Ferromagnetism of thermoelastic martensites: Theory and experiment

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A consistent consideration of ferromagnetic alloys undergoing a cubic-tetragonal martensitic transformation on cooling is carried out within the framework of Landau theory. The concept of two different Curie temperatures, corresponding to the parent (austenitic) and resultant (martensitic) phases, is substantiated by taking into account the volume magnetostriction of an alloy. The difference in these two temperatures is evaluated for different alloys from the Ni-Mn-Ga family typifying ferromagnetic martensites. A statistical dispersion of the local Curie temperatures reflecting the heterogeneity of martensitic states is introduced. The qualitatively different temperature dependencies of the magnetization are predicted theoretically and observed experimentally under an applied magnetic field of about 10 kOe. Quantitative agreement between the theoretical and experimental curves is achieved.

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I. INTRODUCTION

A large number of metallic alloys undergo a martensitic phase transformation associated with the spontaneous deformation of the crystal lattice below the transformation temperature T_m (see, e.g., Refs. 1–3). The high-temperature cubic phase (austenite) is spatially homogeneous, while the low-temperature state (martensite) is inhomogeneous. In the often encountered case of the cubic-tetragonal martensitic transformation (MT) the microstructure of martensite is formed by the elastically self accommodated domains of tetragonal crystal lattice (martensitic variants) with the principal axes oriented along [100], [010], or [001] directions. The quasiequilibrium state of the alloy formed by the self-accommodated martensitic variants is referred to as the thermoelastic martensite.

Some martensitic alloys exhibiting a cubic-tetragonal MT are ferromagnetic with a Curie temperature T_C, which can be higher or lower than T_m. The well-pronounced magnetic and magnetoelastic anomalies accompanying the martensitic transformations in Ni-Mn-Ga, Fe-Pt, and Fe-Pd alloys with $T_m < T_C$ have been the subject of the intense experimental studies.[4–10] In particular, the sharp changes of the spontaneous magnetization,[4,5] magnetic susceptibility[6] and magnetostriction[7] of Ni-Mn-Ga alloys were observed in the vicinity of T_m.

Further theoretical treatment of experimental results made clear the considerable role of the interaction between the order parameters of martensitic and ferromagnetic phase transformations in the ferromagnetic properties of martensites.[11,12] The effect of the random heterogeneity of the alloy on its thermodynamic and magnetic properties was also studied.[13,14]

A giant magnetostrain effect (GMSE), observed first in Ref. 8, is the most fascinating manifestation of the magnetoelastic interaction in ferromagnetic martensites. The GMSE is a strong deformation of an alloy in the moment of magnetic field application. The effect is caused by the field-stimulated variation of martensitic microstructure.[8,9] The first observation of the GMSE brought about an avalanche of studies mainly devoted to a simple theoretical modeling of the GMSE and an experimental realization of the maximum values of the field-induced strains (see, e.g., Refs. 9, 15 and 16). As a result, the strain values close to the theoretical limit were reported recently for Ni-Mn-Ga alloys typifying the ferromagnetic martensites.[16] Thus, substantial progress in the applied studies dealing with the GMSE has been achieved.

In contrast, the fundamental aspect of the problems related to the ferromagnetism of martensites is not completely clear till now. This is owing to the complexity and the large variety of magnetic and magnetoelastic properties inherent to the different martensitic structures (in particular, those observed in the Ni-Mn-Ga alloy system). In this respect, the important objective is an understanding of the magnetic and magnetoelastic behavior of the various martensitic phases, based on a small number of energy parameters and magnetic characteristics of the parent cubic phase. To tackle this problem a consistent theoretical consideration of the ferromagnetic martensites, resulting in an evaluation of their basic magnetic and magnetoelastic energy parameters, is carried out in the present paper. Detailed experimental and theoretical studies of the unusual temperature dependencies of magnetization inherent to the different alloys belonging to the Ni-Mn-Ga alloy family are carried out. The difference in the magnetic characteristics of the alloys with $c/a < 1$ and $c/a > 1$ is emphasized and evaluated numerically (where a and c are the parameters of tetragonal lattice).

