Magnetic and magnetoelastic properties of rare earth intermetallides based on TbFe₂

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Abstract. The paper presents the results of the study of magnetic and magnetostrictive properties of rare-earth intermetallides based on TbFe₂ compound: Tb₁₋ₓZrₓFe₂, Tb₁₋ₓSmₓFe₂ and (Tb₁₋ₓYₓ)₀.₈Sm₀.₂Fe₂. These alloys have a cubic crystal structure of the Laves phase C₁₅ throughout the substitution region. For the system of alloys Tb₁₋ₓZrₓFe₂ the single-phase area is limited to the replacement parameter 0 ≤ x ≤ 0.2 and 0.8 ≤ x ≤ 1.0. The compounds of the Tb₁₋ₓSmₓFe₂ system were studied via X-ray dilatometry. The magnetostriction of alloys within the Tb₁₋ₓZrₓFe₂ and (Tb₁₋ₓYₓ)₀.₈Sm₀.₂Fe₂ systems was studied in the temperature range of 80–320 K in magnetic fields of up to 17 kOe via a strain-gauge method. It was found that each system has the phenomenon of sign inversion of magnetostriction constants: in the system Tb₁₋ₓZrₓFe₂ in the area of replacement parameter x = 0.8, in Tb₁₋ₓSmₓFe₂ – in the area x = 0.45, and in the system of alloys (Tb₁₋ₓYₓ)₀.₈Sm₀.₂Fe₂ at x = 0.6. It was demonstrated that magnetic compensation and spin reorientation phenomena occur in these systems. The obtained results are discussed in the model of alloys with competing exchange interactions.

1. Introduction
In recent years, great attention has been paid to the study of magnetic properties of intermetallic compounds of rare-earth metals with transition metals [1–3]. First of all, these are the compounds of RM₂ stoichiometry, where R – rare earth metal (REM) and M – 3d transition metal of iron group (Fe, Co, Ni or Mn) with Laves phase structure [4, 5, 6–10]. They are of particular interest because they coexist with two different types of electrons that are magnetic moment carriers: localized 4f-electrons of REM ions and band 3d electrons [11]. This is why, with a relatively simple crystal structure, they have unique magnetic properties, such as giant magnetostriction [12], significant magnetocaloric effect [13] and sufficiently high Curie temperatures [11]. It is known that the compounds of this type can have 2 types of structures: cubic structure of MgCu₂ type (structure C₁₅) and hexagonal structure of MgZn₂ type (structure C₁₄) [2].

Intermetallic REM compounds with 3D transition metals are widely known in science and technology due to their unique magnetic properties. These compounds are characterized by high magnetostrictive properties. They include alloy TbFe₂ well-known due to its “giant” magnetostriction. Thus, the study of the structure and magnetic properties of the Laves phases is sufficiently relevant for both the condensed matter physics and their practical use.
To date the most promising area is the creation of alloy systems consisting of many elements, including rare earths with different sign of magnetocrystine anisotropy for complete or partial compensation of magnetic anisotropy constants. As shown, such compensation can be achieved in alloys of mixed compositions of quasi-binary or more complex systems [1, 14–17].

REM intermetallics can be considered as magnets with two magnetic sublattices: REM and 3d-transition metal. Accordingly, the magnetic properties of RFe$_2$ compounds are defined by three types of exchange interactions: R-R, Fe-Fe and R-Fe. In order to find optimal compositions with high FES and magnetostriction values, it is necessary to examine compounds with different substitutions of 3d-, 3p-, and 4f elements. Compound TbFe$_2$ has sufficiently high Curie temperature (~ 711 K) as well as induced and spontaneous “giant” magnetostriction [18].

The [purpose was to study the magnetic and magnetostrictive properties of rare earth alloys based on \((\text{Tb}^3\text{R}^1\text{R}^2)\text{Fe}_2\) in which the atoms of the heavy rare earth element Tb are replaced by those of the light rare earth element Sm and/or non-magnetic atoms Y or Zr.

