Magnetoelastic interaction in the martensitic transformation in an Ni_2MnGa single crystal

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We have studied the temperature and field dependence of the magnetization and magnetostriction of an Ni_2MnGa single crystal near the transition from the cubic to the tetragonal martensitic phase. The value and temperature dependence of the coefficient of magnetoelastic coupling, which determines the efficiency of the direct transformation of electromagnetic and acoustic waves in this compound, have been determined. The possibility of controlling the size of martensite crystals by an external magnetic field is discussed. © *1996 American Institute of Physics.* [S1063-7761(96)02103-3]

The intermetallic compound Ni_2MnGa belongs to the family of Heusler alloys, many representatives of which exhibit pronounced shape memory and superelasticity effects.[1] These effects are due to a special type of structural phase transition—thermoelastic martensitic transformations. In some manganese-based compounds, the martensitic transformation is associated with antiferromagnetic ordering,[2] but in Ni_2MnGa the structural transition of martensitic type takes place in a ferromagnetic matrix. As the temperature is reduced, the matter goes over from a cubic to a tetragonal phase modulated by a static transverse displacement wave.[3] The period of the displacement wave is equal to five interatomic spacings; its wave vector is perpendicular to the planes of {110} type, and the polarization vector is directed along axes of ⟨110⟩ type. In the martensitic phase, the low-field magnetic susceptibility is reduced, and in the region of the transition the elastic moduli soften significantly.[4] The interrelationship of the magnetic and elastic properties in materials with shape memory and superelasticity suggests that is might be possible to induce a structural phase transition in these materials by means of an external magnetic field. The existence of strong magnetoelastic coupling in Ni_2MnGa is indicated by data on the electromagnetic excitation of ultrasound. Between the Curie point T_C and the temperature T_M of the martensitic transformation, an electromagnetic wave incident upon the surface of this material gives rise to intense generation of acoustic vibrations; moreover, near T_M a peak of the conversion efficiency is observed.[4] In the martensitic phase (at $T<T_M$), generation of ultrasound in weak magnetic fields has not been observed.

In the work reported here, we measured, over a temperature interval including that of the martensitic transformation, the temperature and field dependence of the magnetization σ and transverse magnetostriction $\lambda_\perp$ of an Ni_2MnGa single crystal in a magnetic field oriented along the [110] crystallographic direction, and we determined the temperature dependence of the coefficient of magnetoelastic coupling.

The Ni_2MnGa single crystal was grown from the melt by Bridgman's method. In accordance with the data of an x-ray spectroscopic analysis, the composition of the alloy differed from a stoichiometric composition by a reduced (by 1 at. %) amount of manganese, which was made up by nickel. Samples in the form of cubes with edge length of about 0.3 cm and faces parallel to the (110), $(\bar{1}10)$, and (001) atomic planes were cut from the ingot by the electric-spark method. The temperature of the martensitic transformation in the investigated samples was $T_M=290$ K, and the Curie point was $T_C=380$ K. The magnetization σ was measured in fields up to 1 T using a vibration magnetometer. The transverse magnetostriction $\lambda_\perp$ was measured in pulsed magnetic fields up to 30 T obtained by discharging a bank of capacitors through an inductance coil. To the face of the Ni_2MnGa single crystal perpendicular to the direction of the magnetic field, we glued a quartz wafer, and the electric charge that arose on its surface was used to determine the magnetoelastic deformation.

Both the magnetization and the magnetostriction differed strongly between the cubic and tetragonal martensitic phases of Ni_2MnGa. We shall first analyze the magnetization data. In weak magnetic fields, as is shown in Fig. 1, σ decreases strongly upon transition of the crystal to the low-temperature modification. It is natural to attribute this to an increase in magnetic anisotropy in the tetragonal phase, which possesses a superlattice ordering. Since at $T<T_M$ the crystal is divided into structural domains and in this sense is equivalent to a polycrystal, the measured value of σ corresponds to averaging along the direction of easy and hard magnetization. With increasing static magnetic field, the jump in σ at T_M decreases. This agrees both with measurements of the low-field magnetic susceptibility[5] and with measurements in strong magnetic fields.[6] The field dependence of σ also changes in accordance with the growth of magnetic anisotropy. As can be seen from Fig. 2, saturation is achieved at $T>T_M$ in fields of order 0.2 T, while at $T<T_M$ the magnetization tends to saturation only in fields of order 1 T. In the region of the structural transition, the values of the saturation magnetization σ_s in the cubic and tetragonal phases are comparable.

