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Magnetic transition and coercivity in $TbMn_6Sn_6$

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Abstract. In the present paper, the structure and magnetic properties of $TbMn_6Sn_6$ have been investigated. $TbMn_6Sn_6$ is found to be of $HfFe_6Ge_6$-type structure (space group $P6/mmm$) with $a = 5.5461$ Å, $c = 9.0477$ Å and $V = 241$ Å^3. This compound shows ferrimagnetic behaviour with the ordering temperature $T_c = 421$ K. A peak is also observed in the thermal magnetic curve at 330 K. Under magnetic fields of 100, 300 and 400 Oe, the magnetization values first increase with increasing temperature, next exhibit a peak and then decrease with further increase in temperature. When the applied magnetic field is sufficiently large, e.g. 1000 and 2100 Oe, the magnetization of the whole sample decreases with increasing temperature. With increasing temperature from the range 77–300 K, the coercivity first increases, next undergoes a peak at about 200 K and then decreases. At room temperature a magnetization jump is observed in the magnetization curves at a field of about 4 kOe in both the aligned and the free powder samples. This jump may be attributed to the spin-flop or metamagnetic transition. The magnetic anisotropy field at room temperature is found to be 8.33 kOe.

1. Introduction

Recently, new ternary compounds RT_6X_6 (T = Fe or Mn; X = Ge or Sn) have attracted great attention [1–4]. Evidence of ferrimagnetism in RMn_6Sn_6 (R ≡ Gd, Dy, Tb or Ho) has been reported. Both the R and the Mn sublattices show ferromagnetic behaviour at high temperatures. A large coercivity of 11 kOe has been found in $TbMn_6Sn_6$ at 4.2 K [1, 2]. Neutron diffraction of $TbMn_6Sn_6$ [3] indicates that it exhibits a collinear ferrimagnetic arrangement. The magnetic structure of $TbMn_6Sn_6$ at 300 K consists of a stacking of ferromagnetic (001) layers of rare earth and manganese with the coupling sequence Mn(+)R(−)Mn(+)Mn(+)R(−)Mn(+). The magnetic moments are $\mu(Mn) = 2.0\ \mu_B$ and $\mu(Tb) = 4.9\mu_B$, which deviate from the c axis with a deviation angle of 15°. At 2 K the magnetic moments are along [001] with $\mu(Mn) = 2.4\mu_B$ and $\mu(Tb) = 8.6\mu_B$. In the present paper, the magnetic transition and coercivity of $TbMn_6Sn_6$ have been investigated in detail.

2. Experiments

$TbMn_6Sn_6$ was prepared by arc melting from starting materials of at least 99.9% purity. The alloy was melted several times to ensure homogeneity. The crystal structure was analysed

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by the x-ray diffraction using Co Kα. The thermal magnetic behaviours under different magnetic fields of 100, 300, 400, 1000 and 2100 Oe were measured from 77 K to room temperature using a vibrating-sample magnetometer (VSM). The temperature dependence of magnetization in the high-temperature range from 300–500 K at the magnetic field of 400 Oe was also measured using a VSM. The temperature dependence of the coercivity was obtained using a high pulsed magnetic field. The magnetization cuve and the corresponding SPD signal under the external field, which was applied in a direction perpendicular to the aligned direction of the $TbMn_6Sn_6$ sample, were also measured in a pulsed field at 77 K and room temperature. The measurement of magnetization curve of the free powders for $TbMn_6Sn_6$ was performed with a VSM at room temperature.

3. Results and discussion

The crystal structure was analysed by x-ray diffraction using Co Kα. The results indicate that the sample is almost a single phase with $HfFe_6Ge_6$-type structure. The crystal parameters are $a = 5.5461$ Å, $c = 9.0477$ Å and $V = 241$ Å^3. The comparison of the observed and calculated 2θ values are listed in table 1. The crystal structure of $HfFe_6Ge_6$ is a filled derivative of the CoSn B35-type structure (space group, $P6/mmm$). Neutron diffraction results have indicated that the Tb atom occupies the 1b site, Mn atom occupies the 6i site, and Sn atom occupies the 2e, 2d and 2c sites [3].

Table 1. The comparison of observed and calculated 2θ-values for $TbMn_6Sn_6$.

	2θ (deg)	
hkl	Observed	Calculated
003	34.500	34.505
110	37.700	37.635
103	41.000	40.999
200	43.750	43.734
112	44.500	44.460
004	46.600	46.587
202	49.800	49.881
104	51.850	51.837
113	51.980	51.975

