Random anisotropy studies in amorphous Co–Er–B ribbons

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1. Introduction

Amorphous alloys based on rare-earth (R), transition metal (T) and metalloid (M) elements, such as T–R and T–R–M, show interesting magnetic properties and have been studied in the past by a number of authors [1–5]. As usually observed in intermetallics, the magnetic moment of the heavy rare-earth in amorphous alloys couples antiferromagnetically to that of the transition metal. One of the fascinating behaviors in such amorphous alloys arises from the random magnetic anisotropy (RMA) which results from the topological disorder present in these materials. Indeed, Harris, Plischke and Zuckermann have first introduced the random axial anisotropy model for amorphous alloys by adding to the exchange interaction term, a single-atom magnetic anisotropy term with different randomly-oriented directions at each site [6].

Rare-earth metal atoms with an orbital moment are thus well known to give rise to large random anisotropy in amorphous alloys [6]. Some theoretical models have been developed to calculate the random anisotropy and related parameters from the analysis of the approach to magnetic saturation [7,8]. Tejada et al. have demonstrated that magnetic properties of amorphous Dy–Fe–B are well described by the random anisotropy model [3,4]. An experimental method, based upon the approach of Cudnovsky et al., has been suggested, which allows one to distinguish between different models of structural disorder in amorphous ferromagnets [7–10]. In this work, we describe magnetic studies performed on amorphous Co80–xExB20 alloys prepared by conventional melt-spinning technique and the results are discussed on the basis of the RMA model.

2. Experimental methods

Amorphous Co80–xExB20 ribbons with 0 ≤ x ≤ 7.5, were quenched in an inert atmosphere of Ar using the melt-spinning technique. The starting materials were of purity better than 4 N. The melt-spun ribbons were about 30 μm thick with different widths varying from about 3 to 5 mm. X-ray diffraction was used to check the amorphous structure. The exact chemical composition of the samples was determined by electron probe microanalysis. The magnetization M was measured with a precision better than ±1%, under applied magnetic fields of up to 50 kOe at 4.2 K. The Curie temperature TC was also determined using a vibration sample magnetometer from 300 to 900 K in a small magnetic field of about 100 Oe.

3. Results

The field dependence of magnetization shows that saturation is attained only for H of about 30 kOe at all temperatures. A very small high field susceptibility (fH) is seen and which shows a small increase with Er content, the highest value is on the order of 10−4 emu/g Oe which is generally observed in such metallic glasses. Table 1 shows the x concentration dependence of the saturation magnetization Ms (at 4.2 K) and the Curie temperature. Fig. 1 shows a plot of [(Ms − M)/Ms]−2 as a function of H for 0 ≤ x ≤ 7.5, at 4.2 K. It is seen that the experimental points align well on a straight line. The intercept on the abscissa gives the value of the coherent anisotropy field (Hc) related to the coherent anisotropy energy (Kc) by relation Hc = 2Kc/Ms. The variation of Kc...
versus Er concentration is shown in Fig. 2. It can be noticed that the $K_u$ increases with the increasing Er content.

4. Discussion

4.1. Magnetic studies

The $M_s$ decreases with the addition of Er which indicates the antiparallel coupling between Co and Er moments. It is well established that the Co moment $\mu_{Co}$ diminishes when it is alloyed with a rare-earth metal due to 3d–5d hybridization, but this effect is negligible for small concentrations. So we consider $\mu_{Co}=1.25 \mu_B$ obtained for the alloy with $x=0$, and assume this to be the same in the alloys with $x<4$. Knowing the alloy moment $M_s$ and using the relation,

