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Application of nanocrystalline soft magnetic Fe–M–B (M=Zr, Nb) alloys to choke coils

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We have developed a choke coil made of new nanocrystalline soft magnetic Fe–M–B (M=Zr, Nb) alloys (''NANOPERM™ '' material) which exhibit high saturation magnetic induction (B_s), above 1.5 T, excellent soft magnetic properties and zero magnetostriction. A choke coil made of NANOPERM™ material exhibits good dc bias characteristics of inductance because of the high B_s. Furthermore, the choke coil made from NANOPERM™ material showed 1/3rd the temperature rise shown by a core made from Fe–Si–B amorphous alloy. The low core loss and high B_s of NANOPERM™ material allow the reduction of the core size. It is concluded that NANOPERM™ is suitable as a core material for choke coils.
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I. INTRODUCTION

In increasing instances the reactors of phase modifying equipment are disabled by line current which contains higher harmonic distortion generated by switching regulators, etc. Line current correction to sinusoidal wave by using active filters is a useful method to prevent distortion in the reactors. High saturation magnetic induction (B_s) and low core loss are required for the core material of choke coils as active filters because high frequency current with large amplitude superimposed on direct current flows into the choke coil. It has been reported by us that new nanocrystalline soft magnetic Fe–M–B (M=Zr, Nb) alloys (''NANOPERM™ '' material) show high B_s above 1.5 T, excellent soft magnetic properties, low core losses and sufficiently small magnetostriction.[1–4] Figure 1 shows the relation between B_s and permeability (μ_e) at 1 kHz for NANOPERM™ material and other soft magnetic materials. NANOPERM™ material is found to be situated in the top right corner of the figure. NANOPERM™ material is therefore expected to be used as core material for choke coils as active filters. In this article, we report the characteristics of the choke coil made of NANOPERM™ material.

II. EXPERIMENTAL PROCEDURE

The $Fe_{84}Zr_{3.5}Nb_{3.5}B_8Cu_1$ alloy was selected an example of NANOPERM™ material in this study. The NANOPERM™ ribbon with 20 μm in thickness was produced by using a single-roller melt-spinning method in an Ar atmosphere. In order to compare the magnetic properties, a commercial $Fe_{78}Si_9B_{13}$ amorphous alloy (METGLAS® alloy 2605 S-2) ribbon with the same thickness as the NANOPERM™ material was prepared. Table I shows typical magnetic properties for the alloys.[3,6]

Toroidal samples were prepared as follows. A mixture of MgO powders and sodium silica solution (water glass) was applied to both sides of the ribbons to prevent electrical contact between the ribbons. The ribbons were wound into toroidal cores with 38 mm in outer diameter, 23 mm in inner diameter and 15 mm in height. The annealing treatment of the cores was carried out in vacuum by keeping the cores at 953 K for 600 s (NANOPERM™) or at 643 K for 7.2 ks (Fe–Si–B amorphous alloy). The annealed cores were encapsulation in an epoxy resin. Then the cores were processed by cutting a 2 mm air gap and inserting an insulating material in the gap.

Measurements of core losses were carried out using an ac *B-H* analyzer after annealing, after encapsulation, and after introducing an air gap. dc bias characteristics were measured after introducing an air gap.

III. RESULTS AND DISCUSSION

Table II shows the size, the lamination factor and the effective cross section of the cores. The size of the cores is almost the same. Figure 2 shows the change in core loss of the cores after annealing, encapsulation, and introducing an

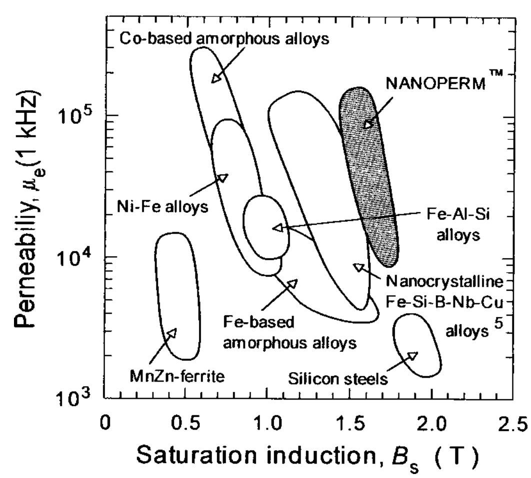

FIG. 1. Relationship between B_s and μ_e at 1 kHz for NANOPERM™, the nanocrystalline Fe–Si–B–Nb–Cu alloys (Ref. 5) and conventional soft magnetic materials.

