A survey on the effect of vanadium content on the magnetoelastic properties of YFe$_{12-x}$V$_x$ alloys

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ABSTRACT

Experimental results on the thermal expansion and magnetostriction of YFe$_{12-x}$V$_x$ ($1.5 \leq x \leq 3.5$) alloys are reported. The results show that the anisotropic magnetostriction ($\Delta\lambda$) at a finite field (1.5 T) increases with increasing vanadium content in the range of $x < 2$. But for $x > 2$, a decrease in the magnetic anisotropy with increasing vanadium content causes a decrease in the saturation values of $\Delta\lambda$. In addition, the thermal expansion coefficient becomes a minimum for $x \approx 2$. Experimental curves exhibit that the forced volume magnetostriction ($\Delta V/V$) is positive and increases linearly with the applied field at high fields. But in the low field region (≤ 0.5 T), a minimum appears in the isothermal curves of $\Delta V/V$ around the saturation field. The results are explained by considering the influence of vanadium content on the magnetization anisotropy of YFe$_{12-x}$V$_x$ compounds.

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1. Introduction

The elements (M=V, Ti, Mo, …) are necessary to stabilize the ThMn$_{12}$ (S.G. I4/mmm) crystal structure, though they decrease the intrinsic magnetic properties of RFe$_{12-x}$M$_x$ compounds [1]. In spite of the common belief, these elements can have a polarization antiparallel to that of iron moments in some specific compounds [1,2]. Therefore, their presence not only affect magnetic interactions of the Fe sublattice but also change the crystal field anisotropy of the R sublattice. In the present work, we study influence of the M=V element on the magnetoelastic interactions of Fe sublattice by choosing R as a nonmagnetic rare earth element (particularly, R=yttrium). Until now, the effects of substitution of Fe by V on the magnetoelastic properties, such as thermal expansion and magnetostriction, have been less considered [3]. The YFe$_{12-x}$V$_x$ compounds with more than 2 T axial anisotropy field at room temperature and low vanadium contents (i.e. $x \leq 2$), are recognized as a good candidate for permanent magnet applications, after improving their Curie temperature, of course [4,5].

Previous results show that the saturation magnetization, Curie temperature and magnetic anisotropy of the YFe$_{12-x}$V$_x$ compounds decrease while the unit cell volume increases with increasing vanadium content [6]. It is commonly argued that the variations in magnetic properties of these compounds are similar to those observed upon their carbonation [7]. In addition, vanadium atoms occupy only the 8i site of the iron within the I4/mmm structure while 8f and 8j sites are exclusively occupied by Fe elements, so that the solid solubility range of vanadium is limited to $0 \leq x \leq 4$ [8]. In this interval, average magnetic moment and Curie temperature decrease whereas unit cell volume increases approximately linearly when the vanadium content increases [1]. A simple analysis illustrates that one may attribute about $-0.88\ \mu_B$ magnetic moment to the vanadium ions in the YFe$_{10.5}$V$_{1.5}$ compound [2]. Hence, we expect considerable changes in the magnetoelastic interactions by the substitution of vanadium atoms within the YFe$_{12-x}$V$_x$ compound. Concerning negligible magnetic moment of Y^{3+} ions ($< 0.2\ \mu_B$) [9], we may assume their contribution to be negligible in the following results and attribute them to the effect of vanadium on the magnetostrictive strains of Fe sublattice in this family of compounds.

2. Experimental details

YFe$_{12-x}$V$_x$ ingots were prepared by high frequency melting of the constituent elements under purified-argon atmosphere. Then, as-cast ingots were enveloped within tantalum foils and annealed for 24 h at 960 °C in a 133×10^{-9} mbar evacuated furnace. After complete removal of the outer oxidized layers by sand paper, the alloys were crushed into powders in alcohol to a size less than 200 μm. Phase purity of the powders was determined by XRD (X-ray diffraction).

