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Magnetic shear stress for the rearrangement of martensite variants in stoichiometric Ni_2MnGa

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Magnetization curve and stress-strain curve associated with rearrangement of martensite variants of a stoichiometric Ni_2MnGa single crystal were examined. The energy dissipation due to rearrangement of variants by magnetic field is almost the same as that by external stress, suggesting that two paths are essentially identical. The uniaxial magnetocrystalline anisotropy constant K_u is derived from magnetization curve at 77 K to be about 350 kJ/m^3. The shear stress required for the rearrangement of variants (τ_{req}) lies between 1.0 and 1.7 MPa at 80 K. Optical microscope observation shows that rearrangement of variants occurs partly under the [110] field, although it occurs perfectly under the [001] field. This behavior was explained by comparing τ_{req} with the magnetic shear stress evaluated from K_u.

Key words: magnetocrystalline anisotropy, mechanical twinning, shear stress, nickel-manganese-gallium

1. INTRODUCTION

Nickel-manganese-gallium alloys have attracted considerable attention because they exhibit giant magnetic field-induced strain (MFIS) due to rearrangement of martensite variants [1]. The rearrangement of variants by magnetic filed is considered to occur because magnetic shear stress generated by magnetic field (τ_{mag}) exceeds the stress required for the migration of twinning plane (τ_{req}). The comparison of τ_{mag} and τ_{req} has been made for some non-stoichiometric alloys whose martensitic transformation temperature is higher than room temperature [2]. For clarifying the mechanism of rearrangement of variants, however, investigation of the stoichiometric Ni_2MnGa is basically important, although its martensitic transformation temperature is far below the room temperature. One reason is that some fundamental physical properties have been examined by using this alloy. Despite such importance, there are few reports related to rearrangement of martensite variants in the stoichiometric Ni_2MnGa.

In this paper, therefore, we examine MFIS, magnetization curve and stress-strain curve associated with rearrangement of martensite variants of stoichiometric Ni_2MnGa. We also compare τ_{mag} evaluated from magnetocrystalline anisotropy constant with τ_{req} obtained from the stress-strain curve. Furthermore, influence of field direction on the rearrangement of variants is examined.

2. EXPERIMENTAL PROCEDURE

A single crystal of the stoichiometric Ni_2MnGa was grown by a floating zone method. From the single crystal, specimens for the measurements described below were cut out. These specimens were subjected to homogenization heat treatment at 1073 K for 100 h followed by ordering heat treatment at 923 K for 3h. The martensitic transformation temperature and Curie temperature of the present alloy were 202 K and 376 K, respectively.

The MFIS was measured by a sensitive three terminal capacitance method. The magnetization was measured by a superconducting quantum interference device (SQUID) magnetometer. Compressive test was made with a constant strain rate of 1×10^{-2} mm/s. Optical microscope observation was made with Nomarski-type differential interference optics.

3. RESULTS

MFIS was measured by applying magnetic field along $[001]_P$ ("P" stands for the parent phase) after cooling down to 77 K under zero magnetic field, and the strain induced along the $[001]_P$ direction is shown in Fig. 1. The saturated MFIS is about −3.8 %, and after this process, a single variants state is obtained. The variant selected to grow is the one whose c axis (easy axis) lies along the field direction.

In order to confirm the rearrangement of variants, we made optical microscope observation and the result is shown in (a), (b) of Fig. 2. The banded surface relief of twinned martensite before field application (Fig. 2(a)) changed to the flat surface of single variant under the $[001]_P$ field (Fig. 2(b)). Similar experiment was made under other field directions. Under the $[110]_P$ field, rearrangement of variants occur only in a part of the whole specimen, i.e., while the upper left region of (c) is changed, other region remained. On the other hand, under the $[111]_P$ field, the rearrangement of variants does not occur at any region, i.e., the twinned surface relief shown in (e) is the same as that in (f).

In order to understand the above behavior, we examined magnetization measurement and compressive tests, and the results are shown in Figs 3 and 4, respectively. In Fig. 4, the vertical axis is converted to the resolved shear stress

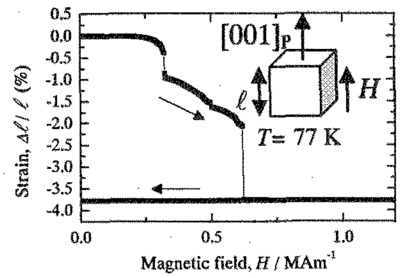

Fig. 1 Magnetic field induced strain at 77 K after zero-field-cooling.

