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Effect of external stress and bias magnetic field on transformation strain of heusler alloy Ni-Mn-Ga ①

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Abstract: The influence of external field(magnetic field and stress field) on the transformation strain of $Ni_{52.9}$-$Mn_{24.4}Ga_{22.7}$ single crystal were investigated and its mechanism was also discussed. When thermally martensitic transformation occurs, about 0.25% transformation strain is obtained which may be obviously enhanced to about 0.8% by a 6 000 Oe magnetic bias field. However, the strain decreases by the external compress stress loaded along the strain-measured direction. When the external compress stress and bias magnetic field are simultaneously applied, the transformation strain decreases with increasing the magnetic field, which is related to the rearrangement of the martensite variants influenced by the external field.

Key words: $Ni_{52.9}Mn_{24.4}Ga_{22.7}$ single crystal; external compress stress; bias magnetic field; transformation strain

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1 INTRODUCTION

In the last decades, ferromagnetic shape memory alloy have been attracting investigations emerged as a new class of active materials showing very large reversible strain, short reaction time. As for such materials, Ni-Mn-Ga, Fe-Pd, Fe-Pt and Co-Ni were reported[1-9]. Ni_2MnGa, as the only known ferromagnetic intermetallic compound undergoing a martensitic transformation from a cubic structure to a tetragonal structure, has received more and more attention. And large magnetic-field-induced strains based on twin boundary movement were observed in non-stoichiometric Ni_2MnGa below the martensitic transformation temperature. Murry et al[10] reported that about 6% magnetic-field-induced strain has been measured on Ni-Mn-Ga single crystal when about 0.1 MPa compression stress is present. Wang et al[11] reported about 1% transformation strain in $Ni_{52}Mn_{24}Ga_{24}$(mole fraction, %) single crystal when single crystal undergoes the thermally martensitic transformation and this strain can be enhanced to about 4.0% by the external bias field. Various models have been established in which the strain is attributed to magnetic-field-induced reorientation of martensitic twin variant[12-14]. In the current paper, the influences of external field(magnetic field and stress field) on the transformation strain of Ni-Mn-Ga single crystal were investigated. It is interesting to note that the transformation strain was largely enhanced by external bias magnetic field. However, it decreased with increasing the magnetic field intensity when the bias magnetic field and compression stress simultaneously applied. These characteristics can be attribute to the preferential orientation of the martensitic variants induced by external field.

2 EXPERIMENTAL

A single crystal of $Ni_{52.9}Mn_{24.4}Ga_{22.7}$(mole fraction, %) alloy was used for present study, and the single crystals were grown in [100] direction of the cubic parent phase by the Czochralski method. The starting materials for the crystal were prepared from metal elements Ni, Mn, Ga with purity of 99.9%. The grown single crystal was annealed at 1 073 K for 48 h to homogenize and then quenched into water for high chemical ordering. The martensitic transformation temperatures were determined by DSC, and the rate of temperature variation during heating and cooling is equal to 3 K/min. The single crystals were oriented by back-reflection Laue diffraction, then cut into the 1 mm × 3 mm × 3 mm pieces with the length direction paralleled to the [100] direction. The metal strain gauges with maximum measurement of 5% and the highly elastic epoxy resin were utilized to ensure the measurement reliability and avoid the gauge debonding.

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3 RESULTS AND DISCUSSION

Fig. 1 shows the DSC curves for the annealed single crystal, in which the upside one represents the exothermal curve and the downside one represents endothermal curve. An exothermic peak and an endothermic peak are observed during the cooling and heating, respectively. The phase transformation temperatures can be measured as follows: M_s= 360 K, M_f= 347 K, A_s= 368 K, A_f= 375 K.

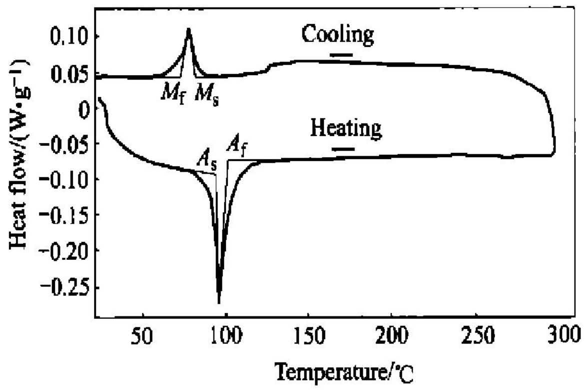

Fig. 1 DSC curves for annealed $Ni_{52.9}Mn_{24.4}Ga_{22.7}$ single crystal

Fig. 2 shows the strain versus temperature curve in the [100] direction without an applied magnetic field or external stress. In the cooling run, the sample shrinks about 0.30% in the longitudinal [100] direction at about 360 K, the start temperature for martensitic transformation. In the heating run, the reverse martensitic transformation occurs at 365 K, and the deformation is completely recovered when the reverse martensitic transformation is over. And this strain loop can be reproduced many times when the sample is thermal-cycled in the temperature range between M_f and A_f.

