

Random anisotropy studies in amorphous $\text{Fe}_{80-x}\text{Ho}_x\text{B}_{20-x}$ alloys ($0 < x < 16$; $0 < x' < 4$)

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In this paper, we have carried out a systematic study of the exchange and anisotropy effects on magnetic behavior of amorphous $\text{Fe}_{80-x}\text{Ho}_x\text{B}_{20-x}$ ($0 < x < 17$; $0 < x' < 4$) alloys. Primary analysis of magnetization data have led to the conclusion that the holmium magnetic structure is collinear. Exchange parameters, governing the magnetic ordering of our alloys, have been calculated from both mean field theory and high-field magnetization analyses. Study of the magnetization using the Chudnovsky's real space model has allowed us to determine the overall anisotropy constant, K_L , from which we have determined, separately, the anisotropy energies for the iron and the holmium sublattices. Comparison of these two parameters to the exchange energies shows that the anisotropy to exchange ratio is small in these alloys.

INTRODUCTION

Amorphous transition-metal based alloys are interesting from both theoretical and technical points of view. Randomness introduces, via spin orbit coupling, locally varying single-site anisotropies, which affect deeply the magnetization behavior under applied magnetic fields. Nevertheless, short range atomic order persists even in the amorphous state and is shown to have a considerable effect on the magnetic properties. Recently, we have reported on the magnetic behavior of amorphous iron(cobalt)-holmium-boron alloys and have shown that the rare earth (holmium) magnetic structure is collinear [1, 2]. Several works devoted to similar alloys containing different rare earth atoms reported on canted moment structures even in sufficiently high fields, this behavior was attributed to strong random anisotropy fields acting on the different rare earth sites, preventing them from complete alignment along the external applied fields.

In this paper, we report on systematic exchange and anisotropy studies on melt spun amorphous $\text{Fe}_{80-x}\text{Ho}_x\text{B}_{20-x}$ alloys. Analysis of thermal behavior of the magnetization within the framework of the mean field model allows us to determine the most relevant exchange interactions, i.e, those between the transition metal atoms, J_{FeFe} , and those between transition metal and rare earth ones, J_{FeHo} . In order to examine the anisotropy effects on the magnetization behavior, we analyze the evolution of the magnetization using Chudnovsky's real space model and determine the overall anisotropy constant, K_L , for the studied compositions.

I. MEAN FIELD ANALYSIS

Mean field theory (MFT) has been shown to be applicable to amorphous systems and was successfully applied for analyzing the thermal

behavior of the magnetization in many amorphous rare earth-transition metal amorphous alloys [3, 4]. The variation of the magnetic moments μ_i with temperature was shown to follow a Brillouin function depending on both the external applied field, the different internal fields acting on the involved subnetworks and the temperature, such as:

$$\mu_i(T) = \mu_i(0K) B_{J_i} \left(g_i \mu_B \mu_i(0) H_i / k_B T \right)$$

where g_i , μ_B , k_B are the Landé factor, the Bohr magneton and the Boltzmann constant, respectively, and H_i is the molecular field acting on the i th subnetwork:

$$H_i = \left(\frac{2N_{ii}J_{ii}}{g_i\mu_B} \right) J_i(T) + \left(\frac{2N_{ij}J_{ij}}{g_i\mu_B} \right) J_j(T) + H_{ext}$$

where N_{ij} is the number of j atoms nearest neighbors of an i atom and J_{ij} are the exchange integral constants. $\mu_i(0K)$ is the magnetic moment of the ion i at zero temperature. Assuming that the alloy magnetic moment can be written as:

$$\mu_a = \left[(80 - x + x') \mu_{\text{Fe}} - x \mu_{\text{Ho}} \right] / 100 \quad (3)$$

and taking $\mu_{\text{Fe}} = 2.06\mu_B$, as reported in the literature, we deduce for Ho, from Eq.1, the value $\mu_{\text{Ho}} = 10.02\mu_B$, which is in accordance with its theoretical value corresponding to the trivalent state. This suggests that the holmium magnetic structure is collinear. Now, supposing this value constant under alloying, one can determine that of the iron magnetic moment for increasing rare earth concentration. Values of μ_{Fe} thus calculated are listed in table 1 where a systematic decrease is observed. A decrease of transition metal magnetic moment as the rare earth content is increased was also reported for several amorphous alloys with different rare earths. Also are unknown, in Eqs.1-2, the coordination numbers, N_{ij} . In amorphous transition metal-rare earth-metalloid amorphous

alloys, referred to as T-R-M, local structural order around T atoms is thought to be similar to that existing in amorphous T-M or T-R alloys[5], depending on whether the short range order is dictated by the metalloid or by the rare earth, respectively. Hence, amorphous $\text{Fe}_{80-x-x'}\text{Ho}_x\text{B}_{20-x'}$ alloys can be viewed as of $(\text{T}_{80+x'-x}\text{M}_{20-x'})\text{R}_x$ or $(\text{T}_{100-x-x'}\text{R}_x)_{18/z}\text{M}_{20-x'}$ with $z=100(20/(100-x))$ type alloys, for which the different experimental coordination numbers are taken from the

