Effects of cobalt substitutions in spring magnets

M. SORESCU*, L. DIAMANDESCU
Duquesne University, Bayer School of Natural and Environmental Sciences, Physics Department, Pittsburgh, PA 15282-0321, USA
E-mail: sorescu@duq.edu

M. VALEANU, A. JIANU
National Institute for Materials Physics, P.O. Box MG/7, Bucharest, Romania

Spring magnets of the type α-Fe/$Nd_2Fe_{14}B$ consist of a soft phase (α-Fe) and a hard phase ($Nd_2Fe_{14}B$), which are exchange coupled [1, 2]. These nanocomposite magnetic materials exhibit high magnetic remanence, high coercivity, high energy product, and low cost. In these nanostructures, the enhancement of magnetic properties is related to the exchange coupling between hard and soft nanograins [3–11].

In this paper we propose to study the effect of Co substitutions on the structural and magnetic properties of spring magnets. We employ X-ray diffraction (XRD) and Mössbauer spectroscopy to characterize the main features of Co additions and in particular, to answer the question of whether Co enters the soft phase or the hard phase.

Three compositions of spring magnets, $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$, $Nd_{10.5}Fe_{78.4}Co_{5.3}B_{5.8}$, and $Nd_{10}Fe_{76.5}Co_{7.9}B_{5.6}$, were prepared by arc melting and annealed for 3 min at 690, 720, 755, and 775 °C. XRD measurements were performed using a Rigaku D-2013 diffractometer with Cu $K_{\alpha 1}$ radiation at $\lambda = 1.5404$ Å. Transmission Mössbauer measurements were made with a constant acceleration spectrometer. The 50 mCi gamma ray source was ^{57}Co in Rh matrix, maintained at room temperature. All spectra were analyzed with the NORMOS-DIST program, which uses the histogram method to obtain the hyperfine magnetic field distributions.

Fig. 1 shows the XRD pattern of the $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$ composition, annealed at 690 and 755 °C. We could identify the soft phase α-Fe(Co), which is crystalline and the hard phase $Nd_2Fe_{14}B$, which is predominantly amorphous. Similar features were exhibited by the samples $Nd_{10.5}Fe_{78.4}Co_{5.3}B_{5.8}$ and $Nd_{10}Fe_{76.5}Co_{7.9}B_{5.6}$, annealed at 690 and 775 °C.

Fig. 2a and b present the room temperature transmission Mössbauer spectra of the $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$ system, annealed at 690 and 755 °C. In (A) and (B) we give the hyperfine magnetic field distributions extracted from these spectra by nonlinear least-squares fitting. Similar spectra were obtained for the compositions $Nd_{10.5}Fe_{78.4}Co_{5.3}B_{5.8}$ and $Nd_{10}Fe_{76.5}Co_{7.9}B_{5.6}$, annealed at 690 and 775 °C. In view of the XRD results, all Mössbauer spectra were analyzed with a six-line pattern corresponding to the α-Fe(Co) crystalline phase, and a hyperfine magnetic field distribution representing the $Nd_2Fe_{14}B$ amorphous component.

Fig. 3 shows the dependence of the hyperfine magnetic field of the crystalline phase on the annealing temperature. It may be observed that the hyperfine magnetic field of the soft phase first increases with increasing Fe content and then increases with increasing the amount of Co substitution. Indeed, it is known [1, 2] that at certain compositions, Co has the tendency to increase the hyperfine fields at Fe sites and this effect prevails over that of increasing Fe content. The combined XRD and Mössbauer findings are consistent with the presence of Co substitutions in the soft magnetic phase.

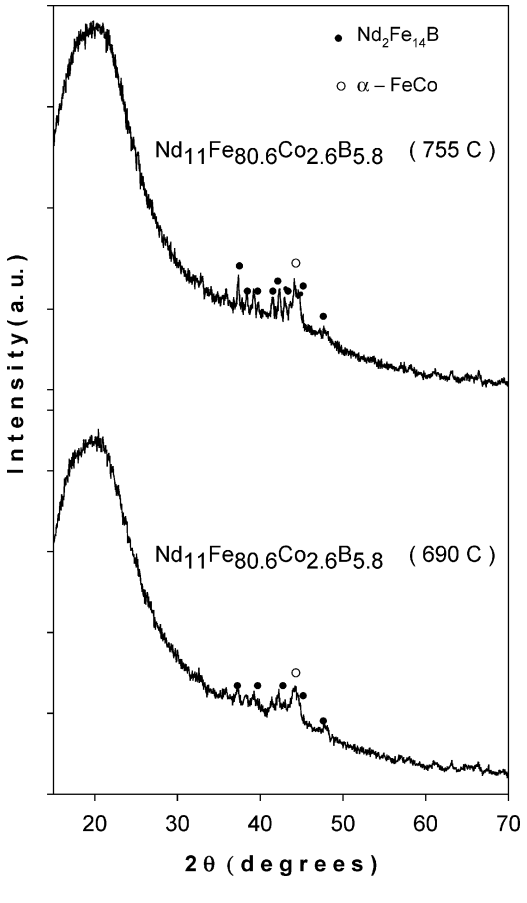

Figure 1 XRD pattern of $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$ after annealing at 690 and 755 °C.

