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Magnetostriction study of a $U_{0.8}Lu_{0.2}Fe_2$ single crystal

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Abstract

Effect of dilution of the U sublattice by non-magnetic Lu on the magnetic anisotropy and magnetostriction of UFe_2 has been studied on single crystals of $U_{0.8}Lu_{0.2}Fe_2$. The observed change of the anisotropy-type from the ⟨1 1 1⟩ easy-magnetization axis in UFe_2 to the ⟨1 0 0⟩ axis in $U_{0.8}Lu_{0.2}Fe_2$ is accompanied by disappearance of the spontaneous magnetostrictive distortion in $U_{0.8}Lu_{0.2}Fe_2$ due to small magnetostriction constant $\lambda_{100} = 0.26 \times 10^{-3}$ (at 4.2 K). Nevertheless, the magnetostriction measurements revealed that $U_{0.80}Lu_{0.20}Fe_2$ has large $\lambda_{111} = 1.2 \times 10^{-3}$ which belongs to a "giant magnetostriction" range.

Keywords: Actinide compounds; UFe_2; Ferromagnetism; Magnetic anisotropy; Magnetostriction

1. Introduction

U and Fe form only two intermetallic compounds, a ferromagnet UFe_2 and a superconductor U_6Fe. Magnetic properties of UFe_2 crystallizing in the cubic Laves phase (the $MgCu_2$-type crystal structure) depend on the off-stoichiometry within a homogeneity range [1]. For the exact stoichiometry, the Curie temperature $T_C = 168$ K and spontaneous magnetic moment $M_s = 1.1\ \mu_B$ per formula unit were reported [1,2]. The easy-magnetization direction is the ⟨1 1 1⟩ axis. The M_s value is ascribed exclusively to the Fe atoms. The U atoms have almost zero magnetic moment due to mutual cancellation of noticeable spin and orbital moments [3] and contribute only about 1% to M_s. The magnetic anisotropy of UFe_2 is rather weak, the first anisotropy constant K_1 at low temperature is of order of -0.1 MJ/m^3 [2,4]. At the same time, the magnetostriction constant λ_{111} reaches 2.9×10^{-3} at low temperatures [2,5] and is comparable with maximal λ_{111} observed in RFe_2 with anisotropic magnetic rare earths ions R. The anisotropic magnetostriction and the magnetic anisotropy have usually the same origin and are either both strong (like in RFe_2 with anisotropic R ions) or both weak (like in RFe_2 with non-magnetic R = Y and Lu) [6]; therefore, the coexistence of giant magnetostriction with low anisotropy observed in UFe_2 is unique for a binary compound (in quasibinaries RFe_2, such a combination is achieved by mixing the R ions with different sign of the anisotropy constants [6]).

In this work, we have studied effect of dilution of U by non-magnetic Lu on magnetic anisotropy and magnetostriction of UFe_2. Previously, the magnetostriction measurements of the $U_{0.8}Lu_{0.2}Fe_2$ crystal have been performed in [7], however, the results look underestimated. Now we changed the geometry of the measurements and used another type of strain gauges.

2. Experimental

The polycrystalline samples of $U_{1-x}Lu_xFe_2$ ($x \leq 0.3$) were prepared by arc melting the stoichiometric amounts of the components. For $x = 0$ and 0.2, the single crystals were pulled by Czochralski method. Details of their preparation

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were published in Ref. [8]. Magnetization was measured by a SQUID magnetometer (Quantum Design). Magnetostriction measurements were carried out with the strain gauges WK-09-031CF-350 (Micro-Measurements, USA). The gauges, glued on the sample and a quartz plate (as a reference), were connected to a dc Wheatstone bridge. Values of the magnetostriction constant λ_{111} were determined from the longitudinal strains along the [1 1 1] axis, whereas that of a much smaller λ_{100} from the strains measured along the [1 0 0] axis when the magnetic field rotates from the [1 0 0] to the [0 1 0] direction.

3. Results and discussion

The sample with $x = 0.3$ was found to be outside the limit of solubility of Lu in UFe_2, although the binary $LuFe_2$ crystallizes in the same C15 Laves phase. Fig. 1 shows the field and temperature dependencies of magnetization measured on polycrystals of single-phase alloys with $x \leq 0.2$. Both T_C and M_s increases considerably with increasing x. This can partly be explained by a small increase of the lattice parameter a (Fig. 2). Nevertheless, the main reason of low values of T_C and the Fe magnetic moment in UFe_2 is an additional charge

