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Note on the effect of cobalt substitution on the hard magnetic properties of NdFeC ingot magnets

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Abstract

The effect of cobalt substitution on the hard magnetic properties of NdFeC-type ingot magnets was studied. It was found that cobalt substitution led to a significant decrease in the field strength needed to magnetize the ingot magnets. A simple production route is described which leads to an isotropic ingot magnet with ($BH_{max} = 70$ kJ m^{-3}, $B_R = 0.65$ T and $_jH_c = 800$ kA m^{-1}. The temperature coefficient ($\beta = -0.6\%$ K^{-1}) of these magnets is the same as that of sintered NdFeB-type magnets.

In a previous investigation [1] it was shown that the tetragonal $Nd_2Fe_{14}C$ phase is formed by a solid state transformation at comparatively low temperatures (less than 850 °C). This behaviour is contrary to that found in the Nd–Fe–B system where the tetragonal $Nd_2Fe_{14}B$ phase forms at a comparatively high temperature directly from the melt. We also found that in the systems $R_2Fe_{14}C_{1-x}B_x$ (R ≡ Pr, Nd) the upper limit of the temperature stability range of the tetragonal phase increases very steeply with the boron content in the range $0 \leqslant x \leqslant 0.05$. An interesting consequence of the solid state transformation is that it can be used for the generation of microstructures in annealed ingot samples, which give rise to substantial coercivities [2]. The ultimate coercivities obtained by us in annealed ingot samples of the type $Nd_2Fe_{14}C_{1-x}B_x$ were fairly large (around 1 T). The drawback of these ingot magnets is, however, the need to apply rather large magnetizing fields (more than 5 T) in order to obtain the coercivities reported [2]. In the present study we have investigated the possibility of reducing the required magnetizing field strength by substituting small amounts of cobalt for iron in these ingot materials.

Alloys of the composition $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ were prepared in an arc furnace from constituent elements which were of at least 99.9% purity. After arc melting, the alloys were wrapped in tantalum foil and sealed in evacuated quartz tubes. The annealing was performed for 3 days at various temperatures between 800 and 1100 °C. After annealing, the quartz tubes containing the sample were cooled to room temperature in air.

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The samples were magnetically characterized by means of a vibrating sample magnetometer. The phase composition was checked by powder X-ray diffraction.

The coercivities measured on pieces of the ingots annealed at various temperatures are shown in Fig. 1. The maximum applied field, without correction for demagnetization, was equal to 2 T in all cases. It can be seen from the figure that the optimal annealing temperature is between 950 and 1000 °C.

The ingots annealed at 950 and 975 °C were selected for more detailed magnetic studies. The room temperature hysteresis loop measured on the ingot annealed at 950 °C is shown in Fig. 2. The values of the magnetic induction I correspond to a density of 7.3 g cm^{-3} and a demagnetizing factor $N = \frac{1}{3}$. In Fig. 3A a comparison is made with the demagnetization curve measured on an optimized cobalt free alloy ($Nd_{16}Fe_{75}C_{8.5}B_{0.4}$ annealed for 1 day at 950 °C) after magnetizing in a field of 4.5 T. It is seen that the remanence as well as the coercivity is significantly lower than in the case of $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$. The room temperature remanences B_R obtained for two types of materials after applying various magnetizing fields H_m can be compared in Fig. 4. It is seen that the tendency to saturate occurs in lower magnetizing fields for $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ than for the cobalt free compound. Even better results were obtained for the ingot annealed at 975 °C. Results are shown in Fig. 3B, where the demagnetizing curves obtained at various temperatures can be compared with each other. The coercivity of the room temperature curve corresponds to 1.1 T. It decreases almost linearly with temperature, as shown in Fig. 5. The energy products of the two ingot magnets at room temperature are close to 70 kJ m^{-3}.

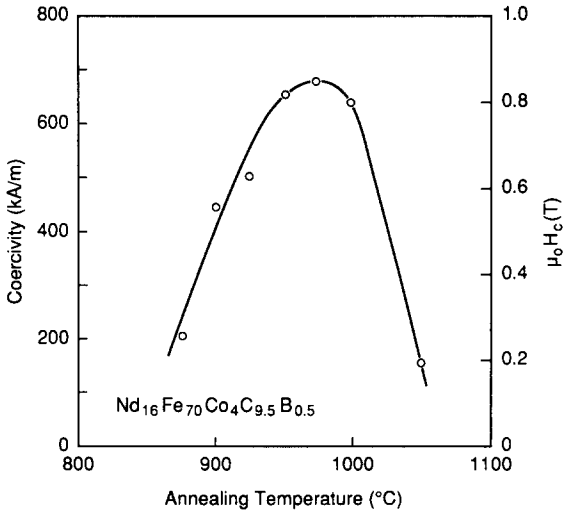

Fig. 1. Coercivity in ingot magnets as a function of the annealing temperature of the ingots.

