Crystal Structures and Permanent Magnet Properties of Fe-Pt Alloys*

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The relations between the order-disorder transformation and the permanent magnet properties of iron-platinum alloys have been investigated. The results show that the water-quenched alloy of γ single phase exhibits the typical soft magnetic properties. On aging at temperatures between about 770 and 870 K, the γ single phase transforms into a mixture of γ and γ_1 phases, whose magnetization is not easily saturated for the high crystal magnetic anisotropy of the γ_1 phase and the coercivity shows a low value. On aging at 903 K, the alloy of the γ_1 single phase which gives rise to broad diffraction lines exhibits the highest value of $H_c = 135 \text{ kA} \cdot \text{m}^{-1}$. The ordering of the γ_1 phase is advanced with the rise of aging temperature, while the coercivity rapidly falls.

It is probable that the origin of the excellent permanent magnet properties of the Fe-Pt alloy is related to the existence of the very imperfect γ_1 phase in regard to constitution and ordering, and these cause the pinning of the magnetic domain wall.

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I. Introduction

It has been known that the equi-atomic FePt alloy of the superlattice (L1₀) type in the Fe-Pt system has the maximum energy product, (BH)_{max}, of about 24 kJ · m⁻³(1)⁽⁵⁾. Recently we have investigated Fe-38.5 ~ 40 at%Pt alloys higher in iron content than the Fe-50 at%Pt alloy, and obtained the highest (BH)_{max} value of 160 kJ · m⁻³(20 MG · Oe)⁽⁶⁾(7). This permanent magnet alloy has the highest value of (BH)_{max} among the machinable magnetic alloys in the transition metal system. We have named the alloy Platiron Magnet.

According to the equilibrium phase diagram of the Fe-Pt alloy⁽⁸⁾ shown in Fig. 1, the curve of the order-disorder transformation shows a maximum at the concentration of Fe-50 at% Pt in a sufficiently high temperature range. Therefore, even by rapid water-quenching, the

crystal structure of the FePt alloy already becomes the highly ordered γ_1 phase⁽⁵⁾ and its coercive force is not high. But the represent-

Fig. 1 Equilibrium phase diagram of Fe-Pt alloys.

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ative Fe-38.5 at%Pt alloy⁽⁶⁾ on the Fe-rich side in this system exhibits high coercivity in the as-water-quenched state. In general the effect of heat-treatment is varied remarkably with the composition of Fe-Pt alloys. Moreover, as the powdered alloys for X-ray analysis are sintered by heating at about 1350 K or more, their detailed crystal structures cannot be examined by the conventional X-ray powder diffraction method.

To clarify the relationships between the crystal structures and magnetic properties of Fe-Pt alloys, the present work was carried out using the plate-shaped specimens, which comparatively clear effects of heat-treatments.

II. Experimental

Iron and platinum used as the alloying materials were of 99.9% purity. The materials were melted in a sintered alumina crucible placed in the Tammann furnace under an argon atmosphere. The melt was sucked up in a silica tube whose inside cross-section is about $0.8\text{--}1.5 \times 10^{-3}$ m in thickness and 6×10^{-3} m in width, from which plate-shaped bars were produced. The alloy of the small crystal grains obtainable in little preferred orientation, about 20×10^{-3} m long, was cut from the middle part of the bars and then polished with emery paper after planing. The specimens thus prepared were used for X-ray diffraction analysis and measurements of the permanent magnet properties. The specimens were sealed in a quartz capsule, homogenized at high temperatures of 1353–1623 K in the γ phase region for 3.6 ks and then quenched into ice water. The specimens were aged at 673–1173 K for 3.6 ks–90 ks.

The permanent magnet properties were measured using an automatic recording fluxmeter in a maximum field of about 1600 kA $\cdot$ m⁻¹. The X-ray diffraction investigation was made using Fe-K α radiation.

