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Frequency and magnetic field dependences of coercivity and core loss in Fe–Mo–Si–P–C–B amorphous alloys

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ABSTRACT

Relations of the coercivity (H_c) and core loss (P) with the frequency (f) as well as the magnetic field (H_0) or the maximum induction (B_m) of Fe–Mo–Si–P–C–B amorphous alloys were investigated. The coercivities and core losses of the Fe-based amorphous alloys were determined by the measurements of dynamic magnetization curves, as functions of frequency (f = 50–1000 Hz) and amplitude (H_0 = 0–600 A/m) of applied field. The coercivities and core losses were fitted by a power law dependence of the frequency and amplitude of applied field as well as the maximum induction respectively. The results indicated that the coercivity and core loss of the Fe-based amorphous alloys significantly depended on the frequency and magnetic field (induction) as well as intrinsic parameters.

1. Introduction

Among the numerous bulk amorphous alloys discovered in the last several decades, Fe-based ones are commercially the most attractive because of their excellent magnetic properties, high strength, high corrosion resistance and relatively low cost [1–3]. A large number of Fe-based amorphous alloys have been developed as soft magnetic materials such as (Fe,Co)–Nb–B–Si [4], Fe–Mo–P–C–B [5] and Fe–Ni–P–B [6]. Recently, the Fe–Mo–Si–P–C–B amorphous alloys with combined significant ductility, high strength and good soft-magnetic properties were synthesized as potential materials utilized in magnetic devices [7].

Fe-based amorphous alloys attract great attention as candidates for various applications at AC fields, therefore, it is important to know frequency dependences of their magnetic characteristics. The coercivity is commonly considered to be one of the most important parameters in applied magnetism. Several papers have been published concerning the coercivity behavior of amorphous wires and ribbons [8–12]. The core loss is a crucial parameter for determining the performance of a material in an electromagnetic device. The dependence of the frequency and induction on the core loss of Fe-based amorphous alloys has been investigated by the domain wall theory and the scaling theory [13–15].

In this paper, the frequency and magnetic field dependences of coercivity and core loss in Fe–Mo–Si–P–C–B amorphous alloys were investigated. The coercivities and core losses determined from dynamic magnetization curves were fitted by a power law dependence of the frequency and amplitude of applied field as well as the maximum induction respectively. The exponents which are the parameters of the function H_c (f, H_0) and P (f, B_m) are discussed.

2. Experimental procedures

The nominal compositions of the alloys were $Fe_{76}Mo_2Si_2P_{10}C_{7.5}B_{2.5}$ and $Fe_{80}Mo_1Si_2P_8C_6B_3$ (at.%), which are labeled as S1 and S2, respectively. Alloy ingots were prepared by induction melting the mixtures of pure Fe (99.9 mass%), Mo (99.9 mass%), Si (99.9 mass%), B (99.9 mass%) and C (99.9 mass%) and prealloyed Fe–P under a high purity argon atmosphere. From the master alloys, thin ribbons with width of 10 mm and thickness of about 40 μm were prepared by melt-spinning. The amorphous structures of the ribbons were confirmed by X-ray diffraction.

The amorphous ribbons of the two alloys were wound into toroids, respectively. Then the toroids were annealed at 678 K (T_g-50 K) and 650 K for S1 and S2 respectively for 600 s in an argon atmosphere to remove residual strain. According to the relevant IEC standard, the dynamic magnetization curves of the samples on which 50 turns of a primary coil and 150 turns of a secondary coil were measured by AC hysteresisgraphs and iron loss analyzer (Rikendenshi ACBH-100K) under sinusoidal induction at the frequency range from 50 to 1000 Hz and various applied field up to 600 A/m (corresponding to inductions range from 0.5 to 1.0 T).

3. Results and discussion

The coercivities of the Fe–Mo–Si–P–C–B amorphous alloys were investigated as dependent on the frequency f and the amplitude H_0 of applied field as shown in Fig. 1. The results indicated that the coercivity H_c increases with the increase in the frequency and magnetic field.

