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Ultra-Soft Magnetic Properties in Nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ Alloy

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Abstract

The extremely soft magnetic behaviors in the nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ alloy annealed at 450 ℃ and 550 ℃ for 1 hour respectively in a vacuum were obtained, and examined by means of the magnetoimpedance(MI) effect and the incremental permeability. Because the MI effect can be obtained only in ultra-soft magnetic materials, the improvement of magnetic softness by proper thermal treatment was carefully monitored by the MI effect for all annealed samples. The changes of the incremental permeability as a function of an external field were also measured to verify the magnetic softness along with the MI measurement.

1. Introduction

Fe - Nb based nanocrystalline alloys are focused on extremely soft magnetic behaviors achieved upon suitable partial nanocrystallization by a proper thermal treatment [1]. Recently, frequency and field-dependent magnetoimpedance effects have been observed in very soft ferromagnetic amorphous ribbons and wires [2]-[4]. The fact that sensitive changes of the magnetoimpedance (MI) effect depending on the internal and external stress, field-annealing, surface structures, etc. were observed in ultra soft ferromagnets strongly suggests that the small effective anisotropy constant and large magnetic permeability play a key role. The electromagnetic origin of the MI effect has been surmised to the combination of the skin effect and the field dependence of the circumferential magnetic permeability associated with the circular motion of magnetic moments [5]. Since the MI effect can be obtained only in ultra-soft magnetic materials, we have investigated the annealing effect on the structural changes in the nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ ribbon via the MI effect.

2. Experiment

The nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ ribbon was prepared by a rapid quenching technique in an Ar atmosphere. The samples were cut out 15 mm in length , 1.5 mm in width and 20 ㎛in thickness. Annealing was performed in a vacuum at various temperatures (450 ℃ and 550 ℃ for 1 hour). For the MI measurement, the external field applied by a solenoid can be swept through the entire cycle equally divided by 800 intervals from -150 Oe to 150 Oe. The frequency of the MI measurement was ranging from 100 kHz to 10 MHz, and the ac current was fixed at 50 mA for all measurements [6]. We have measured the change of the longitudinal incremental permeability as a function of an external field using the MI measurement system by replacing the MI probes with a set of primary and secondary coils located in a solenoid. The structural changes of the nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ alloy were investigated by X – ray diffraction (XRD) and transmission electron microscopy (TEM) after thermal treatment.

3. Result and Discussion

The magnetoimpedance ratio (MIR) can be defined as $MIR(H) = \Delta Z/Z(H_{\max}) = 1 - |Z(H)/Z(H_{\max})|$ where H_{max} is an external magnetic field sufficient for saturating the magnetoimpedance. In our experiment H_{max} = 150 Oe. The permeability ratio(PR) can be defined as $PR(H) = \Delta\mu/\mu(H_{\max}) = 1 - |\mu(H)/\mu(H_{\max})|$ similar to MIR. The nearly zero MIR value in as-quenched sample is evident that the sample is not shown soft magnetic properties. However, the maximum MIR value is increased drastically in the sample annealed at 450 ℃ and 550 ℃ indicating that the sample is ultra-softened by nanocrystallization as shown in Fig. 1. Asymmetric behavior appeared in MIR peaks in Fig. 1 may be due to small residual hysteresis of local anisotropy distribution at a low external field with respect to corresponding magnetic domains for the frequency.

In general, the magnetic softness can be achieved by the decrease of the anisotropy and the reduction of magnetostriction values. From the study of the effective anisotropy in nanocrystalline alloys, it was possible to reduce the anisotropy by the averaging over a large number of grains of the easy directions of the local microcrystalline anisotropy [1].

