Two-way shape memory effect and mechanical properties of Pulse Discharge Sintered Ni$_{2.18}$Mn$_{0.82}$Ga

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Mechanical and shape memory properties of a polycrystalline Ni$_{2.18}$Mn$_{0.82}$Ga alloy prepared by a PDS (Pulse Discharge Sintering) method were investigated. It was found that the material demonstrates the two-way shape memory effect after a loading-unloading cycle performed in the martensitic state, i.e. essentially without special training. The samples exhibiting the two-way shape memory effect show a significant enhancement in the magnitude of magnetic-field-induced strain.

I. INTRODUCTION

Beginning from 1996 when Ullakko and co-workers reported on a magnetic-field-induced strain of about 0.2% in a non-stoichiometric Ni-Mn-Ga single crystal, research in this field has attracted a considerable attention due to the great technological potential of this effect. Later this phenomenon was found in other compounds exhibiting shape memory effect when in the ferromagnetic state, such as Fe-Pd and Fe-Pt. Whereas Fe-Pt and Fe-Pd show magnetic-field-induced strains not exceeding 1%, in Ni-Mn-Ga single crystals the values of magnetic-field-induced strains can be as large as 6% (Ref. 4). The mechanism of this phenomenon is believed to be the redistribution of different twin variants under action of a magnetic field. Since these giant strains are attained in comparatively low magnetic fields (less than 1.5 T), they are easy suppressed by an external stress. For instance, the 6% field-induced strain was completely blocked by a compressive stress of order 2 MPa. This suggests that the giant magnetostrains arising from the process of twin-boundary motion might be useful for large stroke and small force applications.

Another way to attain a large magnetic-field-induced strain in the ferromagnetic shape memory alloys is a shift of the martensitic transition temperature caused by a magnetic field. However, in this case the magnitude of the applied field must be high in order to overcome the temperature hysteresis of martensitic transformation. From general consideration, it can be expected that the maximum achievable strain in this case is equal to the striction of the transition or even more if material is trained for the two-way shape memory effect. The work output has to be large (as in conventional shape memory alloys), which can be useful for mediate stroke and large force applications.

From the point of view of widespread use of magnetic-field-induced strains, observed in the ferromagnetic shape memory alloys, there is a need to investigate polycrystalline materials. Previous studies of a series of Ni$_{2+x}$Mn$_{1-x}$Ga ($x = 0.16 − 0.20$) showed that, among the composition studied, Ni$_{2.18}$Mn$_{0.82}$Ga is characterized by a considerable striction of transition. Because of that we have studied Ni$_{2.18}$Mn$_{0.82}$Ga prepared by a Pulse Discharge Sintering (PDS) process.

II. SAMPLES PREPARATION AND MEASUREMENTS

Ingots of the Ni$_{2.18}$Mn$_{0.82}$Ga composition were prepared by arc-melting of high-purity initial elements. The ingots were annealed at 1100 K for 9 days and quenched in ice water. A part of the arc-melted ingots was used to fabricate PDS samples. For this aim the arc-melted ingots initially were crushed into particles and ground into fine powder with a particle size less than 53 μm. Meshed powder was filled in a graphite die with two graphite punches. The die was set in a pulse discharge system (Sodick Co., Ltd). The pulse discharge system was evacuated to a vacuum of 3 Pa prior to the sintering process. Maximum pressure and temperature during the PDS process were equal to 80 MPa and 1173 K, respectively. Disc-shaped billets with thickness of 6 mm were sintered. X-ray diffraction measurements of the samples, performed in a wide temperature range, showed that the high-temperature austenitic structure has a cubic modification whereas the low-temperature martensitic phase has a complex tetragonally based crystal structure. Samples with dimensions of $3 \times 3 \times 6$ mm³ were spark-cut from the billets. Temperature and magnetic field dependencies of strain were measured by a strain gage technique. For this aim a non-magnetic strain gage with a compensated temperature range from 273 to 423 K was attached along
the longest dimension of the samples. The configuration of the experimental setup allowed detecting the relative change in the length of a specimen with an accuracy of 0.005%. The samples were inserted into a variable temperature chamber of a superconducting magnet. Temperature was monitored by a Lake Shore calibrated platinum resistance thermometer with an accuracy of 0.1 K. Stress-strain measurements and compression of samples were done at room temperature by an Instron machine.

III. RESULTS AND DISCUSSION

Shown in Fig. 1 are the temperature dependencies of Young’s modulus of a Ni$_{2.18}$Mn$_{0.82}$Ga PDS sample during heating and cooling. These dependencies were obtained from ultrasonic measurements performed in a temperature interval from 173 to 373 K. The value of Young’s modulus was evaluated through the formula

$$E = \rho \frac{v_l^2 (3v_l^2 - 4v_s^2)}{(v_l^2 - v_s^2)},$$

where $\rho$, $v_l$ and $v_s$ are the density of the material and the velocities of longitudinal and shear waves, respectively. Marked dips on the temperature dependencies of Young’s modulus correspond to the direct and reverse martensitic transformations. As evident from Fig. 1, the Young’s modulus of Ni$_{2.18}$Mn$_{0.82}$Ga at room temperature is equal to 95 GPa.