As is shown in Fig. 3, the field dependence of the magnetostriction also differs strongly between the cubic and te-

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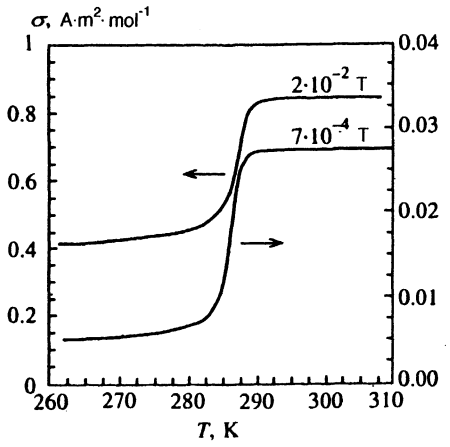

FIG. 1. Temperature dependence of the magnetization of an Ni_2MnGa single crystal in the ⟨110⟩ crystallographic direction.

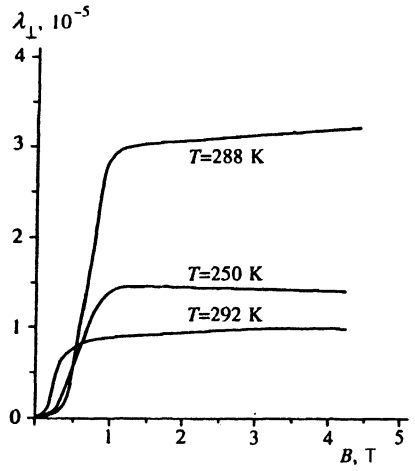

FIG. 3. Field dependence of the transverse magnetostriction of an Ni_2MnGa single crystal in the ⟨110⟩ crystallographic direction.

tragonal phases. At $T>T_M$, the slope of the field dependence of $\lambda_\perp$ is reduced in fields of order 0.2 T, while at $T\leqslant T_M$ the value of $\lambda_\perp$ tends to saturate only in fields of order 1 T. We note that near the temperature of the martensitic transformation an aftereffect was observed in the field dependence of the magnetostriction: the deformation of the sample continued to increase for a certain time after the maximum magnetic field was reached. The temperature dependence of the transverse magnetostriction λ_s extrapolated to zero magnetic field is shown in Fig. 4. It can be seen that this quantity reaches its largest values at T_M.

The effect of magnetoelastic coupling on dynamical processes is characterized by the coefficient of magnetoelastic coupling, which is the ratio of the energy of magnetoelastic coupling to the geometric mean of the energies of the elastic and spin subsystems.[7] The temperature dependence of the coefficient of magnetoelastic coupling

$$\xi=\sqrt{\chi B^2/C\sigma_s^2}, \tag{1}$$

is determined by the magnetic susceptibility χ, the elastic modulus C, the saturation magnetization σ_s, and the characteristic value $B=\lambda_s C$ of the energy of the magnetoelastic interaction. The dependence $\xi(T)$ calculated with allowance for the temperature dependence of the elastic moduli[4] is also shown in Fig. 4. It can be seen that in the tetragonal (martensitic) phase, coupling of the elastic and magnetic subsystems is stronger than in the cubic phase, though it is most prominent at $T=T_M$.

Our results enable us to interpret the temperature dependence of the efficiency of direct conversion of electromagnetic and acoustic waves η in Ni_2MnGa single crystals.[4] In accordance with Ref. 8, the efficiency of the magnetoelastic mechanism of ultrasound generation is

$$\eta \propto (c/s)^3\xi^2\chi/\mu^2, \tag{2}$$

where c and s are the speed of light and sound, and χ and μ are the low-field susceptibility and permeability of the magnet. In the martensitic phase (at $T<T_M$), the low generation efficiency η results, as follows from Fig. 1, from the small value of the magnetic susceptibility χ. In the region of the structural phase transition (at $T=T_M$), the magnetoelastic coupling parameter ξ reaches its greatest value, as can be seen from Fig. 4. At this temperature, there is also a sharp increase in the magnetic susceptibility and a decrease in the