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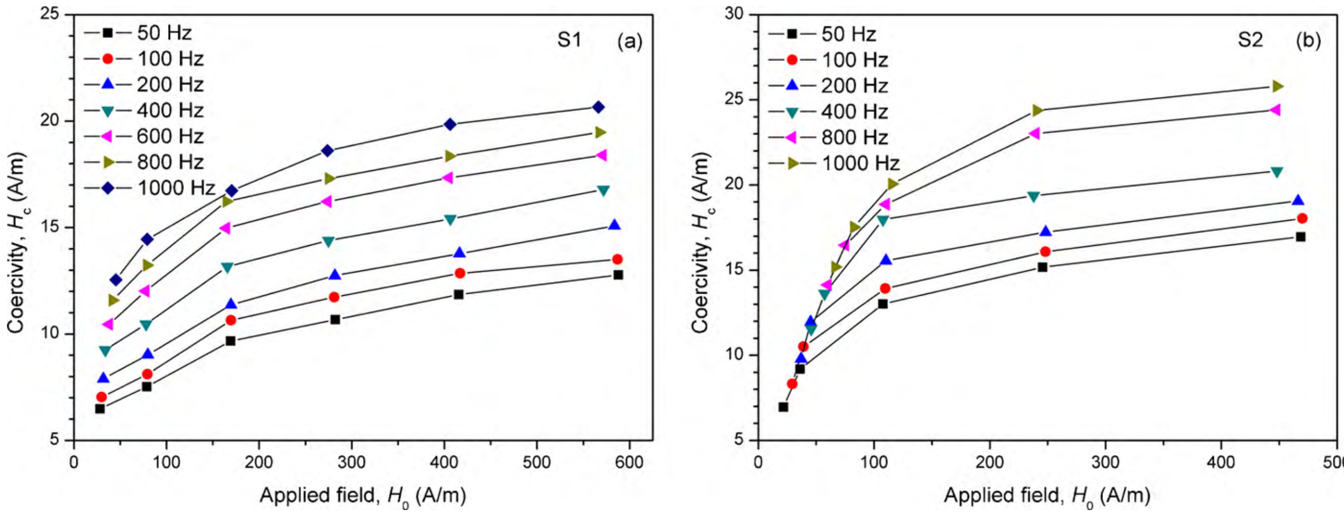

Fig. 1. Coercivity (H_c) as a function of applied field (H_0) and frequency f for amorphous alloys S1 (a) and S2 (b).

The frequency dependences of H_c could be explained by a simple model presented by Gyorgy [11]:

$$H_c = \left[\frac{\pi f H_0 \beta L}{M}\right]^{1/2} \quad (1)$$

where f is measurement frequency, β is an eddy current damping constant, L is the average domain wall spacing, H_0 is the applied field and M is the saturation magnetization. According to this model, the exponent of H_c varying with f and H_0 is 0.5. However, most experimental results on conventional ribbons indicate the exponent is near 0.33 [10,11].

To simplify analysis, the frequency and amplitude of applied field dependences of the coercivity are described by a simple power law function. The relations correspond to the functional form $H_c{\sim}H_0^m$ and $H_c \sim f^p$. The exponents m and p can be defined as below:

$$m = \frac{\partial \ln H_c}{\partial \ln H_0} \quad (2)$$

$$p = \frac{\partial \ln H_c}{\partial \ln f} \quad (3)$$

The exponents m and p were determined by fitting the data for different frequencies f and amplitudes H_0 of applied field. The exponents m and p vary with the frequency and the induction (corresponding to applied field amplitude), respectively, as shown in Figs. 2 and 3, which indicate the dependence of the coercivity responding to the applied field and frequency. The value of m for the sample S2 is larger than that for the sample S1, which suggests the coercivity of the sample S2 responds faster to applied field, especially at high frequency. Because the value of p for the sample S1 is smaller than that for the sample S2 at low amplitude of applied field, the coercivity of the sample S2 responds faster to frequency. The values of m are larger than p, which indicated that the magnetic field dependence of H_c is more pronounced.