II. ANISOTROPY STUDIES

Magnetization data indicate that the holmium moments are collinear; this could suggest that the ratio of anisotropy to exchange is small.

A direct method of determining the anisotropy strengths is that of Chudnovsky and coll.[8]. Magnetization versus external applied field curves are shown to follow inverse square root or inverse square laws, according to whether the external field is much smaller or much greater than an exchange field, defined as:

$$H_{ex} = 2A/M_0 R_a^2 \quad (4)$$

where A is the exchange constant, M_0 is the saturation magnetization and R_a is a characteristic

$$H_s \cong H_r^4 / H_{ex}^3 \quad (6)$$

where H_r is the random anisotropy field, related to the anisotropy constant of the system, K_L , as:

$$H_r = \frac{2K_L}{M_0} \quad (7)$$

In figure 3 are shown the variations of the magnetization, for each rare earth concentration, as a function of the inverse of the square root of the external applied field. Plotting M as a function of $H^{-1/2}$, M_0 , H_s , can be calculated, then, H_{ex} values can be deduced using the exchange integral values as determined from the mean field analysis and by taking $R_a=10\text{\AA}$ [9-10], and by using Eq.6, one can determine H_r and subsequently K_L from Eq.7.

The obtained parameters are gathered in table 2 from which it can be noticed that, for all the studied compositions, the applied field is much smaller than the exchange field, this means that, in this field regime, the magnetic state is a ferromagnetic with wandering axes (FWA) one [11], moreover, the anisotropy field H_r is always much smaller than the exchange one, H_{ex} , indicating thus that our alloys are weak anisotropy-as compared to exchange-systems. One can even characterize the spatial extent of

ferromagnetic order in the alloys by determining the ferromagnetic correlation length, R_f , given by [8, 11]:

literature[6, 7]. Knowing N_{ij} , $\mu_{\text{Fe}}(0\text{K})$ and $\mu_{\text{Ho}}(0\text{K})$, the magnetization versus temperature curves can be fitted to the set of coupled Brillouin functions of Eq.2 and the exchange integrals $J_{\text{Fe-Fe}}$ and $J_{\text{Fe-Ho}}$ can be evaluated, for each composition. Typical magnetization curves are shown in Fig.1, which show the good agreement between the calculated and the experimental magnetizations.

spatial correlation length describing the correlation of the easy axis directions. Due to the high Curie temperatures of our alloys, the exchange field H_{ex} is often too high to be reached by the external field. In this regime, magnetization varies as:

$$M(H) = M_0 - \frac{M_0}{15} \frac{\sqrt{H_s}}{\sqrt{H}} \quad (5)$$

where H_s is the field above which the square root law should apply. H_s is related to both exchange and random anisotropy fields, H_{ex} and H_r , respectively, as:

$$R_f = \frac{15}{2} (A/K_L)^2 R_a^{-3} \quad (8)$$

Values of R_f thus obtained are listed in the last column of table 2 where it can be seen the destroying effect of Ho on the magnetic order (note that A diminishes as well), at least for Ho concentrations below the compensation one.

In Refs. [12-13], it is suggested that, in both crystalline and amorphous intermetallics, the overall anisotropy constant is an effective one, related to the individual anisotropy constants, K_R and K_T , and the intersublattice exchange coupling coefficient, n_{RT} , via:

$$K_{eff} = \frac{K_R + K_T + \frac{2K_R K_T}{n_{RT} M_R M_T}}{1 + \frac{2(K_R M_T^2 + K_T M_R^2)}{n_{RT} M_R M_T M^2}} \quad (9)$$

for systems with sublattice anisotropies much smaller than the intersublattice exchange coupling. In the above expression, K_R and K_T are the anisotropy constants of the rare earth and the transition-metal subnetworks and M_R and M_T their magnetizations, respectively.

