Influence of doping elements (Y, Fe, V) on magnetic properties of RM$_2$ (R= Gd, Er; M= Fe, Co, Ni) Laves phases and their hydrides

H Michor$^1$, B Kotur$^2$, O Myakush$^2$, G Hilscher$^1$

$^1$Institute of Solid State Physics, Vienna University of Technology, Wiedner Hauptstrasse 8-10, A-1040 Wien, Austria
$^2$Department of Inorganic Chemistry, Ivan Franko National University of Lviv, Kyryla and Mefodia St. 6, UA-79005 Lviv, Ukraine

E-mail: kotur@franko.lviv.ua

Abstract. The ternary R$_{0.85}$Y$_{0.15}$Ni$_2$, RNi$_{1.85}$Fe$_{0.15}$ (R=Gd and Er), ErM$_{1.85}$V$_{0.15}$ (M=Fe, Co) and Er(Fe,Co,V)$_2$ phases have been investigated for the influence of doping elements (Y, Fe, V) on magnetic properties of RM$_2$ (R=Gd, Er; M=Fe, Co, Ni) Laves phases and their hydrides. All investigated compounds can easily absorb hydrogen up to 3.3-3.9 at.H/f.u. at 0.1-0.12 MPa pressure without amorphization. The hydrides preserve the structure of the parent compounds. Rare earth substitution of Gd and Er by 5 at. % Y in RNi$_2$ based compounds reduces slightly both the ordering temperature and the magnetic moment due to the dilution effect of a magnetic rare earth element by a non-magnetic one. The corresponding 3$d$ metal substitution of Ni by 5 at. % Fe increases $T_C$ by a factor of 3-7 for Gd and Er, respectively. Er(Fe,Co,V)$_2$ compounds with a Fe content higher than 20 at. % exhibit ordering temperatures above room temperature. Hydrogen absorption reduces the saturation moment and suppresses long range magnetic order in majority of investigated alloys to the temperature below 2 K except for ErFe$_{1.85}$V$_{0.15}$H$_{3.9}$ and ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$H$_{3.6}$.

1. Introduction

Intermetallic compounds of rare earth elements with 3$d$-elements exhibit a large variety of interesting physical properties. Some of them also absorb large amounts of hydrogen which induces changes of their physical properties. Basic intermetallics and alloys and their hydrides attract interest as objects for fundamental investigations and for practical application in the production of magnetic materials, hydrogen accumulators, metal hydride electrodes, etc. [1-3].

During last years we studied a number of binary Laves phases RM$_2$ (R=rare earth; M=3$d$-element) doped with a third component (R’ or M’) with respect to the influence of the doping element on the hydrogenation abilities of alloys and the crystal structure of their hydrides. These results are presented in detail in [4-11]. A literature and authors’ review of influence of hydrogen absorption on the crystal structure of binary RM$_2$ and ternary RM$_2$M’$_x$, R$_{1-x}$R’$_x$Ni$_2$ (R=rare earth; M=Mn, Fe, Co, Ni) Laves phase compounds is presented in [12]. Crystallographic parameters of the RM$_2$ (R=Gd, Er; M=Fe, Co, Ni), and related pseudo-binaries doped by a third component R or M, namely R$_{0.85}$Y$_{0.15}$Ni$_2$, RNi$_{1.85}$Fe$_{0.15}$, ErM$_{1.85}$V$_{0.15}$ (M=Fe, Co) and Er(Fe,Co)$_{1.85}$V$_{0.15}$ alloys and their hydrides are reviewed in Table 1. All investigated compounds can easily absorb a large amount of hydrogen up to 3.3-3.9 at.H/f.u. at 0.1-0.12 MPa pressure without amorphization. Hydrogen uptake leads to a lattice volume expansion for 14-26 %. The hydrides preserve the structure of the parent compounds.