The choice of alloy systems is caused by the fact that in the case of Tb$_{1-x}$Zr$_x$Fe$_2$ system, the substitution of terbium atoms in the rare-earth sublattice is non-magnetic, as well as yttrium, zirconium atoms. In alloys of Tb$_{1-x}$Sm$_x$Fe$_2$ and (Tb$_{1-x}$Y$_x$)$_{0.8}$Sm$_{0.2}$Fe$_2$ systems, compounds TbFe$_2$ and SmFe$_2$ having high magnetostriction constants of the opposite sign are used as the basis [5, 18–20]. In this system, there is competition between the exchange interactions Tb-Fe and Sm-Fe depending on the concentration of yttrium introduced into the rare earth sublattice. Therefore, the study of alloys of this system will make it possible to study not only the intergranular exchange interaction R-Fe at the dilution of the rare-earth sublattice with non-magnetic yttrium atoms, but also the exchange interaction in the rare-earth sublattice itself.

2. Methods and materials

Alloys of quasi-binary systems Tb$_{1-x}$Zr$_x$Fe$_2$, Tb$_{1-x}$Sm$_x$Fe$_2$ and quasi-ternary system (Tb$_{1-x}$Y$_x$)$_{0.8}$Sm$_{0.2}$Fe$_2$ were synthesized and studied. The first two systems were prepared in the entire concentration region of substitution $x = 0 \div 1$ with a step 0.1, the alloys of the third system were synthesized in the same concentration region but with a step of 0.2.

Intermetallic compounds of the systems of alloys Tb$_{1-x}$Zr$_x$Fe$_2$, Tb$_{1-x}$Sm$_x$Fe$_2$ and (Tb$_{1-x}$Y$_x$)$_{0.8}$Sm$_{0.2}$Fe$_2$ were prepared via an arc melting method in the atmosphere of spectroscopically pure helium Tb$_{1-x}$Zr$_x$Fe$_2$ and Tb$_{1-x}$Sm$_x$Fe$_2$ and in the atmosphere of argon at normal pressure \((\text{Tb}_{1-x}\text{Y}_{x})_{0.8}\text{Sm}_{0.2}\text{Fe}_2\). The X-ray diffraction analysis showed that in Tb$_{1-x}$Zr$_x$Fe$_2$ system alloys it is possible to obtain uniform solid solutions only in the limited region of zirconium concentration $0 \leq x \leq 0.2$ and $0.8 \leq x \leq 1.0$ [21]. The alloys of Tb$_{1-x}$Sm$_x$Fe$_2$ system were single-phase for all values of the substitution parameter [22]. Quasi-binary alloys Tb$_{0.8}$Sm$_{0.2}$Fe$_2$, Y$_{0.8}$Sm$_{0.2}$Fe$_2$ are single-phase [4]. More complex structures \((\text{Tb}_{0.8}\text{Y}_{0.2})_{0.8}\text{Sm}_{0.2}\text{Fe}_2\), \((\text{Tb}_{0.4}\text{Y}_{0.6})_{0.8}\text{Sm}_{0.2}\text{Fe}_2\), \((\text{Tb}_{0.2}\text{Y}_{0.8})_{0.8}\text{Sm}_{0.2}\text{Fe}_2\) were characterized by the phenomenon of phase separation. These samples contained a second phase REFe$_3$, which amount varied from 5 to 10 %.

Magnetostriiction measurements were carried out in the area of low and room temperatures in magnetic fields of up to 17 kOe via the strain-gauge method. Magnetostriiction error did not exceed 6%. The compounds of Tb$_{1-x}$Sm$_x$Fe$_2$ system were studied via the X-ray dilatometry. Field and temperature magnetization dependencies were measured using standard equipment in the temperature range from 4.2 to 300 K. Besides, temperature dependencies on susceptibility were obtained in the temperature range from 300 to 800 K.

