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Temperature dependence of transformation strain and magnetic-field-induced strain in $Ni_{51}Mn_{24}Ga_{25}$ single crystal

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Abstract

The martensitic transformation strain up to 0.6% has been obtained in $Ni_{51}Mn_{24}Ga_{25}$ single crystalline sample, which is attributed to the effect of preferential orientation of the martensite variants, resulted from the internal stress introduced by the directional solidification. An enhanced transformation strain up to 1.1 % is observed with a bias magnetic field of 1.2 T. There is a large difference of $MFIS_{max}$ (λ_{max}) from about 600 to 1300 ppm in the temperature range from 192 to 236 K in martensite phase. Based on the shear actuation model, the magnetocrystalline anisotropy energy and the energy for twin variants reorientation as a function of the temperature have been discussed. We proposed that the rate of the decrement of shear modulus (C') with respect to the temperature is much larger than that of the magnetocrystalline anisotropy (K) as a result of the constraint $\lambda_{max} = K/C'\gamma_t$, which has been considered as the reason for the increasing $MFIS_{max}$ with increasing temperature.

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Keywords: NiMnGa; Magnetic shape memory alloy; Magnetic-field-induced strain; Magnetocrystalline anisotropy energy

1. Introduction

Ni_2MnGa alloy exhibits a shape-memory effect upon the martensitic transformation and a magnetic-field-induced strain (MFIS) [1–4] in martensite. The MFIS as a function of magnetic field at a constant temperature has been preciously studied. The MFIS of 0.2% at 265 K [2] and 1.3% at 258 K [5] have been reported. Recently, giant MFIS of 6% [6] and 9.5% [7] at room temperature have been also achieved. Up to now, there have only been a few reports of the temperature dependence on the MFIS of NiMnGa alloy. In this paper, the temperature dependence on the MFIS of single crystalline $Ni_{51}Mn_{24}Ga_{25}$ was investigated. The change of the magnetocrystalline anisotropy energy with increasing temperature was studied. The reason for increasing MFIS with temperature was analyzed on the basis of the shear actuation model proposed by Murray et al. [8]. In addition, a two-way transformation strain without magnetic field and an enhanced strain under a magnetic field of 1.2 T along the strain-measuring direction were observed in the oriented crystal.

2. Experiment

Starting materials of $Ni_{51}Mn_{24}Ga_{25}$ with 230 K for the martensite start temperature (M_s) and 240 K for austensite start temperature (A_s) were synthesized by arc melting high purity Ni, Mn and Ga elements into the buttons for three times. The master rods with a diameter of 7.2 mm and length of 100 mm were then obtained by casting in a chilled copper mold. Preferentially oriented rods were prepared by the vertical zone melting unidirectional solidification method at a rate of 0.3 mm min^{-1}. The preferred crystal growth orientation was identified to be [0 0 1] along the rod axis [9]. Samples of 6 mm × 4 mm × 2 mm pieces with the growth direction along

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the specimen length were used for the strain measurements by standard strain gauges. The MFIS is measured in a given temperature range (192–236 K). The sample was first cooled down to 192 K (below the martensite finish temperature M_f point of 229 K) without applying magnetic field. We apply a magnetic field from 0 to 2 T along the strain-measuring direction. We measure the MFIS at temperature intervals of about 3 K. Magnetization measurements of powder sample were performed in a superconducting quantum interference device (SQUID, Quantum Design MPMS). The MFIS and transformation strain were measured along [0 0 1] direction with magnetic field applied in strain-measuring direction.

