Magnetoimpedance Effect in Amorphous $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ As Cast Ribbon

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In the present work, the magnetoimpedance effect is reported in as cast $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ amorphous ribbon. The magnetoimpedance $(Z(0) - Z(H))/Z(0)$ is about 16% under $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at 5.1 MHz. The magnetoreactance $(X(0) - X(H))/X(0)$ can reach 43.71% under $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at 121 kHz. With increasing ac frequency, the magnetoimpedance $(Z(0) - Z(H))/Z(0)$ increases at first, undergoes a peak and finally drops again. The magnetoimpedance $(Z(0) - Z(H))/Z(0)$, magnetoresistance $(R(0) - R(H))/R(0)$ and magnetoreactance $(X(0) - X(H))/X(0)$ intersect at a frequency. Under a lower field $H = 4.22 \times 10^3 \text{ A}\cdot\text{m}^{-1}$, the peak frequency f_Z is larger than the intersecting frequency f_i . Under higher fields $H \geq 6.92 \times 10^3 \text{ A}\cdot\text{m}^{-1}$, the peak frequency f_Z coincides with the intersecting frequency f_i . Both peak frequency f_Z and intersecting frequency f_i increase with increasing dc field.

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1. Introduction

Most investigation so far on Nd-Fe-B materials have been focused on the hard magnetic behavior of $\text{Nd}_2\text{Fe}_{14}\text{B}$, which can be prepared easily in sintered magnets, melt-spun ribbons and mechanically alloyed powders. Nd-Fe-B type nanocrystalline ribbons consisting $\alpha\text{-Fe/Nd}_2\text{Fe}_{14}\text{B}$ and $\text{Fe}_3\text{B/Nd}_2\text{Fe}_{14}\text{B}$ have been widely studied due to the exchange coupling properties and enhanced magnetic energy product.¹⁻³⁾ The nanocrystalline structure can be obtained by annealing the overquenched amorphous ribbons at temperature above the crystallization temperature. The remanence and coercivity for ribbons $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ after annealing at 670°C for 30 min are about 1.2 T and $2.38 \times 10^5 \text{ A/m}$, respectively.¹⁾ Recently the magnetoimpedance (MI) effect in some soft ferromagnetic materials has attracted much attention because of its potential applications in the field sensing and magnetic heads.⁴⁻¹⁴⁾ The MI effect includes a sensitive change in impedance with the application of a small DC magnetic field. It was suggested that the MI effect strongly depends on the variation in skin depth via the permeability.^{5,6)} Early works on the MI effect are on the nearly non-magnetostrictive FeCoSiB amorphous wires.⁴⁻⁶⁾ The investigation on the MI effect have been quickly extended to amorphous FeCoSiB ribbons^{5,7)} and Fe based nanocrystalline ribbons/wires such as FeCuNbSiB ,⁸⁻¹⁰⁾ FeZrB ^{11,12)} and permalloy ribbons/wires NiFeMo .^{13,14)} In the present work, we report the magnetoimpedance effect in the as cast ribbon $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ with melt-spun quenching speed of 40 m/s.

2. Experiments

The as cast ribbons $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ were prepared by the single roller melt spinning technique with wheel speed of 40 m/s in an argon atmosphere. X-ray diffraction analysis was performed with $\text{Cu-K}\alpha$ radiation. The as cast ribbon $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ with 25 μm thickness, 1.5 mm width, 20 mm length was used in the magnetoimpedance measurement with a HP4294A impedance analyzer at room temperature. AC

Fig. 1 The X-ray diffraction pattern of the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon.

currents (with the current amplitude of 20 mA) and DC magnetic fields were applied in the direction along the ribbon.

3. Results and Discussion

The X-ray diffraction pattern of $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon is shown in Fig. 1. It can be seen that the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon with the wheel speed of 40 m/s is in the amorphous state. Figure 2 shows the ac frequency dependence of resistance R , reactance X and impedance Z for the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon under different fields of $H = 0$, $H = 4.22 \times 10^3 \text{ A}\cdot\text{m}^{-1}$ and $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$, respectively. The impedance as well as the resistance and reactance increase with increasing ac frequency, which are attributed to the skin effect. Under applied DC magnetic fields, values of Z , R and X decrease compared with the case of absence of the DC field.

Figure 3 shows the dependence of impedance Z on DC fields for the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon. With increasing the field from 0 to $2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$, the Z decreases from 8.637 to 8.001 Ω at 964 kHz and from 11.138 to 9.506 Ω at 3.012 MHz. The magnetoimpedance $(Z(H) - Z(0))/Z(0)$ under $H \approx 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ are -7.36% ,

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Fig. 2 The ac frequency dependence of resistance R , reactance X and impedance Z for the Nd₄Fe_{77.5}B_{18.5} as cast ribbon under different fields of $H = 0$, $H = 4.22 \times 10^3 \text{ A}\cdot\text{m}^{-1}$ and $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$, respectively.

−14.65% and −13.05% for $f = 964 \text{ kHz}$, 3.012 MHz and 10 MHz, respectively. It can be also seen from Fig. 3 that under a field of $2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ the impedance approaches its saturation at low frequency such as 964 kHz but not yet at higher frequency such as 10 MHz. Similar field dependence of the resistance and reactance are shown in Figs. 4 and 5, respectively.

