Magnetic properties of $R_3(Fe,Ti)_{29}C_y$ carbides (R=Nd, Sm)

LETTER TO THE EDITOR

Magnetic properties of $R_3(Fe, Ti)_{29}C_y$ carbides (R = Nd, Sm)

Bo-Ping Hu†, Gui-Chuan Liu†, Yi-Zhong Wang†, B Nasunjilegal‡, Ning Tang‡, Fu-Ming Yang‡, Hong-Shuo Li§ and J M Cadogan§

† San Huan Research Laboratory, Chinese Academy of Sciences, PO Box 603, Beijing 100080, People's Republic of China
‡ Magnetism Laboratory, Institute of Physics, Chinese Academy of Sciences, PO Box 603, Beijing 100080, People's Republic of China
§ School of Physics, University of New South Wales, Kensington, Australia 2033

Abstract. $R_3(Fe, Ti)_{29}C_y$ carbides (R = Nd, Sm) have been synthesized by gas–solid phase reaction. The Curie temperature is enhanced by carbonation, with values of 651 K and 641 K for Nd and Sm carbides respectively. The saturation magnetization of the carbides is slightly lower than that of their parent alloys. The Sm carbide has a large uniaxial anisotropy field, 21 T at 4.2 K and 14 T at 293 K. A coercivity of $\mu_{0i}H_c = 0.3$ T at room temperature in the Sm carbide has been developed.

In recent years, researchers in the field of permanent magnet materials have paid much attention to the new type rare-earth iron intermetallic compounds $R_3(Fe, M)_{29}$ (M = Ti, V, Cr, Mn) and their nitrides [1–9]. Among them, the $Sm(Fe, M)_{29}N_y$ nitrides (M = Ti, V) have excellent magnetic properties with high room temperature saturation magnetization (~ 1.3 T) and large anisotropy field (13 T) [3, 7] and are potential candidates for permanent magnet applications. A coercivity of $\mu_{0i}H_c = 0.83$ T in $Sm(Fe, Ti)_{29}N_y$ at room temperature has been achieved [8]. In the present work, we synthesized the $R_3(Fe, Ti)_{29}C_y$ carbides (R = Sm, Nd) and studied their magnetic properties.

Alloys of $Nd_3(Fe_{0.95}Ti_{0.05})_{29}$ and $Sm_3(Fe_{0.933}Ti_{0.067})_{29}$ were prepared by arc melting, subsequently followed by annealing in vacuum at temperatures of 1273–1473 K for 10–60 h, then quenching in water. The ingots were ground into fine powder with an average particle size of about 30 μm. The gas-phase reaction between the alloy powders and acetylene was investigated by a thermopiezic analyser (TPA) [10]. The carbonation conditions used were under a pressure of about 1 bar and at temperatures of 500–540 °C for 3–4 h. In order to avoid the hydrogen being absorbed into the sample, the sample space was pumped before cooling. The phase composition and purity of the samples were identified by x-ray diffraction and thermomagnetic scan at a magnetic field of 0.08 T. The latter measurement was also used to determine the Curie temperature. Magnetization values were derived from the magnetization curves in fields up to 6 T by an extracting sample magnetometer. Anisotropy field values were derived from the magnetization curves parallel and perpendicular to the aligned direction in the field up to 6 T and 10 T of an aligned sample $Sm_3(Fe, Ti)_{29}C_y$ by an extracting sample magnetometer and a pulsed field system.

