

Strong Pressure Effect on the Curie Temperature of Itinerant-Electron Metamagnetic $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$

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The initial pressure shift of the Curie temperature T_c for the first-order transition, dT_c/dP , for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ becomes small after hydrogen absorption. In addition, the hydrogen absorption reduces the ratio of the volume change at T_c to the magnetization squared at T_c , $\Delta\omega(T_c)/M(T_c)^2$, suggesting the decrease of the magnetoelastic coupling constant κC_{mv} . On the other hand, dT_c/dP is enhanced by the partial substitution of Ce for La in connection with the change of the band structure. Consequently, dT_c/dP of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ is larger than that of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ in a wide change of T_c . [doi:10.2320/matertrans.MBW200822]

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1. Introduction

$\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}$ compounds with $0.86 \leq x \leq 0.90$ exhibit the thermal-induced first-order transition between the paramagnetic (P) and the ferromagnetic (F) states at the Curie temperature T_c .¹ By applying magnetic field, the itinerant-electron metamagnetic (IEM) transition, that is, the first-order transition to the F state takes place above T_c .¹ A cubic NaZn_{13} -type structure of the $Fm\bar{3}c$ space group is kept after undergoing the thermal-induced first-order transition^{2,3} and the IEM transition.⁴ In addition, the unit cell volume in the F state is larger than that of the P state because in a large spontaneous volume magnetostriction associated with the local magnetic moment.²⁻⁴ Therefore, T_c is significantly decreased by applying hydrostatic pressure.³ The critical temperature T_0 of the disappearance of the IEM transition also decreases with increasing pressure.⁵ The pressure effect on T_0 is smaller than that on T_c , and hence the temperature difference, $T_c - T_0$, increases with increasing pressure.⁵ A close interplay between magnetism and volume, namely, the large magnetovolume effects in $\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}$ have been explained in terms of band structure and spin fluctuation based on the Landau-Ginzburg model for the IEM transition.^{3,5-7}

The unit cell volume of $\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}$ is isotropically expanded, and T_c is increased up to about 330 K by hydrogen absorption.^{8,9} The both temperatures of T_c and T_0 increase, while the value of $T_0 - T_c$ decreases.¹⁰ In contrast, the unit cell volume is decreased by the partial substitution of Ce for La, because the ionic radius of Ce is smaller than that of La due to the lanthanide contraction.^{11,12} In this case, the temperatures of T_c and T_0 are decreased and the value of $T_0 - T_c$ is increased.¹³ Therefore, the volume dependence of T_c and T_0 for $\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}\text{H}_y$ and $\text{La}_{1-z}\text{Ce}_z(\text{Fe}_x\text{Si}_{1-x})_{13}$ is qualitatively consistent with that of $\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}$ under hydrostatic pressure. However, it has been pointed out that the IEM transition of $\text{La}(\text{Fe}_x\text{Si}_{1-x})_{13}$ under hydrostatic pressure is different from that of $\text{La}_{1-z}\text{Ce}_z(\text{Fe}_x\text{Si}_{1-x})_{13}$ having a similar value of T_c .^{14,15}

In the present paper, to discuss the difference between the influence of the hydrogen absorption and the partial

substitution of Ce, the pressure effect on T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ having a similar value of T_c is investigated.

2. Experiments

The $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ compounds were prepared by arc-melting in an argon gas atmosphere and the heat-treatments were carried out in an evacuated quartz tube. The annealing temperatures of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ were 1423 and 1323 K, respectively. The annealing duration was 10 days. The hydrogen absorption was carried out by annealing under a hydrogen gas atmosphere. In order to control the hydrogen content, the annealing temperature and the hydrogen gas pressure were changed. The powder x-ray diffractions were carried out by using $\text{Cu K}\alpha$ radiation. The magnetization was measured with a SQUID magnetometer. The hydrostatic pressure was applied by using a nonmagnetic Cu-Ti clamp cell. The applied pressures were calibrated by measuring the shift of the superconducting transition temperature of Pb.