As it is seen from the data presented in Table 1 substitution of Fe by V increases the hydrogen sorption capacity of alloys from 3.85 at.H/f.u. for ErFe$_2$ to 4.2 at.H/f.u. for ErFe$_{1.78}$V$_{0.22}$ whereas substitution of Co by V slightly influences the hydrogenation capacity of the samples. All V doped hydrides preserve the...
structure of the parent compounds, in contrast to the ErFeH_{2-1.85} hydride, where hydrogenation is accompanied with the phase transition of the cubic structure (MgCu_2-type) into the rhombohedral one (TbFe_2-type) [6, 12].

Table 1. Crystallographic parameters of the RM_{2-x} (R = Gd, Er; M = Fe, Co, Ni), R_{0.85}Y_{0.15}Ni_2, RNi_{1.85}Fe_{0.15} (R= Gd and Er), ErM_{2-x}V_x (M = Fe, Co) and Er(Fe,Co)_{2-x}V_x alloys and their hydrides.

| Alloys and their hydrides | Structure type | Lattice parameters | Ref |
|---------------------------|---------------|--------------------|-----|
| GdNi_{2}                 | TmNi_{2}      | a, nm              | V, nm^3 | ΔV/V, % |
| Gd_{0.85}Y_{0.15}Ni_{2}  | TmNi_{2}      | 1.44017(7)         | 2.9870(2) | - | 4 |
| Gd_{0.85}Y_{0.15}Ni_{2}H_{3.6} | TmNi_{2} | 1.5209(9) | 3.5180(4) | 17.8 | 4 |
| ErNi_{2}                 | TmNi_{2}      | 1.42678(6)         | 2.9045(2) | - | 5 |
| Er_{0.85}Y_{0.15}Ni_{2}  | TmNi_{2}      | 1.42920(6)         | 2.9193(2) | - | 5, 6 |
| Er_{0.85}Y_{0.15}Ni_{2}H_{3.4} | TmNi_{2} | 1.5010(4) | 3.3816(15) | 15.8 | 5, 6 |
| GdNi_{1.85}Fe_{0.15}    | MgCu_{2}      | 0.72246(3)         | 0.37709(3) | - | 4 |
| GdNi_{1.85}Fe_{0.15}H_{3.8} | MgCu_{2} | 0.7674(11) | 0.452(2) | 19.9 | 4 |
| ErNi_{1.9}Fe_{0.15}     | MgCu_{2}      | 0.71707(3)         | 0.3687(3) | - | 5 |
| ErNi_{1.9}Fe_{0.15}H_{3.3} | MgCu_{2} | 0.7490(4) | 0.4201(4) | 13.9 | 5 |
| ErFe_{2}                 | MgCu_{2}      | 0.7285(1)          | 0.3865(1) | - | 7 |
| ErFe_{2.8}V_{0.15}      | MgCu_{2}      | 0.7298(1)          | 0.3887(1) | - | 7 |
| ErFe_{2.8}V_{0.15}H_{4.9} | MgCu_{2} | 0.7877(1) | 0.4887(1) | 25.7 | 7 |
| ErFe_{2.8}V_{0.22}      | MgCu_{2}      | 0.73125(7)         | 0.3910(4) | - | 8 |
| ErFe_{2.8}V_{0.22}H_{4.8} | MgCu_{2} | 0.7915(1) | 0.4958(3) | 26.8 | 8 |
| ErCo_{2}                 | MgCu_{2}      | 0.71559(5)         | 0.36644(8) | - | 8 |
| ErCo_{2.8}V_{0.15}      | MgCu_{2}      | 0.71773(5)         | 0.3697(8) | - | 8 |
| ErCo_{2.8}V_{0.15}H_{4.8} | MgCu_{2} | 0.7670(7) | 0.4510(1) | 22.0 | 8 |
| ErCo_{2.8}V_{0.33}      | MgCu_{2}      | 0.71976(5)         | 0.37288(8) | - | 8 |
| ErCo_{2.8}V_{0.33}H_{4.8} | MgCu_{2} | 0.7746(1) | 0.4647(3) | 24.6 | 8 |
| ErFe_{0.225}Co_{0.925}V_{0.15} | MgCu_{2} | 0.72560(6) | 0.3820(9) | - | 8 |
| ErFe_{0.225}Co_{0.925}V_{0.12}H_{3.6} | MgCu_{2} | 0.7774(4) | 0.4698(7) | 23.0 | 8 |

