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Magnetic anisotropy of $RCo_{10}Si_2$ compounds (R = Y, Gd, Dy, Ho, Er, Tm)

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Abstract

The magnetic anisotropy of $RCo_{10}Si_2$ compounds has been studied in the temperature range from 4.2 to 300 K by means of AC-susceptibility and magnetization measurements. $GdCo_{10}Si_2$ does not form and crystallizes in the 1:11 phase which has a very low Curie temperature compared with the 1:12 compounds. The anisotropy field of $YCo_{10}Si_2$ decreases with increasing temperature. All 1:12 compounds investigated show easy-plane anisotropy at room temperature. In $DyCo_{10}Si_2$ and $HoCo_{10}Si_2$, spin-reorientation transitions occur at 190 and 75 K, respectively, where the anisotropy changes to easy-axis type. In $ErCo_{10}Si_2$, at 70 K, the easy-magnetization direction changes from basal plane to cone.

Keywords: Magnetic anisotropy; Spin reorientation; $RCo_{10}Si_2$

1. Introduction

The $RCo_{10}Si_2$ compounds crystallize in the $ThMn_{12}$ structure. Si plays the role of stabilizing element, as done by several other elements, such as, for instance, Ti,V, or Mo. The 4f-3d exchange interaction in $R(Co, M)_{12}$ compounds has been investigated in great detail by means of high-field magnetization measurements [1–10]. It has been found that the stabilizing element M has a pronounced influence on the 4f-3d interaction strength in these compounds [2]. In $RCo_{10}Si_2$ compounds, the Co-sublattice moment is about 12 μ_B/f.u. which means 1.2 μ_B/Co atom [10]. In $YCo_{10}Si_2$, the anisotropy of the Co-sublattice is of the easy-plane type. Due to the magnetic coupling between the rare-earth moments and Co-sublattice moments, some very interesting phenomena have been observed in the free-powder magnetization curves of the compounds of $HoCo_{10}Si_2$, $ErCo_{10}Si_2$ and $TmCo_{10}Si_2$, comprising non-linear field dependences of the magnetization [2]. Theoretical analysis suggests that the complex magnetic behaviour observed in these compounds at low temperature originates from the magnetic anisotropy of both the rare-earth and the Co sublattice. In this paper, we report on results dealing with the magnetic anisotropy and spin-reorientation transition in some of the $RCo_{10}Si_2$ compounds at low temperature.

2. Experimental

$RCo_{10}Si_2$ compounds with R = Y, Gd, Dy, Ho, Er and Tm were prepared by arc-melting together

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appropriate amounts of the pure elements, followed by vacuum annealing for two weeks at 1100°C. X-ray diffraction measurements showed all compounds to crystallize in the tetragonal $ThMn_{12}$-type of structure, except for the Gd compound which has the composition $GdCo_9Si_2$ and crystallizes in the $CeMn_6Ni_5$ structure. The results of magnetization measurements on RCo_9Si_2 compounds have been reported elsewhere [11]. In the present paper, we will only consider the 1:12 compounds.

A SQUID magnetometer with maximum field of 5 T and a temperature range from 5 to 320 K was used to measure the easy- and hard-magnetization curves of $YCo_{10}Si_2$ by using magnetically aligned samples that were prepared by mixing fine powder of the compounds with epoxy resin and by letting the mixture solidify in a magnetic field of 0.9 T at room temperature. Aligned samples were also used to study the temperature dependence of the easy-magnetization direction of the $RCo_{10}Si_2$ compounds by measuring the magnetization as a function of the angle between the alignment direction of the sample and the applied field. In this, a field of 1 T was applied.

To determine the easy-magnetization direction of the compounds at room temperature, X-ray-diffraction experiments were carried out both on magnetically aligned samples and on samples consisting of randomly oriented powder particles.

Bulk samples were used in AC-susceptibility measurements in the temperature range from 4.2 to 300 K in order to establish the presence of a spin-reorientation. The Curie temperatures were determined by measuring the magnetization as a function of temperature in a home-built Faraday balance.