For magnetoelastic effects experiments, the homogeneous and isotropic disk-shaped samples (8 mm in diameter and 2 mm thickness) were cut from the body of ingots. Magnetostriction

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and thermal expansion were measured by standard strain gage method in applied fields up to 1.5 T and in the temperature range of 77–320 K. The accuracy of measurements depends on the errors in thermometry and in field setting, the quality of thermal insulation of the samples, the possible modification of the reading of temperature sensor due to the applied field, etc. Considering all these effects, the accuracy is about 2×10^{-6}. By applying the magnetic field parallel to the disk surface, the magnetostrictions parallel (longitudinal magnetostriction, λ_l) and perpendicular (transverse magnetostriction, λ_t) to the field direction were measured in the disk plane. Then, the anisotropic ($\Delta\lambda = \lambda_l - \lambda_t$) and volume ($\Delta V/V = \lambda_l + 2\lambda_t$) magnetostrictions were deduced. For seeking reproducibility of the results, all measurements were repeated by iterative warming and cooling of the sample. Also, no hysteric behavior and no significant difference were observed between magnetostriction and thermal expansion of samples that have been cut along three perpendicular directions of the bulk alloys. This implies absence of thermal cracking and any preferential magnetic orientation in the $YFe_{12-x}V_x$ annealed alloys. Thermal expansion coefficients (α) and their average in the 80–300 K temperature interval were obtained by calculating slopes of the experimental curves and the corresponding linear fits.

3. Results and discussion

Typical X-ray diffraction patterns of the prepared ingots are shown in Fig. 1. Analysis of these figures confirms the $ThMn_{12}$ type tetragonal structure of $YFe_{12-x}V_x$ as the major phase besides tiny traces of α-Fe and 2–17 as minor phases. As shown in Table 1, the refined lattice parameters of the major phase are consistent with the literature [6]. Also, it is clearly seen that the lattice parameters, and accordingly the unit cell volume, increase after substitution of vanadium atoms.

Experimental curves of the thermal expansion are shown in Fig. 2. As clearly seen, thermal expansion curves exhibit similar thermal variations, although their average thermal expansion coefficients show a change of 60% by variation of vanadium content. The average
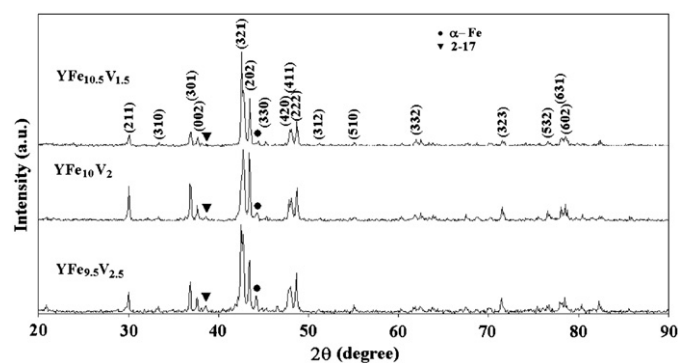
thermal expansion coefficients (α) are given in Table 2. These results show that the thermal expansion coefficient is minimum for the sample with $x \approx 2$. Considering that the magnetic contributions to the thermal expansion of a polycrystalline sample originate from isotropic strictions, this minimum refers to the minimum (softening) of magnetoelastic coupling of the Fe sublattice of $RFe_{12-x}V_x$ compounds for $x \approx 2$. From the fact that the V atoms occupy only 8i crystallographic sites and by assuming their homogeneous distribution, this softening occurs when half of 8i sites are occupied by vanadium atoms ($x \approx 2$).

Fig. 3 shows typical isothermal curves of the anisotropic magnetostriction of the studied samples. It can be seen that the anisotropic magnetostriction of all samples is positive. In addition, although $\Delta\lambda$ curves of the samples with $x=1.5$ and 2 do not reach complete saturation in the range of our available fields ($\mu_0 H \leq 1.5$ T), saturation trend appears on increasing vanadium content. The critical lowest applied fields for appearing saturation trend of $\Delta\lambda$ curves at room temperature (H_{sat}) are shown in Fig. 4. Considering Table 2, a clear correspondence can be assumed between H_{sat} and the anisotropy field of these compounds. Therefore, appearance of the saturation behavior in the $\Delta\lambda$ curves of the samples with higher x values is
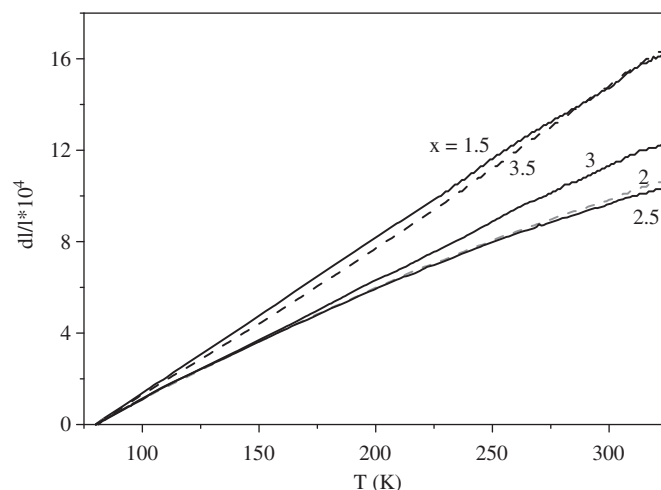
Fig. 2. Thermal expansion curves of $YFe_{12-x}V_x$ alloys. Interval of the data points is 1 K.

