Magnetic and magnetostrictive properties of $Sm_{1-x}Ho_xFe_2$

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Abstract

A series of pseudobinary compounds of $Sm_{1-x}Ho_xFe_2$ ($x = 0.0$, 0.25, 0.35, 0.45, 0.60, 0.80) have been prepared and investigated. Measurements of X-ray diffraction, magnetization and magnetostriction were carried out on these samples. It is shown that the system retains the cubic $MgCu_2$ structure over the whole range and the lattice constant a decreases linearly from 7.421 Å for $x = 0.0$ to 7.307 Å for $x = 0.8$. The concentration dependence of the saturation magnetization exhibits a minimum at $x = 0.35$ for 1.5 K and at $x = 0.42$ for room temperature, reflecting the occurrence of a compensation of the magnetic moment at various Sm:Ho ratios. A compensation of the anisotropy was also observed, while its minimum occurs for $x = 0.25$ at 1.5 K and for $x = 0.35$ at room temperature. The Curie temperature T_C decreases linearly from 677 K for $x = 0.0$ to 617 K for $x = 0.8$, and the magnetostriction declines with increasing Ho content as a result of the compensation of λ_{111} of the $SmFe_2$ and $HoFe_2$ sublattices in the $Sm_{1-x}Ho_xFe_2$ system.

Keywords: Magnetic properties; Magnetostriction

1. Introduction

The rare earth–Fe_2 compounds of cubic Laves phase have shown the largest known magnestostriction at room temperature. However, the large anisotropy they possess makes their saturation magnetostriction hard to obtain. Fortunately, their cubic phase makes it possible to lower the anisotropy while still retaining a comparatively large magnetostriction [1], which is important for technical application. Although the compound $Sm_{1-x}Ho_xFe_2$ is an attractive candidate because of the different signs of the anisotropies of $SmFe_2$ and $HoFe_2$[2], it received little attention during previous studies. It was only found that $Sm_{0.7}Ho_{0.3}Fe_2$ possesses the minimum anisotropy at room temperature [3], which was also proven by the Mössbauer study [4]. In this paper, the structural, magnetic and magnetostrictive properties of $Sm_{1-x}Ho_xFe_2$ have been investigated. The results of the compensation of the magnetic moment, magnetic anisotropy and magnetostriction at various ratios of Sm:Ho are discussed.

2. Experimental

The intermetallic compounds of $Sm_{1-x}Ho_xFe_2$($x = $ 0.0, 0.25, 0.35, 0.45, 0.60, 0.80) were prepared by arc melting with the raw materials of 99.9% purity in an Ar atmosphere of 99.999% purity. The ingots were then annealed at 800 °C under Ar protection for 18 h. X-ray powder diffraction was used to determine the phase of the samples with Co $K\alpha$ radiation, while the magnetization measurements at 1.5 K and 300 K were carried out with an extracting sample magnetometer in an applied field up to 5.2×10^3 kA m^{-1} ($\mu_0 H = 6.5$ T) using samples of diameter 4 mm × 6 mm size. In order to obtain the Curie temperature T_C, the temperature dependence of the magnetization was measured with a vibrating sample magnetometer with the magnetic field kept at about 64 A m^{-1} ($\mu_0 H = 800$ Oe). Strain gauges were used to measure the magnetostriction of the specimens (diameter 12 mm × 1.5 mm) in fields up to 1.6×10^3 kA m^{-1} ($\mu_0 H = 2$ T) at room temperature.