3. Results and Discussion

Figure 1 depicts the thermomagnetization curve in the heating process under a magnetic field of 1 T for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$. The Curie temperature $T_c = 175$ K of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ is increased up to about 320 K by hydrogen absorption. Since the magnetization decreases rapidly in the vicinity of T_c with increasing temperature, the thermal-induced first-order transition at T_c remains after hydrogen absorption. The inset represents the powder x-ray diffraction patterns of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$ and $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ at room temperature. The several vertical short bars below the diffraction patterns are the positions of all the possible Bragg reflections from a cubic NaZn_{13} -type structure with the $Fm\bar{3}c$ space group. The diffraction patterns of all the specimens are identified as the cubic NaZn_{13} -type structure. The diffraction peaks shift to the lower angle region after hydrogen

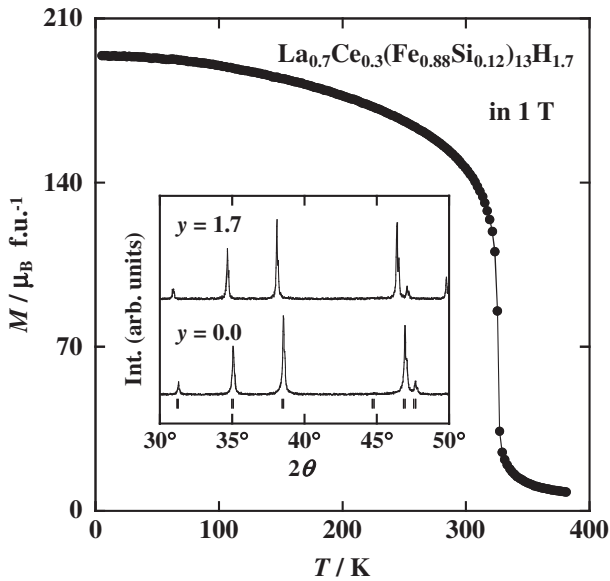


Fig. 1 Thermomagnetization curve in the heating process under a magnetic field of 1 T for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$. The inset shows powder x-ray diffraction patterns of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ with $y = 0.0$ and 1.7. The several vertical short bars below the diffraction patterns stand for the positions of all the possible Bragg reflections from a cubic NaZn_{13} -type structure with the $Fm\bar{3}c$ space group.

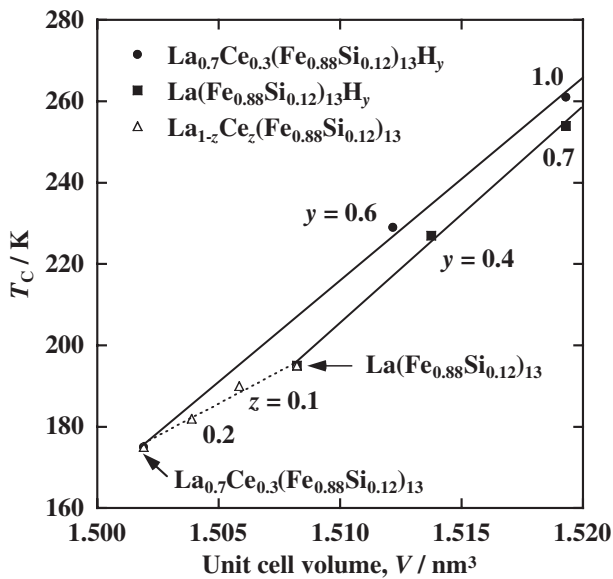


Fig. 2 The Curie temperature T_c as a function of the unit cell volume for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$, together with that of $\text{La}_{1-z}\text{Ce}_z(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$.¹²⁾

absorption, showing an isotropic expansion of the unit cell volume. Such volume expansion is caused by not only the invasion of hydrogen atom but also the spontaneous volume magnetostriction, because $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$ is in the ferromagnetic state at room temperature.

