

Magnetoimpedance Effect in Nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) Alloys

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The magnetoimpedance of $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) alloys has been measured to investigate the influence of structural changes in the nanocrystallization process after thermal treatment. Annealing was performed at temperatures of 350°C, 450°C, and 550°C for 1 hour in a vacuum. Ultra soft magnetic behavior was observed in the samples annealed at 550°C. The magnetoimpedance ratio and the longitudinal permeability ratio coincided with the softness of the magnetic properties of the thermally treated samples.

Key words : magnetoimpedance effect, magnetoimpedance ratio (MIR), permeability ratio (PR); nanocrystalline alloy, incremental permeability

1. Introduction

A number of studies have been reported on Fe-Zr based nanocrystalline alloys because of the extremely soft magnetic behavior achieved upon suitable partial nanocrystallization by thermal treatment. The exchange and the dipolar intergrain interactions, mediated by the amorphous intergranular phases, result in reduced effective values of the local anisotropy [1].

Recently, frequency and field-dependent impedance effects were observed in very soft ferromagnetic amorphous ribbons and wires [2-4]. The magnetoimpedance (MI) effect is a classical electromagnetic phenomena where the impedance of a ferromagnetic conductor changes drastically under the application of a longitudinal magnetic field. The electromagnetic origin of the MI effect has been attributed to a combination of the skin effect and the field dependence of the circumferential magnetic permeability associated with the circular motion of the magnetic moments [5]. Since giant MI effects are obtained only in ultra soft magnetic materials, we have investigated the effect of anneals on the structural changes in nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) ribbons *via* the MI effect.

2. Experiment

The nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) ribbons were prepared by using a rapid quenching technique in an Ar atmosphere. Annealing was performed in vacuum for 1 hour at various temperatures (350°C, 450°C, 550°C). For the MI measurement, the external field applied by a solenoid could be swept through the entire cycle, equally divided into 800 intervals, from -150 Oe to 150 Oe. The schematic diagram of MI measurement sys-

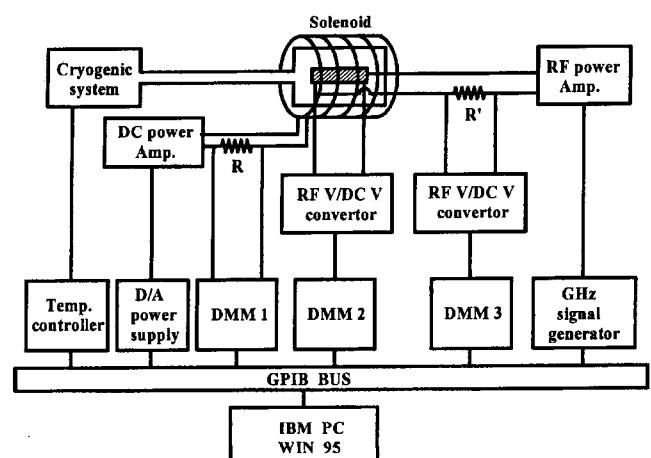


Fig. 1. Schematic diagram of the magnetoimpedance measurement system.

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tem is shown in Fig. 1. A frequency of the MI measurement ranged from 100 kHz to 10 MHz, and the ac current was fixed at 10 mA for all measurements. Averaging the MI while sweeping the fields, changing the frequencies, and keeping the ac current constant were done using a Windows program. We measured the change in the longitudinal permeability as a function of the external field by using the MI measurement system and replacing the MI probes with a set of primary and secondary coils located in a solenoid.

3. Results 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 to saturate the magnetoimpedance. In our experiment, H_{max} was 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 the definition of the MIR.

The magnetoimpedance effect at a high frequency can be explained in terms of an external field dependence of the impedance as a result of the transverse magnetization with respect to the direction of the current flowing through the sample and the skin effect of an ac current. Because an alternating current tends to be concentrated near the surface of a conductor, the impedance Z changes according to the current distribution and the shape of the conductor. This is accompanied by a rapid reduction in the circumferential soft magnetic properties of the samples as the external field affects the voltage across the ribbon ends. Therefore, the MIR can be measured directly from the changes in this voltage. The ac current flowing through the sample generates an easy-axis driving field that causes a circular magnetization field.

Since the external field is a hard axis field with respect to the circumferential anisotropy, the magnetic field applied along the ribbon axis suppresses the circular magnetization due to the motion of localized magnetic moments in the high frequency region. The rapid decrease in the circumferential permeability with increasing external field is responsible for the magnetoimpedance effects in soft ferromagnetic ribbons.

