

[Article ID] 1003- 6326(2002) 05- 0850- 04

# Phase diagram of R-Fe-Co pseudoternary system with $R \leq 33.3\%$ (mole fraction, $R = Sm_{0.5}Dy_{0.5}$ )<sup>①</sup>

WANG Bo-wen(王博文)<sup>1, 2, 3</sup>, LIU Wei-li(刘炜丽)<sup>2</sup>, FENG Wen-jiang(封文江)<sup>2</sup>,JIN Guang(金光)<sup>2</sup>, HAO Yan-ming(郝延明)<sup>1</sup>, LI Yang-xian(李养贤)<sup>1</sup>

(1. School of Electrical Engineering, Hebei University of Technology, Tianjin 300130, China;

2. Department of Materials Science and Engineering,

Shenyang Institute of Technology, Shenyang 110015, China;

3. International Center for Materials Physics, the Chinese Academy of Sciences, Shenyang 110015, China)

**[Abstract]** Phase equilibria of the R-Fe-Co pseudoternary system with  $R \leq 33.3\%$  (mole fraction,  $R = Sm_{0.5}Dy_{0.5}$ ) were determined in an isothermal section at 1 073 K and a vertical section of  $RFe_2-RCO_2$  by using OM, X-ray diffractometer, EPMA DTA techniques. There are seven intermetallic phases:  $(Sm, Dy)(Fe, Co)_2$ ,  $(Sm, Dy)(Fe, Co)_3$ ,  $(Sm, Dy)_6(Fe, Co)_{23}$ ,  $(Sm, Dy)_2(Fe, Co)_7$ ,  $(Sm, Dy)(Fe, Co)_5$ ,  $Th_2Ni_{17}$  type and  $Th_2Zn_{17}$  type  $(Sm, Dy)_2(Fe, Co)_{17}$ . The  $(Sm, Dy)_6(Fe, Co)_{23}$  phase dissolves 36% Co (mole fraction) at 1 073 K. However, the  $(Sm, Dy)_2(Fe, Co)_7$  phase in  $R_2(Fe_{1-x}Co_x)_7$  alloys dissolves about 19% Fe (mole fraction) at 1 073 K.

**[Key words]** rare earth-iron-cobalt; phase diagram; structure; compounds

**[CLC number]** TQ 343

**[Document code]** A

## 1 INTRODUCTION

The two successful families of rare earth cobalt permanent magnets produced commercially are  $SmCo_5$  and  $Sm_2Co_{17}$ . The  $SmCo_5$  magnets have been produced with very high intrinsic coercivity and the  $Sm_2Co_{17}$  magnets have the low temperature coefficient of remanence ( $-0.12\% \cdot ^\circ C$ )<sup>[1]</sup>. In recent years, the calculation of magnetic properties of  $SmCo_5/Co_{1-x}Fe_x$  composite multilayer has found that its energy product is about 520 kJ/m<sup>3</sup> (65 MGOe), which is almost twice the value for the hard phase<sup>[2]</sup>. The investigation of the structure and magnetostriction for  $(Sm, Pr)(Fe, Co)_2$ <sup>[3]</sup>,  $(Sm, Dy)(Fe, Co)_2$ <sup>[4]</sup> and  $(Dy, Pr)(Fe, Co)_2$ <sup>[5]</sup> alloys has found that substitution of Co for Fe can increase the Curie temperature and saturated magnetostriction,  $\lambda_{111}$ <sup>[3]</sup> and  $\lambda_{400}$ <sup>[4]</sup>. At the same time, addition of Dy to  $SmCo_5$  compound causes the temperature coefficient of remanence to be decreased<sup>[6]</sup>. In order to develop permanent magnetic rare earth-iron alloys and magnetostrictive materials, an investigation of the effect of partial substitution of Dy for Sm in the Sm-Co-Fe ternary system on the phase stability and phase relations is interesting, particularly in the Sm-impovertished portion.