II. GENERAL CONSIDERATIONS

A martensitic transformation with the transformation temperature T_m is accompanied by a variation in the interatomic

distances, and therefore, the intensity of the spin exchange interaction is different for the parent and martensitic phases. As a result, the Curie temperature T_{CA} of the parent (austenitic) phase must be different from the Curie temperature of the martensitic phase T_{CM}, and so the following cases are possible:[9]
(i) $T_m<T_{CA}<T_{CM}$,
(ii) $T_m<T_{CM}<T_{CA}$,
(iii) $T_{CA}<T_m<T_{CM}$,
(iv) $T_{CA}<T_{CM}<T_m$,
(v) $T_{CM}<T_{CA}<T_m$,
(vi) $T_{CM}<T_m<T_{CA}$.
We emphasize here that in cases (i)–(v) only one of the above-mentioned Curie temperatures is the real temperature T_C of the ferromagnetic ordering of an alloy; thus the following possibilities exist:
(a) $T_C=T_{CA}$ (i) and (ii)
(b) $T_C=T_m$ (iii)
(c) $T_C=T_{CM}$ (iv) and (v).
Case (vi) looks very exotic, because it provides for the possibility of the phase transition sequence *paramagnetic austenite–ferromagnetic austenite–paramagnetic martensite –ferromagnetic martensite* (on cooling).

The existence of the ''virtual'' Curie temperatures T_{CM} [possibility (a)], T_{CM}, T_{CA} [possibility (b)] or T_{CA} [possibilities (b) and (c)] must affect the magnetic properties of an alloy, particularly the temperature dependence of the alloy magnetization. The dependencies corresponding to cases (i)–(vi) are illustrated in Fig. 1. These dependencies demonstrate the jumps in magnetization, which accompany the martensitic transformation occurring in the ferromagnetic phase, and the high-temperature ''tails'' of magnetization, which occur when the ferromagnetic order arises in the martensitic phase. It will be shown in this paper that the jump of magnetization is related to the difference in the Curie temperatures of two phases $T_{CA}-T_{CM}$ and the tails are caused mainly by the spatial heterogeneity of martensite. It will be proved that cases (i) and (v) provide a very good theoretical description of the temperature dependencies of magnetization measured for three different alloys from the Ni-Mn-Ga family.

III. MAGNETOELASTIC MODEL OF FERROMAGNETIC MARTENSITE

A magnetoelastic model of ferromagnetic martensite[11,12] uses the Landau approach to describe the magnetic properties of an alloy and starts from the following expression for the free energy:

$$F=F_e+F_m+F_{me}, \tag{1}$$

consisting of the elastic, magnetic and magnetoelastic terms (F_e, F_m, and F_{me}, respectively). The energy [Eq. (1)] is invariant under the symmetry group of the paramagnetic cubic phase of an alloy. The cumbersome expression for the elastic energy F_e consists of terms of the second, third and fourth orders in strain tensor components and can be found in Refs. 17 and 18. The magnetic energy can be approximated by the formula[9,14]

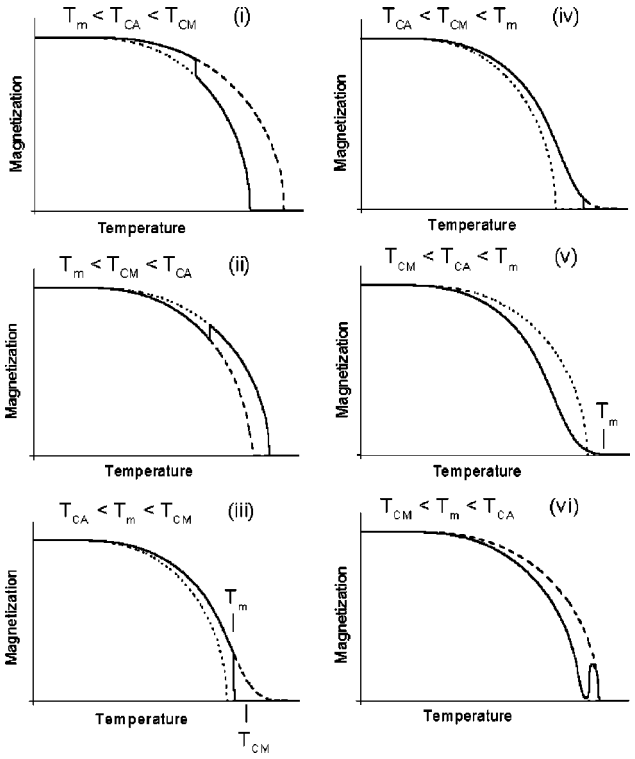

FIG. 1. Different types of the temperature dependence of the magnetization, which are possible for the ferromagnetic alloys undergoing a martensitic transformation (solid lines). The dotted and dashed lines show the supposed magnetization curves for the labile phases.

