A study of the magnetocrystalline anisotropy of $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$(x = 0–1.0)

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The magnetocrystalline anisotropy and the spin reorientation of $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ were investigated in detail. At room temperature, all $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys possess easy *c*-axis anisotropy and the magnetocrystalline anisotropy field decreases with increasing Dy concentration. However, at low temperature, a spin reorientation transition of axis-to-cone type was observed in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys with $x \geq 0.8$. The spin reorientation temperatures increase with increasing Dy concentration in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys.

1. Introduction

In the past ten years, a lot of studies were focused on the R(Fe, M)$_{12}$ compounds and their nitrides (R = rare earth and M = Ti, Cr, V, Mo, Si, W, Nb) for they are hopefully developed into excellent permanent-magnets [1–3]. Among the R(Fe, M)$_{12}$ compounds, R(Fe, Mo)$_{12}$ shows a remarkable difference from other R(Fe, M)$_{12}$ compounds such as M = Ti, Cr, V, Si, W, and Nb in the aspects of: (1) The Curie temperature great more quickly decreases with Mo concentration in R(Fe, Mo)$_{12}$ than with M in other R(Fe, M)$_{12}$ compounds [1, 2]; (2) Magnetohistory effects were observed in the R(Fe, Mo)$_{12}$ compounds with R = Y [4, 5], Lu [4], or Dy [6] on the contrast no magnetohistory effects observed in other R(Fe, M)$_{12}$ compounds; (3) The R(Fe, Mo)$_{12}$ compounds and their nitrides can be easily formed and contain not much Mo concentration so that they were attracted more attention on the potential technological application [7]. Recently, many efforts were concentrated on R(Fe, Mo)$_{12}$N$_y$ compounds including the anisotropic magnetic powders of $NdFe_{10.5}Mo_{1.5}N_y$, which had a maximum energy product of $(BM)_{max} = 169.6$ kJ/m^3 (21.2 MGOe), reported in 1997 [8]. The studies on spin reorientation transition (SRT) were considered as a significant method to understand the anisotropy and crystal-field interactions of the R-sublattice in R(Fe, M)$_{12}$. Many authors have investigated on the magnetic anisotropy

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in Sm(Fe, Mo)$_{12}$ [9–11] and SRT in Dy(Fe, Mo)$_{12}$ [12–16]. In this present work, We emphasise on investigating the magnetocrystalline anisotropy and spin reorientation in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ series.

2. Experimental details

Alloys with composition of $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ ($x = 0$, 0.2, 0.4, 0.6, 0.8 and 1.0) were prepared by arc melting the starting materials with a purity better than 99.5% under an atmosphere of high pure argon, and then annealing in vacuum at 1050 °C for 5–10 h. The quality of the samples was checked by powder X-ray diffraction (XRD) and thermomagnetic analysis (TMA) method. The spin reorientation transition was detected both by TMA using an extracting-sample magnetometer in an applied field of 40 mT from 1.5 K to room temperature and by ac susceptibility (χ_{ac}) measurement in an ac field of 0.1 mT with a frequency of 220 Hz from 4.2 K to room temperature.

The magnetic structure of $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ at room temperature and 1.5 K were determined by X-ray diffraction and the magnetization curves on the magnetically aligned samples respectively. The anisotropy field $\mu_0 H_a$ at room temperature was measured by the singular point detection (SPD) [17] technique on the aligned $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ samples.

3. Results and discussion

Studies of X-ray diffraction patterns and thermomagnetic analysis indicate that all the $Sm_{1-x}Dy_xFe_{10.5}$ $Mo_{1.5}$ samples consist of the main phase of R(Fe, Mo)$_{12}$, which has a tetragonal $ThMn_{12}$-type structure, and a few α-Fe as the impurity phase. The values of Curie temperatures T_c obtained by TMA are listed in Table I. Fig. 1 shows several thermomagnetic curves of $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ measured in a low field of 40 mT from 1.5 K to room temperature. It can be seen that the thermomagnetic curves go smoothly when $x < 0.8$ as seen in the $Sm_{0.6}Dy_{0.4}Fe_{10.5}Mo_{1.5}$ and $Sm_{0.6}Dy_{0.4}Fe_{10.5}Mo_{1.5}$. However, an evident cusp, which indicating a spin reorientation transition, was observed on the samples with $x = 0.8$–1.0. It means that the magnetic structure was changed at low temperature for the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ samples with a high Dy Concentration.

