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## Magnetocrystalline anisotropy of novel $R_3(Fe, M)_{29}$ compounds

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**Abstract.** The structure and magnetic properties of novel  $R_3(Fe, M)_{29}$ -type compounds ( $M$  is the stabilizing element) have been studied by comparing to  $CaCu_5$ -,  $R_2Fe_{17}$ - and  $ThMn_{12}$ -type rare-earth–transition-metal compounds. A phenomenological expression of the magnetocrystalline-anisotropy energy for the monoclinic structure has been derived through symmetry analysis.

### 1. Introduction

Recently, the study of the magnetic properties of the new ternary phase with the  $Nd_3(Fe, Ti)_{29}$ -type structure is attracting considerable interest from both fundamental and practical points of view. This phase has been synthesized at the Fe-rich corner of the  $R$  ( $=$  rare-earth)–Fe phase diagram [1–3]. Initially, it has been reported that this phase has the nominal composition  $Nd_2(Fe, Ti)_{19}$  and that the diffraction patterns can be indexed as a superlattice of the hexagonal cell of the  $TbCu_7$  type of structure. The real stoichiometric composition was later established to be 3:29. The crystallographic structure has been determined to be of the  $Nd_3(Fe, Ti)_{29}$  type with monoclinic symmetry and  $P2_1/c$  space group by x-ray diffraction (XRD) and neutron powder diffraction [4–6]. Subsequent work by Kalogirou *et al* suggests that the  $Nd_3(Fe, Ti)_{29}$ -type structure can be described more accurately in the  $A2/m$  space group than in the  $P2_1/c$  space group [7].

Like  $R_2Fe_{17}$  and  $RFe_{12-x}M_x$  ( $M$  is a stabilizing element) compounds, the new family of intermetallic compounds,  $R_3(Fe, M)_{29}$ , is able to take up N and C as interstitial atoms, which leads to a remarkable improvement of the magnetic properties [8]. The interstitial nitride  $Sm_3(Fe, Ti)_{29}N_y$  can be considered as a novel candidate for application in permanent magnets. Recent study on the hard magnetic properties of  $Sm_3(Fe, M)_{29}N_y$  with  $M = V, Cr$  and  $Mo$  has proved the same conclusion [9–12].

The high-field magnetization and the singular point detection measurements show that Sm-based  $R_3(Fe, M)_{29}N_y$  compounds exhibit a large axial magnetocrystalline anisotropy that is very important for permanent magnet application; at the same time there is an obvious magnetic anisotropy in the basal-plane for the parent compounds. This suggests that the anisotropy energy in  $R_3(Fe, M)_{29}$  compounds with the monoclinic structure not only depends on the polar angle  $\theta$ , but also on the azimuthal angle  $\phi$ . A study of the anisotropy energy as a

function of the monoclinic structure parameters is very important, which will lead to a further understanding of the magnetocrystalline anisotropy of the novel  $R_3(Fe, M)_{29}N_y$  compounds.

In this paper, the structure and magnetization properties of the  $R_3(Fe, M)_{29}$ -type compounds have been summarized in comparison with the 1:5, 1:12 and 2:17 types of structure. The magnetocrystalline anisotropy of the  $R_3Fe_{29-x}M_x$ -type compounds has been studied; a phenomenological expression is presented.

## 2. Crystal structure

The  $R_3Fe_{29-x}M_x$  phase like  $R_2Fe_{17}$  and  $RFe_{12-x}M_x$  phases can be derived from the  $CaCu_5$  structure. Each of them represents a modification of the  $RT_5$  structure in which a fraction of the R atoms is replaced by T-metal dumbbells. This process may be described by [13]



with the 2:17 structure corresponding to  $\delta = 1/3$  and the 1:12 structure corresponding to  $\delta = 1/2$ . The new 3:29 structure corresponds to  $\delta = 2/5$ . In the hexagonal 2:17 phase, this substitution may induce a substantial degree of disorder, leading to non-stoichiometric compounds and mixed stacking. In the rhombohedral 2:17 phase and the other two phases, this kind of substitution appears to be completely regular. The structure of  $Nd_3(Fe, Ti)_{29}$  is intermediate between the well known rhombohedral  $Th_2Zn_{17}$  (or hexagonal  $Th_2Ni_{17}$ ) and the tetragonal  $ThMn_{12}$  structures, and is formed by alternating stacking of 2:17 and 1:12 segments, in the ratio 1:1. This can be proved by the magnetization study below.

