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Magnetic Properties and Glass-Forming Ability of CoFeSiBNb Alloys

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Abstract—The effect of small tin, gallium, and zirconium additions on the magnetic properties of a $Co_{48}Fe_{25}B_{19}Si_4Nb_4$ alloy at high temperatures is studied. The temperature dependences of the magnetic susceptibility of the compositions under study are measured; the electron characteristics, such as the effective magnetic moment, the density of electron states at the Fermi level, and the paramagnetic Curie temperature, are calculated. Amorphous alloy samples are prepared by melt injection and vacuum suction casting.

Keywords: alloys, magnetic moment, Curie temperature
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INTRODUCTION

Ferromagnetic bulk metallic glasses (BMGs) are relatively new materials, which have the great prospect of using in practice. They exhibit the unique combination of magnetic and mechanical properties, which allows one to use these materials, for example, for manufacturing ultrasensitive sensors [1–3]. Despite of the attractiveness of this class of materials for various engineering applications, the industrial production of BMGs is now limited, since many alloys exhibit a relatively low glass-forming ability (GFA).

One of the ways for improving GFA consists in modification of a base composition. Previously, we studied the well-known $Co_{47}Fe_{20.9}B_{21.2}Si_{4.6}Nb_{6.3}$ composition and found that gallium added to the basic composition obviously improved the GFA, whereas antimony additions led to the fact that one failed to prepare amorphous samples in practice. To explain the obtained results, we studied the electric and magnetic properties of the liquid alloy and found that the paramagnetic Curie temperature θ can serve as an indicator of the efficiency of alloying addition [4, 5].

In the present work, we report stuyd the magnetic susceptibility of another composition, namely, $Co_{48}Fe_{25}B_{19}Si_4Nb_4$. Gallium, zirconium, and tin are selected as alloying additions.

EXPERIMENTAL

Samples of the base $Co_{48}Fe_{25}B_{19}Si_4Nb_4$ composition and samples with 2 at % gallium, zirconium, and antimony additions were prepared in a Leybold-HeraeusIS01/II vacuum induction furnace using pure components. For an investigation, samples in the form of cylinders 2 mm in diameter were prepared by casting, vacuum suction casting, and melt injection into a copper mold.

The magnetic susceptibility was studied in the temperature range from 800 to 1500°C using the relative variant of the Faraday method. All experiments were performed in a high-purity helium atmosphere at a heating rate of 3°C/min. The magnetic field was 0.4–0.9 T. Beryllium oxide crucibles were used in these studies.

RESULTS AND DISCUSSION

The studies of the structure of amorphous samples showed that melt injection is a preferable method, since vacuum suction casting often cause micropores on the sample surface, within which surface $(Fe,Co)_{23}B_6$ crystals can form. The amount of surface micropores is higher in tin-containing samples.

Figure 1 shows the typical temperature dependence of the magnetic susceptibility of the base composition. The curve can be divided into three arbitrary portions. According to DSC studies, the transition from portion *1* to portion *2* is not accompanied by thermal effect; the transition from portion *2* to portion *3* corresponds to melting. For all alloys, a hysteresis of the property is observed, which is due to undercooling.

For the Zr-containing composition, experiments were performed using step-by-step heating to various temperatures. During heating of a sample to 1250°C and subsequent cooling, the hysteresis due to the melt undercooling is less pronounced than that observed in the case of melt heating to 1450°C.