$$M_s = \frac{|(80-x)\mu_{Co}-x\mu_{Er}|}{100}, \quad (1)$$

the Er moment $\mu_{Er}$ is estimated at $7.2 \pm 0.2 \mu_B$, where $\mu_B$ is the Bohr magneton. This moment which is a projection along the applied field is smaller than the theoretical value ($g \mu_B$) of 9 $\mu_B$. This reduction could be attributed to the non-collinear and conical spin structure of Er. This phenomenon is due to the strong random anisotropy of Er. Now $\mu_{Co}$ for other alloys could be calculated based on the reasonable assumption that $\mu_{Er}$ is independent of $x$. If we take $\mu_{Er}=7.2 \mu_B$ at 4.2 K, then we can calculate the value of $\mu_{Co}$ from the experimentally determined value of $M_s$ by using Eq. (1). $\mu_{Co}$ is 1.25 $\mu_B$ for $x=0$ and decreases to about 1.09 $\mu_B$ for $x=7.5$. The decrease of the Co moment with the Er content can be understood as due to an increase filling of the 3d spin-up band of the Co atom by the $6s^2/5d$ electrons of Er and by the sp electrons from B atoms since the relative concentration of B with respect to Co increases. Curie temperature $T_C$ of amorphous $Co_{80-x}Er_xB_{20}$ alloys were determined from the thermomagnetic data. The values of $T_C$ thus obtained are reported in Table 1. The decrease in $T_C$ could be caused by the weakening of de Co–Co interaction and the results are characteristic of antiferromagnetic interaction between Er and Co which is well known.

4.2. Random magnetic anisotropy modeling

The approach to saturation in the magnetization can be described in the following two ways according to Chudnovsky et al. [8–10]. For applied fields higher than the exchange field $H>H_{eq}$, the field dependence is expected to follow an $H^{-2}$ law, whereas when $H<H_{eq}$, which incidentally is appropriate to our study, the dependence is best described by an $H^{-1/2}$ law. Therefore, in the latter case if one plots $M$ as a function of $H^{-1/2}$, a linear dependence will be obtained and one can then write;

$$\frac{(M_s-M)/M_s}{M_s} = \frac{H_s/(H+H_{eq})^{1/2}}{15}, \quad (2)$$

where

$$H_s = H_{eq}^3/H_{ex}^2. \quad (3)$$

For the intermediate field regime, $H_s<H<H_{eq}$, the system retains its alignment due to the combined effects of both the applied field and the exchange energy. Nevertheless, the system is not completely ordered, since the random anisotropy causes the local direction of magnetization to wander slightly. For this reason we describe the system in this regime as a ferrimagnet with wandering axes.

The saturation magnetization and the random local anisotropy field $H_r$ are related to the local anisotropy energy $K_i$ by the relation

$$H_r = 2K_i/M_s. \quad (4)$$

The exchange field $H_{eq}$ can also be expressed as

$$H_{eq} = 2A/M_s(R_f)^2. \quad (5)$$

where $R_f$ is the length over which the local anisotropy axes show a correlation (short-range structural order). We assume $R=10$ Å, as

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### Table 1

<table>
<thead>
<tr>
<th>X</th>
<th>M_s (emu/g) ± 0.5 emu/g</th>
<th>$T_C$ (K) ± 10 K</th>
<th>$A$ (10^{-8} erg/cm)</th>
<th>$H_{eq}$ (kOe)</th>
<th>$H_r$ (kOe)</th>
<th>$K_i$ (10^7 erg/cm^2)</th>
<th>$H_{eq}$ (kOe)</th>
<th>N</th>
<th>R_f (Å)</th>
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<td>1.37</td>
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<td>206.6</td>
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</table>

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**Fig. 1.** $[(M_s-M)/M_s]^{-2}$ as a function of the applied magnetic field at 4.2 K. The solid line was obtained by linear regression.

**Fig. 2.** $K_u$ as a function of the Er concentration at 4.2 K.
determined experimentally on similar alloys [11–15]. The exchange constant follows from the relation [16]:

\[ A = C S_{Co} k_b T_c / (4(1 + S_{Co}) \tau_{CoCo}) \]  

(6)

where \( C = (80 - x)/100 \) is the iron concentration, \( S_{Co} \) is the Co spin, and \( \tau_{CoCo} \), the interatomic Co-Co distance, is taken as 2.5 Å. Knowing all the parameters, we can now calculate \( A \) and one finds that \( A \) decreases with increasing Er concentrations (Table 1).