3. Results and discussion

Ni_2MnGa alloy undergo a thermoelastic martensite transformation and constitute a new family of shape memory alloys. It also has magnetic-field-controllable shape memory effect [8]. Fig. 1 shows the strain of sample as a function of temperature upon the martensitic transformation measured in the growth direction without (curve a) and with a bias magnetic field of 1.2 T (curve b) in single crystal $Ni_{51}Mn_{24}Ga_{25}$. The martensite transformation occurs at 230 K on cooling and it causes a strain of 0.6%. During heating, the reverse transformation takes place at 240 K and the strain is entirely recovered. A two-way transformation strain was observed and the temperature hysteresis for martensitic transformation is 10 K. Generally, such large transformation strain is not expected to occur due to the random arrangement of the martensite variants [10]. This large transformation implies the existence of the preferred orientation of the martensite variants along the growth direction, which is considered as the effect of the axis stress caused by the unidirectional solidification during the growth [9]. The strain up to 1.1%, near two times higher than that observed without applying magnetic field has been obtained. The bias magnetic field of 1.2 T was applied on the strain-measuring direction, consistent with the intrinsic preferential orientation direction. This result indicates that the magnetic field can drive more variants to further orient in the field direction as the sample carried out martensitic transformation.

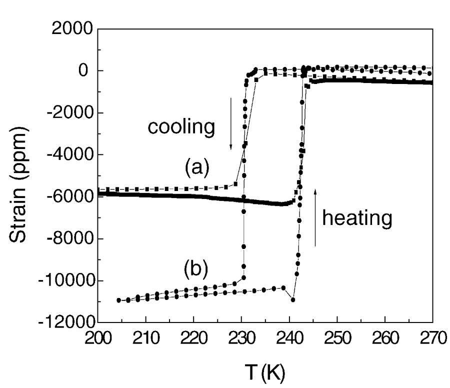

Fig. 1. Strain vs. temperature curves measured (a) without a field and (b) with 1.2 T field bias applied in the growth direction of $Ni_{51}Mn_{24}Ga_{25}$ single crystalline specimen.

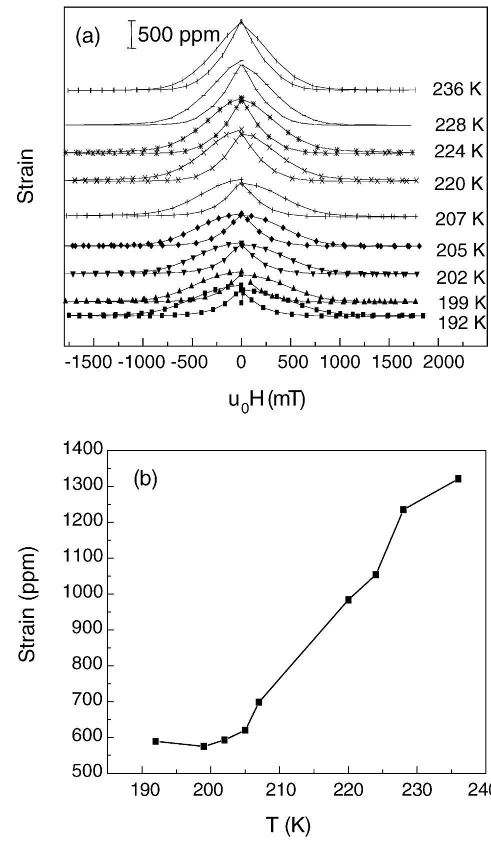

Fig. 2. (a) Magnetically-field-induced strain curves measured in the martensitic phase at 192, 199, 202, 205, 207, 220, 224, 228 and 236 K along the crystal growth direction of the $Ni_{51}Mn_{24}Ga_{25}$ single crystal. (b) Temperature dependence of the $MFIS_{max}$ under the magnetic field of 1.2 T.

Fig. 2(a) shows MFIS measured as a function of magnetic field along the growth direction at different temperatures in martensite. After the sample was cooled down to 190 K in the absence of the magnetic field, we applied a magnetic field from 0 to 2 T and measured the MFIS at 192, 199, 202, 205, 207, 220, 224, 228 and 236 K. It can be seen that the obtained MFIS was reversible and reached saturation at the field of about 0.8 T. This reversible behavior was similar to that previous reported by Ullakko et al. [2]. It was well known that the magnetic field controls the reorientation of the twin variants was in an analogous way as the twin variants are controlled by stress in conventional shape memory alloys. The MFIS can be obtained when the magnetocrystalline anisotropy energy comparable to or greater than the energy required to reorient the twin variants [2].

Based on O'Handley's [11] model, the maximum strain output can be written as

$$\lambda_{max} = \frac{M_s H}{2Ce_0} \tag{1}$$