Journal of Magnetism and Magnetic Materials 408 (2016) 159–163

Contents lists available at ScienceDirect

Journal of Magnetism and Magnetic Materials

journal homepage: www.elsevier.com/locate/jmmm

Dynamic magnetic characteristics of $Fe_{78}Si_{13}B_9$ amorphous alloy subjected to operating temperature

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ARTICLE INFO

Article history:
Received 19 November 2015
Received in revised form
11 February 2016
Accepted 20 February 2016
Available online 22 February 2016

Keywords:
Amorphous alloy
Dynamic magnetic characteristic
Core loss
Complex permeability

ABSTRACT

The operating temperature dependence of dynamic magnetic characteristics of the annealed $Fe_{78}Si_{13}B_9$ amorphous alloy core was systematically investigated. The core loss, magnetic induction intensity and complex permeability of the amorphous core were analyzed by means of AC *B–H* loop tracer and impedance analyzer. It is found that the operating temperature below 403 K has little impact on core loss when the induction (B) is less than 1.25 T. As B becomes higher, core loss measured at high temperature becomes higher. For the cores measured at power frequency, the B at 80 A/m and the coercivity (H_c) at 1 T decline slightly as the temperature goes up. Furthermore, the real part of permeability (μ') increases with the rise of temperature. The imaginary part of permeability (μ'') maxima shifts to lower frequency side with increasing temperature, indicating the magnetic relaxation behavior in the sample. In addition, with the rise in the operating temperature of the annealed amorphous core, the relaxation time tends to increase.

1. Introduction

Fe-based amorphous alloys have emerged as an attractive core material for transformers, inductors and electric motors due to their excellent soft magnetic properties such as high saturation magnetization, high permeability, low coercivity and low core loss [1–4]. Since the power transmission and energy conversion systems often work under the AC magnetic field with a various amplitude and frequency, it is extremely essential to study the dynamic magnetic properties of the amorphous magnetic cores. Great efforts have been devoted to describe the various factors which influence the dynamic magnetic characteristics, e.g. the thermal treatment conditions [5,6], the DC current excitation [7–9], the non-sinusoidal excitation [10], the AC magnetic field amplitude [11,12]. However, few investigations have been done on analyzing the AC magnetic properties of ferromagnetic amorphous alloys at various operating temperature.

Nevertheless, thermal consideration is one of the most critical aspects of electronics design, because of the components can be heated by external sources and their own energy losses. Inductors and transformers are often designed for significant temperature rise in order to accommodate the operating temperature or optimize cost, size, and performance. Therefore, it is important for the magnetic designer to understand the behavior of magnetic cores at elevated temperatures. Having this understanding is also vital for selecting the best type of material for each application, and for ensuring that the magnetic device will be functionally safe at its maximum operating temperature. It is necessary to investigate the temperature dependence of dynamic magnetic characteristics of the amorphous alloy core.

In this paper, the dynamic magnetic characteristics including magnetic induction intensity, core loss and magnetic permeability under different operating temperature in the annealed $Fe_{78}Si_{13}B_9$ amorphous alloy cores are systematically investigated. The research is carried out by means of complex permeability measurements as a function of two independent variables, $\mu = \mu'(f, T) - i\mu''(f, T)$, where f is the AC frequency, T is the operating temperature and i is the imaginary number. Furthermore, the relations among the magnetic relaxation frequency, relaxation time and the operating temperature are illustrated.

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http://dx.doi.org/10.1016/j.jmmm.2016.02.068
0304-8853/

2. Experimental procedures

Commercial amorphous alloy ribbon prepared by single copper roller melt-spinning technique with nominal composition $Fe_{78}Si_9B_{13}$ (at%) and thickness of about 23 µm was bought and cut into 15 mm wide. The as-quenched ribbon was wound automatically into the toroidal core with the inner diameter of 20.4 mm and the outer diameter of 31.3 mm. For measuring the dynamic magnetic properties of the amorphous alloy, the core samples were isothermally annealed at 693 K for 60 min (the optimal annealing condition) in a flowing Argon atmosphere to remove residual strain. A coating was applied then for dielectric protection and extra physical strength. The as-quenched and annealed ribbons were confirmed to be full amorphous structure by X-ray diffraction (XRD) with Cu Kα radiation. Enameled copper wire which can bear the measurement temperature were chosen for the winding coil. The operating temperature from room temperature to 433 K was adjusted by putting the core in a muffle furnace.

In situ measurement for the AC hysteresis loops and core loss were performed by using AC *B*–*H* loop tracer under the frequency of 50 Hz. The exciting coil and searching coil are 20 turns and 2 turns, respectively. Complex permeability at a frequency range from 100 Hz to 10 MHz of the amorphous core with 20 turns coil was in situ measured by using an impedance analyzer (Agilent 4294) equipped with a test fixture (16047E). The amplitude of AC current was kept at constant value during the frequency sweep (with 201 discrete frequencies) to produce the constant amplitude of AC magnetic field on the sample.

