On the High-Energy Product Fe-Pt Permanent Magnet Alloys*

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The permanent magnetic properties of Fe-34–67.5 at%Pt alloys have been investigated. It is found that the magnetic properties of an Fe-38.5 at%Pt alloy quenched from the disorder phase γ (*fcc*) region and subsequently aged at 773 K (500°C) for 360 ks (100 h) in the ordered phase γ_1 (*fcc*, L1₀-type) region, are $B_r=1.08$ T (10.8 kG), $H_c=340$ kA·m⁻¹ (4.3 kOe) and $(BH)_{\max}=159$ kJ·m⁻³ (20 MG·Oe).

X-ray analysis and microstructural observations indicate that the magnetic hardening is due to the ordering stage from the γ phase to the γ_1 phase having a high crystal magnetic anisotropy.

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I. Introduction

The permanent magnetic properties of the order-disorder alloys in the Fe-Pt system have been investigated^{(1)–(4)}. According to the results, the highest maximum energy product obtained in FePt alloy is as small as 24 kJ·m⁻³⁽⁴⁾, compared with 96 kJ·m⁻³⁽⁵⁾ for a CoPt magnet alloy of a similar transformation type. The crystal magnetic anisotropy which plays an important role in the permanent magnetic properties is 7×10^6 J·m⁻³ in the FePt alloy⁽⁶⁾, much larger than 2.8×10^6 J·m⁻³ in the CoPt magnet alloy⁽⁷⁾. The order-disorder transformation temperature of the Fe-50 at% Pt alloy is as high as 1573 K as shown in Fig. 1⁽⁸⁾. The transformation of the ordered γ_1 phase (*fcc*, L1₀-type) is making progress, when the Fe-50 at% Pt alloy is quenched from the disordered lattice γ phase (*fcc*, A1-type) range into ice-water at a high temperature. The superiority of permanent magnetic properties depends on the coexistence of the ordered and disordered phases as in the Co-50 at% Pt magnet alloys, and it could not

Fig. 1 Equilibrium diagram of Fe-Pt alloy.

be achieved in the Fe-50 at% Pt alloy. Previous investigations of the permanent magnetic properties for Fe-Pt alloys have been based on the disordering of the Fe-50 at% Pt alloys with plastic deformation by forced grinding and rolling of the alloys, or with additions of third elements^{(9)–(11)}. As mentioned above, the excellent permanent magnetic properties can-

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not be obtained for the Fe-Pt alloys as in the case of the CoPt magnet alloy.

The authors noticed that the temperature of the order-disorder transformation decreases remarkably with the deviation from the stoichiometric composition FePt, and thus the permanent magnetic properties in the Fe-Pt alloys are investigated. The purpose of the present paper is to describe the results in detail.

II. Experimental

Fe-34–67.5 at%Pt alloys, as shown in Fig. 5, were chosen in the present investigation. The alloys were melted in an argon atmosphere with a Tammann furnace from 99.9% electrolytic iron and 99.9% platinum, and sucked up into a quartz tube approximately 3×10^{-3} m in inside diameter. The specimens were cut to be $25\text{--}30 \times 10^{-3}$ m long, from the middle part of the ingots, sealed in a quartz capsules, solution-treated at 1273–1623 K (1000–1350°C) for 3.6 ks (1 h) and quenched into ice-water or slowly cooled. The specimens were aged at 723–1023 K for 0.6 ks to 2.8 Ms (10 min–800 h).

X-ray diffraction was performed by Fe-K α radiation, and the measurement of the permanent magnetic properties was made using an automatic recording fluxmeter in a field of about $1600 \text{ kA} \cdot \text{m}^{-1}$. Electron micrographs of the Fe-Pt alloys were taken by the carbon-replica method.

