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Studying the Temperature Dependence of the Intensity of Magnetization of Rapidly Quenched Fe–Cu–Nb–Si–B Alloys

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Abstract—A study is performed of rapidly quenched alloys of the Finemet type with different compositions. The Curie temperature, Bloch constant, critical exponent, and spontaneous magnetization at 0 K are calculated by analyzing the low- and high-temperature dependences of magnetization. A linear correlation is found between the constant of spin-wave stiffness and the Curie temperature.

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INTRODUCTION

Alloys based on Fe–Si–B with small additives of Cu and Nb and obtained via quenching from the liquid state (Finemet) are of great interest. These alloys with an amorphous nanocrystalline structure can surpass both amorphous and nanocrystalline materials with respect to a number of service properties [1, 2].

The widespread use of nanocrystalline and amorphous Fe-based alloys of the Finemet type is due mainly to their magnetic properties [1]. Knowledge of the magnetic characteristics of these materials and their behavior under external impacts (e.g., the application of external magnetic fields and rising temperature) is important in creating magnetoelectronic products.

The temperature dependence of magnetization is one of the fundamental characteristics of a ferromagnet and determines such important parameters as spontaneous magnetization at 0 K $M_S(0)$, Curie temperature T_C, and Bloch constant B.

The behavior of magnetization $M_S(T)$ in the range of low temperatures is considered in terms of spin waves and can be described using Bloch's law [3–5]:

$$\frac{M_S(T)}{M_S(0)} = 1 - BT^{3/2} - CT^{5/2} - O\left(T^{7/2}\right). \qquad (1)$$

According to the theory of critical phenomena, dependence $M_S(T)$ takes the following form as we approach the Curie point:

$$M_S(T) \sim (T_C - T)^{\beta}. \qquad (2)$$

The aim of this work was to study in a wide range of temperatures the behavior of spontaneous magnetization $M_S(T)$ of rapidly quenched Fe–Cu–Nb–Si–B alloys with nine different compositions (Table 1), obtained via spinning. These compositions can be considered precursors for nanocrystalline soft magnetic alloys [1].

EXPERIMENTAL

Magnetization was studied in the temperature range of 4 to 975 K (up to temperatures above the Curie temperature of the above rapidly quenched alloys [6, 7]) using an MPMS 7XL Quantum Design SQUID magnetometer and a vibration magnetometer. The structure of the faces was studied using a Carl Zeiss Ultra 55+ scanning electron microscope.

RESULTS AND DISCUSSION

The temperature dependence of the spontaneous magnetization of Fe–Cu–Nb–Si–B alloys in the temperature range of 4 to 975 K is shown in Figure 1. This dependence allowed us to determine experimentally the Curie temperatures of the amorphous state of the studied alloys: T_C^{am} ~ 600 K. The emergence of spontaneous magnetization upon a rise in temperature (for, e.g., samples $Fe_{73}Cu_{1.5}Nb_3Si_{16.5}B_6$ and $Fe_{74}Cu_1Nb_3Si_{16}B_6$ (Fig. 1)) was associated with the start of a multiple-stage transition to the nanocrystalline state [7]. T_C^{am} has not been determined experi-

Table 1. Magnetic parameters of Fe–Cu–Nb–Si–B alloys

Composition	B, 10^{-5} K$^{-3/2}$	C, 10^{-8} K$^{-5/2}$	T_C, K	β	$M_S(0)$, G	D, MeV Å^2	A, 10^{-7} erg cm^{-1}
$Fe_{70}Cu_1Nb_3Si_{13}B_{13}$	1.55	2.64	657	0.380	725	187	5.59
$Fe_{71.5}Cu_1Nb_5Si_{16.5}B_6$	2.65	8.68	562	0.389	1006	92	3.79
$Fe_{73}Cu_{1.5}Nb_3Si_{16.5}B_6$	1.63	3.41	612	0.378	943	152	5.90
$Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$	1.66	–	617	–	950	150	5.85
$Fe_{74}Cu_1Nb_3Si_{16}B_6$	1.33	2.87	628	0.364	1092	158	7.10
$Fe_{74.3}Cu_{0.2}Nb_3Si_{16.5}B_6$	1.64	3.09	615	0.375	1034	143	6.07
$Fe_{77}Cu_1Nb_3Si_{13}B_6$	1.35	4.58	627	0.405	1087	168	7.51
$Fe_{77.5}Cu_{0.5}Nb_3Si_{8.5}B_{10.5}$	1.73	4.13	584	0.423	1159	128	6.09
$Fe_{77}Cu_1Si_{16}Nb_6$	0.99	2.31	733	0.456	1034	200	8.50
3D Heisenberg [10]				0.365			

mentally for $Fe_{77}Cu_1Si_{16}B_6$, since this alloy's transition to the equilibrium state starts below the critical temperature of the ferromagnetic–paramagnetic phase transition.