The exponents m and p vary from 0.13 to 0.29, which are less than 0.33. The reason for discrepancy of the exponents may be accounted for the combined influence of the constituent elements Mo, P, C and B on coercivity of Fe-based amorphous alloys as well as the changes of the number of active domain walls with the frequency and amplitude of magnetic field. The number of active domain walls increases more easily at high frequency and applied field [16], and moreover, larger number of active domain walls may decrease the dynamic loss [17]. Therefore, the exponents decrease with frequency and applied field increasing. On the other hand, the

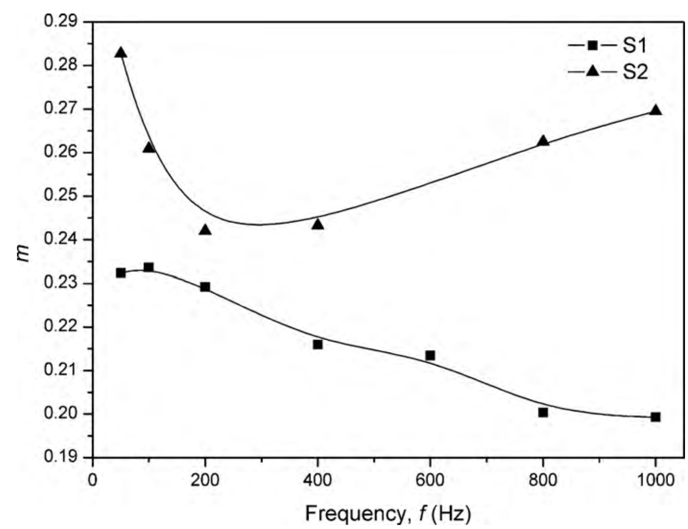

Fig. 2. Frequency dependence of the exponent m for amorphous alloys S1 and S2.

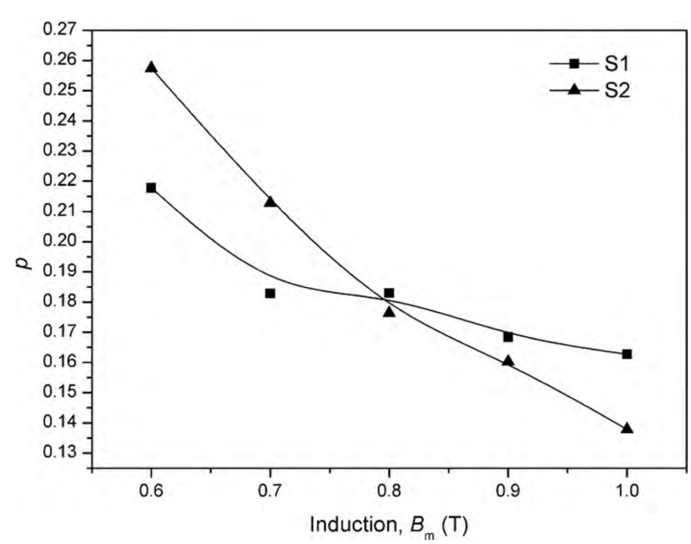

Fig. 3. Induction dependence of the exponent p for amorphous alloys S1 and S2.