Figure 2 represents T_c as a function of the unit cell volume at room temperature for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$, together with that of $\text{La}_{1-z}\text{Ce}_z(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$.¹²⁾ To discuss the relation between the unit cell volume and T_c without the contribution from the large spontaneous volume magnetostriction, the data on the speci-

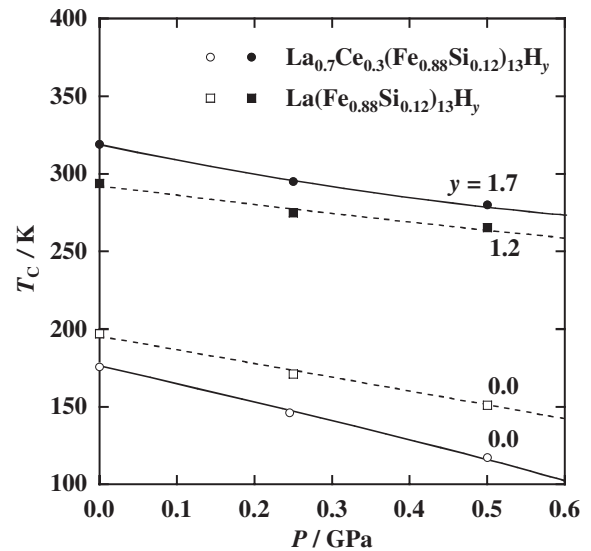


Fig. 3 Pressure shift of the Curie temperature T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$, $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$, $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.2}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$.³⁾

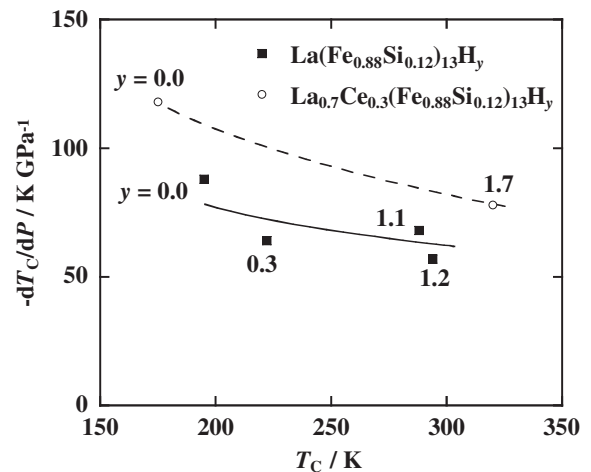


Fig. 4 Relationship between the Curie temperature T_c and the initial pressure shift dT_c/dP for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$.

men with $T_c < 273$ K are plotted. The value of T_c increases with increasing y and decreases with increasing z . The slope of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ is quite similar to that of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$. However, T_c of the former is slightly higher than that of the latter at the same volume. In addition the volume dependence of T_c for the two compound systems mentioned above is stronger than that of $\text{La}_{1-z}\text{Ce}_z(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$.

Figure 3 depicts the pressure shift of T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$ and $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$. For comparison, the data of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.2}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ ³⁾ are also plotted in the same figure. Shown in Fig. 4 is the relationship between T_c and dT_c/dP for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$. The value of dT_c/dP was estimated from the initial pressure shift of T_c shown in Fig. 3. The pressure shift of T_c for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ is increased by the partial substitution of Ce, whereas it is decreased by hydrogen absorption.