$$F_m=Jy^2/2+M^2(\mathbf{m}\cdot\mathbf{D}\cdot\mathbf{m})-\mathbf{mH}M, \tag{2}$$

where the first, second, and third terms express the exchange, magnetostatic and Zeeman energies respectively, and J is the spin exchange parameter. The dimensionless variables $y=M(T)/M(0)$ and $\mathbf{m}=\mathbf{M}(T)/M(T)$ characterize the absolute value and direction of the magnetization vector $\mathbf{M}$. The energy terms of the forth order in magnetic vector components are regarded as comparatively small, and therefore, are omitted. (This simplification of the theory will be justified below.)

Since the cubic-tetragonal MT is described by the diagonal components of a strain tensor, the magnetoelastic energy is expressed as[11,12,14]

$$F_{me}=-\delta_0 y^2 u_1-\delta_1[\sqrt{3}(m_x^2-m_y^2)u_2+(2m_z^2-m_y^2-m_x^2)u_3], \tag{3}$$

where

$$u_1=(\varepsilon_{xx}+\varepsilon_{yy}+\varepsilon_{zz})/3,$$

$$u_2=\sqrt{3}(\varepsilon_{xx}-\varepsilon_{yy}), \quad u_3=2\varepsilon_{zz}-\varepsilon_{yy}-\varepsilon_{xx},$$

The minimization of the energy [Eq. (1)] carried out in Refs. 11 and 12, leads to the following conclusions.

A ferromagnetic ordering of the cubic parent phase is accompanied by the spontaneous magnetostriction with the relevant volume change $3u_1\sim\delta_0/(C_{11}+2C_{12})$ and the shear strains $\varepsilon_{ii}^{me}\sim\delta_1/C$ (standard notation for the elastic modules

is used here). In the case when a spontaneous ferromagnetic moment is directed along ⟨100⟩, the strains ε_{ii}^{me} reduce the symmetry of the crystal lattice from cubic to tetragonal.

A cubic-tetragonal martensitic transformation of the paramagnetic phase is accompanied by the spontaneous strains ε_{ii}^{M}. The strains inherent in the *i*-variant of a tetragonal martensite with the principal crystallographic axis aligned with *i* coordinate direction are[18]

$$\varepsilon_{zz}^{M}\approx u_0/3, \quad \varepsilon_{yy}^{M}=\varepsilon_{xx}^{M}\approx -u_0/6 \quad \text{for the z variant,}$$

$$\varepsilon_{yy}^{M}\approx u_0/3, \quad \varepsilon_{zz}^{M}=\varepsilon_{xx}^{M}\approx -u_0/6 \quad \text{for the y variant,}$$

$$\varepsilon_{xx}^{M}\approx u_0/3, \quad \varepsilon_{yy}^{M}=\varepsilon_{zz}^{M}\approx -u_0/6 \quad \text{for the x variant,}$$

where the parameter $u_0 \ll 1$ is related to the lattice parameters *a* and *c* of the tetragonal phase as $u_0 \approx 2(c/a-1)$. One can see that the sum of the strain tensor components is approximately equal to zero. It means that u_1 is of the order of u_0^2 (for further details see Refs. 18 and 19).

In the ferromagnetic martensitic phase both ε_{ii}^{M} and ε_{ii}^{me} strains exist, and therefore $\varepsilon_{ii}=\varepsilon_{ii}^{M}+\varepsilon_{ii}^{me}$. It should be stressed, however, that for real alloys $\varepsilon_{ii}^{M} \gg \varepsilon_{ii}^{me}$. In the case when both spontaneous and magnetoelastic strains correspond to the tetragonal symmetry, the magnetoelastic strains are hardly observable, and so may be disregarded. Substituting $\varepsilon_{ii}=\varepsilon_{ii}^{M}$ into Eqs. (2) and (3) we express the energy of the *i* variant of ferromagnetic martensite in the form

$$F_m+F_{me}=J^*y^2/2-Am_i^2+\mathbf{m}\cdot\mathbf{D}\cdot\mathbf{m}/2-\mathbf{mH}M, \qquad (4)$$

where
$J^*(T)=J(T)-2\delta_0 u_1$,
$A=6\delta_1(c/a-1)$.

