Introduction

The heavy rare earth (R) – transition metal (M) ferri-
magnets (RM$_2$) are widely studied for their fundamental
interest and practical applications [1, 2, 12]. The electronic
band structure of these intermetallics, and in particular of
their transition metal sublattice, is rather complex and
poorly understood up to now. In order to check the effect
of cobalt atoms on the crystal structure and hyperfine
interactions, the new intermetallics Dy(Fe$_{0.4}$Co$_{0.6}$
$-\alpha$Al$_{\alpha}$)$_2$ with Co/Al substitution were synthesized and detailed
X-ray crystallographic studies and $^{57}$Fe Mössbauer effect
measurements were performed. Magnetic properties of
Dy(Mn-Fe)$_2$, Dy(Fe-Co)$_2$ series and especially of the
studied series are poorly known up to now. Nevertheless
the ordering temperatures for $\alpha = 0$ and for $\alpha = 0.6$ can be
appreciated as being equal to 620 K and 109 K, correspon-
dingly [9, 11].

Materials, crystal structure

The series of intermetallics Dy(Fe$_{0.4}$Co$_{0.6}$
$-\alpha$Al$_{\alpha}$)$_2$ ($\alpha = 0, 0.1, ...
,..., 0.5 and 0.6) was prepared by arc melting with contact-
less ignition [7], in a high purity argon atmosphere, from
the appropriate amounts of Dy (99.9% purity), Fe, Co and
Al (all 99.999% purity) starting materials. After 48 h
treatment at 1150 K, good quality X-ray diffraction patterns
were obtained at room temperature for all the samples,
using Mo K$_\alpha$ radiation. For the compounds with $\alpha = 0–0.2$,
the cubic, $Fd3m$, MgCu$_2$-type Laves phase was evidenced.
For $0.3 \leq \alpha \leq 0.5$ a mixture of two Laves phases was observed
[8], the second one corresponding to the hexagonal, $P6_3/mmc$, 
MgZn$_2$-type structure. For $\alpha = 0.6$ only the MgZn$_2$-type
phase was observed. The phase contribution, lattice par-
parameters and unit cell volume for both Laves phases are
presented in Table 1.
Mössbauer effect studies

The Mössbauer effect measurements (at 77 K) were performed by using a standard transmission technique, with a $^{57}$Co source in Rh. The experimental spectra of the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ series are presented in Fig. 1. The spectra are complex which can be related principally to the Fe/Co/Al substitution and also to the crystallography of the constituent MgCu$_2$- and MgZn$_2$-type phases and to the direction of the easy axis of magnetization [10]. In the present complex case the general Bernoulli law [4] was used to find probabilities of particular local Fe/Co/Al configurations of atoms. During fitting procedure the used starting amplitude distribution of subspectra followed the Bernoulli distributions, considering, as an approximation, only significant probabilities. This approximation results in change of the halfwidth ($\Gamma/2$) of the Mössbauer line. Namely, it varies across the series from 0.137(5) mm/s ($x = 0$) to 0.23(1) mm/s ($x = 0.5$) and even to 0.33 mm/s ($x = 0.6$). The average values of the hyperfine interaction parameters are the fitted amplitude weighted data. These parameters, i.e. the isomer shift IS (with respect to pure iron metal, at 300 K), the magnetic hyperfine field $H_{hf}$ (IS = 0.37 mm/s for the MgCu$_2$-type phase and 0.3 mm/s for the MgZn$_2$-type phase) and the quadrupole interaction parameter $eQ/2$ (as defined in [13]) obtained for the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ series are presented in Fig. 2. The errors $\delta(H_{hf})$ of the $H_{hf}$ parameters are less than dimensions of experimental points. For instance, $\pm\delta(H_{hf}) = 0.09$ T ($x = 0$), 0.1 T ($x = 0.3$), 0.13 T ($x = 0.5$). The magnetic hyperfine field $H_{hf}$ equals 23.4(1) T for Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ and decreases with increasing Al content $x$. The line through the experimental points corresponds to a linear fit: $H_{hf} = -30.28x + 23.03$ T. The isomer shift, IS, increases with $x$ (IS = 0.37x - 0.011 mm/s), whereas the quadrupole interaction parameter $eQ/2$ remains constant, except perhaps for $x = 0.6$. Although the crystal structure changes across the series, the observed average hyperfine interaction parameters do not reflect these crystal transitions since they vary continuously with $x$ (IS and $H_{hf}$) or do not significantly vary ($eQ/2$). This behaviour can be understood by considering that the nearest neighbourhoods of the studied iron atoms are similar in both the Laves structures [3].

