Training of the Ni-Mn-Fe-Ga ferromagnetic shape-memory alloys by cycling in a high magnetic field

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The temperature and magnetic field dependencies of Ni-Mn-Ga polycrystals deformation are investigated. Ingot were prepared by arc-melting in argon atmosphere and further annealing. A training procedure (cycling across the martensitic transition point) for the two-way shape-memory effect was performed with Ni2+5Fe0.04Mn0.96Ga samples. Changes in sample deformations were noticed with changing the magnetic field at a constant temperature. The first cycle deformation increment as compared with the initial value (in the austenitic state at zero field) in the course of the martensitic transition was 0.29%, 0.41% and 0.48% for the second and third cycles, respectively.

I. INTRODUCTION

The Heusler alloys of Ni-Mn-Ga system are materials with well-investigated structural and magnetic properties that reveal shape-memory effect (SME) as the following process of the first-order structural phase transition (SPT). Stress and temperature-induced SPT in Ni-Mn-Ga proceeds in a similar way to that in Ni-Ti where SME was demonstrated. Alloys with SME are now used as basic elements for actuators, thermo- and magnetosensors and are widespread in technique and medicine.

Ferromagnetic order of Ni-Mn-Ga allows one to consider the alloys to be a prominent kind of "smart materials" that are to be thoroughly investigated and practically used. Predicted possibility of magnetic field controlling of the polycrystalline sample shape was proved to be correct.6–8 The magnetic field action on deformation of a NiMnGa single crystal was first investigated by Ulakkko et al.9 Associated with twin boundaries motion, deformations of about 0.2% had been induced by an external field of 8 kOe, applied along [001] axis of the crystal. The field-induced deformation of 4.3% after mechanical preloading was reported by James et al.10

In Ref. 6 the one-way magnetic-field-induced SME was demonstrated. Restorable deformation value ɛ reaches 3.5% at a 100 kOe field. In this case deformation is caused by SPT.

Magnetic properties of Ni2+5Mn1−xGa alloys are conditioned by Mn atoms at which magnetic moments of 4.17 µB are localized that is strongly more than 0.3 µB at Ni atoms.11 Thus partial substitution of Mn by Ni gives a region of concentrations x = 0.16–0.19 where magnetic and SPT are close to each other or coincide.12 SPT temperatures of these non-stoichiometric alloys most heavily depend on the applied magnetic field. Realization of a reversible magnetic-field-induced SPT at constant temperature and stress for these concentrations needs the field of about 100 kOe.13 Inclusion of Fe allows to enhance the mechanical properties of the alloy without sacrificing its magnetic and structural properties.

The present work describes an attempt of training a ferromagnetic Ni2+5Fe0.04Mn0.96Ga polycrystalline sample for two-way shape memory by magnetic field cycling across the transition point.

II. EXPERIMENTAL

Polycrystalline ingots of Ni2+5Fe0.04Mn0.96Ga were produced by arc-melting of high-purity initial elements in argon gas atmosphere on a cold bottom. For homogenisation they were annealed at 1100 K for 9 days. Then the samples of 8 × 2.5 × 0.36 mm3 were cut out. An optical method was used to perform the investigation.14 The maximal available magnetic field provided by the Biter magnet was of 85 kOe value. Ordinary weight up to 0.05 kg was used to load the sample employing the three-point method. The temperature was varied by an electric oven.

The investigated material has Curie temperature TC = 340 K higher than the finish reverse martensite transition point AF. Therefore, it is ferromagnetic both in the austenite and martensite phases. Martensite transition goes from martensite transition start temperature Ms = 312.5 K to martensite transition finish Mt = 305.5 K for untrained sample. Reverse transition points are austenite transition start Ar = 308.5 K and finish Af = 314.0 K.