III. Results and Discussion

Figure 2 shows the representative X-ray diffraction patterns (1)–(4) of the Fe-36 at%Pt alloy⁽⁶⁾ of which the coercive force, H_c , is

Fig. 2 X-ray diffraction patterns of Fe-36 at%Pt cast alloy aged at above-cited temperatures and times after heating at 1598 K for 3.6 ks and subsequent water-quenching.

rather low, but shows remarkable effects by various heat-treatments. In the figure, the pattern (1) shows that the crystal structure consists of the γ (f.c.c.) single phase when water-quenched after solution-treatment; the pattern (2) shows the coexistence of the γ and γ_1 (L1₀-type structure) phases when tempered at 848 K; the pattern (3) shows the broad diffraction lines of the γ_1 phase and the disappearance of the γ phase when tempered at 903 K; and the pattern (4) shows the large separation between (200) and (002) in the fundamental diffraction lines of γ_1 , and the progress of ordering when

Fig. 3 Lattice parameters of Fe-36 at%Pt alloy aged at 773–1173 K for 90 ks after heating at 1598 K for 3.6 ks and subsequent water-quenching.

the tempering temperature is further increased.

Figure 3 shows the lattice parameters a and c of the Fe-36 at%Pt alloy which was tempered over a temperature range of 773–1173 K after water-quenching and then air cooled. As can be seen in the figure, the lattice parameter a of the water-quenched γ phase is 0.377 nm. The γ phase is transformed into the two phases of $\gamma + \gamma_1$ when tempered at about 770–870 K, and the (200) diffraction line of the γ phase observed in Fig. 2-(2) disappears when tempered at the temperatures above the broken lines. Two diffraction lines indexed as (200) and (002) of the γ_1 phase are obtained in the case where only the γ_1 single phase appears. The lattice parameters of the γ phase increase linearly with the rise of temperature in this temperature range, while the lattice parameters of the c axis in the γ_1 phase decrease to its minimum. With further increase of the tempering temperature, the ordering progresses. At the same time the lattice constant c increases sharply, and the two phase region of $\gamma + \gamma_1$ appears in the narrow temperature range over the broken lines

Fig. 4 Relative integrated intensities of X-ray diffraction lines in Fe-36 at%Pt alloys aged between 673 and 1273 K for 90 ks after heating at 1598 K for 3.6 ks and subsequent water-quenching.

shown in the vicinity of 1120 K, and it is next to the γ single phase region.

Figure 4 shows the integrated intensity vs aging temperature curve for the representative X-ray diffraction lines observed in the above alloy under transformation: (200) in the γ phase and (001) in the γ_1 phase as against the main diffraction line (111) of γ or γ_1 . As can be seen from the figure, the intensity of (200) line in the γ phase is almost constant at 673 K, beyond which the intensity slightly increases and then rapidly decreases at about 770–870 K with the precipitation of the γ_1 phase and there are observed the diffraction lines of the two-phase region. However, the intensities of the fundamental and superlattice lines for the γ_1 phase change with a similar tendency. The diffraction lines of the γ_1 phase which appear after the disappearance of those of the γ phase are broadened. The integrated intensities of the γ_1 phase increase gradually at first, and then considerably in the temperatures range of about 950–1080 K, and finally decrease abruptly with tempering temperature, followed by transforming of γ_1 into the γ single phase.

