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The Magnetization Behavior of Amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0, 1, 4$) Alloys

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We report the salient features of the magnetic properties of amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0, 1, 4$) alloys. The study of dc-magnetization properties and the ac-susceptibility was carried out. The temperature dependence of the magnetization follows the predictions of spin wave excitations with long wavelengths. Especially, the addition of boron modifies the magnetic properties: the spin wave stiffness increases from 56.8 to 65.7 meVÅ^2 and Curie temperature increases from 298 K to 352 K. This result indicates a magnetic hardening of the exchange interaction by higher exchange energy. Thus, the substitution of iron by boron favours the increase of magnetic order in this system.

1. Introduction

Fe rich transition metal type amorphous alloys such as Fe-M-B-Cu (M = Zr, Hf and Nb) system with high boron content of about 10 at.% have been reported to have good soft magnetic properties as shown by static magnetic measurement [1, 2]. Such materials are considered to have a potential for high frequency core material applications because of possibilities to obtain a high effective permeability and a low coercive force after the appropriate heat treatment. In amorphous alloys it is well known that induced magnetic anisotropy can be effectively suppressed by controlling the quench rate or by annealing the same in a rotating magnetic field [3]. The high saturation magnetization of iron-rich rapid quenched amorphous materials are explained by the Fe atoms being located in the same body-centered cubic (bcc) lattice as there conventional polycrystalline counterpart with only minor difference in lattice constant[4]. In metal-metalloid alloys the magnetic and electron transport properties of the amorphous materials are strongly affected by the type of element and its concentration because of the superposition of structural and compositional disorder. It is known that the exchange interaction between two Fe atoms depends sensitively on the relation between their interatomic separation and the range of their 3d-orbitals. Many works about soft magnetic materials have been published, especially about how functional properties depend on annealing conditions [5, 6, 7]. With the aim of understanding these amorphous alloys before the crystallization, we studied the low temperature dependence of magnetization and AC susceptibility. In order to get the better understanding of the magnetic properties, it is required to investigate the magnetization behavior. In this paper, we study and discuss the effect of replacing iron with boron in the $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0, 1, 4$) alloy system.

2. Experimental

Ingots were prepared using conventional arc-melting in an argon atmosphere and the ribbons were produced by single roller melt spinning technique. The ribbons obtained were 20 μm thick and about 2 mm wide. The glassy state of the samples were verified by X-ray diffraction using Cu $K\alpha$ radiation. DC magnetization measurements were carried out using a SQUID magnetometer at temperatures ranging from 5 K to 300 K in a field of 2 T. The spectroscopic splitting factor, g was measured using ferromagnetic resonance (FMR) spectrometer. AC susceptibility measurements were performed using a home-built balanced mutual inductance bridge. We measure simultaneously both the elastic component, x' and the loss component, x'' of the AC susceptibility at 129.6 Hz and in field strengths varying from 5 mOe to 1 Oe depending on the particular situation. Curie temperature for the samples with T_c's above the range accessible with the AC susceptometer was determined with a magneto-thermo gravimetric (TGS) instrument.

3. Results and Discussion

3.1. Temperature dependence of magnetization

In amorphous structures the wave vector is not well defined and no easily definable Brillouin zone exists. However, much experimental evidence has shown that the long wave length spin waves can be clearly and stably defined in

amorphous alloys with a topologically disordered type, which is manifested by the random closing packing of the atomic spheres. Low temperature magnetization measurements enable us to estimate the intrinsic magnetic properties of the samples. The decrease in magnetization with increasing temperature at low temperatures in both crystalline and non-crystalline ferromagnets can be adequately described by the Bloch's relation. Also from a fit to the temperature dependence of the magnetization in terms of the spin wave approximation using the expression [8],

$$[(M_s(0)-M_s(T)) / M_s(0)] = BT^{3/2} + CT^{5/2} \quad (1)$$

where B and C are coefficients related to spin wave excitiations. Fig. 1 show the temperature dependence of magnetization on amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys. In Fig. 2 we show the $T^{3/2}$ temperature dependence of magnetization on amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys. Our curves are well fitted with this temperature dependence and from the coefficients B and C we can calculate the spin wave stiffness constant, D. Bloch coefficient