Equation (4) establishes the interrelation between the energy parameters *J*, δ_0, and δ_1 of the parent phase, the spontaneous strains $\varepsilon_{ii}\sim c/a-1$ and the magnetic properties of the martensitic phase. This equation shows two effects of magnetostriction on the magnetic properties of the martensitic phase.

First, the renormalization of the spin exchange energy $J \rightarrow J^*$ occurs due to the volume magnetostriction. This conclusion is quite natural in view of the sharp (exponential) dependence of the exchange integral on the distances between the magnetic atoms.

Second, the magnetic anisotropy energy Am_i^2 caused by the nonisotropic magnetoelastic interaction and the spontaneous shear strain arises below the MT temperature.[19,20] This result can be explained in a very general way: the existence of the second-order magnetocrystalline anisotropy energy Am_i^2 is prohibited by the cubic symmetry, so *A* is a function of the parameter $c/a-1$, vanishing when the parameter tends to zero. If this parameter is much smaller than 1, the *A* function can be expanded in a series and approximated by the first term of the expansion. This explanation was substantiated very recently by microscopic consideration.[21] If $\delta_1<0$, the martensitic phase with $c/a<1$ possesses an ''easy magnetic axis,'' while an ''easy magnetic plane'' is inherent for the martensites with $c/a>1$. This conclusion is in agreement with the recent experimental results obtained for the Ni-Mn-Ga family.[22]

IV. MAGNETIC CHARACTERISTICS OF THE ALLOY

A. Curie temperatures

According to the orthodox Landau theory, the exchange parameter depends on the temperature as $J(T)=\zeta(T-T_{CA})/T_{CA}$, and so, the equation for the Curie temperature of alloys with $T_m<T_C$ is $J(T_{CA})=0$. In contrast, for alloys with Curie temperature $T_m>T_C$, the appropriate equation is $J^*(T_{CM})=0$, and, hence,

$$T_{CM}=T_{CA}[1+2(\delta_0/\zeta)u_1]. \qquad (5)$$

The parameter u_1 expresses the volume change accompanying M*T*, and, hence, is related to the mass density of the alloy. Due to the spatial heterogeneity of the polyvariant martensite, the configurational dispersion *s* of this parameter around the average value $\langle u_1\rangle$ can be expected: $u_1=\langle u_1\rangle+s$. The spatial configuration of the heterogeneous martensitic state depends on a number of random factors, such as the spatial positions of the defects in the crystal lattice. Therefore, the quasicontinuous statistical distribution $f(s)$ of *s* can be found from the maximum principle for the entropy function

$$S=-\int_{-\infty}^{\infty} f(s)\ln f(s)ds, \qquad (6)$$

considered with the additional condition $\langle s^2\rangle=s_0^2$. In such a way, a well-known Gaussian distribution arises:

$$f(s)=\frac{1}{s_0\sqrt{2\pi}}\exp\left(-\frac{s^2}{2s_0^2}\right). \qquad (7)$$

[A rapid decrease of function (7) in the range $s>s_0$ justifies the extension of the integration range in Eq. (6) to infinity.]

According to Eq. (5), the spatial dispersion of u_1 results in the dispersion of Curie temperature. The ''dispersed'' T_{CM} value corresponds to the temperatures of the local ferromagnetic ordering of the heterogeneous martensitic phase.

B. Magnetization

When a magnetic field exceeding the saturation value H_S is applied to the specimen, the temperature dependence of the magnetization in the parent phase is satisfactorily described by the standard equation from the theory of ferromagnetism:

$$y(T)=\tanh[(T_{CA}/T)y(T)]. \qquad (8)$$

The average magnetization of the magnetically saturated polyvariant martensite is

$$\langle M(T)\rangle=M_0\int_{-\infty}^{\infty} y(T,s)f(s)\,\theta(T_{CM}-T)ds, \qquad (9)$$

where $M_0=M(0)$, $\theta(T_{CM}-T)$ is a stepwise Heaviside function, and $y(T,s)$ satisfies the equation $y(T,s)=\tanh[(T_{CM}/T)y(T,s)]$.

