Magnetic Field-Induced Martensitic Transformation in Single Crystals of Fe-31.6 at%Ni Alloy*

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The magnetic field-induced martensitic transformation in Fe-31.6 at%Ni alloy single crystals, whose length-wise directions are nearly parallel to $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$, has been studied to clarify the influence of grain boundaries and crystal orientations on the transformation behavior by measuring magnetization and by observing microstructure, applying a pulsed ultra high magnetic field parallel to the length-wise directions. As a result, the following were found: (i) The critical magnetic field to induce martensitic transformation, which has been plotted as a function of temperature difference from M_s , ΔT , is consistent with that for a previously examined polycrystalline specimen with nearly the same composition irrespective of crystal orientations. That is, the magnetic effect on M_s temperature is not influenced by the existence of grain boundaries as well as the difference in crystal orientations. (ii) The amount of magnetic field-induced martensites is almost constant (about 80%) without regard to maximum strength of applied magnetic field, formation temperature and crystal orientation. (iii) Morphology of magnetic field-induced martensites (including internal substructures) is the same as that of thermally-induced ones irrespective of formation temperature and strength of magnetic field, as in polycrystalline specimens. (iv) Several plates of magnetic field-induced martensites are lengthily grown nearly parallel to the direction of an applied magnetic field irrespective of crystal orientation (sometimes they grow from one end to the other of 7 mm length specimens).

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I. Introduction

Many studies have so far been made as to magnetic effects on martensitic transformations in ferrous alloys and steels, especially by Sadovsky's group in the U.S.S.R.⁽¹⁾⁻⁽⁴⁾ and recently by the present authors⁽⁵⁾⁻⁽¹⁰⁾. Much fundamental information has been obtained on the critical magnetic field to induce martensitic

transformation, the amount of magnetic field-induced martensites and so on. However, all of those studies were concerned with polycrystalline specimens, and therefore, the information might be affected by the existence of grain boundaries. Moreover, no information has been obtained about the influence of crystal orientation on magnetic field-induced martensitic transformation. It is thus important to clarify the influences of grain boundary and crystal orientation on the magnetic field-induced martensitic transformation. In a previous paper⁽⁸⁾, the present authors have pointed out that the martensitic transformation under a magnetic field is accelerated not only by the Zeeman effect but also by the high field susceptibility and forced volume magnetostriction effects, and proposed an equation to estimate the shift of M_s temperature due to a magnetic field. However, the existence of grain boundaries and the difference in crystal orientation have not been

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taken into consideration in the equation. So, a question arises as to whether the proposed equation is correct for a single crystal and any crystal orientation. In the present study, therefore, the magnetic field-induced martensitic transformations in Fe-Ni alloy single crystals with different crystal orientations have been examined to make the above question clearer by magnetization measurement and optical microscopy, by applying a pulsed ultra high magnetic field parallel to the length-wise direction of the crystals.

The results have been compared with the previous ones for polycrystalline specimens with nearly the same composition.

II. Experimental Procedures

An Fe-31.6 at%Ni alloy was prepared by melting the component metals in a high frequency induction furnace under argon atmosphere and casting into a water-cooled iron mold. Single crystals were tried to get by the Bridgman method. Unfortunately, ideal single crystals were not obtained, although a crystal with large grain size was obtained. The large crystal ($14\phi \times 30$ mm) was cut and homogenized at 1473 K for 8.64×10^4 s in an evacuated silica capsule. Chemical analysis was done after the homogenization, the composition shown above being the analysed one. The orientation of the large crystal was determined by the back reflection Laue method, and ribbon-shaped specimens ($4 \text{ mm} \times 7 \text{ mm} \times 0.3 \text{ mm}$) were cut from the large crystal so that the length-wise direction might be parallel to the $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ of austenite crystal. They were austenitized at 1473 K for 1.08×10^4 s in evacuated silica capsules and subjected to furnace cooling. All the austenitized

single crystal specimens were cut into half width ($2 \text{ mm} \times 7 \text{ mm} \times 0.3 \text{ mm}$) by a spark cutting machine, and one half was used for electrical resistivity measurement to determine transformation temperatures and the other for magnetization measurements. Pulsed magnetic field whose maximum strength was about 31.75 MA/m was applied along the length-wise direction of single crystals of three orientations.