The thermal magnetic behaviour under different magnetic fields of 100, 300, 400, 1000 and 2100 Oe are shown in figure 1. Under magnetic fields of 100, 300 and 400 Oe, the magnetization values first increase with increasing temperature, next exhibit a peak and then decrease with further increase in temperature. The compound $TbMn_6Sn_6$ exhibits a ferrimagnetic behaviour. The coupling between the heavy rare-earth atom Tb and the transition atom Mn is antiferromagnetic, which is similar to the case of the interaction between the heavy rare-eath atom and the iron atom in $R(Fe, Ti)_{12}$ compounds. The sublattices of the rare-earth atoms and manganese atoms are ferromagnetic. The magnetizations of the two sublattices are opposite and decrease with increasing temperature. However, the variations in magnetization with respect to the temperature for the two sublattices are different, and thus up to a certain temperature the magnetization of one sublattice dominates the whole magnetization of the compound. In the high-temperature range, the magnetization of the other sublattice with the opposite direction is hidden by

the temperature dependence of the magnetization of the dominant sublattice. When the applied magnetic field is sufficiently large, e.g. 1000 and 2100 Oe, the magnetization of whole sample decreases with increasing temperature in the temperature range from 100 to 280 K. This temperature dependence of the total measured magnetization in the direction of the external field shows ferromagnetic behaviour. This is because the magnetizations of two sublattices rotate, respectively, under the influence of the external field. The net component of the magnetizations for the two sublattices along the direction of the external field decreases with increasing temperature as a ferromagnetic phase. However, there may be an angle between the magnetizations of the two sublattices at a small applied magnetic field. Here we wish to point out that, in order to obtain a true field-induced ferromagnetism, where the antiferromagnetic structure between R and Mn atoms is destroyed and the magnetizations of the two sublattices are bent towards each other, a stronger magnetic field would need to be applied. The temperature dependence of the magnetization in the high-temperature range from 300 to 500 K at a magnetic field of 400 Oe is shown in figure 2. It shows that the ordering temperature is 421 K. A peak appears in the thermal magnetization behaviour at 330 K, which was also observed in a previous paper [1].

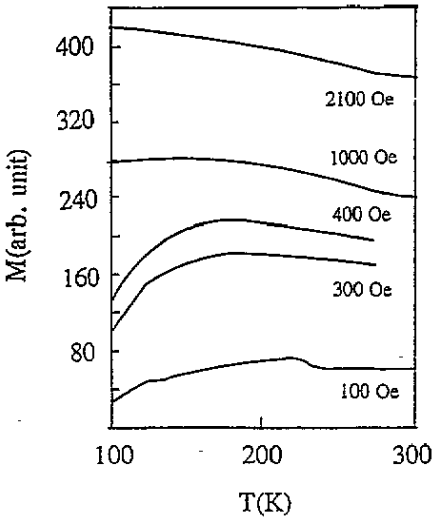

Figure 1. The thermal magnetic behaviour under different magnetic fields of 100, 300, 400, 1000 and 2100 Oe in the temperature range 77–300 K for $TbMn_6Sn_6$.

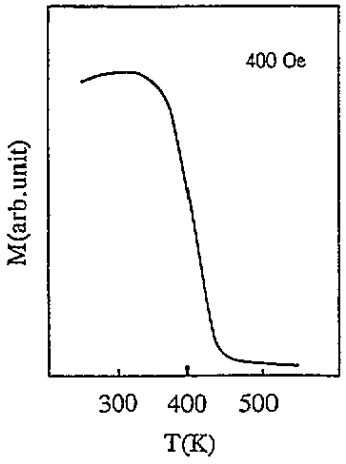

Figure 2. The thermal magnetic behaviour in the high-temperature range from 300 to 500 K at a magnetic field of 400 Oe for $TbMn_6Sn_6$.

The magnetization curve and the corresponding SPD signal at room temperature in an external field, which is applied in a direction perpendicular to the aligned direction of $TbMn_6Sn_6$, are shown in figure 3. It can be seen that the magnetic anisotropy field of $TbMn_6Sn_6$ at room temperature is 8.33 kOe. It is interesting that there exists a magnetization jump which occurs at a field of about 4 kOe. A similar transition is also evident in the magnetization curve of free powders of $TbMn_6Sn_6$ shown in figure 4. Such a transition at a small magnetic field may result from the metamagnetic or spin-flop transition. The large transition field of 22 T observed for $DyMn_6Ge_6$ at 4.2 K was attributed to the bending of the antiparallel rare earth and 3d sublattice moment towards each other [4]. An SPD signal of $TbMn_6Sn_6$ at 77 K was not found.

