Journal of Magnetism and Magnetic Materials 383 (2015) 208–214

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Magnetic anisotropy and magnetic phase transitions in RFe_5Al_7

D.I. Gorbunov [a,*], S. Yasin [b], A.V. Andreev [a], Y. Skourski [b], N.V. Mushnikov [c], E.V. Rosenfeld [c], S. Zherlitsyn [b], J. Wosnitza [b,d]

[a] Institute of Physics, Academy of Sciences, Na Slovance 2, 182 21 Prague, Czech Republic
[b] Dresden High Magnetic Field Laboratory (HLD), Helmholtz-Zentrum Dresden-Rossendorf, D-01314 Dresden, Germany
[c] Institute of Metal Physics, Ural Branch of Russian Academy of Sciences, Kovalevskaya 18, 620990 Ekaterinburg, Russia
[d] Institut für Festkörperphysik, TU Dresden, D-01062 Dresden, Germany

ARTICLE INFO

Article history:
Received 15 June 2014
Received in revised form
12 September 2014
Accepted 2 October 2014
Available online 7 October 2014

Keywords:
Rare-earth intermetallics
Magnetic anisotropy
Ferrimagnetism
High magnetic fields
Spontaneous transition
Field-induced transition

ABSTRACT

RFe_5Al_7 (R – Gd, Tb, Dy, Ho, Er and Tm) single crystals have been studied by measurements of magnetization, sound propagation (in static and pulsed magnetic fields up to 60 T) and specific heat. Fundamental magnetic properties have been determined and compared for all these materials. RFe_5Al_7 are highly anisotropic ferrimagnets. Spontaneous and field-induced magnetic phase transitions of anisotropic and exchange nature have been observed in RFe_5Al_7. Strong magnetoelastic interactions are manifested by pronounced acoustic anomalies at the phase transformations. The detected magnetization jumps provide important information on the R–Fe inter-sublattice exchange interactions.

1. Introduction

Intermetallic compounds based on rare-earth R and 3*d* transition elements T, crystallizing in the tetragonal crystal structure of the $ThMn_{12}$ type, form a wide group of magnetic materials (see Ref. [1] for a review). They combine localized magnetism of the rare-earth sublattice and itinerant electron magnetism of the transition metal sublattice. Since the combination of the 3*d* and 4*f* elements in the same compound makes it possible to achieve very hard magnetic characteristics, some of them are considered as materials for permanent magnets [2–6]. On the other hand, complex interactions that involve the 3*d* and 4*f* electrons lead to complicated magnetic properties that render these systems interesting for fundamental studies. An investigation of a family of compounds with a particular stoichiometry makes it possible to vary the rare-earth element and, therefore, study them systematically. Such a variation of the rare-earth component results in different ground states and magnetic properties.

From the fundamental point of view, RFe_5Al_7 compounds with magnetic heavy rare-earth elements deserve special attention. In the crystal lattice of RFe_5Al_7 (Fig. 1), the R atoms reside on the 2*a* site, Fe and Al occupy the 8*f* and 8*i* sites, respectively [7–12]. The excess of Fe atoms shares the 8*j* site with Al. The compounds are ferrimagnets. Polycrystalline samples of RFe_5Al_7 display strong magnetic and thermal hysteresis, which suggests strong magnetocrystalline anisotropy [8,9]. The magnetic anisotropy arises from both, the R and Fe sublattices. Spontaneous spin-reorientation transitions may occur if the sublattices provide a contribution to the anisotropy of opposite signs. Furthermore, field-induced transitions may be expected as the R and Fe magnetic moments rotate in a magnetic field from the initial ferrimagnetic structure towards the forced ferromagnetic state.