X-ray diffraction patterns show that the $R_3(Fe, Ti)_{29}C_y$ carbides are single phase with the same structure as that of the parent compounds, except for a little α-Fe inside. Figures 1(a) and (b) show the x-ray diffraction patterns for the Sm alloy and its carbide respectively. The
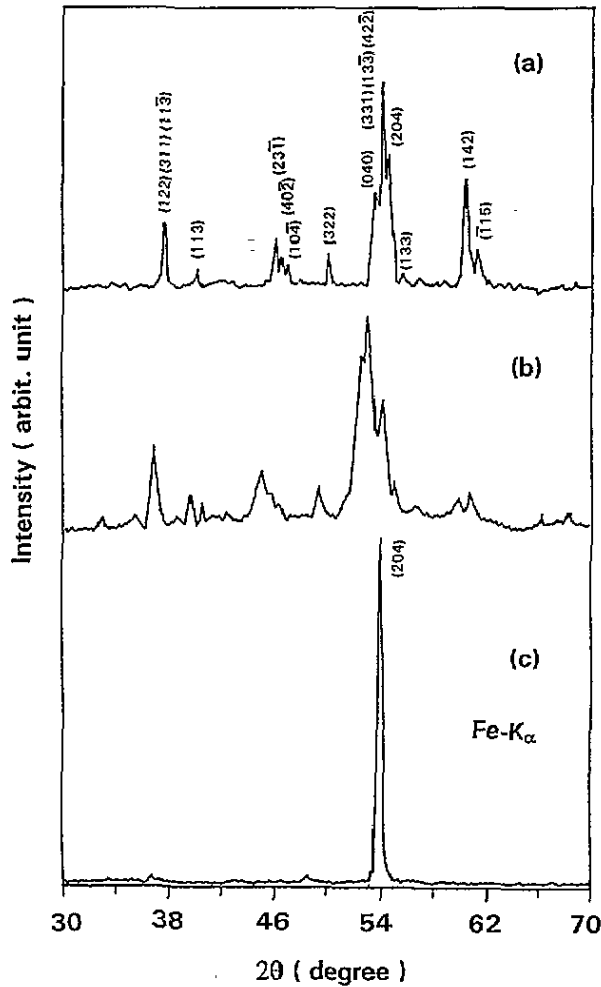
Figure 1. X-ray diffraction patterns of: (*a*) the parent alloy $Sm_3(Fe_{0.933}Ti_{0.067})_{29}$; (*b*) the carbide $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$; (*c*) the aligned carbide sample.

lattice parameters of the carbides are listed in table 1, together with the data of magnetic properties. After carbonation the relative volume expansion $\Delta V/V$ is about 5%, which is smaller than that for the corresponding 3:29 nitrides [1, 7] and that for the 2:17 carbides [11] and nitrides [12].

Table 1. Structural and magnetic properties of $Nd_3(Fe_{0.95}Ti_{0.05})_{29}C_y$ and $Sm_3(Fe_{0.933}Ti_{0.067})_{29}$ C_y compared with their parent compounds.

Compound	a (nm)	b (nm)	c (nm)	β (°)	$\Delta V/V$ (%)	T_c (K)	M_S (J T^{-1} kg^{-1}) 1.5 K	293 K	B_a (T) 1.5 K	293 K
Nd	1.066	0.8571	0.9753	97.85		435	152	124	—	—
Nd+C	1.069	0.8900	0.9860	97.40	5.2	651	142	133	—	—
Sm	1.065	0.8580	0.9720	96.98		486	130	113	—	—
Sm+C	1.089	0.8730	0.9850	97.40	5.1	641	109	97	21	14

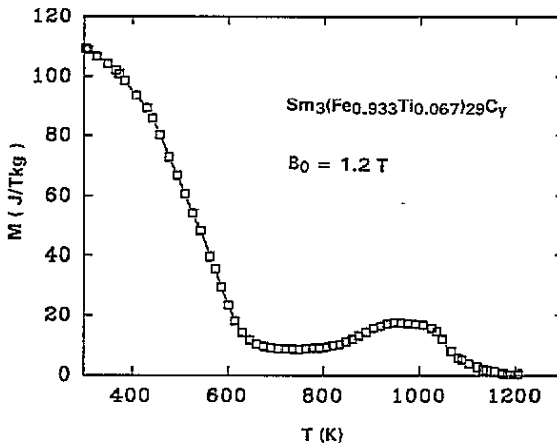**Figure 2.** Thermomagnetic scan curve on $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ in a field of 1.2 T.

