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Critical Behavior Studies in the Vicinity of the Curie Temperature in the MnCoGe Alloy

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The main goal of the present work was to study the critical behavior in the MnCoGe alloy in the vicinity of the critical temperature T_C. The second-order phase transition from ferro- to paramagnetic state was preliminarily confirmed by the positive slope of the Arrott plots. The critical exponents have been revealed using the Kouvel–Fisher method and yield $\beta = 0.474 \pm 0.005$, $\gamma = 0.917 \pm 0.005$, and $\delta = 2.985 \pm 0.005$. The Curie temperature for the MnCoGe equals 293.3 ± 0.1 K.

topics: magnetocaloric materials, critical behavior, the Curie temperature

1. Introduction

Nowadays, energy saving is the main theme of public discussion. Novel ergonomic techniques are extremely important, especially in cooling devices. The most efficient technique for lowering temperature is magnetic cooling based on the magnetocaloric effect (MCE) [1]. The MCE causes the temperature variations of magnetic material under the change of external magnetic field. For over twenty years, the MCE has been studied in a wide range of materials. A natural magnetocaloric material working at room temperature is pure Gd [2, 3]. Moreover, rare earth–transition metal alloys, i.e., $Gd_5Ge_2Si_2$- or $La(Fe,Si)_{13}$-type [1–4], are also characterized by relatively good magnetocaloric properties. For several years, the MM'X group of alloys (M and M' denote 3*d* transition elements, and X denotes main group elements) have been intensively studied due to their excellent magnetocaloric properties [5–8]. The MM'X family of alloys manifests good physical properties and promising application potential. This type of alloy has two crystalline structures: orthorhombic TiNiSi-type structure and hexagonal Ni_2In-type structure [9].

In the present paper, the critical exponents analysis of the MnCoGe alloy in the vicinity of the Curie temperature was conducted. The thermomagnetic investigation was described in the previous paper [10]. The studies were conducted in order to better understand the behavior of the physical quantities of continuous phase transition in MnCoGe alloy. The analysis of critical behavior was carried out using two techniques, namely the Kouvel–Fisher method and scaling analysis.

2. Experimental techniques

The polycrystalline MnCoGe alloy sample was prepared by arc-melting of the high-purity constituent elements under a protective atmosphere (Ar gas). Samples were re-melted several times in order to ensure their homogeneity. Thermomagnetic curves and magnetic isotherms were measured using a Quantum Design physical property measurement system (PPMS), the vibrating sample magnetometer (VSM) option, in a magnetic field up to 5 T and in a wide temperature range.

3. Results and discussion

The critical phenomena in the vicinity of the Curie temperature were analyzed for the MnCoGe alloy. Measured isothermal magnetization against the applied field allowed the construction of the Arrott plots using critical exponents corresponding to mean field theory ($\beta = 0.5$ and $\gamma = 1$). A positive slope of the M^2 vs B/M isotherms is clearly seen in Fig. 1, and it is related to second-order phase transition, according to the Banerjee criterion [11].

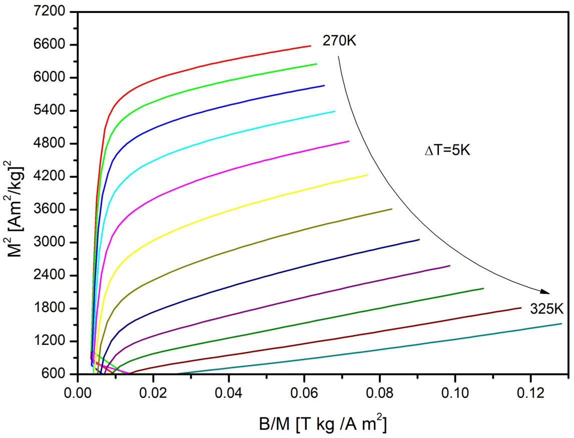

Fig. 1. The Arrott plots constructed for the MnCoGe alloy using mean field values of critical exponents.