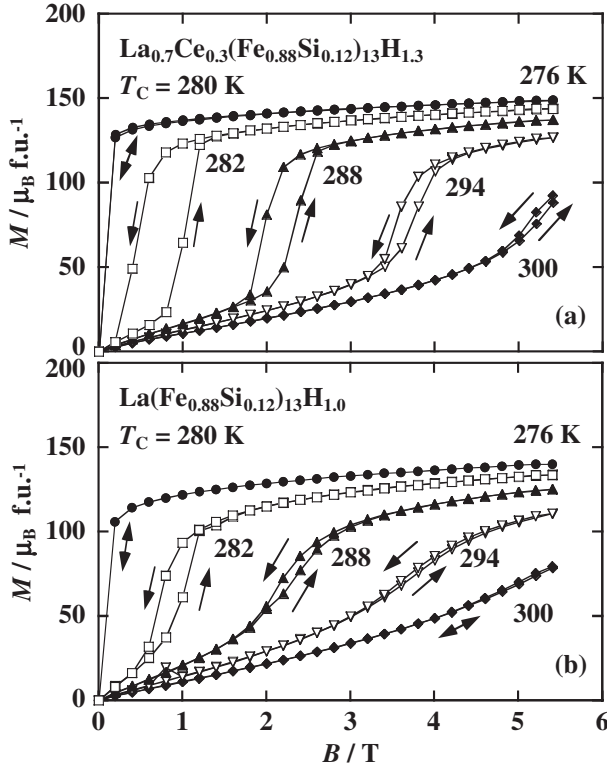


Fig. 5 Magnetization curves of (a) $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.3}$ and (b) $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.0}$ in the vicinity of the Curie temperature T_c . The increasing and decreasing processes of applied magnetic fields are indicated by the arrows.

Similarly, the pressure shift of T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ becomes small after hydrogen absorption. It should be noted that the pressure shift of T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.7}$ is larger than that for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.2}$, though T_c of the former is higher than that of the latter, showing that the enhancement of dT_c/dP caused by the partial substitution of Ce remains after hydrogen absorption. Accordingly, dT_c/dP for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ is larger than that for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ in a wide change of T_c .

The magnetization curves of (a) $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.3}$ and (b) $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.0}$ are shown in Fig. 5. The value of T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.3}$ is about 280 K, being the same as that for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.0}$. The increasing and decreasing processes of applied magnetic fields are indicated by the arrows. A characteristic S-shape magnetization curve with hysteresis is observed above T_c because of the itinerant-electron metamagnetic (IEM) transition. The hysteresis in the magnetization curve of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.3}$ appears at higher temperatures, indicating that the critical temperature T_0 of the disappearance of the IEM transition is much higher than that of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.0}$. Such results make it clearer that the influence of the partial substitution of Ce cannot be explained by the volume contraction only.

The magnetovolume effects in itinerant-electron metamagnets have been discussed in terms of the Landau-type expansion of magnetic free energy.¹⁶⁾ In the theory, the magnetic free energy is given by the following expression by taking the effects of spin fluctuations, the magnetoelastic energy and the elastic energy into account.¹⁶⁾

$$F(M) = \frac{1}{2} \{ \tilde{a}(T) + 2\kappa C_{mv} P \} M^2 + \frac{1}{4} \tilde{b}(T) M^4 + \frac{1}{6} \tilde{c}(T) M^6, \quad (1)$$

with

$$\begin{aligned} \tilde{a}(T) &= \tilde{a}(0) + \left\{ \frac{5}{3} \tilde{b}(0) + \frac{4}{3} \kappa C_{mv}^2 \right\} \xi(T)^2 + \frac{35}{9} \tilde{c}(0) \xi(T)^4, \\ \tilde{b}(T) &= \tilde{b}(0) + \frac{14}{3} \tilde{c}(0) \xi(T)^2, \quad \tilde{c}(T) = \tilde{c}(0), \end{aligned} \quad (2)$$

where ξ^2 is the mean-square amplitude of thermal spin fluctuations. The values of $\tilde{a}(0)$, $\tilde{b}(0)$ and $\tilde{c}(0)$ are the Landau coefficients related to the 3d band structure, and κC_{mv} is the magnetoelastic coupling constant. When $\tilde{a}(0) > 0$, $\tilde{b}(0) < 0$, $\tilde{c}(0) > 0$ and $5/28 - \eta < \tilde{a}(0)\tilde{c}(0)/\tilde{b}(0)^2 < 3/16$ ($\eta = 2\kappa C_{mv}^2/7|\tilde{b}(0)|$), the magnetic free energy has two minima at $M = 0$ in the paramagnetic state and at a finite value of M in the ferromagnetic state, resulting in the thermal-induced first-order transition at T_c and the IEM transition above T_c .¹⁶⁾ Under these conditions, the pressure shift of ξ^2 at T_c for the first-order transition is given by¹⁶⁾

$$\frac{d\xi(T_c)^2}{dP} = -\frac{6}{\sqrt{7}} \frac{\kappa C_{mv}}{|\tilde{b}(0)|} \left[\frac{\tilde{a}(0)\tilde{c}(0)}{\tilde{b}(0)^2} - \frac{5}{28} + \eta + 28\eta^2 \right]^{-1/2}. \quad (3)$$

