High Temperature Magnetic Properties of Fe–Cu–Nb–Si–B Cores With Creep-Induced Anisotropy

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***Abstract*—Fe–Cu–Nb–Si–B ribbons with creep-induced anisotropy fabricated by continuous stress-annealing were formed into toroidal cores. The temperature dependence of their magnetic loss and relative permeability at $B_m = 0.1$ T was evaluated in the frequency range of 0.5–1 MHz and temperature range from room temperature to 523 K. We found that the cores can be used up to 523 K without magnetic property deterioration. This suggests that the proposed cores have superior high temperature properties compared with conventional gapped-ferrite cores allowing use at high temperature.**

***Index Terms*—Continuous stress-annealing, creep-induced anisotropy, high temperature properties, low permeability, magnetic core, nanocrystalline.**

I. Introduction

In RECENT years, size reduction and efficiency improvement of magnetic devices in electrical circuits are necessary. Thus, we studied and developed high performance soft magnetic materials for reactor and choke coils. For these materials, high saturation magnetization, low magnetic loss and suitably low permeability are needed to suppress magnetic saturation due to dc-bias field. Accordingly, we proposed Fe–Cu–Nb–Si–B toroidal cores with creep-induced anisotropy [1]–[4] and demonstrated their superior magnetic properties for choke cores compared with previous reported cores [5]–[11] and conventional air-gapped ferrite choke cores [12]–[14].

Cores with creep-induced anisotropy rather than conventional ferrite cores are proposed to be used under high temperature conditions because of their high Curie temperature. However, as creep-induced anisotropy varies in magnitude with temperature, permeability may be affected by operating temperature. Thus, we studied the high temperature magnetic properties of nanocrystalline Fe–Cu–Nb–Si–B toroidal cores prepared with creep-induced anisotropy, and confirmed that their use at high temperatures exceeding the maximum operating temperature for conventional ferrite cores.

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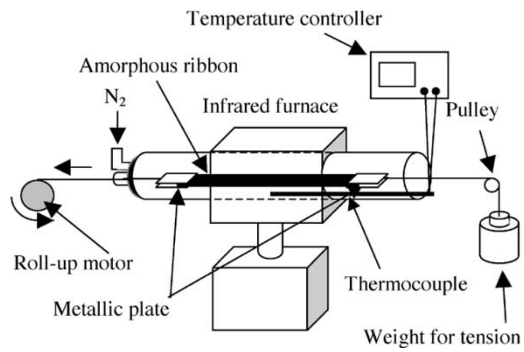

Fig. 1. Schematic representation of continuous stress-annealing equipment using an infrared furnace.

II. Experimental Procedure

A. Development of Creep-Induced Anisotropy

Amorphous $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbons (Hitachi Metals Ltd.), 500-mm long, 2-mm wide, and 20-μm thick, were nanocrystallized by continuous stress-annealing in an N_2 flow. Creep-induced magnetic anisotropy was induced perpendicularly to the ribbon axis. Fig. 1 shows the schematic representation of continuous stress-annealing equipment. The amorphous ribbon under tensile stress from 100 to 150 MPa passed through an infrared furnace at the designated temperature of 803 K. The moving velocity of the ribbon was set at 1 cm/min.

B. Measurements

Dc-hysteresis loops of annealed-ribbons and prepared cores were traced with a computer-aided B-H loop tracer (Riken BHS-40), and we determined the saturation magnetization I_s and uniaxial anisotropy energy constant K_u from a dc-hysteresis loop. K_u was obtained by numerical integration of $H \cdot \Delta I$.

The annealed ribbons were formed into toroidal cores using ceramic bobbins, and then their ac magnetic loss and relative permeability at $B_m = 0.1$ T were measured with a B-H analyzer (Iwatsu SY-8232) in the frequency range from 0.1–1 MHz. The measurement temperature was raised from room temperature to 523 K in an oven.

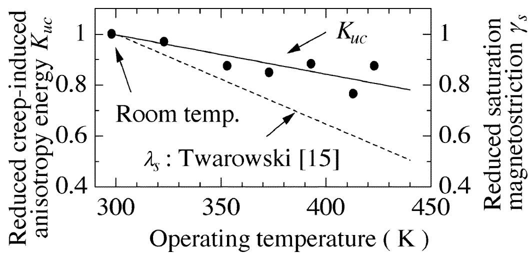

Fig. 2. Reduced creep-induced anisotropy constant K_{uc} of a prepared core with $D/D_c > 1$ and saturation magnetostriction λ_s as a function of operating temperature. The temperature dependence of λ_s is quoted from [15].

