Giant Magnetoimpedance in As Cast Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ Ribbons

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In the present work the giant magnetoimpedance of Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ as cast ribbons was reported. With increasing Cu content, the magnetoimpedance increases at first, experiences a maximum value at about 3% Cu, and then decreases again at high Cu content. The value of magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 3) as cast ribbon is -37.5% under $H = 7162$ A/m at 700 kHz. The large magnetoimpedance for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ is connected with the strong change of transverse permeability. The grain size of $\alpha$-Fe derived from (200) peak based on Scherrer’s equation is 19 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 3), 13 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 4) and 11 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 5), respectively. The high Cu addition in Fe-(Nb,Zr)-B-Cu not only enhances the nucleation of $\alpha$-Fe in as cast ribbon, but also reduces its grain size. The present experimental results indicated that Fe-(Nb,Zr)-B-Cu nanocrystalline materials with large magnetoimpedance can be fabricated with melting-spinning method without annealing.

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1. Introduction

The giant magnetoimpedance (GMI) effect has recently attracted much attention because of its important application in magnetic heads and sensors.1–6) The main point of GMI is that similar to nanocrystalline Fe-Cu-Nb-Si-B and Fe-Zr-B-Cu,16) Fe-(Nb,Zr)-B-Cu nanocrystalline ribbons with large magnetoimpedance can be fabricated with melting-spinning method without additional annealing processes.16,17) In the present work, the giant magnetoimpedance in Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ as cast ribbons was reported. Results indicated that similar to nanocrystalline Fe-Cu-Nb-Si-B and Fe-Zr-B-Cu,17) Fe-(Nb,Zr)-B-Cu nanocrystalline ribbons with large GMI effect can also be directly fabricated through melting-spinning technique. The high Cu addition in NANOPIERM not only enhances the nucleation of $\alpha$-Fe in as cast ribbon, but also reduces its grain size.

2. Experiments

The alloys Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 1, 2, 2.5, 3, 3.5, 4 and 5) were obtained by arc-melting in argon atmosphere. The buttons were melted four times to ensure homogeneity. The Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_9$Cu$_x$ ribbons of about 25 µm thickness were prepared by the single roller melting-spinning technique with wheel speed of 35 m/s in argon atmosphere. As cast ribbons with 2 mm width, 30 mm length were used in the magnetoimpedance measurement with a HP 4294A impedance analyzer at room temperature. The sample was connected to the analyzer with the accessory test lead, which was carefully designed and contains four cables. The ribbon was placed within Helmholtz coils, which produced a dc magnetic field $H \leq 7958$ A/m. The Helmholtz coils were so placed that the applied dc field was perpendicular to the earth’s magnetic field. The ac currents with the amplitude of 20 mA and dc fields were applied in the direction along the ribbon length for longitudinal magnetoimpedance measurement. The relative change of transverse permeability under field was measured using a small coil with the equivalent impedance method by a HP 4294 impedance analyzer, where dc fields were applied perpendicular to the ribbon length. The X-ray diffraction measurement of Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 2, 3, 4 and 5) as cast ribbons was performed with Cu Kα radiation.

3. Results and Discussion

Figure 1 showed the dc field dependence of magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ (x = 3) as cast ribbon, where $Z(H)$ and $Z(0)$ were absolute values of the impedance at dc fields of H and zero, respectively. At 700 kHz and 1.5 MHz, the magnetoimpedance shows monotonous change due to the decrease of transverse permeability with field. The monotonous variation in magnetoimpedance is of some advantages for practical application in magnetic micro-sensors. At 5 MHz, there is a very small peak under $H = 159$ A/m, such smaller peak originates from the transverse anisotropy in ribbons.10–13)