*Author to whom all correspondence should be addressed.

0022–2461

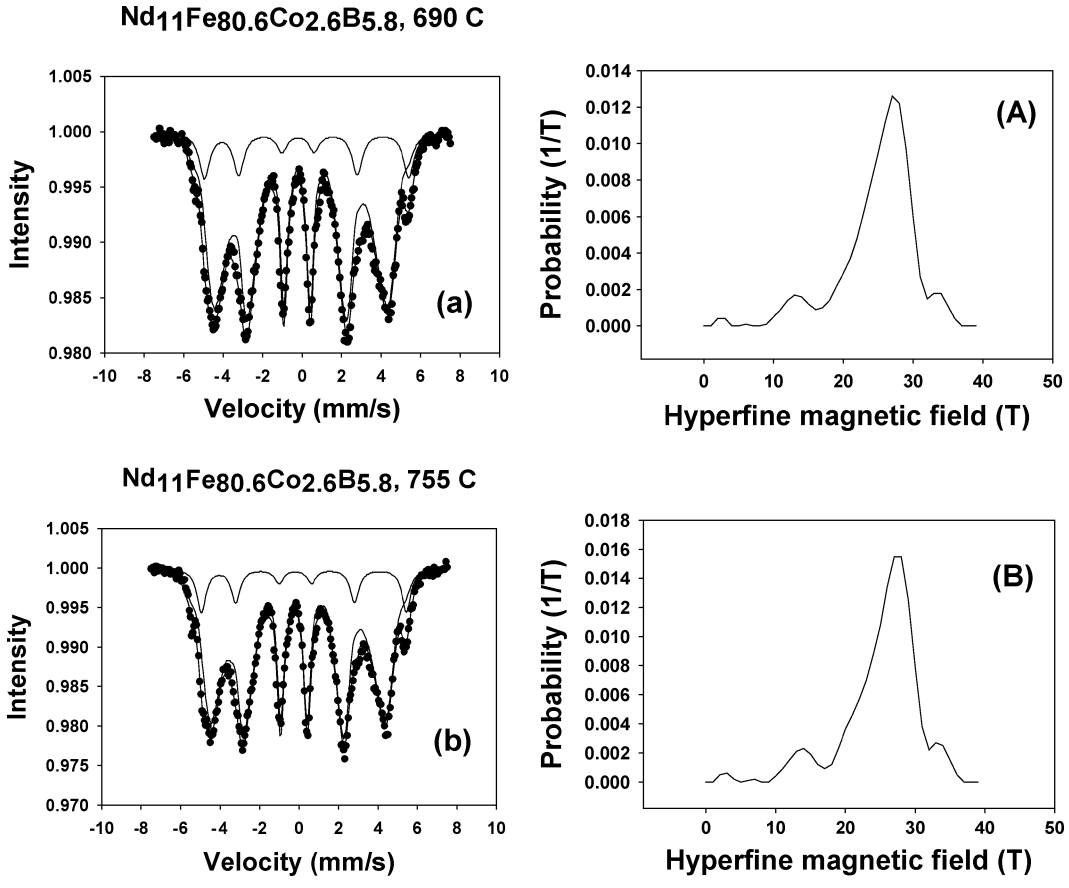

Figure 2 Room temperature transmission Mössbauer spectra of $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$ after annealing at (a) 690 and (b) 755 °C. In Fig. 2A and B the corresponding hyperfine magnetic field distributions are given.

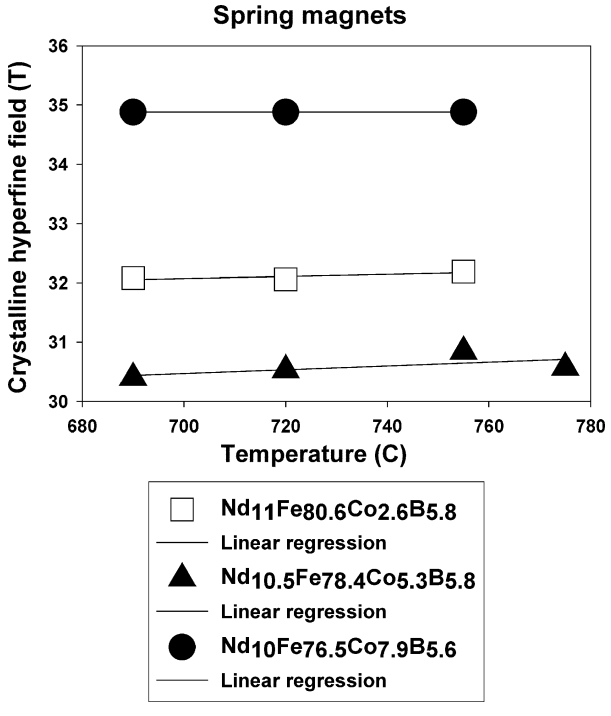

Figure 3 The hyperfine magnetic field of the crystalline component α-Fe(Co) as a function of the annealing temperature for all three compositions.

