

Magnetic properties and heat expansion of a binary Fe-Ni amorphous alloys

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DOI: 10.26565/2222-5617-2020-32-03

A comprehensive study of the magnetic properties (magnetostriction, magnetic susceptibility, Curie temperature) and thermal expansion of amorphous alloys of the $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ system of five compositions was carried out.

The samples were cut from a strip 30 μm thick and had a rectangular shape. Two variants of orientation of the long side of the sample were used: along and across the tape (longitudinal and transverse samples). Measurements of magnetization and thermal expansion were carried out in the temperature range 90 – 300 K in fields up to 6.5 kOe. To determine the change in the length of the sample under the influence of a magnetic field or in connection with a change in temperature, we used the method of wire constant strain gauges connected according to the DC bridge circuit. The sensitivity of the setup to the relative change in the length of the sample was $8 \cdot 10^{-7}$. The basis for determining the Curie temperature was the temperature dependence of the initial magnetic susceptibility obtained by the induction method.

It is shown that the linear magnetostriction constant and the Curie temperature decrease with increasing nickel concentration. The nonlinear character of the $T_c(x)$ dependence indicates an active participation of Ni atoms in the exchange interaction in alloys containing boron, in contrast to alloys with phosphorus. The volume (forced) magnetostriction was detected and estimated from the linear portions of the curves $\delta l/l(H)$ in fields above the saturation field. Bulk magnetostriction, like linear, is positive and also decreases with increasing nickel content in the alloy.

Measurements of the dependence $\delta l/l(H)$ at different temperatures showed that the character of the curves does not qualitatively change, the saturation magnetostriction increases with decreasing temperature in the range 300 – 100 K. The independence of the character of the curves $(\delta l/l)_s(T)$ on x indicates that the predominance of the single-ion mechanism of the formation of magnetostriction in Ni-substituted iron-based alloys of the studied compositions is preserved.

Thermal expansion curves recorded in the range 90 – 300 K do not show anomalies, the linear expansion coefficient monotonically increases with increasing nickel concentration, which correlates with a decrease in volume magnetostriction.

Keywords: amorphous alloy, magnetostriction, Curie temperature, thermal expansion.

Магнітні властивості та теплове розширення бінарних Fe-Ni аморфних сплавів

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Проведено комплексне дослідження магнітних властивостей (магнітострикції, магнітної сприйнятливості, температури Кюрі) і теплового розширення аморфних сплавів системи $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ п'яти складів.

Зразки вирізалися з стрічки товщиною 30 мкм і мали прямокутну форму. Використовувалися два варіанти орієнтації довгої сторони зразка: уздовж і поперек стрічки (поздовжні і поперечні зразки). Вимірювання намагніченості і теплового розширення проводилися в температурному інтервалі 90 – 300 К в полях до 6.5 кЕ. Для визначення зміни довжини зразка під дією магнітного поля або в зв'язку зі зміною температури використовувався метод дротяних константових тензодатчиків, включених за схемою моста постійного струму. Чутливість установки до відносної зміни довжини зразка становила $8 \cdot 10^{-7}$. Основою для визначення температури Кюрі служила температурна залежність початкової магнітної сприйнятливості, отримана індукційним методом.

Показано, що константа лінійної магнітострикції і температура Кюрі зменшуються зі збільшенням концентрації нікелю. Нелінійний характер залежності $T_c(x)$ свідчить про активну участь атомів Ni в обмінній взаємодії в сплавах, що містять бор, на відміну від сплавів з фосфором. Виявлена і оцінена з лінійних ділянок кривих $\delta l/l(H)$ в полях вище поля насичення об'ємна (вимушена) магнітострикція. Об'ємна магнітострикція, як і лінійна, позитивна і також зменшується зі збільшенням вмісту нікелю в сплаві.

Вимірювання залежності $\delta l/l(H)$ при різних температурах показало, що характер кривих якісно не змінюється, магнітострикція насичення зростає з пониженням температури в інтервалі 300 – 100 К. Незалежність характеру кривих $(\delta l/l)_s(T)$ від x вказує на те, що переважання одноіонного механізму формування магнітострикції в Ni-заміщених сплавах на основі заліза досліджених складів зберігається.

Криві теплового розширення, зняті в інтервалі 90 - 300 К, не виявляють аномалій, коефіцієнт лінійного розширення монотонно збільшується зі збільшенням концентрації нікелю, що корелює зі зменшенням об'ємної магнітострикції.

Ключові слова: аморфний сплав, магнітострикція, температура Кюрі, теплове розширення.

