Magnetic moments of Fe and Y in the FeBY glass forming system

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Available online 5 November 2007

Abstract

The new Fe71.2B24Y4.8 glassy alloy has been prepared in amorphous ribbon form via melt spinning and splat cooling. The high degree of sample homogeneity and structural quality of the ribbon is revealed by the observation of narrow linewidths in the spectra of the field derivatives of the absorbed microwave power in ferromagnetic resonance experiments. Combination of vibrating sample magnetometry and element-specific X-ray magnetic circular dichroism experiments at the L_3,2-edges of Y revealed an induced magnetic moment of 0.065 μB/atom for Y antiparallel oriented to an Fe magnetic moment of 1.83 μB/atom.

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PACS: 61.43.Dq; 61.10.Ht; 75.30.Cr

Keywords: Amorphous metals, metallic glasses; X-ray diffraction; Magnetic properties; X-ray absorption

1. Introduction

Amorphous and nanocrystalline metallic alloys are considered nowadays as advanced materials which demonstrate superior properties in a wide range of conditions and have, therefore, a large number of important applications. They include materials with excellent static and dynamic mechanical strength, soft magnetic properties and good corrosion resistance, see for example [1–7]. It is not surprising then, that there is a strong tendency for searching for new multielement metallic systems with high glass forming ability (GFA) [1,6,7]. Recently, it was reported that the addition of small amounts of Y in FeB results in a material with enhanced GFA [8,9]. The optimum stoichiometry was found to be Fe71.2B24Y4.8 [9]. Furthermore, this material exhibits high permeability as desired for magnetic transformer applications.

In the present work we have prepared this new material in form of ribbons via melt spinning and of splat via splat cooling. The samples were characterized combining conventional laboratory and synchrotron X-ray techniques. The materials were found to be completely or partially amorphous depending on the preparation method and the thickness. The high magnetic homogeneity and the soft magnetic nature of the amorphous samples were revealed. Finally, we have determined the magnetization as well as the induced magnetic moment at the Y sites in proximity with Fe. This is, to our knowledge, the first quantification...
of the Y-magnetic moment and its separation into spin and orbital moments.

2. Experimental details

The present work deals with the Fe$_{71.2}$B$_{24}$Y$_{4.8}$ glassy alloy. This composition has been chosen because it was reported in Ref. [9] to have the highest GFA among the other investigated alloys of the FeBY family. Samples have been prepared via melt spinning in the form of ribbons 1 mm wide and 20 μm thick. Since these ribbons are too narrow for the quantitative evaluation of the X-ray absorption (XAS) spectra, splats were also produced by a splat cooling device based on a melt sucking unit. The average thickness of these samples is near to 200 μm.

High-energy X-ray diffraction (XRD) measurements were performed at HASYLAB at DESY (Hamburg, Germany), on the experimental station PETRA 2, using monochromatic synchrotron radiation of 106 keV. The samples measured at room temperature in transmission mode were illuminated for 240 s by a well-collimated incident beam of 1 mm$^2$ cross-section. XRD patterns were recorded using a 2D detector (mar345 Image plate) in asymmetric mode to obtain data at high wave vector transfer ($Q$). The background intensity was subtracted directly from the 2D XRD pattern and the result was integrated to the 2$\theta$-space, by using the program Fit2D [10]. Complementary XRD measurements were also performed using a standard powder diffractometer (Berthold-SEIFFERT) with Ni-filtered Cu K$_\alpha$ radiation ($\lambda = 0.154059$ nm).

X-ray magnetic circular dichroism (XMCD) measurements have been performed at the ID12 beam line of the European synchrotron radiation facility (E.S.R.F.) [11]. The Y L$_{2,3}$-edges and the Fe K-edge have been recorded by means of the fluorescence detection mode and by using two type of undulators: EMU388 (for the Y L-edges) and Apple II (for the Fe K-edge). The intense photon flux provided by these types of undulators allows for a clear recording of even minor details of the XMCD spectra. The as-quenched ribbons exhibit the characteristic diffuse scattering pattern for metallic glasses with a maximum at $2\theta = 3.27^\circ$ and pronounced oscillations, typical for amorphous materials, are visible up to $2\theta = 15^\circ$, as shown in Fig. 1. The large number of oscillations and the noise-free XRD pattern as compared to the regular ones recorded in conventional laboratories, are attributed to the use of photons of very high-energy (106 keV) in combination with the high photon flux provided by synchrotron sources such as the one at HASYLAB. The amorphous nature of the sample was also confirmed by the near-edge X-ray absorption fine structure (NEXAFS) spectrum recorded at the K-edge of Fe at E.S.R.F (not shown here). This spectrum was practically structureless unlike the typical ones reported for crystalline Fe. For the gradual transition of the spectra from crystalline to amorphous Fe see as a reference, for example [13]. The splat-cooled sample, on the other hand, was a mixture of amorphous and crystalline structure, as its XRD pattern revealed. Besides the larger total thickness (∼200 μm) the dominantly crystalline structure, according to our experience, it might also be connected to a thin non-melted layer typical of ingots melted on the water-cooled hearth. It promotes crystal growth on solidification.