III. Results

1. Transformation temperature and austenitic magnetic moment

The electrical resistivity has been measured as a function of temperature in the range from 77 K to 800 K, in order to determine transformation temperatures, M_s , M_f , A_s and A_f of each specimen. The determined values for three single crystal specimens are listed in Table 1, together with those for a polycrystalline specimen previously examined. It is noted in the table that M_f and M_s temperatures are the same in each single crystal specimen, although they are different in the polycrystal. This means that all martensites in a single crystal are formed instantaneously at M_s temperature due to a burst phenomenon, and that those in a polycrystal are formed over some temperature range. Such a difference in transformation behavior may be attributed to whether grain boundaries exist or not. On the other hand, reverse transformation behavior is not so different between single crystal and polycrystalline specimens, because a similar temperature difference exists between A_s and A_f temperatures of both the specimens. This may be due to the fact that the martensite

Table 1 Transformation temperatures of three Fe-Ni single crystals and an Fe-Ni polycrystal previously examined.

Composition		Transformation temperature			
		M_s (K)	M_f (K)	A_s (K)	A_f (K)
Fe-31.6 at%Ni single	$\langle 100 \rangle$	165	165	504	670
	$\langle 110 \rangle$	163	163	500	670
	$\langle 111 \rangle$	160	160	498	667
Fe-31.7 at%Ni	poly.	164	< 77	584	723

states before reverse transformation in both the specimens similarly consist of a large number of martensite plates.

The magnetic moment of austenite has been determined by measuring the magnetization in the austenitic state. It did not depend on the crystal orientations of single crystals, and was in good agreement with that of the previously examined Fe-31.7 at%Ni alloy polycrystal⁽⁸⁾. The magnetic moment of the martensitic state can be assumed to be $2\mu_B$ at 0 K by referring to the Slater-Pauling curve⁽¹¹⁾, and the value may be valid in the temperature range where the magnetization measurements have been made, as mentioned in the previous paper⁽⁸⁾.

2. Critical magnetic field to induce martensite

Magnetization $M(t)$ was plotted as a func-

Fig. 1 Magnetization vs magnetic field ($M(t)-H(t)$) curves for Fe-Ni single crystals of three kinds of orientations.

tion of magnetic field $H(t)$ in one pulse whose maximum strength is higher than a critical field to induce martensitic transformation. Typical $M(t)-H(t)$ curves are shown in Fig. 1(a), (b) and (c) being for crystals with $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ orientations, respectively. On each of the curves, an abrupt increase in magnetization can be recognized at a certain strength of the magnetic field, which corresponds to the occurrence of martensitic transformation and, therefore, this value of the magnetic field corresponds to the critical field, as indicated with an arrow. Such critical fields have been measured for various ΔT values of temperature difference from M_s temperature, and they are shown in Fig. 2. In this figure, symbols, $\circ$, $\bullet$ and $\blacksquare$, represent the critical fields for the crystals with $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ orientations, respectively, and the solid line represents the critical field vs ΔT relation for the previously examined Fe-31.7 at%Ni alloy polycrystalline specimen. It is seen from the figure that the critical field increases with in-

Fig. 2 Critical magnetic fields to induce martensites, plotted as a function of $\Delta T (= T - M_s)$.

creasing ΔT for all the single crystal specimens, and they lie nearly on the dotted line irrespective of crystal orientation. This result gives an important information with respect to the magnetic effect on M_s temperature, as will be discussed later.

3. Amount of magnetic field-induced martensite

The amount of magnetic field-induced martensites has been calculated from the magnetization in the same manner as in a previous work⁽⁵⁾⁽⁶⁾. The calculated amount for three single crystal specimens at their critical fields is shown in Fig. 3 as a function of ΔT . This figure indicates that the amount is almost

constant (about 80%) without regard to ΔT and crystal orientation. Moreover, it does not increase, even if any magnetic field higher than

Fig. 3 Amount of magnetic field-induced martensites at the critical field, plotted as a function of ΔT .

Fig. 4 Optical micrographs of thermally-induced martensites, (a), (d) and (g), and magnetic field-induced ones, (b), (c), (e), (f), (h) and (i). Transformation temperature, ΔT and H for the magnetic field-induced martensites are indicated in each photograph.

the critical field is applied from the beginning. This can be known from the magnetization curves in Fig. 1, that is, the abrupt increase of magnetization due to martensitic transformation is observed at the critical field, which is always the same even if any higher magnetic field is applied. Such a burst phenomenon of magnetic field-induced martensitic transformation at critical field is very similar to that of thermally-induced one at M_s temperature.

