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Permeability-frequency spectra of $(Fe_{1-x}co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ nanocrystalline alloys under different magnetic fields

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Abstract

Under various amplitude of AC magnetic fields domain wall motion is the main mechanism in the magnetization process. This includes domain wall bulging and domain wall displacing. In this paper complex permeability-frequency spectra of $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ($x = 0, 0.5$) nanocrystalline alloys were measured as a function of the AC magnetic field, ranging from 0.001 to 0.04 Oe. Obvious changes have been found in complex permeability spectra for alloy $x = 0$ with the change of the amplitude of AC magnetic field, but variation of AC magnetic field has little effect on complex permeability spectra for alloy $x = 0.5$. This is attributed to the increased pinning field after substitution of Fe with Co in $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ nanaocrystalline alloy.

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Keywords: Permeability-frequency spectrum; Nanocrystalline alloy; Magnetic field; Soft magnetic material

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1. Introduction

Since Yoshizawa first developed Finemet–based alloys, the Fe–Cu–Nb–Si–B nanocrystalline soft magnetic materials have been extensively studied in recent years because of their excellent soft magnetic properties [1–3]. Finemet alloys have high permeability in low-frequency region. With increase of frequency, the permeability of Finemet alloys usually decreases rapidly [1,4]. Various nanogranular soft magnetic films with good high frequency properties have been developed recently [5]. However, these films are not applicable for high power applications, where a large component size is required. With the rapid development of the computer technology, the information and electronic technology, materials bearing good soft magnetic properties in high-frequency range are presently required because the operating frequencies of electronic equipment continue to increase. Therefore, it is important to develop soft magnetic materials that can be used at a higher frequency range and higher power electric applications. It is known that partial substitution of Fe by Co in Fe–Nb–(Cu–Si–)B is an effective way to further improve the soft magnetic properties of Finemet alloys in high-frequency range [6–9]. Whether this replacement also increases the working power of Fe–Nb–Cu–Si–B nanocrystaline is still unknown. That is the question this paper tries to investigate.

The complex permeability spectrum under different fields is closely related to the material's magnetization mechanism [9]. It has been widely used to characterize the frequency dependence of complex permeability of soft magnetic materials. The measured spectra were proved to be associated with the relaxation process of domain wall motions, which include domain wall bulging, displacement, and rotation [10–12]. Although some research works on the mechanism of magnetization process have been published, study on the permeability spectra of nanocrystalline $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ alloy and alloy with Fe partially substituted by Co in $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ under various AC fields is yet unseen.

In this paper, our main interest is to study the characteristics of complex permeability spectra of $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ ($x = 0, 0.5$) nanocrystalline alloys under various AC magnetic field, where we have

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substituted Fe with Co in $Fe_{73.5}Cu_1Nb_3Si_{13.5}B_9$ nanocrystalline alloy. We also discuss the high frequency performance of $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ $(x = 0, 0.5)$ nanocrystalline alloys.

2. Experimental

Amorphous $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ $(x = 0, 0.5)$ alloy ribbons were prepared by the single roller melt spinning technique. The amorphous ribbons obtained from this process were 18–30μm in thickness, and 10–13 mm in width. The as-quenched ribbons were confirmed to be amorphous by X-ray diffraction. The core samples were fabricated by winding the ribbons into toroidal cores 20 mm outer diameter and 16 mm inner diameter. These specimens were annealed for 0.5 h in vacuum. All the heat treatments were carried out without the presence of any magnetic field. To apply an AC magnetic field, a copper wire covered by enamel was wound around the toroidal core as a coil. The frequency spectrum of complex permeability was $\mu = \mu'(f) - i\mu''(f)$, measured by HP 4294A impedance analyzer, which is in the frequency range of 40 Hz–110 MHz. The amplitude of AC current was kept at constant value during the frequency sweep in order to produce the constant amplitude of AC field on the sample. The inductance and resistance were measured and the real and imaginary parts of complex permeability were determined by the relations

$$\mu'(f) = \frac{L(f)}{L_0(f)}, \tag{1}$$

$$\mu''(f) = \frac{R(f) - R_0(f)}{2\pi f L_0(f)}, \tag{2}$$

where L and R are the equivalent inductance and resistance of sample, L_0 and R_0 are those of empty solenoid, respectively, and f is the frequency of the AC field.