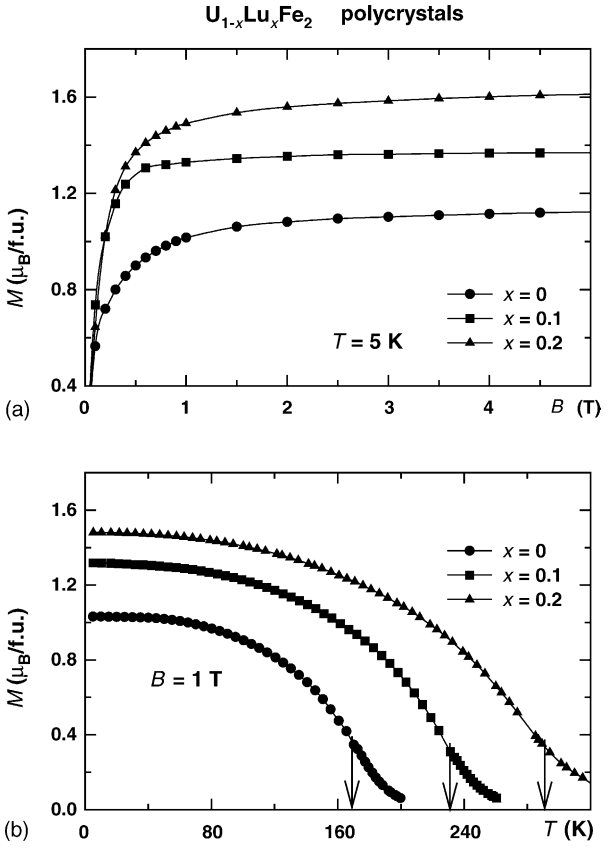

Fig. 1. Magnetic properties of the $U_{1-x}Lu_xFe_2$ polycrystals. (a) Magnetization isotherms at 5 K. (b) Temperature dependence of magnetization in a 1 T field. The arrows indicate T_C values obtained from the temperature scans in 0.01 T.

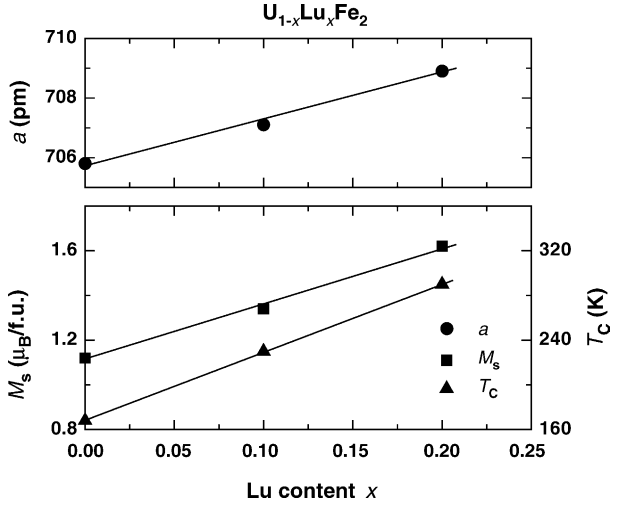

Fig. 2. Concentration dependence of the lattice parameter a, Curie temperature T_C and spontaneous magnetic moment M_s (at 5 K) of $U_{1-x}Lu_xFe_2$.

transfer (compared to trivalent R) from U to the 3d-band of Fe. The Curie temperature of the binary $LuFe_2$ is as large as 590 K.

In order to explain the low anisotropy of UFe_2, it was proposed that a large intrinsic cubic magnetic anisotropy described by the positive K_1^0 constant is exceeded slightly in absolute value by the negative magnetoelastic contribution to the anisotropy ΔK_1^{me} [2].

$$K_1 = K_1^0 + \Delta K_1^{me},$$

$$\Delta K_1^{me} = \left(\frac{9}{4}\right)[(c_{11} - c_{12})\lambda_{100}^2 - 2c_{44}\lambda_{111}^2], \quad (1)$$

where c_{ij} are the elastic constants. Since in UFe_2 $\lambda_{100} \ll \lambda_{111}$ [2],

$$\Delta K_1^{me} \approx -\left(\frac{9}{2}\right) c_{44}\lambda_{111}^2, \quad (2)$$

In UFe_2, $c_{44} \approx 2 \times 10^{10}$ N/m^2 [2], therefore, $\Delta K_1^{me} \approx -0.8$ MJ/m^3 and $K_1^0 \approx 0.7$ MJ/m^3, i.e. K_1^0 and ΔK_1^{me} exceed K_1 by one order of magnitude and the low K_1 value is indeed the result of mutual cancellation of the two large terms. K_1^0 and λ_{111} are expected to decrease in a similar way upon dilution of the magnetic sublattice responsible for their high values. Since $\Delta K_1^{me} \propto \lambda_{111}^2$, ΔK_1^{me} will decrease faster than K_1^0 and their sum K_1 may change its sign from negative to positive, i.e. a spin reorientation can be observed.