Магнитные свойства и тепловое расширение бинарных Fe-Ni аморфных сплавов

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Проведено комплексное исследование магнитных свойств (магнитострикции, магнитной восприимчивости, температуры Кюри) и теплового расширения аморфных сплавов системы $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ пяти составов.

Образцы вырезались из ленты толщиной 30 мкм и имели прямоугольную форму. Использовались два варианта ориентации длинной стороны образца: вдоль и поперек ленты (продольные и поперечные образцы). Измерения намагниченности и теплового расширения проводились в температурном интервале 90 – 300 К в полях до 6.5 кЭ. Для определения изменения длины образца под действием магнитного поля или в связи с изменением температуры использовался метод проволочных константановых тензодатчиков, включенных по схеме моста постоянного тока. Чувствительность установки к относительному изменению длины образца составляла $8 \cdot 10^{-7}$. Основой для определения температуры Кюри служила температурная зависимость начальной магнитной восприимчивости, полученная индукционным методом.

Показано, что константа линейной магнитострикции и температура Кюри убывают с увеличением концентрации никеля. Нелинейный характер зависимости $T_c(x)$ свидетельствует об активном участии атомов Ni в обменном взаимодействии в сплавах, содержащих бор, в отличие от сплавов с фосфором. Обнаружена и оценена из линейных участков кривых $\delta l/l(H)$ в полях выше поля насыщения объемная (вынужденная) магнитострикция. Объемная магнитострикция, как и линейная, положительна и также уменьшается с увеличением содержания никеля в сплаве.

Измерение зависимости $\delta l/l(H)$ при различных температурах показало, что характер кривых качественно не изменяется, магнитострикция насыщения возрастает с понижением температуры в интервале 300 – 100 К. Независимость характера кривых $(\delta l/l)_s(T)$ от x указывает на то, что преобладание одноіонного механизма формирования магнитострикции в Ni-замещенных сплавах на основе железа исследованных составов сохраняется.

Кривые теплового расширения, снятые в интервале 90 – 300 К, не обнаруживают аномалий, коэффициент линейного расширения монотонно увеличивается с увеличением концентрации никеля, что коррелирует с уменьшением объемной магнитострикции.

Ключевые слова: аморфный сплав, магнитострикция, температура Кюри, тепловое расширение.

Introduction

One of the most important amorphous materials for techniques is transition metal-metalloid (T-M) type alloys. As transition metals, commonly used are Fe, Ni, Co, and combinations thereof. The magnetic properties of these alloys also depend on the quantitative and qualitative metalloid composition. In Ref. [1] results of studies investigations of induction B , coercive force H_c , magnetic permeability μ in low fields, and Curie temperature T_c of an amorphous alloy based on Fe-Ni composition $(\text{Fe}_{1-x}\text{Ni}_x)_{0.78}\text{Si}_y\text{B}_{0.22-y}$, where $x = 0.0 \div 0.70$, $y = 0.04 \div 0.11$ are reported. It was shown that H_c varies from 0.02 to 0.04 Oe almost independently of the nickel content. The saturation induction B_s and, accordingly, residual induction of B_r decrease with increasing nickel

content, the maximum permeability $\mu_{max} = \frac{B_r}{H_c}$ has the same tendency as B_r . The crystallization temperatures T_x for alloys containing Si and B was found to be 40-70 °C

higher than for alloys with P, B and Al. Such alloys also have the highest values of T_c . These factors are useful for many practical applications.

The purpose of this work was to study several properties and characteristics (linear and volume magnetostriction, magnetic susceptibility, Curie temperature, thermal expansion) of amorphous alloys with the composition $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$.

1. Samples

In the work, amorphous metal ribbons of the composition $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ with a nickel content of $x = 0.0; 0.104; 0.208; 0.263; 0.416$ were investigated. The ribbons had a thickness of 30 microns and a width of 16 mm. To measure magnetostriction, the samples were cut from the ribbons in two directions: along and across its length (Fig. 1). Sample sizes were: 10 mm in length and 5 mm in width.

When measuring the magnetic susceptibility, a piece of tape was wound on the end of a ceramic straw in which there were wires of a thermocouple.

2. Experimental technique

2.1. Magnetostriction and thermal expansion

To measure magnetostriction and thermal expansion, we used the method of wire strain gauges connected by a bridge circuit. The working sensor R was glued to the sample under investigation, the compensating R_k – to a quartz plate. Constantan sensors with equivalent parameters – $R = R_k = 100 \pm 0.3 \Omega$ were used. The relative change in the length of the sample, equal to the relative change in the length of the wire strain gauge, is calculated by the formula:

$$\frac{\delta l}{l} = \frac{1}{C} \cdot \frac{\Delta R}{R}, \quad (1)$$

where C is the strain gauge (strain gauge sensitivity to deformation), R is the resistance of the working sensor, ΔR – is the change in the resistance of the working sensor, which is determined by the deviation of the zero pointer from the relation:

$$\Delta R = \frac{10^{-2}}{\alpha_{stand}} \alpha \quad (2)$$

where α_{stand} is the deviation when the resistance of the magazine connected in series with the working sensor changes by 0.01Ω , α is the deviation when the resistance of the working sensor changes by ΔR .