Table 2
Average thermal expansion coefficient of $YFe_{12-x}V_x$ alloys between 80 and 325 K. Anisotropy fields (H_a) deduced from Ref. [10] have also been given.

Alloy	α ($*10^{-6}$ K^{-1})	$\mu_0 H_a$ (T) (at 300 K)
$YFe_{10.5}V_{1.5}$	6.732 ± 0.013	2.8
$YFe_{10}V_2$	4.366 ± 0.008	2
$YFe_{9.5}V_{2.5}$	4.383 ± 0.008	1.4
YFe_9V_3	5.104 ± 0.010	–
$YFe_{8.5}V_{3.5}$	6.563 ± 0.013	–

Fig. 1. Typical XRD patterns of $YFe_{12-x}V_x$ alloys.

Table 1
Lattice parameters of $YFe_{12-x}V_x$ alloys at 300 K, and estimated phase fractions of α-Fe and Y_2Fe_{17} phases.

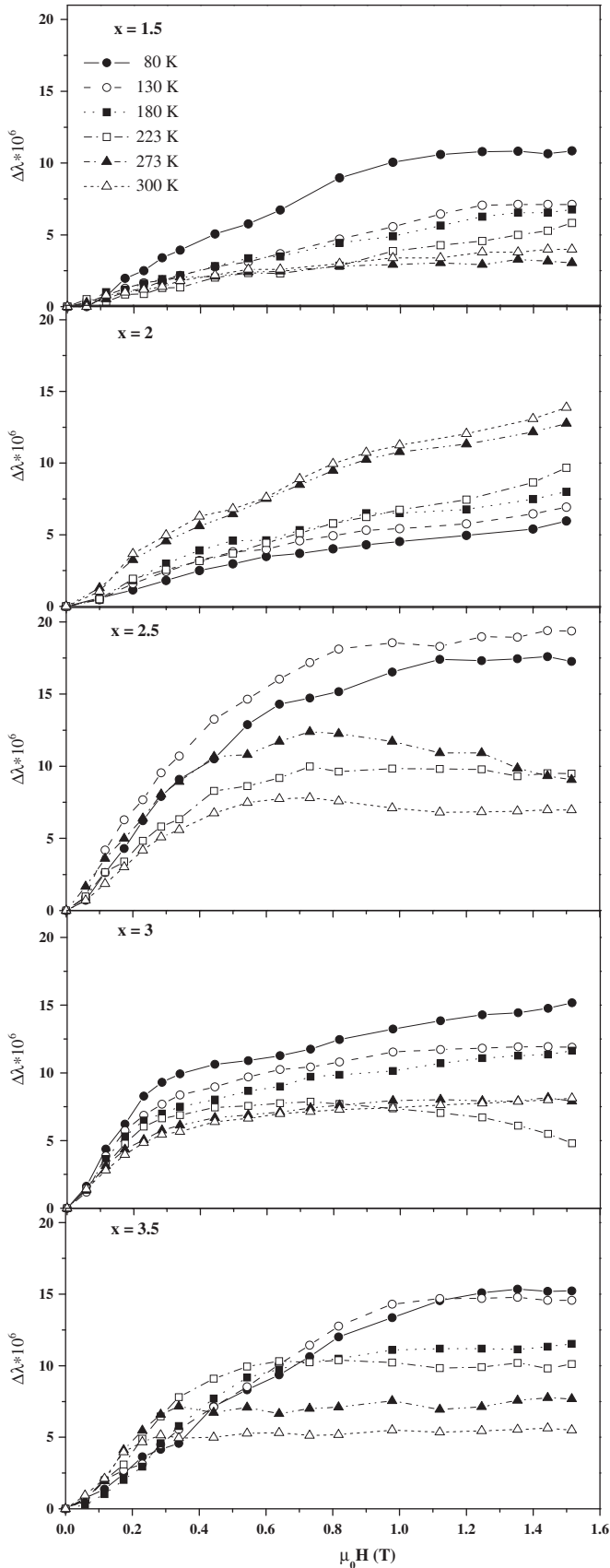| Alloy	a (Å)	c (Å)	V (Å^3)	$\Delta V/V$ (%)	Phase fraction (%)	
					α-Fe	Y_2Fe_{17}
$YFe_{10.5}V_{1.5}$	8.4795 ± 0.0007	4.7650 ± 0.0005	342.613	–	0.69	0.25
$YFe_{10}V_2$	8.4953 ± 0.0004	4.7734 ± 0.0003	344.497	0.005	0.98	0.43
$YFe_{9.5}V_{2.5}$	8.4987 ± 0.0007	4.7772 ± 0.0003	345.047	0.007	1.55	0.76
YFe_9V_3	8.4990 ± 0.0005	4.7841 ± 0.0003	345.570	0.009	1.83	0.90
$YFe_{8.5}V_{3.5}$	8.5102 ± 0.0007	4.7852 ± 0.0004	346.561	0.012	2.1	1.12