When a field lower than the saturation field H_S is applied in the $\langle 100\rangle$ direction, the value $M_0y(T,s)$ in the Eq. (9) must be replaced by the function

$$M^{(s)}(H,T)=M_0y(T,s)[\beta\Delta(H)+(1-\beta)\cos\psi(H)]. \tag{10}$$

The first term in the square brackets describes the magnetization process caused by the displacements of the walls separating the magnetic domains with the antiparallel magnetic vectors directed along the applied field. β is the volume fraction of these domains in the specimen. The second term describes the rotation of those magnetic vectors, which initially were directed perpendicular to the field. Thus

$$\Delta=(H/H_c)\,\theta(H_c-H),$$
$$\cos\psi=(H/H_S)\,\theta(H_S-H), \tag{10}$$

where H_c denotes the field for the disappearance of the 180° magnetic domains and H_S is the magnetic saturation field. These fields can be expressed through the anisotropy parameter A and the elements of a demagnetization matrix **D**. This matrix is diagonal for the ellipsoidal specimen. In the case of the ellipsoid of revolution with the revolution axis parallel to $[010]\|\mathbf{H}$, the field H_c is approximately equal to D_2M, and the saturation field is

$$H_S=2|A|/M+(D_2-D_1)M, \tag{11}$$

where $D_1=D_3\neq D_2$ are the elements of matrix **D** expressed in the coordinate system associated with direction $\langle 100\rangle$.

C. Energy parameters

The magnetoelastic parameter δ_0 is evaluated from the experimental dependence $T_{CA}(P)$, where P is a hydrostatic pressure applied to the alloy. The appropriate formula is[6]

$$\delta_0=\frac{\zeta}{2}\,\frac{C_{11}+2C_{12}}{T_{CA}(0)}\,\frac{dT_{CA}}{dP}, \tag{12}$$

where the value $\zeta=nk_BT_C$ can be used for rough estimations (n is the number of magnetic atoms per unit volume and k_B is Boltzmann's constant).

The magnetoelastic parameter δ_1 can be evaluated in two different ways-from the magnetostriction measured for the parent phase and from the experimental value of saturation field H_S measured for the martensitic phase, since, on the one hand, this parameter is related to the transverse magnetostriction $\lambda_\perp$ and shear modulus C' of the parent phase as $\delta_1=\lambda_\perp C'$ and, on the other hand, Eq. (11) results in the estimation

$$\delta\equiv\delta_1/M^2=-\frac{H_S+|D_1-D_2|M}{12M|1-c/a|}. \tag{13}$$

[The expression $A=6\delta_1(1-c/a)$ for the parameter of the magnetic anisotropy was taken into account.]

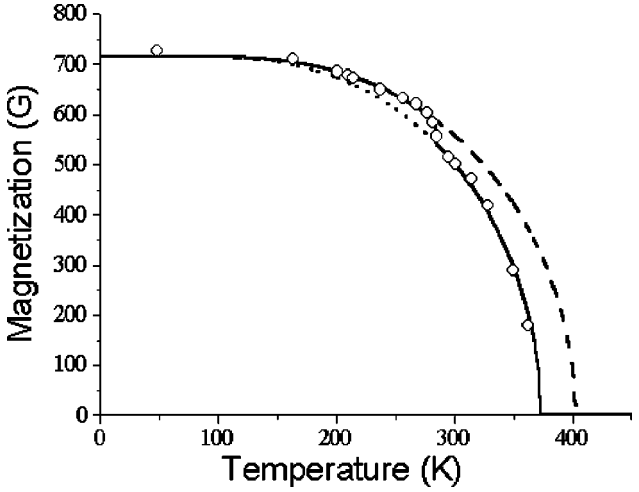

FIG. 2. Experimental (circles) and theoretical (solid line) temperature dependencies of the saturation magnetization obtained for alloy 1 with $c/a=0.94$, $T_C=375$ K, and $T_m=285$ K. (The dotted and dashed lines show the magnetization curves computed for the labile phases.)