According to the theoretical discussion, ξ^2 increases in proportion to T^2 at low temperatures, and to T at high temperatures.¹⁷⁾ It has been pointed out that the critical field B_c of the IEM transition for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ increases in line with $T^{1.2}$ above $T_c = 195$ K.¹⁰⁾ This result means that ξ^2 for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ depends on $T^{1.2}$ in the vicinity of 195 K, because B_c has a proportional relation with ξ^2 .¹⁷⁾ Thus $d\xi(T_c)^2/dP$ of the present compound system can be approximately given by dT_c/dP . By adapting the thermodynamic relation: $\partial F/\partial M = B$ to eq. (1), it reveals that the volume change causes not only the decrease of T_c but also the change of magnetization curve. However, it has been pointed out that the IEM transition of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.86}\text{Si}_{0.14})_{13}$ with the same T_c is clearer than that of $\text{La}(\text{Fe}_{0.86}\text{Si}_{0.14})_{13}$ under the hydrostatic pressure $P = 0.25$ GPa,¹⁴⁾ resulting in the changes of $\tilde{a}(0)$, $\tilde{b}(0)$ and $\tilde{c}(0)$. Therefore, the enhancement of dT_c/dP due to the partial substitution of Ce is attributed to the change of the band structure as can be understood from eq. (3).

The value of dT_c/dP is also affected by the value of κC_{mv} as seen from the same equation. Based on the theoretical discussion of itinerant-electron magnetism by taking the effect of spin fluctuations into account, the magnetic contribution to the thermal dependence of the volume, namely, the spontaneous volume magnetostriction $\omega(T)$ is given by¹⁸⁾

$$\omega(T) = \kappa C_{mv} \{ M(T)^2 + \xi(T)^2 \}. \quad (4)$$

Thus, the volume change $\Delta\omega$ at T_c for the first-order transition is expressed as¹⁸⁾

$$\Delta\omega(T_c) = \kappa C_{mv} \{ M(T_c)_F^2 - \xi(T_c)_P^2 \}, \quad (5)$$

where $M(T_c)_F$ is M at T_c in the F state and $\xi(T_c)_P^2$ is ξ^2 at T_c in the P state. Summarized in Table 1 are $\Delta\omega(T_c)$, $M(T_c)_F$ and $\Delta\omega(T_c)/M(T_c)_F^2$ of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.6}$. The values of $\Delta\omega(T_c)$ and $M(T_c)_F^2$ were

Table 1 The volume change $\Delta\omega(T_c)$ at the Curie temperature T_c and magnetization $M(T_c)$ at T_c , together with the ratio $\Delta\omega(T_c)/M(T_c)^2$ of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ and $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.6}$.

	$\Delta\omega(T_c)(\%)$	$M(T_c)/\mu_B$	$\Delta\omega(T_c)/M(T_c)^2/\mu_B^{-2}$
$\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$	0.82	1.0	0.82
$\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.6}$	0.54	0.9	0.67

evaluated from x-ray diffraction patterns³⁾ and Mössbauer spectra,^{3,19)} respectively. As seen from Table 1, $\Delta\omega(T_c)$ of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.6}$ is about 65% of that before hydrogen absorption. On the other hand, $M(T_c)_F^2$ for the former is about 80% of that for the latter. As a result, $\Delta\omega(T_c)/M(T_c)_F^2$ of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.6}$ corresponds to about 80% of that before hydrogen absorption. It is clear from eq. (5) that such behavior can be explained by the decrease of κC_{mv} and/or the increase of $\xi(T_c)_P^2$ due to the hydrogen absorption, although the values of κC_{mv} and $\xi(T_c)_P^2$ are not evaluated qualitatively at the present stage. It should be noted that the decrease of dT_c/dP for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_{1.2}$ is about 70% as shown in Fig. 4. This value is close to that of $\Delta\omega(T_c)/M(T_c)_F^2$, suggesting that the decrease of dT_c/dP for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ is mainly attributed to the decrease of κC_{mv} rather than the increase of $\xi(T_c)_P^2$. Such influence of hydrogen absorption differs from that of the partial substitution of Ce. Consequently, it stands to reason that the influence of the partial substitution of Ce on dT_c/dP remains after hydrogen absorption, resulting in the stronger pressure effect on T_c for $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$.