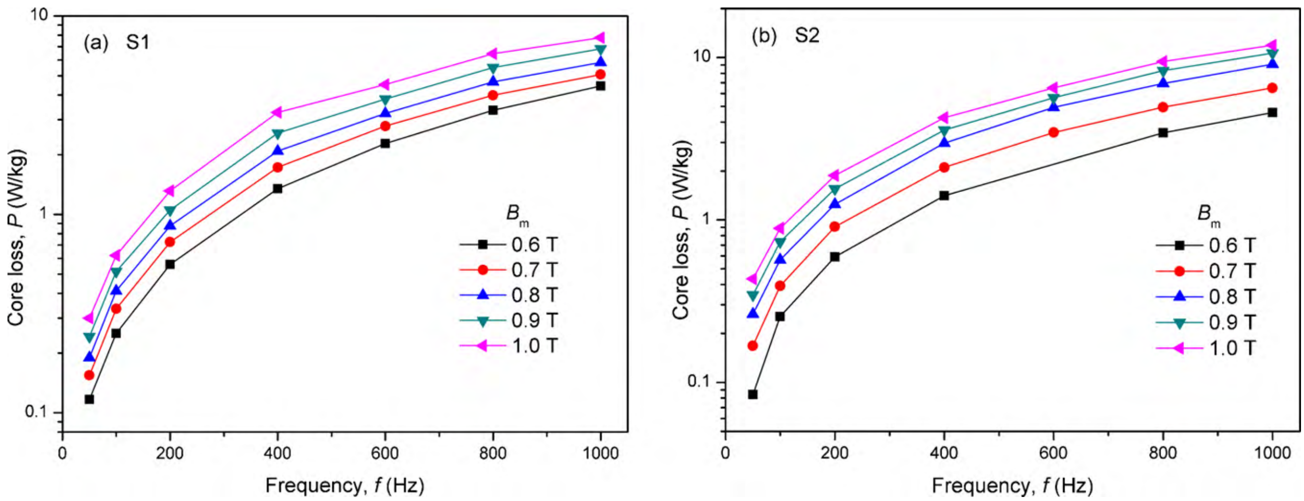

Fig. 4. Core loss P as a function of the induction B_m and frequency f for amorphous alloys S1 (a) and S2 (b).

exponent m for the sample S2 does not monotonically vary with frequency, which could be due to the different behaviors during the dynamic magnetization processes and domain configurations for the two alloys, and further experiment is necessary for confirming to this assumption.

Core losses dependence on the frequency f and the maximum induction B_m for the Fe–Mo–Si–P–C–B amorphous alloys are shown in Fig. 4. Similarly, the induction and frequency dependences of core loss P are described by the functional form $P \sim B_m^x$ and $P \sim f^y$. The exponents x and y can be defined as below:

$$x = \frac{\partial \ln P}{\partial \ln B_m} \qquad (4)$$

$$y = \frac{\partial \ln P}{\partial \ln f} \qquad (5)$$

The exponents x and y determined by fitting the data vary with the induction and the frequency respectively as shown in Figs. 5 and 6. The results indicate that the core losses of the sample S2 increase more rapidly than that of the sample S1 with the frequency and the induction. The changing trends of the magnetic field dependences of the coercivity and core loss for the samples S1 and S2 are similar. It is concluded that the induction dependence of P is more pronounced by comparing with the values of x and y.

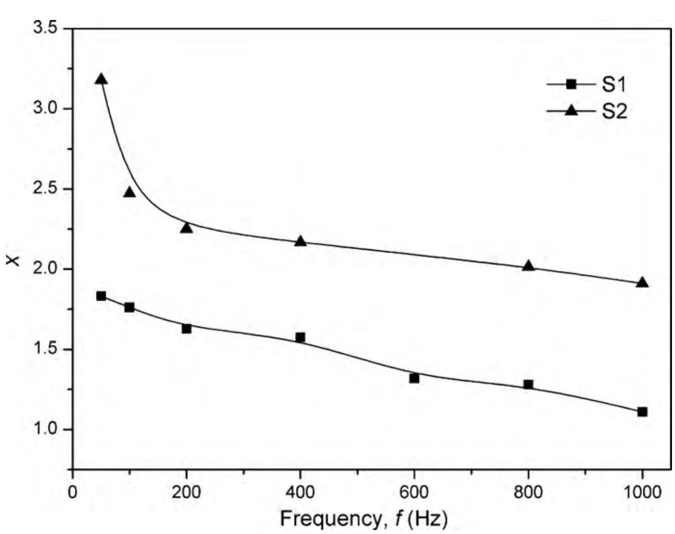

Fig. 5. Frequency dependence of the exponent x for amorphous alloys S1 and S2.