The sensitivity of the mount to relative deformation was $8 \cdot 10^{-7}$.

The temperature dependence of the linear deformation was studied in the temperature range from 90 K to 300 K. The sample temperature was measured with a copper-constantan thermocouple.

The magnetic field was created by an electromagnet. The maximum field in a gap of 108 mm was 6.5 kOe. The sample was located in a plane parallel to the magnetic field.

2.2. Magnetic susceptibility. Curie temperature

Measurement of the susceptibility of the sample was carried out in an alternating magnetic field created by a solenoid. The solenoid serves as the primary winding of the air transformer. The secondary winding consists of two coils: a measuring coil, into which the sample under study is placed, and a compensation coil.

Without the sample, the signal from the measuring coil is compensated by the compensation coil, for which the following relationship must be satisfied:

$$W_1 S_1 = W_2 S_2. \quad (3)$$

Here W_1, W_2 are the number of turns of the measuring and compensation coils, respectively, S_1, S_2 are their cross sections.

The final balancing is carried out by selecting the number of turns of the compensation coil and choosing its position in the non-uniform magnetic field of the solenoid.

When a sample is placed in a measuring coil, a signal appears that is proportional to the magnetic permeability (susceptibility) of the sample. The signal is amplified, detected and fed into the "y" input of the two-coordinate self-recording potentiometer. Thermo-e.m.f. of thermocouple, which is in thermal contact with the sample, is fed to the "x" input. The sample temperature is changed by the furnace. The furnace is wound bifilar, its mode of operation is chosen experimentally.

3. The discussion of the results

3.1 Magnetostriction

In amorphous magnetic materials, where magnetocrystalline anisotropy is absent, magnetostriction plays a very important role in magnetization processes. Due to magnetostriction, in the presence of internal mechanical stresses, magnetoelastic anisotropy occurs. As a result, such parameters as the initial susceptibility χ_0 , the saturation field H_s , the coercive force H_c become depend on the magnetostriction.

In this work, measurements of magnetostriction were performed for four variants of the geometry of the experiment, which are shown in Table. 1. The x axis is directed along length of ribbon, and the y axis is across.

Table. 1.

The geometry of the experiment

Orientation of samples	The field direction	The measuring direction
Longitudinal	x	x
	y	x
Transverse	x	y
	y	y

At room temperature, the longitudinal and transverse isotherms of magnetostriction relative to the applied field were measured. At other temperatures, only longitudinal magnetostriction was measured. In both type of samples, cut along the ribbon and across the ribbon, the longitudinal magnetostriction was found to be positive, and the transverse was found to be negative. In fig. 1 $\frac{\delta l}{l}(H)$

curves for longitudinal samples of compositions $x = 0.0; 0.104$ at room temperature are shown. The dependences

$\frac{\delta l}{l}(H)$ are similar for transverse and longitudinal samples.

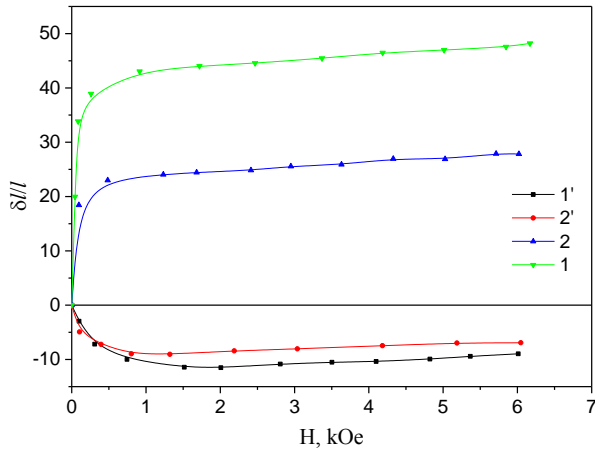


Fig. 1. Field dependences of longitudinal (1, 2) and transverse (1', 2') magnetostriction; T = 290 K:
 1, 1' - x = 0,0
 2, 2' - x = 0.104

For samples cut along the ribbon, at T = 290 K, saturation is observed in the fields of strength 770 ÷ 330 Oe, depending on the composition. The saturation field decreases with increasing nickel content (Fig. 2). For samples cut across the ribbon, saturation occurs in fields of strength 400 ÷ 340 Oe.