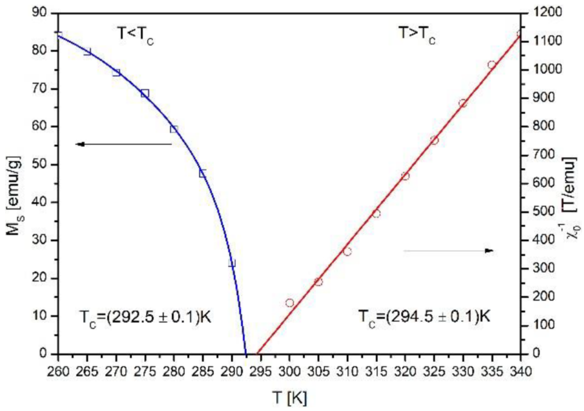

Fig. 2. The temperature dependences of spontaneous magnetization M_S and inverse initial susceptibility χ_0^{-1} of the MnCoGe alloy.

The second-order phase transition is defined by the critical exponents β, γ, and δ related to spontaneous magnetization M_S, initial susceptibility χ_0, and critical magnetization isotherm at the Curie temperature, respectively. The relations between physical magnitudes and critical exponents are described by the following relations [12]

$$M_S(T) = M_0\left(-\frac{T - T_C}{T_C}\right)^{\beta}, \qquad T < T_C, \qquad (1)$$

$$\chi_0^{-1}(T) = \frac{H_0}{M_0}\left(\frac{T - T_C}{T_C}\right)^{\gamma}, \qquad T > T_C, \qquad (2)$$

$$M = D\,H^{1/\delta}, \qquad T = T_C, \qquad (3)$$

where M_S is spontaneous magnetization and H_0, M_0, and D are critical amplitudes.

In order to reveal values of M_S and inverse susceptibility $1/\chi_0$, linear extrapolation was done. The temperature evolution of M_S and $1/\chi_0$ was presented in Fig. 2.

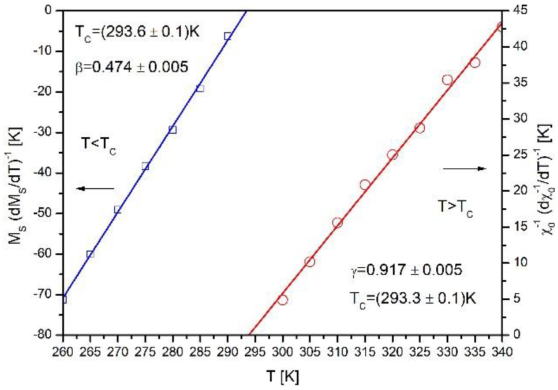

Fig. 3. The Kouvel–Fisher plots for determination β and γ in the MnCoGe alloy.

The M_S and χ_0^{-1} vs T dependences allowed us to reveal more detailed values of the Curie point of 292.5 K and 294.5 K for ferromagnetic ($T < T_C$) and paramagnetic ($T > T_C$) state, respectively.

Kouvel and Fisher in [13] proposed a relatively simple technique for calculating the critical exponents. Taking into account the Kouvel–Fisher approach, the equations (1) and (2) should be rewritten in the following form

$$\frac{M_S(T)}{\left[\mathrm{d}M_S(T)/\mathrm{d}T\right]} = \frac{T - T_C}{\beta}, \qquad (4)$$

$$\frac{\chi_0^{-1}(T)}{\left[\mathrm{d}\chi_0^{-1}(T)/\mathrm{d}T\right]} = \frac{T - T_C}{\gamma}. \qquad (5)$$

Such modification of these relations, according to the Kouvel and Fisher guidelines, allows their linearization with slopes $1/\beta$ and $1/\gamma$. Linear fitting revealed values of critical exponents β and γ. Extrapolation of generated linear dependences to T-axis has shown the Curie points. The Kouvel–Fisher plots are plotted in Fig. 3.

The last critical exponent δ could be determined based on the Widom scaling relation [14]

$$\delta = 1 + \frac{\gamma}{\beta}. \qquad (6)$$

Taking into account values of exponents β and γ delivered by the Kouvel–Fisher method and equation (7), the exponent δ is 2.935.

Another way to determine exponent δ is based on a simple modification of (3). The M vs $\mu_0 H$ isotherm measured in the vicinity of the Curie point on a log–log scale is shown in Fig. 4. The Curie temperature revealed during the current analysis was established as 293.3 K, and it corresponds well with the results described in paper [8]. Due to this fact, the field dependence of magnetization collected at 295 K was chosen as critical isothermal magnetization and used to determine exponent δ. The linear fitting with a slope of $1/\delta$ has revealed that the δ value is 2.985 ± 0.005. Such value corresponds well with δ determined by the Widom scaling relation.