Equation (1) can be used for amorphous alloys up to temperatures on the order of ~$0.5T_C$ [8, 9]. As a result, Bloch constants B were calculated according to dependence $M_S(T)/M_S(0) = f(T)$ (Figs. 2a, 2c, 2e, 2g) in the temperature range of 4 to 250–300 K (Table 1).

As we approach T_C, dependences $M_S(T)/M_S(0) = f(T)$ for the studied spinning bands based on Fe (Figures 2b, 2d, 2f, 2h) allowed us to determine critical exponents of β alloys according to Eq. (2) (Table 1). The calculated values of the critical exponent were close to the theoretical ones in [10] (β = 0.365), allowing us to consider rapidly quenched Fe–Cu–Nb–Si–B alloys as homogeneous three-dimensional Heisenberg ferromagnets from a magnetic point of view.

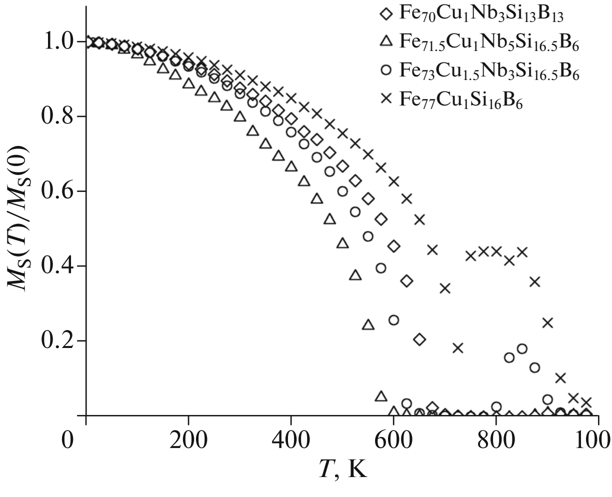

Fig. 1. Temperature dependence of the reduced magnetization of Fe–Cu–Nb–Si–B alloys.

The value of the Bloch constant can be expressed in terms of spin-wave stiffness D of ferromagnetic alloys [3]:

$$B = \frac{g\mu_B}{M_S(0)}\left(\frac{k}{4\pi D}\right)^{3/2}\zeta(3/2), \tag{3}$$

where $g = 2.1$ is the Lande factor for iron-based alloys, $M_S(0)$ is the saturation magnetization at 0 K, and $\zeta(3/2) = 2.612$ is the Riemann zeta function.

We calculated the values of saturation magnetization at room temperature using the experimental data obtained in [11] for studying fast-quenched Fe–Cu–Nb–Si–B alloys according to ferromagnetic resonance. In this work, they were normalized to the value of spontaneous magnetization $M_S(0)$ (Table 1).

Spin-wave stiffness D is directly related to constant A of exchange stiffness [3, 5] by the equation

$$A = \frac{DM_S(0)}{2g\mu_B}. \tag{4}$$

The values obtained for parameters T_C, D, and A for Fe–Cu–Nb–Si–B alloys of different compositions are presented in Table 1.

Figure 3 shows the correlation between spin-wave stiffness and the Curie temperature for the rapidly quenched iron-based alloys examined in this work. This $D = f(T_C)$ dependence was approximated using the linear equation

$$D\left[\text{meV Å}^2\right] = 0.9T_C[\text{K}] - 406. \tag{5}$$

It is worth noting that the D and T_C values for the sample $Fe_{77}Cu_1Si_{16}B_6$ do not follow the general trend. This indicates there was already a crystalline phase in the amorphous matrix in the initial (unannealed) state (Fig. 4), allowing us to consider this alloy partially crystallized.

