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Variation of permeability of Nb-poor Finemet under different field amplitudes

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Abstract

The effect of magnetic field amplitude on permeability spectra was studied by using permeability spectroscopy. Results show that the permeability spectra can be greatly affected by magnetic field amplitude—they become complicated under a higher field, which means that the initial permeability increases with an increase of the applied field at first and then decreases with further increase. Meanwhile, another relaxation peak appears and the relaxation frequency increases during the same process. In addition, the permeability is improved significantly over the basic Finemet composition with appropriate substitution of Al for Nb. Moreover, the effect of annealing condition on the permeability spectra as well as the influence of eddy current was also discussed. All these phenomena were explained by using the dynamic magnetization theory and random anisotropy model.

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Keywords: Permeability spectra; Nanocrystalline; Domain wall; Finemet

1. Introduction

In recent years, the Fe–Si–B–Cu–Nb nanocrystalline materials (Finemet) [1] have attracted much attention of researchers because of their excellent soft magnetic properties such as high saturation magnetization and high permeability. The possible application of nanocrystalline magnetic materials includes magnetic parts of power transfers, solenoid valves, magnetic sensors, actuators, and so on. It is necessary to make systematic studies on the effects of field amplitude because the alloys are always under a changing magnetic field in actual applications. However, the application of Finemet is less popular than expected because it is more expensive than the conventional magnetic materials. Among these constituents, Nb is the most expensive element and is generally considered to hinder the growth of crystallites in the annealing process; hence special two-phase structures can be formed and the α-FeSi crystallites are in nanoscale [2]. Experiments of using other elements to take the place of Nb were performed, showing that the effect is not good [3–5]. Additionally, Al was also used to substitute Fe or Si to achieve different magnetic properties [6,7], but little literature on the substitution of Al for Nb has been found.

Meanwhile, permeability spectra have been shown to be useful for studying magnetization process in ferromagnetic materials because the permeability and relaxation frequency for both reversible and irreversible magnetization processes can be determined from them [8]. However, the use of permeability spectra needs to be further studied.

The studies of variation of permeability of Nb-poor Finemet alloys under different field amplitudes may provide us valuable information about the dynamic properties of this kind of material.

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2. Experimental

A series of $Fe_{73.5}Si_{13.5}B_9Cu_1Nb_{3-x}Al_x$ ($x = 0$, 0.5, 1.5, 2.0, and 3.0) alloys were melted in an Ar atmosphere, and amorphous ribbons (approximately 1 mm in width and 20 μm in thickness) were prepared from each alloy by a single-roller melt-spinning method on a Cu wheel in an Ar atmosphere. The surface velocity of the Cu wheel was 48 m/s, and the ejection pressure was about 60 kPa. For magnetic spectra measurement, the ribbons were cut into lengths of 50 cm and were wound around ceramics sample holders 5 mm in diameter to make a toroid of about 30 turns. Then the ribbons were isothermally annealed at 793 K for 1 h followed by quenching in an Ar atmosphere. The samples, numbered according to their Al content as A0, A5, A15, A20, and A30, were put into a tube filled with Ar and the annealing process was conducted without any applied magnetic field. The complex permeability of the samples, $\mu = \mu'(f) - j\mu''(f)$, was measured by using an impedance analyzer controlled by a computer (Agilent HP 4284A). The amplitude of AC current applied to the small solenoid coil around the sample was kept at a constant value during the frequency sweep for measuring the permeability spectra. The annealed ribbons were cut into small pieces and the *B*–*H* loops were measured at room temperature by a vibrating sample magnetometer (VSM) made by Nanjing University and the coercivity was determined from the loops. The structure of the ribbons was characterized by X-ray diffraction (XRD) and the grain size was estimated by using Scherrer formula.

3. Results and discussion

3.1. Permeability spectra and the effect of Al substitution

The frequency dependence of permeability spectra of samples A0–A20 was measured at $H = 0.106$ A/m (shown in Fig. 1) and under different field amplitudes (Figs. 2–5).

