Study on magnetic loss properties of ultra-thin nanocrystalline soft magnetic alloy $Fe_{73.4}Cu_{0.6}Nb_{3.5}Si_{13.5}B_{9.0}$

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Abstract. The magnetic loss characteristics of ultra-thin nanocrystalline magnetic alloy $Fe_{73.4}Cu_{0.6}Nb_{3.5}Si_{13.5}B_{9.0}$ with 14μm were studied, and compared with conventional nanocrystalline magnetic alloy strip with the thickness of the 26μm. It was found that reducing the thickness of alloy strip could significantly reduce the magnetic loss (P) of the alloys. The frequency magnetic loss (P_f) of nanocrystalline soft magnetic alloy has shown a typical fractal structure, namely, $P_f = P_O f^{Df}$. The strip thickness had a significant impact on the variation of the fractal dimension D_f, the parameter Po, and its work magnetic induction B_m.

Introduction

Soft magnetic material as key functional materials, which are widely used in electronics, electricity, communications, automatic control, computer and defense fields, and so on, are indispensable to modern engineering, and played major functions for the transfer, processess and storage of energy and information [1-5]. With the development of engineering technology, a higher performance requirement for the soft magnetic material is necessary. The higher performance requirements imply that the soft magnetic material must possess a high saturation magnetic flux density, high magnetic permeability and low loss in performance, namely the high overall soft magnetic properties. The Japanese scholars Yoshizawa, who firstly and successful excogitate the nanocrystalline soft magnetic materials with the virtue of nano duplex structure. The nano duplex structures which are composed of nanocrystals and ferromagnetic amorphous phase in its internal structure, which could induced the ferromagnetic AC coupling. In the history of the development of a soft magnetic material, it is the first time to set the traditional performance advantages of soft magnetic material into one material, and integrated very excellent soft magnetic properties [6]. The new materials are used in the workplace, and replaced the traditional soft magnetic materials, in which the traditional soft magnetic materials can not be in it, and show great advantages and had a broad application prospects.

Magnetic loss is an important performance indicator for soft magnetic material. Under the background of the rapid development, the trend of electronic power apparatus is toward to miniaturization of small, high-frequency direction, and the magnetic loss index have become a key factor in achieving the compact high frequency. There exist two technical means to reduce the magnetic loss for soft magnetic. Firstly, it is to develop the new low-loss magnetic materials, such as nanocrystalline soft magnetic materials. Another important technical approach is to reduce the thickness of the soft magnetic alloy ribbon in order to reduce eddy current losses, which can reduce the magnetic loss remarkably, especially for the apparatus working at high frequencies, such as nanocrystalline soft magnetic materials, amorphous soft magnetic materials, nanocrystalline soft magnetic alloy film. These soft magnetic materials are currently being studied by many researchers, are a typical example of new low-loss magnetic materials, which can be used with the aim to further improve the use of the frequency. At present, the Fe-based nanocrystalline soft magnetic alloy, can be prepared with the thick of strip below 20 μm in Japan, but in China manufacturers only can produced the thick of strip above 25μm [7, 8]. If we can further reduce the strip thickness of nanocrystalline soft

magnetic alloy and reduce the losses, it can be used at higher frequencies, to extend the class of new materials applications, and exhibit undoubtedly significant.

In this paper, the nanocrystalline soft magnetic alloy thin ribbon, its magnetic loss characteristics and magnetic loss mechanism are studied, and compare with the conventional alloy thin strip through comparing the thick discuss.

Experiments

Cast ingots of soft magnetic alloy with nominal composition (in at. %) Fe 73.5, Cu1, Nb3, Si13.5, B9, were obtained by arc melting the metals Fe, Cu, Nb, Si, Fe-B alloy (Fe, Cu, Nb, Si, Fe-B 99.9%, Fe 99.8 pure) under high purity Ar atmosphere. Then the ultra-thin amorphous ribbons about 20 mm wide, 14 and 26 μm thick were prepared by single-roller melt spinning method. Afterwards these ultra-thin ribbons were wound into toroidal core samples of 10 mm inner diameter and 18 mm outer diameter. To obtain the characteristic nanocrystalline structure, these toroidal samples were submitted to isothermal annealing at temperatures of 580 ℃ for 40min under the protection of hydrogen atmosphere. Then the magnetic losses of the sample were measured under the frequency range of 100KHZ ~ 600KHZ with the B-H instrument.

Results and Discussions

Magnetic Loss. The magnetic losses of the samples were measured at the frequency range of 100K H_Z ~ 600 KH_Z with the B-H instrument under the working magnetic induction value Bm of 0.1 ~ 0.04T, and the magnetic loss P (f) values were listed in Table 1. The thickness of thin ribbon had a remarkable effect on the magnetic loss. From Table 1, it could be found that the magnetic losses of the ribbons with the thickness of 14 μm were reduced by 30% compared with that of the ribbons with the thickness of 26 μm. With increase of the frequency, the reductions of the magnetic losses become smooth slightly compared the 14 μm ribbons with the 26 μm ribbons. The results indicated that reducing the strip thickness to reduce the magnetic loss of soft magnetic materials was new technical approach, which could be used to the new nanocrystalline soft magnetic alloy.