For magnetic materials, the transverse circumferential permeability, μ_ϕ , affects the penetration depth, $c/(2\pi\omega\mu_\phi)^{1/2}$ [6]. Therefore, we can expect that the impedance in the case of the skin effect will be proportional to $(\omega\mu_\phi)^{1/2}$. Our experimental MIR curves show this tendency.

The PR curves measured at 1.1 MHz in the as-quenched samples and the samples annealed at 550°C are shown in Fig. 2. The big changes in the magnitude and

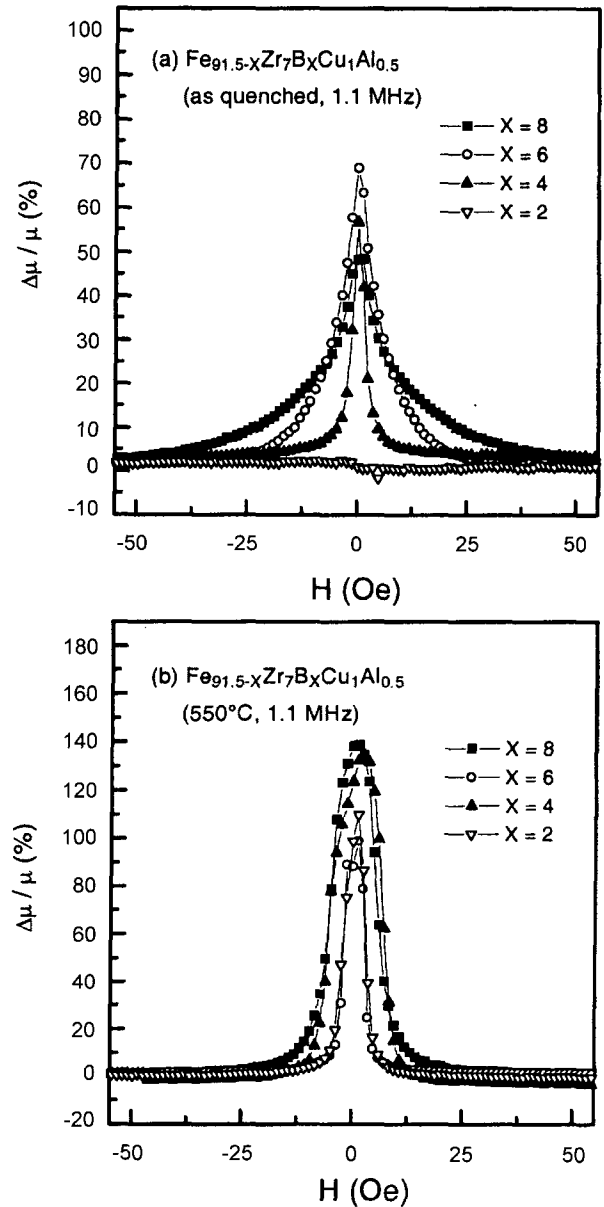


Fig. 2. PR curves measured at 1.1 MHz in (a) as-quenched $Fe_{91.5-x}Zr_7B_xCu_1Al_{0.5}$ ($x=2, 4, 6, 8$) alloys and (b) $Fe_{91.5-x}Zr_7B_xCu_1Al_{0.5}$ ($x=2, 4, 6, 8$) alloys samples annealed at 550°C.

the shape of the PR curves for the $Fe_{89.5}Zr_7B_2Cu_1Al_{0.5}$, $Fe_{85.5}Zr_7B_6Cu_1Al_{0.5}$, and $Fe_{83.5}Zr_7B_8Cu_1Al_{0.5}$ alloys annealed at 550°C indicate that structural changes, such as nanocrystallization, have occurred. The sharpness of PR curves for the as-quenched $Fe_{87.5}Zr_7B_4Cu_1Al_{0.5}$ alloy and the nanocrystalline $Fe_{89.5}Zr_7B_2Cu_1Al_{0.5}$, $Fe_{85.5}Zr_7B_6Cu_1Al_{0.5}$, and $Fe_{83.5}Zr_7B_8Cu_1Al_{0.5}$ alloys annealed at 550°C indicates that the magnetization can be saturated at a very low external magnetic field.