Fig. 3. Anisotropic magnetostriction of YFe$_{12-x}$V$_x$ alloys as a function of applied field at typical temperatures.
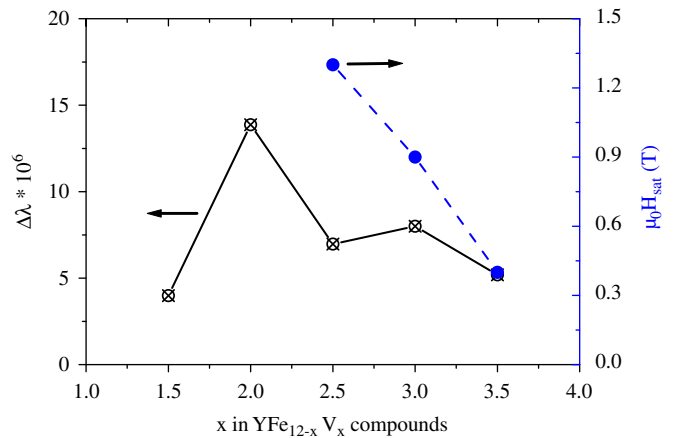

Fig. 4. Influence of vanadium content on the room temperature anisotropic magneto-striction at 1.5 T field and critical saturation field (H_{sat}) of YFe$_{12-x}$V$_x$ compounds at room temperature.
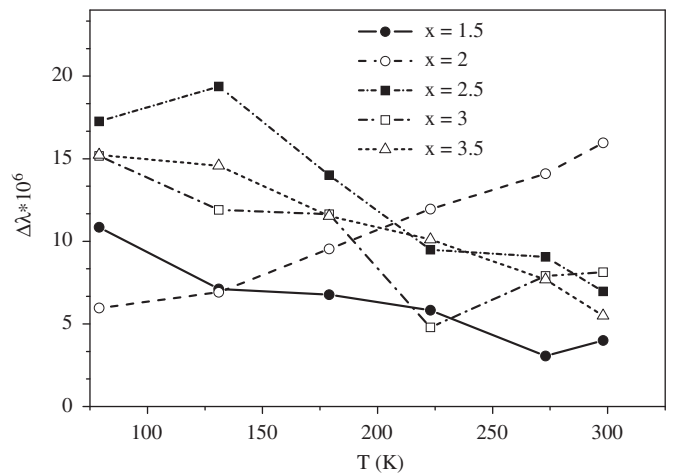

Fig. 5. Isofield curves of the anisotropic magnetostriction of YFe$_{12-x}$V$_x$ alloys at $\mu_0 H = 1.5$ T.

consistent with the fact that the magnetic anisotropy decreases with increasing vanadium content. Similarly, variation of $\Delta\lambda$ (at 1.5 T and $T = 300$ K) versus vanadium content in Fig. 4 can be ascribed to the variation of magnetic anisotropy. In fact, saturation behavior of $\Delta\lambda$ curves in Fig. 3 appears for the samples with $x \geq 2.5$. In the range of $x > 2$, decrease in the magnetic anisotropy with increasing vanadium content causes decrease in $\Delta\lambda_{(1.5 \text{ T}, 300 \text{ K})}$.

