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Materials

Fractal Structure of the Core Loss Spectrum of Co-based Amorphous Soft Magnetic Alloy with Constant Permeability

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Abstract: In order to check the traditional core loss formula, the core loss spectrum $P(f)$ of Co-based amorphous soft magnetic alloy with constant permeability has been studied. It is found that within a high frequency range from 10 kHz to 200 kHz and at B_m = 0.1 T, the $P(f)$ has the fractal structure $P(f) = P_0 f^{D_f}$, and with the increasing of induced anisotropy energy K_u, the fractal dimension D_f rises, thus the total power loss at high frequency increases and the frequency characteristic of $P(f)$ becomes worse.

Key words: amorphous soft magnetic alloy; constant permeability; core loss; fractal

Traditional constant permeability materials are crystalline alloys. When working at high frequency, however, crystalline alloy has disadvantages—— the total power loss is rather great and the stability of its permeability decreases. Recently, Zhang and Li *et al.* have developed Co-based amorphous soft magnetic alloys with constant permeability [1]. Compared with crystalline alloy, amorphous alloy has much lower loss, more stable constant permeability μ and better quality factor Q. The permeability of three kinds of amorphous alloys developed by Zhang *et al.* is from 620 to 2880 H/m. Generally, these alloys work at high magnetization frequency in the range of 10 ~ 200 kHz and with a magnetic induction B_m = 0.1 T. Under the above working conditions, the total power loss spectrum is traditionally given by the following separation formula [2]:

$$P(f) = P_e + P_h + P_c = eB_m^2 f^2 + \eta B_m^{1.6} f + P_c \qquad (1)$$

where $P_e = eB_m^2 f^2$ is the eddy-current loss, $P_h = \eta B_m^{1.6} f$ the magnetic hysteretic loss, and P_c the residual loss. Through an assumed physical model of technology magnetization, the loss coefficient e and η can be calculated by using specific material's properties (electric resistivity and thickness, *etc.*) and magnetic domain structure.

Many experimental results have proven that formula (1) is not suitable for high permeability soft magnetic alloy at high frequency. Their total loss per cycle $P(f)/f$ can not be simply separated .

In this paper, the loss spectrum $P(f)$ of three kinds of Co-based amorphous constant permeability alloys has been investigated in a high frequency range as B_m = 0.1 T. It is found that there is a non-scale frequency range of $P(f)$ and $P(f)$ has a typical fractal structure within this range [3]. Furthermore, the influence of anisotropy K_u induced by transverse magnetic heat treatment on the fractal dimension of $P(f)$ is discussed.

1 Experimental

The chemical compositions of the specimens were shown in **table 1**. The specimens were annealed at

Table 1 Composition of specimens (mass fraction) %

specimen	Co	Fe	Ni	Si	B
a	64	8	10	6	12
b	64	10	2	14	8
c	52	20	8	7	13

different temperatures (a. 315 ℃, b. 340 ℃, c. 370 ℃) in transverse magnetic field for 3 h. The specimens were thin sheet (0.05 mm in thickness and 10 mm in width) rolled cores with 16mm in internal diameter and 26 mm in external diameter. The anisotropy energy K_u and D. C. magnetic properties were measured by magnetization work and ballistic methods respectively. The total power loss $P(f)$ and dynamic permeability as B_m = 0.1 T were tested with a transformer-bridge.

2 Experimental Results and Discussions

2.1 Fractal formula of $P(f)$

The $P(f)$ data of specimen a, b, and c measured as

B_m = 0.1 T are listed in **table 2**.

Table 2 Total power loss $P(f)$ of specimens (B_m=0.1 T)

f / kHz	P/ W·kg^{-1}		
	a	b	c
10	1.00	0.85	1.05
20	2.08	2.01	2.50
50	5.70	6.30	8.92
70	8.20	9.70	13.00
100	11.90	15.00	21.60
150	18.90	25.00	33.50
200	25.00	35.50	47.00

If log$P(f)$ is plotted as a function of log f, the three curves are all straight lines, which is a typical character reflecting the fractal structure of $P(f)$. For example, both curves of specimen a (its μ= 1556 H/m and constant range is 0 ~ 240 A/m) and c (its μ= 621 H/m and constant range is 0 ~ 1194 A/m) are illustrated in **figure 1**. The curve of specimen b is similar to those of a and c.