structure of the parent compounds, in contrast to the ErFeH_{2-1.85} hydride, where hydrogenation is accompanied with the phase transition of the cubic structure (MgCu_2-type) into the rhombohedral one (TbFe_2-type) [6, 12].

2. Experimental procedure

Alloys have been prepared by arc melting of the initial elements with a purity not less than 99.9 wt. % under argon. During arc melting the weight losses were less than 1 % of the total mass of the ingots. The alloys were annealed in quartz ampoules under vacuum at 600°C for 720 h.

All hydrides were synthesized at room temperature under 0.12 MPa hydrogen pressure in autoclave after preliminary activation of the samples in vacuum at 350–400°C. The amount of absorbed hydrogen was determined volumetrically.

The amount of absorbed hydrogen was preliminarily activated in vacuum at 350–400°C. The amount of absorbed hydrogen was determined volumetrically.
The samples were examined by X-ray powder diffraction using diffractometers HZG-4a, (FeKα-radiation) and DRON-3M (CuKα-radiation). For crystal structure determination the diffraction data were collected using a θ-2θ scan mode with steps of 0.05° 2θ and exposition time 20 sec. at every point. All the crystal structure calculations were performed by the Rietveld method using the FullProf [18] and CSD [19] programs.

Magnetization measurements have been performed with a SQUID magnetometer in the temperature range 2-300 K in magnetic fields up to 6T.

3. Results and discussion

The available literature data and the present data on magnetic properties of the RM2, R0.85Y0.15Ni2, RNi1.85Fe0.15 (R = Gd and Er), ErM2.5Vx (M = Fe, Co) and Er(Fe,Co)2.5Vx alloys and their hydrides are collected in Table 2. All ternary compounds exhibit long range magnetic order, in particular compounds with more than 20 at. % Fe exhibit ordering temperatures above room temperature and are not accessible with the SQUID magnetometer used. As can be seen from Table 2 hydrogen absorption reduces the saturation moment and suppresses long range magnetic order in majority of the investigated alloys to below 2K except for ErFe1.85V0.15H3.9 and ErFe0.925Co0.095V0.15H3.6.

Table 2. Magnetic characteristics of the RM2 (R = Gd, Er; M = Fe, Co, Ni), R0.85Y0.15Ni2, RNi1.85Fe0.15 (R = Gd and Er), ErM2.5Vx (M = Fe, Co) and Er(Fe,Co)2.5Vx alloys and their hydrides.