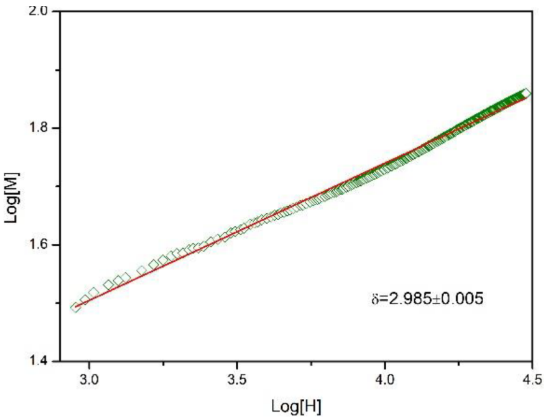

Fig. 4. The M vs $\mu_0 H$ isotherm on a log–log scale at 295 K. The red line is the linear fitting according to (3).

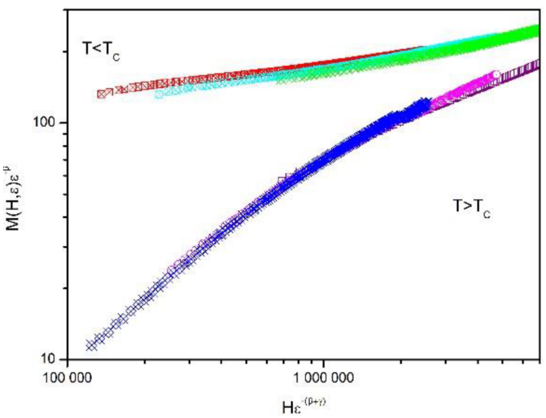

Fig. 5. Scaling plots (on a log–log scale) constructed for the MnCoGe alloy.

The validation of calculated critical exponents is possible taking into account magnetic state relation [15]

$$M(H,\varepsilon) = \varepsilon^{\beta} f_{\pm}\left(\frac{H}{\varepsilon^{\beta+\gamma}}\right), \tag{7}$$

where $\varepsilon = (T - T_{\mathrm{C}})/T_{\mathrm{C}}$, $f_{\pm}$ mean regular functions with f_+ and f_- for $T > T_{\mathrm{C}}$ and $T < T_{\mathrm{C}}$, respectively. Relation (7) shows dependence between $M(H,\varepsilon)\varepsilon^{-\beta}$ and $H\varepsilon^{-(\beta+\gamma)}$. Such construction with correct critical exponents should produce two universally different curves: (i) first for temperatures higher than T_{C} and (ii) second one for temperatures lower than T_{C}. All curves in a specific temperature range (below or higher than T_{C}) should collapse in these two independent scaling curves. In the present case, the independent scaling curves (on a log–log scale) for exponents β and γ calculated by the Kouvel–Fisher method are shown in Fig. 5.

The data presented in Fig. 5 collapse on two independent curves related to ferromagnetic and paramagnetic states. It is clear evidence that revealed values of critical exponents are reasonable and reliable.

Calculated critical exponents are comparable to those delivered by Debnath and coworkers in [16]. They analyzed the critical phenomena for the $Mn_{0.94}Nb_{0.06}CoGe$ alloy and revealed the following values of critical exponents $\beta = 0.576$, $\gamma = 1.002$, and $\delta = 2.716$. Moreover, Rahman et al. in [9] investigated the critical behavior in the $MnCoGe_{0.97}Al_{0.03}$ and delivered similar results, i.e., $\beta = 0.44$, $\gamma = 0.83$, and $\delta = 2.89$.

The calculated values correspond quite well with the mean-field model.

4. Conclusions

In the present paper, the critical phenomena in the MnCoGe alloy were investigated at Curie point using the Kouvel–Fisher technique. Calculated values of critical exponents were reliable and reasonable, which was confirmed by appropriate tests. The values of the critical exponents of $\beta = 0.474$, $\gamma = 0.917$, $\delta = 2.985$, and the Curie temperature 293.3 K have been achieved.

Acknowledgments

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