From equation (1), it is likely that, besides the 3:29 phase, other intermediate phases based on the stacking of the rhombohedral 2:17 and tetragonal 1:12 segments may exist. For example, a 2:1 stacking (3/8 dumb-bell replacement) would correspond to a 5:46 phase, whereas a 1:2 stacking (3/7 dumb-bell replacement) would correspond to a 4:41 phase. According to model descriptions which are useful in the search for novel compounds [14–16], it is reasonable to suppose that many R–T structure types are still awaiting discovery.

In the Descartes coordinate system, with  $\vec{i}$ ,  $\vec{j}$  and  $\vec{k}$  as unit vectors along the  $x$ ,  $y$  and  $z$  axes, the basis vectors for the unit cells of the 1:5, 2:17H, 1:12 and 3:29 structures, respectively, can be written as follows [7]:

for the 1:5 structure

$$\begin{aligned} \vec{a} &= \frac{\sqrt{3}}{2}a_0\vec{i} + \frac{1}{2}a_0\vec{j} \\ \vec{b} &= -\frac{\sqrt{3}}{2}a_0\vec{i} + \frac{1}{2}a_0\vec{j} \\ \vec{c} &= c_0\vec{k} \end{aligned} \quad (2)$$

for the 2:17H structure

$$\begin{aligned} \vec{a} &= \sqrt{3}a_0\left(\frac{1}{2}\vec{i} - \frac{\sqrt{3}}{2}\vec{j}\right) \\ \vec{b} &= \sqrt{3}a_0\left(\frac{1}{2}\vec{i} + \frac{\sqrt{3}}{2}\vec{j}\right) \\ \vec{c} &= 2c_0\vec{k} \end{aligned} \quad (3)$$

for the 1:12 structure

$$\begin{aligned} \vec{a} &= \sqrt{3}a_0\vec{i} \\ \vec{b} &= 2c_0\vec{k} \\ \vec{c} &= -a_0\vec{j} \end{aligned} \quad (4)$$

for the 3:29 structure

$$\begin{aligned}\vec{a} &= -2a_0\vec{j} + c_0\vec{k} \\ \vec{b} &= \sqrt{3}a_0\vec{i} \\ \vec{c} &= a_0\vec{j} + 2c_0\vec{k}\end{aligned}\quad (5)$$

where  $a_0$  and  $c_0$  represent the lattice parameters of the 1:5 unit cell. The relations between the monoclinic  $R_3T_{29-x}T_x$  (3:29) structure and the  $RCO_5$  (1:5), the hexagonal  $R_2T_{17}$  (2:17H) and the tetragonal  $RT_{12-x}M_x$  (1:12) are given by the vector transformations in reciprocal space:

$$\begin{aligned}\begin{pmatrix} h \\ k \\ l \end{pmatrix}_{3:29} &= \begin{pmatrix} -2 & -2 & 1 \\ 1 & -1 & 0 \\ 1 & 1 & 2 \end{pmatrix} \begin{pmatrix} h \\ k \\ l \end{pmatrix}_{1:5} \\ \begin{pmatrix} h \\ k \\ l \end{pmatrix}_{3:29} &= \begin{pmatrix} 0 & 1/2 & 2 \\ 1 & 0 & 0 \\ 0 & 1 & -1 \end{pmatrix} \begin{pmatrix} h \\ k \\ l \end{pmatrix}_{1:12} \\ \begin{pmatrix} h \\ k \\ l \end{pmatrix}_{3:29} &= \begin{pmatrix} 2/3 & -2/3 & 1/2 \\ 1 & 1 & 0 \\ -1/3 & 1/3 & 1 \end{pmatrix} \begin{pmatrix} h \\ k \\ l \end{pmatrix}_{2:17H}.\end{aligned}\quad (6)$$

