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LETTER TO THE EDITOR

Recovery processes of magnetic transition due to plastic deformation in Pt_3Fe single crystal

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Abstract. The magnetic structure of Pt_3Fe alloy changes from antiferromagnetic to ferromagnetic as a result of plastic deformation. The recovery processes of the magnetic transition have been studied in Pt_3Fe alloy deformed plastically by 36% strain. Three recovery processes have been discovered; the spontaneous magnetization decreases in the 473 K and 673 K annealing and disappears in 1073 K annealing. Each recovery process is discussed from the viewpoint of the atomic migration and the dislocation displacement through the activation process.

The Pt_3Fe crystal has an $L1_2$-type atomic structure and an antiferromagnetic structure; below 100 K the magnetic structure is characterized by the wave vector $2\pi(1/2a, 1/2a, 0)$ in which Fe moments of 3.3 μ_B are aligned ferromagnetically on (110) subsheets (Bacon and Crangle 1963). By plastic deformation, a remarkable magnetic transition from antiferromagnetism to ferromagnetism was discovered by Bacon and Crangle (1963). The mechanism of the magnetic transition was elucidated in terms of superlattice dislocations from the viewpoint of a localized electron model; the spontaneous magnetization, M_s, increases in proportion to the dislocation density, ρ, (Takahashi and Ikeda 1983). Recently the relation between M_s and ρ has been experimentally studied by magnetic measurement and electron microscopic observation (Takahashi and Umakoshi 1990). Some remarkable phenomena have been discovered: (i) along the antiphase boundary (APB) between superpartial dislocations, Fe atoms couple ferromagnetically and make neighbouring Fe atoms, up to 10 nm distant, ferromagnetic; (ii) M_s has a local maximum near 140 K; (iii) the magnetic susceptibility, χ, is influenced by a slight plastic deformation. These phenomena seem difficult to explain by the localized electron model, though the magnetic structure in Pt_3Fe could be explained by the quasi-localized electron model (Kohgi and Ishikawa 1980). Then, it is of interest to us to discover whether the quasi-localized electron model is effective in explaining the magnetic structure in Pt_3Fe alloy. In the present study, the recovery process of the magnetic transition due to plastic deformation is investigated. Unexpected recovery processes have been found; by annealing M_s decreases and disappears through three activation processes.

The transformation temperature of atomic order–disorder structure is obscure in the Pt_3Fe crystal (Kussmann and Rittberg 1950). A second purpose of the present study is to investigate the transformation temperature.

Rectangular prism specimens were cut from a single crystal rod of 25.6 at.% Fe–Pt alloy. The specimens were annealed at 1300 K for 1 day in vacuum to remove imperfections and then cooled very slowly at the rate of 30 K/day from 1073 K to 873 K. They were then plastically deformed at 36% by compression. Their surface imperfections were removed by chemical polishing. Magnetic measurements were made on a balance suitable for measuring the susceptibility of paramagnetic specimens at temperatures from 77 K to room temperature. Following this, the specimen was annealed at different temperatures from 373 K to 1073 K in sequence for 60 min in vacuum, and was then quenched to room temperature. The magnetic measurements were made again in a range of magnetic field between 0.43 MA m^{-1} and 1.10 MA m^{-1}.

No significant variation of χ with magnetic field is detected in the undeformed specimen, implying that no ferromagnetism is present. After plastic deformation, the magnetization is greater than it is for the undeformed specimen at every temperature. Variation of the magnetization with applied magnetic field is found to yield straight lines except for in the low-field range where there is deviation of magnetization from a straight line. The values of M_s and χ are obtained from the linear parts of magnetization curves by a least-squares fit to the isothermal magnetic data.

Figure 1 shows the variation of M_s with test temperature in the specimen deformed to 36% strain (A) and annealed at T_a in sequence (B to G). M_s decreases with increasing test temperature and is observed at room temperature. After 673 K annealing, however, M_s disappears at room temperature. The temperature, T_c, where M_s disappears, corresponds to the Curie temperature. T_c decreases with increasing T_a.

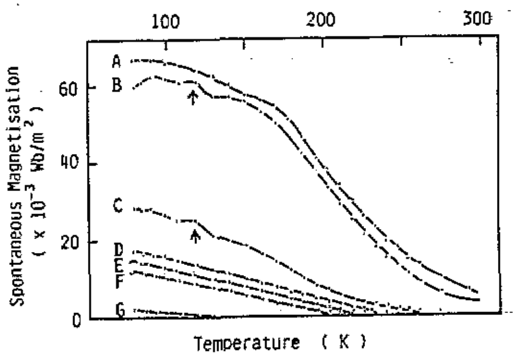

Figure 1. The variation in the spontaneous magnetization with test temperature for the 36% strained specimen before, A, and after the annealing at T_a. B: T_a = 473 K; C: T_a = 673 K; D: T_a = 723 K; E: T_a = 773 K; F: T_a = 873 K; G: T_a = 973 K.

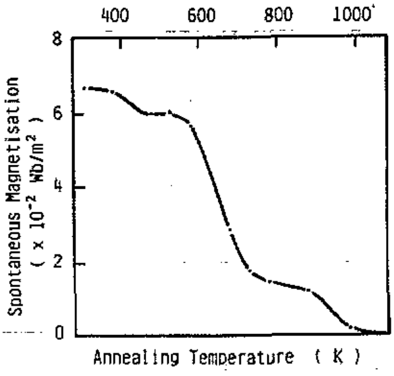

Figure 2. The variation in spontaneous magnetization at 77 K with annealing temperature T_a.