TABLE I. Typical example of the saturation induction (B_s), permeability (μ), core loss (W), and saturation magnetostriction (λ_s) for the alloys (Refs. 3 and 6).

Alloys	$B_s(T)$	$\|\mu\|$ 1 kHz	$\|\mu\|$ 100 kHz	W (W/kg) 1 kHz, 1T	W (W/kg) 100 kHz, 0.1 T	$\lambda_s(10^{-6})$
NANOPERM™	1.53	100 000	18 000	1.1	15	~0
Fe–Si–B amorphous alloy	1.56	10 000	5 000	4.0	48	+27

TABLE II. Outer diameter (OD), inner diameter (ID), height (H), lamination factor (K), and effective cross section (S).

Alloys	OD (mm)	ID (mm)	H (mm)	K (%)	S (mm2)
NANOPERM™	37.1	23.2	15.5	77.1	79.0
Fe–Si–B amorphous alloy	36.9	22.9	15.5	65.8	71.4

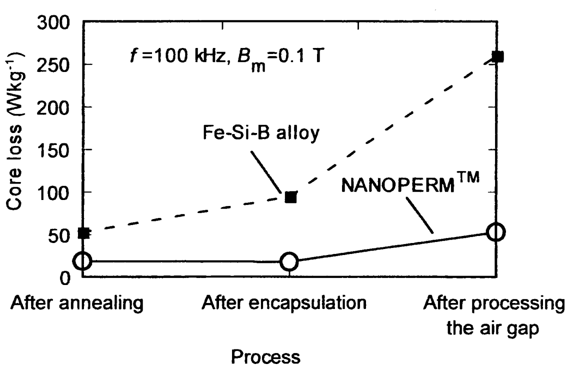

FIG. 2. Change in the core loss of the cores with annealing, encapsulation, and processing the air gap.

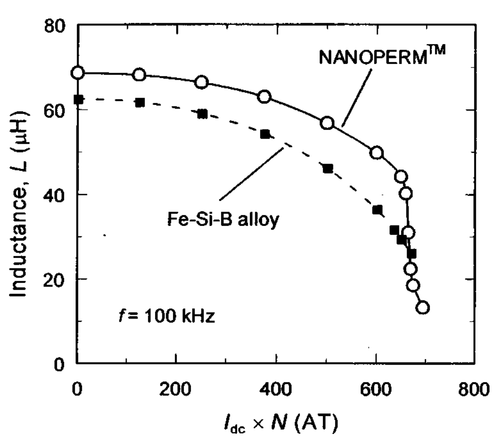

FIG. 3. Change of inductance as a function of dc bias current (I_{dc}) times number of turns (N) for choke coils made of NANOPERM™ and Fe–Si–B alloy.

air gap. The core loss of NANOPERM™ core after annealing is about 1/3rd as large as that of the Fe–Si–B core. After encapsulation in the epoxy resin, the core loss of the Fe–Si–B core showed a large increase due to stress from the resin. Since the magnetostriction of the Fe–Si–B amorphous alloy is large, the soft magnetic properties are inferior in the stressed state. On the other hand, the NANOPERM™ core exhibits almost the same low core loss value as that of the core before encapsulation because of its zero magnetostriction. The encapsulation treatment is necessary to cut an air gap. It can be said that the zero magnetostriction is necessary for the toroidal core with a gap to exhibit a low core loss. After introducing an air gap, the core loss increase in both NANOPERM™ and Fe–Si–B alloys. However, the NANOPERM™ core exhibits smaller core loss which is only 1/5th that of the Fe–Si–B core.