3. Results

3.1. Magnetostriiction of alloys Tb$_{1-x}$Zr$_x$Fe$_2$

Magnetization of \((\text{Tb},\text{Zr})\text{Fe}_2\) system compounds was studied in a wide range of temperatures in magnetic fields of up to 15 kOe. It was shown that for compounds with high concentration of terbium ions \((\text{TbFe}_2, \text{Tb}_{0.2}\text{Zr}_{0.8}\text{Fe}_2\) and \(\text{Tb}_{0.8}\text{Zr}_{0.2}\text{Fe}_2\)) the magnetic field of up to 12 kOe is not sufficient to achieve saturation magnetization, which can be explained by the presence of a large magnetic
anisotropy typical for Tb atoms. In compounds with low terbium content \( \text{Tb}_0.2\text{Zr}_{0.8}\text{Fe}_2 \), \( \text{Tb}_{0.1}\text{Zr}_{0.9}\text{Fe}_2 \) and \( \text{ZrFe}_2 \) the magnetization saturation is observed in the fields above 6 kOe.

In order to determine the saturation magnetization, the magnetization dependencies \( \mu(1/H) \) on the inverse value of the magnetic field were built. The saturation magnetization \( (\mu_s) \) for structures with high concentration of terbium ions is determined by the extrapolation of dependence \( \mu(1/H) \) to the maximum field \( (1/H \rightarrow 0) \).

The method of thermodynamic coefficients was used to define the Curie temperatures, which allowed determining the Curie temperatures according to magnetic data. The results for saturation magnetization and Curie temperature of the compounds \((\text{Tb, Zr})\text{Fe}_2\) are summarized in Table 1. The Curie temperature of compounds with increasing \( \text{Zr} \) concentration decreases linearly from 711 K for \( \text{TbFe}_2 \) to 628 K in \( \text{ZrFe}_2 \). This is caused by the decrease of the energy of exchange interactions due to the decrease of interacting pairs of magnetoactive \( \text{Tb-Fe} \) atoms.

The results of magnetic measurements of \((\text{Tb, Zr})\text{Fe}_2\) system compounds together with the literature data [23] make it possible to conclude that there are large exchange fields acting on rare-earth ions from iron sublattice in cubic RFe\(_2\) compounds. Exchange R-Fe interaction causes magnetic ordering of rare-earth sublattice and serves one of the reasons for giant magnetostriction deformations observed in \((\text{Tb, Zr})\text{Fe}_2\) alloys.

The alloys of quasi-binary system \( \text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2 \) are highly strictional materials, similar to \( \text{TbFe}_2 \) compound. In these compounds, the giant magnetostriction typical for terbium atoms is observed not only at low but also at room temperatures. The longitudinal magnetostriction of \( \text{TbFe}_2 \) compound is positive and in field of 17 kOe reaches \( \lambda_\parallel \approx 0.9 \times 10^{-3} \) at room temperature. Giant magnetostriction is observed in all compounds of \( \text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2 \) system in the field of small concentration of zirconium \((0 \leq x \leq 0.2)\). This magnetostriction is caused by the contribution of \( \text{Fe} \) sublattice and emerges from single-ion magnetoelastic contributions of its ions.

Figure 1 shows field dependencies of longitudinal and cross magnetostriction of \( \text{Tb}_{0.1}\text{Zr}_{0.9}\text{Fe}_2 \) compound. At room temperature, the saturation of magnetostrictive curves is observed in the field above 12 kOe. For compounds with 10 % substitution of \( \text{Tb} \) ions with \( \text{Zr} \) the longitudinal magnetostriction at \( T=80 \) K reaches \( \lambda_\parallel \approx 0.9 \times 10^{-3} \). With 20 % substitution of terbium atoms with zirconium the longitudinal magnetostriction makes \( \lambda_\parallel \approx 0.5 \times 10^{-3} \).

Table 1. Magnetic characteristics: Curie temperature \( (T_C) \) and saturation magnetization \( (\mu_s) \) at a temperature of 4.2 K of \( \text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2 \) system compounds

| Compounds          | \( T_C, \text{K} \) | \( \mu_s, \mu_0/\text{f.u.} \) |
|--------------------|---------------------|-------------------------------|
| \( \text{TbFe}_2 \) | 711                 | 5.8                           |
| \( \text{Tb}_{0.2}\text{Zr}_{0.8}\text{Fe}_2 \) | 699                 | 4.6                           |
| \( \text{Tb}_{0.1}\text{Zr}_{0.2}\text{Fe}_2 \) | 690                 | 3.6                           |
| \( \text{Tb}_{0.2}\text{Zr}_{0.8}\text{Fe}_2 \) | 640                 | 2.4                           |
| \( \text{Tb}_{0.1}\text{Zr}_{0.9}\text{Fe}_2 \) | 636                 | 2.9                           |
| \( \text{ZrFe}_2 \) | 628                 | 3.4                           |