The first step for the magnetic field training experiment was heating the sample to a temperature just above AF. Then the temperature was stabilized. After this the magnetic field was slowly being increased from 0 to 85 kOe (for about 3 min) to induce SPT. After a minute pause, the field was decreased at the same rate to transfer the sample back to the austenite state. This was the procedure of a single cycle.
III. RESULTS AND DISCUSSION

The procedure of temperature training has been elaborated. The temperature dependence of Ni$_{2.16}$Fe$_{0.04}$Mn$_{0.80}$Ga polycrystal deformation is depicted in Fig. 1. Non-zero initial deformation is conditioned by the load. For example, the processes during the first cycle are as follows.

The flat section of the curve from 323 to 314 K is a 100% austenite region. At $M_s = 312.5$ K the martensite transition starts. The crystal lattice transforms from cubic to tetragonal. This leads to change of volumes occupied by each phase and thus to considerable deformation of the sample. This section is the superplasticity region. At heating, one can observe the reverse process with a temperature hysteresis of about 5 K. As a result the crystal recovers its initial shape in austenite phase doing work against the external force. This loop exhibits a one-way SME. With the number of cycle maximal deformation progressively rises. This is exactly the training process.

The $M_s - M_f$ region shifts to the range of higher temperatures with the number of processed thermocycle increase. This is followed by hysteresis loop diminution.

The existence of a reversible magnetic-field-induced SPT at constant temperature in a magnetic field of about 80 - 100 kOe allows one to change the sample deformation caused by phase transition not only by temperature change, but also by magnetic field; and to train the sample for the two-way SME by this method. The field dependence of deformation for Ni$_{2.16}$Fe$_{0.04}$Mn$_{0.80}$Ga during training at a constant temperature of about 314 - 315 K and load $p = 0.5$ N is presented in Fig. 2. The $\epsilon(H)$ plots at the first, second and third cycles are shown.

Let us discuss the procedure of field cycling in more detail. As magnetic field switching off acts as a temperature rise, the graphs in Figs. 1 and 2 are reflection symmetric; and in this case we observe all the thermoelastic effects that we do at $\epsilon(T)$ dependence. These are superplasticity — actual non-elastic change of deformation during phase transition caused by crystalline lattice transformation induced by the magnetic field, and SME — the sample shape restoration at field value decrease. The deformation value at the first cycle is 0.29% for maximal martensite, at the second cycle is 0.41% and at the third cycle is 0.48% as compared with the initial value. This increasing of maximal deformation with the number of cycles indicates the possibility of attaining the two-way shape memory by magnetic field training. The incomplete recovering of deformation is caused by unstable temperature ($\pm 1$ K) and the highest available field (85 kOe) which was not enough to induce complete reverse transition.

Hysteresis loops are slightly shifted to lower fields with the cycle number increase. An effect, related to the martensitic transition start field decrease (or $M_s$ rise) and hysteresis loop diminution (in this case from 68 kOe for the first cycle to 60 kOe for the third cycle) is observed like in many materials with the SME at thermocycling (see, for example, Ref. 9) and can be explained as follows.

Vestiges of martensite plates in the form of dislocation tangles and local stress fields remain in the parent phase after the repeated formation and reversion of stress-induced martensite. The dislocation structure de-
FIG. 3: Temporal $\epsilon$ and $H$ curves of the sample during magnetic field cycling.

The plot in Fig. 3 is of an illustrative interest. Temporal dependencies of magnetic field and deformation show some delay of field-induced deformation change. This is exactly field hysteresis. The maximal deformation rise with cycle number is evident while the highest field at each cycle is the same and equals 85 kOe.

IV. CONCLUSION

In conclusion we note that the attempt to train Ni$_{2.16}$Mn$_{0.80}$Fe$_{0.04}$Ga sample by magnetic field cycling demonstrated that the material during the cycling revealed behaviour similar to that during the thermocycling.

There are two reasons related to each other to predict that magnetic field training of Ni-Mn-Ga alloys permits higher efficiency of field-induced SPT. The first reason is that the SPT tends to reverse transition in the same thermodynamic way as the direct one and this scheme also works at further cycles, the method of training is a principal factor of field-induced shape change efficiency. While second reason is that the transition induced by magnetic field switching off and on structurally differs from that induced by temperature change. So magnetic field should influence field cycling trained sample shape more strongly than the temperature cycling trained one.

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