A rather clear indication of this spin reorientation can be seen in Fig. 1. Whereas in the compounds with $x = 0$ and 0.2, the magnetization saturates in field of about 2 T, the saturation field does not exceed 0.5 T for $x = 0.1$, i.e. the first anisotropy constant changes its sign in vicinity of this Lu content. It is confirmed by the single-crystal results. Fig. 3 shows magnetization curves along the principle axes of the single crystals with $x = 0$ and 0.2. The easy-magnetization axis changes from

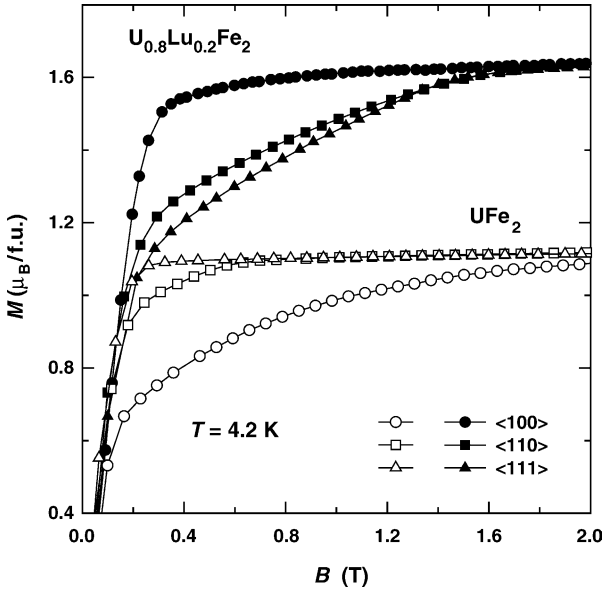

Fig. 3. Magnetization curves along the principle axes of the UFe_2 and $U_{0.8}Lu_{0.2}Fe_2$ single crystals.

$\langle 1\,1\,1\rangle$ in UFe_2 to $\langle 1\,0\,0\rangle$ in $U_{0.80}Lu_{0.20}Fe_2$. The K_1 values at 4.2 K are -0.21 and 0.15 MJ/m^3, respectively. The critical Lu concentration corresponding to $K_1 = 0$ can be interpolated as $x_{cr} = 0.12$ which is indeed in vicinity of $x = 0.1$. Preparation and study of the single crystal with x_{cr} are in progress.

The giant magnetostriction of UFe_2 manifests itself in the spontaneous (rhombohedral) distortion of the cubic lattice. In $U_{0.8}Lu_{0.2}Fe_2$, no (tetragonal) distortion is observed [8] because the corresponding magnetostriction constant $\lambda_{1\,0\,0}$ should be rather low, nevertheless, the magnetostriction measurements in magnetic field revealed a large $\lambda_{1\,1\,1}$ [7]. The obtained $\lambda_{1\,1\,1}$ value (0.43×10^{-3} at 4.2 K) is much lower than the estimates expected from linear (2.3×10^{-3}) or quadratic (1.8×10^{-3}) decrease of $\lambda_{1\,1\,1}$ with dilution. Comparison of the magnetization and magnetostriction curves led us to a conclusion that the quartz strain gauge used in Ref. [7] induced additional strains in the crystal and thus the state of the sample was not equilibrium in zero field as it was assumed for calculation of the magnetostriction constants. Now we performed more careful magnetostriction measurements of the $U_{0.8}Lu_{0.2}Fe_2$ crystal by changing the geometry of the measurements and using another type of strain gauges.

Fig. 4 shows the field dependencies of magnetostriction. The strain was measured along the hard [1 1 1] axis whereas the magnetic field was applied either along the same axis (a) or along another axis of the $\langle 1\,1\,1\rangle$-type (b). In both cases, the curves saturate at approx. 1.6 T for 4.2 K, which agrees well with the anisotropy field at this temperature determined from the magnetization curve (see Fig. 3). This is valid for other temperatures as well. If the distribution of magnetic domains with different orientation of the spontaneous magnetization