Therefore the coordinate transformation relationship of the 3:29 phase with the 1:5, 1:12 and 2:17H phases is represented by:

$$\begin{aligned}\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{3:29} &= \begin{pmatrix} 1/5 & -1/5 & 1/5 \\ 1/2 & -1/2 & 0 \\ 1/10 & 1/10 & 2/5 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{1:5} \\ \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{3:29} &= \begin{pmatrix} 0 & 2/5 & -2/5 \\ -1 & 0 & 0 \\ 0 & 4/5 & 1/5 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{1:12} \\ \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}_{3:29} &= \begin{pmatrix} -3/5 & 3/5 & 2/5 & -1/10 \\ -1/2 & -1/2 & 0 & 0 \\ 3/10 & -3/10 & 4/5 & -1/5 \\ 0 & 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}_{2:17H}.\end{aligned}\quad (7)$$

One can transform the atomic positions in the 1:12 and 2:17H structures into those of the 3:29 structure. The relationships between the lattice parameters of the 3:29 and the 1:5 structure are

$$\begin{aligned}a &= \sqrt{(2a_0)^2 + (c_0)^2} \\ b &= \sqrt{3}a_0 \\ c &= \sqrt{(a_0)^2 + (2c_0)^2} \\ \beta &= \tan^{-1}\left(\frac{2a_0}{c_0}\right) + \tan^{-1}\left(\frac{a_0}{2c_0}\right).\end{aligned}\quad (8)$$

Based on the above description, the structural relation between the 3:29 and the 1:5 structure can be plotted, as shown in figure 1. The indices of the 1:5 structure are described as  $(hktl)$  with  $h$ ,  $k$ , and  $t$  representing the three axes  $a_1$ ,  $a_2$  and  $a_3$  in the basal plane and  $l$  representing the  $z$  axis. The indices  $h$ ,  $k$  and  $t$  obey the equation  $h+k+t=0$ . The  $a$  and  $c$  axes of the 3:29 structure are in the  $(a_3, c)$  plane of the 1:5 structure, whereas the  $b$  axis of the 3:29 structure is in the  $(a_1, a_3)$  plane of the 1:5 structure. The 3:29 structure is built up from layers containing both R and Fe atoms (similar to the  $z=0$  layer of the 1:5 structure) and layers of only Fe atoms (with the same arrangement as in the  $z=1/2$  layer of the 1:5 structure) along the  $[102]_{1:5}$  direction. The main difference between the two structures concerns the mixed



Normally, ten generating matrices for the 32 crystal classes can be chosen as shown below:

$$\begin{aligned}
 \sigma^{(0)} = [1] &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} & \sigma^{(1)} = [\bar{1}] &= \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \\
 \sigma^{(2)} = [2_y] &= \begin{bmatrix} -1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} & \sigma^{(3)} = [2_z] &= \begin{bmatrix} -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 \sigma^{(4)} = [\bar{2}_y] &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 1 \end{bmatrix} & \sigma^{(5)} = [\bar{2}_z] &= \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -1 \end{bmatrix} \quad (11) \\
 \sigma^{(6)} = [3_z] &= \begin{bmatrix} -\frac{1}{2} & \frac{\sqrt{3}}{2} & 0 \\ -\frac{\sqrt{3}}{2} & -\frac{1}{2} & 0 \\ 0 & 0 & 1 \end{bmatrix} & \sigma^{(7)} = [4_z] &= \begin{bmatrix} 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \\
 \sigma^{(8)} = [\bar{4}_z] &= \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & -1 \end{bmatrix} & \sigma^{(9)} &= \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix}.
 \end{aligned}$$

For crystals with cubic, tetragonal and hexagonal structures, the magnetocrystalline anisotropy can be described in terms of anisotropy constants [18], as summarized in table 1. For the monoclinic structure, there will be three possibilities for the point group; with generating matrix of  $\sigma^{(3)}$  for the point group 2,  $\sigma^{(5)}$  for the point group  $m$ ,  $\sigma^{(1)}$  and  $\sigma^{(3)}$  for the point group  $2/m$  (see equation (11)). In the following, the forms of general polar tensors of second and fourth rank for this crystal symmetry are formulated. The non-zero components of these tensors may be written in compact form by using the notation of [17]:

$$\begin{aligned}
 b_{11} &= b_{11} \\
 b_{22} &= b_{22} \\
 B_2 : b_{33} &= b_{33} \quad (12)
 \end{aligned}$$

$$\begin{aligned}
 b_{12(2)} &= b_{12} \\
 b_{1111} &= b_{1111} \\
 b_{2222} &= b_{2222} \\
 b_{3333} &= b_{3333} \\
 b_{1112(4)} &= b_{2111} \\
 B_4 : b_{1222(4)} &= b_{2221} \quad (13) \\
 b_{1122(6)} &= b_{2211} \\
 b_{1133(6)} &= b_{3311} \\
 b_{2233(6)} &= b_{3322} \\
 b_{1233(12)} &= b_{3312}
 \end{aligned}$$