For a classical ferromagnet, the relation between the spin-wave stiffness and the Curie temperature in

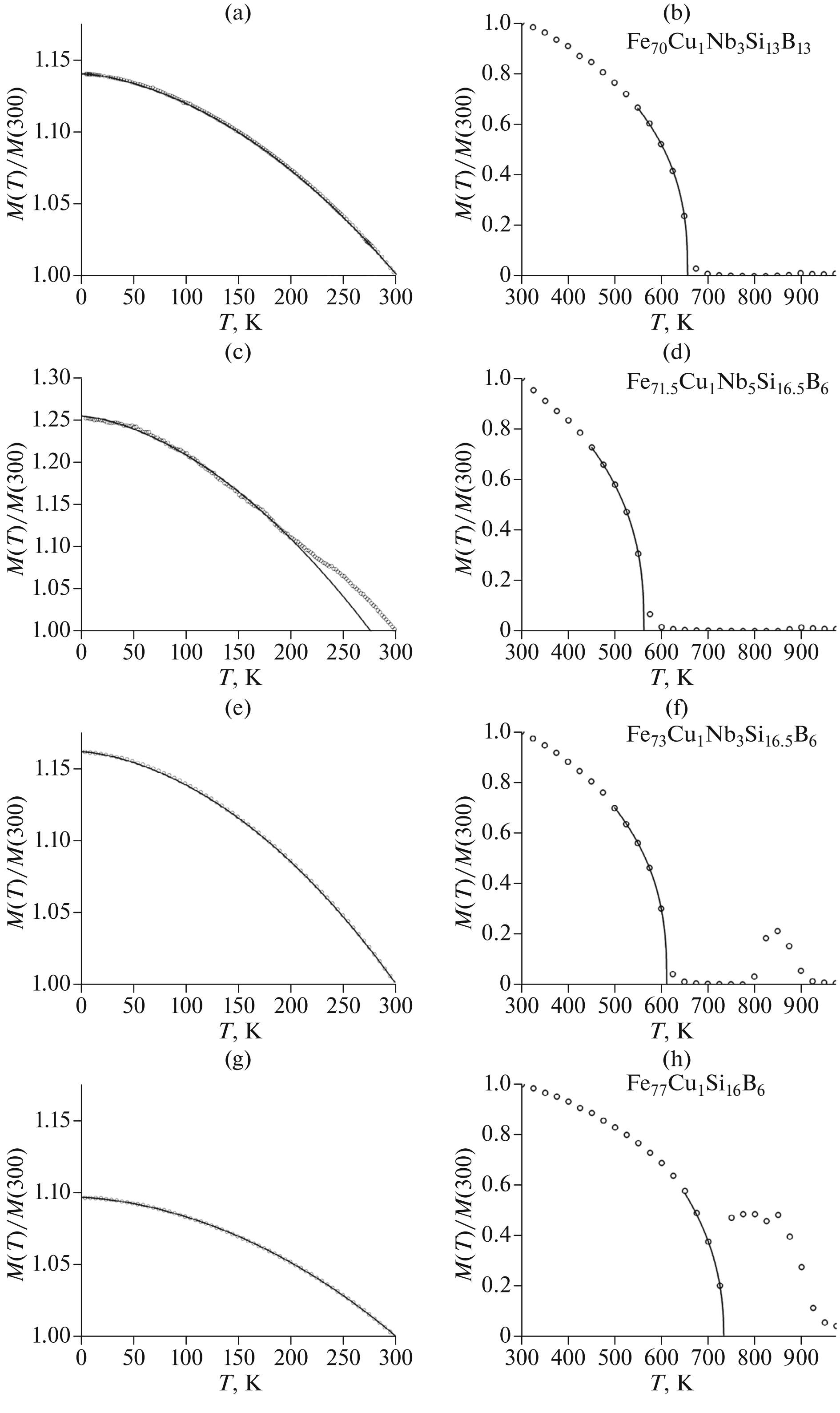

Fig. 2. Approximation of experimental data according to (a, c, e, g) Bloch's law (Eq. (1) and (b, d, f, h) the equation of critical phenomena (Eq. (2)).

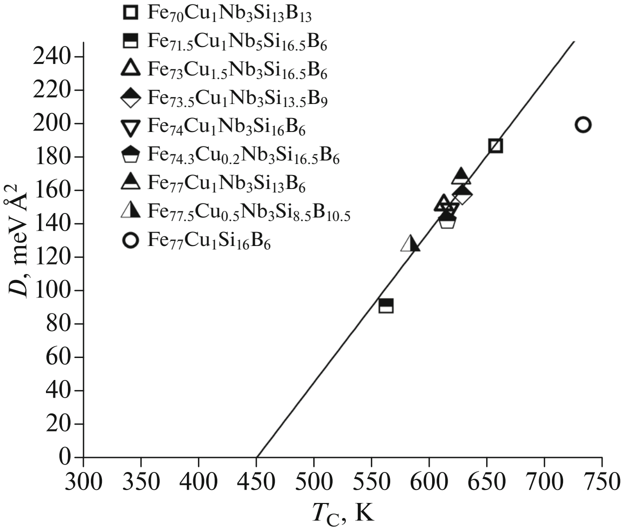

Fig. 3. Spin-wave stiffness D in the dependence of Curie temperatures T_C of Fe–Cu–Nb–Si–B alloys.