Figure 2 shows the concentration dependence of longitudinal and cross magnetostriction in the compounds of \( \text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2 \) system. As the zirconium concentration increases, the iron content in the system increases, resulting in the prevalence of the magnetostriction of iron sublattice, which is opposite to the magnetostriction of terbium sublattice. In the field of concentration \( x>0.8 \) the longitudinal magnetostriction is negative and equals approximately \( \lambda_\parallel \approx -0.04 \times 10^{-3} \).

The insertion to Figure 2 shows the concentration dependence of the magnetostriction constant \( \lambda_s = \lambda_\parallel - \lambda_\perp \) at a temperature of 80 K. The figure shows that the sign of magnetostriction constant changes near the concentration \( x = 0.8 \).

\( \text{TbFe}_2 \) and \( \text{ZrFe}_2 \) compounds are isostructural to the C15 Laves phase. The compound \( \text{TbFe}_2 \) – ferrimagnetic with Curie temperature of 711 K, \( \text{ZrFe}_2 \) – ferrimagnetic with \( T_C = 628 \) K. The vectors of spontaneous magnetic moment in both compounds are oriented along crystallographic direction [111].
so the increase in the concentration of non-magnetic zirconium atoms leads only to dilution of rare-earth sublattice [23]. As a result, at a certain concentration the magnetism of the 3d sublattice begins to prevail.

Figure 1. Isotherms of Tb$_{0.1}$Zr$_{0.9}$Fe$_2$ alloy magnetostriction.

In the areas of single-phase condition of samples $0 \leq x \leq 0.2$ and $0.8 \leq x \leq 1$ longitudinal and cross magnetostriction decreases linearly with the growth of zirconium content (Fig. 2), which illustrates a single-ion mechanism of magnetostriction. Another interesting phenomenon here is the inversion of the sign of magnetostriction constants, which combines this system with Tb$_{1-x}$Sm$_x$Fe$_2$ and (Tb$_{1-x}$Y$_x$)$_{0.8}$Sm$_{0.2}$Fe$_2$ systems.

Figure 2. Concentration dependence of longitudinal $\lambda_\parallel$ and cross $\lambda_\perp$ magnetostriction of alloys of Tb$_{1-x}$Zr$_x$Fe$_2$ system
3.2. Magnetic properties of $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ system

Compounds $\text{TbFe}_2$ and $\text{SmFe}_2$ are quite interesting since they possess not only record values of magnetostriction constants of the opposite sign, but also different signs of intersublattice exchange interactions. The Tb-Fe exchange interaction is negative and leads to ferrimagnetic ordering of magnetic moments of terbium and iron, while the Sm-Fe interaction is positive, so the order of orientation of atomic magnetic moments of samarium and iron is ferrimagnetic [22]. In $(\text{Tb},\text{Sm})\text{Fe}_2$ system as Tb atoms are replaced by Sm atoms, in addition to the inversion of spontaneous magnetostriction sign the competition between Tb-Fe and Sm-Fe exchange interactions results in the change of direction of the light magnetization axis from the direction [111] typical for $\text{TbFe}_2$ towards direction [110] typical for $\text{SmFe}_2$ compound [5, 18–20]. In work [22], we showed that in the field of temperatures from 5 to 300 K in the concentration area $x<0.45$ in $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ system there are two spin-reorientated phase transitions from the state with the direction of light magnetization axis [111] to the state with the direction [110], which are followed by the formation of angular magnetic phases $<\text{hk}l>$ (Fig. 3) [22].

The occurrence of angular phases results in complex distortions of the crystal structure and the decrease of crystal symmetry.

We revealed that in terbium concentration area $x = 0.45–0.5$ there is a structural phase transition from the rhombohedral phase in purely cubic, i.e. in $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ system of alloys there was a distortive structural phase transition. It is in the region of these concentrations that a compound, in which magnetocrystalline anisotropy is almost completely compensated, can be obtained and giant magnetostriction can be expected.

