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Soft magnetic characteristics of laminated magnetic block cores assembled with a high *Bs* nanocrystalline alloy

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This paper focuses on an evaluation of core losses in laminated magnetic block cores assembled with a high *Bs* nanocrystalline alloy in high magnetic flux density region. To discuss the soft magnetic properties of the high *Bs* block cores, the comparison with amorphous (SA1) block cores is also performed. In the high *Bs* block core, both low core losses and high saturation flux densities *Bs* are satisfied in the low frequency region. Furthermore, in the laminated block core made of the high *Bs* alloy, the rate of increase of iron losses as a function of the magnetic flux density remains small up to around 1.6 T, which cannot be realized in conventional laminated block cores based on amorphous alloy. The block core made of the high *Bs* alloy exhibits comparable core loss with that of amorphous alloy core in the high-frequency region. Thus, it is expected that this laminated high *Bs* block core can achieve low core losses and high saturation flux densities in the high-frequency region. *Q 2018 Author(s)*. *All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).* https://doi.org/10.1063/1.5006098

I. INTRODUCTION

Soft magnetic materials such as Si-steels, Fe-based amorphous alloys, conventional nanocrystalline alloys (Fe-Si-B-Cu-Nb, FT-3M),¹ and high *B*s nanocrystalline alloys² have been developed for use as electrical power devices such as transformers, inductors, and motors. For these electronics applications, to achieve high effectiveness, efficiency, and miniaturization, both low core losses and higher saturation flux densities *B*s are required. In order to satisfy this requirement, some studies have focused on high *B*s Fe-Cu-B- and Fe-Cu-Si-B-based nanocrystalline alloys which exhibit high *B*s and low core loss corresponding to one half of that of grain oriented Si-steels.² In our study, a high *B*s Fe-based nanocrystalline alloy is tested in laminated magnetic block cores.

Recently, many studies have addressed magnetic properties of toroidal wound cores and racetrack-style core assembled with a high *Bs* nanocrystalline alloy.^{3–11} For example, M. Ohta and R. Hasegawa have shown that both low core loss and high *Bs* in the high *Bs* racetrack-style core can be realized in the high-frequency (more than about 10 kHz) region in comparison with those in the amorphous core.¹¹ The next step is to examine laminated magnetic block cores with gaps assembled with this high *Bs* alloy in high magnetic flux density region.

Under the same total gap length condition, the multi-gap can reduce the eddy current loss of the core compared to the case of the single-gap core.¹² The laminated block cores are suitable for use as the multi-gap core. By separating gap in the laminated block cores, the gap length per location can be reduced and then fringing magnetic flux can be suppressed. The laminated block cores with multi-gap allow us to reduce eddy current losses caused by fringing magnetic flux. Therefore, it is important to



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understand fundamental magnetic characteristics of laminated magnetic block cores assembled with the high *B*s nanocrystalline alloy in high magnetic flux density.

In our study, the laminated magnetic block core based on the high *B*s alloy ribbon is presented. In addition, to discuss the soft magnetic properties of the high *B*s block cores, the comparison with amorphous block cores is also performed. We use a resonant circuit¹³ to examine the core loss properties of the block core under sinusoidal excitation in high magnetic flux density region. The proposed measurement includes higher frequency operation than the commercial one. The core losses of the block core are also measured as a function of the excitation frequency because we consider that this laminated high *B*s block core exhibits low core loss as well as that of the racetrack-style core¹¹ in the high-frequency (around 10 kHz) region. The authors have published a paper¹⁴ in a conference to discuss a part of the experimental results of this work.

II. BLOCK CORE AND ITS MEASUREMENT SYSTEM

Figure 1 shows laminated magnetic block cores assembled with high *Bs* Fe-based nanocrystalline alloy and amorphous alloy (SA1) that consist of Fe_{bal}.Cu₁Mo_{0.2}Si₄B₁₄ (at%) and Fe-Si-B, respectively. Table I shows the specifications of two different materials used for the laminated core.

The high *B*s nanocrystalline alloy ribbons are prepared by a single-roller melt spinning technique and then are annealed at 500 °C to develop the high *B*s Fe-based nanocrystalline alloy. In our study, the high *B*s ribbons have the width of about 19.5 mm. In the inline annealing process, the temperature rising rate is set to higher than 100 °C/s to obtain nanocrystalline phases. The high *B*s nanocrystalline alloy ribbons are laminated and impregnated with acrylic resin to make the block core. After cutting and etching the cut surface, the laminated block cores assembled with the high *B*s nanocrystalline alloy are prepared. Here, after impregnating, the laminated block cores of the desired size are cut because the high *B*s ribbons are brittle and fragile. We make two sizes of laminated magnetic cores. The first (second) core type has a width, length, and thickness of about 18.6 (19.2), 63.4 (84.6), and 35.0 (35.0) mm, respectively. The stacking factor δ and the total weight of four cores are about 88 % and approximately 1287 g. The high *B*s nanocrystalline material ribbon utilized in our study exhibits a high saturation magnetic flux density of 1.74 T.¹¹

By using the above same laminating, cutting and etching methods, the laminated magnetic block cores assembled with amorphous alloy are prepared. The block cores for two different materials are the same design. In block cores assembled with amorphous alloy, the stacking factor δ and the total weight of four cores are about 93 % and approximately 1300 g.