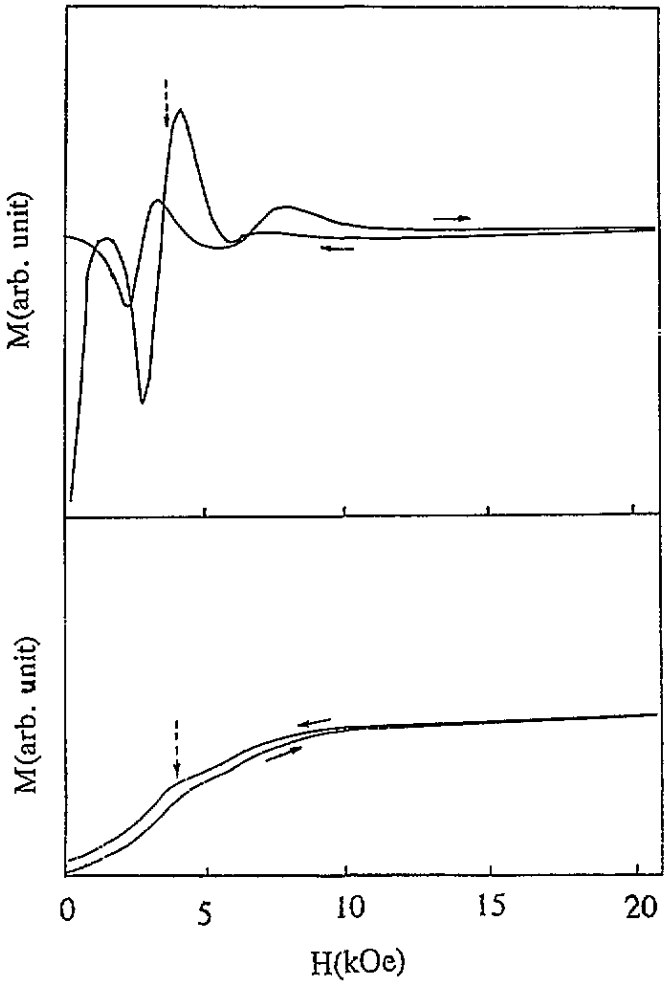

Figure 3. The magnetization curve and the corresponding SPD signal under increasing and decreasing external fields perpendicular to the aligned direction of $TbMn_6Sn_6$ at room temperature. The position of the magnetic transition is indicated by a vertical arrow.

A larger coercivity of 11 kOe has been found at 4.2 K in a previous paper [1]. However, the coercivities at 77–120 K of $TbMn_6Sn_6$ are very small. With increasing temperature in the range 77–300 K, the coercivity first increases, next undergoes a peak at about 200 K and then decreases. This temperature dependence of the coercivity of $TbMn_6Sn_6$ is shown in figure 5. It seems that the trend of the coercivity dependence on temperature is very similar to that of the thermal magnetic behaviour under low magnetic fields of 100, 300 and 400 Oe. Furthermore we wish to point out that the decrease in the coercivity with increasing temperature in the high-temperature range may be due to the decrease in the anisotropy.

In conclusion, the structure and magnetic properties of $TbMn_6Sn_6$ have been investigated in this paper. $TbMn_6Sn_6$ is found to be of a $HfFe_6Ge_6$-type structure (space group, $P6/mmm$) with $a = 5.5461$ Å, $c = 9.0477$ Å and $V = 241$ Å^3. This compound shows ferrimagnetic behaviour with an ordering temperature $T_c = 421$ K. A peak is also observed in thermal magnetic curve at 330 K. Under magnetic fields of 100, 300 and

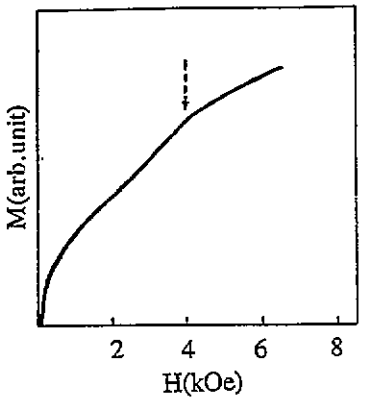

Figure 4. The magnetization curve of the free $TbMn_6Sn_6$ powder at room temperature. The position of the magnetic transition is indicated by a vertical arrow.

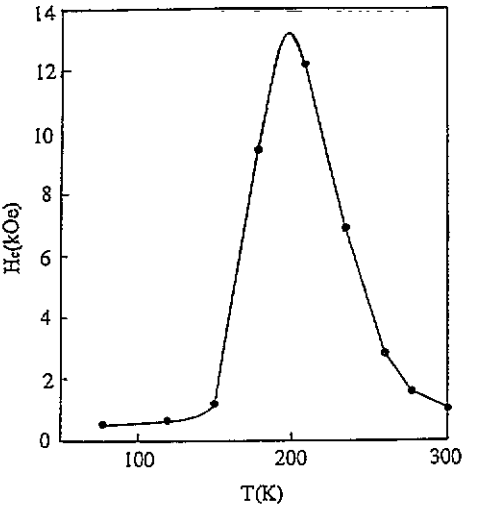

Figure 5. The temperature dependence of the coercivity of $TbMn_6Sn_6$.

400 Oe, the magnetization values first increase with increasing temperature, next exhibit a peak and then decrease with further increase in temperature. When the applied magnetic field is sufficiently large, e.g. 1000 and 2100 Oe, the magnetization of the whole sample decreases with increasing temperature. On increasing the temperature from 77 to 300 K, the coercivity first increases, next undergoes a peak at about 200 K and then decreases. At room temperature a magnetization jump is observed in the magnetization curves at a field of about 4 kOe in both the aligned and the free powder samples; this may be attributed to the spin-flop or metamagnetic transition. The magnetic anisotropy field at room temperature is found to be 8.33 kOe.

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