4. Conclusion

The initial pressure shift of the Curie temperature T_c , namely, dT_c/dP , for $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}$ becomes small after hydrogen absorption. In addition, the hydrogen absorption causes the reduction of the ratio of the volume change at T_c to the magnetization squared at T_c , $\Delta\omega(T_c)/M(T_c)_F^2$. Therefore, it is suggested that the decrease of dT_c/dP due to the hydrogen absorption is mainly attributed to the decrease of the magnetoelastic coupling constant κC_{mv} . On the other hand, dT_c/dP is enhanced by the partial substitution of Ce for La in connection with the change of the band structure. As a

result, the enhancement of dT_c/dP due to the partial substitution of Ce remains after hydrogen absorption. Consequently, the pressure effect on T_c of $\text{La}_{0.7}\text{Ce}_{0.3}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ is stronger than that of $\text{La}(\text{Fe}_{0.88}\text{Si}_{0.12})_{13}\text{H}_y$ in a wide change of T_c .

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REFERENCES

- 1) A. Fujita, Y. Akamatsu and K. Fukamichi: J. Appl. Phys. **85** (1999) 4756–4758.
- 2) K. Fukamichi and A. Fujita: J. Mater. Sci. Technol. **16** (2000) 167–171.
- 3) A. Fujita, S. Fujieda, K. Fukamichi, H. Mitamura and T. Goto: Phys. Rev. B **65** (2002) 014410, 1–6.
- 4) A. Fujita, K. Fukamichi, K. Koyama and K. Watanabe: J. Appl. Phys. **95** (2004) 6687–6689.
- 5) A. Fujita, K. Fukamichi, M. Yamada and T. Goto: J. Appl. Phys. **93** (2003) 7263–7265.
- 6) A. Fujita, K. Fukamichi, M. Yamada and T. Goto: Phys. Rev. B **73** (2006) 104420, 1–5.
- 7) A. Fujita, K. Fukamichi, J.-T. Wang and Y. Kawazoe: Phys. Rev. B **68** (2003) 104431, 1–6.
- 8) S. Fujieda, A. Fujita, K. Fukamichi, Y. Yamazaki and Y. Iijima: Appl. Phys. Lett. **79** (2001) 653–655.
- 9) S. Fujieda, A. Fujita, K. Fukamichi, Y. Yamaguchi and K. Ohoyama: J. Phys. Soc. Jpn. **77** (2008) 074722, 1–8.
- 10) A. Fujita, S. Fujieda, Y. Hasegawa and K. Fukamichi: Phys. Rev. B **67** (2003) 104416, 1–12.
- 11) S. Fujieda, A. Fujita and K. Fukamichi: Mater. Trans. **45** (2004) 3228–3231.
- 12) S. Fujieda, A. Fujita, K. Fukamichi, N. Hirano and S. Nagaya: J. Alloy. Compd. **408–412** (2006) 1165–1168.
- 13) S. Fujieda, A. Fujita and K. Fukamichi: J. Magn. Magn. Mater. *in press*.
- 14) A. Fujita and K. Fukamichi: First Int. Conf. on Magnetic Refrigeration at Room Temperature, ed. by P. W. Egolf (Int. Institute of Refrigeration, Paris, 2005) pp. 201–209.
- 15) A. Fujita, S. Fujieda and K. Fukamichi: J. Appl. Phys. **99** (2006) 08K910, 1–3.
- 16) H. Yamada, K. Fukamichi and T. Goto: Phys. Rev. B **65** (2002) 024413, 1–6.
- 17) H. Yamada: Phys. Rev. B **47** (1993) 11211–11219.
- 18) H. Yamada and K. Terao: J. Phys.: Condens. Matter. **6** (1994) 10805–10809.
- 19) A. Fujita, S. Fujieda and K. Fukamichi: J. Magn. Magn. Mater. *in press*.