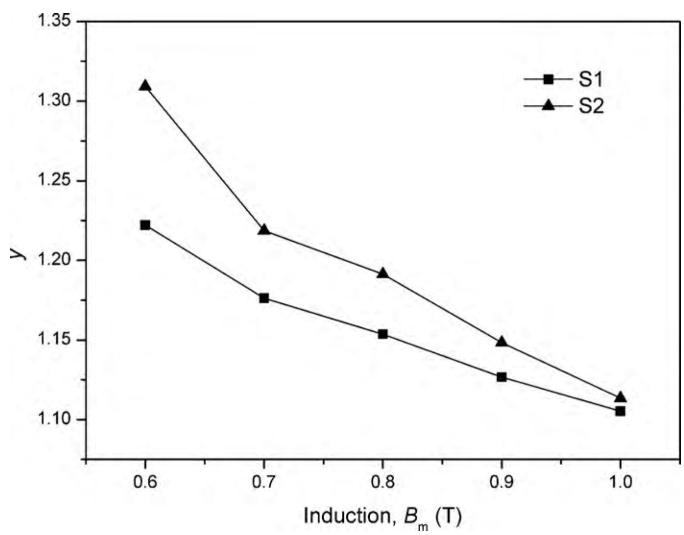

Fig. 6. Induction dependence of the exponent y for amorphous alloys S1 and S2.

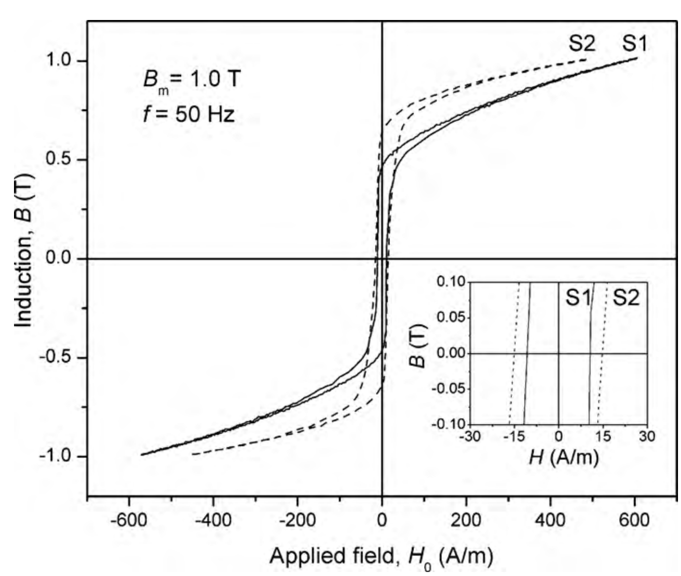

Fig. 7. Hysteresis loops for amorphous alloys S1 and S2 (B_m = 1.0 T, f = 50 Hz).

The hysteresis loops for the Fe–Mo–Si–P–C–B amorphous alloys (B_m = 1.0 T, f = 50 Hz), typical of soft magnetic alloys, are shown in Fig. 7. The higher coercivity and remanence ratio for S2 are observed. The material with a high remanence ratio has a high value of effective permeability at low frequencies [18]. The mode of magnetization changes from the domain walls motion at fields lower than H_c to the magnetization rotation at higher fields. The contribution of the domain walls motion to magnetization process for S2 is more than that of S1, which is consistent with the results of the power law function analysis.

Based on the above analyses of the exponents and hysteresis loops for S1 and S2, it is deduced that $Fe_{76}Mo_2Si_2P_{10}C_{7.5}B_{2.5}$ amorphous alloy (S1) is suitable to be used as the core in the transformer for electric power distribution and $Fe_{80}Mo_1Si_2P_8C_6B_3$ amorphous alloy (S2) is suitable to be used as the candidate material for the coils in the sensors with high sensitivity.

4. Conclusions

The dependences of the coercivity and core loss on the frequency and amplitude of applied field for Fe–Mo–Si–P–C–B amorphous alloys have been analyzed by a simple power law function. The magnetic field dependence of the coercivity more pronounced than the frequency, and the maximum induction dependence of the core loss is more pronounced than the frequency. The characterization of the dynamic coercivity and core loss may be useful for understanding the dynamic magnetization of Fe-based amorphous alloys and for exploiting magnetic components for construction of miniaturized and high efficient magnetic devices.

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