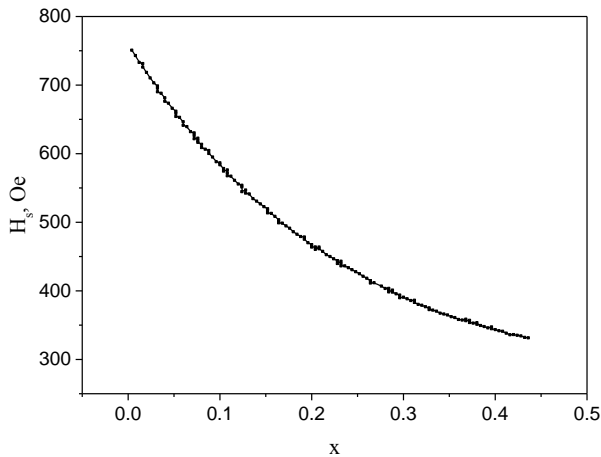


Fig. 2. The dependence of saturation field from nickel content (longitudinal samples, T = 290 K)

To calculate the magnetostriction constant λ_s , we used the formula valid for isotropic materials [2]:

$$\frac{\delta l(\theta)}{l} = \frac{3}{2} \lambda_s (\cos^2 \theta - \cos^2 \theta_0), \quad (4)$$

where θ and θ_0 are the angles between the direction of deformation measurement and the direction of the magnetization vectors \vec{I}_s in a multi-domain sample in the final and initial magnetic states. At saturation, the angle θ

is the same for all \vec{I}_s (they are oriented along the field) and the formula has the form

$$\left(\frac{\delta l}{l}\right)_s = \frac{3}{2} \lambda_s (\cos^2 \theta - \cos^2 \theta_0). \quad (5)$$

For longitudinal saturation magnetostriction $\theta = 0$ and

$$\left(\frac{\delta l}{l}\right)_s^{\parallel} = \frac{3}{2} \lambda_s (1 - \cos^2 \theta_0). \quad (6)$$

For transverse saturation magnetostriction $\theta = \pi/2$ and

$$\left(\frac{\delta l}{l}\right)_s^{\perp} = \frac{3}{2} \lambda_s (0 - \cos^2 \theta_0). \quad (7)$$

From (6) and (7) follows:

$$\lambda_s = \frac{2}{3} \left[\left(\frac{\delta l}{l}\right)_s^{\parallel} - \left(\frac{\delta l}{l}\right)_s^{\perp} \right]. \quad (8)$$

Figure 3 presents the dependence of λ_s on the composition at room temperature. With an increase in the nickel content, the magnetostriction decreases. The dependence $\lambda_s(x)$ is non-linear.

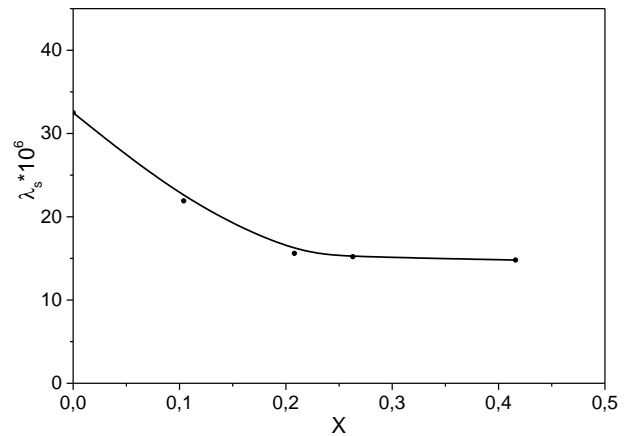


Fig. 3. The dependence of magnetostriction constant from nickel content

The review in Ref. [3] presents the dependence of magnetostriction on the composition for the system $(\text{Fe, Co, Ni})_{78}\text{Si}_8\text{B}_{14}$ at room temperature. The value of λ_s in this system (with a higher boron content) is somewhat higher than in the system under study. This difference is associated with a change in the ratio of the number of Si and B atoms. Although for alloys with a high content of cobalt, the type of metalloid atoms does not have a

noticeable effect on the magnitude of magnetostriction, for iron-based alloys, the situation is different. Therefore, as a result of varying the ratio of the percentage of phosphorus to the boron content from 4 to 2.3 λ_s varies from $2.6 \cdot 10^{-6}$ to $16 \cdot 10^{-6}$. In the system under study $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ the silicon-boron ratio is 0.69, which is 1.2 times less than in $\text{Fe}_{78}\text{Si}_{10}\text{B}_{12}$ – this causes a lower value of λ_s . The percentage decrease in λ_s (43%) in the same nickel concentration range practically coincides with that observed in this work.