![Figure 3. Magnetic spin-reorientation phase diagram of the $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ system.](image)

3.3. Magnetic properties of multi-component alloys $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$

Magnetization study of $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ system compounds was carried out in small magnetic fields of 2 kOe in the temperature range from 2 to 300 K.

Figure 4 shows the concentration dependence of magnetization in the field of 2 kE for temperatures from 2 to 300 K. We see the magnetic compensation of rare-earth and iron sublattices in the range of the parameter $x = 0.6$ in $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ system.

For compound $(\text{Tb}_{0.4}\text{Y}_{0.6})_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ the magnetization is almost reduced to zero compared to the other connections, i.e. the sum of magnetic moments of sublattices (directed antiparallel to each other) compensate each other. The composition and temperature at which the compensation effect occurs are referred to as the compensating composition and the compensation temperature, respectively [24, 25]. The most important factors for the transformation of this effect are the concentration of atoms and temperature. This phenomenon has great practical importance: by varying the concentrations of atoms substitution near the compensating composition, the magnitude of spontaneous magnetization can be
controlled. Temperature studies of \((Tb_{0.4}Y_{0.6})_{0.8}Sm_{0.2}Fe_2\) \((x = 0.6)\) magnetization show that at \(T_{\text{comp}} = 136\) K there is a complete compensation of magnetization for this composition.

The Curie temperature values of alloys of this system are defined on the basis of the results of magnetic susceptibility study and are shown in Table 2. By diluting the rare-earth sublattice of \(Tb_{0.8}Sm_{0.2}Fe_2\) compound with nonmagnetic yttrium ions, a monotonic decrease in Curie temperature occurs with an increase of \(Y\) concentration caused by the decrease in \(R-Fe\) exchange interaction integral. The Curie temperature of the ferrimagnetic compound \(Y_{0.8}Sm_{0.2}Fe_2\) almost coincides with the \(T_C\) of \(YFe_2\) compound, but is significantly lower than the \(T_C\) of \(SmFe_2\) compound. This fact makes it possible to conclude that the strong dilution of the rare-earth \(SmFe_2\) compound with yttrium ions suppresses the \(Sm-Fe\) exchange interaction. For light rare-earth ion \(Sm\), the sign of the exchange integral of \(Sm-Fe\) interaction is positive and the direction of the magnetic moment coincides with the direction of the magnetic moment of the iron sublattice. For heavy rare-earth ion \(Tb\), the \(Tb-Fe\) exchange interaction integral is negative and hence the magnetic moment of \(Tb\) sublattice is directed anticozlinearly to the magnetic moment of the iron sublattice.

**Figure 4.** Dependence of magnetization of alloys \((Tb_{1-x}Y_x)_{0.8}Sm_{0.2}Fe_2\) on replacement parameter \(x\) in the temperature range from 2 to 300 K.

It is shown that in order to connect this system the saturation magnetization is achieved in the fields above 10 kOe. The amount of saturation magnetization was determined by the curves \(\mu(1/H)\) and is shown in Table 2.

**Table 2.** Magnetic characteristics: Curie temperature \((T_C)\) and saturation magnetization \((\mu_s)\) at a temperature of 4.2 K of \((Tb_{1-x}Y_x)_{0.8}Sm_{0.2}Fe_2\) system compounds.