III. Results and Discussion

Figure 2 shows the permanent magnetic properties of the Fe-36, 38 and 40 at% Pt alloys when aged for 90 ks at different temperatures between 673 and 973 K after water-quenching. All the properties of the Fe-36 at% Pt alloy were scarcely varied below 773 K, but their values were rapidly increased above this temperature and decreased after having reached their maxima. However, the 38 and 40 at% Pt alloys exhibited considerably large values of the properties even in the as-water-quenched state, and no remarkable increases in the values were found after the ageing.

Fig. 2 Effect of ageing between 673 and 973 K for 90 ks after water-quenching from 1598 K on the magnetic properties of Fe-36, 38 and 40 at% Pt alloys.

Figures 3 and 4 show the permanent magnetic properties of the representative Fe-35 at% and 38.5 at% Pt alloys. These alloys were aged at various temperatures between 748 and 1023 K after water-quenching from 1598 K. First, the permanent magnetic properties of the Fe-35 at% Pt alloy, as shown in Fig. 3, begin to appear just by ageing for 18 ks at 898 K, increase gradually with the lapse of time, attain maxima and then decrease gradually. The highest value of the coercive force, H_c , obtained by ageing at 973 K is $159 \text{ kA} \cdot \text{m}^{-1}$ (2 kOe), with the residual flux density $B_r = 0.91 \text{ T}$ (9.1 kG) and $(BH)_{\text{max}} = 62 \text{ kJ} \cdot \text{m}^{-3}$ (7.8 MG·Oe).

The Fe-38.5 at% Pt alloy in Fig. 4 shows the superiority of permanent magnetic properties in the as-water-quenched state,

Fig. 3 Effect of ageing between 898 and 1023 K after water-quenching from 1598 K on the magnetic properties of Fe-35 at%Pt alloy.

whereas the effect of ageing is relatively insignificant compared with the Fe-35 at% Pt alloy, indicating an inconspicuous maximum on the curves. In particular, the maximum of B_r does not appear on the curves at high temperature ageing above 873 K. The highest $(BH)_{\max}$ obtained from these results is $159 \text{ kJ} \cdot \text{m}^{-3}$ ($20 \text{ MG} \cdot \text{Oe}$), when aged at 773 K, and in this case H_c is $340 \text{ kA} \cdot \text{m}^{-1}$ (4.3 kOe) and B_r is 1.08 T (10.8 kG).

Figure 5 shows the permanent magnetic properties that correspond to the highest value of $(BH)_{\max}$ obtained in the present work. The permanent magnetic properties of the Fe-34 at% Pt alloy which are considerably inferior to other alloys are rapidly improved when the platinum content is increased, and shows the maximum values at the composition of 38.5 at% Pt. While the stoichiometric FePt

alloy has a very low value of $(BH)_{\max}$, it becomes clear that superior permanent magnetic properties are revealed in the non-stoichiometric alloys in the imperfectly ordered. This tendency can be seen at the Fe-60 at% Pt alloy on the Pt side. In this case, the saturation magnetization which is lower than that of the Fe side alloy results in a $(BH)_{\max}$ of $40 \text{ kJ} \cdot \text{m}^{-3}$, but the value is low, as compared with the maximum of $(BH)_{\max}$ in the Fe side alloys.

Figure 6 shows a hysteresis loop of the Fe-38.5 at% Pt alloy with the highest value of $(BH)_{\max}$ in the Fe-Pt system. The saturation magnetization value of this alloy is as large as 1.15 T in a magnetic field of $1600 \text{ kA} \cdot \text{m}^{-1}$. The demagnetization curve is approximately rectangular, reflecting a very large value of $(BH)_{\max}$.

Furthermore, Fig. 7 shows an X-ray diffrac-

Fig. 4 Effect of ageing between 748 and 948 K after water-quenching from 1598 K on the magnetic properties of Fe-38.5 at%Pt alloy.

Fig. 5 Permanent magnetic properties of Fe-Pt alloys.

