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Crystallographic Orientation Dependence of Magnetic Field-Induced Strain in an Fe-31.2at.%Pd Alloy

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The present work reports how three martensite variants of an Fe-31.2at.%Pd single crystal convert under the magnetic field H along $[001]_P$, $[011]_P$ and $[111]_P$ (P represents parent phase), respectively. Thermal expansion measurement and optical microscope observation were made in the field-cooling process. When H // $[001]_P$, three variants almost perfectly convert into the variants with a-axis parallel to the magnetic field but when H // $[011]_P$, they do not perfectly convert or when H // $[111]_P$, they hardly convert. This behavior is explained if we assume that the stress required for the movement of the twinning plane increases as the conversion of variants proceeds.

Key words: iron-palladium alloy, ferromagnetic shape memory alloy, magnetocrystalline anisotropy, magnetostriction

1. INTRODUCTION

Recently, a ferromagnetic shape memory alloys have attracted attention since Ullakko *et al.*[1] found a Ni-Mn-Ga single crystal exhibited giant strain by applying the magnetic field. Disordered Fe-Pd alloys containing nearly 30at.% of Pd are also the material showing such a large magnetic field-induced strain (MFIS)[2,3]. They exhibit an Invar effect[4] below their Curie temperature of about 600 K and a thermoelastic transformation from an f.c.c. structure to a tetragonal, so-called f.c.t. structure[5] whose a-axes are easy axes. The martensite is composed of three variants which are connected with each other on the (011) twinning plane[5]. According to our results, when magnetic field is applied to an Fe-31.2at.%Pd single crystal along $[001]_P$, a large MFIS of about 3 % appeared[3]. However, crystallographic orientation dependence of MFIS is not reported until now. This MFIS appears when variants convert in order that the difference of magnetocrystalline anisotropy energy between variants can be lowered. When magnetic field H // $[001]_P$, the maximum difference of magnetocrystalline anisotropy energy between variants ΔU_{max} is K_u, where K_u is the uniaxial magnetocrystalline anisotropy constant. It is expected that conversion of variants will also occur when H // $[011]_P$ as well as $[001]_P$ because ΔU_{max} is $K_u/2$ for this orientation. On the other hand, conversion of variants cannot be expected when H // $[111]_P$ because ΔU_{max} is 0.

In the present study, we report how three martensite variants of Fe-31.2at.%Pd convert under the magnetic field along $[001]_P$, $[011]_P$ and $[111]_P$, respectively.

2. EXPERIMENTAL PROCEDURE

A single crystal of Fe-31.2at.%Pd was prepared by floating zone method in argon atmosphere. Two rectangular parallelepiped specimens were cut from the single crystal. One has the dimension of 3.7 mm along $[001]_P$, 3.1 mm $[011]_P$ and 3.1 mm $[01\bar{1}]_P$. The other has the dimension of 1.6 mm along $[111]_P$, 1.9 mm $[1\bar{1}0]_P$ and 2.1 mm $[11\bar{2}]_P$. The specimens were homogenized at 1373 K for 24 h, followed by quenching into iced water. MFIS and thermal expansion were measured by a capacitance or strain gauge method. In these measurement, magnetic field was applied along $[001]_P$, $[011]_P$ or $[111]_P$ and strain was measured along $[001]_P$, $[011]_P$ or $[111]_P$, respectively. Optical microscopy observation was made during the field-cooing process.

3. RESULTS AND DISCUSSION

Thermal expansion was first measured from room temperature to 77 K under the magnetic field of 3.2 MA/m along $[001]_P$, $[011]_P$ and $[111]_P$, respectively. On cooling, the strain along $[001]_P$ begins to increase at about M_s = 230 K and reaches 1.9 % at 77 K. According to calculation of the variant fraction by using the lattice parameters[3], the fraction of the variants with a-axis parallel to the magnetic field along $[001]_P$ is almost 100 % at 77 K, which means almost perfect conversion of variants occurred. In contrast, when field direction is $[011]_P$ or $[111]_P$, the thermal expansion was much smaller than that expected from perfect conversion of variants.