In order to determine the spin reorientation transition temperature (T_{sr}) precisely, susceptibility measurements were performed on the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ samples. Fig. 2 gives several typical results of the χ_{ac} measurements. The position of the peak in χ_{ac} curves was defined as spin reorientation transition temperature T_{sr} which marked by an arrow in Fig. 2. The values of T_{sr} measured from χ_{ac} curves are also listed in Table I. It follows that T_{sr} increases with Dy concentration in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys. Theoretically, the magnetic structure of R(Fe, M)$_{12}$ is a result of the anisotropy competition between the R and Fe-sublattices [18]. In the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ system, $SmFe_{10.5}Mo_{1.5}$ has an easy c-axis type due to the uniaxial anisotropy of Sm, because of a positive second-order Stevens coefficient α_2. However, with increasing the Dy concentration, a spin reorientation transition could be expected to occur in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys with a high Dy concentration when the planar anisotropy of Dy-sublattice overcomes the total uniaxial anisotropy of Sm and Fe-sublattice. A similar change of T_{sr} was also observed in

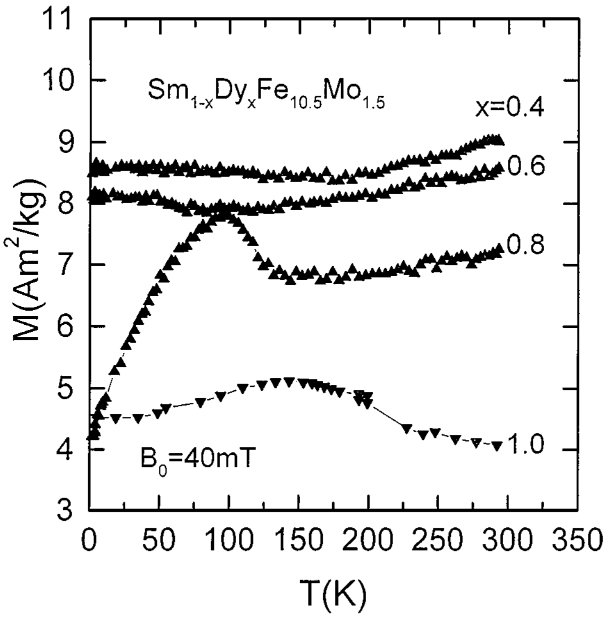

Figure 1 Typical thermomagnetic curves at 1.5–293 K in a field of 40 mT for $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$.

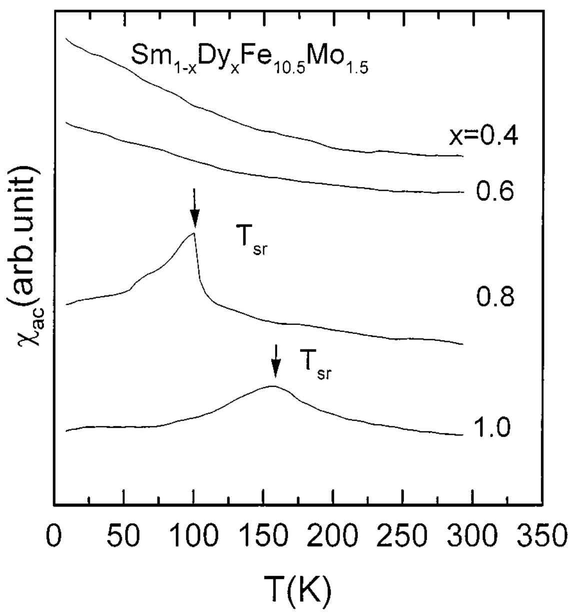

Figure 2 Temperature dependence of ac susceptibility χ_{ac}(T) at 4.2–293 K for several $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys.

TABLE I The data of the Curie temperatures T_c, the saturation magnetization M_s, the spin reorientation transition temperatures T_{sr}, the easy magnetization direction EMD and the magnetocrystalline anisotropy fields $\mu_0 H_a$ for $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys

X	T_c (K)	M_s (A m^2/kg) 1.5 K	T_{sr} (K) by χ_{ac}	EMD 1.5 K	EMD 293 K	$\mu_0 H_a$ (T) 1.5 K	$\mu_0 H_a$ (T) 293 K
0	485	113.90	0	c-axis	c-axis	14.0	7.90
0.2	481	112.82	0	c-axis	c-axis	10.5	5.70
0.4	472	93.67	0	c-axis	c-axis	6.0	3.70
0.6	466	75.65	0	c-axis	c-axis	2.0	2.49
0.8	454	66.16	98	cone	c-axis	—	2.02
1.0	440	62.21	156	cone	c-axis	—	1.03