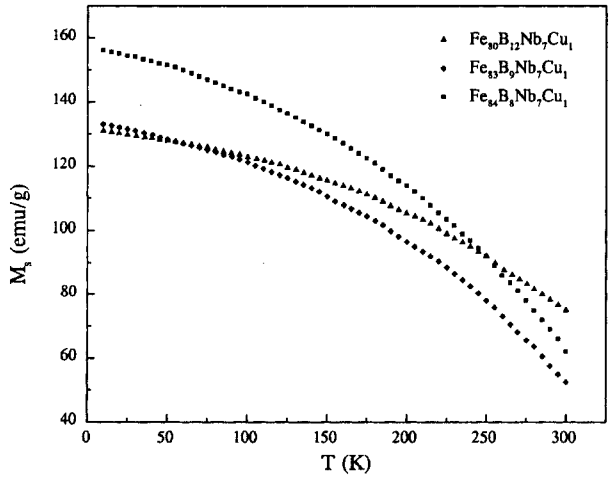

Fig. 1. The temperature dependence of the magnetization of amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys.

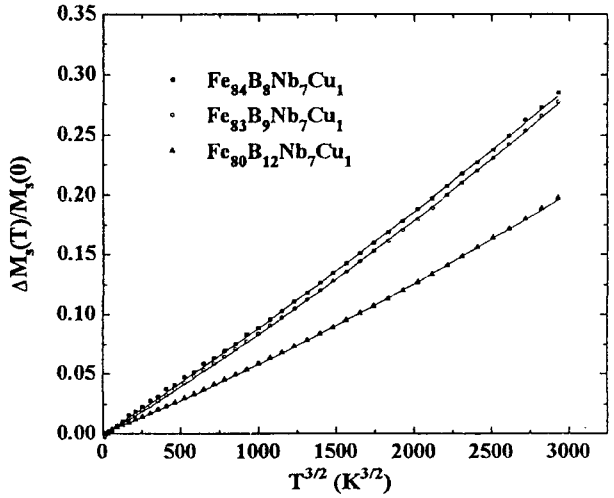

Fig. 2. $T^{3/2}$ temperature dependence of the magnetization of amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys.

B is related to the spin wave stiffness constant D given by the expression.

$$D = \xi(3/2)^{2/3}[g\mu_B / M_s(0)\, B]^{2/3}(\kappa_B/4\pi). \quad (2)$$

Here $\xi(3/2)$ is the Riemann zeta functions, g is the spectroscopic splitting factor, μ_B is Bohr magneton and k_B is the Boltzmann constant. From magnetic data we determine B which is the thermal average of the spin wave contribution for all wave length. We estimate the spin wave stiffness constant and the range of the exchange interaction in their glassy alloys. The spectroscopic splitting factor g represents the relative contribution of orbital magnetic moment to total magnetic moment. From our spectroscopic measurements we estimate the values for g to be 2.051, 2.063 and 2.098 for as-quenched $Fe_{84}Nb_7B_8Cu_1$, $Fe_{83}Nb_7B_9Cu_1$ and $Fe_{80}Nb_7B_{12}Cu_1$ alloys, respectively. Our results indicate that the contribution of orbital magnetic moment increases with increasing boron concentration. From our analysis we obtain for the spin wave stiffness, D values of 56.8, 58.5 and 65.7 meVÅ^2, with increasing boron concentration. This result implies that the magnetic structure of these alloy system changes with the substitution of Fe with boron. In addition, this behavior shows a "magnetic hardening" of the exchange interaction by higher exchange energy. In the spin wave theory, $\langle r^2 \rangle$ is the mean square range of exchange interaction, defined by

$$\langle r^2 \rangle = (16/3\kappa_B)[\xi(3/2) / \xi(5/2)]\,(CD/B). \quad (3)$$

The values of mean square range of exchange interaction are obtained to be 1.24, 1.34 and 1.43 Å^2, for as-quenched $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys, respectively. Our results show that the addition of boron enhances the exchange energy of Fe and increases of the magnetic order. The Curie temperatures obtained by magneto-thermo gravimetric measurements of these samples are 305 K, 316 K and 352 K with increasing boron concentration. Fig. 3 show the spin wave stiffness constant and Curie temperature as a function of boron content on amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys. Thus, it is seen that the addition of

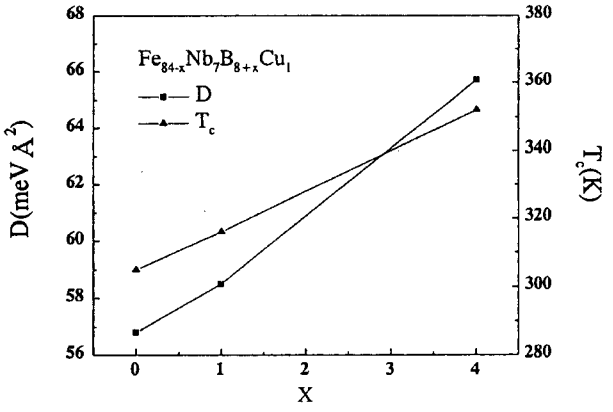

Fig. 3. The spin wave stiffness constant and Curie temperature as a function of boron content on amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys.