The present work reports fundamental magnetic properties, exchange interactions and magnetocrystalline anisotropy, of RFe_5Al_7 compounds. Their systematic investigation makes it possible to determine a correlation between these properties and the type of the rare-earth element. Since RFe_5Al_7 should display strong magnetic anisotropy, their studies require high-quality single crystals and pulsed magnetic fields. Fulfillment of both conditions makes it possible to extract fundamental parameters that determine the system's behavior as a function of temperature and magnetic field. Additional information on phase transitions can be obtained by measuring physical properties affected by the presence of ordered magnetic moments. In particular, sound propagation due to the magnetoelastic interactions is very sensitive to changes in the magnetically ordered state. Therefore, magnetism and magnetoelasticity of the RFe_5Al_7 compounds with heavy

* Corresponding author.
E-mail address: gorbunov@fzu.cz (D.I. Gorbunov).

http://dx.doi.org/10.1016/j.jmmm.2014.10.002
0304-8853/

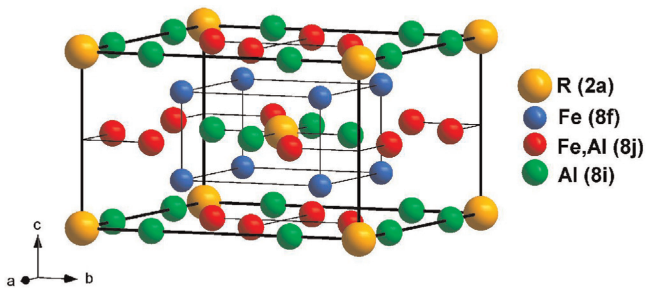

Fig. 1. Crystal structure of RFe_5Al_7.

rare-earth elements are systematically investigated in the present work.

2. Experimental

Single crystals of RFe_5Al_7 with R=Gd, Tb, Dy, Ho, Er and Tm were grown by a modified Czochralski method in a tri-arc furnace from a stoichiometric mixture of the pure elements (99.9% R, 99.98% Fe and 99.999% Al) on a rotating water cooled copper crucible under protective Ar atmosphere. The crystal structure was refined by a standard powder X-ray diffraction analysis performed on part of the single crystals crushed into a fine powder. Back-scattered Laue patterns were used to check the quality of the crystals and to orient them along the [100], [110], and [001] axes.

Temperature and field variations of the magnetization between 2 and 300 K were measured along the principal crystallographic directions using a standard PPMS-14 magnetometer (Quantum Design) in magnetic fields up to 14 T. PPMS-14 was also used to measure specific heat in a zero magnetic field by the relaxation method.

High-field magnetization data were obtained between 2 and 145 K in pulsed magnetic fields up to 60 T (pulse duration 20 ms) at the high-field laboratory in Dresden (HLD). The magnetization was measured by the induction method using a coaxial pick-up coil system. More details about the magnetometer can be found in Ref. [13]. Absolute values of the magnetization were calibrated using data from the measurements in static magnetic fields.

Relative changes of the ultrasound velocity and attenuation were measured using a pulse-echo technique [14,15] in zero field from 2 to 300 K and in pulsed fields up to 63 T between 2 and 145 K. The magnetic field was applied along one of the main crystallographic directions, and longitudinal acoustic waves with the wave vector $\boldsymbol{k}$ and polarization $\boldsymbol{u}$ were propagated along the same direction. Two piezoelectric film transducers were glued to opposite parallel surfaces in order to excite and detect acoustic waves.

3. Results and discussion

Powder X-ray diffraction indicates that all grown crystals contain a single phase based on the $ThMn_{12}$-type structure. Fig. 2 shows parameters a and c of the tetragonal crystal lattice of RFe_5Al_7 (the data for $LuFe_5Al_7$ not considered in the present work were taken from Ref. [16]). Parameter a decreases from R=Gd to R=Lu by 0.7%, whereas parameter c stays practically constant. Such an anisotropic compression of the crystal lattice leads to an increase in the c/a ratio. As a result of lanthanide contraction the unit-cell volume V shrinks by 1.8% from R=Gd to R=Lu.