To explain temperature dependence of the anisotropic magnetostriction in Fig. 5, one should consider the following possibilities: (1) natural thermal decrease in the magnetization and (2) magnetic anisotropy. The former leads to a decrease in $\Delta\lambda$, while the latter gives rise to an increase in the unsaturated values of $\Delta\lambda$ when temperature increases. As depicted in Fig. 5, the second possibility is dominated only in the case of YFe$_{10}$V$_2$ and the first one plays predominant role in the temperature dependence of $\Delta\lambda$ of other samples.

Isothermal curves of the forced volume magnetostriction of the studied alloys at room temperature are shown in Fig. 6. It is clear that the volume magnetostrictions of all samples in the high field region are positive and increase with the applied fields. But in the low field region ($\mu_0 H \leq 0.5$ T), a minimum appears in the isothermal curves of $\Delta V/V$. By increasing the x value, these minimums not only become deeper but are also displaced at lower applied fields. By comparison of Figs. 3 and 6, it follows that the minimums appear about $H = H_{sat}$. Hence, with reference to the magnetization processes [11], it may be said that the domain walls motion and
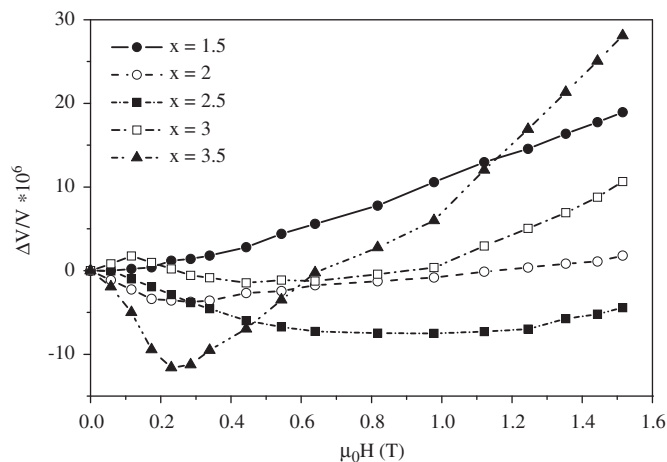
Fig. 6. Influence of the vanadium content on the isothermal curves of volume magnetostriction of YFe$_{12-x}$V$_x$ alloys at 300 K.

rotation of the magnetic moments of domains toward the applied field direction are accompanied by negative forced isotropic strains. In fact, as the applied field increases above a few tenth of tesla, the magnetostriction originates mainly from the magnetocrystalline anisotropy that mainly contributes to the anisotropic magnetostriction. Parallel to this effect, the dependence of magnetic interactions on the inter-atomic distances, which is at first order isotropic, can contribute to the volume magnetostriction.

4. Conclusions

In this report, a brief survey has been given on the effect of substitution of V for Fe atoms on the magnetoelastic interactions in YFe$_{12-x}$V$_x$ alloys. Results show that the thermal expansion coefficient becomes a minimum for $x \approx 2$. In addition, variation in the saturation values of anisotropic magnetostriction by vanadium content can be ascribed to the variation in magnetic anisotropy. On the other hand, temperature dependence of the anisotropic magnetostriction is explained by the natural decrease in magnetization and magnetic anisotropy when temperature is increased. Experimental curves of the forced volume magnetostrictions exhibit that it is positive and increases by increasing applied fields at high field region. But at low field region ($\mu_0 H \leq 0.5$ T), a minimum appears in the isothermal curves of $\Delta V/V$ in the vicinity of the saturation field. These minimums not only become deeper but also move toward lower applied fields by increasing the x value. The results were explained by considering the influence of vanadium content on the magnetic anisotropy of YFe$_{12-x}$V$_x$ compounds.

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