The Sm-Co binary system contains  $SmCo_2$ ,  $SmCo_3$ ,  $Sm_2Co_7$ ,  $Sm_5Co_{19}$ ,  $SmCo_5$  and  $Sm_2Co_{17}$  phases with Sm  $\leq 33.3\%$  (mole fraction)<sup>[7, 8]</sup>. However, there is no  $Dy_5Co_{19}$  phase in the Dy-Co system<sup>[9]</sup>. The Sm-Fe system possesses  $SmFe_2$ ,  $SmFe_3$  and  $Sm_2Fe_{17}$

phases. Four phases,  $DyFe_2$ ,  $DyFe_3$ ,  $Dy_6Fe_{23}$ ,  $Dy_2Fe_{17}$ , exist in the Dy-Fe system<sup>[10]</sup>. Schneider et al<sup>[11]</sup> and Hening et al<sup>[12]</sup> reported the phase diagram of the Sm-Fe-Co ternary system and found five intermetallic phases,  $Sm(Fe, Co)_2$ ,  $Sm(Fe, Co)_3$ ,  $Sm_2(Fe, Co)_7$ ,  $Sm(Fe, Co)_5$  and  $Sm_2(Fe, Co)_{17}$  in the isothermal section at 1 073 K. The complete miscibility of Fe and Co for  $Sm(Fe, Co)_2$ ,  $Sm(Fe, Co)_3$ ,  $Sm_2(Fe, Co)_{17}$  phases is confirmed, but no  $Sm_5(Fe, Co)_{19}$  phase exists in the system<sup>[11, 12]</sup>. The phase diagram of the Dy-Co-Fe ternary system has not been published. In this paper, the phase diagram of R-Fe-Co pseudoternary system with  $R \leq 33.3\%$  (mole fraction,  $R = Sm_{0.5}Dy_{0.5}$ ) is investigated.

## 2 EXPERIMENTAL

The purity of the raw material was 99.9% for Sm, Dy, Co and 99.8% for Fe. Alloy specimens were prepared in a magnetically-controlled arc furnace under high purity argon. To compensate for evaporation losses of Sm during melting, 10% more of Sm was added in excess of the stoichiometric amount. The mass loss of each sample was controlled below 1%. 45 alloy buttons were prepared. The as-cast samples wrapped in Mo foil were sealed in silica tube filled with high purity argon. Specimens with  $R \geq 25\%$  (mole fraction) were homogenized at 1 073 K for 20 d and then quenched in water. Specimens with  $R \leq 22.2\%$  (mole fraction) were first homogenized at 1 273 K for 5 d and then at 1 073 K for 15 d. After

① [Foundation item] Project(59871030) supported by the National Natural Science Foundation of China, project(501027) supported by the Natural Science Foundation of Hebei Province, China and project supported by Education Commission of Hebei Province

[Received date] 2001-10-09; [Accepted date] 2002-01-23;

homogenizing, they were quenched in water.

Characterization of the specimens was performed using optical microscopy. The etchant used was 2% nital. Differential thermal analysis was done in an LCP-1-type high temperature differential thermal dilatometer under purified argon using alumina crucibles. X-ray diffraction analysis was carried out in a D/max-rA diffractometer equipped with a pyrolytic graphite monochromator. CuK $\alpha$  radiation was used and the specimens were ground to powders under ethanole. Electron probe microanalysis (EPMA) was performed in a Camebax-micro analyser.

### 3 RESULTS AND DISCUSSION

#### 3.1 Intermetallic phases

Based on the results of metallographic examination, X-ray diffraction analysis and EPMA, seven intermetallic phases were found: (Sm, Dy)(Fe, Co)<sub>2</sub>, (Sm, Dy)(Fe, Co)<sub>3</sub>, (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub>, (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub>, (Sm, Dy)(Fe, Co)<sub>5</sub>, Th<sub>2</sub>Ni<sub>17</sub>-type and Th<sub>2</sub>Zn<sub>17</sub>-type (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>17</sub>.

