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Modification of Fe–Ni Invar alloys by high-energy ion beams

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Abstract

Measurements of temperature dependence of AC-susceptibility were made in Fe–30.2at.%Ni Invar alloy before and after 100 MeV Xe ion irradiation up to the dose of 10^{14} ions/cm^2. Measurements were performed at various angles θ between the direction of the ion beam and the external AC-magnetic field. It was found that in partially irradiated area, locally ferromagnetic parts exist at temperatures above the Curie temperature of the body where high-energy ions did not penetrate. The easy axis of the locally ferromagnetic parts was determined to be parallel to the beam direction. Those locally ferromagnetic parts can be considered to be in thin needle-like shape. This type of modification has a possibility of applications for perpendicular high-density memory and giant magneto-resistance materials.

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Keywords: Fe–Ni Invar alloy; Heavy ion irradiation; Electronic excitation; Curie temperature

1. Introduction

Fe–Ni alloys around the Invar composition of 35 at.%Ni are known to show various anomalies in physical properties [1]. These alloys show anomalously low thermal expansion that was interpreted in relation to the large positive value of the magnetovolume coupling constant, and therefore, attracted wide variety of interest from 3d-electron ferromagnetism to practical applications.

Anomalies in magnetic properties seen in Fe–Ni Invar alloys are sudden deviation of the spontaneous magnetization from the Slater-Pauling curve, anomalously large values of high field susceptibility and strong pressure dependence of the Curie temperature. Those anomalies have been understood as a result of the instability of the 3d-band ferromagnetism in fcc metals and alloys [2]. Due to the existence of a large sharp peak at the top of the 3d-electron band in fcc phase, the ferromagnetic state becomes energetically unstable when the number of outer electrons is decreased by decreasing the Ni concentration down to 29 at.%.

Concerning the crystal structure, Fe–Ni Invar alloys are in an fcc phase, but when the Ni concentration is decreased below 29 at.%, a

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martensitic transformation takes place. Therefore, many crystallographic studies have been made relating the Invar anomalies to the phase stability and local lattice distortion [3].

From the standpoint of looking for a new functional material [4], irradiation with high energy ions seems to be one of the most effective way for modification of lattice structure and physical properties of metals and alloys.

2. Experiments

Specimens of Fe–30.2at.%Ni Invar alloy were prepared by melting iron and nickel metals of purity of 99.9% using an induction furnace. The shape of the specimen was a thin plate of 5×5 mm^2 and the thickness of 200 μm. They were annealed at 1000 °C for 3 h and quenched into water.

High-energy ion irradiation was made by using a tandem accelerator which was installed at the Japan Atomic Energy Research Institute (JAERI). The ions used for irradiation were Xe with the energy of 100 MeV and with the irradiation dose up to 10^{14} ions/cm^2.

Measurements of AC-susceptibility were made before and after the irradiation by using a specially designed apparatus for rapid measurements. By using this apparatus one full temperature scan was made within 90 s. The frequency and the intensity of the external AC-magnetic field were 1 kHz and 10^{-4} T, respectively. To detect any induced component along the beam direction, the measuring system was modulated to make the angle θ between the surface of the specimen and the direction of the external AC-field variable. The configuration of the specimen and the external AC-magnetic field is illustrated in Fig. 1. In the present irradiation, the range of the Xe ion beam was 7 μm which is smaller than the thickness of the sample.

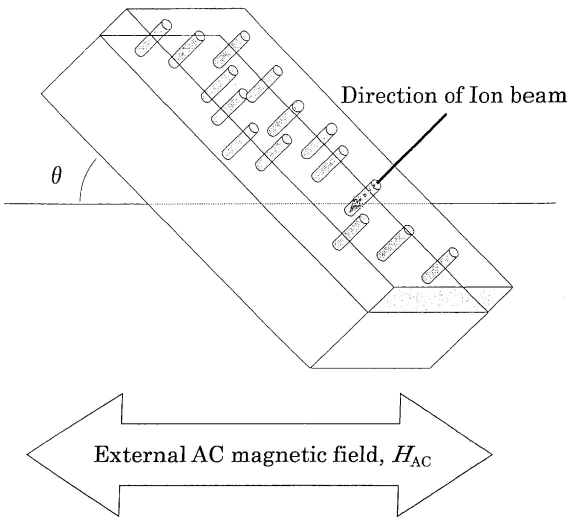

Fig. 1. Schematic illustration of a square plate specimen irradiated by 100 MeV Xe ions and the direction of external AC-magnetic field.