3. Results and discussion

3.1. Structure and magnetization

From the results of X-ray powder diffraction, it was found that all the $Sm_{1-x}Ho_xFe_2$ samples exhibit the cubic Laves phase. The lattice constant a decreases
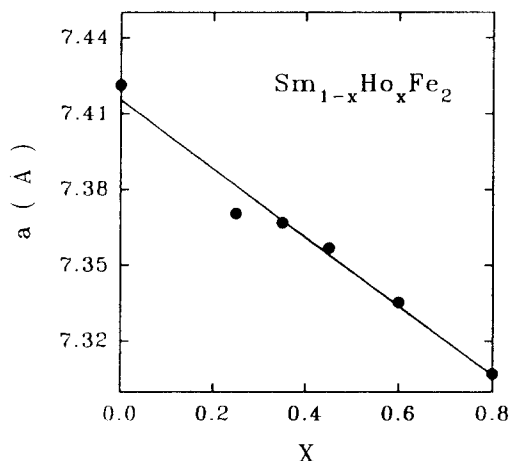
Fig. 1. Lattice constant a as a function of Ho content x.

linearly with the increase in x from 7.421 Å for $x = 0.0$ to 7.307 Å for $x = 0.8$ as shown in Fig. 1.

The Curie temperature T_C of each sample was obtained by the measurements of M vs. temperature. Fig. 2 shows that T_c decreases linearly from 677 K for $x = 0.0$ to 617 K for $x = 0.8$ as $HoFe_2$ has a lower T_c than $SmFe_2$ ($T_c(SmFe_2) = 677$ K, $T_c(HoFe_2) = 606$ K [5]), which indicates a stronger coupling between Sm and Fe atoms than that of Ho and Fe. A similar phenomenon can be found in $Sm_{1-x}Er_xFe_2$ [6] and $Sm_{1-x}Dy_xFe_2$ [7].

The law of approach to saturation was expressed in Ref. [8] as

$$M = M_s(1 - a/H - 2b/H^2) + x_pH \qquad (1)$$

Here M_s indicates the saturation magnetization, a is usually called the hard magnetic coefficient, and b is associated with magnetic anisotropy, while x_p is the paramagnetic susceptibility. By fitting the magnetization curves of $M(H)$ measured at 1.5 K and 300 K to Eq. (1), we obtained the saturation magnetization M_s.
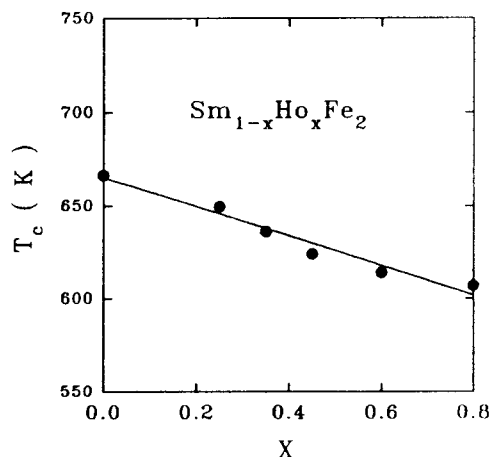

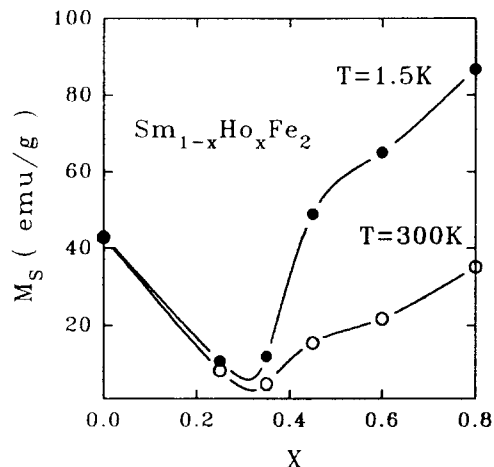Fig. 2. Curie temperature T_c as a function of Ho content x.

Fig. 3. Saturation magnetization M_s as a function of Ho content x at 1.5 K and 300 K.