Fig. 3 presents magnetic characteristics of RFe_5Al_7 compounds. The ferrimagnetic order results in low values of a spontaneous magnetic moment, M_s, at low temperatures (Fig. 3a). One observes

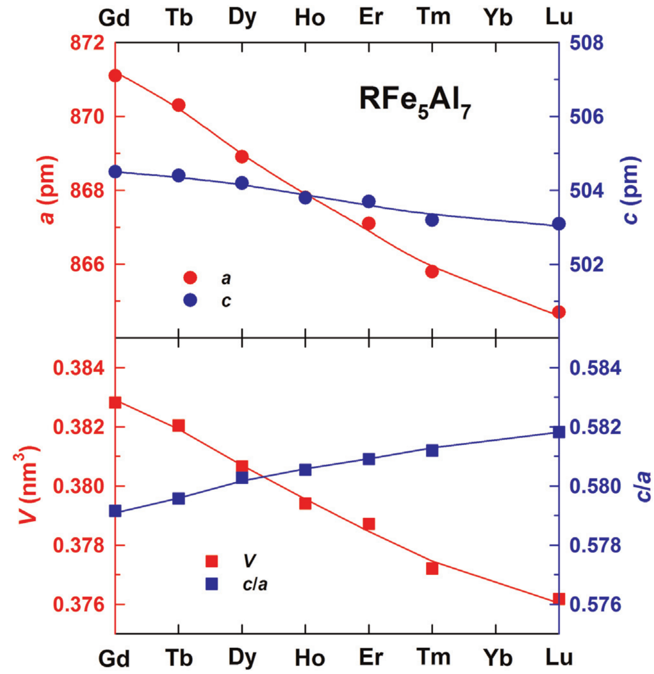

Fig. 2. Lattice parameters a and c (upper panel), ratio c/a, and unit cell volume V (lower panel) of RFe_5Al_7.

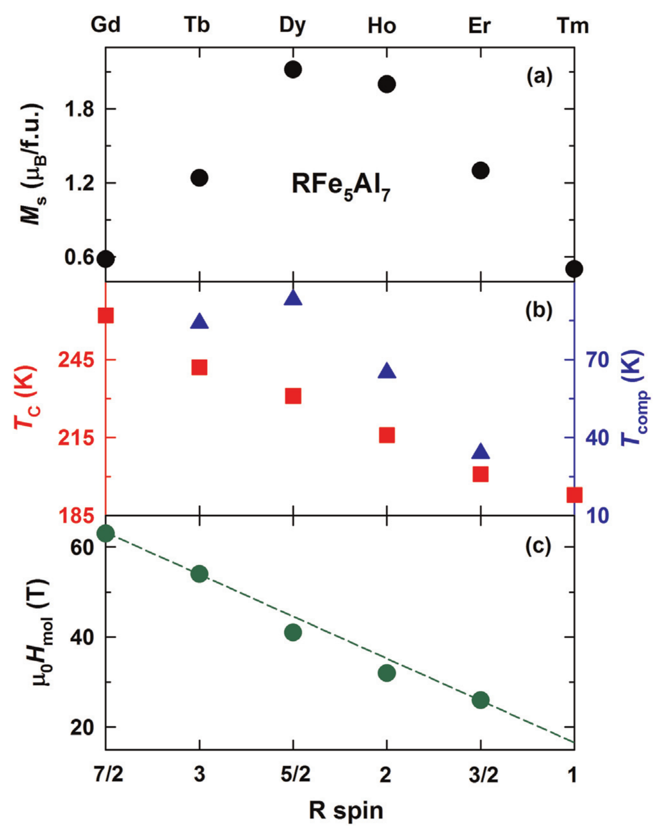

Fig. 3. Spontaneous magnetic moment at 2 K (a), magnetic ordering temperature, and compensation point, (b) and inter-sublattice molecular field at 2 K (c) of RFe_5Al_7.

close values of M_s for the following pairs of the compounds: those with Gd and Tm, Tb and Er, Dy and Ho. The reason is that in each pair the rare-earth magnetic moments are equal. From these data it follows that the magnetic moment of the whole Fe sublattice in RFe_5Al_7 is $M_{Fe}=7.6–8\ \mu_B$ at 2 K. The compounds $GdFe_5Al_7$ and