The complex permeability spectrum, containing of frequency dependence of real and imaginary part of complex permeability, is expressed as a complex quantity have a form, $\mu=\mu'-i\mu''$. The real and imaginary parts of the complex permeability was calculated based on the equivalent circuit by the following relations [13–15]:

$$\mu' = \frac{2\pi L_s}{\mu_0 N^2 h \ln\left(\frac{OD}{ID}\right)} \quad (1)$$

$$\mu'' = \frac{R_s - R_0}{f\mu_0 N^2 h \ln\left(\frac{OD}{ID}\right)} \quad (2)$$

where μ' is the real part of the complex permeability that describes the inductive part which store the energy. μ'' is the imaginary part of the complex permeability that represents the dissipative part which contribute to energy loss. μ' and μ'' both vary with frequency and temperature. L_s and R_s are the equivalent inductance (*H*) and resistance (Ω) of the core with winding. R_0 is the DC resistance of enameled copper windings (Ω). *f* is the measuring frequency (Hz). *N* is the number of turns of windings. *h* is the height of the toroidal core (mm). *OD* and *ID* are the outer and the inner diameter of the toroidal core (mm). μ_0 is the permeability of free space: $4\pi \times 10^{-7}$ (H/m).

3. Results and discussion

The AC *B*–*H* loops of the annealed $Fe_{78}Si_9B_{13}$ amorphous toroidal core at the frequency of 50 Hz were measured under operating temperature of 343 K, 373 K and 433 K. The results are presented in Fig. 1. It can be observed that the applied magnetic field (*H*) increases with increasing operating temperature when the magnetic induction intensity (*B*) achieve same values. In order to gain a *B* up to 1.35 T, the applied *H* are 115 A/m under 343 K, 145 A/m under 373 K, and 180 A/m under 433 K, respectively. Fig. 1 also shows that the area within the AC hysteresis loops generally increases with the rise in the temperature. The area enclosed by the hysteresis loops is directly related to the core loss. It has been accepted that the total core loss contains of three parts [16,17]: (1) the hysteresis loss determined by the dynamic hysteresis loops, (2) the eddy current loss caused when the lines of flux pass through the core, including electric current in it, and (3) the residual loss caused by the magnetic relaxation or the magnetic after-effect.

Since the AC hysteresis curves and core loss are very useful information from the application point, the temperature dependence of core loss at the frequency of 50 Hz as a function of magnetic induction intensity are also measured. As shown in Fig. 2, the influence of operating temperature on core loss is not obvious when the induction (*B*) is less than 1.25 T. As *B* becomes higher, core loss measured at high temperature becomes higher. Take the sample measured at $B=1.35$ T and $f=50$ Hz for an example, the core losses are 0.331 W/Kg under 343 K, 0.349 W/Kg under 373 K, and 0.403 W/Kg under 433 K, respectively (shown in Table 1). The $P_{1.35/50}$ increased 34.5% at 403 K compared with that at room temperature (293 K). It indicates the core loss of the amorphous core is sensible to the temperature when *B* is more than 1.25 T.

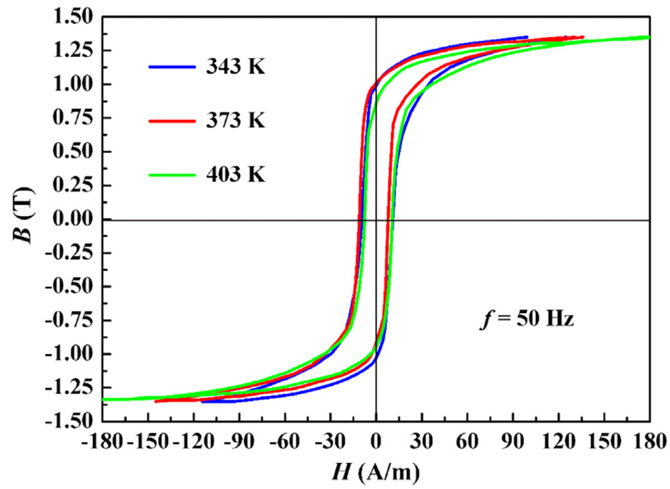

Fig. 1. Temperature dependence of AC *B*–*H* loops at a frequency of $f=50$ Hz for annealed $Fe_{78}Si_9B_{13}$ amorphous alloy toroidal core.

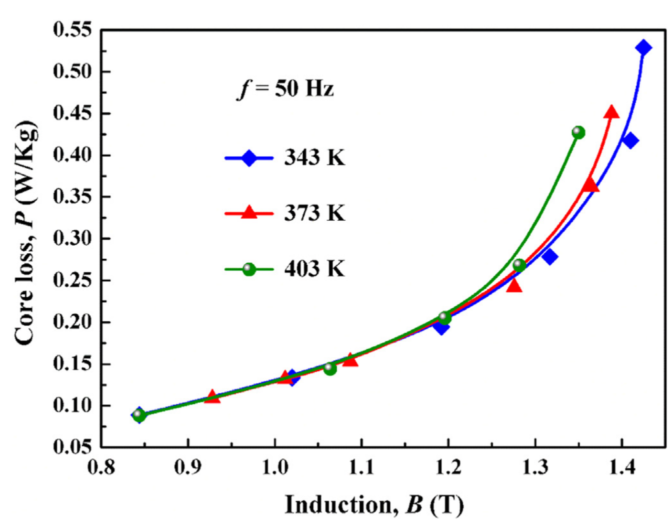

Fig. 2. Temperature dependence of core loss at a frequency of $f=50$ Hz as a function of magnetic induction intensity for annealed $Fe_{78}Si_9B_{13}$ amorphous alloy toroidal core.