The enhancement of the Curie temperature, T_C, by the effect of the interstitial carbon is 216 K for $Nd_3(Fe_{0.95}Ti_{0.05})_{29}C_y$ and 155 K for $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ respectively (see table 1). These values are lower than those for $Nd_3(Fe, Ti)_{29}N_y$ (240 K) [1] and $Sm_3(Fe_{0.933}Ti_{0.067})_{29}N_y$ (264 K) [7]. Figure 2 shows a typical thermomagnetic scan on $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ in an applied field of 1.2 T, performed on a magnetic balance. It can be seen that the 3:29 carbide starts to decompose at a temperature of about 600 °C, which is similar to 2:17 nitrides [13] and carbides [11]. $T_C = 641$ K and $\Delta V/V = 5\%$ for $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ compared with $T_C = 670$ K and $\Delta V/V = 6\%$ for $Sm_2Fe_{17}C_2$ which might indicate that the carbon concentration y in the former is less than 3, while it was found that y is about 5 in $Sm_3(Fe_{0.933}Ti_{0.067})_{29}N_y$ [7].
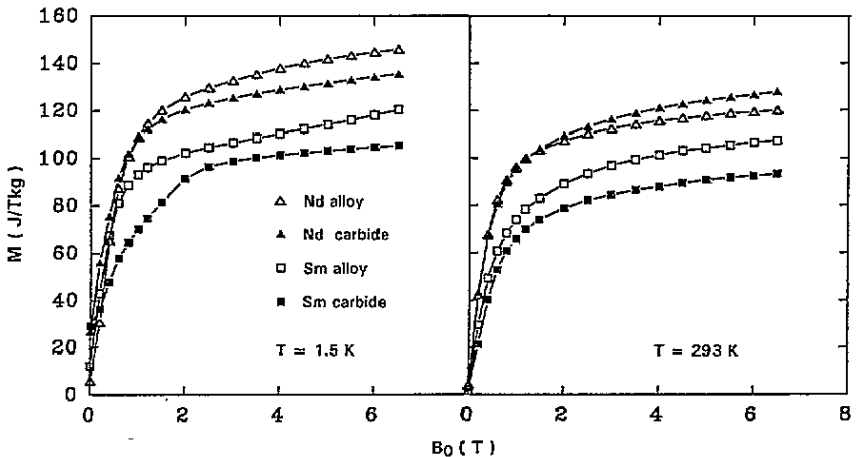

Figure 3. Magnetization curves at 1.5 K and 293 K for $Nd_3(Fe_{0.95}Ti_{0.05})_{29}$ and $Sm_3(Fe_{0.933}Ti_{0.067})_{29}$ and their carbides.

Figure 3 shows the magnetization curves at 1.5 K and 293 K for $Nd_3(Fe_{0.95}Ti_{0.05})_{29}$ and $Sm_3(Fe_{0.933}Ti_{0.067})_{29}$, and their carbides. The saturation magnetization M_s values are listed in table 1. At 1.5 K, the M_s values of both the carbides are lower than those of their parent
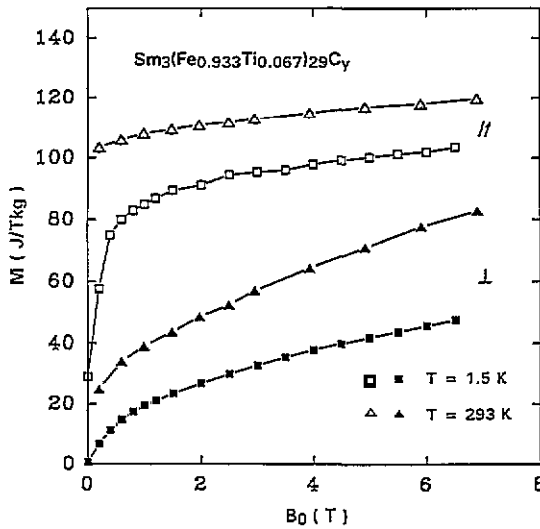
Figure 4. Magnetization curves in an applied field parallel and perpendicular to the aligned direction on an oriented $Sm_2(Fe_{0.933}Ti_{0.067})_{29}C_y$ sample at 1.5 K and 293 K respectively.

compounds, which is different from the case of the 3:29 nitrides [7]. It has previously been found that the interstitial carbon does not increase the magnetization [11, 14].