Eq. (2) can be rewritten as

\[ (M_s - M)/M_s \]  

(7)

where \( B = 225/H_s \). So by plotting \( (M_s - M)/M_s \) as a function of \( H \), one can obtain \( H_s \) from the slope \( B \) and the coherent anisotropy field from the intercept [17]. Fig. 1 shows such a plot for different composition \( 0 \leq x \leq 7.5 \) at 4.2 K in the amorphous \( \text{Co}_{80-x}\text{Er}_x\text{B}_{20} \) alloys. Table 1 shows the various parameters obtained from the analysis of the data using the models described above. It is well known that the presence of rare-earth ions with a strong spin-orbit coupling such as Er, Tb, Dy gives rise to much larger \( K_U \) as compared to Gd-based alloys [18,19]. This is evidenced in the observed increase of \( K_U \) as a function of Er content (Fig. 2). Any technological process of preparation of amorphous solids inevitably induces some coherent anisotropy. This \( K_U \) can transform the correlated spin glass into a long-range ferromagnetically ordered state similar to that in crystalline ferromagnets. Finite random anisotropy is required to destroy long-range ferromagnetism in the presence of coherent anisotropy [9].

The value of \( K_U \) deduced from the Chudnovsky’s model is found to be practically the same in the alloy with \( x = 7 \) and decreases with Er content (Table 1). In our case, we have the contribution of two sub-networks at the magnetic anisotropy: in one hand the Er which is a rare-earth possessing an important magnetic anisotropy, and on the other hand the Co for which the mean magnetic moment is lower than that of the metallic counterpart. This situation shows that the Co orbital momentum is incompletely quenched in the alloy, then we will find a spin-orbit interaction which will give rise to a local magnetic anisotropy in the Co sub-network [20]. The decrease of \( K_U \) with \( x \) for \( x \geq 7 \), may be explained by a modification of the main local structural order around the Co atoms, which occurs within a very narrow composition range of \( 7-8 \) at.\%. Thus, different kinds of structural order appear to exist below and beyond this Er concentration. Previously, an anomalous wide-angle X-ray scattering (AWAXS) study performed on \( \text{Co}_{80-x}\text{Er}_x\text{B}_{20} \) ribbons also showed a structural change [21,22]. Below 7 at.\% Er, the structure was heterogeneous, while some kind of amorphous solid solution was found beyond.

Following Chudnovsky’s work [6–8], the dimensionless parameter \( \lambda \) is expressed as

\[ \lambda = \left( 2/15 \right)^{1/2} H / H_{ex} = \left( 2/15 \right)^{1/2} K_C / A. \]  

(8)

It is found that the \( \lambda \) is less than unity in our alloys (Table 1) that suggest a ferrimagnetic system with weak anisotropy. Finally, the ferromagnetic correlation \( R_f \) depends on \( R_r \) and \( \lambda \) according to the following relation: \( R_f = R_r / \lambda^2 \). It is found that \( R_f \) decreases with increasing Er content (Table 1).

5. Conclusion

In conclusion, we have prepared amorphous \( \text{Co}_{80-x}\text{Er}_x\text{B}_{20} \) alloys and carried out magnetization studies. We have analyzed the high field magnetization curve of amorphous \( \text{Co}_{80-x}\text{Er}_x\text{B}_{20} \) alloys in the framework of the model of Chudnovsky et al. The results show several features (exchange field, random anisotropy field and ferromagnetic correlation length) all consistent with each other and in agreement with theoretical predictions. Finally, the anisotropy studies show that these alloys are weak anisotropy ferrimagnet.

Acknowledgments

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References