Fig. 2 shows the room temperature spectrum of the field derivative of the absorbed microwave power in FMR experiments for the Fe$_{71.2}$B$_{24}$Y$_{4.8}$ amorphous ribbon. The magnetic field was applied parallel to the easy magnetic axis of the sample, which is the direction parallel to the ribbon plane due to the dominant shape anisotropy. The position of the FMR, determined precisely by the derivative of the absorption spectrum, is $H_R = 66.4$ kA/m.

Amorphous alloys have small magnetocrystalline anisotropy. FMR measurements (together with a precise value of the magnetization) are in principle suitable for the determination of magnetic anisotropy constants [14,15]; it would, however, go beyond the scope of this study.

3. Results

The maximum applied field was 1000 kA/m.

![Fig. 1. X-ray diffraction patterns recorded for an amorphous Fe$_{71.2}$B$_{24}$Y$_{4.8}$ ribbon.](image-url)
short contribution. Most important for our purpose is the
very narrow linewidth $D_H = 5 \text{kA/m}$ of the FMR line. This
is indicative for samples of high structural and magnetic
homogeneity, as explained in detail in Ref. [16]. The line-
width values are as low as found in other high quality
amorphous Fe-based alloys, Fe-whiskers and single-crys-
talline Fe/V superlattices [17].

In Fig. 3, the VSM magnetization curve is presented for
a Fe$_{71.2}$B$_{24}$Y$_{4.8}$ amorphous ribbon. The magnetic field was
applied parallel to the ribbon’s plane (easy axis). One may
notice that the sample saturates very easily. The saturation
magnetization of the sample is about 142 Am$^2$/kg. Our
result is comparable to recent magnetic measurements on
FeBY bulk metallic glasses with similar stoichiometry [8].
The magnetization curve shown in Fig. 3, which is typical
for soft magnetic materials, reveals a coercivity value of
$H_C \sim 190 \text{A/m}$. This value is quite close to the figures
reported for similar amorphous magnetic alloys, see for
example [18].

In Fig. 4, the XAS and the XMCD spectra are plotted.
They have been recorded at room temperature at the L$_{3,2}$-
edges of Y for the splat-cooled (partially crystalline) sam-
ple. Qualitatively similar data were also recorded for the
amorphous ribbon. This is expected as the nearest neighbor
atomic environments and, therefore, the distribution of
magnetic moments is closely related. While the corrections
for the self-absorption and saturation effects (necessitated
by the relatively large sample thickness of the splats as
compared to the penetration depth of the X-rays) can be
carried out quantitatively, the background correction for
the narrow ribbon samples cannot be made with the neces-
sary accuracy. This is the reason why the absolute values
(spin and orbital moments of the Y atom) are only deter-
mined for the splats; they are expected to be close to the
parameters relevant for the amorphous alloy. For the
XAS spectra the ratio of the L$_3$/L$_2$ was normalized to 2/1
according to Ref. [19]. The existence of finite XMCD sig-
nals reveals the presence of magnetic moments [15]. In
our case it shows unambiguously that Y has acquired an
induced magnetic moment. The XMCD signals are rather
small, however the high photon flux and degree of polar-
ization offered by the third generation synchrotron radia-
tion facilities [20] allow us to record such small XMCD
signals with large signal-to-noise ratio. By knowing the
direction of the magnetic field and the helicity of the beam,
we conclude that Y is polarized antiparallel to the magnetic
moment of Fe. This behavior is consistent with the fact
that Y is in the beginning of the 4d transition elements,
i.e. it has an almost empty 4d electronic band. The practi-
cally noise-free signal has allowed us to trace also element-
specific hysteresis curves at the Y L$_3$-edge. As a relative
measurement it was also possible to trace for the narrow
amorphous ribbon sample. Fig. 5 depicts a signal propor-
tional to the projection of the Y-magnetic moment along

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Fig. 2. Ferromagnetic resonance signal recorded for the Fe$_{71.3}$B$_{24}$Y$_{4.8}$
ribbon. The small linewidth value indicates the high degree of structural
and magnetic homogeneity.