| Alloys and their hydrides | Structure type | Tc, K | μf.u., μB | μs/R, μB | θu, K | Ref |
|---------------------------|----------------|-------|-----------|-----------|--------|-----|
| GdNi2                     | TmNi2          | 75    | 6.9       | 7.92      | 73     | 20, * |
| GdNi2H3.9                 | TmNi2          | 8     | 4.2       | 7.84      | 3      | 20, * |
| ErNi2                     | TmNi2          | 14-16 | 5.4       | 9.55      | 10     | 13,21 |
| ErNi2H4                   | TmNi2          |       |           |           | 21     |      |
| Gd0.85Y0.15Ni2            | TmNi2          | 60    | 5.89#     | 7.89      | 65     | *    |
| Gd0.85Y0.15Ni2H3.6        | TmNi2          | <2    | 5.64#     | 7.89      | 9      | *    |
| Er0.85Y0.15Ni2            | TmNi2          | 15    | 6.75#     | 10.1      | 15     | *    |
| Er0.85Y0.15Ni2H3.4        | TmNi2          | <2    | 5.52#     | 10.35     | 4.5    | *    |
| GdNi1.85Fe0.15            | MgCu2          | 217   | 6.5#      | 8         | 224    | *    |
| GdNi1.85Fe0.15H3.8        | MgCu2          | <2    | 5.9#      | 7.3       | 25     | *    |
| ErNi1.85Fe0.15            | MgCu2          | 118   | 7.6#      | 9.88      | 113    | *    |
| ErNi1.85Fe0.15H3.3        | MgCu2          | <2    | 5.45#     | 4.0       | - 5    | *    |
| ErFe2                     | MgCu2          | 590   | 4.85      |           |        | 22,25 |
| ErFe2H1.2,2.5             | MgCu2          | >300  | 5.6#      |           |        | 23,29 |
| ErFe2H3.5                 | TbFe2          | <300  | ~5.6      |           |        | 22-24 |
| ErFe2H5.0                 | ErFe2H5.0      |       | 3.6       |           |        | 24    |
| ErFe1.85V0.15             | MgCu2          | >300  | 5.6#      |           |        | *     |
| ErFe1.85V0.15H3.9         | MgCu2          | >300  | 2.85#     |           |        | *     |
| ErCo2                     | MgCu2          | 32-33 | 7         |           |        |      |
| ErCo2H3.5                 | MgCu2          | 25    | 4.35      |           |        | 25    |
| ErCo1.4Fe0.6              | MgCu2          | 510   | 4.85      |           |        | 25    |
| ErCo1.4Fe0.6H3.5          | MgCu2          | >300  | 3.8       |           |        | 25    |
| ErCo0.6Fe1.34             | MgCu2          | 670   | 4.65      |           |        | 25    |
| ErCo0.6Fe1.34H3.5         | MgCu2          | >300  | 2.9       |           |        | 25    |
| ErCo1.85V0.15             | MgCu2          | 33    | 6.8#      | ~8.61     | 34     | *     |
| ErCo1.85V0.15H3.80        | MgCu2          | <2    | 4.9#      | 9.6       | - 6    | *     |
| ErFe0.925Co0.095V0.15     | MgCu2          | >300  | 5.6#      |           |        | *     |
| ErFe0.925Co0.095V0.15H3.6 | MgCu2          | 25    | 5.05#     |           |        | *     |

* - present paper; $^*$ - μf.u. taken at 3 K and 6 T
Figure 1. Magnetisation (a) and susceptibility (b) as a function of temperature of Gd$_{0.85}$Y$_{0.15}$Ni$_2$ and Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$ for various fields as labeled.

Shown in Fig. 1a is the temperature dependent magnetization of Gd$_{0.85}$Y$_{0.15}$Ni$_2$ and Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$.

The dilution of the Gd and Er moment in RNi$_2$ by 5 at. % Y substitution reduces $T_c$ from 75 K for GdNi$_2$ to 60 K for Gd$_{0.85}$Y$_{0.15}$Ni$_2$ (Fig. 1a) while the analogous Er/Y substitution has only a minor influence upon $T_c$ (Table 2). Previously it was suggested that Ni appears to have no or a rather small moment due to filled Ni 3$d$ band [20] in GdNi$_2$, however, according to X-ray magnetic circular dichroism (XMCD) the Ni moment is 0.2-0.26 $\mu_B$ antiparallel to the Gd moment [26, 27]. The saturation moment for Gd$_{0.85}$Y$_{0.15}$Ni$_2$ at 3 K and 6 T is 5.89 $\mu_B$/f.u. Taking account for the above mentioned Ni moment antiparallel to Gd yields a Gd moment of 7.4 $\mu_B$ being slightly larger than that expected for Gd$^{3+}$ (7 $\mu_B$), which can be attributed to the conduction electron polarisation. Hydrogen absorption reduces the saturation moment at 3 K and 6 T to 5.64 $\mu_B$/f.u. for Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$ corresponding to a Gd moment of 6.63 $\mu_B$. Long range order is suppressed to below 2 K in both hydrides Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$ and Er$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.4}$ according to an analysis of the M(H) curves of in terms of Arrott plots (M$^2$ versus M/H plots). The scaling behaviour of the magnetic isotherms as a function of the normalized external field with respect to the temperature ($\mu_B H / T$) indicates that antiferromagnetic correlations are still preserved in the paramagnetic regime of Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$ which may be responsible for the reduced Gd moment mentioned above.