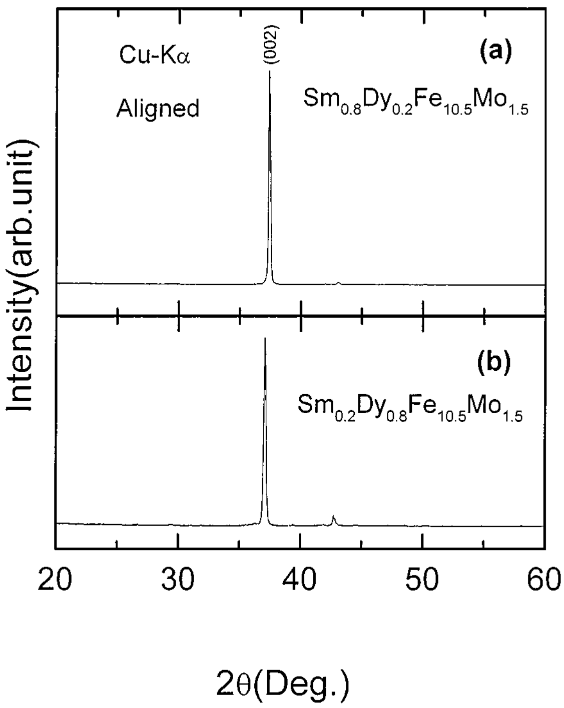

Figure 3 Typical X-ray diffraction patterns on magnetically aligned samples of (a) $Sm_{0.8}Dy_{0.2}Fe_{10.5}Mo_{1.5}$ and (b) $Sm_{0.2}Dy_{0.8}Fe_{10.5}Mo_{1.5}$.

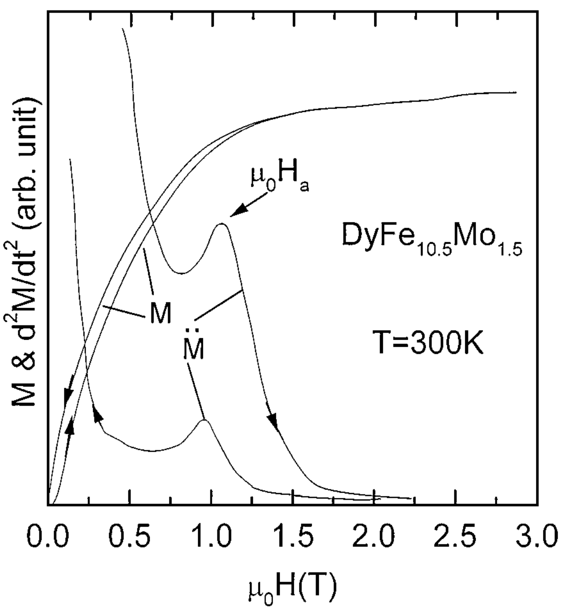

Figure 4 SPD curve of $DyFe_{10.5}Mo_{1.5}$ at room temperature.

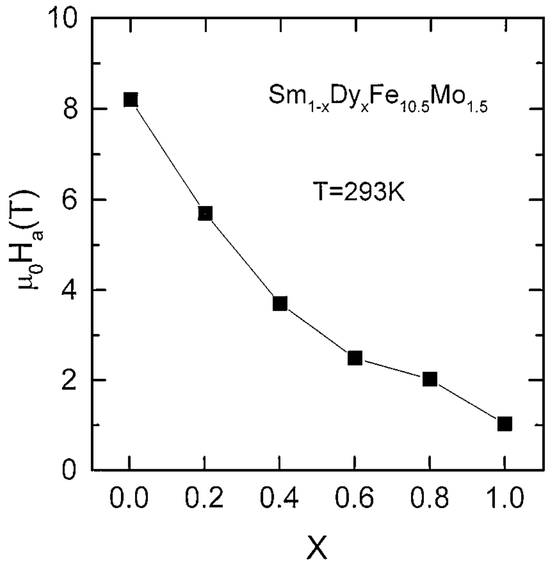

Figure 5 Dy-concentration dependence of the magnetocrystalline anisotropy fields measured by SPD at room temperature for $Sm_{1-x}Dy_x Fe_{10.5}Mo_{1.5}$.