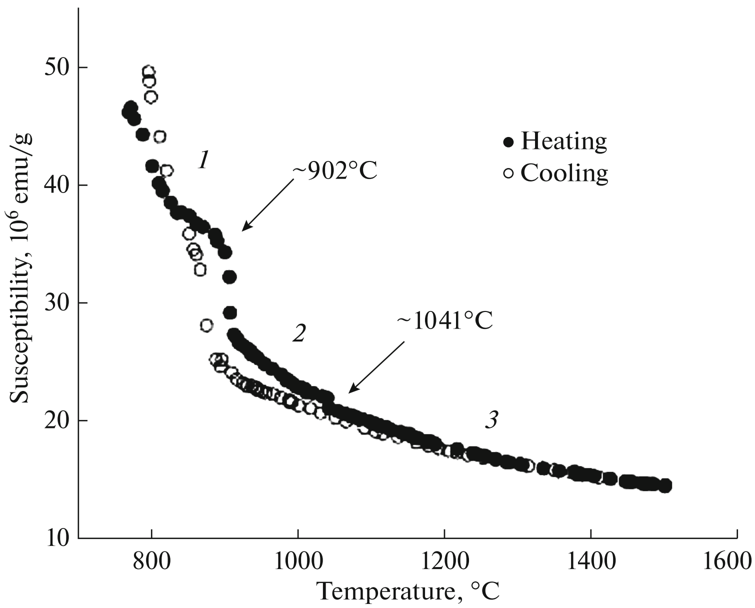

Fig. 1. Temperature dependence of the magnetic susceptibility of the base composition.

It is well known [6, 7] that the metastable $(Fe,Co)_{23}B_6$ phase first precipitates during the crystallization of amorphous FeCoBSiNb alloys. As the temperature increases, stable borides and α(Co,Fe) particles precipitate from the metastable phase. Assuming the presence of α(Co,Fe) particles in the crystalline sample, the jump in the temperature dependence of the magnetic susceptibility, which corresponds to the transition from portion *1* to portion *2*, can be attributed to the polymorphous transformation of the particles.

When preparing amorphous samples, we found the effect of preliminary heating of the melt before quenching on the quality of samples. The melt overheating also affects the hysteresis of the magnetic susceptibility, which is due to undercooling. It is likely that, at low overheatings above the liquidus temperature, the short-range order structure of the melt is similar to that observed before melting. Heating to high temperatures irreversibly changes the melt structure and is likely to lead to the disappearance of a short-range order, which is responsible for the high undercooling of the melt.

The temperature dependences of the magnetic susceptibility of the melts can be approximated by the generalized Curie–Weiss law

$$\chi(T) = \chi_0 + \frac{C}{T - \theta},$$

where χ_0 is the temperature-independent contribution to the magnetic susceptibility, C is the Curie constant, and θ is the paramagnetic Curie temperature. The Curie constant allows the effective magnetic moment per magnetic atom to be estimated, and χ_0 depends on the density of electron states at the Fermi level. The θ parameter is proportional to the exchange integral of neighboring atoms. Table 1 shows the obtained parameters and the calculated electron characteristics. It was found that the effective magnetic moment remains almost unchanged for all alloys, whereas, θ increases in adding zirconium to the base composition, remains almost unchanged in adding gallium,

Table 1. Electronic characteristics of the alloys

Composition	$\chi_0 \times 10^6$, emu/g	$N(E_f)$, eV^{-1}	θ, K	$C \times 10^3$, emu K/g	μ_{eff}, μ_B
$Co_{48}Fe_{25}B_{19}Si_4Nb_4$	7.09	2.7	740	7.7	2.0
$[Co_{48}Fe_{25}B_{19}Si_4Nb_4]_{98}Ga_2$	6.82	2.6	750	7.3	2.0
$[Co_{48}Fe_{25}B_{19}Si_4Nb_4]_{98}Zr_2$	6.82	2.6	765	7.4	2.0
$[Co_{48}Fe_{25}B_{19}Si_4Nb_4]_{97}Sn_2$	7.33	2.8	670	7.3	2.0

and substantially decreases in adding tin as compared to θ for the base composition.

CONCLUSIONS

Samples of bulk CoFeBSiNb amorphous alloys with Ga, Zr, and Sn additions were prepared. The magnetic properties of these alloys were studied at high temperatures. It was found that gallium and zirconium additions led to an increase in the paramagnetic Curie temperature of the liquid alloys. A tin addition substantially decreases the value; this fact can indicate a decrease in the mutual overlapping of atomic shells and, therefore, can lead to a weakening of the interatomic interaction in the melt. The paramagnetic Curie temperature can be used as an indicator of the efficiency of alloying addition.

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