4. Morphology and arrangement of magnetic field-induced martensite

Figure 4 shows optical micrographs of thermally-induced lenticular martensites, (a), (d) and (g), and magnetic field-induced ones, (b), (c), (e), (f), (h) and (i). Three micrographs of the first, second and third columns are taken from three single crystals with $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ orientations, respectively, and formation temperature, its difference from M_s , ΔT , and applied magnetic field H are inscribed in each of the photographs. It is noted in the figure that the morphology (including internal substructures) of magnetic field-induced martensites is the same as that of thermally-induced ones irrespective of ΔT and H . This result is the same as that of the previously examined Fe-Ni alloy polycrystalline specimens. Figure 5 shows more macroscopic photographs showing the whole view of thermally-induced martensites, (a), and magnetic field-induced ones, (b), (c) and (d). Crystal orientation, formation temperature, magnetic field H and its direction are inscribed in the figure. Photographs (b), (c) and (d) reveal that several martensite plates grow nearly parallel to the direction of magnetic field and some of them run through from one end to the other of crystals. However, such a characteristic array of martensite plates is not observed for thermally-induced martensite plates in (a). Therefore, the arrangement of martensite plates seems to be characteristic of magnetic field-induced martensites. Figure 5(e) is an enlargement of the framed area of Fig. 5(c), from which it is clearly known that one plate grows lengthily along the direction of magnetic field, and that the other plates terminate at the directionally grown martensite plate. This

means that the directionally grown plate is first induced and then the other plates are induced. The reason for such a formation of lengthily grown martensite plates under a magnetic field is not clear now, but a shape magnetic anisotropy effect may be speculated to play an important role, as will be discussed later.

Fig. 5 Macroscopic optical micrographs of thermally-induced, (a), and magnetic field-induced ones in three single crystal specimens with $\langle 100 \rangle$, $\langle 110 \rangle$ and $\langle 111 \rangle$ orientations, (b), (c) and (d). (e) is an enlargement of the framed area of (c). The direction of an applied magnetic field, crystal orientation, transformation temperature, ΔT and H are indicated in each photograph.

IV. Discussion

1. Influence of grain boundary and crystal orientation on the magnetic effect

It has been shown in the above that the critical field plotted as a function of ΔT lies approximately on a line consisting of two straight parts, and that the linear relation is almost consistent with that for the previously examined Fe-31.7 at%Ni alloy polycrystal. This result reveals two important facts. One is that the magnetic effect on M_s temperature is not influenced by the existence of grain boundaries, that is, the magnetic effect is the same in both single crystals and polycrystals. The other is that the magnetic energy contributing to the shift of M_s temperature must be an isotropic one because the magnetic effect is independent of crystal orientation. It was previously pointed out⁽⁸⁾ that the magnetic energies contributing to the shift of M_s temperature consist of three parts due to the Zeeman, high field susceptibility and forced volume magnetostriction effects. The magnetic energies due to the three effects contain no anisotropic factor by crystal orientation, and this is consistent with the above experimental fact. Therefore, it may be concluded that the previously proposed magnetic effects and the equation to estimate the shift of M_s temperature are correct irrespective of the existence of grain boundaries and the difference in crystal orientation.

2. Reason for the formation of directionally grown martensite

It has been found that several lengthily grown martensite plates are observed along the direction of an applied magnetic field irrespective of crystal orientation. Those plates appear to be first formed, judging from a characteristic arrangement of other plates around them. Such an arrangement of martensite plates can be supposed to correspond to the most favorable state for an unknown magnetic energy which depends on the direction of magnetic field. A shape magnetic anisotropic energy is possibly supposed as the unknown magnetic one, which has been adopted to explain the fact that the

longitudinal direction of precipitates formed under a magnetic field orientates to the direction of an applied magnetic field⁽¹²⁾⁽¹³⁾. The shape magnetic anisotropic energy E is expressed by $-k \cdot \Delta M_T^2 \cos^2 \theta$, where k is a constant containing a demagnetization factor, ΔM_T the difference in magnetic moment between the matrix phase and the precipitate and θ the angle between the longitudinal direction of precipitates and the direction of an applied magnetic field. When θ is zero, the energy becomes a minimum, and thus the longitudinal direction of precipitates has a tendency to orientate to the direction of applied magnetic field. The formation of lengthily grown magnetic field-induced martensite plates may be similarly explained by the shape magnetic anisotropic energy, because both the martensite plates and precipitates are lengthily grown along one direction. However, martensite plates are formed by a shear mechanism, as well known, and so all the magnetic field-induced martensite plates can not orientate to the direction of magnetic field, being different from the case of a diffusion controlled precipitation. Only a few martensite plates induced in the beginning can orientate to the direction, and many other martensite plates form to relax the strain caused by the formation of initial lengthily grown martensite plates. In this way, the amount of lengthily grown martensite plates is not so large because of the beginning phenomenon of magnetic field-induced martensitic transformation. Incidentally, the shape magnetic anisotropic energy is very small compared with those due to the Zeeman, high field susceptibility and forced volume magnetostriction effects, and therefore, it may be negligible for the shift of M_s temperature.

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