Fig. 3. Vibrating sample magnetometry loop recorded at room temper-
ature for the Fe$_{71.3}$B$_{24}$Y$_{4.8}$ ribbon, with the magnetic field applied parallel
to the ribbon plane. The inset shows the magnification of the loop near
small fields, revealing a coercivity value of $H_C \sim 190 \text{A/m}$ typical for
magnetostrictive soft magnetic materials.

Fig. 4. (Top) X-ray absorption and (bottom) X-ray magnetic circular
dichroism spectra recorded at the L$_{3,2}$-edges of Y in a splat-cooled
Fe$_{71.2}$B$_{24}$Y$_{4.8}$ sample. The step-like functions used in the analysis of the
XAS spectra are also plotted.
the direction of the applied field. The curve was recorded with the magnetic field applied in the direction normal to the film plane for the ribbon prepared from the ingot. This is a typical hard-axis magnetization curve with saturation field of about 1 MA/m. The reversed path of the curve indicates the negative sign of the Y-magnetic moment with respect to the Fe one.

In order to determine the magnetic moment of Y and separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the spectra of separate it into spin and orbital contributions we have applied the sum-rule analysis [21,22] to the
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In this work, the new Fe$_{71.2}$B$_{24}$Y$_{4.8}$ glassy alloy has been investigated in the form of ribbons and splat-cooled samples with a combination of synchrotron X-ray and conventional laboratory techniques. X-ray diffraction experiments at HASYLAB have shown that the ribbons are amorphous. This observation is further supported by the X-ray absorption fine structure spectrum recorded at the K-edge of Fe at E.S.R.F. Ferromagnetic resonance measurements carried out on the ribbons have revealed a high structural and magnetic homogeneity of the samples. Vibrating sample magnetometry in combination with X-ray magnetic circular dichroism measurements at the La$_{5}$Fe$_{5}$Y$_{25}$-edges of Y at E.S.R.F. have allowed for the determination of Fe and induced Y-magnetic moments; the latter ones were quantitatively determined, to our knowledge, for the first time.

5. Summary

The induced magnetic moment of Y is relatively small. It, however, has definitely a non-zero value, unlike a recent report for the magnetic moment of Y in YCo$_2$ films [19]. Whereas the local electronic structure of Y should evidently be different in YCo$_2$ and in amorphous Fe$_{71.2}$B$_{24}$Y$_{4.8}$ alloy due to the different atomic surroundings, the qualitatively different Y response to the neighboring magnetic moments is quite remarkable. In that case the zero magnetic moment of Y had been attributed to an almost empty 4d electronic band [19]. We believe that the very small, but finite, induced magnetic moment of Y determined, to our knowledge, for the first time in this work by XMCD, is made possible by the technical evolution of the third generation synchrotron radiation sources. One may notice that this evolution has already allowed for the determination of induced magnetic moments even smaller than the one of Y, such as the ones of Ta in CoCrPtTa alloys [23] and of Au in Co/Au multilayers [24]. Taking into account the small proportion of the Y to Fe atoms (~6.7%) and the ratio of the Y to Fe magnetic moments (~3–4%), it is safely concluded that the magnetic contribution of the induced magnetic moment of Y to the total magnetization of the FeBY samples should be only of about 0.2–0.3%.

Following the analysis described in Ref. [25], we combined the XMCD information for the Y-moment with the VSM information for the total magnetization. Furthermore, we considered the 10% decrease of the magnetization between 10 and 300 K. This way, we determined the magnetic moment of Fe to be 1.83 $\mu_B$/atom ± 5%. This value is somewhat decreased as compared to the bulk-Fe moment [18]. This is evidently caused by the d–d (Fe–Y) and p–d hybridization (Fe–B) of the Fe d-electrons with the orbitals of the surrounding non-magnetic atoms. In contrast to the earlier concept of charge transfer (which is not confirmed by direct techniques as photoelectron spectroscopy) it is now understood that the change of magnetization is dominantly caused by the hybridization of the electron states. The influence of the nearest neighbor atoms is best described as the admixture of the external atomic orbitals, i.e. by the hybridization of the d-electron states (which dominate the magnetic moment) with the neighboring atom d and p-electron states [26].
Acknowledgements

We thank the E.S.R.F. for the excellent operation conditions. The work has been carried out in the framework of the Hungarian–Greek collaboration, GR-6/03 (B.323 for the Greek side). The research project 03E667 PENEED2003 ‘Self-assembled networks of magnetic nanoparticles for applications of permanent magnets, sensors and magnetic recording media’ is acknowledged for partial financial support. Finally, the Research Committee of the University of Patras is also acknowledged (project Karatheodori2003: ‘Growth, characterization and properties of technologically important magnetic and superconducting thin films’, Grant B.101).

References