3. Results and discussion

Fig. 1 shows the easy- and hard-magnetization curves of $YCo_{10}Si_2$ measured at 10 and 300 K. It can be seen that both, the anisotropy field and the magnetization, decrease with increasing temperature. The poor alignment of the samples should be attributed to the easy-plane magnetization of the compound at room temperature. As the rare-earth sublattice anisotropy usually decreases much faster with increasing temperature than the transition-metal sublattice anisotropy, we may expect the Co-sublattice anisotropy to be dominating at room temperature in the $RCo_{10}Si_2$ compounds containing a magnetic R element. At low temperature, the competition between the anisotropies of the R and T sublattices may result in a spin reorientation. Indeed, this is observed in the AC-susceptibility measurements (Fig. 2). Except $TmCo_{10}Si_2$, all

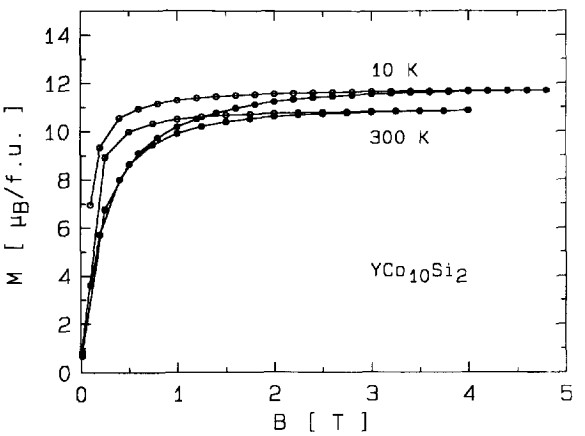

Fig. 1. Magnetization curves of $YCo_{10}Si_2$. The open and filled circles represent measurements made with the field applied parallel and perpendicular to the alignment direction, respectively. The lines are guides to the eye.

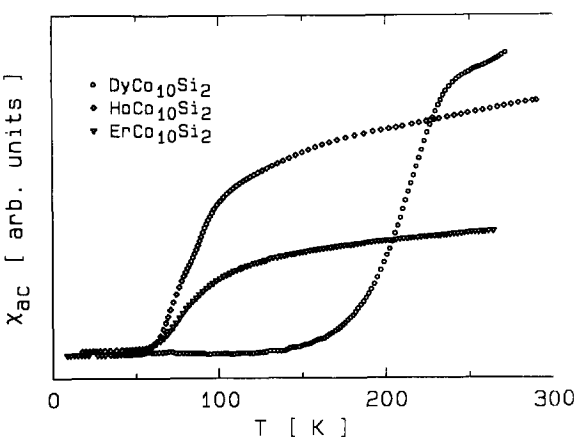

Fig. 2. Temperature dependence of the AC-susceptibility of the compounds $DyCo_{10}Si_2$, $HoCo_{10}Si_2$ and $ErCo_{10}Si_2$.

compounds that contain a magnetic rare-earth element show a very pronounced anomaly below room temperature, presumably associated with the fact that the rare-earth-sublattice anisotropy becomes comparable to the Co-sublattice anisotropy.

In order to determine the easy-magnetization direction of the compounds below and above the spin-reorientation transition, we first measured the X-ray-diffraction patterns on both randomly oriented powder and magnetically oriented powder at room temperature, so that the easy direction at room temperature could be established. Subsequently, we measured the magnetization as a function of the angle between the alignment direction and the external-field direction at different temperatures. The X-ray-diffraction results show that all compounds have easy-plane type of anisotropy at room temperature which, as discussed above, is due to the dominating Co-sublattice anisotropy in the compounds. The magnetization measured along different directions with respect to the alignment direction is shown for $DyCo_{10}Si_2$, $HoCo_{10}Si_2$ and $ErCo_{10}Si_2$ in Fig. 3. In these experiments, the aligned sample is mounted in such a way that, at room-temperature, the alignment direction is along the external field direction. Therefore, at high temperature the magnetization will have a maximum value. If the sample is rotated 90° with respect to the direction of the external field, the magnetization measured along the external field direction reaches a (relative) minimum. With decreasing temperature, if the anisotropy changes either from easy c-axis to easy basal plane or from easy basal plane to easy c-axis, then the angle where the minimum and the maximum occur will shift by 90°. In $DyCo_{10}Si_2$, the position of the maximum magnetization changes from 0° for $T > 190$ K to 90° for $T < 190$ K. This means that the easy-magnetization direction changes from basal plane above 190 K to c-axis below 190 K. Also in $HoCo_{10}Si_2$, the easy-magnetization direction changes, in this case at about 75 K, from basal plane at high temperature to c-axis at low temperature. For $ErCo_{10}Si_2$, two weak maxima are observed at temperatures below about 50 K. This is indicative of an easy-cone type of magnetization. The difference of the angles where these weak maxima occur corresponds to twice the cone angle. In