Figure 1b shows the temperature dependent magnetic susceptibility $\chi$ for Gd$_{0.85}$Y$_{0.15}$Ni$_2$ and the hydride plotted as 1/$\chi$ versus T. The almost linear temperature dependence of 1/$\chi$ above 20 K and 70 K for the hydride and parent compound, respectively, can well be described with a modified Curie-Weiss law $\chi = \chi_0 + C/(T - \Theta)$. $\chi_0 = 4 \times 10^{-8}$ m$^3$/kg represents a temperature independent Pauli susceptibility, C is the Curie constant yielding an effective moment 7.89 $\mu_B$/Gd for both the parent compound and the hydride while the paramagnetic temperature $\Theta$ is reduced from 64 K for the parent compound to 9 K for the hydride. A similar behaviour is observed for Er$_{0.85}$Y$_{0.15}$Ni$_2$ and its hydride where the effective moment of 10.1 $\mu_B$/Er is slightly raised to 10.35 $\mu_B$/Er while the paramagnetic Curie temperature is reduced from 15 K to 4.5 K under hydrogen absorption. Both effective moments are close to those expected for Gd$^{3+}$ (7.94 $\mu_B$) and Er$^{3+}$ (9.58 $\mu_B$).

As shown in figure 2 substitution of 5 at. % Ni by Fe in RNi$_2$ (R=Gd, Er) increases $T_c$ to 217 K and to 118 K for GdNi$_{1.85}$Fe$_{0.15}$ and ErNi$_{1.85}$Fe$_{0.15}$, respectively, while hydrogen absorption suppresses long range order to below 2 K. The saturation moment for GdNi$_{1.85}$Fe$_{0.15}$ (6.5 $\mu_B$) indicates that the 3$d$ moment is antiparallel to the Gd moment and can be estimated to be 0.25 $\mu_B$/(Fe, Ni) if one assumes a Gd 4$f$ moment of 7 $\mu_B$. The irreversibility of the magnetization for zero field cooling and field cooling of the ErNi$_{1.85}$Fe$_{0.15}$ which is preserved in fields up to 1 T can be attributed to domain wall pinning. This is also seen in a metamagnetic like behaviour of the magnetic isotherms associated with a pronounced hysteresis at low temperatures. The effective moments of parent compounds are 8 $\mu_B$/Gd and 9.88 $\mu_B$/Er while those of the hydrides are 7.3 $\mu_B$/Gd and 4 $\mu_B$/Er.
Figure 2. Magnetisation as a function of temperature of (a) GdNi$_{1.85}$Fe$_{0.15}$ and GdNi$_{1.85}$Fe$_{0.15}$H$_{3.8}$ for various fields and (b) ErNi$_{1.85}$Fe$_{0.15}$ and ErNi$_{1.85}$Fe$_{0.15}$H$_{3.3}$ for various fields for zero field cooling (ZFC) and field cooling (FC).

Figure 3. Magnetisation as a function of temperature of (a) ErFe$_{1.85}$V$_{0.15}$ and ErFe$_{1.85}$V$_{0.15}$H$_{3.9}$ and (b) ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$ and ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$H$_{3.6}$ for various fields.

Co/V substitution in ErCo$_2$ ($T_C$=32-33 K) has hardly an effect upon the first order transition $T_C$ (33 K) for a V concentration of 5at% (Table 2) in a similar way as Co/Ti substitution [16]. Hydrogenation suppresses long range order to below 2 K in ErCo$_{1.85}$V$_{0.15}$H$_{3.8}$. The data of the effective moment and paramagnetic Curie temperature for the parent compound of the hydride are summarized in Table 2.