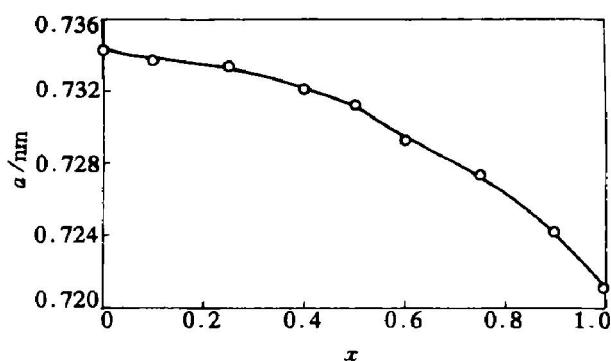
##### 1) (Sm, Dy)(Fe, Co)<sub>2</sub>

According to Sm-Fe and Dy-Fe systems, SmFe<sub>2</sub> and DyFe<sub>2</sub> phases are stable. X-ray diffraction analysis confirms that the (Sm, Dy)Fe<sub>2</sub> phase with MgCu<sub>2</sub>-type cubic structure exists in RFe<sub>2</sub> alloy. However, metallographic examination found that there is a small amount of second phase, which is confirmed as (Sm, Dy)Fe<sub>3</sub> by EPMA. This result implies that the homogeneity range of (Sm, Dy)Fe<sub>2</sub> phase is probably shifted slightly to the rare earth-rich side of the ideal stoichiometric ratio. Mei et al<sup>[13]</sup> investigated the (Tb<sub>0.3</sub>Dy<sub>0.7</sub>)-Fe vertical section and found that the (Tb, Dy)Fe<sub>2</sub> phase region obviously deviates from the stoichiometric Laves phase composition. Similar situation has been found in (Dy, Tb, Pr)Fe<sub>2</sub> compound<sup>[14]</sup>. When Co is substituted for Fe, the second phase (Sm, Dy)Fe<sub>3</sub> clearly decreases and R(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>2</sub> alloys are nearly a single (Sm, Dy)(Fe, Co)<sub>2</sub> phase in the range of 0.1  $\leq x \leq 1$ .

The composition dependence of the lattice parameter of the (Sm, Dy)(Fe, Co)<sub>2</sub> phase for R(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>2</sub> alloys is shown in Fig. 1. It decreases with increasing Co content in the range of 0  $\leq x \leq 1$ . The decrease in the lattice parameter is attributed to the small size of Co atom. This result is similar to that previously reported in Ref. [3] or Ref. [4].

##### 2) (Sm, Dy)(Fe, Co)<sub>3</sub>

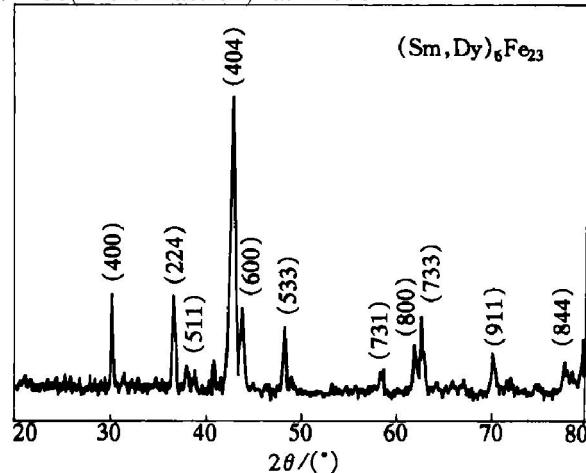
From Sm-Fe, Sm-Co, Dy-Fe and Dy-Co systems, SmFe<sub>3</sub>, SmCo<sub>3</sub>, DyFe<sub>3</sub> and DyCo<sub>3</sub> phases are stable. X-ray diffraction analysis confirms that the (Sm, Dy)-Fe<sub>3</sub> phase exists in RFe<sub>3</sub> alloy. When Co is substituted for Fe, R(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>3</sub> alloys are a single (Sm, Dy)-(Fe, Co)<sub>3</sub> phase with PuNi<sub>3</sub>-type structure up to  $x = 1$ .



**Fig. 1** Composition dependence of lattice parameter of (Sm, Dy)(Fe, Co)<sub>2</sub> phase in R(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>2</sub> alloys

##### 3) (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub>

Dy<sub>6</sub>Fe<sub>23</sub> phase is stable only in the Dy-Fe binary system and is of the Th<sub>6</sub>Mn<sub>23</sub>-type cubic structure. X-ray diffraction analysis found the (Sm, Dy)<sub>6</sub>Fe<sub>23</sub> phase in R<sub>6</sub>Fe<sub>23</sub> alloy is stable (Fig. 2). When Co is substituted for Fe, R<sub>6</sub>(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>23</sub> alloys are a single (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub> phase up to  $x = 0.45$ . The R<sub>6</sub>(Fe<sub>0.5</sub>Co<sub>0.5</sub>)<sub>23</sub> alloy consists of (Sm, Dy)(Fe, Co)<sub>3</sub> and (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub> phases as well as a small amount of (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>17</sub> phase. It seems that the (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub> phase dissolves 36% Co (mole fraction) at 1 073 K.