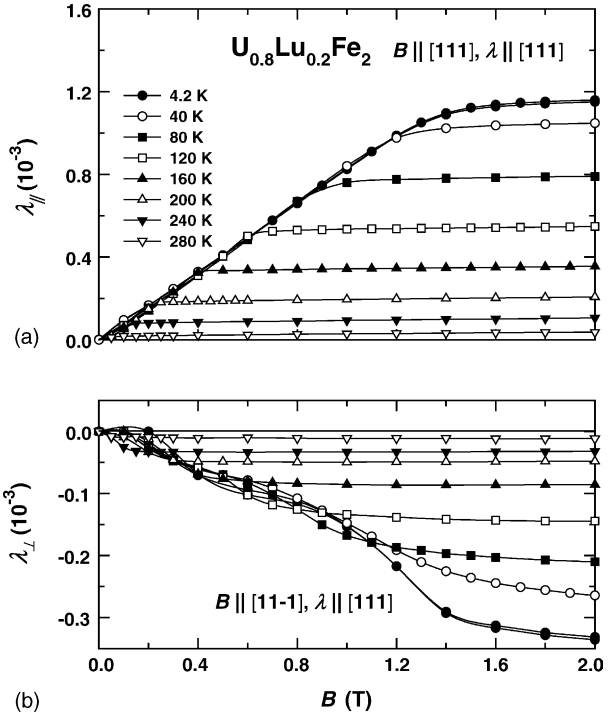

Fig. 4. Magnetostriction isotherms of the $U_{0.8}Lu_{0.2}Fe_2$ single crystal. The strain was measured along the $[1\,1\,\bar{1}]$ axis in the magnetic field applied along the [1 1 1] (panel a) and $[1\,1\,\bar{1}]$ axes (panel b).

over the sample volume is equilibrium in zero field, the saturation magnetostriction value in Fig. 4a should be three times larger than that in Fig. 4b. One can see that this is valid. Therefore, we can determine correctly the $\lambda_{1\,1\,1}$ value. Its temperature dependence is shown in Fig. 5. At 4.2 K, $\lambda_{1\,1\,1}$

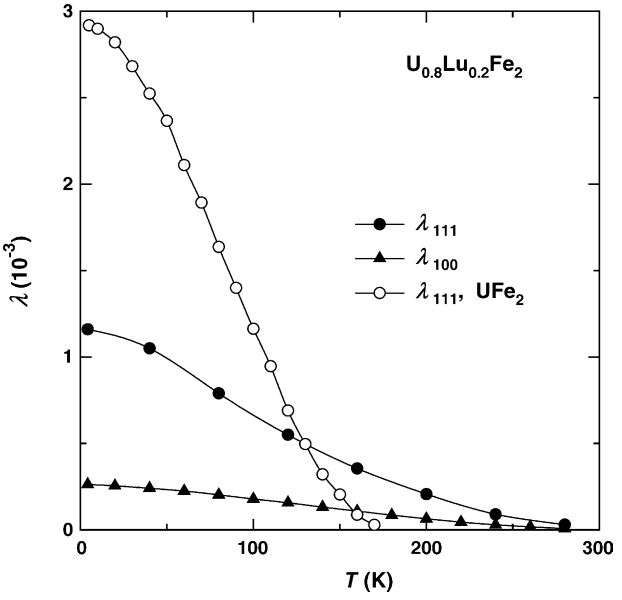

Fig. 5. Temperature dependencies of the magnetostriction constants $\lambda_{1\,1\,1}$ and $\lambda_{1\,0\,0}$ of $U_{0.8}Lu_{0.2}Fe_2$. The $\lambda_{1\,1\,1}(T)$ dependence for UFe_2 is also shown.

reaches 1.2×10^{-3}, which is much larger than that reported in Ref. [7] and much closer to 1.8×10^{-3}, the value predicted on the basis of evidently simple assumptions of unchanged state of U compared to that in UFe_2 and negligible contribution to the anisotropy and magnetostriction from the Fe sublattice. The λ_{100} constant is found to be 0.26×10^{-3} at 4.2 K, thus the relation $\lambda_{100} \ll \lambda_{111}$ holds for $U_{0.80}Lu_{0.20}Fe_2$ similar to UFe_2 and other Laves phase magnetostrictive materials.

4. Conclusion

The concentration spin reorientation from the ⟨1 1 1⟩ to the ⟨1 1 1⟩ easy-magnetization axis, observed upon dilution of the uranium sublattice of UFe_2 by a non-magnetic Lu as a consequence of the competition between the cubic magnetic anisotropy and the magnetoelastic contribution to the magnetic anisotropy, is accompanied by disappearance (within experimental error) of the spontaneous distortion of the crystal lattice in $U_{0.80}Lu_{0.20}Fe_2$. The reason is a small value of the magnetostriction constant $\lambda_{100} = 0.26 \times 10^{-3}$. Nevertheless, $U_{0.80}Lu_{0.20}Fe_2$ is also a "giant magnetostriction" material, but its large $\lambda_{111} = 1.2 \times 10^{-3}$ is "hidden" and manifests itself only in applied magnetic field.

Acknowledgments

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