Both Fe-containing alloys ErFe$_{1.85}$V$_{0.15}$ and ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$ exhibit long range order above room temperature (Fig. 3). Hydrogenation in the former gives rise to a significant reduction of the bulk moment from 5.6 $\mu_B$/f.u. to 2.83 $\mu_B$/f.u. associated with a weakening of the Er-Fe exchange interaction. This has been studied extensively in ErFe$_2$H$_x$ [22-24, 28] where the compensation point of the parent compound at 410 K linearly decreases with the hydrogen content to 170 K for ErFe$_{1.85}$V$_{0.15}$H$_{3.6}$. Also for ErFe$_{1.85}$V$_{0.15}$H$_{3.9}$ a compensation point occurs at about 80 K which is shifted to higher temperatures with rising fields but long range order remains above room temperature which is in line with the literature data mentioned above. Domain wall pinning in ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$ gives rise to a metamagnetic like behaviour of the magnetic isotherms at low temperatures associated with pronounced hysteresis. The additional feature of the magnetization at about 60 K in higher fields may be indicative for a spin-reorientation. According to Arrott plots the metamagnetic transition associated with long range order is reduced to $T_C$=25 K in the hydride ErFe$_{0.925}$Co$_{0.925}$V$_{0.15}$H$_{3.6}$.

4. Conclusions
RNi$_{1.85}$Fe$_{0.15}$ (R=Gd, Er), ErM$_{1.85}$V$_{0.15}$ (M=Fe, Co) occur in the cubic MgCu$_2$-type structure, however R$_{0.85}$Y$_{0.15}$Ni$_2$ (R=Gd, Er) crystallize with the TmNi$_2$-type cubic structure with doubled cell parameter $a$. The above mentioned phases absorb 3.3-3.9 at.H/f.u. with increasing the cell volume up to 26%. The structure of the parent compounds and their hydrides remains unchanged.

Gd by Y substitution (5 at. %) in GdNi$_2$ reduces $T_C$ from 75 K to 60 K. The analogous Er/Y substitution has only a minor influence upon $T_C$ ($T_C$ = 14-16 K for ErNi$_2$, $T_C$ = 15 K for Er$_{0.85}$Y$_{0.15}$Ni$_2$). Hydrogen absorption suppresses long range order to below 2 K in both hydrides Gd$_{0.85}$Y$_{0.15}$Ni$_2$H$_{3.6}$ and

(a) (b) (c) (d)
Er_{0.975}Y_{0.15}Ni_{3}H_{3.4}, Ni by Fe substitution (5 at. %) increases $T_C$ to 217 K and to 118 K for GdNi_{1.85}Fe_{0.15} and ErNi_{1.85}Fe_{0.15}, respectively, and hydrogenation suppresses long range order to below 2 K. Co by V substitution (5 at. %) in ErCo$_2$ ($T_C$=32-33 K) has no effect upon the $T_C$ (33 K) for this V concentration. Hydrogenation reduces long range order to below 2 K in ErCo$_{1.85}$V$_{0.15}$. Both Fe-based alloys ErFe$_{1.85}$V$_{0.15}$ and ErFe$_{0.975}$Co$_{0.075}$V$_{0.15}$ exhibit long range magnetic order up to above room temperature and $T_C$ remains above room temperature for the hydride ErFe$_{1.85}$V$_{0.15}$H$_{3.4}$.

This work was supported by the Ukrainian-Austrian WTZ project No. UA 06/2009.

