Magnetostriction in (CexTb1−x)0.5Pr0.5Fe2 compounds
Chengchun Tang, Jiang Du, Yangxian Li, Fangwei Wang, Guanghen Wu et al.

Citation: Appl. Phys. Lett. 73, 692 (1998); doi: 10.1063/1.121950
View online: http://dx.doi.org/10.1063/1.121950
View Table of Contents: http://apl.aip.org/resource/1/APPLAB/v73/i5
Published by the American Institute of Physics.

Related Articles
Discuss on using Jiles-Atherton theory for charactering magnetic memory effect
Microstructure and magnetostriction of melt-spun Fe73Ga27 ribbon
Colossal low-frequency resonant magnetomechanical and magnetoelectric effects in a three-phase ferromagnetic/elastic/piezoelectric composite
Magnetostriction of TbFe2-based alloy treated in a semi-solid state with a high magnetic field
Modeling of resonant magneto-electric effect in a magnetostrictive and piezoelectric laminate composite structure coupled by a bonding material

Additional information on Appl. Phys. Lett.
Journal Homepage: http://apl.aip.org/
Journal Information: http://apl.aip.org/about/about_the_journal
Top downloads: http://apl.aip.org/features/most_downloaded
Information for Authors: http://apl.aip.org/authors
Magnetostriction in (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ compounds

Chengchun Tang, Jiang Du, Yangxian Li, Fangwei Wang, Guanghen Wu, and Wenshan Zhan

State Key Laboratory for Magnetism, Institute of Physics, Chinese Academy of Sciences, Beijing 100080, People’s Republic of China

Jingping Qu

Hebei University of Technology, Tianjin 300130, People’s Republic of China

(Received 1 April 1998; accepted for publication 3 June 1998)

The structural and magnetostrictive properties of (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ were investigated. The Ce concentration must exceed $x = 0.6$ in order to obtain the pure Laves phase. The magnetostriction and anisotropy constant increase with the Tb content in this system. The anisotropy value of PrFe$_2$ is lower than that of isostructural DyFe$_2$. From the x-ray step-scanned data, we find that $\lambda_{111}$ of PrFe$_2$ is 1310 ppm. A large increase can be observed under a small prestress of 6 MPa for Ce$_{0.4}$Pr$_{0.5}$Fe$_2$.

© 1998 American Institute of Physics. [S0003-6951(98)04731-7]

According to the single-ion model, the cubic Laves phase compound PrFe$_2$ is a potential candidate for giant magnetostrictive material due to the large second-order Stevens’ factor $\alpha_f$, ground state angular momentum $J$ and average radius squared $\langle r_f^2 \rangle$ of the 4$f$ electron shell of the Pr$^{3+}$ ion. However, the large radius of Pr$^{3+}$ ion makes it difficult to get a single phase PrFe$_2$, and almost all syntheses at ambient pressure were unsuccessful up to now. Considerable efforts have focused on the various high-pressure techniques to lower the volume of Pr ion in this compound and, however, none of the reaction products was free of impurity.

There have been our recent works on the studying of the effect of Ce 4$f$ bonding in (Ce,R)Fe$_2$ system (where R=rare earth). Our experimental results indicate that partial substitution of Ce for Pr enhances the stability of the formation of Laves phase containing high Pr content. We believe that the Ce 4$f$ bonding, or even $f$-$d$ hybridizations, plays an important role in the structural, magnetic and magnetoelastic properties of this system. After appropriate heat treatment for Pr$_x$Ce$_{1-x}$Fe$_2$, Pr concentration can be extended up to $x = 0.8$ at ambient pressure and a clear single Laves phase occurs at least at $x = 0.5$. The magnetostriction increases drastically with the Pr content. A saturation magnetostriction $\lambda_s = 1138$ ppm of PrFe$_2$ can be calculated by extrapolating the magnetostriction versus Pr concentration relation to $x = 1.0$. The measurement of low temperature magnetization curve indicates that the PrFe$_2$ has a lower anisotropy constant than that of RE$_2$ when R is a heavy rare earth atom, which leads to a low bias field for saturation magnetostriction that is required in the potential use of magnetostrictive materials.

Considering the important effect of rare earth Tb ion in magnetostrictive materials, we attempted to introduce Tb ion into the (Ce, Pr)Fe$_2$ pseudobinary compound in order to further study light rare-earth contributions to the magnetostriction and anisotropy. In the present letter we will report the phase transformation and magnetostrictive properties in the system of (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$.

The starting materials of (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ with $x$ from 0.2 to 1.0 were prepared from Ce, Pr, Tb, and Fe of the purity of 99.9%. The samples were prepared by arc melting in an argon atmosphere and remelted four times to ensure homogeneity. The as-cast ingots were wrapped in tantalum foils and vacuum annealed in sealed quartz capsules. We followed the same annealing procedure as that previously reported, that is, a heat treatment of 600 °C for two days, 700 °C for five days, 800 °C for two days and 850 °C for one day. The samples were powdered under an argon atmosphere and their crystallographic structure and phase purity were determined by x-ray diffraction measurement using Cu K$\alpha$ radiation. The magnetostrictions were measured using the standard strain-gauge technique in directions parallel (l$_1$) and perpendicular (l$_2$) to the magnetic field up to 20 kOe at room temperature. The intrinsic magnetostrictive parameter $\lambda_{111}$ was obtained by fitting the x-ray step-scanned data from (440) reflection of the cubic crystalline structure measured using the mentioned x-ray system.