Generally speaking, a self-accommodation effect usually occurs in familiar martensitic transformation materials to distribute the variants on a rough average in every crystal direction so the transformation strain is about zero and the free energy of the system keeps minimum. Thus the results imply that an internal stress caused by the directional solidification during the single crystal growth has imposed to the experimental samples to reduce the self-accommodation of matensite variants and established a preferential orientation of the variants.

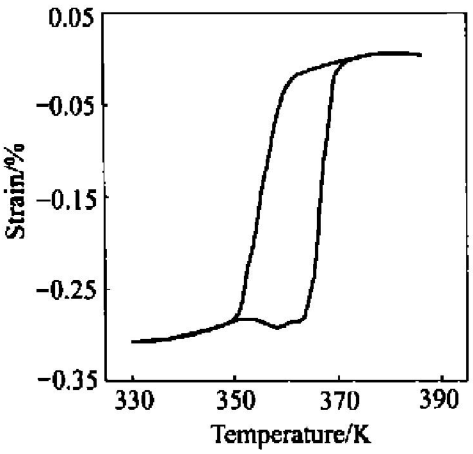

Fig. 2 Strain versus temperature without external magnetic field or stress

Fig. 3 shows the strain versus temperature curves taken in the [100] direction with a biasing magnetic field applied along the [100] direction, the strain-measuring direction. It has been found that the strain in the [100] direction increased from 0.26% to 0.80% with the bias field from 0 Oe to 6 kOe. The strain enhanced by magnetic field is about 0.54%. It is interesting to note that the magnetic field has no obviously influence on the phase transformation temperatures and the transformation temperature hysteresis, which indicates that the mechanism of field-enhanced strain in this material is the magnetic-field-induced reorientation of martensitic twin variant established by twin boundary motion, not the magnetic-field-induced martensitic transformation. And the magnetic field energy is not involved in the free energy of the phase transformation.

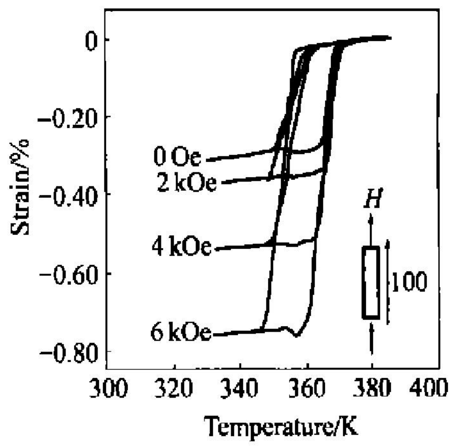

Fig. 3 Transformation strain versus temperature under bias magnetic field

The transformation strain versus temperature curves were measured in the [100] direction of the sample with a compress stress about 0.1 MPa applied along the [100] direction, as shown in Fig. 4. The strain is dramatically decreased to about 0.15% under about 0.1 MPa stress, decreasing by about 50% compared to the transformation strain without the stress.

The strain—temperature curves were also measured when a biasing magnetic field and a compression stress were simultaneously applied along [100] direction, the strain-measuring direction. The result is shown in Fig. 5. The compression stress was first loaded on the sample, then the sample was heated and cooled under the 2 kOe magnetic field, and a strain of about 0.15% was ob-

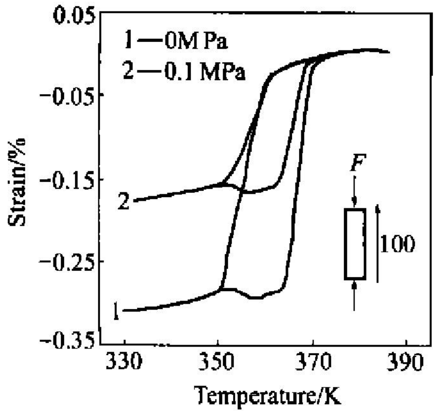

Fig. 4 Strain versus temperature curves measured with external compression stress