V. RESULTS FOR Ni-Mn-Ga ALLOYS

For the Ni-Mn-Ga alloy system, a Curie temperature about 375 K has been reported, while the MT temperature depends strongly on the alloy composition. Three different alloys are studied below: $Ni_{52.6}Mn_{23.5}Ga_{23.9}$ (alloy 1), $Ni_{53.1}Mn_{26.6}Ga_{20.3}$ (alloy 2), and $Ni_{51.2}Mn_{31.1}Ga_{17.7}$ (alloy 3).

Alloy 1, with a MT temperature of about 285 K, is of type (i) in view of the negative values of δ_0/ζ and $\langle u_1\rangle$ reported in Refs. 14 and 19. For this alloy $(dT_{CA}/dP)=8$ K/GPa, $C_{11}=213$ GPa and $C_{12}=87$ GPa. In such a case, Eq. (12) gives $\delta_0/\zeta=-4$. The estimation $\zeta\approx 0.1$ GPA [see the explanation following Eq. (12)] results in the value $\delta_0\approx -0.4$ GPa. Moreover, $\langle u_1\rangle\sim -2\times10^{-4}$ or -2×10^{-2} (the lower value is evaluated from the Clausius-Clapeyron relationship while the upper one results from the lattice parameters measured for the parent and martensitic phases). The temperature dependence of magnetization computed from Eq. (9) shows excellent agreement with experimental data when $\langle u_1\rangle=-10^{-2}$, $s_0=10^{-3}$, $T_{CA}=372$ K, and $M_0=715$ G (see Fig. 2). Equation (5) results in the estimation $T_{CM}-T_{CA}=30$ K. The value $2(c/a-1)=-0.124$ and estimations $\delta_1=-1.2$ MPa, $\delta=\delta_1/M^2=-23$, obtained from the magnetostriction of cubic phase,[20] enable the evaluation of the anisotropy constant $A=0.4$ MPa and saturation field $H_S\approx 10$ kOe. The real values of the saturation field are close to this value, but depend on the specimen shape [see Eq. (11)] and the alloy microstructure.[11]

For alloy 2, the MT temperature is close to T_C and the martensitic phase with $c/a>1$ arises below this temperature. The temperature dependence of magnetization measured at the constant field value $H=10$ kOe is presented by dots in Fig. 3. As can be seen from the experimental $M(H)$ dependencies,[22] the field value $H=10$ kOe is lower than the field of magnetic saturation in alloys with $c/a>1$. Thus Eq. (10) was used for computations. The resultant $M(T)$ curve is shown in Fig. 3. The best fit to the experimental data was

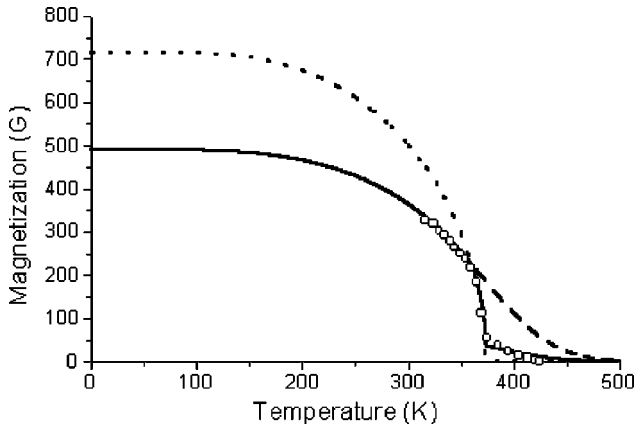

FIG. 3. Experimental (circles) and theoretical (solid line) temperature dependencies of magnetization obtained for alloy 2 with $c/a=1.2$, $T_C=375$ K, and $T_m=363$ K under the magnetic field $H=10$ kOe$<H_s$. (The dotted and dashed lines show the magnetization curves computed for the labile phases.)