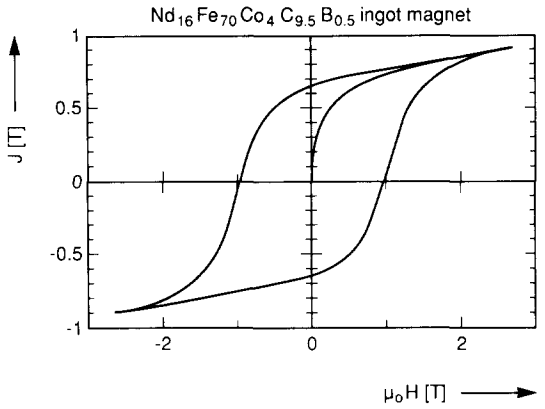

Fig. 2. Room temperature hysteresis loop of an ingot magnet of composition $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ after annealing for 3 days at 950 °C.

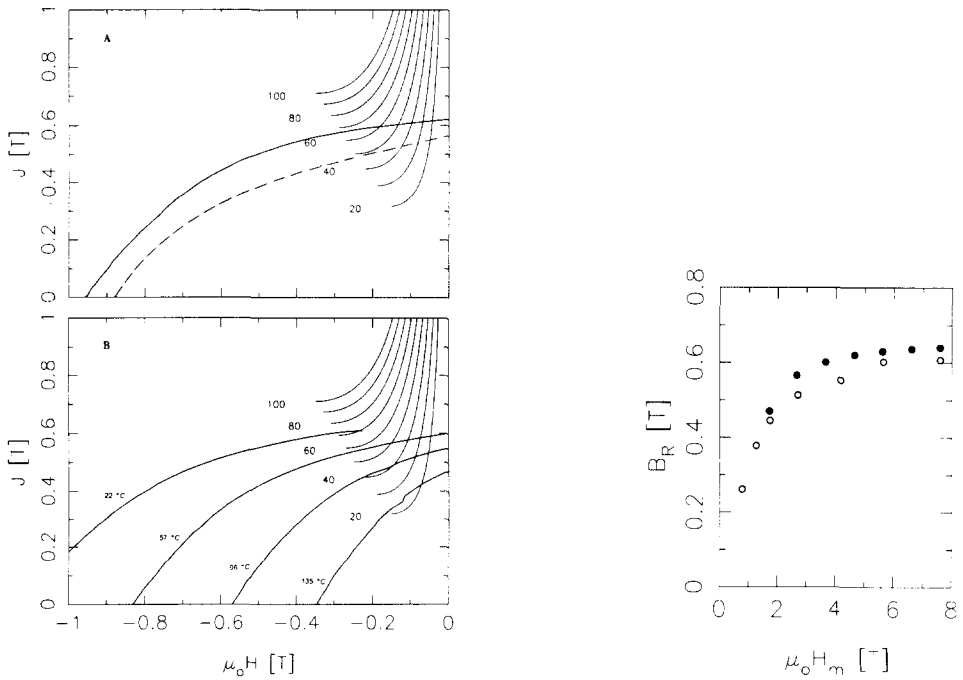

Fig. 3. Demagnetizing curves of an ingot magnet of composition $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ after annealing for (A) 3 days at 950 °C and (B) 3 days at 975 °C. The broken curve in A corresponds to an optimized cobalt-free alloy after magnetizing in the same field (4.5 T).

Fig. 4. Dependence of the room temperature remanence B_R on the magnetizing field for $Nd_{16}Fe_{75}C_{8.55}B_{0.45}$ (filled symbols) and $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ (open symbols).

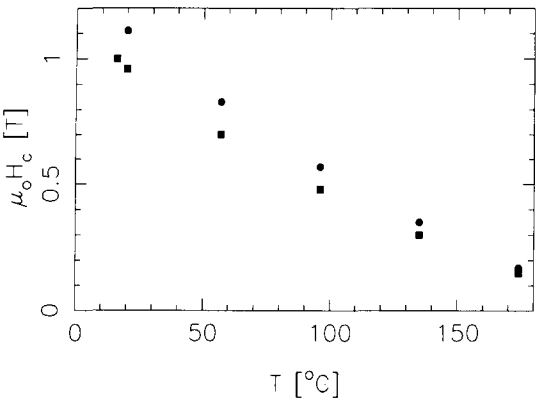

Fig. 5. Temperature dependence of two ingot magnets obtained after annealing at 950 °C (squares) and 975 °C (circles).

The results obtained in the course of the present investigation can be summarized as follows. Isotropic ingot magnets with energy products close to 70 kJ m^{-3} can be prepared from $Nd_{16}Fe_{70}Co_4C_{9.5}B_{0.5}$ by a simple annealing treatment of the ingots after casting. The room temperature coercivity of these ingots is close to 1 T. The magnetizing fields are lower than in alloys without cobalt substitution and need generally not be higher than about 4 T. The temperature coefficient of the coercivity is $\beta = -0.6\%\ K^{-1}$, which is the same value as generally obtained in sintered NdFeB-type magnets [3].

References

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