3. Results and discussion

Figs. 1 and 2 show the frequency spectra of real parts (a) and imaginary parts (b) of complex permeability, under various amplitudes of applied AC magnetic field for the sample nanocrystalline alloy $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ $x = 0, 0.5$, respectively.

To our knowledge, there is a pinning field H_p in magnetic materials. When exerted driving field H is lower than H_p, the domain walls are pinned to defects and only bulge reversibly around their equilibrium positions, and this is responsible for initial permeability. If $H > H_p$, the domain walls may be unpinned and move to new positions, then irreversible processes are involved. When the driving field H increases from less than H_p to greater than H_p, we may observe a significant change of permeability occurs from frequency independent to frequency dependent. The reason is that the domain wall is unpinned.

From Fig. 1(a), we can see that for very small amplitude of applied AC magnetic field, $H = 0.001$ Oe, the spectrum exhibits a typical Debye-type relaxation, the real part of initial permeability in low-frequency range is insensitive to frequency. With the increase of H, the values of the real part increase and a frequency dependence of μ' is observed. This indicates that the low-field behavior corresponds to reversible bowing of domain walls pinned at the original sites. For the high fields, the domain walls are unpinned and irreversibly displaced, leading to hysteresis. All the μ'–f lines join together and nearly become one line in high-frequency range. However, μ' is dependent on H. At first, μ' increases with the increase of H, after μ' hitting its maximum at $H = 0.02$ Oe, it decreases with increase in H. According to classical magnetism, if $H > H_p$, the domain wall can move more easily in the material, then lead to a rise of μ'; if H go on rising, domain wall motion corresponds to the knee part of magnetization curve, then decrease in μ' occurs.

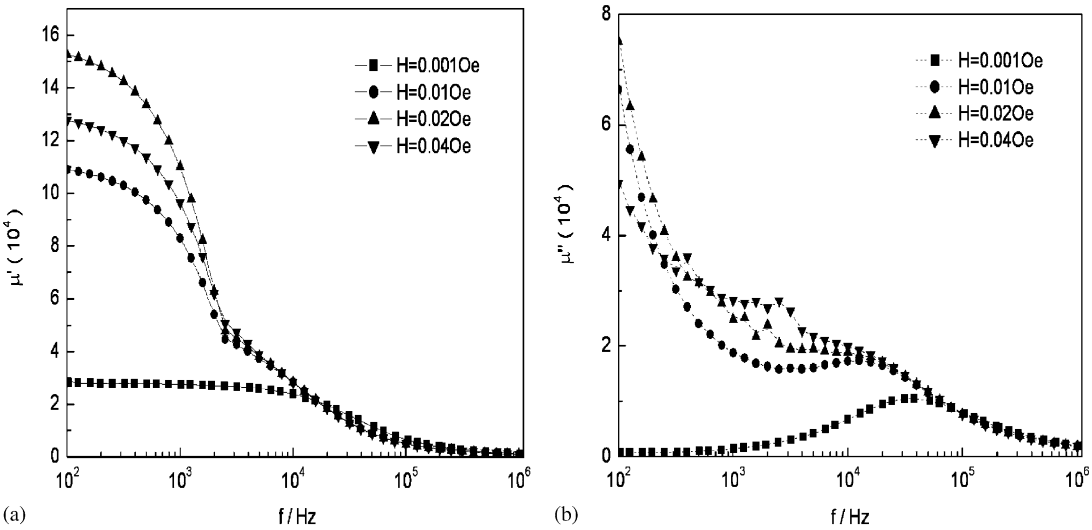

Fig. 1. Permeability spectra of real parts (a) and imaginary parts (b) for various amplitudes of the applied AC field for sample $(Fe_{1-x}Co_x)_{73.5}Cu_1Nb_3Si_{13.5}B_9$ $(x = 0)$.