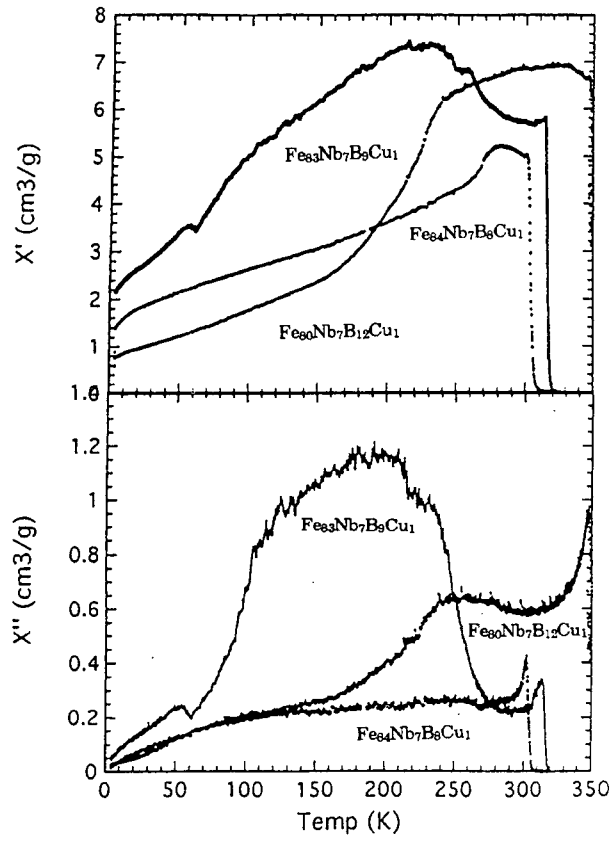

Fig. 4. The elastic and viscous part of the susceptibility for the amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys.

boron increases T_c reflecting an increase in the mean exchange interaction.

3.2. Temperature dependence of susceptibility

We have also measured the temperature dependence of the AC susceptibility. As this kind of measurement is a probe of the magnetization process which in turn is sensitively affected by a number of phenomena among which we believe anisotropy and magnetoelasticity are the most important, we expect a more complex picture. On increasing the temperature both x' (T) and x'' (T) start increasing slightly below the transition temperature. The values of Curie temperature obtained from AC susceptibility are same with magneto-thermo gravimetric measurements. The Curie temperature increases with increasing boron content and have a sharp peak somewhat just below T_c, which is the so called Hopkinson peak arising because of domain wall motion and hysteretic effects [9]. The temperature at which this peak occurs is strongly dependent on the applied AC-field. In Fig. 4 we show the elastic and viscous part of the susceptibility for the three different compositions. The susceptibility of $Fe_{84}Nb_7B_8Cu_1$ and $Fe_{83}Nb_7B_9Cu_1$ samples is slightly increasing response up to the T_c. We observe that elastic part of $Fe_{83}Nb_7B_9Cu_1$ sample has a broad peak at around 220 K. The loss part is even smaller and peaks close to T_c. The temperature at which this peak occurs is strongly dependent on the applied ac-field. We also observe that loss part of $Fe_{83}Nb_7B_9Cu_1$ sample is strongly temperature dependent in the 50-270 K temperature region and strongly fluctuating. The fluctuations weaken with lower field-strengths but despite using below 10 mOe for this sample we are not able to completely remove these complicating fluctuations. The susceptibility curve for this sample should not be regarded with the same confidence as the other two. The very broad and very high loss-peak for 50 mOe measurement clearly suggests that the H_c of the material has been surpassed and the magnetization process is mainly irreversible.

4. Conclusion

The temperature dependence of the magnetization of amorphous $Fe_{84-x}Nb_7B_{8+x}Cu_1$ ($x = 0$, 1, 4) alloys apparently follow the predictions of spin wave theory. We have shown that the replacement of Fe with boron in this system effectively increases the exchange interaction between two Fe atoms. The increased exchange interaction is manifested by an increase in T_c and spin wave stiffness constant. This indicates a magnetic hardening of the exchange interaction. These magnetization data could be explained by a giving rise to higher degree of ferromagnetic interaction increasing with boron concentration. Thus, the addition of boron favours the increase of magnetic order in this system.

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