Title

In-situ studies of low-field large magnetostriction in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds by synchrotron-based high-energy x-ray diffraction

Authors

Zhihua Nie ^{a,*}, Sen Yang ^{b,*}, Yan-dong Wang ^{c,*}, Zilong Wang ^a, Dongmei Liu ^d,
Yang Ren ^e, Tieyan Chang ^b, Rui Zhang ^b

^a *School of Materials Science and Engineering, Beijing Institute of Technology,
Beijing 100081, China*

^b *School of Science, MOE Key Laboratory for Nonequilibrium Synthesis and
Modulation of Condensed Matter and State Key Laboratory for Mechanical Behavior
of Materials, Xi'an Jiaotong University, Xi'an 710049, China*

^c *State Key Laboratory for Advanced Metals and Materials, University of Science and
Technology Beijing, Beijing 100083, China*

^d *State Key Laboratory for Fabrication and Processing of Nonferrous Metals, General
Research Institute for Nonferrous Metals, Beijing 100088, China*

^e *X-Ray Science Division, Argonne National Laboratory, Argonne, IL 60439, USA*

*Corresponding authors. Email: zhihua_nie@yahoo.com; yangsen@mail.xjtu.edu.cn;
ydwang@ustb.edu.cn

Abstract

Partial substitution of Dy for Tb in TbFe_2 compounds results in improved magnetostriction with high strains obtained at low fields. The structural evolutions of TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds are studied in situ using synchrotron-based high-energy x-ray diffraction under an applied magnetic field. It is found that the rhombohedral distortion in TbFe_2 is remarkably reduced by substituting Dy for Tb. When a low magnetic field is applied, a preferential rearrangement of rhombohedral domains is directly evidenced in TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds. Based on the concept of crystallographic domain-switching, the enhancement in the magnetostriction in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds is discussed.

Keywords: Magnetostriction; Laves phase; X-ray diffraction; Domain switching; Lattice distortion

1. Introduction

The magnetostrictive effect, defined as a change of shape or dimension in magnetic materials due to the application of an external magnetic field, is an important magnetic property due to its use in a wide range of actuators and sensors [1,2]. Among the magnetostrictive materials, RT_2 intermetallic compounds (R = rare earth, T = Co, Fe) have attracted much attention due to their large magnetostriction, which occurs on the order of 10^{-3} under a moderate saturation field (usually less than 1 tesla), below the Curie temperature (T_C) [3-5]. Recent synchrotron data show that the ferromagnetic transition in RT_2 compounds is also a structural transition, yielding a low crystallographic symmetry conforming to spontaneous magnetization [6-8]. Therefore, the switching of magnetic domains by the magnetic field is also a switching of non-cubic crystallographic domains [6,9].

It is well known that high strains at low applied fields are necessary for the applications of magnetostrictive materials. For the maximization of the domain wall mobility and easy of domain rotation at a low magnetic field, pseudobinary compounds with low magnetic anisotropies, such as $Tb_{1-x}Dy_xFe_2$, have been synthesized [10]. The physical mechanism of the large magnetostriction in $Tb_{1-x}Dy_xFe_2$ compounds has been well established since the 1960s [10-12]. However, crystallographic studies of the origin of the large low-field magnetostriction in these compounds have been rare. In this work, the structural evolution of $TbFe_2$, $Tb_{0.4}Dy_{0.6}Fe_2$ and $DyFe_2$ compounds as a function of magnetic field strength is studied in situ by synchrotron-based high-energy x-ray diffraction (HE-XRD). The HE-XRD technique provides an in-situ tool for obtaining an in-depth understanding of a large number of physical processes (including domain switching, phase transformation, and lattice distortion) in a variety of environments [13]. A rearrangement of the rhombohedral domains is observed in $TbFe_2$ and $Tb_{0.4}Dy_{0.6}Fe_2$ when a low magnetic field is applied. Moreover, the crystallographic domain-switching in $Tb_{0.4}Dy_{0.6}Fe_2$ is found to be more sensitive to the applied field.