Figure 6 shows the ac frequency dependence of the fractional change of magnetoeimpedance $(Z(0) - Z(H))/Z(0)$, magnetoresistance $(R(0) - R(H))/R(0)$ and magnetoreactance $(X(0) - X(H))/X(0)$ for the Nd₄Fe_{77.5}B_{18.5} as cast ribbon under different DC fields. With increasing ac frequency, the magnetoeimpedance $(Z(0) - Z(H))/Z(0)$ increases at

Fig. 3 The dependence of impedance Z on dc fields for the Nd₄Fe_{77.5}B_{18.5} as cast ribbon.

first, undergoes a peak at a frequency f_Z , and finally decreases again with further increase of the frequency. In contrast, the magnetoreactance decreases but magnetoresistance increases with increasing frequency from 0.121 to 10 MHz. Similar case has been found in NiFeMo ribbons.¹⁴⁾ The magnetoreactance $(X(0) - X(H))/X(0)$ reaches 43.71% under $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at 0.121 MHz. It is evident from Fig. 6 that the magnetoeimpedance, magnetoresistance and magnetoreactance intersect at a frequency. Figure 7 shows the dc field dependence of the peak frequency f_Z , intersecting frequency f_i and their magnetoeimpedance values at f_Z and f_i , respectively. Under a lower field $H = 4.22 \times 10^3 \text{ A}\cdot\text{m}^{-1}$, the intersecting frequency f_i is 3.13 MHz, which is smaller than the peak fre-

Fig. 4 The resistance R dependence on dc fields for the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon.

quency f_Z of 3.37 MHz. Under fields $H \geq 6.92 \times 10^3 \text{ A} \cdot \text{m}^{-1}$, the peak frequency f_Z and intersecting frequency f_i coincide. Both peak frequency f_Z and intersecting frequency f_i increase with increasing dc field. The f_Z is 5.10 MHz under a field of $H = 2.08 \times 10^4 \text{ A} \cdot \text{m}^{-1}$. The peak value of the magnetoimpedance $\Delta Z/Z(0) = (Z(0) - Z(H))/Z(0)$ at f_Z increases from 9.28 to 16.04% with increasing field from 4.22×10^3 to $2.08 \times 10^4 \text{ A} \cdot \text{m}^{-1}$.

It should be pointed that the MI effect is lower for $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ amorphous ribbon than for FeCoSiB amorphous materials. It was observed that the $(Z(0) - Z(H))/Z(0)$ for the as cast FeCoSiB amorphous wire can

Fig. 5 The reactance X dependence on dc fields for the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon.

reach -85% under $H = 557 \text{ A} \cdot \text{m}^{-1}$ at 12 MHz and 71% under $H = 4.77 \times 10^3 \text{ A} \cdot \text{m}^{-1}$ at 100 kHz,¹⁵⁾ meanwhile the value $(Z(0) - Z(H))/Z(0)$ of 40% can be obtained for the FeCoSiB ribbon under $H = 3.98 \times 10^3 \text{ A} \cdot \text{m}^{-1}$ at 10 MHz.¹⁶⁾ The coercivity H_C of the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ amorphous ribbon was measured as about $637 \text{ A} \cdot \text{m}^{-1}$, which may be approximately equal to the anisotropy field H_K . In general, there are two field-positions where the large magnetoimpedance usually appears. One position is near the H_K where there may exist a peak in the field dependence of magnetoimpedance. Another position may occur at the magnetic field H_S for the saturation magnetoimpedance at low frequencies. For example, it was found that $H_S = 1.59 \times 10^3 \text{ A} \cdot \text{m}^{-1}$ at $f = 100 \text{ kHz}$ and $H_S > 3.98 \times 10^3 \text{ A} \cdot \text{m}^{-1}$ at $f = 10 \text{ MHz}$ for the soft

Fig. 6 The ac frequency dependence of the change ratios of magnetoeimpedance ($(Z(0) - Z(H))/Z(0)$), magnetoresistance ($(R(0) - R(H))/R(0)$) and magnetoreactance ($(X(0) - X(H))/X(0)$) for the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon under different dc fields, respectively.

amorphous FeCoSiB ribbons.¹⁶⁾ For the $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ amorphous ribbon H_S is $2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at $f = 964 \text{ kHz}$ but $H_S > 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at $f = 10 \text{ MHz}$, as shown in Fig. 3. The H_S may be correlated with the interplay between the anisotropy field⁴⁾ and the eddy-current field.¹⁷⁾ In fact, up to now the theoretical explanation of the amplitude of the H_S is not clear, and it is still an open problem.

In conclusion, in the present work, the magnetoeimpedance effect in $\text{Nd}_4\text{Fe}_{77.5}\text{B}_{18.5}$ as cast ribbon is investigated. The magnetoeimpedance $(Z(0) - Z(H))/Z(0)$ is about 16% under $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at 5.10 MHz. The magnetoreactance $(X(0) - X(H))/X(0)$ can reach 43.71% under $H = 2.08 \times 10^4 \text{ A}\cdot\text{m}^{-1}$ at 121 kHz. This shows that amorphous Nd-Fe-

B as cast ribbons may be useful in potential applications for magnetic sensors.

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Fig. 7 The dc field dependence of the magnetoimpedance peak frequency f_z , intersecting frequency f_i and their magnetoimpedance values at f_z and f_i , respectively.

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