3. Results and discussion

AC-susceptibility versus temperature curves observed before irradiation for Fe–30.2at.%Ni Invar alloy at various angles θ are shown in Fig. 2. From this figure the Curie temperature T_c was determined to be 315 K. In this figure it is seen that

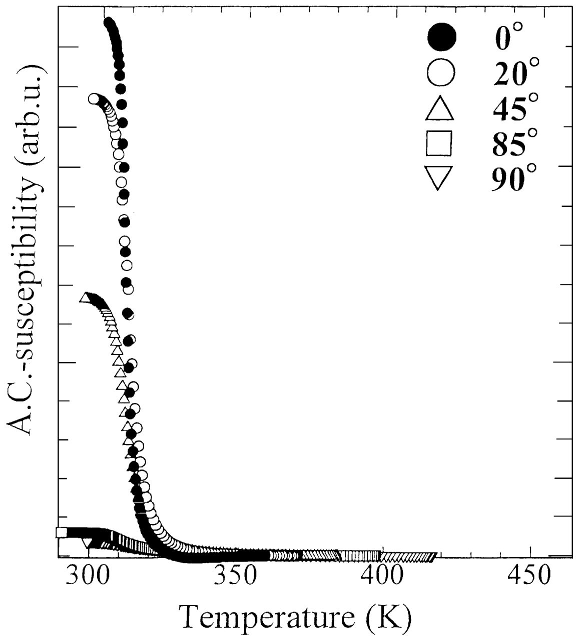

Fig. 2. Temperature dependence of AC-susceptibility for Fe–30.2at.%Ni Invar alloy before irradiation: The angles shown are between the surface of the specimen and the direction of external field.

the intensity of the AC-susceptibility decreases with θ. This effect is due to the shape anisotropy. To investigate the temperature variation of AC-susceptibility above T_c in detail, all the curves were normalized to the value of $\theta = 0$ at $T = 300$ K and shown in Fig. 3. As seen in this figure, the decreasing rate above T_c becomes small as θ is increased.

AC-susceptibility versus temperature curves at various angles θ observed for irradiated specimen are shown in Fig. 4. In this figure it is seen that the curves have two stages of magnetic transition. The first stage corresponds to the original Curie temperature that comes from the part where ion beams did not penetrate. The second stage is caused by the irradiation-induced ferromagnetism. To investigate the temperature variation of AC-susceptibility above T_c in detail, all the curves were again normalized to the value for $\theta = 0$ at $T = 300$ K, and shown in Fig. 5. As seen in this figure, the decreasing rate above T_c also becomes small as θ is increased. The second stage becomes wider as θ

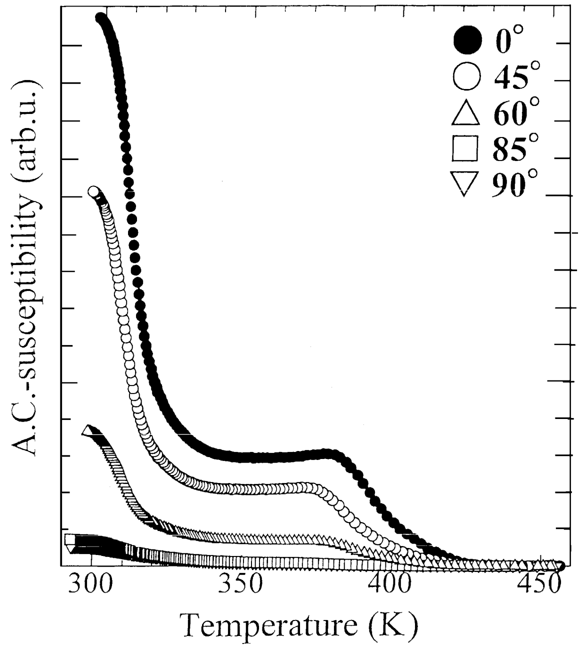

Fig. 4. Temperature dependence of AC-susceptibility for Fe–30.2at.%Ni Invar alloy after irradiated with 100 MeV Xe to the dose of 10^{14} ions/cm^2. The angles shown are between the surface of the specimen and the direction of external field.

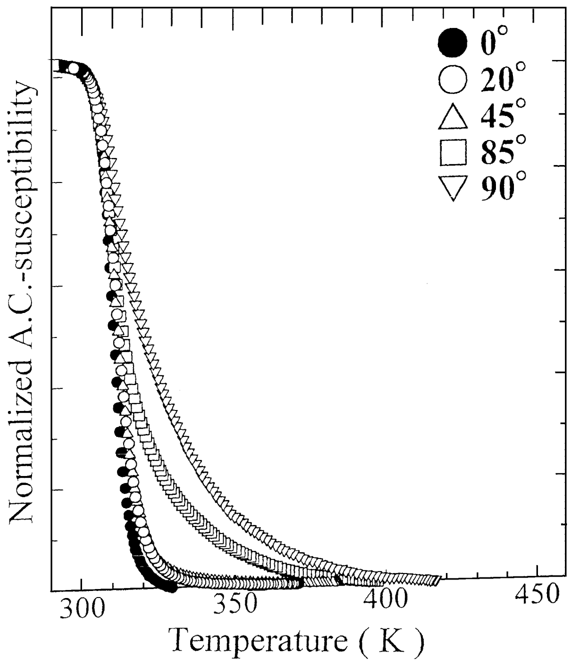

Fig. 3. AC-susceptibility versus temperature curves for Fe–30.2at.%Ni Invar alloy before irradiation in normalized scale at $T = 300$ K and $\theta = 0$.