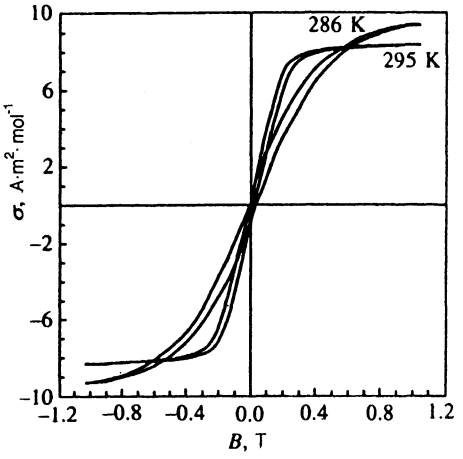

FIG. 2. Field dependence of the magnetization of an Ni_2MnGa single crystal in the ⟨110⟩ crystallographic direction near the temperature of the martensitic transformation.

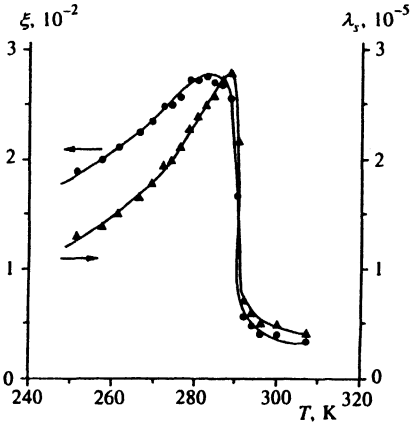

FIG. 4. Temperature dependence of the transverse saturation magnetostriction λ_s and the parameter ξ of the magnetoelastic coupling in an Ni_2MnGa single crystal in the ⟨110⟩ crystallographic direction.

shear modulus. This explains the peak in the efficiency of ultrasound generation at T_M. In the cubic phase (at $T>T_M$), efficient ultrasound generation is explained by the high magnetic susceptibility of the material together with the fairly large value of the magnetoelastic coupling parameter.

In a certain sense, application of a magnetic field to a material with magnetoelastic coupling is equivalent to the application of external pressure and loading of the sample. In materials with shape memory and superelasticity, the kinetics of the martensitic transformation are important for the manifestation of these effects. A reversible change in the size and shape of the crystal can be achieved only in the case of quasistationary loading. The pulsed magnetic fields used in this experiment to measure magnetostriction are probably capable of initiating a martensitic transformation near T_M. However, this transition takes place with a rate of change of the magnetic field that in our experiment reached 10^3 T/s. At the maximum rate of change of the magnetic field, the mechanical stresses that arose in the samples led to their failure—to cracking along cleavage planes. In the case of quasistationary variation of the magnetic field, it would probably be possible to avoid this.

Thus, our measurements of the magnetization and magnetostriction of the Ni_2MnGa single crystals explain the electromagnetic excitation of ultrasound in this material over a restricted temperature range from T_M to T_C and suggest the feasibility of controlling the size of crystals with shape memory and superelasticity by means of an external magnetic field.

[1] A. G. Khundzhua, *Introduction to the Structural Physics of Alloys with Shape Memory Effects* [in Russian], Moscow State University, Moscow (1991).

[2] E. Z. Vintaĭkin, V. A. Udovenko, D. F. Litvin *et al.*, Izv. Vyssh. Uchebn. Zaved. Fiz. No. 5, 104 (1985).

[3] V. V. Kokorin, V. V. Martynov, and V. A. Chernenko, Ser. Met. et Mat. **26**, 175 (1985).

[4] A. N. Vasil'ev, V. V. Kokorin, Yu. I. Savchenko, and V. A. Chernenko, Zh. Éksp. Teor. Fiz. **98**, 1437 (1990) [Sov. Phys. JETP **71**, 803 (1990)].

[5] A. N. Vasil'ev, A. Kaĭper, V. V. Kokorin *et al.*, Pis'ma Zh. Éksp. Teor. Fiz. **58**, 297 (1993) [JETP Lett. **58**, 306 (1993)].

[6] P. J. Webster, K. R. A. Ziebeck, S. L. Town, and M. S. Peak, Philos. Mag. B **49**, 295 (1984).

[7] *Physics Encyclopedia*, Vol. 3 [in Russian], Bol'shaya Rossiĭskaya Éntsiklopediya, Moscow (1992), p. 18.

[8] V. D. Buchel'nikov and A. N. Vasil'ev, Usp. Fiz. Nauk **162**, 89 (1992) [Sov. Phys. Usp. **35**, 192 (1992)].

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