Structurally, the enhancement of magnetostriction in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds can be attributed to the decrease of the rhombohedral distortion due to the substitution of Dy for Tb.

2. Experimental

$\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds are the subject of the present study. TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 polycrystalline ingots were prepared by arc melting high-purity Tb, Dy and Fe in an argon atmosphere. Magnetostriction measurements were performed using the standard strain gauge method. The samples used for HE-XRD measurements were ground by hand in ethanol prior to being sealed in 0.3 mm diameter quartz capillaries. In-situ HE-XRD experiments (photon energy = 111 keV) were performed at the 11-ID-C beamline of the Advanced Photon Source (APS), Argonne National Laboratory. Fig. 1 shows the HE-XRD experimental setup. A pair of NdFeB permanent magnets was installed on the beamline to generate magnetic fields of up to 0.69 T. The magnetic field strength was changed by adjusting the distance between the two permanent magnets. The magnetic field direction was aligned perpendicular to the incident x-ray beam and parallel to the horizontal direction. A PerkinElmer α -Si flat-panel large-area detector was used to collect two-dimensional (2D) diffraction patterns and was installed 1.8 meters away from the sample to achieve sufficient instrument resolution. The FIT2D software package was used to integrate the 2D diffraction patterns along the azimuthal angle to obtain the one-dimensional (1D) diffraction pattern [14]. Based on the experimental layout (see Fig. 1), horizontal diffraction patterns (azimuthal angle $\varphi = 0^\circ$) were generated from the crystal grains with diffraction vectors approximately parallel to the external field. Simultaneously, the vertical diffraction patterns (azimuthal angle $\varphi = 90^\circ$) were generated from these crystal grains with diffraction vectors perpendicular to the field.

3. Results and discussion

Fig. 2 shows the room temperature magnetostriction curves for TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 compounds. The samples were measured in a stress-free state. Fig. 2 shows that both TbFe_2 and DyFe_2 compounds exhibit positive magnetostriction. Based on the single-ion theory, the two compounds exhibit opposite signs of magnetic anisotropy [15-18]. Pseudobinary $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds can be synthesized to minimize magnetic anisotropy while still maintaining a large positive magnetostriction. As shown in Fig. 2, an enhancement of magnetostriction is achieved in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compared to TbFe_2 ; this material is sensitive to the applied field and is easily saturated.

The crystal structures of the TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 compounds at room temperature were analyzed. Fig. 3 shows the Bragg reflections (black circles) for TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 compounds together with the fitted curves (blue and pink solid lines). The XRD patterns for TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ can be indexed to the rhombohedral $R\bar{3}m$ symmetry [6,19]. As shown in Fig. 4(a), the rhombohedral structure can be rationalized as an elongation of the Laves MgCu_2 -type structure along the [111] direction. Based on the crystal symmetry relation between the Laves phase cubic structure and the rhombohedral structure, below T_C , the cubic (440) reflection splits into $(242)_R$ and $(20\bar{2})_R$ peaks; the cubic (533) reflection splits into $(344)_R$ and $(401)_R$ peaks; and the cubic (800) reflection does not split and is indexed by the $(440)_R$ peak [6,19]. The subscript R denotes rhombohedral symmetry. As shown in Fig. 3, the distance between the diffraction peaks at positions of $(242)_R$ and $(20\bar{2})_R$ [or the distance between the $(344)_R$ and $(401)_R$ peaks] in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ is smaller than that in TbFe_2 . This suggests that the rhombohedral distortion is smaller in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ than in TbFe_2 . The room temperature phase for the DyFe_2 compound is anticipated to be of tetragonal $I4_1/amd$ symmetry [8,20], which can be rationalized as an elongation of the MgCu_2 -type structure along the [001] direction, as shown in Fig. 4(b). However, the tetragonal distortion in the DyFe_2 compound is so small ($c/a \approx 1$) that it cannot be resolved by the present synchrotron XRD measurements [8,20]. Here, the Bragg reflections for DyFe_2 are indexed by the MgCu_2 -type structure, with

subscript T denoting tetragonal symmetry, as shown in Fig. 3.