The plots of M_s vs. x at 1.5 K and 300 K are shown in Fig. 3. They all first decrease and then increase with the increase in x, exhibiting a minimum at $x = 0.35$ for 1.5 K and at $x = 0.42$ for room temperature. This can be interpreted in the framework of molecular field theory by the compensation of the sublattice magnetization. For $Sm_{1-x}Ho_xFe_2$ compounds, the moments of the Fe and Sm atoms are coupled parallel to each other [9] and antiparallel to that of Ho [10]. With the increasing replacement of Sm by Ho, the moment of Ho increases, which causes the total magnetic moment M_s to decrease and reach a compensation point as described above. With further increase in Ho content, the contribution to the whole magnetization is given mainly by the Ho atoms, which leads to an increase in M_s. Similar explanations have been given for $Sm_{1-x}Er_xFe_2$ [11] and $Sm_{1-x}Dy_xFe_2$ [7].

According to the previous papers, $SmFe_2$ and $HoFe_2$ have exhibited a very different behaviour of the temperature dependence of the magnetic moment. While the magnetic moment of $HoFe_2$ experiences a sharp drop as the temperature increases ($\mu_{300\,K} = 3.06\ \mu_B$, $\mu_{0.0\,K} = 6.70\ \mu_B$) [5], $SmFe_2$ almost does not change at all ($\mu_{300\,K} = 2.20\ \mu_B$, $\mu_{0.0\,K} = 2.25\mu_B$ [12], or $\mu_{300\,K} = 2.20\mu_B$, $\mu_{4.2\,K} = 2.8\mu_B$ [13]). Consequently, it can be estimated using molecular field theory that the magnetic moments in $Sm_{1-x}Ho_xFe_2$ compounds compensate at about $x = 0.27$–0.35 for 1.5 K and $x = 0.40$–0.45 for 300 K, which is in a good agreement with our experiment results.

3.2. Magnetic anisotropy of $Sm_{1-x}Ho_xFe_2$

From the saturation law, the coefficient b can be derived and expressed as in Ref. [14] as

$$b = 8\,K_1^2/105\,M_s^2\mu_0^2 \qquad (2)$$

Here K_1 indicates the first-order term of the magnetic anisotropy. We have neglected the higher terms $K_n (n > 1)$ of magnetic anisotropy and the strain force because K_n is extremely small compared with K_1 and the strain force has been reduced significantly after annealing. During the medium approach to saturation, the susceptibility χ is proportional to $1/H^3$ and the slope is $2 M_s b$ [14].

Using the least-squares method, we can obtain the curve of χ vs. H from the function $M(H)$ and therefore the dependence of χ on $1/H^3$ is determined. Through the calculation of the linear segment's slope, the coefficient b and K_1 can easily be derived using eq. (2). Such a method can reduce the influence of measurement error effectively, but we cannot determine the sign of K_1. Fig. 4 shows the plots of K_1 vs. x at 1.5 K and 300 K from which we could see that both plots have similar trends. At 1.5 K, the anisotropy decreases from $x = 0.0$ to $x = 0.25$ because the anisotropy of $HoFe_2$ has a different sign from that of $SmFe_2$, which causes the alloy to compensate. Beyond the compensation point of $x = 0.25$, it starts to increase since the anisotropy of the $HoFe_2$ sublattice becomes dominant. At 300 K, from $x = 0.0$ to $x = 0.35$, the anisotropy decreases, and it begins to increase when $x > 0.35$, which results in the compensation point at $x = 0.35$. Such phenomena have been observed in other kinds of pseudobinary compounds such as $Tb_{1-x}Ho_xFe_2$ [4]. The behaviour that the compensation point shifts from $x = 0.25$ at 1.5 K to $x = 0.35$ at 300 K shows that the anisotropy of the $HoFe_2$ sublattice decreases more rapidly than that of $SmFe_2$ owing to the different orbital couplings under crystal fields.