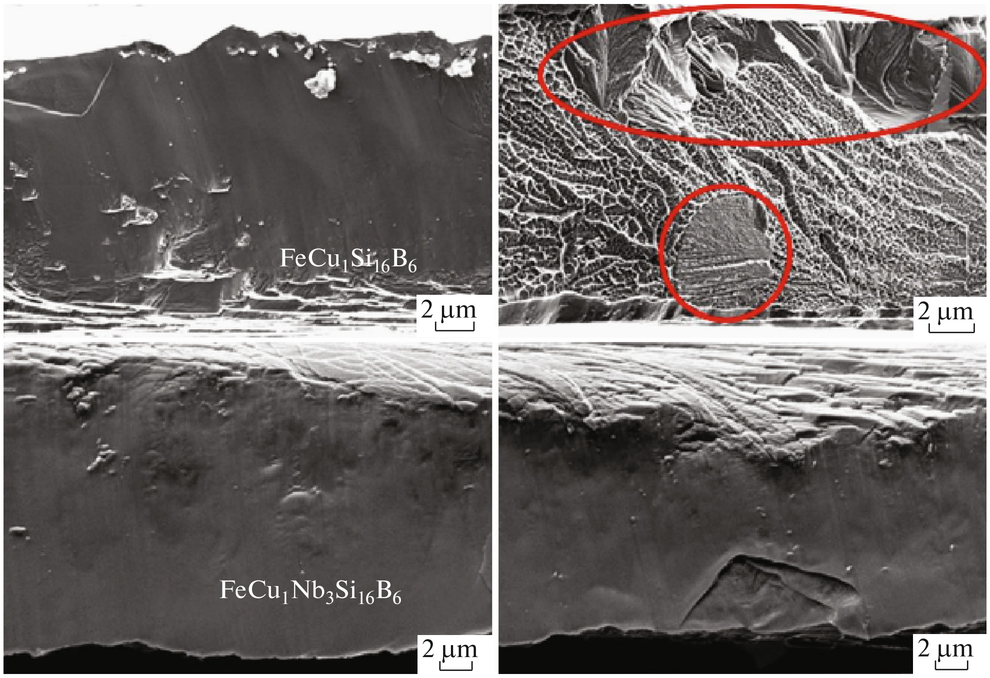

Fig. 4. Electron microscope images of the faces of Fe–Cu–Nb–Si–B alloys. The areas with characteristic damage corresponding to the crystal structure are marked in red.

the theory of localized magnetism can be presented as the dependence [5]

$$D \sim Ja^2 = \mathrm{const}\, T_C, \qquad (6)$$

where J is the exchange integral and a is the lattice constant. The constant of spin-wave stiffness must therefore be zero at zero Curie temperature. In our study of amorphous ferrimagnetic Fe–Cu–Nb–Si–B alloys, the D constant displayed an unusual linear correlation with the Curie temperature and predicted a zero value of D at a non-zero value of the Curie temperature: $T_C = 451$ K.

CONCLUSIONS

Our study of the behavior of the magnetization of rapidly quenched Fe–Cu–Nb–Si–B alloys upon changes in temperature revealed a linear relationship between spin-wave stiffness and the Curie temperature. This allowed us to predict the value of the constant of exchange stiffness, a parameter needed for micromagnetic modeling and micromagnetic calculations.

The obtained linear correlation between D and T_C and Eq. (5) assumed a zero value of spin-wave stiffness at a non-zero final value of the Curie temperature. This $D = f(T_C)$ dependence testifies to the complex nature of ferromagnetic ordering in amphoric alloys.

The obtained value of critical exponent β for most of our rapidly quenched Fe–Cu–Nb–Si–B alloys was close to the one calculated theoretically for a three-dimensional homogeneous Heisenberg ferromagnet, demonstrating the possibility of applying this model to the studied alloys.

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