In order to determine the anisotropy constants, separately, expression (9) can be used in two ways, either by simulating, at low temperature, the variation of K_L as a function of the rare earth composition, taking K_R and K_T as fitting parameters, or by adjusting, for each composition, the temperature variation of K_L determined from $M(H)$ curves at different temperatures, to the expression (9) where K_i and M_i ($i \equiv \text{Fe, Ho}$) are made temperature dependant, and by assuming the anisotropy constant K_i to vary as:

$$K_i(T) = K_i(0) \left(M_i(T) / M_i(0K) \right)^3 \quad (10)$$

In the following, we adopt the latter method. The n_{RT} parameter can be evaluated either from the high-field magnetization curves or by using the exchange integrals deduced from molecular field analysis [1, 14]. Figure 3 illustrates an example of such an adjustment and the anisotropy constants $K_i (= K_i(0K))$, determined in this way, are listed, together with K_L , in table 3.

Rare earth sites are subject to competing interactions, issuing from both the exchange field, exerted by the neighboring transition metal sites, and the single site random anisotropy, preventing rare earth moments from complete alignment. Comparison of these interaction forces may give insight into the magnetic order in the rare earth sublattice. The exchange energy of a rare earth site can be written as:

$$E_R^{ex} = \sum_T 2J_{RT} S_R S_T \quad (11)$$

where the sum extends to the neighboring transition metal sites of a rare earth site, and the anisotropy

energy, per rare earth site can be calculated as $D_R = K_R / N_R$, where N_R is the number of rare earth atoms per unit volume. The 4th column of table 3 shows that this ratio is smaller than 10^{-2} in all of the compositions studied.

Ravach and coll. [15] showed, through high field Mössbauer spectroscopy measurements, that, for the $Fe_{67.6}Ho_{16.2}B_{16.3}$ alloy, the iron magnetic structure is collinear from 2T. This result, when correlated to magnetization results presented here, shows that the magnetic structure of our alloys is ferrimagnetic. Nevertheless, except in Fe-Gd-B amorphous alloys, canted magnetic structures were found in amorphous Fe-Dy-B[16] and Fe-Er-B[17] alloys. Although holmium ion possesses strong orbital moment and the spin orbital coupling is expected to be strong, random anisotropy is found not to be strong to be overcome by the exchange and external fields. Collinear rare earth structures found for amorphous Ho and Gd based alloys are in accordance with the lower Stevens factors of Ho and Gd[18].

References

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- [1] A.Kaal, O. ElMarrakechi, S. Sayouri, M. Tlemçani, H. Lassri and M. Kellati; *Physica B*. **325**.(2003) 89.
 - [2] O. ElMarrakechi, A. Kaal, S. Sayouri, H. Lassri and M. Tlemçani; Submitted to *J. Magn. Magn. Mater.*
 - [3] R. Hasegawa, B. E. Argyle and L. J. Tao; *A. I. P. Conf. Proc.* **24** (1974)
 - [4] K. Yano; *J. Magn. Magn. Mater.* **208** (2000) 207.
 - [5] F. Machizaud, G. Ravach, J. Teillet and J. M. Le Breton, *J. Phys.: Condens. Matter.* **12** (2000) 8101.
 - [6] W. Matz, H. Hermann and M. Mattern, *J. Non-Cryst. Solids* **93** (1987) 217.
 - [7] F. Machizaud, M. Laridjani, E. Du Trémolet De Lacheisserie, *J. Magn. Magn. Mater.* **92** (1990) 207.
 - [8] E. M. Chudnovsky, W. M. Saslow and R. A. Serota; *Phys. Rev. B*. **33**, N°1 (1986) 251.
 - [9] R. Krishnan, H. Lassri and L. Driouch; *J. Magn. Magn. Mater.* **146** (1995) 355.
 - [10] H. Lassri, A. Habiballah, E. H. Sayouti and R. Krishnan; *J. Magn. Magn. Mater.* **163** (1996) 345.
 - [11] E. M. Chudnovsky; *J. Appl. Phys.* **64** (1988) 5770.
 - [12] A. Sarkis and E. Callen; *Phys. Rev. B*. **26**, N° 7 (1982) 3870.
 - [13] A. Itri, H. Lassri and M. ElYamani; *Physica B* **269** (1999) 189.
 - [14] R. J. Radwanski, J. J. M. Franse and S. Sinnema; *J. Magn. Magn. Mater.* **51** (1990) 175.
 - [15] G. Ravach and J. Teillet, *J. Phys. Condens. Matter.* **10** (1998) 7065.
 - [16] L. Driouch; Thèse de l'Université de Rouen (1996).
 - [17] H. Lassri, Thèse de l'Université de Rouen (1990)
 - [18] N. Heiman, and N. Kazama; *J. Appl. Phys.* **49** (1978) 1686.