Until now there have not been any experimental data on K_1 of $SmFe_2$ because single-crystal $SmFe_2$ is hard to synthesize. However, there are some clues from which we can make some rational suggestions. Clark and his colleagues have made some calculations
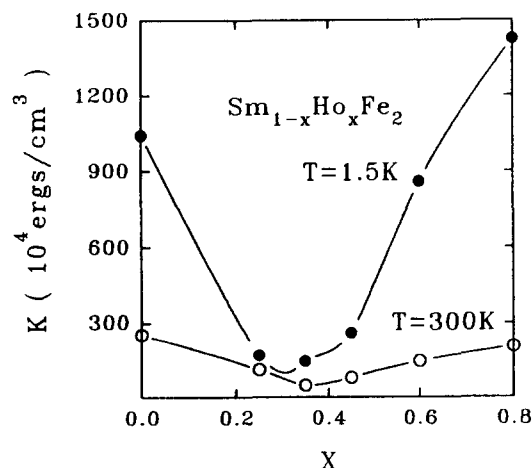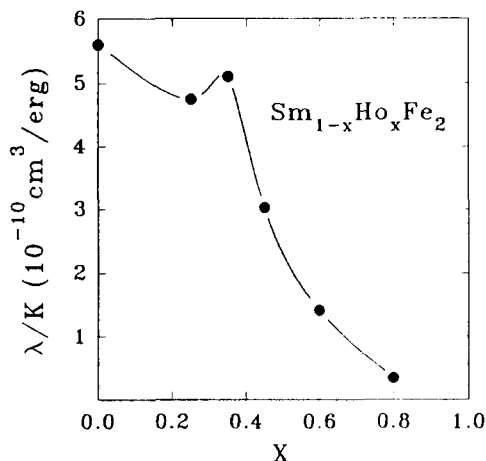

Fig. 5. The ratio $(\lambda_\parallel - \lambda_\perp)/K_1$ as a function of x.

for $HoFe_2$ $(K_1(300\,K) \approx 5.8 \times 10^6\ \mathrm{ergs\,cm}^{-3}$ [15]; $K_1(0\,K) \approx 2.7 \times 10^8\ \mathrm{ergs\,cm}^{-3})$; Abd El-Aal et al. [11] have made some investigations suggesting that K_1 of $SmFe_2$ is nearly $10^7\ \mathrm{ergs\,cm}^{-3}$ at 4.2 K. All these are in good agreement with our results.

3.2. Magnetostriction

The magnetostriction of different samples of $Sm_{1-x}Ho_xFe_2$ has been measured in directions parallel $(\lambda_\parallel)$ and perpendicular $(\lambda_\perp)$ to the applied field up to $1.6 \times 10^3\ \mathrm{kA\,m}^{-1}$ $(\mu_0 H = 2\ \mathrm{T})$. The magnetostriction decreases as the Ho content increases owing to the opposite signs of magnetostriction of $SmFe_2$ and $HoFe_2$. The curve of $(\lambda_\parallel - \lambda_\perp)/K$ vs. x is plotted in Fig. 5. We see that the ratio $(\lambda_\parallel - \lambda_\perp)/K$ decreases when $x < 0.25$; then it increases from $x = 0.25$ to $x = 0.35$, peaking at $x = 0.35$, and decreases again when $x > 0.35$. Such a phenomenon is probably due to the changes in the anisotropy and magnetostriction of $Sm_{1-x}Ho_xFe_2$ with x. From $x = 0.0$ to $x = 0.25$, the magnetostriction drops more rapidly than the anisotropy, which causes the ratio $(\lambda_\perp - \lambda_\parallel)/K$ to decline. However, for the sample of $x = 0.35$, the anisotropy arrives at a minimum while the magnetostriction does not drop much, and therefore the ratio increases. For the samples with $x > 0.35$, the anisotropy stops declining and begins to increase as explained above while the magnetostriction continues to decrease and the easy axis has turned to the (100) direction [3,17], which leads to the decrease in $(\lambda_\parallel - \lambda_\perp)/K$ once again with an even steeper slope as shown in Fig. 5.

Fig. 4. Magnetic anisotropy K_1 as a function of Ho content x at 1.5 K and 300 K.

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