Table 1. Magnetic loss P (f) of samples, WKg^{-1}.

Bm/T	$P(f)/w.Kg^{-1}$
	f/KHz
	\multicolumn{2}{c}{600}	\multicolumn{2}{c}{500}	\multicolumn{2}{c}{400}	\multicolumn{2}{c}{300}	\multicolumn{2}{c}{200}	\multicolumn{2}{c}{100}
	14μm	26μm	14μm	26μm	14μm	26μm	14μm	26μm	14μm	26μm	14μm	26μm
0.1	246.97	354.85	171.21	256.16	115.53	175.75	64.20	112.87	31.82	54.10	10.08	16.14
0.08	161.36	238.25	112.12	171.64	67.80	122.76	40.53	69.59	20.83	37.13	6.48	10.86
0.06	81.82	142.72	60.23	105.78	38.26	65.86	22.73	41.23	10.98	20.62	3.56	6.32
0.04	35.61	63.06	26.52	45.52	18.18	30.97	9.91	18.47	4.68	9.37	1.67	2.63

Spectrum of Magnetic Loss. Table 1 given the double logarithmic numerical analysis of *P(f)* and *f* data, and the relationship between the log*P(f)* and the log*f* for the examples were shown in Fig. 1 (under the condition of B_m= 0.1T, 0.04T, respectively). it was found that under certain value of B_m the log*P(f)* and the log*f* exhibited a good linear relationship, which shown that in the scale-free interval of *f*=100~600KHz, the P(f) exhibited a typical characteristics of fractal structure, and the P (f) could be expressed as the formula (1):

$$P(f)=P_O f^{Df} \tag{1}$$

In which, the D_f was the fractal dimension of the magnetic loss spectrum, the P_o was a parameter. At different B_m , the values of D_f and P_o of both samples were listed in Table 2.

In traditional engineering applications, the magnetic loss P of soft magnetic alloy could be expressed by the empirical formula as the formula (2) [9]:

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

where, the P_e was eddy current loss as equal to $eB_m^2 f^2$, the P_h was hysteresis loss as equal to $\eta B_m^{1.6} f$, in which the e and the η were the loss coefficient, and the P_a was the remaining loss. However, the formula (2) didn't hold for the highly permeable material at high frequencies, which were approved by a large number of experimental results, and the total loss P couldn't be simplify formulize by the formula (2). The Table 2 shown that, in the present study the fractal dimension D_f were fractional value, indicated that the description P(f) were fractal structure. The result implied that in the hysteresis loss and the eddy current loss the integer index of 2 and 1 didn't had corresponding physical meaning for the $P_h \propto f^2$ and the $P_h \propto f$, only expressed a unified total loss mechanisms eddy currents, hysteresis, magnetic after effect, which caused by the frequency dependence of the frequency characteristic. The D_f was more greater, the magnetic material loss became worse. In addition, the formula (1) also had the characteristics of simple form, and the two parameters P_o and D_f could be determined by the small amount of available experimental data, and could be applied in practical engineering design very easily. Existing research suggested that, the 1J79 soft magnetic alloy with high permeability magnetic loss P(f) had shown a similar fractal structure [10].
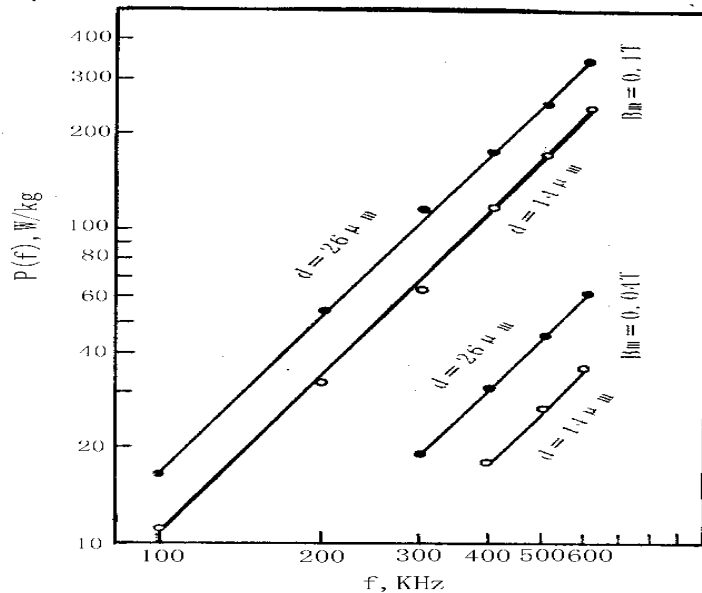

Fig. 1 The relationship between the log *P(f)* and the log *f*.