In our measurements, we perform two kinds of laminated block core loss tests. The first core loss test measures a DC hysteresis loop by using a DC hysteresis (B - H) loop tracer (SK110, Metron,



FIG. 1. Laminated magnetic block cores assembled with high *Bs* Fe-based nanocrystalline alloy (left) and amorphous alloy (right, SA1).

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	High <i>B</i> s alloy	Amorphous alloy
Reference	_	SA1 ¹⁵
Density [kg/m ³]	7420	7180
Composition	Fe-Cu-Mo-Si-B	Fe-Si-B
Thickness [µm]	24	25
Relative permeability (at 10 kHz)	about 2000	3000
Saturation magnetic flux density [T]	1.74	1.56
Resistivity $[\mu \Omega \cdot m]$	around 0.8 ³	1.3

TABLE I. Specifications of different materials used for laminated cores.

Inc.). The second test is to measure core losses based on AC hysteresis loops; The core losses are measured by using a resonant circuit, which has a low-loss capacitor in parallel with the inductor, as shown in Fig. 2. Here, we use the parallel resonant circuit to obtain the large current through the inductor. The resonance frequency is adjusted by tuning the capacitor value at each measurement point (See Ref. 13 for details of the measurements). The measurement by using a resonant circuit has two advantages. The first advantage of such circuit is high power amplification. The second advantage is a high accuracy measurement by tuning the setup to perform measurements at the resonant frequency. The input voltage in the AC hysteresis loop measurement is supplied by a function generator (FGX-295, Texio) and two linear amplifiers (HSA 4014, nf). Note that the B - H loop tracer can measure DC hysteresis loops, which correspond to the hysteresis losses. Note also that by using the resonant circuit we measure the hysteresis and eddy current losses that correspond to the classical eddy current and excess losses. In our experiments, the fixed coils¹³ are used. By using the alignment mark, four laminated block cores are assembled and then clamped in two vises. The gap distance between cores is estimated as about 5 μ m.

In our measurements, the magnetic flux density B and the core losses W of laminated magnetic cores can be described by

$$B = \frac{1}{N_2 S \delta} \int V \mathrm{d}t,\tag{1}$$

$$W = \frac{f_0}{\phi} \int H \mathrm{d}B,\tag{2}$$

where ϕ is the density of the magnetic sheet, $H = N_1 I/L$ is the magnetic field intensity, N_2 (= 5) is the number of turns of *B*-coils, *V* is the *B*-coil voltage, and *S* (= about 650 mm²) is the cross-sectional area of the core. Here *I* is the input current, N_1 is the number of turns of the exciting coil, and *L* (= about 295 mm) is the average magnetic path length. N_1 is set to 32 or 108 in the AC hysteresis loop measurement by the resonant circuit and the DC hysteresis measurement, respectively. In our measurements by using the resonance circuit, a high performance analog-to-digital (A/D) converter (PXI-5122, National Instruments) is utilized. Then, the current and voltage are measured by a current probe (SS-260, Iwatsu) and a voltage probe (701921, Yokogawa), respectively.



FIG. 2. Schematic of measurement system of laminated block core losses under sinusoidal excitations by using a resonant circuit.

III. RESULTS AND DISCUSSION

Figure 3 shows laminated core loss characteristics with respect to the magnetic flux density based on the DC hysteresis loop, which has only hysteresis loss. In the experiments, the high *B*s and amorphous block cores have the maximum magnetic flux density of 1.7 T and 1.5T, respectively. The high *B*s block core exhibits the hysteresis loss at 1 T of 5 mJ/kg, which is as large as that made of amorphous alloy. In the high *B*s block core, both low core losses and high saturation flux densities *B*s are satisfied in the low frequency region compared to the case of the amorphous block core.

Figure 4 shows the laminated core loss characteristics with respect to the magnetic flux density under sinusoidal excitation at excitation frequencies of 50, 200, 400, and 600 Hz by using the resonant circuit. The measured results include higher frequency operation than the commercial one. For every condition, the laminated core losses have the same tendency. In this experimental setup, the laminated block core assembled with high *B*s nanocrystalline alloy can exhibit the high magnetic flux density of more than 1.6T at 50, 200, 400 Hz and 600 Hz. The magnetic flux density is limited to around 1.6 T due to the limitation of the linear amplifier. Under the same conditions, the magnetic flux density of the laminated block core assembled with amorphous alloy has less than 1.5 T.



FIG. 3. Laminated core loss characteristics with respect to the magnetic flux density by using a B - H loop tracer (SK110, Metron, Inc.), which measures DC hysteresis loops.