Fig. 6 Hysteresis loop of Fe-38.5 at%Pt alloy aged at 773 K for 360 ks after water-quenching.

tion pattern of a powder specimen of the Fe-38 at% Pt alloy. The fundamental diffraction lines in the figure are (111), (200) and (002), and the super-lattice diffraction lines are (001), (110) and (201). From the pattern, the crystal structure is clearly shown to be of the same Ll_0 -type as the stoichiometric FePt alloy, and

Fig. 7 X-ray diffraction pattern obtained with Fe-K α radiation from Fe-38 at%Pt alloy aged for 90 ks at 773 K.

the alloy is in the γ_1 single phase region.

Moreover, Fig. 8 presents the results of X-ray diffraction from the order-state in the Fe-36 and 38 at% Pt alloy. The curves in the figure show the relative integral intensities of the super-lattice lines versus the fundamental (111) diffraction, $I_{(hkl)}/I_{(111)}$, when aged for 90 ks at various temperatures between 673 and 1123 K. At first, the relative integral intensity of the Fe-36 at% Pt alloy increases linearly with increasing age-temperature and attains

Fig. 8 Relative integral intensities of X-ray diffraction lines in Fe-36 and 38 at%Pt alloys aged between 673 and 1123 K for 90 ks after water-quenching.

a maximum at 1073 K. That of the Fe-38 at% Pt alloy is approximately constant at low age-temperatures, then increases gradually with increasing ageing temperature and attains a maximum at 1023 K in the (001) curve and at 1073 K in the curve (110) curve. From a comparison of these results with the curves of the permanent magnetic properties versus heat-treatments in Fig. 2, it is apparent that ordering of the permanent magnetic properties of the Fe-36 at% Pt alloy is linearly developed. The permanent magnetic properties of these alloys are remarkably deteriorated in the highest order-state between 1023 and 1123 K, whereas the most desirable properties are obtained with the relative integral intensities of about 14–18%.

Figure 9 shows the microstructure of the Fe-35 at% Pt alloy quenched from the γ single phase region in to water. Figure 10 is an electron micrograph of the Fe-38.5 at% Pt alloy which exhibits the excellent permanent magnetic properties, where the band microstructure is the γ_1 single phase. It has been known that CuAu⁽¹²⁾⁽¹³⁾ and CoPt⁽¹⁴⁾⁽¹⁵⁾ alloys of the *fcc*→*fcc* transformation-type reveal the twin band microstructures as ordering is developed sufficiently. The Fe-Pt alloys undergoes the same transformation as the CoPt alloys. Figure 11 shows that the Fe-50 at% Pt alloy has a similar twin band microstructure ($H_c \approx 120 \text{ kA} \cdot \text{m}^{-1}$) based on the order-disorder transformation.

From the above results, it is assumed that the excellent permanent magnetic properties

Fig. 9 Electron micrograph of Fe-35 at%Pt alloy water-quenched from 1573 K. ($\times 10,000$)

Fig. 10 Electron micrograph of Fe-38.5 at%Pt alloy aged at 823 K for 324 ks after water-quenching from 1598 K. ($\times 20,000$)

Fig. 11 Electron micrograph of Fe-50 at%Pt water-quenched from 1598 K. ($\times 20,000$)

originate from the high crystal magnetic anisotropy of the γ_1 phase and are related with the band microstructure.

IV. Conclusion

Magnetic and other properties of the Fe-Pt alloy containing 34–67.5 at% Pt were measured and observed electron-microscopically after water-quenching and ageing.

(1) The iron side alloys of the compositions centered at around 38.5 at% Pt have the permanent magnetic properties superior to

those of the stoichiometric FePt alloy. That is, the highest maximum energy product is $159 \text{ kJ} \cdot \text{m}^{-3}$ ($20 \text{ MG} \cdot \text{Oe}$), with $H_c = 340 \text{ kA} \cdot \text{m}^{-1}$ (4.3 kOe) and $B_r = 1.08 \text{ T}$ (10.8 kG).

(2) The magnetic hardening is caused by the ordering process from the γ phase to the γ_1 phase having a high crystal magnetic anisotropy.

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