The results of compression tests for Ni$_{2.18}$Mn$_{0.82}$Ga prepared by the PDS method and by a conventional arc-melting technique are shown in Fig. 2. The compression tests were done at room temperature with the same speed of compression for both the samples. The comparison of these curves clearly indicates that the PDS sample shows higher yield strength than the arc-melted one. This characteristic is of importance for some practical applications, and it makes the PDS materials more attractive in this sense.

Figure 3 shows the temperature dependencies of strain measured in a Ni$_{2.18}$Mn$_{0.82}$Ga PDS sample upon cooling and heating in zero and 5 T magnetic fields. In zero magnetic field the sample length monotonously increases upon heating up to the onset of the reverse martensitic transformation, $A_s = 343$ K. The martensite - austenite transformation is accompanied by a rapid increase in the sample length, which flattens out at austenite finish temperature $A_f = 357$ K. Subsequent cooling down results in the direct martensitic transformation at $M_s = 342$ K, which is accompanied by a shortening of the sample. As evident from Fig. 3, the striction of the transition is approximately 0.18%. The temperature dependencies of strain measured in a magnetic field of 5 T revealed that the striction of the transition remains essentially the same as in the case of the measurements without
magnetic field. The results of the measurements performed in zero and 5 T magnetic fields leads to the conclusion that the application of the magnetic field results in an upward shift of the characteristic temperatures of the martensitic transition with a rate of about 1 K/T. This value agrees very well with the results reported for polycrystalline Ni$_{2+y}$Mn$_{1-x}$Ga prepared by arc-melting method.

An interesting feature of the PDS samples is that the two-way shape memory effect can be induced in these materials by a simple loading - unloading cycle. This feature is presented in Fig. 4. Indeed, the increase in the sample length caused by the martensitic transition is approximately 0.18% in the case of the sample which was not subjected to compression. Another sample cut from the same ingot was compressed for 2% at room temperature in the martensitic state. After unloading the residual deformation was approximately 1.2% (Fig. 2). The sample recovered approximately 75% of its initial length upon the first heating, showing shape memory effect. The subsequent cooling - heating process revealed that for this sample the change in the length associated with the martensitic transformation increased twofold as compared with the uncompressed sample and reached 0.4%. It is also seen from Fig. 4 that the change in slope of the curves at the characteristic temperatures of martensitic transformation in the compressed sample becomes less pronounced than in the compression-free sample. Further themocyclings demonstrated that this compression-induced two-way shape memory effect does not degrade and the 0.4% change in the length of the sample is very well reproducible at least up to the tenth heating - cooling cycle. It is interesting to note that a well-defined two-way shape memory effect has also been found recently in Ni-Mn-Ga thin films.

To study this compression-induced two-way shape memory effect in more detail, several Ni$_{2+y}$Mn$_{1-x}$Ga PDS samples were compressed for values of strain, ranging from 1 to 6%. After unloading the residual deformation in these samples was from 0.4 to 4%, respectively. The behavior of the samples upon the first heating process was found to be dependent on the value of residual deformation. Thus, the sample with 0.4% residual deformation showed a perfect shape memory effect whereas the sample with the largest residual deformation did not exhibit shape memory effect, which means that the residual deformation in this sample was essentially plastic one. The two-way shape memory effect was found only in the samples compressed for 2 and 3%. Together with the observation that the sample compressed for 2 and 3% did not revert the original shape completely after the first heating, these facts evidence that the two-way shape memory effect appears when the applied stress exceeds some critical limit which is enough for the occurrence of an irreversible slip. We suggest that it arises from the strain field of dislocations induced upon compression.

The measurements of magnetic-field-induced strain...
shape memory effect the magnetic-field-induced strain is six times greater as compared to the samples without two-way shape memory effect. In fact, such a tendency could be expected, since in this case the magnetic-field-induced strain is due to the shift of the martensitic transition temperature caused by the applied magnetic field. The magnetic-field-induced strain is proportional to the relative change in the dimension of the sample per 1 K and this characteristic is much better in the samples with the two-way shape memory effect. It can be suggested that an appropriate training procedure of the PDS material will result in enhancement of the magnitude of the two-way shape memory effect, leading to an increase in the value of magnetic-field-induced strain. It should be noted, however, that the strain of about 0.12% is not perfectly recovered. Figure 5 shows that the reversible magnetic-field-induced strain is equal to 0.06%. This value of magnetic-field-induced strain has been reversible for many cycles of application and removal of the magnetic field.

IV. CONCLUSION

In conclusion, the most interesting findings of this study are that the two-way shape memory effect can be induced in the Ni$_{2.18}$Mn$_{0.82}$Ga PDS materials by an ordinary compression of the samples in the martensitic state. The samples with the two-way shape memory effect show a significant enhancement in the magnitude of magnetic-field-induced strain observed in the temperature interval of martensitic transformation.

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