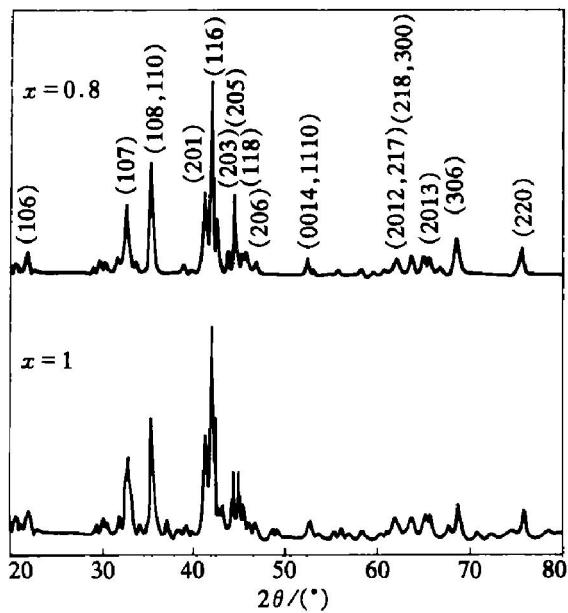


**Fig. 2** X-ray diffraction pattern of (Sm, Dy)<sub>6</sub>Fe<sub>23</sub> in R<sub>6</sub>Fe<sub>23</sub> alloy

##### 4) (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub>

The Sm<sub>2</sub>Co<sub>7</sub> and Dy<sub>2</sub>Co<sub>7</sub> phases are stable in the Sm-Co and Dy-Co systems, respectively, and are of a hexagonal Ce<sub>2</sub>Ni<sub>7</sub> structure. When Dy is substituted for Sm, the (Sm, Dy)<sub>2</sub>Co<sub>7</sub> phase in R<sub>2</sub>Co<sub>7</sub> alloy is stable in the R-Co system. When Fe is substituted for Co, the microstructure of R<sub>2</sub>(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>7</sub> alloys is nearly a single (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub> phase in the range of 0.75  $\leq x \leq 1$  (Fig. 3). The X-ray diffraction analysis and EPMA confirm that R<sub>2</sub>(Fe<sub>0.3</sub>Co<sub>0.7</sub>)<sub>7</sub> alloy consists of (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub> and (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>17</sub> as well as small amount of (Sm, Dy)(Fe, Co)<sub>5</sub>.

$\text{Co}_3$  phases. Ref. [11] reported that the  $\text{Sm}_2(\text{Fe}, \text{Co})_7$  phase in  $\text{Sm}-\text{Fe}-\text{Co}$  alloys dissolves less than 4% Fe(mole fraction) at 1 473 K and Fe is not found in the  $\text{Sm}_2(\text{Fe}, \text{Co})_7$  phase in the 95Co5Fe/Sm diffusion couple annealed at 1 073 K. It means that the substitution of Dy for Sm is beneficial to the formation of  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  phase in  $\text{R}_2(\text{Fe}_{1-x}\text{Co}_x)_7$  alloys. Therefore, the  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  phase in  $\text{R}_2(\text{Fe}_{1-x}\text{Co}_x)_7$  alloys dissolves about 19% Fe(mole fraction) at 1 073 K.



**Fig. 3** X-ray diffraction patterns of  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  in  $\text{R}_2(\text{Fe}_{1-x}\text{Co}_x)_7$  alloys

### 5) $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5$

The  $(\text{Sm}, \text{Dy})\text{Co}_5$  phase in  $\text{RCo}_5$  alloy is stable and is of a hexagonal  $\text{CaCu}_5$ -type structure. When Fe is substituted for Co, the microstructure of  $\text{R}(\text{Fe}_{1-x}\text{Co}_x)_5$  alloys is nearly a single phase in the range of  $0.9 \leq x \leq 1$ . However, the microstructure of  $\text{R}(\text{Fe}_{0.2}\text{Co}_{0.8})_5$  alloy consists of  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$  and a small amount of  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  phases. It means that the Fe solubility in  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5$  phase is nearly 8% at 1 073 K, which is similar to that reported in Ref. [11].