The x-ray diffraction from the aligned sample (figure 1(c)) shows that the (204) line for $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ is dominant, which is different from its parent compound where the (402) line is dominant. The easy magnetization direction along [102] for $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ corresponds to the [001] direction in the superstructure of $CaCu_5$ type. Figure 4 shows the magnetization curves measured on the aligned powder sample parallel and perpendicular to the aligned direction at 1.5 K and 293 K. By plotting $\Delta M = M_\| - M_\perp$ versus B_0 and linearly extrapolating ΔM to zero, we obtained the values of the anisotropy field. The anisotropy fields of $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ carbide $B_a = 21$ T at 1.5 K and $B_a = 14$ T at 293 K are slightly higher than those of $Sm_3(Fe_{0.933}Ti_{0.067})_{29}N_y$ nitride [7], but are close to those of $Sm_2Fe_{17}C_y$ nitride [11]. Experimental data showed that the $Nd_3(Fe_{0.95}Ti_{0.05})_{29}C_y$ carbide has planar anisotropy.

The hard magnetic properties of the new interstitial carbide $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ have been investigated. As an initial result, an intrinsic coercivity of $\mu_{0i}H_c = 0.3$ T has been achieved at room temperature.

In conclusion, the carbides $R_3(Fe, Ti)_{29}C_y$ (R = Nd, Sm) prepared by gas–solid phase reaction have been synthesized. The new $Sm_3(Fe_{0.933}Ti_{0.067})_{29}C_y$ carbide with $Nd_3(Fe, Ti)_{29}$-type structure has good intrinsic magnetic properties close to $Sm_2Fe_{17}C_y$ carbide with Th_2Zn_{17}-type structure [11], especially the high Curie temperature and large room temperature anisotropy field. So the 3:29 phase of Sm–Fe–Ti carbide may be a promising candidate for permanent magnet applications.

References

[1] Collocott S J, Day R K, Dunlop J B and Davis R L 1992 *Proc. 7th Int. Symp. on Magnetic Anisotropy and Coercivity in Rare-Earth Transition Metal Alloys (Canberra, 1992)* pp 437–44
[2] Ivanova G V, Shcherbakova Ye V, Belozerov 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, Belozerov Ye V and Gaviko V S 1992 *J. Alloys Compounds* **182** 199

[4] Furest C D, Pinkerton P E and Herbst J F 1994 *J. Magn. Magn. Mater.* **129** L115

[5] Yang Fu-Ming, Nasunjilegal B, Pan Hua-Yong, Wang Jian-Li, Zhao Ru-Wen, Hu Bo-Ping, Wang Yi-Zhong, Li Hong-Shuo and Cadogan J M 1994 *J. Magn. Magn. Mater.* at press

[6] Cadogan J M, Li Hong-Shuo, Davis R L, Margarian A, Collocott S J, Dunlop J B and Gwan P B 1994 *J. Appl. Phys.* **75** 7114

[7] Yang Fu-Ming, Nasunjilegal B, Wang Jian-Li, Pan Hua-Yong, Qing Wei-Dong, Zhao Ru-Wen, Hu Bo-Ping, Wang Yi-Zhong, Li Hong-Shuo and Cadogan J M 1994 *J. Appl. Phys.* at press

[8] Hu Bo-Ping, Liu Gui-Chuan, Wang Yi-Zhong, Nasunjilegal B, Zhao Ru-Wen, Yang Fu-Ming, Li Hong-Shuo and Cadogan J M 1994 *J. Phys.: Condens. Matter* **6** L197

[9] Li Hong-Shuo, Cadogan J M, Davis R L, Margarian A and Dunlop J B 1994 *Solid State Commun.* **90** 487

[10] Ryan D H and Coey J M D 1986 *J. Phys. E: Sci. Instrum.* **19** 693

[11] Hu Bo-Ping and Liu Gui-Chuan 1991 *Solid State Commun.* **79** 785

[12] Sun Hong, Coey J M D, Otani Y and Hurley D P F 1990 *J. Phys.: Condens. Matter* **2** 6465

[13] Hu Bo-Ping, Rao Xiao-Lei, Xu Jian-Min, Liu Gui-Chuan, Wang Yi-Zhong, Dong Xiao-Lin, Zhang Deng-Xia and Cai Ming 1993 *J. Appl. Phys.* **74** 489

[14] Zhong X P, Radwanski R J, De Boer F R, Jacobs J H and Buschow K H J 1990 *J. Magn. Magn. Mater.* **86** 333