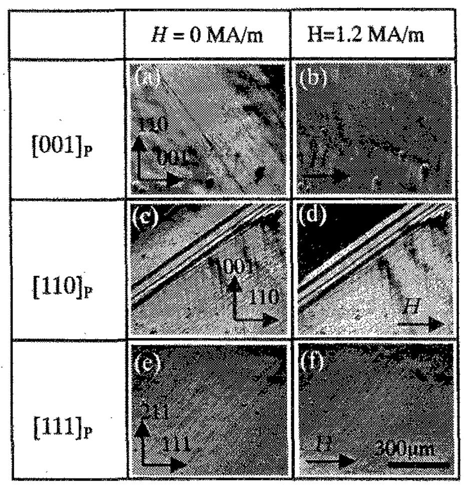

Fig. 2 Optical micrographs showing the rearrangement of variants at 80 K after zero-field-cooling. Magnetic field up to 1.2 MA/m is applied along $[001]_P$, $[110]_P$ and $[111]_P$ directions.

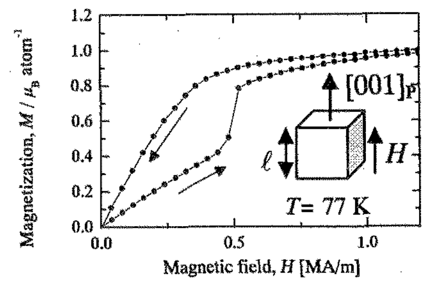

Fig. 3 Magnetization curve associated with rearrangement of variants at 77 K.

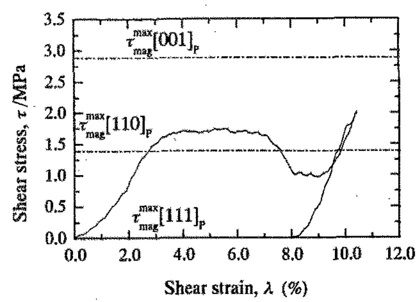

Fig. 4 Stress-strain curve at 80 K obtained from compressive test along $[110]_P$ direction. The vertical axis is converted to the resolved shear stress. The shaded area is the region in which τ_{req} lies.

acting across the twinning plane. The area of hysteresis of the magnetization curve corresponds to the energy dissipation due to the twinning plane migration under the magnetic field, and the area of the hysteresis of the stress-strain curve divided by the Schimidt factor (0.25) corresponds to the energy dissipation due to the twinning plane migration under the external stress: these two energy dissipation are almost identical, suggesting that the path of the rearrangement of variants by magnetic field is essentially the same as that by external stress. From the magnetization curve, we estimated the magnetocrystalline anisotropy K_u to be about 350 kJ/m^3, based on the equation $|K_u|=H_A M_s/2$, where H_A (0.74 MA/m) is the anisotropy field and M_s (0.95 T) is the spontaneous magnetization. This value is nearly the same as that reported for a non-stoichiometric alloy [3]. The τ_{req} obtained in this study (1.0 ~ 1.7 MPa) is the same order as that reported for non-stoichiometric Ni-Mn-Ga alloy at room temperature [4], and it is lower than that reported previously for the stoichiometric Ni_2MnGa. [5] In the following, we discuss the influence of the field orientation by considering shear stresses acting across the {101} twinning plane along the <101> direction. Under a magnetic field, a shear stress τ_{mag} should be generated by the magnetic field. This shear stress τ_{mag} will be expressed as $\tau_{mag}= \Delta U_{mag}/s$, where ΔU_{mag} is the difference between the magnetic energy before and after the rearrangement of variants, and s is the twinning shear (0.124 at 77 K). The maximum value of ΔU_{mag} is the magnetocrystalline anisotropy constant K_u under the $[001]_P$ field; it is $K_u/2$ under the $[110]_P$ field; and it is zero under the $[111]_P$ field. Then, the maximum of τ_{mag} is obtained to be 2.8 MPa under the $[001]_P$ field, 1.4 MPa under the $[110]_P$ field and 0 MPa under the $[111]_P$ field; these values are indicated by lines in Fig. 4. By comparing τ_{mag} and τ_{req}, we notice that the maximum of τ_{mag} is larger than the region of τ_{req} under the $[001]_P$ field, but it lies in the region of τ_{req} under the $[110]_P$ field. These relations explain semi-quantitatively the reason why the rearrangement of variants occurs perfectly under the $[001]_P$ field but imperfectly under the $[110]_P$ field. That is, under the $[110]_P$ field, τ_{mag} does not become sufficiently larger than τ_{req}.

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