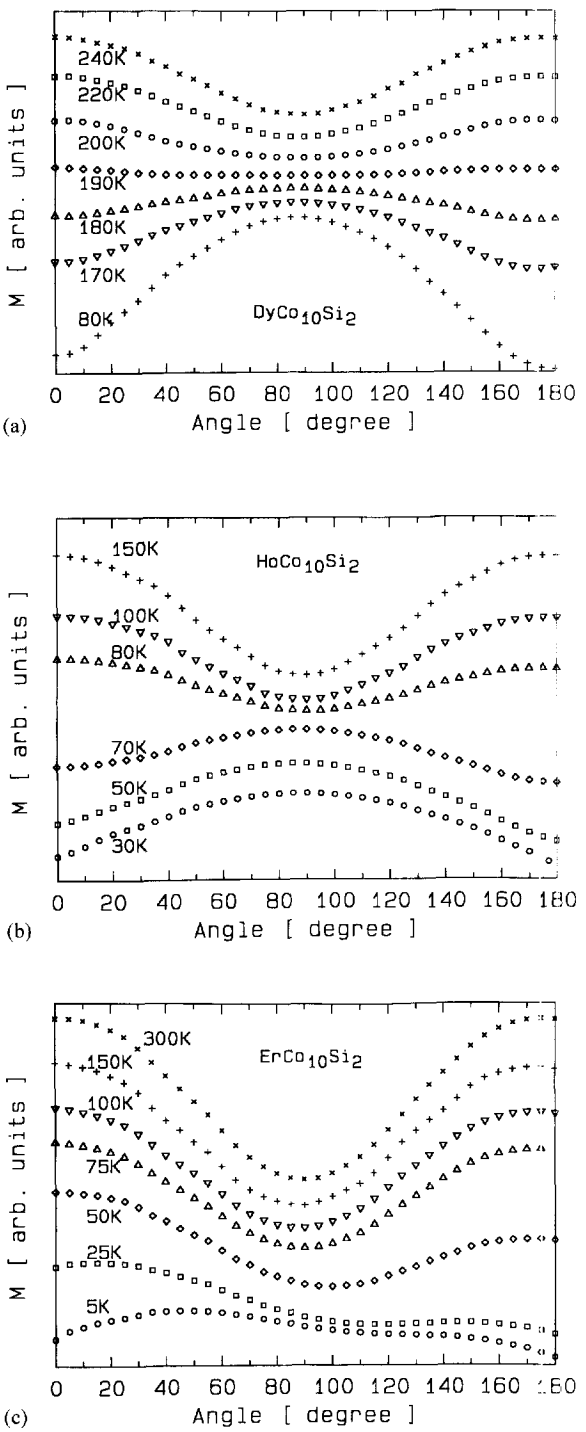

Fig. 3. Dependence of the magnetization of (a) $DyCo_{10}Si_2$, (b) $HoCo_{10}Si_2$ and (c) $ErCo_{10}Si_2$ on the angle between the alignment direction and the direction of the external field of about 1 T.

this way, we can determine the temperature dependence of the cone angle. It can be seen in Fig. 3 that there is a difference between the magnetization values at 0° and 180°, of which the relative value increases with decreasing temperature, in particular for $ErCo_{10}Si_2$. This is probably due to magnetic hysteresis and may result in a shift of the positions of the maxima, accompanied by a shift of the central minimum. We derived the cone angles of $ErCo_{10}Si_2$ at low temperatures by subtracting the angles of the two maxima. Fig. 4 shows the temperature dependence of the cone angle in $ErCo_{10}Si_2$. One can see that the easy-magnetization direction of the compound is in the basal plane above about 70 K. Below this temperature, the easy-magnetization direction starts to deviate from the basal plane and at 10 K the cone angle is about 40°.