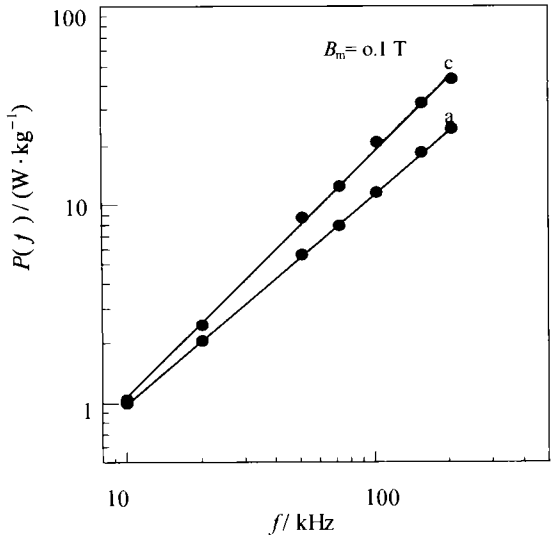

Figure 1 log$P(f)$ *vs.* log$f$ curves of specimen a and c

Figure 1 shows that when B_m= 0.1 T the loss spectrum of three amorphous constant permeability alloys has fractal structure within the non-scale frequency range from 10kHz to 200 kHz. $P(f)$ can be unitedly given by the following fractal formula:

$$P(f) = P_o f^{D_f} \quad (2)$$

where D_f, generally a fraction in value, is the fractal dimension of loss spectrum, and P_o is a parameter. The values of P_o and D_f are related to the intrinsic properties of materials and heat treatment technology conditions. The values of D_f, P_o, anisotropy K_u, permeability μ and magnetization field strength H are summarized in **table 3**.

The value of D_f is really a fraction (refer to table 3). Its meaning, describing the fractal structure of $P(f)$,

Table 3 D_f, P_o, K_u and μ of the specimens

Specimen	D_f	$P_o\times10^6$	K_u/ J·m^{-3}	μ / H·m^{-1}	H/A·m^{-1}
a	1.08	47.90	10.15	1 556	**0~ 240**
b	1.25	8.56	42.00	840	0~796
c	1.27	9.16	65.00	621	0~119

differs from that of integral number 2 and 1 appearing in the traditional eddy-current loss $P_e \propto f^2$ and magnetic hysteresis loss $P_h \propto f^1$ formulas respectively. D_f indicates that the character—— the total loss, caused by various mechanisms (such as eddy-current, magnetic hysteresis, relaxation, *etc.*), increases with the increasing frequency. The larger D_f is, the worse the frequency characteristic of $P(f)$ is.

2.2 A Comparison between two $P(f)$ formulae

For specimen a, when B_m = 0.1 T, the fractal formula of loss spectrum can be written as:

$$P(f) = 47.90\times10^{-6} f^{1.08} \text{ (W/kg)} \quad (3)$$

The traditional $P(f)$ formula can be obtained with quite high confidence level according to formula (2), it is:

$$P(f)=0.70\times10^{-10}f^2+1.14\times10^{-4}f-0.17 \text{ (W/kg)} \quad (4)$$

Through equations (3) and (4), the values of $P(f)$ in different frequencies can be calculated (listed in **table 4**).

Table 4 A comparision between two formulae of $P(f)$

f / kHz	P/ W·kg^{-1}		
	observed	formula(3)	formula(4)
10	1.00	0.99	0.97
20	2.08	2.12	2.13
50	5.70	5.68	5.70
70	8.20	8.17	8.15
100	11.90	12.02	11.93
150	18.90	18.63	18.51
200	25.00	25.12	25.43

From table 4, it is found that the values of $P(f)$ calculated using the two formulae agree with the observed values well. In traditional formula (4), the eddy-current loss ($0.70\times10^{-10}f^2$) is low at the above frequency range. For example, when f = 100 kHz, the eddy-current loss is only 6% of the magnetic hysteresis loss ($1.14\times10^{-4}f$) and P_e / P_h = 12% as f rises to 200 kHz. This result indicates the fact that the total power loss of amorphous alloy at high frequency is mainly caused by magnetic hysteresis. In fractal formula (3), this fact can be revealed by fractal dimension D_f. For specimen a, D_f = 1.08 and is close to the integral number 1 appearing in traditional magnetic hysteresis loss $P_h \propto f^1$, which directly indicates that the

total power loss is mainly determined by magnetic hysteresis loss if $D_f \to 1.0$. The residual loss P_c in the tradition formula (4) is negative, which is difficult to explain in physics. While the fractal formula (3) has no such difficulty. As discussed above, though the two formulae can describe the behaviors of the total power loss spectrum, the fractal formula is better.