| Compounds            | \(T_C\), K | \(\mu_s, \mu_B/f.u\) |
|----------------------|------------|----------------------|
| \(Tb_{0.8}Sm_{0.2}Fe_2\) | 673        | 3.6                  |
| \((Tb_{0.8}Y_{0.2})_{0.8}Sm_{0.2}Fe_2\) | 658        | 2.2                  |
| \((Tb_{0.6}Y_{0.4})_{0.8}Sm_{0.2}Fe_2\) | 640        | 1.5                  |
| \((Tb_{0.4}Y_{0.6})_{0.8}Sm_{0.2}Fe_2\) | 609        | 0.5                  |
| \((Tb_{0.2}Y_{0.8})_{0.8}Sm_{0.2}Fe_2\) | 589        | 2.4                  |
| \(Y_{0.8}Sm_{0.2}Fe_2\) | 541        | 2.0                  |
Figure 5 shows the longitudinal and cross magnetostriction of \((\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2\) system alloys depending on the replacement parameter \(x\). It is found that the longitudinal magnetostriction of all alloys of \((\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2\) system with the replacement parameter \(x \leq 0.8\) in the external magnetic field of \(H = 12\) kOe is positive, while the cross magnetostriction is negative. In alloys with \(x \geq 0.9\), on the contrary, the longitudinal magnetostriction is negative, and the cross – positive. Thus, in this system, the sign inversion of magnetostriction constants occurs in the value range of \(x = 0.8\).

![Figure 5. Longitudinal \(\lambda_{||}\) and cross \(\lambda_{\perp}\) magnetostriction of alloys \((\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2\) depending on the replacement parameter \(x\).](image)

4. Discussion

The behavior of magnetization of alloys \((\text{Tb,Zr})\text{Fe}_2\) can be considered in the model of two-sublattice ferrimagnet with magnetic sublattices \(\text{Tb}\) and \(\text{Fe}\). In this case, the exchange interactions \(\text{Fe-Fe}, \text{Tb-Fe}\) shall be taken into account. The exchange interaction integral \(\text{Tb-Fe}\) is negative.

In compounds \(\text{RFe}_2\) the most potent is the \(\text{Fe-Fe}\) exchange interaction, it is this type of interaction that determines high Curie temperatures in these compounds. Our results for \(\text{ZrFe}_2\) magnetization allow defining the magnetic moment of iron ions \(\mu_{\text{Fe}} = \mu_{\text{S(ZrFe}_2)}/2 = 1.7\mu_{\text{B}}/\text{Fe}\). The magnetic moment of \(\text{Tb}\) ion makes \(\mu_{\text{Tb}} = 9\mu_{\text{B}}\) [18]. The magnetization of \(\text{Tb}\) sublattice as a function of the concentration of \(\text{Tb}\) ions in \(\text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2\) compounds can be calculated as \((1-x)\mu_{\text{Tb}}\). Accordingly, within the collinear ferromagnet model, it can be shown that the magnitude of the total magnetic moment is linearly dependent on the concentration of the replacement element \(\text{Zr}\):

\[
\mu_{\text{cal}} = 2\mu_{\text{Fe}} – (1-x)\mu_{\text{Tb}}. \tag{1}
\]

Similar reasoning can be applied to \(\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2\) compound system. However, the magnetization behavior of a given alloy shall be considered in a model of a three-sublattice collinear ferrimagnetic in which the magnetic moment of \(\text{Tb}\) ions is directed anticoollinearly to the moments of \(\text{Sm}\) and \(\text{Fe}\) ions. In this case, it is necessary to consider a larger spectrum of exchange interactions: inner-sublattice \(\text{Fe-Fe}, \text{Tb-Fe}\) and \(\text{Tb-Tb}\), Sm-Sm and inter-sublattice \(\text{Tb-Fe}, \text{Sm-Fe}, \text{Tb-Sm}\). The integral of \(\text{Tb-Fe}\) exchange interaction will be negative, and for the interaction \(\text{Sm-Fe}\) – positive. Respectively, the contribution from \(\text{Sm sublattice to magnetization of } \text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2\) compounds makes \(x\mu_{\text{Sm}} \text{ where } \mu_{\text{Sm}} = 0.7\mu_{\text{B}}/\text{Sm}\).

Within the collinear ferrimagnetic model with three magnetic sub-sublattices \((\text{Tb, Sm, Fe})\) the magnitude of the magnetic moment is linearly dependent on \(\text{Sm}\) concentration:

\[
\mu_{\text{cal}} = 2\mu_{\text{Fe}} + x\mu_{\text{Sm}} – (1-x)\mu_{\text{Tb}}. \tag{2}
\]

Applying the above reasoning, it is possible to show the linear dependence of the total magnetic moment in the system of compounds \((\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2\) on \(\text{Y}\) concentration:

\[
\mu_{\text{cal}} = 2\mu_{\text{Fe}} + 0.2 \mu_{\text{Sm}} - 0.8 (1-x)\mu_{\text{Tb}}. \tag{3}
\]
Figure 6 shows the experimental saturation magnetization at $T = 4.2$ K for alloys of systems $(\text{Tb},\text{Zr})\text{Fe}_2$ (unpainted symbols) and $(\text{Tb},\text{Y})_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ (painted symbols). The lines show the calculations made according to formulas (1–3).