The magnetic field is applied at room temperature. Fig. 5 shows the variations of the $(344)_R$ and $(401)_R$ diffraction peaks of $TbFe_2$ and $Tb_{0.4}Dy_{0.6}Fe_2$ as a function of the magnetic field strength. The diffraction patterns are shown as black circles. The fitted curves (blue and pink solid lines) and the peak positions (blue and pink dashed lines) are also depicted in Fig. 5. Following the visual guides of the dashed lines, it can be clearly observed that the peak positions of $(344)_R$ and $(401)_R$ do not shift with the increasing applied magnetic field. However, a systematic variation in the diffraction peak intensities is clearly observed. As shown in Fig. 5(a), parallel to the field, the intensity of the $(401)_R$ peak gradually decreases with the increasing magnetic field. In contrast, the $(344)_R$ peak intensity is progressively enhanced with the increasing magnetic field. All of the above-mentioned intensity changes generated by the increasing magnetic field can be reversed stepwise by decreasing the magnetic field. Fig. 5(b) shows the variations of the $(344)_R$ and $(401)_R$ diffraction peaks for $TbFe_2$ in the direction perpendicular to the field. A comparison of Fig. 5(a) and 5(b) shows that the x-ray diffraction peaks in Fig. 5(b) are much broader than the peaks in Fig. 5(a). This is attributed to the intrinsic characteristic of the monochromator. Due to the limited instrument resolution and the small rhombohedral distortion in $Tb_{0.4}Dy_{0.6}Fe_2$, the variations of the $(344)_R$ and $(401)_R$ peak intensities cannot be quantitatively traced for $Tb_{0.4}Dy_{0.6}Fe_2$ in the direction perpendicular to the field. The peak intensities for the $(344)_R$ and $(401)_R$ peaks in the direction perpendicular to the field [see Fig. 5(b)] show opposite behaviors to the intensity changes in the direction parallel to the field [see Fig. 5(a)], i.e., an increase of the $(401)_R$ peak intensity and a decrease of the $(344)_R$ peak intensity with increasing magnetic field strength.

The intensity changes of the $(344)_R$ and $(401)_R$ diffraction peaks have been quantitatively studied. Fig. 6(a) shows the variation of the integrated intensity fraction of the $(344)_R$ diffraction peak $[I_{344_R}/(I_{344_R} + I_{401_R})]$ as a function of the magnetic field strength. For the initial state, the $(344)_R$ peak intensity fraction is ~ 0.3 for $TbFe_2$

and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$. Under the application of a parallel magnetic field, the $(344)_R$ intensity fractions for TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ increase monotonically with the increasing magnetic field strength. In contrast, the $(344)_R$ intensity fraction for $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ grows much faster than that for TbFe_2 . The value for $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ becomes saturated beyond 0.5 T. When the magnetic field strength reaches 0.69 T, the $(344)_R$ intensity fraction reaches ~ 0.9 and ~ 0.8 for $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and TbFe_2 , respectively. On the other hand, under the application of a perpendicular magnetic field, the $(344)_R$ intensity fraction for TbFe_2 decreases linearly with the increasing the magnetic field strength.

As demonstrated in Fig. 5, the diffraction peak positions for the $(344)_R$ and $(401)_R$ peaks do not shift in TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ under the applied magnetic field. This suggests that the unit cell of the rhombohedral phase remains rigid under the external magnetic field. This observation is consistent with the previous x-ray absorption fine structure studies of $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$, where no field-induced internal distortion of the unit cell was observed [21]. A systematic variation in the diffraction peak intensities is clearly observed when a low magnetic field is applied to TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds [see Figs. 5 and 6(a)]. This reflects a switching of the low crystal-symmetry domains (crystallographic texture) [6,9]. Fig. 6(b) shows a schematic of the microstructural evolutions of the TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds under the application of a magnetic field. During the first order magnetic transition, the rhombohedral distortion of the cubic lattice results in a complex microstructure with multiple crystallographic domains [22]. The easy magnetization direction $\mathbf{M}_S$ is highlighted in blue in Fig. 6(b) (demagnetized state). Upon the application of a magnetic field, the magnetic domain with $\mathbf{M}_S$ close to the field direction is preferred and grows at the expense of the other domains [see Fig. 6(b), magnetized state]. The growth of the field-preferred crystallographic domain is, in fact, a mechanism for the reorientation of the magnetization by the applied field. Such a mechanism of field-induced crystallographic domain-switching has been used to explain the large low-field magnetostriction in the DyCo_2 compound [9].