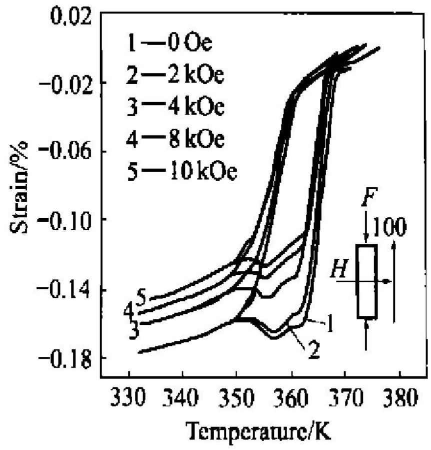

Fig. 5 Strain- versus- temperature curves measured when bias magnetic field and 0.1 MPa compression stress simultaneously applied

tained. Then the transformation strain was measured at 4 kOe, 6 kOe, 8 kOe and 10 kOe, respectively. It can be seen that when the magnetic is lower than 4 kOe, the transformation strain is almost not changed with increasing the magnetic field. However, when the magnetic field is over 4 kOe, the transformation strain is obviously decreased with increasing the magnetic field. When 8 kOe magnetic field applied, the transformation strain achieved a stable value. With increasing the magnetic field further, the transformation strain is kept stable. As mentioned above, the transformation strain could be greatly enhanced by the external magnetic field, which has been attributed to the increasing of the volume fraction of favorable variants present through the twin boundary motion induced by external magnetic field. However, it is interesting to note that in our experiment, when the compression stress and a bias magnetic field simultaneously applied, the transformation strain decreased with increasing the magnetic field.

As we known, twin boundary motion results in the rearrangement of the martensite variants configuration to minimize the system energy when external field applied. Thus when bias magnetic field and stress applied, two stable states can be defined: one stable under bias magnetic field, the other stable under load, and a mobile twin boundary allows the sample to switch between these two states. The two stable states and the intermediate state of a twinned sample are schematically shown in Fig. 6.

Under loading, the change of the free energy can be represented as strain energy($\sigma \cdot \varepsilon_0$), which drive the twin boundary motion to the rearrangement of the martensite variants. For the magnetic field, the change can be shown as Zeeman energy($\boldsymbol{M} \cdot \boldsymbol{H}$), in which M refers to the saturated magnetization and H refers to the external magnetic field. When an axial load and bias magnetic field simultaneously applied, there are two energy variables, and one of them will dominate another. If the effect of the strain energy is greater than that of the magnetic energy, the twin boundaries should be migrated to favor the variants that is stable under stress; or else, the system will release the energy by migrating the twin boundaries to

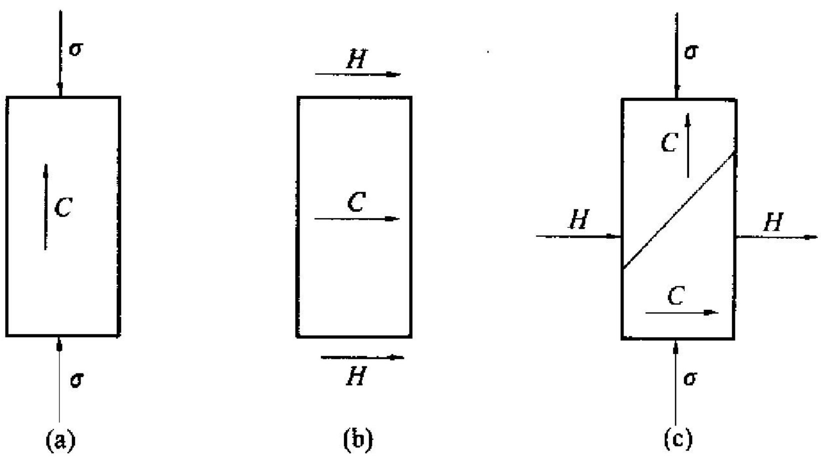

Fig. 6 Schematic of effect of external field on rearrangement of martensitic variants
(a) —Stable variants under axial load; (b) —Stable variant under transverse field;
(c) —Twin boundary linking two

rotate the magnetization until the sample has arranged its variants configuration into the stable state for magnetic energy. Furthermore, a certain part of the favorable energy must be used to dispel the unfavorable energy in this case. In present study, the strain energy is the favorable energy. When the magnetic field perpendicular to the stress direction applied, the part of strain energy should be used to dispel the effect of magnetic field. Thus, when magnetic field and stress simultaneously applied, the energy used to drive the twin boundary motion is lower than that of the pure stress state. As the twin boundary motion need to overcome the energy barrier, it is reasonable to believe that the amount of the moving twin boundary is decreased. Consequently, the transformation strain decreased with increasing the magnetic field when the axial stress and magnetic field simultaneously applied.

4 CONCLUSION

The 0.25% transformation strain is obtained in the single crystal growth direction, and this strain can be obviously enhanced by about three times, up to 0.8% with a 6 kOe magnetic bias field. However, the strain decreased to about 0.15% by 0.1 MPa compression stress loaded along the strain-measured direction. When the external compression stress and bias magnetic field simultaneously applied, the transformation strain decreases with increasing the magnetic field, which related to the rearrangement of the martensitic variant.

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