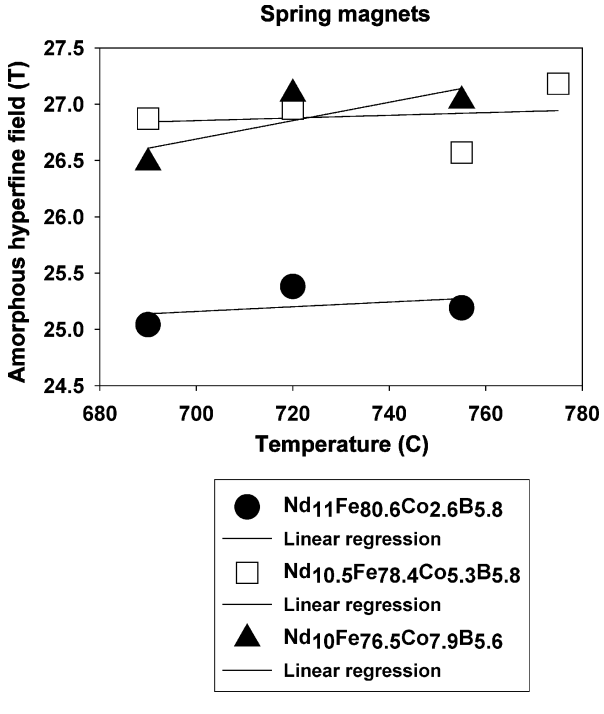

Figure 4 The hyperfine magnetic field of the amorphous component Nd_2Fe_{14} B with cobalt as a function of the annealing temperature for all three compositions.

Fig. 4 displays the dependence of the average hyperfine magnetic field of the hard, amorphous phase as a function of the annealing temperature for the $Nd_{11}Fe_{80.6}Co_{2.6}B_{5.8}$, $Nd_{10.5}Fe_{78.4}Co_{5.3}B_{5.8}$, and $Nd_{10}Fe_{76.5}Co_{7.9}B_{5.6}$ systems. It can be observed that the hyperfine magnetic field increases with increasing the Co content. In view of the ability of cobalt substitutions to increase the hyperfine field at Fe sites, this result is possible only if Co also enters the hard phase. Moreover, the hyperfine magnetic field increases

slightly with increasing the annealing temperature of the compound.

To conclude, this study demonstrates that Co substitutions in spring magnets are present both in the soft and hard phases of the Nd-Fe-B exchange-coupled magnets.

Acknowledgment

This paper was prepared with the support of the U.S. Department of Energy, under Award No. DE-FC26-02NT41595. However, any opinions, findings, conclusions, or recommendations, expressed herein are those of the authors and do not necessarily reflect the views of DOE.

References

1. M. SORESCU, A. GRABIAS and M. VALEANU, *Intermet.* **9** (2001) 67.
2. *Idem.*, *IEEE Trans. Magn.* **39** (2003) 2959.
3. E. F. KNELLER and R. HAWIG, *ibid.* **27** (1991) 3588.
4. A. MANAF, R. A. BUCKLEY and H. A. DAVIES, *J. Magn. Magn. Mater.* **128** (1993) 302.
5. J. BAUER, M. SEEGER, A. ZERN and H. KRONMULLER, *J. Appl. Phys.* **80** (1996) 1667.
6. J. DING, Y. LI and K. Y. LEE, *J. Phys.: Cond. Matt.* **10** (1998) 9081.
7. T. KOBAYASHI, M. YAMASAKI and M. HAMANO, *J. Appl. Phys.* **87** (2000) 6579.
8. Y. Q. WU, D. H. PING, K. HONO, M. HAMANO and A. INOUE, *ibid.* **87** (2000) 8658.
9. H. ONODERA, A. FUJITA, H. YAMAMOTO, M. SAGAWA and S. J. HIROSAWA, *J. Magn. Magn. Mater.* **68** (1997) 6.
10. Z. H. CHENG, G. SHEN, M. X. MAO, J. J. SUN, Y. D. ZHANG and F. S. LI, *Phys. Rev.* B **52** (1995) 9427.
11. M. M. RAJA and A. NARAYANASAMI, *J. Appl. Phys.* **84** (1998) 5715.

Received 1 March
and accepted 3 June 2004