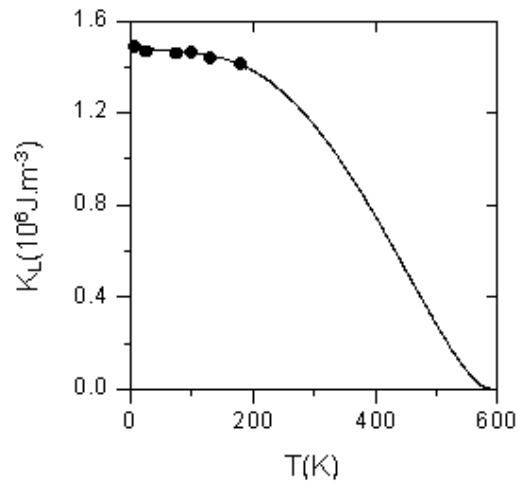


Figure Erreur! Document principal seulement.: Temperature variation of magnetic moments in $\text{Fe}_{73.4}\text{Ho}_{7.6}\text{B}_{19}$ (left figure) and $\text{Fe}_{67.6}\text{Ho}_{16.2}\text{B}_{16.3}$ (right figure) alloys. Solid circles: experimental data.

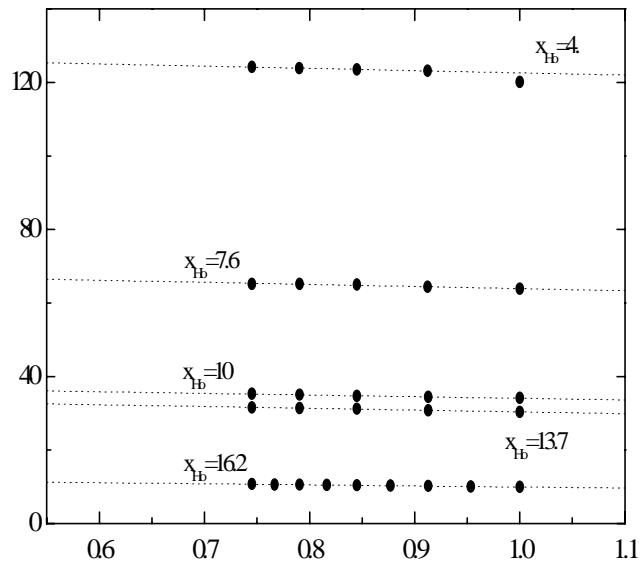


Figure 2: Variation of the magnetization as a function of $H^{-1/2}$ of the Fe-Ho-B alloys for different concentrations in rare earth (at $T=0\text{K}$).