Since formulas (1–3) produce both positive and negative values (for substitution parameter $x$ in the range from 0 to 1), the figure shows the $\mu_{\text{cal}}$ modulus. As rare-earth Tb is replaced by non-magnetic Zr, Y or light REM ions, the samarium decreases the total magnetic moment $\mu_{\text{cal}}(x)$ for three systems studied in this work. Our experimental values are near the calculated lines. Linear dependencies $\mu_{\text{cal}}(x)$ reach zero at $x$ near 0.6 for all systems, confirming our conclusion that $(\text{Tb}_{0.4}\text{Y}_{0.6})_{0.8}\text{Sm}_{0.2}\text{Fe}$ compound is compensatory. Similar behavior of magnetization is also found in the system of multicomponent alloys $(\text{Tb}_{0.2}\text{Pr}_{0.8})_{1-x}\text{Y}_x\text{Fe}_2$ – introduction of nonmagnetic Y leads to the compensation composition at yttrium concentration of $x = 0.6$ [4]. It shall be noted that the change in the magnetostriction sign is observed for compounds with $x = 0.8$, as shown in the inserts to Figures 2 and 5.

![Figure 6](image_url)  
*Figure 6. The concentration dependence of saturation magnetization of $\text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2$ system compounds (unpainted symbols), $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$. Solid lines indicate the design values of the magnetic moment of the specified compounds.*

5. Conclusion

Alloys $(\text{Tb}^\text{III}\text{R}^\text{II})\text{Fe}_2$ are shown to be sufficiently convenient for model studies of many properties of rare-earth alloys: magnetic, magnetoelastic, spectroscopic and optical. A distinctive feature of these compounds is that $\text{TbFe}_2$ exhibits positive spontaneous and field induced magnetostriction, whereas $\text{SmFe}_2$ and $\text{ZrFe}_2$ exhibit reverse sign magnetostriction. This results in a number of interesting effects in the systems as the concentration of the non-magnetic diluent (yttrium or zirconium) changes. In each of the studied systems, there is an inversion of the sign of magnetostriction constants in the area $x = 0.8$ and a phenomenon of magnetic compensation near $x = 0.6$. In the alloys of $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ system, two spin-reorientation phase transitions were established to form regions of angular magnetic structures. In $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ alloy system the magnetic compensation by concentration and temperature is observed.

In our opinion, the reason for all these features in $\text{Tb}_{1-x}\text{Zr}_x\text{Fe}_2$, $\text{Tb}_{1-x}\text{Sm}_x\text{Fe}_2$ and $(\text{Tb}_{1-x}\text{Y}_x)_{0.8}\text{Sm}_{0.2}\text{Fe}_2$ is that the combination in the same rare-earth sublattices of light and heavy element ions (Tb and Sm), and then dilution by its non-magnetic atoms lead to the change of the sign and value of exchange interactions $\text{Tb-Fe}$ and $\text{Sm-Fe}$, at the same time the exchange interactions also change in magnetic sublattices $\text{Tb-Tb}$, $\text{Nb-Sm}$, $\text{Fe-Fe}$. Competition between the above types of interactions resulted in the composition with complete magnetic compensation for magnetization over a wide range of temperatures. Exchange interactions, their type, sign and magnitude ultimately determine the entire spectrum of magnetic and magnetostrictive properties of this type of compounds. The study of compounds with Laves phase structure presents a great applied importance. This is
caused by the fact that due to the variety of properties these intermetallides (and their related ones) find their application in metallurgy, laser engineering, semiconductor electronics, and are used as neutron absorbers in nuclear engineering. Besides, alloys with such properties can be used in robotics.

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