The magnetic anisotropy (or the anisotropically shaped electron charge cloud) of TbFe_2 compound is reduced by the substitution of Dy for Tb, because TbFe_2 and DyFe_2 have opposite signs of anisotropy [15-18]. Structurally, the reduction of the magnetic anisotropy results in the reduction of the rhombohedral distortion in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds (see Fig. 3). Based on the concept of field-induced crystallographic domain-switching, the theoretical saturation magnetostriction (ε_0) in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds can be evaluated using $\varepsilon_0 = |1 - \alpha|$, where $\alpha = d_{111_R}/d_{010_R}$ [23,24]. α is used to estimate the magnitude of the rhombohedral distortion. The rhombohedral distortion of TbFe_2 is larger than that of $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ (see Fig. 3), resulting in a larger magnetostriction in TbFe_2 than in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ at high fields, such as 1.2 T (see Fig. 2). Domain-switching occurs when the shear stress applied by a magnetic field is larger than the shear stress required for the crystallographic domain boundary movement (σ_{BON}). σ_{MAG} , the magnetic stress induced by saturating magnetic field, is given by

$$\sigma_{MAG} = \varepsilon_0^{-1} K_U, \quad (1)$$

where K_U is the magnetocrystalline anisotropy energy [23,24]. Here K_U is defined as the region between the magnetization response of the ferromagnetic single crystallographic domains along the easy and hard axes [25]. K_U can be directly measured in a stress-confined single crystal [26]. The external stress is used to obtain a single crystallographic domain state in the single crystal. Currently, the value of K_U is still unknown for the $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds. Equation (1) indicates that the product of ε_0 and σ_{MAG} is constant (K_U). This means that we cannot simultaneously improve these two parameters. If K_U is assumed to be the same (or of a similar order magnitude) in $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds, then a large driving force can be obtained in a sample with a small rhombohedral distortion. The rhombohedral distortion of $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ is smaller than that of TbFe_2 (see Fig. 3). As shown in Fig. 6(a), using HE-XRD, we have observed that the field-induced crystallographic domain-switching is easier in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ than in TbFe_2 (sensitivity to the applied field) and that domain-switching is accomplished in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ at a lower field (easy saturation).

The pseudobinary $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds exhibit a peak magnetostriction at room temperature for compositions near to the morphotropic phase boundary (MPB) composition (typically, $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$ at room temperature with near zero magnetic anisotropy) [8,10]. The MPB separates a ferromagnetic rhombohedral phase (with easy magnetization $\mathbf{M}_s \parallel [111]$) on the TbFe_2 side and a ferromagnetic tetragonal phase (with $\mathbf{M}_s \parallel [001]$) on the DyFe_2 side [8]. Nano-sized rhombohedral domains with tetragonal phase have been observed recently in $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$ by high resolution transmission electron microscopy [27]. However, due to the limited instrument resolution of the present HE-XRD, the above mentioned two phases cannot be quantitatively resolved in $\text{Tb}_{0.3}\text{Dy}_{0.7}\text{Fe}_2$. Thus, structural evolutions under applied magnetic fields are still unknown in the compounds with compositions near the MPB. More advanced experimental studies are needed to complete the microstructure picture.

4. Conclusions

We performed HE-XRD studies on TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds with different magnetic field strength values. A preferential rearrangement of the rhombohedral domains by a low magnetic field is directly evidenced in TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$. We find that the crystallographic domain-switching in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ is more sensitive to the applied field. Thus, domain-switching is accomplished at a low field in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ to reach the saturation of the magnetization. Structurally, the enhancement of magnetostriction in $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compound can be attributed to the decrease of the rhombohedral distortion due to the substitution of Dy for Tb.