**Table 1.** Expressions for magnetocrystalline-anisotropy energy for various crystal systems.

Crystal class	International symbol of symmetry class	Magnetocrystalline-anisotropy energy
Triclinic [18]	1, $\bar{1}$	$K_1\alpha_1^2 + K_2\alpha_2^2 + K_3\alpha_3^2 + K_4\alpha_1\alpha_2 + K_5\alpha_2\alpha_3 + K_6\alpha_1\alpha_3 + \dots$
Monoclinic [this work]	2, $m$ , $2/m$	$K_1 \sin^2 \theta + K_2 \sin^2 \theta \cos 2\phi + K_3 \sin^2 \theta \sin 2\phi + K_4 \sin^4 \theta + K_5 \sin^4 \theta \cos 2\phi + K_6 \sin^4 \theta \sin 2\phi + K_7 \sin^4 \theta \cos 4\phi + K_8 \sin^4 \theta \sin 4\phi$
Orthorhombic [18]	222, $mm2$ , $mmm$	$\sin^2 \theta (K_1 \cos^2 \phi + K_2 \sin^2 \phi) + \sin^4 \theta (K_3 \cos 2\theta + K_4 \sin^2 \phi \cos^2 \phi + K_5 \sin^4 \phi) + \sin^2 \theta \cos^2 \theta (K_6 \cos^2 \phi + K_7 \sin^2 \phi)$
Cubic [18]	23, $m\bar{3}$ , 432, $\bar{4}3m$ , $m\bar{3}m$	$K_1(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2) + K_2\alpha_1^2\alpha_2^2\alpha_3^2 + K_3(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_1^2\alpha_3^2)^2$
Tetragonal [18]	4, $\bar{4}$ , $4/m$ , 422, $4mm$ , $\bar{4}2m$ , $4/mmm$	$K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + K_4 \sin^4 \theta \cos 4\phi$
Trigonal [18]	3, $\bar{3}$ , 32, $3m$ , $\bar{3}m$	$K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3^1 \sin^3 \theta \cos \theta \cos 3\phi + K_2^2 \sin^6 \theta \cos 6\phi + K_3 \sin^6 \theta + K_3^1 \sin^3 \theta \cos^3 \theta \cos 3\phi$
Hexagonal [18]	6, $\bar{6}$ , $6/m$ , 622, $6mm$ , $\bar{6}m2$ , $6/mmm$	$K_1 \sin^2 \theta + K_2 \sin^4 \theta + K_3 \sin^6 \theta + K_4 \sin^6 \theta \cos 6\phi$

where the notations of the type  $b_{1122}(6)$  denote the six components which may be obtained from the component '1122' by unrestricted permutations of its indices. It follows directly from equation (12) that

$$b_{ij}\alpha_i\alpha_j = b_{11}\alpha_1^2 + b_{22}\alpha_2^2 + b_{33}\alpha_3^2 + 2b_{12}\alpha_1\alpha_2. \quad (14)$$

Similarly, it follows from equation (13) that

$$b_{ijkl}\alpha_i\alpha_j\alpha_k\alpha_l = b_{1111}\alpha_1^4 + b_{2222}\alpha_2^4 + b_{3333}\alpha_3^4 + 4b_{1112}\alpha_1^3\alpha_2 + 4b_{1222}\alpha_1\alpha_2^3 + 6b_{1122}\alpha_1^2\alpha_2^2 + 6b_{1133}\alpha_1^2\alpha_3^2 + 6b_{2233}\alpha_2^2\alpha_3^2 + 12b_{1233}\alpha_1\alpha_2\alpha_3^2. \quad (15)$$

In the above expression, the factors 2, 4, 6 and 12 arise from the multiplicity implicit in the sets of relations of  $B_2$  and  $B_4$ .