Study of the temperature dependence of magnetostriction allows one to obtain information about the microscopic nature of anisotropy, since magnetostriction is determined by the derivative of the magnetic anisotropy energy with respect to strain and, therefore, is a reflection of the same microscopic mechanisms that lead to magnetic anisotropy.

To study of the temperature dependence of magnetostriction $\frac{\delta l}{l}(H)$ curves were taken at various temperatures. With a change in temperature, the shape of the curves does not change qualitatively, as can be seen from Fig. 4 for a transverse sample of composition $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$. Figure 5 presents $\frac{\delta l}{l}(T)$ for a series of samples cut across the ribbon. With decreasing temperature, an increase in magnetostriction is observed.

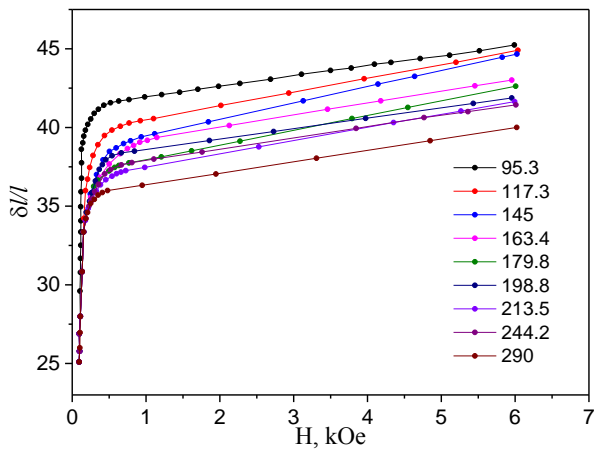


Fig. 4. Isotherms of the field dependence of the longitudinal magnetostriction of a transverse sample of composition $\text{Fe}_{78}\text{Si}_9\text{B}_{13}$.

In amorphous alloys, two mechanisms of magnetostriction (and microscopic anisotropy) are possible: single-ion and two-ion [4]. It has been established that, for iron-based alloys, the single-ion mechanism predominates, which is caused by magneto-ion being acted

upon non-uniform electric field in their local environment [5].

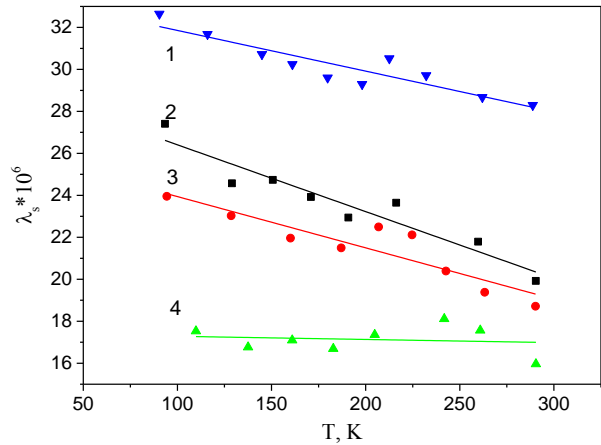


Fig. 5. Dependence of linear magnetostriction constant of $\text{Fe}_{78-x}\text{Ni}_x\text{Si}_9\text{B}_{13}$ alloy from temperature, x: 1 – 0.0; 2 – 0.104; 3 – 0.208; 4 – 0.416.

The fact that the character of the temperature dependence of magnetostriction observed in our samples does not change noticeably with an increase in the nickel content (Fig. 5) indicates the preservation of the single-ion nature of microscopic magnetic anisotropy.

The observed dependencies $\frac{\delta l}{l}(H)$ have a characteristic paraprocess region: after reaching saturation, the magnetostriction will increase linearly with increasing field. The growth of magnetostriction is caused by the so-called forced magnetostriction, which is due to the fact that a sufficiently strong external magnetic field orients the spins in one direction, overcoming their thermal misorientation [6]. Forced magnetostriction is volumetric in nature – $d\omega/dH = (1/V)(dV/dH)$ by definition, and is isotropic, as can be seen in Fig.1.

The volume magnetostriction was determined from the slope of the curves $\frac{\delta l}{l}(H)$ above saturation:

$$\frac{d\omega_s}{dH} = h_{||} + 2h_{\perp}, \quad (9)$$

where $h_{||}$ and h_{\perp} are the tangents of the angle of inclination of the linear sections for longitudinal and transverse magnetostriction. The obtained values of $\frac{d\omega_s}{dH}$ are of the order of $10^{-10} \div 10^{-9} \text{ Oe}^{-1}$, which is consistent with the literature data for other amorphous alloys [7-9].