Figure 1 shows the room temperature x-ray patterns for (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ with the different Ce content. It is found that the samples with $x \approx 0.5$ exhibit a perfect single Laves phase, and for those with $x < 0.5$ secondary phase occurs inevitably. This phenomenon is in keeping with the previously reported result that Pr concentration should not exceed $x = 0.2$ in Pr$_x$Tb$_{1-x}$Fe$_2$ and $x = 0.8$ in Pr$_x$Ce$_{1-x}$Fe$_2$ to obtain single phase. The amount of the secondary phase in (Ce$_{0.4}$Tb$_{0.6}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ is about 10% in weight fraction and there is a solubility limit of Tb content $x < 0.3$ in the investigated system.

Figure 2 shows the room temperature magnetostrictions of those samples with single phase. Magnetostriective value under 20 kOe increases from 320 ppm when free of Tb ($x = 1.0$) to 859 ppm when Tb rich ($x = 0.5$). The increasing rate is a constant of about 2200 ppm/Tb, which is very close to the magnetostrictive value of TbFe$_2$ (2629 ppm) at room temperature. It indicates that the magnetoelastic properties of the Tb ion in this system is not affected by the concentration change of Ce ion which shows a mixed-valence behavior. The required applied magnetic field for saturation magnetostriction increases with the increase of Tb concentration, and for (Ce$_{0.5}$Tb$_{0.5}$)$_{0.5}$Pr$_{0.5}$Fe$_2$, the magnetostriction does not
saturate even at 20 kOe. In comparison with Tb$_{0.27}$Dy$_{0.73}$Fe$_2$ (Terfenol-D) which possesses a low anisotropy value due to anisotropy compensation, we can infer that the anisotropy constant of the Pr ion is far smaller than that of the Dy ion in the isostructural compound because they have the same sign of Stevens’ equivalent operator. This conclusion is in accordance with the observation from the magnetization curve of Pr$_x$Ce$_{1-x}$Fe$_2$ in which the anisotropy constant $K_1$ of PrFe$_2$ is of the order of $7.3 \times 10^5$ J m$^{-3}$ (compared with $-7.3 \times 10^6$ J m$^{-3}$ for TbFe$_2$ and $2.1 \times 10^6$ J m$^{-3}$ for DyFe$_2$). This small anisotropy constant $K_1$ also indicates that the anisotropy compensation in the system of Tb$_{1-x}$Pr$_x$Fe$_2$ cannot be expected unless Pr content in the compounds is high enough. That is, Pr concentration cannot be lower than $x = 0.9$ to obtain a low bias field of magnetostriction by roughly calculating the anisotropy compensating point according to the above data.

In order to study the intrinsic magnetostriction $\lambda_{111}$, we have to measure the splitting of the (440) reflection by the step-scanned way due to the occurrence of the large saturation field for the samples with high Tb content. The (440) reflection can be considered as a superposition of two separate diffracted $K\alpha_1\alpha_2$ profiles reflected from two separate lattices with a small difference in their interplanar distance. The value of $\lambda_{111}$ was calculated from $\lambda_{111} = 1 - \sin \theta_2 / \sin \theta_1$, where $\theta_1$ and $\theta_2$ are the Bragg angles. Figure 3 shows the splitting of (440) reflection in (Ce$_{0.5}$Tb$_{0.5}$)$_{0.5}$Pr$_{0.5}$Fe$_2$. The Bragg angles of the two profiles are obtained by fitting the step-scanned data to modified pseudo-Voigt function with the Rietveld method. The fitting result is also shown in Fig. 3. The $\lambda_{111}$ calculated for (Ce$_{0.5}$Tb$_{0.5}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ is 1593±50 ppm, comparable to that of Terfenol-D. $\lambda_{111}$ of PrFe$_2$ will be 1310 ppm if $\lambda_{111}$ of about 2629 ppm for TbFe$_2$ is adopted and the contribution from Ce ion is ignored. This value is slightly larger than that of DyFe$_2$ at room temperature.

Figure 4 shows the relationships between the magnetostriction and the compressive prestress in direction parallel to magnetic field for the Tb free sample Ce$_{0.5}$Pr$_{0.5}$Fe$_2$. When the prestress is increased to 6 MPa, the magnetostriction at a
field of 20 kOe increases from 320 ppm at 0 MPa to 510 ppm at 6 MPa while the saturation field has no large variation. With further increase of the prestress the magnetostriction maintains a small increasing rate about 25 ppm/MPa. The origin of large increase of the magnetostriction at small prestress might be from the loss of homogeneous microstructure or from the Invar effect of Ce ion in this system. The underlying physics is still under investigation. However, the small anisotropy and stability of magnetostriction under pre-stress, as well as the inexpensive raw materials (only contain Ce, Pr rare earth), make Ce$_{0.5}$Pr$_{0.5}$Fe$_2$ a promising material for application.

In conclusion, in (Ce$_x$Tb$_{1-x}$)$_{0.5}$Pr$_{0.5}$Fe$_2$ there exists a solubility limit of Tb. The anisotropy and magnetostriction increase with the Tb concentration. The Pr ion in this system has a lower anisotropy constant compared with Dy(Tb) ion. The huge anisotropy value of Tb ion cannot be canceled out by the small anisotropy value of Pr ion with opposite sign unless the compound with high Pr concentration be synthesized. The magnetostriction of Tb free Ce$_{0.5}$Pr$_{0.5}$Fe$_2$ exhibits a large increase with a small prestress.