References
[1] Buschow K H J 1984 Hydrogen absorption in intermetallic compounds, in: Gschneidner Jr K A and Eyring L. (Eds) Handbook on the Physics and Chemistry of Rare Earths, Vol. 10, (North–Holland Publishing Co.) 1–111
[2] Yvon K and Fischer P 1988 Crystal and Magnetic Structures of Ternary Metal Hydrides: A Comprehensive Review, in: Topics in Applied Physics, Vol. 63. Hydrogen in Intermetallic Compounds I. Electronic, Thermodynamic and Crystallographic Properties, Preparation, (Springer–Verlag, Berlin) 87–138
[3] Wiesinger G and Hilscher G 2008 Magnetism of Hydrides, in: K-H-J Buschow (Ed.) Handbook on Magnetic Materials Vol. 17 (Elsevier B.V.) Ch 5 293-456
[4] Kotur B, Myakush O and Zavaliy I 2007 J Alloys Compounds 442 17
[5] Myakush O, Verbovtsky Yu, Kotur B, Kovalchuk I, Beresovetz V and Zavaliy I 2007 J Phys.: Conf. Ser 79 012018
[6] Myakush O V, Verbovtskyi Yu V, Berezovets V V, Ershova O H, Dobrovolskhyi V D and Kotur B Ya 2007 Materials Science 43 682-688
[7] Myakush O, Martyniuk G, Verbovtsky Yu and Kotur B 2006 Visnyk Lviv Univ Ser Chem 47 25
[8] Myakush O, Verbovtskyi Yu, Saldan I, Kovalchuck I, Zavalii I and Kotur B 2004 Materials Science 40 781
[9] Verbovtsky Yu, Myakush O, Soldak A and Kotur B 2005 Visnyk Lviv Univ Ser Chem 46 48
[10] Myakush O V, Denys R V, Kovalchuk I V, Verbovtskyi Yu V, Zavalii I Yu and Kotur B Ya 2003 Materials Science 39 849
[11] Kovalchuk I Myakush O Denys R and Kotur B 2007 Visnyk Lviv Univ Ser Chem 48 194
[12] Kotur B, Myakush O and Zavaliy I 2009 Croat Chem Acta 82 469
[13] Burzo E, Chelkowski A and Kirchmayr H-R in: H-P-J Wijn (ed.),1990 Landolt-Börstein, Numerical Data and Functional Relationships in Science and Technology, New Series, Magnetic Properties of Metals Vol. 19-D2,(Springer, Berlin)
[14] Hilscher G 1982 J Magn Magn Mat 25 229
[15] Hilscher G 1982 J Magn Magn Mat 27 1
[16] Öner Y and Kamer O 2008 J Alloys Compd 464 51
[17] Mushnikov N V, Gaviko V S and Goto T 2005 J Alloys Compd 398 36
[18] Rodrigues-Carvajal J Program: FullProf.2k Version 2.20 (France: Lab Leon Brillouin CEA-CNRS)
[19] Akselrud L G, Zavalii P Yu, GrinYu N, Pecharsky V K, Baumgartner B and Wolfel E 1993 Mater Sci Forum 133-136 335
[20] Malik S K and Gschneidner Jr K A 1987 Solid State Comm 24 283
[21] Wang D, Li Y, Long Y, Ye R, Chang Y and Wan F 2007 J Magn Magn Mat 311 6971
[22] Fruchart D, Berthier Y, de Saxce T and Vulliet P 1987 J Solid State Chem 67 197-209
[23] Paul–Boncour V and Perchéron–Guegan A 1999 J Alloys Compounds 293-295 237
[24] Paul-Boncour V, Filipek S M, Perchéron–Guegan A, Marchuk I, Pielaszek J 2001 J Alloys Compounds 317-318 83
[25] Pourarian F, Wallace W E and Malik S K 1982 J Magn Magn Mat 25 299
[26] Mizumaki M, Yano K, Umehara I, Ishikawa F, Sato K, Koizumi A, Sakai N and Muro T 2003 Phys. Rev. B 67 132404
[27] Yano K, Umehara I, Miyazawa T, Adachi Y and Sato K 2005 Physica B 367 81
[28] Paul–Boncour V, Giorgetti C, Wiesinger G and Perchéron–Guegan A 2003 J Alloys Compounds 356-357 195
[29] De Saxce T, Berthier Y and Fruchart D 1985 J Less Common Met 107 35