3.2. Magnetic susceptibility. Curie temperature.

The behavior of the initial magnetic susceptibility as a function of temperature was investigated. With an increase in temperature in the range of 180–610 °C, the susceptibility practically remains constant. With a further increase it grows rapidly, and then drops sharply as the sample reaches the Curie temperature. Upon subsequent cooling, the course of the heating curve is reproduced until the maximum is reached, below that point the curve $\chi(T)$ is significantly higher than during heating: susceptibility increases about 2.5 times for all samples (Fig. 6). The observed increase in susceptibility is due to a decrease in internal stresses in the sample with nickel content in the alloy. The nonlinear character of the dependence $T_c(x)$ is associated with the participation of nickel atoms in the exchange interaction in alloys containing boron. The initial magnetic susceptibility increases after heating to temperatures $T > 350$ °C due to a decrease in internal stresses in the sample and the associated magnetoelastic anisotropy.

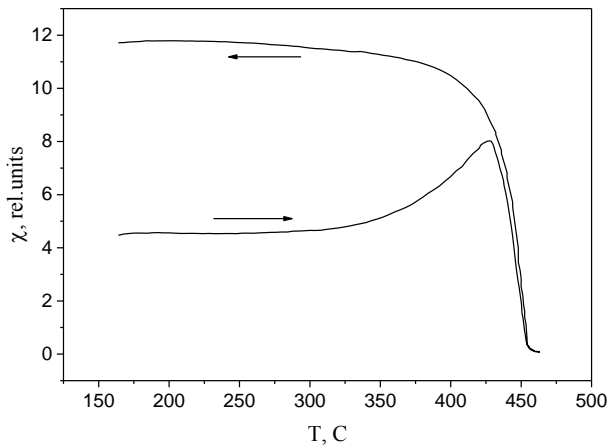


Fig. 6. Temperature dependence of initial magnetic susceptibility of $\text{Fe}_{78}\text{Ni}_8\text{Si}_9\text{B}_{13}$

The thermal expansion curves $\delta\ell/\ell(T)$ show no anomalies in heating to T_c , since the initial susceptibility is inversely related to them:

$$\chi_0 = C_1 \frac{I_s^2}{\lambda_s \sigma + C_2 K_1 + C_3}, \quad (10)$$

where σ is the stress, K_1 is the anisotropy constant.

To determine the temperature above which internal stresses are effectively removed, the sample with the maximum nickel content ($x = 0.416$) was subjected to heat-cooling thermal treatment with a constantly increasing maximum cycle temperature. T_{\max} equaled 150, 200, 250, 300, 350, 370, 400°C. The non-reversibility of the curve χ

(t) was observed starting from $T_{\max} 350$ °C becoming more pronounced with further growth of T_{\max} .

It should be noted that heating to T_c , carried out 3–4 times, led to an embrittlement of samples, which is an indicator of possible partial crystallization processes. The observed susceptibility behavior is consistent with the results given in Ref. [10].

From the dependencies of $\chi(T)$ T_c was determined for all compositions. The obtained values are presented in and in Fig. 7.

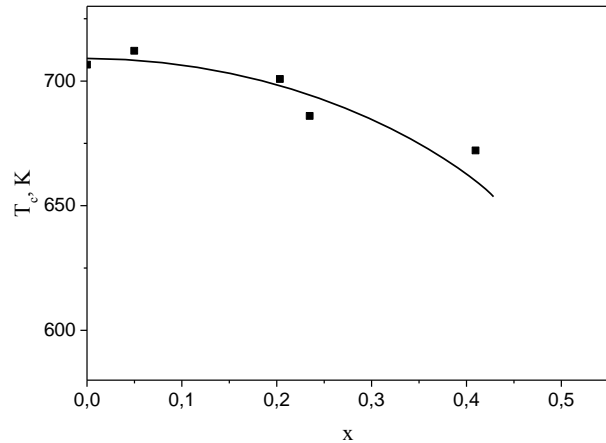


Fig. 7. Curie temperature dependence of composition

As reported in literature [3], the dependence of the Curie temperature of amorphous alloys on the concentration of (3d + 4s) electrons is similar to the dependence of the magnetic moment, but it is more sensitive to the composition of the transition metals contained in them. Thus, the magnetic moment of the alloy $(\text{Fe}_{0.5}\text{Ni}_{0.5})_{80}\text{M}_{20}$ is almost identical to the magnetic moment of $\text{Co}_{80}\text{M}_{20}$, and T_c for $\text{Co}_{80}\text{M}_{20}$, significantly higher than for $(\text{Fe}_{0.5}\text{Ni}_{0.5})_{80}\text{M}_{20}$. Fe-Ni based alloys are one of the most intensively studied systems. However, the exchange interactions in this system are complex, as indicated by the character of the dependence of T_c on the composition [11].