X-ray diffraction (XRD) patterns showed that all the

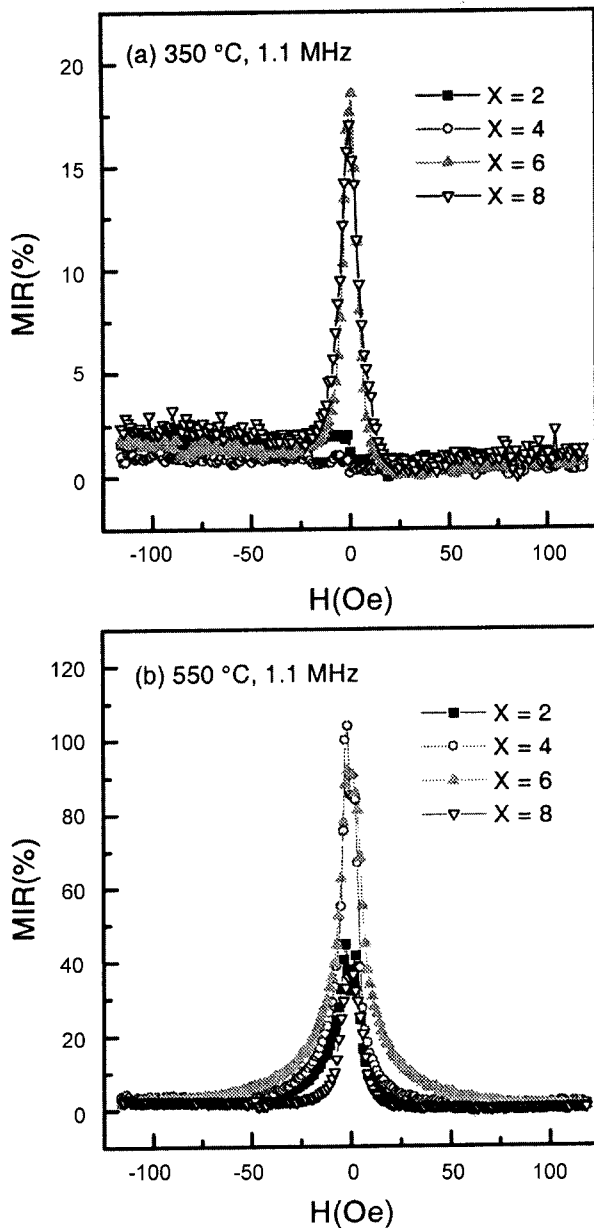


Fig. 3. MIR vs the external field H measured at 1.1 MHz in the $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) alloys annealed at (a) 350°C and (b) 550°C.

samples annealed at 550°C had nanocrystalline structures. The as-quenched $\text{Fe}_{85.5}\text{Zr}_7\text{B}_6\text{Cu}_1\text{Al}_{0.5}$ and $\text{Fe}_{83.5}\text{Zr}_7\text{B}_8\text{Cu}_1\text{Al}_{0.5}$ alloys were in an amorphous state, and the as-quenched $\text{Fe}_{89.5}\text{Zr}_7\text{B}_2\text{Cu}_1\text{Al}_{0.5}$ and $\text{Fe}_{87.5}\text{Zr}_7\text{B}_4\text{Cu}_1\text{Al}_{0.5}$ alloys were in a mixed state of the amorphous phase and the α -Fe phase. The electron diffraction patterns also showed the appearance of α -Fe peaks for the samples annealed at 550°C. Transmission electron microscopy showed that the α -Fe

phase didn't precipitate to a nanocrystalline structure in samples annealed at 350°C and 450°C.

Fig. 3 represents the magnetoimpedance ratio (MIR) versus the external field, H , measured at 1.1 MHz for the $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ alloys annealed at 350°C and 550°C. The MIR curves of the $\text{Fe}_{89.5}\text{Zr}_7\text{B}_2\text{Cu}_1\text{Al}_{0.5}$ alloy and the $\text{Fe}_{87.5}\text{Zr}_7\text{B}_4\text{Cu}_1\text{Al}_{0.5}$ alloy annealed at 350°C are nearly zero due to the poor magnetic softness. However, the MIR values were drastically higher in the nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) alloys annealed at 550°C due to their very soft magnetic properties. The sharpness of MIR curves after annealing implies that the internal anisotropy had been reduced very much by the thermal treatment.

4. Conclusion

The magnetoimpedance effect in nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) alloys has been studied. An ultra magnetic softness in these alloys can be obtained by proper thermal treatment. The nanocrystalline $\text{Fe}_{91.5-x}\text{Zr}_7\text{B}_x\text{Cu}_1\text{Al}_{0.5}$ ($x = 2, 4, 6, 8$) alloys annealed at 550°C for 1 hour showed the ultra magnetic softness, such as a nearly zero coercivity and anisotropy, a high permeability ratio (PR), and high MIR values.

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