Since the three direction cosines are connected by the equation  $\alpha_1^2 + \alpha_2^2 + \alpha_3^2 = 1$ , equation (9) may be rewritten as

$$\begin{aligned} E = & b_{33} + b_{3333} + \alpha_1^2(b_{11} + b_{33} - 2b_{3333} + 6b_{1133}) + \alpha_2^2(b_{22} - b_{33} - 2b_{3333} + 6b_{2233}) \\ & + \alpha_1\alpha_2(2b_{12} + 12b_{1233}) + \alpha_1^4(b_{1111} + b_{3333} - 6b_{1133}) \\ & + \alpha_2^4(b_{2222} + b_{3333} - 6b_{2233}) + \alpha_1^2\alpha_3^2(2b_{3333} + 6b_{1122} - 6b_{1133} - 6b_{2233}) \\ & + \alpha_1^3\alpha_2(4b_{1112} - 12b_{1233}) + \alpha_1\alpha_3^3(4b_{1222} - 12b_{1233}). \end{aligned} \quad (16)$$

If the  $c$ -axis is assumed to be the polar axis then the polar and azimuthal angles  $\theta$  and  $\phi$  are related to the direction cosines  $\alpha_i$  by the equations

$$\begin{aligned} \alpha_1 &= \sin \theta \cos \phi \\ \alpha_2 &= \sin \theta \sin \phi \\ \alpha_3 &= \cos \theta. \end{aligned} \quad (17)$$

Equation (16) can be rewritten, to fourth order in the  $\alpha_i$ , in the form

$$\begin{aligned} E = & K_0 + K_1 \sin^2 \theta + K_2 \sin^2 \theta \cos 2\phi + K_3 \sin^2 \theta \sin 2\phi + K_4 \sin^4 \theta + K_5 \sin^4 \theta \cos 2\phi \\ & + K_6 \sin^4 \theta \sin 2\phi + K_7 \sin^4 \theta \cos 4\phi + K_8 \sin^4 \theta \sin 4\phi \end{aligned} \quad (18)$$

with the anisotropy constants

$$\begin{aligned}
 K_0 &= b_{33} + b_{3333} \\
 K_1 &= \frac{1}{2}b_{11} + \frac{1}{2}b_{22} - b_{33} + b_{3333} + 3b_{1133} + 3b_{2233} - 2b_{3333} \\
 K_2 &= \frac{1}{2}b_{11} - \frac{1}{2}b_{22} + 3b_{1133} - 3b_{2233} \\
 K_3 &= b_{12} + 6b_{1233} \\
 K_4 &= \frac{3}{8}b_{1111} + \frac{3}{8}b_{2222} + b_{3333} + \frac{3}{4}b_{1122} - 3b_{1133} - 3b_{2233} \\
 K_5 &= \frac{1}{2}b_{1111} - \frac{1}{2}b_{2222} - 3b_{1133} + 3b_{2233} \\
 K_6 &= b_{1112} + b_{1222} - 6b_{1233} \\
 K_7 &= \frac{1}{8}b_{1111} + \frac{1}{8}b_{2222} - \frac{3}{4}b_{1122} \\
 K_8 &= \frac{1}{2}b_{1112} - \frac{1}{2}b_{1222}.
 \end{aligned} \tag{19}$$

Taking only the  $K_1$  term into account in equation (18),  $E$  is found to be a minimum or a maximum for [001], depending only on the sign of  $K_1$ . However, when all  $\sin^2 \theta$  terms with  $K_1$ ,  $K_2$  and  $K_3$  are taken into account, there will be eight preferential directions with a tilt angle of  $\pi/4$  with respect to the  $xy$  plane. This can be seen from the following anisotropy energy expressions for three directions derived from equation (18):

$$\begin{aligned}
 E_{100} &= K_0 + K_1 + K_2 \\
 E_{110} &= K_0 + K_1 + K_3 \\
 E_{001} &= K_0
 \end{aligned} \tag{20}$$

where the subscripts on the left-hand side refer to the direction of the magnetization.