In this work, the introduction of nickel atoms instead of iron atoms leads to a decrease in T_c from 706 K for $x = 0.0$ to 683 K for $x = 0.416$. The dependence of $T_c(x)$ is nonlinear, which indicates that nickel atoms are actively involved in the exchange interaction. Moreover, the magnetic activity of nickel atoms depends on the metalloid composition: in alloys containing boron, nickel atoms are more magnetically active than in alloys containing phosphorus. Cluster calculations show [5, 3] that boron expands the d-zone of Ni much more than phosphorus does, and in $\text{Ni}_2\text{Fe}_2\text{P}$ in the place occupied by nickel, there

is a small magnetic moment antiparallel to the moment of iron, while in $\text{Ni}_2\text{Fe}_2\text{P}$ magnetic moment of nickel is almost zero.

It is assumed that in $(\text{Fe,Ni})_{80}\text{B}_{20}$ alloys, two types of exchange interactions contribute to T_c : direct exchange Fe-Fe, describing that part of T_c , which is similar to the value T_c of the alloy $(\text{Fe,Ni})_{80}\text{P}_{20}$, and indirect Fe-Ni-Fe exchange.

Another feature observed in this work should be noted: with an increase in the nickel content, the susceptibility decreases (Fig. 8).

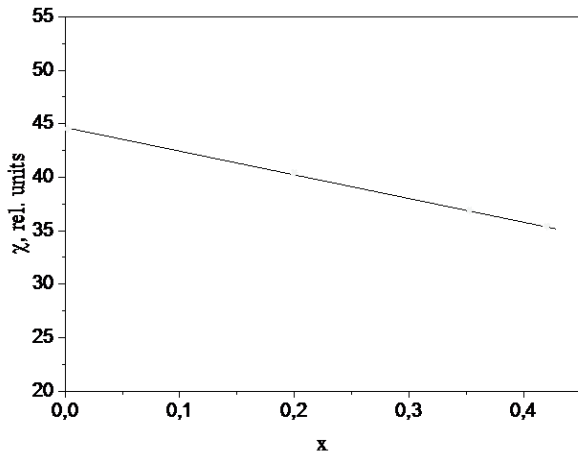


Fig. 8. Dependence of initial magnetic susceptibility from nickel content

3.3. Thermal expansion

It is known [12] that for crystalline Fe – Ni alloys, a complex dependence of the temperature coefficient of linear expansion (TCLE) on the nickel content is observed. TCLE varies non-monotonously and for most of the compositions of this system has the value of $(9 \div 13) \cdot 10^{-6} \text{ K}^{-1}$. The sharp minimum ($\alpha \sim 1 \cdot 10^{-6} \text{ K}^{-1}$) corresponds to the technically important invar structure containing 36% at% of Ni. The invar effect is caused by the temperature dependence of the bulk magnetostriction, which has a maximum ($\frac{d\omega}{dH} \sim 2.86 \cdot 10^{-8} \text{ Oe}^{-1}$) near 30 at% Ni in the field of $H = 1050 \text{ Oe}$.

In this work, the dependences of the relative elongation on temperature were measured for samples cut along the ribbon.

For all samples a monotonic change in the relative elongation with temperature was observed in the range of 90 ÷ 300 K. In fig. 9 $\frac{\delta l}{l}(T)$ is plotted for a sample with a concentration of Ni $x = 0.104$. The values of the linear

expansion coefficient near $T = 270 \text{ K}$ are found in the range $(7 \div 11.5)10^{-6} \text{ K}^{-1}$, depending on the composition. With an increase in nickel concentration, the linear expansion coefficient increases (Fig. 10).