The Slater-Pauling curve

Figure 3 gives the 3d/3d Slater-Pauling curve $\mu_{hf}(n)$ for the Dy(M-M)$_2$ compounds (M-M = Mn-Fe, Fe-Co) at 77 K, (analogous to the curve previously reported for these compounds at 4.2 K [5]) (lines 1) and the $\mu_{hf}(n)$ dependence for the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ series (line 2). Lines 1 are fitted using the formulae: $\mu_{hf}(n) = 11.55n - 47.87$ T and $\mu_{hf}(n) = -5.89n - 61.73$ T. Line 2 is fitted using the formula $\mu_{hf}(n) = 4.33n - 5.52$ T. The average number $n$ of 3d electrons, calculated per site of the M – sublattice, equals $n(x) = 0.4 \cdot 6 + (0.6 - x)7$, where 6 and 7 are the numbers of 3d electrons for iron and cobalt atoms, respect-

![Fig. 1. $^{57}$Fe Mössbauer spectra of the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ intermetallics (77 K) for several $x$ values.](image1)

![Fig. 2. Evolution of the hyperfine parameters of the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ series (77 K) with the aluminium content ($x$): 1 – the isomer shift; 2 – the magnetic hyperfine field; 3 – the quadrupole interaction parameter.](image2)

![Table 1. Crystal data (300 K) for the Dy(Fe$_{0.4}$Co$_{0.6}$Al$_x$)$_2$ intermetallics: the phase contribution (%), parameters $a$ and $V$ for the MgCu$_2$-type phase and $a$, $c$, $V$ for the MgZn$_2$-type phase.](image3)
Summary and discussion

The influence of Al substitution on the crystal lattice, magnetic properties and hyperfine interactions observed in several intermetallics was previously discussed elsewhere [6, 10]. The main problem to discuss below is the \( \mu_H(n) \) dependence. The series Dy(Fe\(_{0.07}Co_{0.06}Al\))\(_2\) starts from the Dy(Fe\(_{0.07}Co_{0.06}Al\))\(_2\) compound with the majority subband totally filled up, and the minority subband only partly filled [8, 10]. We did not observe the Slater-Pauling mechanism since the typical maximum does not occur on our \( \mu_H(n) \) curve.

This type of \( \mu_H(n) \) dependence could be understood qualitatively considering that the Al substitution of Co – atoms reduces the average number \( u \) of the magnetic nearest neighbours surrounding the probed Fe atom and thus reduces the energy shift \( \Delta E \sim J_{M,M}m_m \) between the 3d-subbands, where \( J_{M,M} \) is the exchange integral and \( m_m \) is an average magnetic moment of transition metal (M) atom. As a result the 3d electrons should become gradually redistributed over the 3d subbands [8, 10] and the difference between the spin-up \( \rho_{3d}^+ \) and spin down \( \rho_{3d}^- \) densities should become reduced step by step with \( x \). Consequently, the magnetic moment \( m_{st} \), the magnetic hyperfine field \( \mu_H \) should also decrease and finally the 3d/3p branch is observed. A more advanced explanation including the change of Fermi energy needs further experimental, theoretical and numerical studies.

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References

11. Pszczoła J, Żukrowski J, Suwalski J, Pańta A (2000) \(^{161}\)Dy and \(^{57}\)Fe Mössbauer effect studies of Dy(Fe\(_{0.07}Co_{0.06})\(_2\)Mn\(_2\)) intermetallics. J Alloys Compd 306:56–65

![Graph showing magnetic hyperfine fields \( \mu_0H(n) \) compared for series: 1 – Dy(M-M)\(_2\) (M-M = Mn-Fe, Fe-Co) and 2 – Dy(Fe\(_{0.07}Co_{0.06}Al\))\(_2\) (n is the average number of 3d electrons).]