Figure 5 indicates the magnetic hysteresis loops of the alloys corresponding to the diffraction lines in Fig. 2: the loop (1) shows that of the alloy of the γ single phase formed by water-quenching, showing the typical soft magnetic properties; the loop (2) shows that of the alloy of the two phases of $\gamma + \gamma_1$ formed by temper-

Fig. 5 Magnetic hysteresis loops of Fe-36 at%Pt alloy corresponding to Fig. 2. (1): As water quenched from 1598 K. (2): Aged at 848 K for 90 ks. (3): Aged at 903 K for 90 ks. (4): Aged at 1073 K for 18 ks.

ing at 848 K, where H_c is as very low as $15 \text{ kA} \cdot \text{m}^{-1}$ but the magnetization does not readily approach the saturation value because of the high crystal magnetic anisotropy energy⁽⁹⁾⁽¹⁰⁾ of the γ_1 phase; the loop (3) shows that of the alloy of the γ_1 single phase formed by tempering at 903 K, where H_c increases abruptly to $135 \text{ kA} \cdot \text{m}^{-1}$; and the loop (4) shows that of the alloy in advanced ordering of the γ_1 phase formed by tempering at 1073 K, where H_c markedly decreases, but the magnetization is not readily saturated. Further, the alloy structure becomes the γ single phase when tempered at a further high temperature, and the magnetic hysteresis loops become similar to those of (1). From the above-mentioned measurements of the permanent magnet properties and X-ray diffraction analysis, the effects of the heat-treatment in this system are known to be varied with alloy composition. In the case of the Fe-36 at%Pt alloy under study the γ single phase can be obtained by water-quenching, and became the γ_1 single phase by the subsequent tempering treatment. This γ_1 phase has an imperfect atomic arrangement because the composition is shifted to the higher Fe side than the equi-atomic FePt. Immediately after the ordering of the γ_1 phase at the tempering

temperature of 903 K, there is a possibility that a small amount of γ phase remains, but it can not be detected by X-ray diffraction. The origin of the excellent permanent magnet properties of the Fe-Pt alloy may be attributed to the above phenomena, which induce the pinning⁽¹¹⁾ of the magnetic domain walls. The fine structure of the crystal in the alloy which shows some other interesting phenomena⁽¹²⁾⁽¹³⁾ will be reported elsewhere. The well-known CoPt magnet alloys exhibit high permanent magnet properties⁽¹⁴⁾⁻⁽¹⁷⁾ under the state of the two phases of $\gamma + \gamma_1$ in which the γ_1 phase is finely dispersed in the γ phase matrix (see Fig. 6). Although there are some differences between the Co-Pt and the Fe-Pt alloys mentioned above, the origin of their excellent permanent magnet properties may be attributed to a similar mechanism.

IV. Conclusions

The plate specimens of the Fe-36 at%Pt alloys which were homogenized, water-quenched and aged at various temperatures were examined in relation to the permanent magnet properties and X-ray diffractions. The results are summarized as follows:

Fig. 6 X-ray diffraction pattern of Co-50 at%Pt magnet alloy of $(BH)_{\max} = 90 \text{ kJ} \cdot \text{m}^{-3}$.

(1) Fe-36 at%Pt alloy is in the γ single phase state and exhibits the soft magnetic properties by water-quenching from 1598 K. The γ phase becomes the two phase of $\gamma + \gamma_1$ by tempering at about 770–870 K. However, the coercivity of the tempered alloy is very low and the magnetization is not readily saturated because of the high crystal magnetic anisotropy energy of the γ_1 phase. Further, the γ phase disappears by tempering at 903 K and only the γ_1 phase appears; in this case the lattice parameter c of the γ_1 phase exhibits a minimum, and the highest coercivity of $135 \text{ kA} \cdot \text{m}^{-1}$ is obtained. At tempering temperatures higher than 903 K, the ordering of γ_1 rapidly proceeds, but the coercivity is considerably lowered.

(2) On water-quenching, the Fe-36 at%Pt alloy is in the γ_1 phase state by tempering and takes an imperfect atomic arrangement because the alloy composition is shifted to the higher Fe side than the FePt alloy. Furthermore, immediately after the completion of the γ to γ_1 transformation, the γ_1 phase seems to be in an incomplete ordered state accompanied by the remaining γ phase. Thus, the origin of

the excellent permanent magnet properties may be attributed to the above-mentioned phenomena, which induce the pinning of the magnetic domain walls.

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