It can be seen from these figures that the real part μ' of the complex permeability is almost constant and independent of frequency in the low-frequency region under a low field for all the samples. The value of μ' measured under low magnetic field and at low frequency can be considered as the initial permeability μ_i. The value of μ' decreases with an increase of the field frequency; however, as the amplitude of applied AC field increases, μ' increases with and decreases with an increase of frequency. However, a decrease of μ' can be seen as the amplitude of the applied AC field further increases. Similar to the real part, the imaginary part μ'' is also almost constant and independent of frequency at low frequency and low field, but it increases with an increase of frequency and shows a peak for various field amplitudes at almost a constant frequency for each sample. The relaxation frequency, f_0, can be determined from the maximum point in the imaginary part of complex permeability in low field; however, μ'' also increases with the applied AC magnetic field and becomes complicated at higher fields. The rms amplitude of applied AC field is calculated from the solenoid geometry and the current.

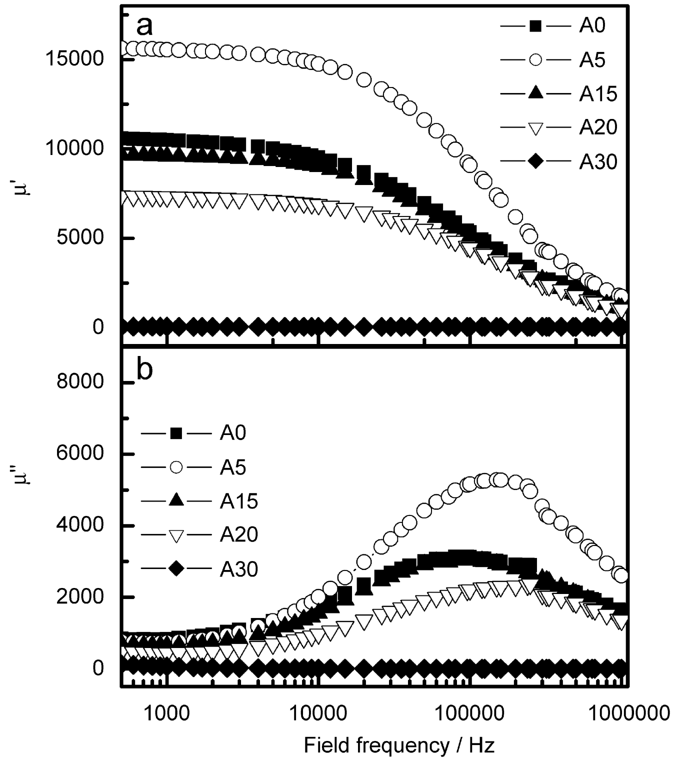

Fig. 1. Variation of complex permeability with frequency: (a) real parts and (b) imaginary parts.

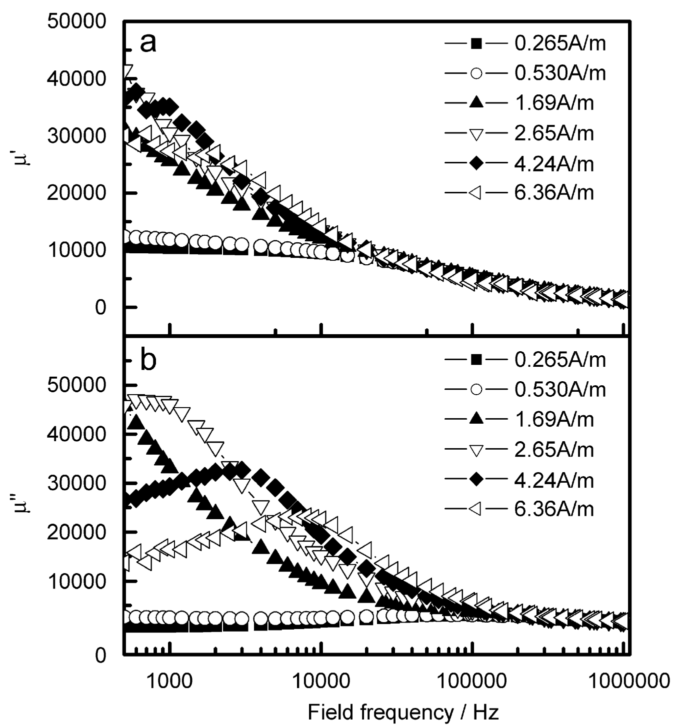

Fig. 2. Variation of complex permeability with frequency of A0 under different field amplitudes.

It can be also seen from Figs. 1 and 7 that, with a small substitution of Al for Nb ($x = 0.5$), μ_i increases obviously.