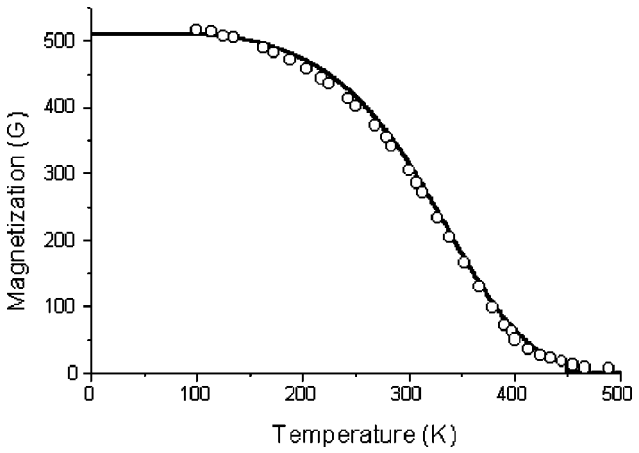

FIG. 4. Experimental (circles) and theoretical (solid line) temperature dependencies of magnetization obtained for alloy 3 with $c/a=1.2$, $T_C=375$ K, and $T_m=450$ K under the magnetic field $H=10$ kOe.

observed for $s_0=0.015$, $T_m=363$ K, $H_S=19$ kOe (when $\beta=\frac{1}{3}$), or $H_S=15$ kOe (when $\beta=0$). All others values used in the course of computations are equal to those reported for alloy 1. Alloy 2 is of type (i), but close to type (ii) in view of the small difference between T_C and T_m. The value $H_S=15$ kOe is in good agreement with the $M(H)$ curves measured recently for the single-variant Ni-Mn-Ga martensite with $c/a>1$.[22] The substitution of this value into Eq. (13) enables the estimation of magnetoelastic parameters and the magnetic anisotropy energy of the alloy. In this case $c/a=1.2$, the estimations carried out for the elongated specimen with $D_1=6.1$ and $D_2=0.39$ give

$$\delta_1=-0.57 \text{ MPa}, \quad \delta=-11, \quad A=-0.68 \text{ MPa}.$$

Therefore, the magnetoelastic coupling in the alloy with $c/a>1$ is two times weaker, than in the alloy with $c/a<1$. Despite this, the absolute value of the anisotropy energy is 1.7 times larger, due to the large value of $c/a-1$.

It can be concluded, hence, that for the alloys with $c/a>1$ the work needed for the martensite variant reorientation is 1.7 times larger while the "efficiency" of the magnetic field action on the martensite structure is 2 times smaller, than for the alloys with $c/a<1$. It may be considered as one of the reasons retarding the observation of a giant magnetostrain effect in the alloys with $c/a>1$.

Finally, alloy 3, of type (v), with $T_m=450$ K and $c/a>1$, was studied. For this alloy the best fit of the theoretical curves to the experimental data was observed at $s_0=0.015$, $H_S=14$ kOe ($\beta=0$), and $\langle u_1\rangle=0$ (see Fig. 4). One can see that this set of the parameters is close to one found above for alloy 2.

VI. CONCLUSIONS

The set of experimental data needed for the quantitative description of the magnetic properties of martensitic alloys in the framework of Landau theory is outlined above. The following are shown.

(i) The magnetic anisotropy constant of the low temperature martensitic phase can be evaluated from the magnetostriction of the high-temperature parent phase and the spontaneous deformation of the cubic lattice accompanying the martensitic transformation; the absolute value of the anisotropy constant for the tetragonal martensite with $c/a=1.2$ is two times larger while the magnetoelastic constant is half less than for the martensite with $c/a=0.94$.

(ii) The volume magnetostriction of the alloy can be evaluated from the pressure shift of the Curie temperature; the volume magnetostriction of Ni-Mn-Ga alloy is related to the energy parameter $\delta_0\approx-0.4$ GPa.

(iii) The difference in the Curie temperatures of high-temperature (austenitic) and low-temperature (martensitic) phases can be estimated from the volume change accompanying martensitic transformation; for the Ni-Mn-Ga alloys $T_{CM}-T_{CA}=30$ K.