Figure 3 shows dc bias characteristics of the gapped cores with 25 turn coil. The inductance of the NANOPERM™ and the Fe–Si–B cores show a decrease around $N\times I=700$ AT because the saturation magnetic inductions of both the core materials are almost equal. When leakage flux from the air gap can be neglected, inductance (L) of the gapped core can be written as

$$L=N^2S \Big/ \left(\frac{l-l_g}{\mu}+\frac{l_g}{\mu_0}\right), \tag{1}$$

where l_g is gap length, l is length of magnetic path, μ is permeability of material, and μ_0 is permeability of vacuum. When μ is much larger than μ_0, a term of $(l-l_g)/\mu$ can be neglected. Therefore, the inductance of the gapped core is independ of μ. However, although the NANOPERM™ and the Fe–Si–B cores have the same size and the same gap length, the inductance of the NANOPERM™ core is 10% larger than that of the Fe–Si–B core at a dc bias current of zero. The difference in inductances is caused by the difference in effective cross sections of the cores. As shown in Table II, the effective cross section of the NANOPERM™ core is 14% larger than that of the Fe–Si–B core, which is in good agreement with the difference in inductances.

Next, we have examined the relation between the choke coil loss and temperature rise (ΔT) of the choke cores. The miniaturization of the core is limited by B_s and by the core loss of the core material. If the core loss is large, the core volume should be increased because maximum magnetic induction (B_m) should be decreased to reduce ΔT. Figure 4 shows the B_m dependence of the choke coil loss which consists of the core loss and the copper loss. The operating frequency is 50 kHz and B_m is changed from 0.01 to 0.1 T. The choke coil loss is 4.2 W for Fe–Si–B alloy, and is 1.3 W for

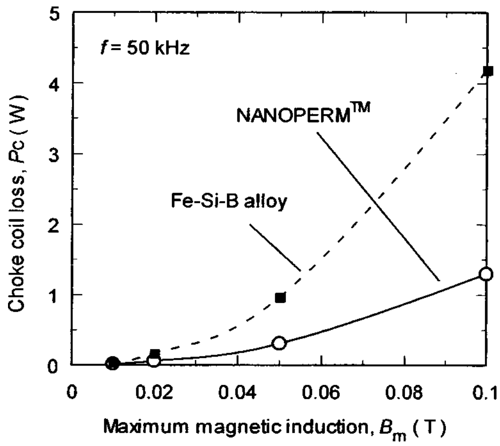

FIG. 4. B_m dependence of the choke coil loss, which consists of the core loss and the copper loss.

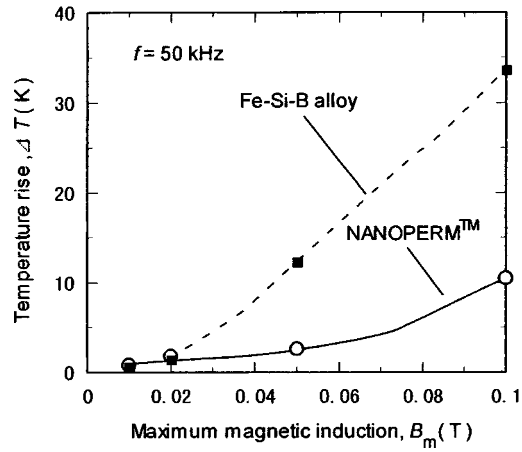

FIG. 5. ΔT of the choke coils as a function of B_m.

NANOPERM™ material at $B_m = 0.1$ T. Figure 5 shows ΔT of the choke coils as a function of B_m. When $B_m = 0.1$ T, ΔT is 34 K for the Fe–Si–B choke coil and 11 K for the NANOPERM™ choke coil, respectively. The ΔT of the NANOPERM™ choke coil is only 32% that of the Fe–Si–B one. In order to achieve a small ΔT of 11 K for Fe–Si–B core, it is necessary to reduce the B_m value to 0.05 T. This means that core volume should be doubled for the Fe–Si–B choke coil.

NANOPERM™ shows a high B_s which is comparable to that of Fe–Si–B amorphous alloys, and its choke coil loss is only 1/3rd that of Fe–Si–B amorphous alloys. The very low loss allows a reduction in core size. It is concluded that the size of the choke coils can be significantly reduced by replacing the core material from Fe–Si–B amorphous alloys to NANOPERM™. Therefore, NANOPERM™ material is suitable as core material for the choke coils of active filters.

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