Subsequently, the field-cooling process was observed by optical microscopy. Fig.1 shows a series of micrographs taken in a successive cooling process under magnetic field H // $[001]_P$. In parent phase, surface relief is not observed [Fig.1(a)]. Below M_s, the bright and dark contrast of surface relief is partly observed [Fig.1(b)]. On further cooling, the bright band becomes narrower and the dark one wider [Fig.1(c)]. Finally, the surface relief is hardly observed [Fig.1(d)]. When H // $[011]_P$, the surface relief appears below M_s [Fig.2(b)]. On further cooling, the region of the surface relief spreads and the ratio of the bright band width to the dark band one changes [Fig.2(c)], but the surface relief does not disappear [Fig.2(d)]. When H // $[111]_P$, the surface relief appears below M_s [Fig.3(b)], and its contrast becomes sharper and sharper as the specimen is cooled down [Fig.3(c), (d)]. However, the arrangement of variants does not change. These observations in Fig.1, 2 and 3 are in good agreement with above MFIS measurement.

From the results of the MFIS measurement and the optical microscope observation, three variants are found to convert almost perfectly when H // $[001]_P$, but not to convert perfectly when H // $[011]_P$ or to convert hardly when H // $[111]_P$. The results of the $[001]_P$ and $[111]_P$ direction are consistent with the expectation, but that of the $[011]_P$ direction is not. This behavior is explained if we assume that the stress required for the movement of the twinning plane τ increases as the conversion of variants proceeds. That is, when H // $[001]_P$, $\tau \cdot S < K_u$ is always satisfied during the conversion of variants, where S is the twinning shear. On the other hand, when H // $[011]_P$, $\tau \cdot S < K_u/2$ is satisfied at the early stage but is not after conversion of variants has partly proceeded.

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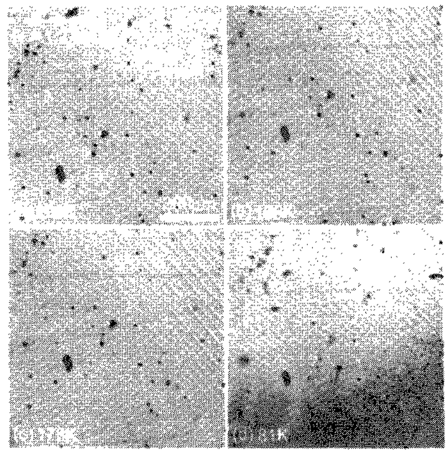

Fig.1 Optical micrographs of Fe-31.2at.%Pd in cooling process under the magnetic field along the $[001]_P$ direction.

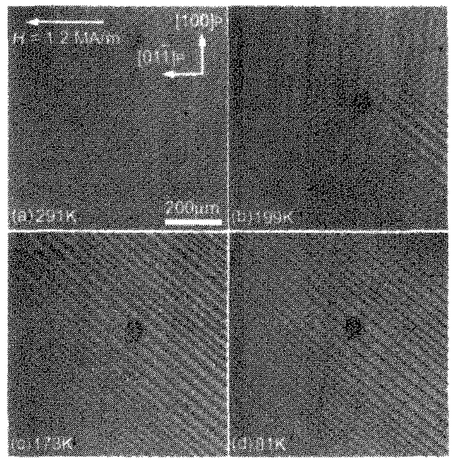

Fig.2 Optical micrographs of Fe-31.2at.%Pd in cooling process under the magnetic field along the $[011]_P$ direction.

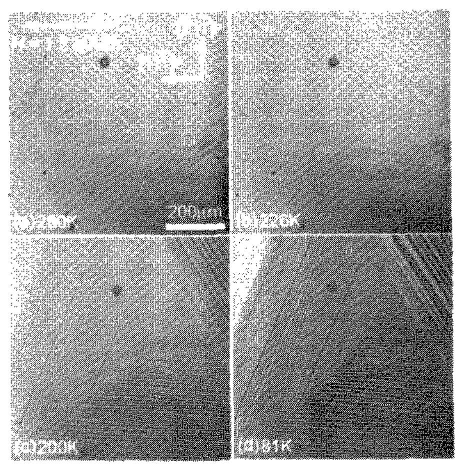

Fig.3 Optical micrographs of Fe-31.2at.%Pd in cooling process under the magnetic field along the $[111]_P$ direction.