It is interesting to see that the spin-reorientation temperatures that can be deduced from the AC-susceptibility data shown in Fig. 2 are very similar to the spin-reorientation temperatures derived from the SQUID measurements. All spin-reorientation transitions observed in Fig. 2 show a sharp decrease of the AC-susceptibility going from high temperature to low temperature. This in contrast with the peak-like behaviour, observed for $ErCo_{10}Mo_2$ and other compounds [5]. As we have seen, at low temperatures, the magnetic states of $DyCo_{10}Si_2$, $HoCo_{10}Si_2$ and $ErCo_{10}Si_2$ are quite different. However, from the AC-susceptibility data alone, as presented in Fig. 2, it is impossible to distinguish between these states.

As we have mentioned in the introduction, the competition between the rare-earth sublattice anisotropy and the Co-sublattice anisotropy, may lead to interesting behaviour of the magnetization. This is confirmed by previously reported high-field magnetization measurements on single-crystalline powder particles which were free to rotate in the applied field. Due to the existing cone structure, a three-dimensional rotation process between the Er- and the Co-sublattice moments may occur in $ErCo_{10}Si_2$. The deviation of the observed number of the oscillations observed in the free-powder magnetization measurement from the number predicted by a simple molecular-field model [1, 2, 11], may be related to this three-dimensional rotation process. It is worth mentioning that only in $TmCo_{10}Si_2$ the

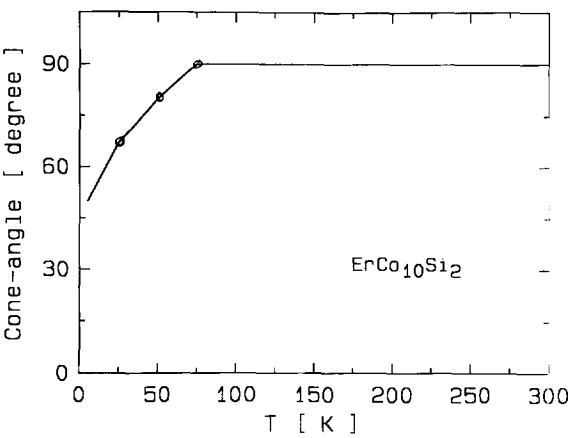

Fig. 4. Temperature dependence of the cone angle for $ErCo_{10}Si_2$. The line is a guide to the eye.

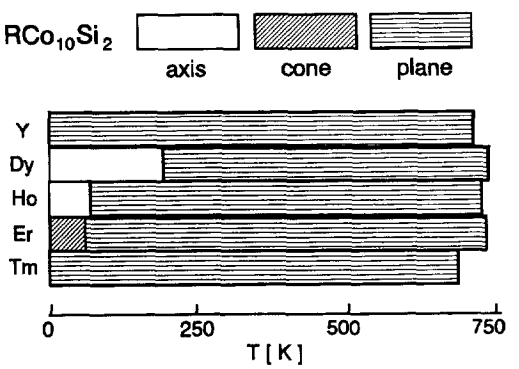

Fig. 5. Magnetic anisotropy phase diagram of $RCo_{10}Si_2$ compounds.

Table 1
Magnetic properties of $RCo_{10}Si_2$ compounds

Compound	T_C(K)	T_{SR}(K)	Anisotropy (4.2 K)
$YCo_{10}Si_2$	729	—	Plane
$GdCo_{10}Si_2$[a]	504	—	—
$DyCo_{10}Si_2$	737	190	Axis
$HoCo_{10}Si_2$	726	75	Axis
$ErCo_{10}Si_2$	732	70	Cone
$TmCo_{10}Si_2$	681	—	Plane

[a] $GdCo_{10}Si_2$ forms as 1:11 phase.

easy-magnetization direction remains in the basal plane in the whole temperature range. This also means that during the free-powder magnetization measurements, the bending of the Tm- and the Co-sublattice moments will always occur within the basal plane. In this case, the prediction of the simple molecular-field model is expected to be better.

According to the results reported above, an anisotropy phase diagram is proposed (Fig. 5). The T_C and T_{SR} values are listed in Table 1.

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