For specimen c, the fractal and traditional formulae of $P(f)$ are

$$P(f)=9.16\times10^{-6}f^{1.27} \quad \text{(W/kg)} \qquad (5)$$

and

$$P(f)=1.50\times10^{-10}f^{2}+21.58\times10^{-4}f-2.14 \quad \text{(W/kg)} \qquad (6)$$

respectively. There still exists a negative component ($P_c = -2.14$ W/kg) in the traditional formula (6), though (6) closely corresponds to the observed $P(f)$. It can be calculated by formula (6) that when $f = 100$ kHz, $P_e/P_h = 7\%$; when $f = 200$ kHz $P_e/P_h = 14\%$. Both values are larger than 6% and 12% of specimen a, so it is concluded that the increase of D_f means the increasing of the ratio of eddy-current loss to magnetic hysteresis loss.

As noted in this section, the fractal formula (2) can describe the behavior of core loss. The value of fractal dimension D_f can not only indicate the frequency characteristic of $P(f)$, but also represent the ratio of eddy-current loss to magnetic hysteresis loss qualitatively, thus reveals the main mechanism causing the total loss .

Through the transverse magnetic heat treatment, anisotropy is induced in amorphous constant permeability alloys. The procedure of magnetization is dominantly the rotation of magnetic domain. Though magnetic domain rotation may also result in the anomalous eddy-current loss [4], the value is quite low. Hence the core loss is mainly produced by magnetic hysteresis, which is consistent with the small values of D_f in the three alloys ($D_f = 1.08$, 1.25 and 1.27).

2.3 Influence of induced anisotropy energy K_u on D_f

Permeability μ is related to the saturation magnetic induction B_s and induced anisotropy energy K_u ($\mu \propto B_s^2/K_u$). After B_s is determined by selecting the chemical compositions of alloy, the increase of K_u, will result in the decrease of μ and widen the constant range. Here it must be pointed out that K_u affects not only μ directly but also fractal dimension D_f greatly. The curves of D_f, *vs* K_u are shown in **figure 2**.

The decrease of K_u will cause the value of D_f to decrease (shown in figure 2), and thus, reduces the total power loss and improves the frequency characteristic of $P(f)$, but at the same time, inevitably results in the increase of μ and a narrow constant range. In order to develop the constant permeability alloy with exceedingly wide constant range, besides searching for the appropriate chemical compositions of alloy, We can only rely on the heat treatment conditions to obtain a large value of K_u so that the value of μ can be decreased. However, the increase of K_u, in turn, causes D_f to rise and thus increases the total power loss and worsens the frequency characteristic. Therefore, it is difficult to develop the wide constant range alloy with extremely low power loss and excellent frequency characteristic.

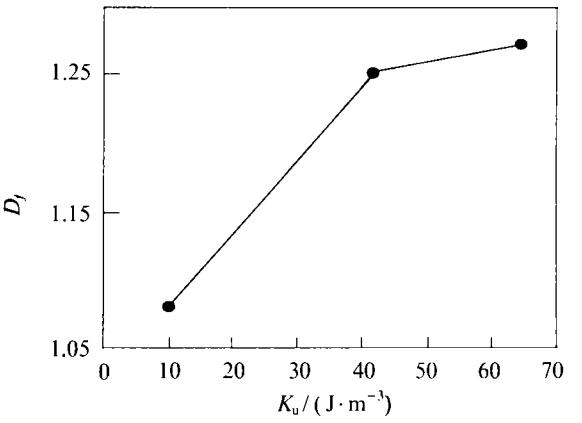

Figure 2 The dependence of D_f on K_u in amorphous constant permeability alloys

3 Conclusions

(1) Within a high frequency range from 10 kHz to 200 kHz and at a constant $B_m = 0.1$ T, the power loss spectrum $P(f)$ of three kinds of Co-based amorphous soft magnetic constant permeability alloys has the fractal structure $P(f) = P_o f^{D_f}$, where D_f is fractal dimension.

(2) In Co-based amorphous soft magnetic constant permeability alloys, with the increasing of induced anisotropy energy K_u, the fractal dimension D_f rises. Thus the total power loss at high frequency increases and the frequency characteristic of $P(f)$ becomes worse.

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