### 6) $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$

From the  $\text{Sm}-\text{Fe}$ ,  $\text{Sm}-\text{Co}$ ,  $\text{Dy}-\text{Fe}$  and  $\text{Dy}-\text{Co}$  systems, there are  $\text{Sm}_2\text{Fe}_{17}$ ,  $\text{Sm}_2\text{Co}_{17}$ ,  $\text{Dy}_2\text{Fe}_{17}$  and  $\text{Dy}_2\text{Co}_{17}$  phases. The  $(\text{Sm}, \text{Dy})_2\text{Fe}_{17}$  phase in  $\text{R}_2\text{Fe}_{17}$  alloy is stable and is of an hexagonal  $\text{Th}_2\text{Ni}_{17}$ -type structure. This result is different from that of  $\text{Sm}_2\text{Fe}_{17}$  or  $(\text{Sm}, \text{Pr})_2\text{Fe}_{17}$ <sup>[15]</sup>, which is of rhombohedral  $\text{Th}_2\text{Zn}_{17}$ -type structure. It seems that the substitution of Dy for Sm is beneficial to forming the phase with the  $\text{Th}_2\text{Ni}_{17}$ -type structure. When Co is substituted for Fe, the  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$  phase with the  $\text{Th}_2\text{Ni}_{17}$ -type structure in  $\text{R}_2(\text{Fe}_{1-x}\text{Co}_x)_7$  alloys is stable when  $x \leq 0.2$ . However, the  $(\text{Sm},$

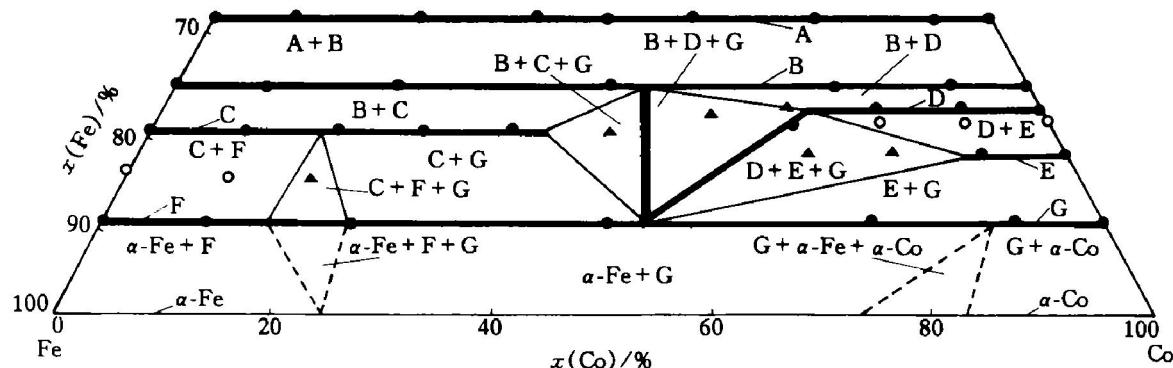
$\text{Dy})_2(\text{Fe}, \text{Co})_{17}$  phase possesses the  $\text{Th}_2\text{Zn}_{17}$ -type structure when  $x > 0.3$ . Both the  $\text{Th}_2\text{Ni}_{17}$ -type and  $\text{Th}_2\text{Zn}_{17}$ -type structures coexist in the range of  $0.2 \leq x < 0.3$ .