It is easy to see that when we choose an angle  $\eta = \tan^{-1}(K_2/K_3)$  equation (18) can be changed to the form obtained by Courtois *et al* from the symmetry analysis [19, 20]:

$$\begin{aligned}
 E &= K_0 + K_1 \sin^2 \theta + K_2 \sqrt{K_2^2 + K_3^2} \sin^2 \theta \cos 2(\phi + \eta) + K_4 \sin^4 \theta + K_5 \sqrt{K_5^2 + K_6^2} \\
 &\quad \times \sin^4 \theta \cos 2(\phi + \eta) + K_7 \sqrt{K_7^2 + K_8^2} \sin^4 \theta \cos 4(\phi + \eta) + \dots
 \end{aligned} \tag{21}$$

The studies on the single crystal  $Y_3(Fe, V)_{29}$  have shown that the above anisotropy energy expression for the  $R_3(Fe, M)_{29}$ -type compounds can explain the magnetization curves along  $a_{1:5}$ ,  $b_{1:5}$  and  $c_{1:5}$  axes [19, 20]. More single crystals are needed for further study on the crystal structure and magnetocrystalline-anisotropy properties of the  $R_3(Fe, M)_{29}$ -type compounds.

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## References

- [1] Collocott J, Day R K, Dunlop J B and Davis R C 1992 *Proc. 7th Int. Symp. on Magnetic Anisotropy and Coercivity in Rare Earth Transition Metal Alloys (Canberra, 1992)* p 437
- [2] Ivanova G V, Shcherbakova Ye V, Belozherov Ye V, Yermolenko A S and Teytel Ye I 1990 *Phys. Met. Metall.* **70** 63
- [3] Shcherbakova Ye V, Ivanova G V, Yermolenko A S, Belozherov Ye V and Gaviko V S 1992 *J. Alloys Compounds* **182** 199



- [4] Li H S, Cadogan J M, Xu J M, Dou S X and Lin H K 1993 *Int. Conf. on Application of the Mössbauer Effect (Vancouver, 1993)* paper 15-29B
- [5] Hu Z and Yelon W B 1994 *J. Appl. Phys.* **76** 6147
- [6] Hu Z and Yelon W B 1994 *Solid State Commun.* **91** 223
- [7] Kalogirou O, Psycharis V, Saettas L and Niarchos D N 1995 *J. Magn. Magn. Mater.* **146** 335
- [8] Yang Fuming, Nasunjilegal B, Wang Jianli, Zhu Jiangjun, Qin Weidong, Tang N, Zhao Ruwen, Hu Bo-Ping, Wang Yi-Zhong and Li Hong-Shuo 1995 *J. Phys.: Condens. Matter* **7** 1679
- [9] Pan Hongge, Chen Changpin, Wang C S, Han Xiufeng and Yang Fuming 1997 *J. Magn. Magn. Mater.* **170** 331
- [10] Wang Yi-Zhong, Hu Bo-Ping, Liu Gui-Chuan, Li Hong-Shuo, Han Xiu-Feng and Yang Chang-Ping 1997 *J. Phys.: Condens. Matter* **9** 2787
- [11] Han Xiu-Feng, Yang F M, Pan H G, Wang Y G, Wang J L, Liu H L, Tang N, Zhao R W and Li H S 1997 *J. Appl. Phys.* **81** 7450
- [12] Han Xiu-Feng, Pan Hong-Ge, Liu Hong-Li, Yang Fu-Ming and Zheng Yi-Wei 1997 *Phys. Rev. B* **56** 8867
- [13] Johnson Q and Smith G S 1968 *Lawrence Radiation Laboratory Report UCRL-71094*
- [14] Pettifor D G 1989 *Physica B* **149** 3
- [15] Villars P 1985 *J. Less-Common Met.* **110** 11
- [16] de Boer F R, Boom R, Mattens W C M, Miedema A R and Niessen A K 1988 *Cohesion in Metals* (Amsterdam: North-Holland)
- [17] Birss R R 1964 *Symmetry and Magnetism* (Amsterdam: North-Holland)
- [18] Kalvius G M and Tebble R S (eds) 1979 *Experimental Magnetism* vol 1 (New York: Wiley)
- [19] Courtois D, Amako Y, Givord D, Cadogan J M and Li H-S 1998 *J. Magn. Magn. Mater.* **177** 995
- [20] Courtois D, Givord D, Lambert-Andron B, Bourgeat-Lami E, Amako Y, Li H-S and Cadogan J M 1998 *J. Magn. Magn. Mater.* **189** 173