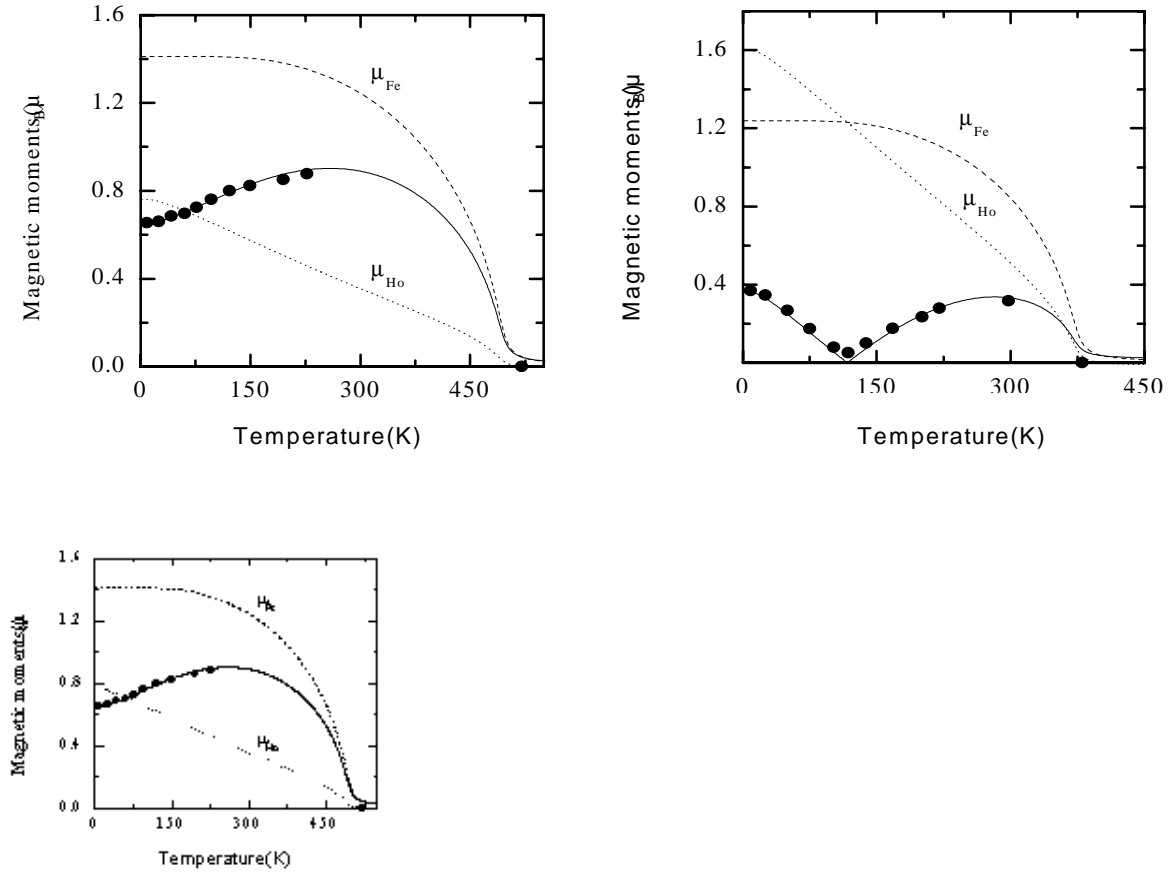


Figure 3: Variation of the anisotropy constant K_L as a function of the temperature for the $\text{Fe}_{77}\text{Ho}_4\text{B}_{19}$ alloy (Solid circles represent K_L determined from $M(H)$ curves for each temperature using Chudnovsky's theory. Line represents K_L calculated using Eq. 9-10 with $K_R=0.1 \cdot 10^6 \text{ Jm}^{-3}$ and $K_T=1.4 \cdot 10^6 \text{ Jm}^{-3}$).

Alloy	$\mu_{\text{Fe}} (\pm 0.05 \mu_B)$	$J_{\text{Fe-Fe}} (10^{-22} \text{ J})$	$J_{\text{Fe-Ho}} (10^{-22} \text{ J})$	$J_{\text{Ho-Ho}} (10^{-22} \text{ J})$	$T_c^{\text{exp}} (\pm 5 \text{ K})$
$\text{Fe}_{78}\text{Ho}_4\text{B}_{18}$	2.0	5.8	1.3	0.34	600
$\text{Fe}_{73.4}\text{Ho}_{7.6}\text{B}_{19}$	1.92	5.66	1.08	0.27	520
$\text{Fe}_{73.4}\text{Ho}_{10}\text{B}_{16.6}$	1.87	4.7	1.14	0.20	490
$\text{Fe}_{68.3}\text{Ho}_{13.7}\text{B}_{18}$	1.83	4.69	1.17	0.18	430
$\text{Fe}_{67.6}\text{Ho}_{16.2}\text{B}_{16.3}$	1.83	4.14	1.22	0.11	380

Table Erreur! Document principal seulement.: Magnetic parameters of amorphous $\text{Fe}_{80-x}\text{Ho}_x\text{B}_{20-x}$ alloys obtained from MFT analysis. T_c^{exp} is the experimental Curie temperature

x	$M_s (\text{uem.g}^{-1})$	$A (10^{-12} \text{ J.m}^{-1})$	$H_{\text{ex}} (T)$	$H_r (T)$	$K_L (10^6 \text{ J.m}^{-3})$	$R_f (\text{\AA})$
4	128.7	2.96	6.64	3.51	1.55	271

8	66.9	2.42	10.38	6.39	1.53	197
10	39.5	2.13	15.45	10.1	139	175
14	12.8	1.81	40.61	29.5	1.33	141
16	34.6	1.6	13.12	9.2	1.11	154

Table 2: Ho concentration dependencies of anisotropy parameters of Fe-Ho-B amorphous alloys.

<i>Alloy</i>	$K_L(10^6 J/m^3)$	$K_T(10^6 J/m^3)$	$K_R(10^6 J/m^3)$	D_R/E_R^R
Fe ₇₈ Ho ₄ B ₁₈	1.47	1.4	0.1	0.003
Fe _{73.4} Ho _{7.6} B ₁₉	1.26	1.13	0.32	0.0084
Fe _{73.4} Ho ₁₀ B _{16.6}	1.35	1.4	0.41	0.0089

Table 3: Some of the anisotropy parameters (at T=0K) relevant of amorphous Fe_{82-x}Ho_xB_{20-x} alloys