Using the Landau potential and the determined values of energy parameters, a quantitative theoretical treatment of the magnetization vs temperature dependencies measured in the saturating magnetic field for three different Ni-Mn-Ga alloys was carried out. The experimentally observed distinctions in the magnetic behavior of the martensites with $c/a<1$ and $c/a>1$ are explained. First, the drops in the saturation magnetization values are related to the difference in the Curie temperatures of martensitic and austenitic phases. Second, the high-temperature "tails" of the magnetization are attributed to the statistical dispersion of the local Curie temperatures in the inhomogeneous martensitic state. As a general conclusion it should be emphasized, that the well-elaborated Landau approach to the description of the ferromagnetism phenomenon, in fact, provides an efficient theoretical tool for the quantitative study of ferromagnetic martensites.

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[1] J. W. Christian, *The Theory of Transformations in Metals and Alloys* (Pergamon, Oxford, 1965).
[2] C. M. Wayman, *Introduction to Crystallography of Martensitic Transformations* (MacMillan, New York, 1964).
[3] K. Otsuka and X. Ren, Intermetallics **7**, 511 (1999).
[4] P. J. Webster, K. R. A. Ziebeck, S. L. Town, and M. S. Peak, Philos. Mag. B **49**, 295 (1984).
[5] V. A. Chernenko and V. A. Kokorin, in *Proceedings of the International Conference on Martensatic Transformations (ICOMAT-92)*, edited by C.M. Wayman and J. Perkins, (Monterey Institute for Advanced Studies, Monterey, California, 1993), p. 1205.
[6] A. N. Vasil'ev, V. V. Kokorin, Y. I. Savchenko, and V. A. Chernenko, Zh. Eksp. Teor. Fiz **98**, 1437 (1990) [Sov. Phys. JETP **71**, 803 (1990)].
[7] A. N. Vasil'ev, S. A. Klestov, R. Z. Levitin, V. V. Snegirev, V. V. Kokorin, and V. A. Chernenko, Zh. Eksp. Teor. Fiz **109**, 973 (1996) [Sov. Phys. JETP **82**, 524 (1996)].
[8] K. Ullakko, J. K. Huang, C. Kantner, R. C. O'Handley, and V. V. Kokorin, Appl. Phys. Lett. **69**, 1966 (1996).
[9] R. D. James and M. Wuttig, Philos. Mag. A **77**, 1273 (1998).
[10] T. Kakeshita, T. Takeuchi, T. Fukuda, M. Tsujiguchi, R. Oshima, and S. Muto, Appl. Phys. Lett. **77**, 1502 (2000).
[11] V. A. L'vov, E. V. Gomonaj, and V. A. Chernenko, J. Phys.: Condens. Matter **10**, 4587 (1998).
[12] A. N. Vasil'ev, A. D. Bozhko, V. V. Khovailo, I. E. Dikshtein, V. G. Shavrov, V. D. Buchel'nikov, M. Matsumoto, S. Suzuki, T. Takagi, and J. Tani, Phys. Rev. B **59**, 1113 (1999).
[13] V. P. Silin, D. Wagner, and V. M. Zverev, Phys. Lett. A **199**, 395 (1995).
[14] V. A. Chernenko, V. A. L'vov, M. Pasquale, S. Besseghini, C. Sasso, and D. A. Polenur, Int. J. Appl. Electromagn. Mech. **12**, 3 (2000).
[15] R. C. O'Handley, J. Appl. Phys. **83**, 3263 (1998).
[16] R. C. O'Handley, S. J. Murray, M. Marioni, H. Nembach, and M. S. Allen, J. Appl. Phys. **87**, 4712 (2000).
[17] J. K. Liakos and G. A. Saunders, Philos. Mag. A **46**, 217 (1982).
[18] E. V. Gomonaj and V. A. L'vov, Phase Transitions **47**, 9 (1994).
[19] V. A. Chernenko and V. A. L'vov, Philos. Mag. A **73**, 999 (1996).
[20] V. A. Chernenko, V. A. L'vov, and E. Cesari, J. Magn. Magn. Mater. **196–197**, 859 (1999).
[21] J. Enkovaara, A. Ayuela, L. Nordstrom, and R. M. Nieminen, Phys. Rev. B **65**, 134422 (2002).
[22] A. Sozinov, A. A. Likhachev, and K. Ullakko, in *SPIE 8th Annual Symposium of Smart Structures and Materials, Newport Beach, 5 March 2001*, edited by C. S. Linch [Proc. SPIE **4333**, 189 (2001)].