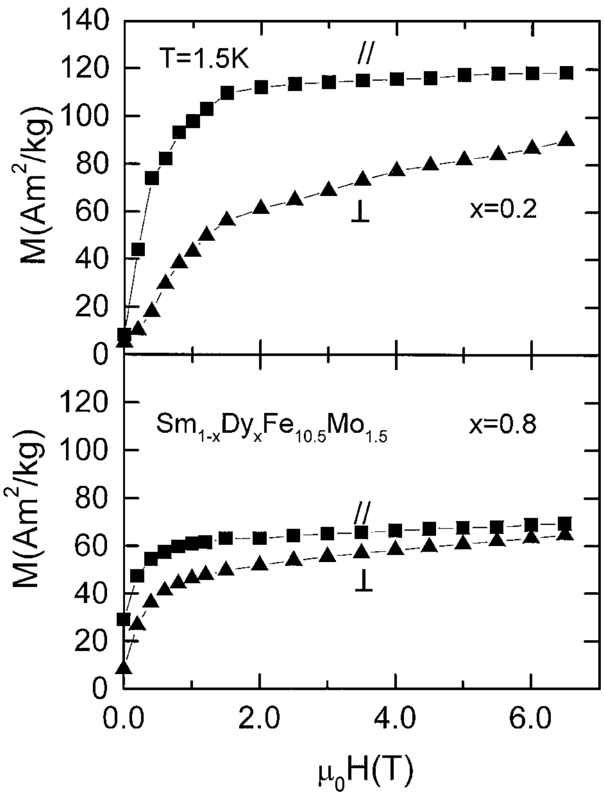

Figure 6 Magnetization curves of magnetization parallel component $M_{\parallel}$ and perpendicular component $M_{\perp}$ at 1.5 K as a function of applied field $\mu_0 H_a$.

$Dy_{1-x}Y_xFe_{11}Mo$ [19], $Dy_{1-x}Y_xFe_{11.35}Nb_{0.65}$ [20] and $Dy_{1-x}Y_xFe_{11}Ti$ compounds [21].

Fig. 3 illustrates typical X-ray diffraction patterns on the magnetically aligned samples at room temperature. It indicates all $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys exhibit uniaxial anisotropy at room temperature for only line (002) left in the diffraction patterns. It is reasonable as considering of even $DyFe_{10.5}Mo_{1.5}$, which possessing the largest planar anisotropy in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ system, still shows a uniaxial anisotropy of 1.03 T at room temperature [6]. The anisotropy field $\mu_0 H_a$ at room temperature was measured by singular point detection (SPD) technique on the magnetically aligned sample in a pulsed-field up to 25.0 T. Fig. 4 gives the SPD curve of $DyFe_{10.5}Mo_{1.5}$ as a typical example. The position of the cusp in the curve of the second-order time derivative $dM^2(B_0)/dt^2$ presents the magnetocrystalline anisotropy field. The $\mu_0 H_a$ values are listed in Table I and plotted in Fig. 5. The magnetocrystalline anisotropy field remarkably decreases monotonically with increasing Dy concentration till a lowest value of $\mu_0 H_a = 1.03$ T arriving at $DyFe_{10.5}Mo_{1.5}$.

Fig. 6 gives the applied field dependence of magnetization parallel component $M_{\perp}$ and perpendicular component $M_{\perp}$ for several $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ samples at 1.5 K. Saturation magnetizations M_s, obtained from $M_\parallel$ curves by applying the law of approach to saturation, are also listed in Table I. From Fig. 6, we can see that the feature of the magnetization curve of $Sm_{0.8}Dy_{0.2}Fe_{10.5}Mo_{1.5}$ shows a great difference from $Sm_{0.2}Dy_{0.8}Fe_{10.5}Mo_{1.5}$ for the two samples have the different types of magnetic structure and anisotropy at 1.5 K. It is clear that $Sm_{0.8}Dy_{0.2}Fe_{10.5}Mo_{1.5}$ exhibits a uniaxial anisotropy of about 10.5 T at 1.5 K while $Sm_{0.2}Dy_{0.8}Fe_{10.5}Mo_{1.5}$ shows a canted anisotropy for the magnetization $M_\perp(0)$ of the hard direction has a considerable value of about 12% of the saturation magnetization M_s near to the zero field. A similar spin reorientation transition of easy *c*-axis to cone was also observed in the Dy(Fe, Mo)$_{12}$ compounds [6, 15].

In conclusion, the Curie temperatures, saturation magnetizations, and especially, the anisotropy and spin reorientation transition were investigated on the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ system. The Curie temperatures and saturation magnetizations at 1.5 K monotonically decrease with increasing Dy concentration. At room temperature, all $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ alloys exhibit uniaxial anisotropy when rapidly decrease from 8.2 T for $SmFe_{10.5}Mo_{1.5}$ to 1.03 T for $DyFe_{10.5}Mo_{1.5}$. However, a spin reorientation transition of axis-to-cone type take place in the $Sm_{1-x}Dy_xFe_{10.5}Mo_{1.5}$ samples with a high Dy concentration of $x = 0.8$–1.0. The spin reorientation temperatures T_{sr} are 98 K and 156 K for $Sm_{0.2}Dy_{0.8}Fe_{10.5}Mo_{1.5}$ and $DyFe_{10.5}Mo_{1.5}$ respectively.

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