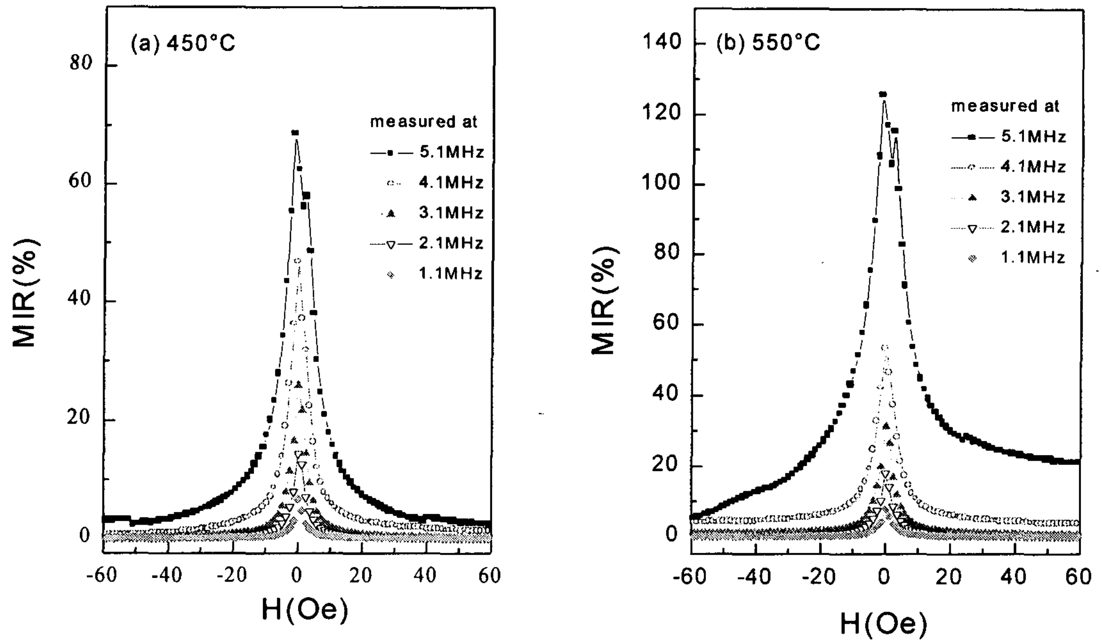

Fig. 1. The MIR vs the external field H measured at various frequencies in $Fe_{81}B_{11}Nb_7Cu_1$ alloy annealed at (a) 450℃ and (b) 550 ℃.

Furthermore, the decrease of the magnetoelastic coupling reduces the magnetostriction values. Therefore the giant magnetoimpedance effect can be observed only in ultra - soft magnetic materials with nearly zero magnetostriction constant, nearly zero coercivity, and high circumferential permeability.

The PR curves are also plotted in Fig. 2 as a function of the external field. One notes that the changes of the magnetoimpedance are much related to the changes of longitudinal permeability in the present of an external field as clearly shown in Fig. 2. The full width at half maximum(FWHM) in the longitudinal PR curves didn't changed very much for the samples annealed at 450 ℃ regardless of the presenting magnetic field during the heat treatment. However big changes of the FWHM in the PR curves of the sample annealed at 550 ℃ indicate that structural changes such as crystallization have been occurred.

The broadening MIR curves along with increment of frequency may arise from the circumferential permeability that is somewhat different form longitudinal permeability as shown in Fig. 2. The sharpness of PR curves after annealing implies the decrease of the local anisotropy distribution by nanocrystallization.