Table 2. The values of D_f and P_o of both samples under different B_m

Bm/T	0.1		0.08		0.06		0.04	
	14μm	26μm	14μm	26μm	14μm	26μm	14μm	26μm
Df	1.70	1.71	1.70	1.72	1.67	1.72	1.62	1.72
Po×10⁻³	4.19	6.36	2.77	3.90	1.78	2.38	1.03	1.01

The Effect of Thickness d on D_f and P_o. The P_o and D_f values of both samples under different B_m values were shown in Fig. 2. At different B_m values, the P_o and D_f values of the ribbons with the thickness of 14 μm were small than that of conventional alloy thin ribbons with the thickness of 26 μm. This suggested that the decrease of D_f and P_o were induced by reducing the strip thickness d, so that the magnetic loss of the alloy was lowered, which indicated that the magnetic loss frequency characteristic of ultra-thin ribbons was superior to the conventional alloys. With the increase of the value B_m, the Po values of both samples were increased too, but the growth rate of f Po in the ultra-thin ribbons were far lower than that of the conventional alloys ribbons. The D_f values of both samples

were quite different with variation of B_m, the D_f values of the ultra-thin ribbons increased with the increase of B_m, but the D_f values of the conventional alloys ribbons deceased slightly.

In addition, compared the D_f and P_o of the ultra-thin ribbons and the conventional alloys ribbons, it could be found, at lower B_m, the P_o value between the two samples were different, the P_o values of the ultra-thin ribbons was much lower than that of the conventional alloys ribbons; at higher B_m, the difference of D_f value between the two samples were small, but the P_o values of the ultra-thin ribbons were little lower than that of the conventional alloys ribbons. This indicated that, at different values of B_m, with a reduced thickness to reduce the magnetic loss had different mechanisms. At lower B_m, the P(f) primarily decreased by reducing the value D_f, but at higher B_m, the P (f) were mainly controlled by P_o, and decreased by reducing the value P_o. Therefore, in practice, when working at a lower value of magnetic induction B_m occasions, compared with the conventional alloys ribbons, the ultra-thin ribbons were selectable to use at high frequency; in the case of higher B_m, the ultra-thin ribbons could work at a more higher value of B_m. It was undoubted that the ultra-thin ribbons were very useful for the miniaturization of small high-frequency soft magnetic device.
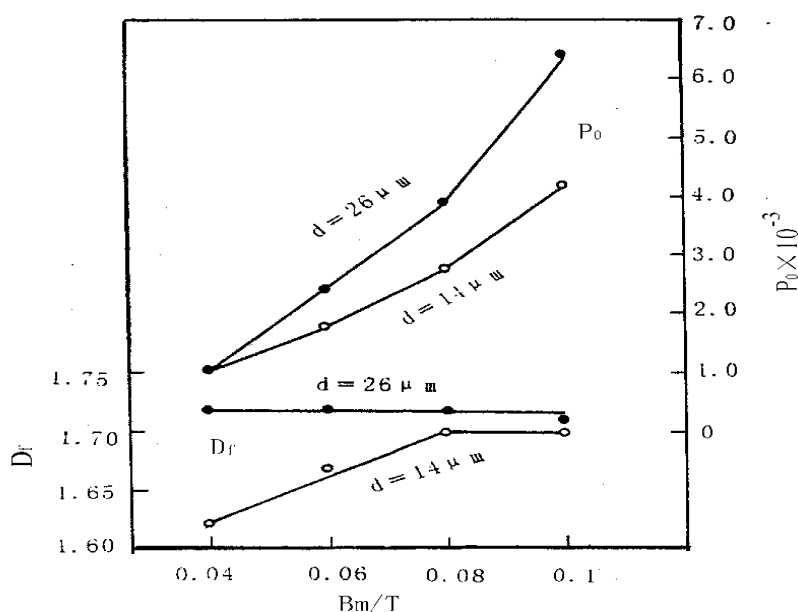

Fig. 2 Relations between D_f, P_0 and d, B_m.

Summary

The magnetic loss nanocrystalline soft magnetic ribbons could be significantly reduced with reducing the thickness of the nanocrystalline soft magnetic ribbons. The magnetic loss of the ribbons with the thickness of 14 μm was reduced to 70% of that of the ribbons with the thickness of 26 μm.

The magnetic loss P (f) of nanocrystalline soft magnetic ribbons had a fractal structure, and could be formulized as: $P(f) = P_o f^{Df}$.

The P_o and D_f values were decreased with reducing the thickness of the nanocrystalline soft magnetic ribbons. Under different ribbons thickness, the Po and Df of nanocrystalline soft magnetic ribbons shown a different disciplinarian under changes of work magnetic induction Bm values.

Acknowledgments

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