Acknowledgements

This work is supported by the National Basic Research Program of China (973 Program) under Contract No. 2012CB619405, the National Natural Science

Foundation of China (Grant Nos. 51571032 and 51471125), the Fundamental Research Funds for the Central Universities (Grant No. 06111020), and the fundamental research fund by State Key Laboratory for Advanced Metals and Materials (Grant No. 2014Z-01). Use of the Advanced Photon Source is supported by the U. S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357.

References

- [1] H. D. Chopra, M. Wuttig, *Nature* 521 (2015) 340-344.
- [2] S. N. Jammalamadaka, S. Kuntz, O. Berg, W. Kittler, U. M. Kannan, J. A. Chelvane, C. Sürgers, *Sci. Rep.* 5 (2015) 13621.
- [3] S. N. Jammalamadaka, G. Markandeyulu, K. Balasubramaniam, J. A. Chelvane, J. *Alloys Compd.* 624 (2015) 40-43.
- [4] Y. Liu, Q. Wang, T. Liu, P. F. Gao, Y. Yuan, J. C. He, *J. Alloys Compd.* 590 (2014) 110-115.
- [5] Z. J. Zuo, D. A. Pan, Y. M. Jia, J. J. Tian, S. G. Zhang, L. J. Qiao, *J. Alloys Compd.* 587 (2014) 287-289.
- [6] S. Yang, X. B. Ren, *Phys. Rev. B* 77 (2008) 014407.
- [7] S. Yang, H. Bao, C. Zhou, Y. Wang, X. Ren, Y. Matsushita, Y. Katsuya, M. Tanaka, K. Kobayashi, X. Song, J. Gao, *Phys. Rev. Lett.* 104 (2010) 197201.
- [8] R. Bergstrom, M. Wuttig, J. Cullen, P. Zavalij, R. Briber, C. Dennis, V. O. Garlea, M. Laver, *Phys. Rev. Lett.* 111 (2013) 017203.
- [9] Z. H. Nie, S. Yang, Y. D. Wang, Z. L. Wang, D. M. Liu, Y. Ren, *Appl. Phys. Lett.* 103 (2013) 111903.
- [10] A. E. Clark, in *Ferromagnetic Materials*, edited by E. P. Wohlfarth (North-Holland, Amsterdam, 1980), Vol. 1, pp. 557-567.
- [11] A. E. Clark, B. F. De Savage, E. R. Callen, *J. Appl. Phys.* 35 (1964) 1028-1029.
- [12] A. E. Clark, H. S. Belson, H. N. Tamagawa, *AIP Conf. Proc.* 10 (1973) 749-753.
- [13] Y. Ren, *JOM* 64 (2012) 140-149.
- [14] A. P. Hammersley, "FIT2D: An Introduction and Overview", ESRF Internal Report (1997) ESRF97HA02T.

- [15] K. P. Belov, R. Z. Levitin, B. K. Ponomarev, J. Appl. Phys. 39 (1968) 3285.
- [16] K. P. Belov, G. I. Kataev, R. Z. Levitin, S. A. Nikitin, V. I. Sokolov, Sov. Phys. Usp. 26 (1983) 518.
- [17] A. E. Clark, AIP Conf. Proc. 18 (1974) 1015-1029.
- [18] A. E. Clark, R. Abbundi, W. R. Gillmor, IEEE Trans. Magn. MAG-14 (1978) 542-544.
- [19] A. E. Dwight, C. W. Kimball, Acta Crystallogr. B 30 (1974) 2791-2793.
- [20] B. Barbara, J. P. Giraud, J. Laforest, R. Lemaire, E. Suard, J. Schweizer, Physica (Amsterdam) 86-88B (1977) 155-157.
- [21] Y. R. Bonin, E. D. Crozier, Can. J. Phys. 74 (1996) 295-304.
- [22] A. E. Clark, J. P. Teter, O. D. McMasters, J. Appl. Phys. 63 (1988) 3910-3912.
- [23] A. A. Likhachev, K. Ullakko, Phys. Lett. A 275 (2000) 142-151.
- [24] A. A. Likhachev, A. Sozinov, K. Ullakko, Mater. Sci. Eng. A 378 (2004) 513-518.
- [25] H. Karaka, I. Karaman, B. Basaran, Y. Ren, Y. I. Chumlyakov, H. J. Maier, Adv. Funct. Mater. 19 (2009) 983-998.
- [26] S. J. Murray, M. Marioni, S. M. Allen, R. C. O'Handley, T. A. Lograsso, Appl. Phys. Lett. 77 (2000) 886-888.
- [27] T. Y. Ma, X. L. Liu, X. W. Pan, X. Li, Y. Z. Jiang, M. Yan, H. Y. Li, M. X. Fang, X. B. Ren, Appl. Phys. Lett. 105 (2014) 192407.