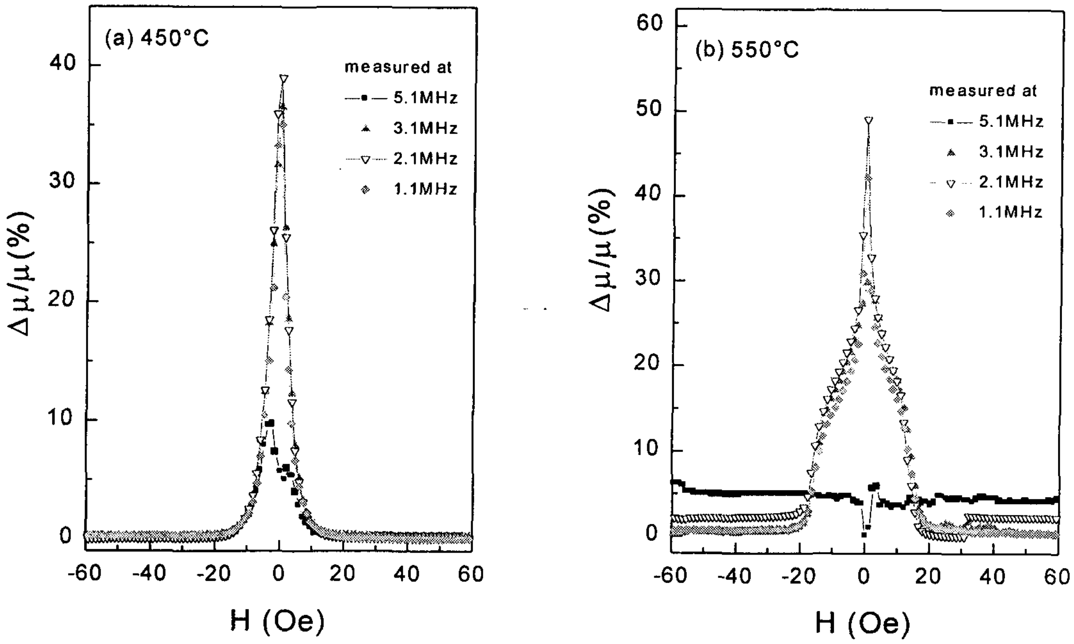

Fig.2. The PR vs the external field H measured at various frequencies in $Fe_{81}B_{11}Nb_7Cu_1$ alloy annealed at (a) 450℃ and (b) 550 ℃.

XRD and TEM patterns confirm that the sample annealed at 450 ℃ is in a nanocrystalline phase. However, the sample annealed at 550 ℃ is found to be in a polycrystalline phase. In general, the changes of the magnetoimpedance are closely related to the changes of the longitudinal incremental permeability. Therefore the magnetic softness can be estimated by the MIR or the PR.

Fig. 3. shows that values of MIR varies as the increment of frequency in as-quenched, annealed at 450 ℃ and 550 ℃. As shown Fig. 3, the curve of MIR is saturated at 5.1 MHz. Since H_{ex} is a hard axis field with respect to the circumferential anisotropy, the magnetic field applied along the ribbon axis suppresses the circular magnetization by domain wall movements at the low frequency region, or the motion of localized magnetic moments at the high frequency region. Our experiment was performed in the high frequency region (100 kHz - 10 MHz) where domain wall movements are highly damped. As the circumferential permeability decreases rapidly

along with the increment of the external field, it is responsible for MI effects in the soft ferromagnetic ribbons. This process accompanied by rapid reduction in the circumferential soft magnetic properties of the samples as the external field increases affects the voltage across the ribbon ends. Therefore MIR can be measured directly from the changes of this voltage. The ac current flowing through the sample generates an easy-axis driving field that causes a circular magnetization field H_ϕ.