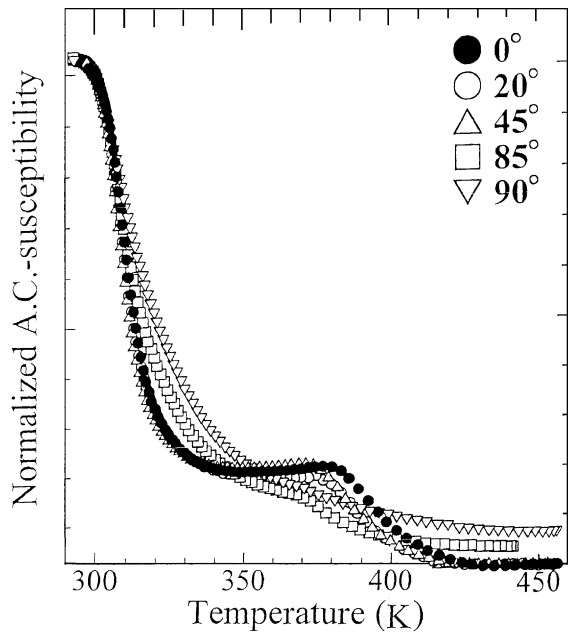

Fig. 5. AC-susceptibility versus temperature curves for Fe–30.2at.%Ni Invar alloy after the irradiation in normalized scale at $T = 300$ K and $\theta = 0$.

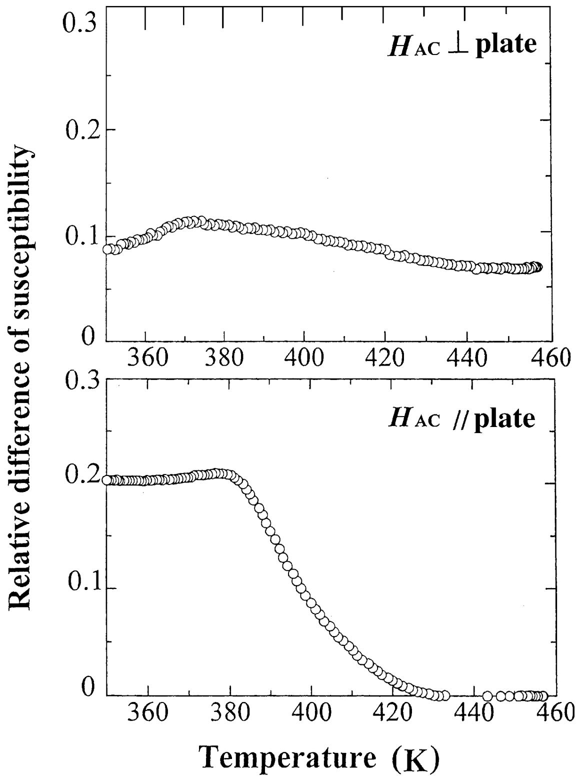

Fig. 6. Temperature dependence of the differences of AC-susceptibility between before and after the irradiation in normalized scale.

reaches 90°, while the first stage remains unchanged. The differences between the normalized values of AC-susceptibilities before and after the irradiation for the cases of $\theta = 0$ and $\theta = 90°$ are plotted in Fig. 6 as functions of temperature. From this figure it is seen that in the case of $\theta = 90°$, the AC-susceptibility signal is still ferromagnetic at the maximum investigated temperature of 460 K, which is about 150 K higher than the original Curie temperature. This tailing effect can be attributed to an existence of locally ferromagnetic parts in the irradiated specimen. Considering the fact that this tailing effect was most clearly seen when the external AC-magnetic field was applied along the direction of the ion beams, the magnetically easy direction is determined to be parallel to the beam axis. These locally ferromagnetic parts exist at high temperatures far above the original Curie temperature are considered to be produced along the paths of high energy ions through high density election excitations [5]. The present type of modification of introducing thin ferromagnetic needles in paramagnetic media has a possibility of applications for perpendicular high-density memory and giant magneto-resistance materials.

4. Conclusions

Measurements of AC-susceptibility versus temperature curves were made for Fe–30.2at.%Ni Invar alloy before and after high-energy Xe ion irradiation. Anomalous two-stage curves were observed after the irradiation. It was shown that locally ferromagnetic parts exist in the irradiated area above the Curie temperature of 315 K. Easy direction of the magnetization for the ferromagnetic parts was induced along the ion beams. The shape of the locally ferromagnetic parts can be considered to be in thin needle like.

Acknowledgements

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