### 3.2 Isothermal section at 1 073 K

The 1 073 K isothermal section of the  $\text{R}-\text{Fe}-\text{Co}$  pseudoternary system with  $R \leq 33.3\%$  (mole fraction) is shown in Fig. 4. This isothermal section consists of nine single-phase regions:  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_2$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3$ ,  $(\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5$ ,  $\text{Th}_2\text{Ni}_{17}$ -type and  $\text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $\alpha$ -Fe and  $\alpha$ -Co; 14 two-phase regions:  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_2 + (\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3 + (\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23}$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3 + (\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7 + (\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3 + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5 + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23} + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \text{Th}_2\text{Ni}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \text{Th}_2\text{Ni}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \alpha$ -Fe,  $\text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \alpha$ -Fe,  $\text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \alpha$ -Co and  $\alpha$ -Fe +  $\alpha$ -Co; and six three-phase regions:  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3 + (\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23} + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_3 + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + (\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7 + (\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_5 + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23} + \text{Th}_2\text{Ni}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17}$ ,  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \alpha$ -Fe and  $\text{Th}_2\text{Zn}_{17}$ -type  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_{17} + \alpha$ -Fe +  $\alpha$ -Co. Compared with the  $\text{Sm}-\text{Fe}-\text{Co}$  ternary system reported in Ref. [11], the isothermal section of  $\text{R}-\text{Fe}-\text{Co}$  pseudoternary system with  $R \leq 33.3\%$  (mole fraction) contains  $(\text{Sm}, \text{Dy})_6(\text{Fe}, \text{Co})_{23}$  phase, and the homogeneity range of  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  phase for the  $\text{R}-\text{Fe}-\text{Co}$  system is larger than that of  $\text{Sm}_2(\text{Fe}, \text{Co})_7$  phase for the  $\text{Sm}-\text{Fe}-\text{Co}$  system.

### 3.3 Vertical section of $\text{RFe}_2-\text{RCO}_2$

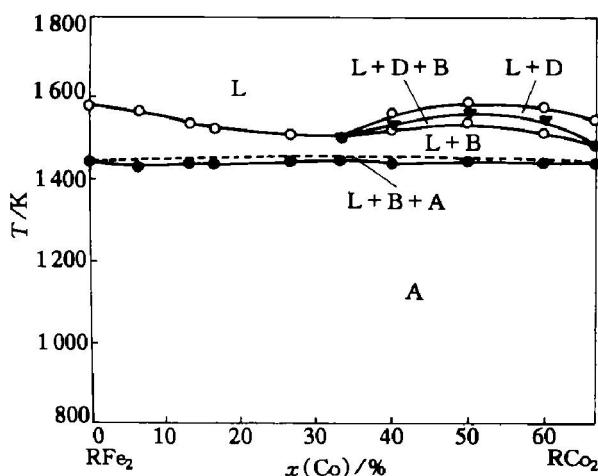
Based on the results of DTA, OM and XRD, a vertical section of  $\text{RFe}_2-\text{RCO}_2$  in  $\text{R}-\text{Fe}-\text{Co}$  pseudoternary system is tentatively drawn in Fig. 5. It consists of two single-phase regions: L and  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_2$ ; two two-phase regions: L +  $(\text{Sm}, \text{Dy})(\text{Fe}, \text{Co})_2$  and L +  $(\text{Sm}, \text{Dy})_2(\text{Fe}, \text{Co})_7$  and two three-



**Fig. 4** Isothermal section of R-Fe-Co pseudoternary system with  $R \leq 33.3\%$  (mole fraction) at 1073 K

A= (Sm, Dy)(Fe, Co)<sub>2</sub>; B= (Sm, Dy)(Fe, Co)<sub>3</sub>; C= (Sm, Dy)<sub>6</sub>(Fe, Co)<sub>23</sub>; D= (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub>; E= (Sm, Dy)(Fe, Co)<sub>5</sub>; F= Th<sub>2</sub>Ni<sub>17</sub> type (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>17</sub>; G= Th<sub>2</sub>Zn<sub>17</sub> type (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>17</sub>

●—Single phase region; ○—Two phase region; ▲—Three phase region



**Fig. 5** Vertical section of RFe<sub>2</sub>-RCO<sub>2</sub> in R-Fe-Co pseudoternary system

A= (Sm, Dy)(Fe, Co)<sub>2</sub>; B= (Sm, Dy)(Fe, Co)<sub>3</sub>; C= (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub>

phase regions: L+ (Sm, Dy)(Fe, Co)<sub>3</sub>+ (Sm, Dy)<sub>2</sub>(Fe, Co)<sub>7</sub> and L+ (Sm, Dy)(Fe, Co)<sub>2</sub>+ (Sm, Dy)(Fe, Co)<sub>3</sub>.