Figure captions

Fig. 1

Schematic of the experimental setup for high energy x-ray diffraction. A pair of NdFeB permanent magnets was used to generate a magnetic field of up to 0.69 T.

Fig. 2

Room temperature magnetostriction curves for TbFe₂, Tb_{0.4}Dy_{0.6}Fe₂ and DyFe₂ compounds in stress-free state.

Fig. 3

Room temperature Bragg reflections (black circles) and fitted curves (blue and pink solid lines) for TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 compounds. TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ are in a rhombohedral structure at room temperature. The tetragonal distortion in DyFe_2 cannot be identified from the obtained diffraction patterns.

Fig. 4

Crystallographic relations for $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds between paramagnetic and ferromagnetic states: (a) rhombohedral phase with $\mathbf{M}_s \parallel [111]$; (b) tetragonal phase with $\mathbf{M}_s \parallel [001]$.

Fig. 5

Variations of the $(344)_R$ and $(401)_R$ diffraction peaks for TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ under various magnetic field strength values: (a) parallel to the field; (b) perpendicular to the field. The fitted curves (blue and pink solid lines) and the peak positions (blue and pink dashed lines) are shown.

Fig. 6

Integrated intensity fraction of $(344)_R$ diffraction peak $[I_{344_R}/(I_{344_R} + I_{401_R})]$ (a) and schematic of the microstructural evolutions in TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds under an applied magnetic field (b).

Demagnetized State

$$\varepsilon_0 > 0$$

Magnetized State

Fig. 1

Schematic of the experimental setup for high energy x-ray diffraction. A pair of NdFeB permanent magnets was used to generate a magnetic field of up to 0.69 T.

Fig. 2

Room temperature magnetostriction curves for TbFe₂, Tb_{0.4}Dy_{0.6}Fe₂ and DyFe₂ compounds in stress-free state.

Fig. 3

Room temperature Bragg reflections (black circles) and fitted curves (blue and pink solid lines) for TbFe_2 , $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ and DyFe_2 compounds. TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ are in a rhombohedral structure at room temperature. The tetragonal distortion in DyFe_2 cannot be identified from the obtained diffraction patterns.

Fig. 4

Crystallographic relations for $\text{Tb}_{1-x}\text{Dy}_x\text{Fe}_2$ compounds between paramagnetic and ferromagnetic states: (a) rhombohedral phase with $\mathbf{M}_s \parallel [111]$; (b) tetragonal phase with $\mathbf{M}_s \parallel [001]$.

Fig. 5

Variations of the $(344)_R$ and $(401)_R$ diffraction peaks for TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ under various magnetic field strength values: (a) parallel to the field; (b) perpendicular to the field. The fitted curves (blue and pink solid lines) and the peak positions (blue and pink dashed lines) are shown.

Fig. 6

Integrated intensity fraction of $(344)_R$ diffraction peak $[I_{344R} / (I_{344R} + I_{401R})]$ (a) and schematic of the microstructural evolutions in TbFe_2 and $\text{Tb}_{0.4}\text{Dy}_{0.6}\text{Fe}_2$ compounds under an applied magnetic field (b).