FIG. 4. Measured core loss characteristics as a function of magnetic flux density in high *B*s and amorphous (SA1) cores by using resonant circuit, as shown in Fig. 2: (a) 50 and 200 Hz. (b) 400 and 600 Hz.

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FIG. 5. Experimentally obtained core loss properties as a function of the excitation frequency by using the resonant circuit at 0.1 T.

The core loss increases with increasing the magnetic flux density and the frequency. The high *Bs* block core exhibits core losses of about 12.7 W/kg at f = 600 Hz and B = 1.62 T, of 8.2 W/kg at f = 400 Hz and B = 1.61 T, of 4.0 W/kg at f = 200 Hz and B = 1.61 T, and of 1.1 W/kg at f = 50 Hz and B = 1.65 T, respectively. It is found that the high *Bs* block core shows slightly large core loss compared with that of amorphous core at the frequency of 50 Hz to 600 Hz. For example, the core loss of the present high *Bs* alloy is around 1.25 times of that of amorphous alloy at 1 T and 200 Hz. Nevertheless, in the laminated block core made of the high *Bs* alloy, the rate of increase of iron losses for the amorphous block core become small at low values of *B*, losses rapidly increase above 1.5 T. Therefore, the laminated magnetic block core assembled with the high *Bs* nanocrystalline alloy is suitable for use at magnetic flux density of 1.5 to 1.6 T.

Figure 5 shows the experimentally obtained core loss characteristics as a function of excitation frequency (50 Hz < f < 10 kHz) by using the resonant circuit. Tests are done at magnetic flux densities of 0.1 T. The difference between the core losses of high *B*s and amorphous cores slightly increases and then decreases with the increase of the excitation frequency. The block core made of the high *B*s alloy exhibits comparable core loss with that of amorphous alloy core at 10 kHz.

A high *Bs* wound core with cut exhibits the core loss of about 2 W/kg at 10 kHz and 0.1T.⁷ Under the same conditions, the core loss of the laminated high *Bs* block cores has about 3 W/kg. The core loss of a high *Bs* racetrack-style core without cut is about 1.5 W/kg at 400Hz and 1T.¹¹ Under the same conditions, the core loss of the laminated high *Bs* block cores has about 3.9 W/kg, which corresponds to about 2.6 times that of the racetrack-style core. Note that the eddy current losses of the core increase locally due to fringing flux caused by the cut (gap) between cores.

Consequently, this work examines for the first time the laminated magnetic block core assembled with the high *B*s alloy in high magnetic flux density region. The iron loss of these two different magnetic materials (high *B*s alloy and amorphous alloy) is much smaller than that of conventional non-oriented (NO) silicon steel. In the laminated high *B*s block core, the rate of increase of core losses as a function of the magnetic flux density remains small up to around 1.6 T, which cannot be realized in conventional laminated block cores based on amorphous and conventional nanocrystalline materials (FT-3M). The laminated high *B*s block core exhibits comparable core loss with that of amorphous alloy core at 10 kHz. Therefore, it is thought that this laminated high *B*s block cores can achieve very low core losses and high saturation flux densities as well as those of the high *B*s racetrack-style core¹¹ in the high-frequency (more than about 10 kHz) region.

IV. CONCLUSION

We for the first time examined the laminated magnetic block core assembled with the high *Bs* alloy in high magnetic flux density region. In addition, the laminated magnetic block core losses were compared for the high *Bs* nanocrystalline and amorphous materials. The conclusions of this study are presented as follows:

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- 1. In the high *B*s block core, both low core losses and high saturation flux densities *B*s were satisfied when the DC hysteresis loops were measured. The core loss of high *B*s block core was as large as that of amorphous core in the low frequency region.
- 2. In the laminated block core made of the high *B*s alloy, the rate of increase of iron losses as a function of the magnetic flux density remained small up to around 1.6 T, which cannot be realized in conventional laminated block cores based on amorphous alloy. Therefore, the laminated magnetic block core assembled with the high *B*s nanocrystalline alloy was suitable for use at magnetic flux density of 1.5 to 1.6 T.
- 3. The block core made of the high *B*s alloy exhibited comparable core loss with that of amorphous alloy core in the high-frequency region. Thus, it is expected that this laminated high *B*s block core can achieve low core losses and high saturation flux densities in the high-frequency (more than about 10 kHz) region.

The future work is discussed as follows. In our high *B*s block core, the annealing process is only one time. When the high *B*s core without cut and gap is secondarily annealed, core loss has one of the lowest among the metallic cores that have higher *B*s than 1.5 T.¹¹ Therefore, to reduce the core loss, the block core made of the high *B*s alloy will be secondarily annealed. The annealing process for the high *B*s nanocrystalline sheets will be considered to reduce the process steps. The evaluation of building factor¹⁶ and the core losses for each process step will be examined to understand the iron losses caused by factors such as the manufacturing process.

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