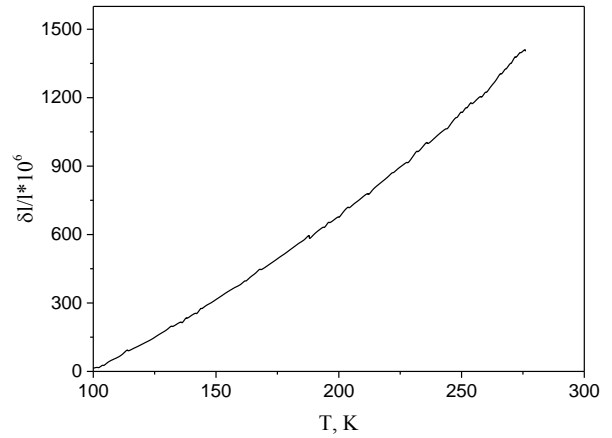


Fig. 9. Dependence of relative extension from temperature

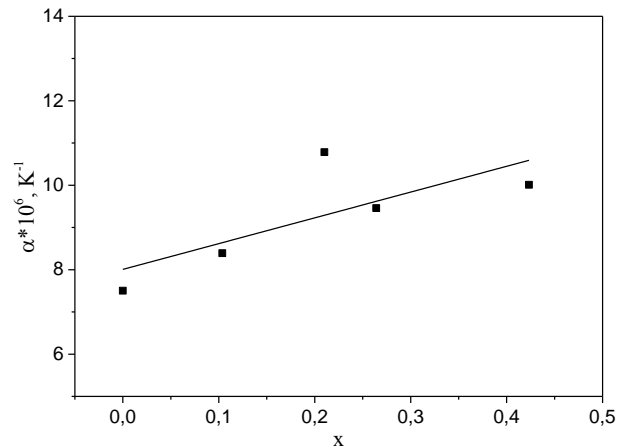


Fig. 10. Dependence of linear extension coefficient from nickel content, $T = 270 \text{ K}$

TCLE depends on volumetric magnetostriction as [12]:

$$\alpha_H = \alpha_l - \frac{1}{3} \left(\frac{d\omega}{dH} \right)_T \cdot \left(\frac{dH}{dT} \right)_l, \quad (11)$$

where α_H is TKLE at a constant field strength; α_l is TCLE which the material would have if its magnetization were kept constant; $\left(\frac{dH}{dT} \right)_l$ describes variation of the field required to maintain a constant value of the saturation magnetization with temperature, it tends to decrease with temperature; $\left(\frac{dH}{dT} \right)_l > 0$, therefore, if $\left(\frac{d\omega}{dH} \right)_T > 0$, as in

our case, $\alpha_H < \alpha_I$. The observed increase in $\alpha(x)$ correlates with a decrease in $\frac{d\omega}{dH}(x)$ – see fig.11.

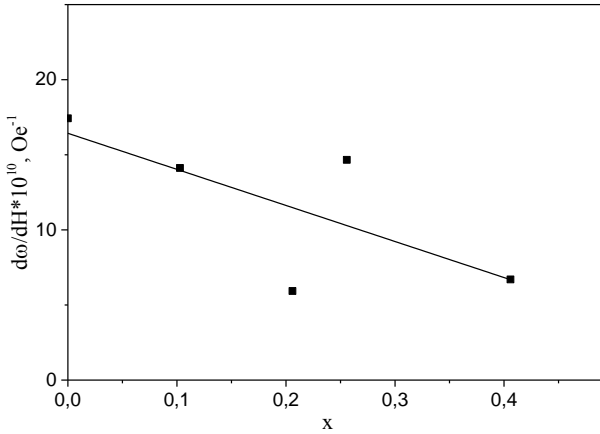


Fig. 11. Dependence of volume magnetostriction from nickel content, T = 270 K

Conclusion

Our studies of the magnetic properties and thermal expansion of amorphous alloys of the $(\text{Fe}_{1-x}\text{Ni}_x)_{78}\text{Si}_9\text{B}_{13}$ system ($0.0 \leq x \leq 0.416$) revealed:

1. Linear magnetostriction is positive. At room temperature, the constant linear magnetostriction λ_s decreases nonlinearly with increasing nickel content.

2. As the temperature decreases, the saturation magnetostriction increases. The similar character of the dependence $(\frac{\delta\ell}{\ell})_s(T)$ for samples with different nickel contents indicates the predominance of the single-ion magnetostriction mechanism in the entire investigated range of compositions.

3. In fields of intensities $H > (330 \div 770 \text{ Oe})$, a linear change in $\frac{\delta\ell}{\ell}$ is observed, due to the forced volume magnetostriction. The volume magnetostriction is positive, has the value of $\frac{d\omega}{dH} \sim 10^{-9} \text{ Oe}^{-1}$ and decreases with increasing x.

4. The Curie temperature decreases with increasing nickel content in the alloy. The nonlinear character of the dependence $T_c(x)$ is associated with the participation of nickel atoms in the exchange interaction in alloys containing boron.

5. The initial magnetic susceptibility increases after heating to temperatures $T > 350^\circ \text{C}$ due to a decrease in

internal stresses in the sample and the associated magnetoelastic anisotropy.

6. The thermal expansion curves $\frac{\delta l}{l}(T)$ show no anomalies. The linear expansion coefficient α has a value $7 \div 11.5 \cdot 10^{-6} \text{ K}^{-1}$ and varies depending on the composition monotonically. The dependence $\alpha(x)$ correlates with the dependence $\frac{d\omega}{dH}(x)$.

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