The frequency dependence of magnetoimpedance $\Delta Z/Z_0 = (Z(H) - Z(0))/Z(0)$ under $H = 7162$ A/m for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9-x}$Cu$_x$ as cast ribbons (x = 2, 3 and 5) were shown in Fig. 2, respectively. With increasing frequency, the $\Delta Z/Z_0$ increases at first, undergoes a maximum ($\Delta Z/Z_0)_{\text{max}}$ at a certain frequency, and finally drops again. It has been showed that the impedance Z being dependent on the field...
and frequency is proportional to the root of the product of permeability and frequency at the case of strong skin effect.\textsuperscript{18} As shown in Fig. 3, the permeability change $\Delta \mu'/\mu'(0) = (\mu'(H) - \mu'(0))/\mu'(0)$ under transverse field $H = 7162$ A/m reduces with an increase of frequency. The maximum of $\Delta Z/Z_0$ is a result of the competition between a decrease of permeability change and an increase of skin effect. The Cu content dependence of the maximum value $(\Delta Z/Z_0)_{\text{max}}$ under $H = 7162$ A/m for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9.5}$Cu$_x$ as cast ribbons was shown in Fig. 4. The $(\Delta Z/Z_0)_{\text{max}}$ for $x = 1$ is smaller, only about $-13.1\%$. With increasing Cu content, the magnetoimpedance under $H = 7162$ A/m increases at first, experiences a maximum value of $-37.5\%$ at $x = 3$, and then decreases again at high Cu content. The $(\Delta Z/Z_0)_{\text{max}}$ for $x = 5$ is $-9.4\%$. As shown in Fig. 3, the relative change of permeability under transverse field $H = 7162$ A/m at 50 kHz are $-77.9\%$ and $-60.5\%$ for the $x = 3$ and $x = 5$, respectively. The large magnetoimpedance for $x = 3$ is connected with the strong change of transverse permeability.

Figure 5 presented X-ray diffraction patterns for as cast ribbons Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9.5}$Cu$_x$ $(x = 2, 3, 4$ and $5)$. $\alpha$-Fe phase occurs in the as cast ribbons without annealing. For as cast $x = 2$, the (200) peak-intensity of $\alpha$-Fe is very weak and its (211) peak is almost invisible, which is due to few amount of $\alpha$-Fe phases in the as cast ribbon. In contrast, the (200) and (211) peaks appear evidently for $x = 3, 4$ and $5$. This implies that high Cu addition in Fe-(Nb,Zr)-B-Cu enhances the nucleation of $\alpha$-Fe in as cast ribbon. This is consistent with the previous suggestion\textsuperscript{19} that in Fe-Zr-B-Cu alloy Cu induces significant fluctuation in Fe concentration, which cause high density of nucleation sites for primary crystallization. The grain-size of $\alpha$-Fe derived from (200) peak based on Scherrer’s equation\textsuperscript{20} is about 19 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9.5}$Cu$_3$ $(x = 3)$, 13 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9.5}$Cu$_4$ $(x = 4)$ and 11 nm for Fe$_{84}$Nb$_{3.5}$Zr$_{3.5}$B$_{9.5}$Cu$_5$ $(x = 5)$, respectively. The addition of Cu reduces the grain size of $\alpha$-Fe in as cast nanocrystalline Fe-(Nb,Zr)-B-Cu ribbons. The role of Cu in grain refinement for Fe$_{87}$Nb$_{1.25}$Zr$_{1.25}$B$_{0.25}$Cu$_x$ $(x = 0$–$2)$ annealed ribbons was also observed previously.\textsuperscript{9}
α-Fe nano-grains, a very little of Fe₃Zr-type phase exists in as cast ribbons as shown in Fig. 5. Fe₃Zr-type phase was previously observed in nanocrystalline ribbons Fe₉₁Zr₇B₂ and Fe₈₆Zr₇B₂Cu₁ annealed at a high temperature such as 700°C. ⁷,⁸

4. Conclusions

In conclusion, in the present work the giant magnetoimpedance of Fe₈₄Nb₃Zr₃B₉ₓCuₓ as cast ribbons was reported. With increasing Cu content, the magnetoimpedance increases at first, experiences a maximum value at about x = 3, and then decreases again at high Cu content. The longitudinal magnetoimpedance ΔZ/Ζ₀ for Fe₈₄Nb₃Zr₃B₉Cuₓ (x = 3) as cast ribbon is ~37.5% under H = 7162 A/m at 700 kHz. The large magnetoimpedance for x = 3 is connected with the strong change of transverse permeability. The grain size of α-Fe derived from (200) peak is 19 nm for Fe₈₄Nb₃Zr₃B₉Cu₃ (x = 3), 13 nm for Fe₈₄Nb₃Zr₃B₅Cu₄ (x = 4) and 11 nm for Fe₈₄Nb₃Zr₃B₅Cu₅ (x = 5), respectively. The high Cu addition in Fe-(Nb,Zr)-B-Cu not only enhances the nucleation of α-Fe in as cast ribbon, but also reduces its grain size.

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