M_s has a local maximum at about 120 K in the T_a range between 473 K and 673 K (shown by arrows in figure 1), where M_s is unstable and changes discontinuously in the magnetic measurement. This peak was not observed for T_a higher than 673 K before annealing.

Figure 2 shows the variation of M_s with T_a, where M_s is the value at 77 K. The recovery processes of M_s occur in three stages, i.e. the value of M_s decreases near

473 K, 673 K and 973 K and only a small change of M_s is observed in the T_a range between 493 K and 573 K and between 725 K and 873 K. The rate of decrease of M_s to T_a is highest near 673 K, and M_s disappears at 973 K.

The superpartial dislocation creates an APB on the {111} glide plane after it has slipped and another superpartial recovers the glide plane to the ordered state. Then, the APB stripe is induced between two superpartials by plastic deformation and spreads on the glide plane. The separation of the two superpartials or the width of the APB stripe has a constant value given by the energy minimum of elastic interaction energy between superpartials and the APB energy. The separation, r_0, is 13 nm (Takahashi and Umakoshi 1990). Fe atoms occupy the corner sites and the second nearest neighbour (NN) sites in atomically ordered state. In the APB, Fe atoms make pairs at the first NN and couple ferromagnetically. The ferromagnetic Fe atoms exert a magnetic influence on the neighbouring Fe atoms and make them ferromagnetic. The magnetic influence extends over 20 atomic distances. The spontaneous magnetization, M_0, at 0 K induced by plastic deformation is given as (Takahashi and Ikeda 1983)

$$M_0 = S^2\ n\ r_0\ \rho\ \mu_{\mathrm{Fe}}/\sqrt{3}\ a^2 \tag{1}$$

where a is a lattice constant. S is the degree of order and μ_{Fe} is the magnetic moment of the Fe atoms. Here the effects of the magnetic transition from antiferromagnetism to ferromagnetism are extended as far as the nth NN distance. The relation between M_0 and ρ was examined experimentally and a good agreement was obtained when $n = 20$ and $\mu_{\mathrm{Fe}} = 3.3\mu_{\mathrm{B}}$ (Takahashi and Umakoshi 1990). The present specimen is compressed to $\epsilon = 36\%$ and the value of ρ can be estimated by the above relation; $\rho = 3 \times 10^{11}\ \mathrm{cm}^{-2}$. Then the average distance between APB stripes is 18 nm.

The M_s due to plastic deformation is reduced by annealing. The reduction of M_s is attributed to atomic migration through the thermal activation process. The array of ferromagnetic Fe atoms in the APB would be destroyed by the atomic migration. Three activation processes have been found in the present investigation; the first is observed near 473 K and the second and the third are near 673 K and 973 K, respectively.

Kussmann and Rittberg (1950) reported that the atomic order–disorder transformation takes place somewhere between 973 K and 1073 K. The third activation process in the 973 K annealing is caused by the atomic migration due to the order–disorder transformation. The transformation temperature is expected to be near 973 K.

The second activation process is observed in the 673 K annealing, which is saturated near 723 K. 23% of M_s remains even after the 873 K annealing. This second activation process is attributed to the local atomic migration near the APB. The vacancy density is high near the dislocation; the vacancies help the atomic migration. The atomic configuration of APB is unstable compared within the ordered state because of the APB energy. The unstable atomic configuration becomes a motivational force for the second activation process. The atomic configuration of APB corrupts at a lower temperature than the transformation temperature. Some ferromagnetic coupling remains, the atomic configuration of which is vague. There exists an atomic phase difference across the corrupt APB. The mechanism of the second recovery process could be confirmed by electron microscopic observation. The APB energy is reduced by the corruption of the APB and the separation of superpartials widens.

We are not yet confident that we understand the first activation process. One hypothesis can be put forward. The displacement of superpartial dislocations on the glide plane is possible at a lower temperature than that of the atomic migration. The superlattice dislocations would not have a constant value of r_0 in general, since the superpartials are caught in obstacles such as the impurity atoms. The mean value of r_0 in the specimen would be larger than the value obtained at the energy minimum. The superpartials in unstable positions would jump over the obstacles under the motivational force of the APB energy by means of the thermal activation process. After 473 K annealing, the mean value of r_0 would decrease and then M_s would decrease according to (1). The credibility of this hypothesis could be ascertained directly by electron microscopic observation.

T_c is above room temperature (= 428 K, Bacon and Crangle 1960) before the annealing and decreases as T_a increases, being about 210 K after the 773 K annealing. T_c would depend on the configuration of Fe atoms as well as the size of the ferromagnetic clusters.

The value of χ at 77 K is 1.34 $\times 10^{-8}$ H m^{-1} in the 36% strained specimen. χ decreases in the same activation processes and the value of χ at 77 K recovers to 1.05 $\times 10^{-7}$ H m^{-1} in the 1073 K annealing, which is 1.6 times as large as that before plastic deformation. The value of χ in the 1073 K annealing is the value for the automatically disordered state, since the specimen was quenched to room temperature after the annealing.

A detailed study is now in progress.

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