## [ REFERENCES]

- [1] Leupold H A, Potenza E, Tauber A, et al. High coercivity 2:17 cobalt rare earth magnets [J]. *J Appl Phys*, 1984, 55(6): 2097– 2099.
- [2] Sabiryanov R F, Jaswal S S. Magnetic properties of hard/soft composites: SmCo<sub>5</sub>/Co<sub>1-x</sub>Fe<sub>x</sub> [J]. *Phys Rev B*, 1998, 58(18): 12071– 12074.
- [3] GUO Z J, ZHANG Z D, WANG B W, et al. Giant magnetostriiction and spin reorientation in quaternary (Sm<sub>0.9</sub>Pr<sub>0.1</sub>)(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>2</sub> [J]. *Phys Rev B*, 2000, 61(5): 3519– 3523.
- [4] GUO Huiqun, GONG Hua-ying, YANG Hong-ying, et al. Effect of Co substitution for Fe on magnetic and magnetostrictive properties in Sm<sub>0.88</sub>Dy<sub>0.12</sub>(Fe<sub>1-x</sub>Co<sub>x</sub>)<sub>2</sub> compounds [J]. *Phys Rev B*, 1996, 54(6): 4107– 4112.
- [5] WANG Bowen, GUO Zhijun, ZHANG Zhidong, et al. Structure and magnetostriction of (Pr<sub>x</sub>Dy<sub>1-x</sub>)Fe<sub>2</sub> and (Pr<sub>0.4</sub>Dy<sub>0.6</sub>)(Fe<sub>1-x</sub>M<sub>x</sub>)<sub>2</sub> (M = Co, Ni) alloys [J]. *J Appl Phys*, 1999, 85(5): 2805– 2809.
- [6] Velu E M T, Obermyer R T, Sankar S G, et al. Temperature compensated Pr<sub>1-x-y</sub>Sm<sub>x</sub>RyCo<sub>5-y</sub> permanent magnets (R = Er, Dy, Ho, Gd, and Tb; x = 0.24; y = 0.2, 0.3, and 0.4) [J]. *J Appl Phys*, 1990, 67(9): 4662– 4664.
- [7] Cataldo L, Lefevre A, Ducret F, et al. Binary system Sm-Co: revision of the phase diagram in the Co rich field [J]. *J Alloys and Compounds*, 1996, 241: 216– 223.
- [8] GE W Q, WU C H, CHUANG Y C. Reinvestigation of the Sm-Co binary system [J]. *Z Metallkd*, 1993, 84: 165– 169.
- [9] Massalski Thaddeus B. *Binary Alloy Phase Diagrams* [M]. Metals Park: American Society for Metals, 1990.
- [10] van der Goot A S, Buschow K H J. The dysprosium-iron system: structural and magnetic properties of dysprosium iron compounds [J]. *J Less-Common Met*, 1970, 21: 151– 157.
- [11] Schneider G, Henig E -Th, Lukas H L, et al. Phase relations in the samarium-poor Sm-Co-Fe system [J]. *J Less-Common Met*, 1985, 110: 159– 170.
- [12] Hening E -Th, Grieb B. Phase diagrams for permanent magnet materials [A]. Long Gary J, Grandjean Fernande. *Supermagnets, Hard Magnetic Materials* [C]. London: Kluwer Academic Publishers, 1990, 171– 126.
- [13] MEI Wu, Okane Toshimitsu, Umeda Takateru. Phase diagram and inhomogeneity of (TbDy)-Fe(T) (T = Mn, Co, Al, Ti) systems [J]. *J Alloys and Compounds*, 1997, 248: 132– 138.
- [14] Wang B W, Wu C H, Chuang Y C, et al. Study of R-Fe pseudobinary system in Laves phase region (R = Dy<sub>0.65</sub>Tb<sub>0.25</sub>Pr<sub>0.1</sub>) [J]. *J Mater Sci Tech*, 1996, 12: 119– 122.
- [15] Wang B W, Li Y X, Hao Y M, et al. Isoplethic section in the quaternary system Fe-Co-Sm-Pr at 800 °C with Sm/Pr = 1 and R ≤ 33.3% (R = Sm<sub>0.5</sub>Pr<sub>0.5</sub>) [J]. *J Alloys and Compounds*, 2001, 319: 214– 217.

(Edited by HUANG Jin-song)