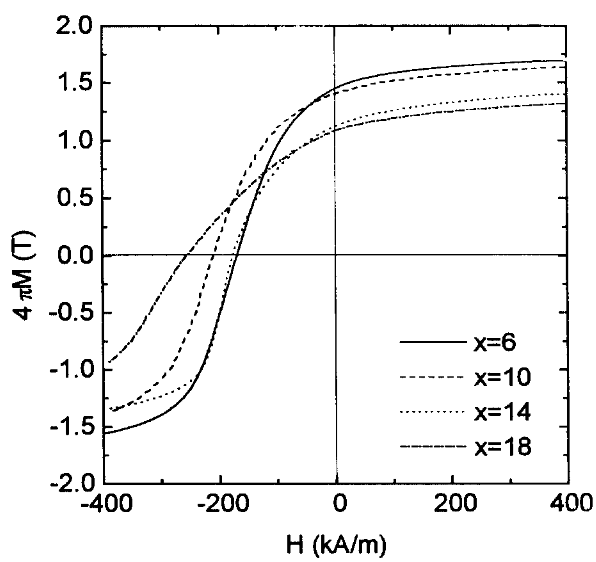

Fig. 5 The demagnetization curves of an optimally annealed $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ alloys

decrease of the mean grain size. Fig. 5 shows the demagnetization curves of optimally annealed $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ alloys. The remanence shows an opposite trend because of the decrease of saturation magnetization due to the change of soft phase from α-Fe to Fe_3B. Fig. 6 shows the analysis of x-ray diffraction patterns of optimally annealed $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ alloys. It is found that the increase of B content in the alloy system changes the structure of soft phase as follows : α-Fe→α-Fe+Fe_3B→Fe_3B.

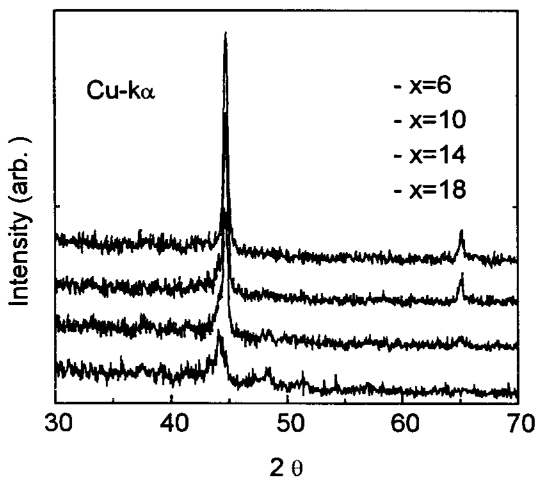

Fig. 6 The analysis of x-ray diffraction patterns of optimally annealed $Nd_4(Fe_{0.9}Co_{0.1})_{92-x}B_xMo_3Cu_1$ alloys

Fig. 7 is the coercivity of $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ alloys as a function of annealing temperature. The coercivity of the alloys increases according to the increase of Nd content. Fig. 8 is the demagnetization curves of optimally annealed $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ melt spun alloys. The remanence decreased with increasing Nd contents. The behaviors are considered that the increase of Nd content decreases the exchange interaction between α-Fe and $Nd_2Fe_{14}B$ grains and increases the exchange interaction between $Nd_2Fe_{14}B$ and $Nd_2Fe_{14}B$ grains becaues of the increase of amount of $Nd_2Fe_{14}B$ phase.

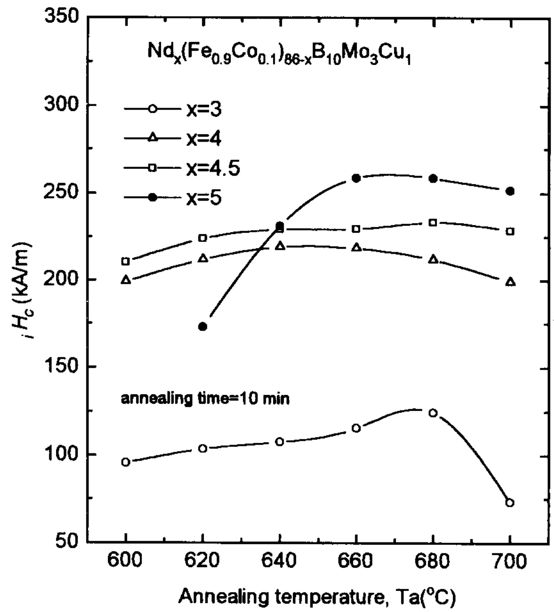

Fig. 7 Coercivities of $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ alloys as a function of annealing temperature

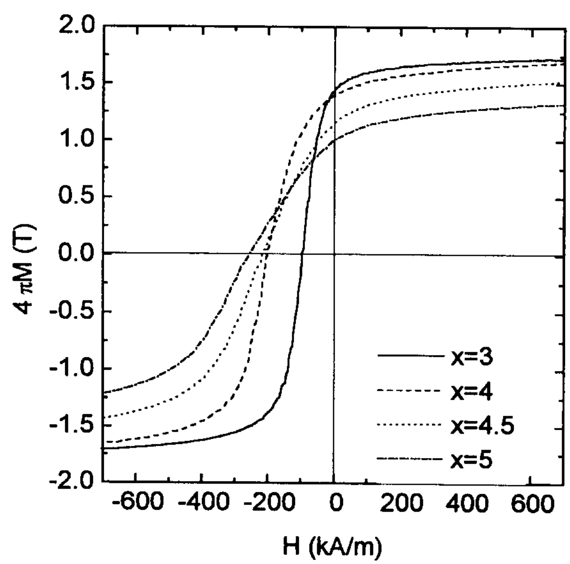

Fig. 8 The demagnetization curves of an optimally annealed $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$ alloys

IV. CONCLUSION

In the present work we have found that the change of B content in Nd-(Fe,Co)-B-Mo-B alloys with low Nd content results in the change of structure of soft phase from Fe_3B phase into α-Fe phase according to the decrease of B content. The increase of B content in the $Nd_4(Fe_{0.9}Co_{0.1})_{96-x}B_xMo_3Cu_1$ (x=6, 10, 14, 18) nanocrystalline decreases the mean grain size and increase coercivity. The increase of Nd content in $Nd_x(Fe_{0.9}Co_{0.1})_{86-x}B_{10}Mo_3Cu_1$(x=3, 4, 4.5, 5) nanocrystallines was improved coercivity because of the increase of amount of $Nd_2Fe_{14}B$ phase.

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