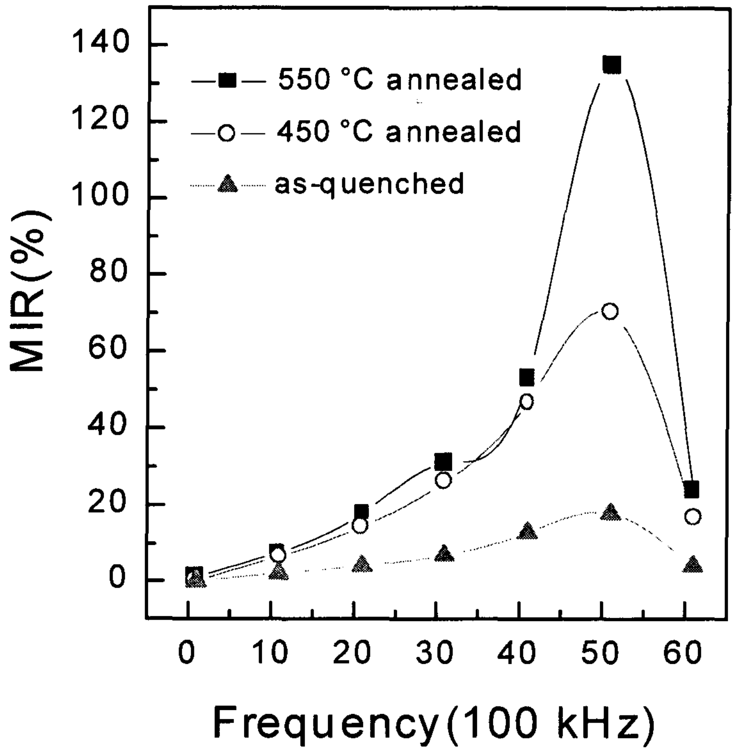

Fig. 3. The MIR vs frequency curves at various temperatures in as-quenched, annealed at 450 ℃ and 550 ℃ $Fe_{81}B_{11}Nb_7Cu_1$ alloy.

Otherwise, the variation of PR curves vs frequency shows that PR decreases as frequency increase to 5.1 MHz in Fig. 4. One may adapt a model for the transverse biased permeability in thick ferromagnetic films where eddy current damping and the ripple field H_R incorporating with the anisotropy field H_K give rise to the peak of permeability at an external field as well as the broadening of the permeability changes as a function of the external field to explain broadening MIR curves at high frequency. It is worthily noting that the magnetoimpedance increases as frequency increases because the impedance is proportional to $(\omega\mu_\phi)^{1/2}$ even in case of the decrement of the transverse permeability at high frequency.

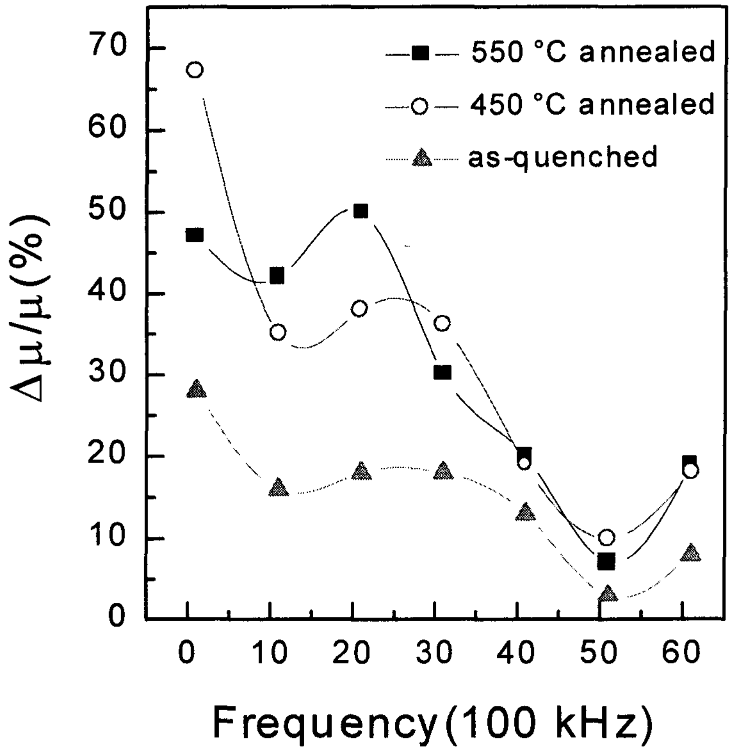

Fig. 4. The PR vs frequency curves at various temperatures in as-quenched, annealed at 450 ℃ and 550 ℃ $Fe_{81}B_{11}Nb_7Cu_1$ alloy.

4. Conclusion

The ultra-soft magnetic properties in nanocrystalline $Fe_{81}B_{11}Nb_7Cu_1$ alloy have been studied. The maximum MIR value increases drastically in the sample annealed at 450 ℃ and 550 ℃ indicating that the sample is ultra-softened by nanocrystallization. The full width at half maximum(FWHM) in the longitudinal PR curves didn't changed very much for the samples annealed at 450 ℃ regardless of the presenting magnetic field during the heat treatment. However big changes of the

FWHM in the PR curves of the sample annealed at 550 ℃ indicate that structural changes such as crystallization have been occurred. The sharpness of the PR curve is helpful to examine soft magnetic properties.

Acknowledgment

This work was supported by the Korea Science and Engineering foundation through the Research Center for Advanced Magnetic Materials at Chungnam National University.

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