C. Critical Diameter

We previously reported "Critical Diameter, D_c" [14], and D_c plays an important role in determining magnetic properties of toroidal cores.

When an annealed ribbon is formed into a toroidal core, mechanical stress induces a magnetic anisotropy through its magnetostriction ($\approx 10^{-6}$). This anisotropy compensates creep-induced anisotropy on the outer or inner surface of the ribbon, which causes deterioration of magnetic properties such as increasing magnetic loss. Anisotropy developed by the magnetoelastic effect increases with reduction in core diameter D. Consequently, the magnetoelastic energy becomes equal to the creep-induced anisotropy energy at D_c. D_c was determined using ribbon thickness d, Young modulus E, creep-induced anisotropy energy K_{uc}, and saturation magnetostriction constant λ_s as

$$D_c = \frac{3|\lambda_S|Ed}{2K_{uc}}. \tag{1}$$

In a typical annealed ribbon, d, E and λ_s were approximately 20 μm, 7.2×10^{11} MPa and 2×10^{-6} at room temperature, respectively.

$D/D_c > 1$ indicates that magnetoellastic energy K_{um}, induced by mechanical stress during toroidal core fabrication, is smaller than K_{uc}.

III. High Temperature Properties

A. Critical Diameter

D_c varies with temperature because K_{uc}, λ_s, and E vary with temperature. The measured K_{uc} value of a prepared core with $D/D_c > 1$ is shown in Fig. 2 as a function of operating temperature, and temperature dependence of λ_s, as reported by Twarowski *et al.* [15]. In this figure, K_{uc} and λ_s are reduced by the values at room temperature. K_{uc} and λ_s decreased with an increase in operating temperature above room temperature. In addition, the Young modulus of conventional metallic materials tends to decrease with increasing operating temperature. Thus, D_c is expected to decrease with increasing operating temperature.

In this experiment, high temperature properties were evaluated with $D/D_{c/\mathrm{RT}}$ as a parameter, where $D_{c/\mathrm{RT}}$ is the critical diameter at room temperature.

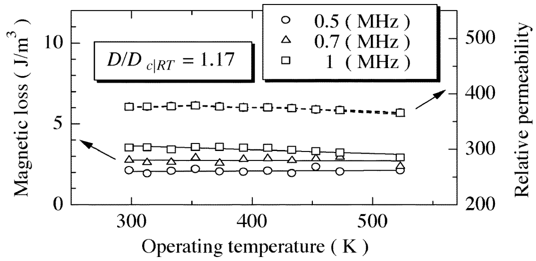

Fig. 3. Magnetic loss and relative permeability of the prepared core with $D/D_{c/\mathrm{RT}} > 1$ at $B_m = 0.1$ T as a function of operating temperature.

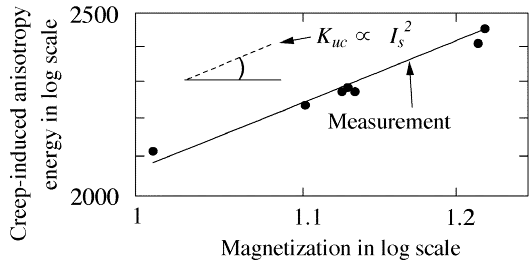

Fig. 4. Relationship between creep-induced anisotropy energy K_{uc} and saturation magnetization I_s of the prepared core.

B. Cores With $D/D_{c/\mathrm{RT}} > 1$

Fig. 3 shows the ac magnetic loss and relative permeability of the core with $D/D_{c/\mathrm{RT}} > 1$ at $B_m = 0.1$ T as a function of the operating temperature. The magnetic loss was constant from room temperature to 523 K. This result suggests that $D/D_{c/\mathrm{RT}} > 1$ condition is retained under high temperatures, consistent with the discussion in section Section III-A. Herzer and Mazaleyrat *et al.* have studied the temperature dependence of coercivity H_c in nanocrystalline Fe–Cu–Nb–Si–B ribbons and reported that H_c increased abruptly when the temperature exceeded the Curie temperature of the residual amorphous phase ($\approx$590 K) [16], [17]. In our experiment, the evaluation was carried out at temperatures below 573 K. Therefore, the hysteresis loss of our core was low in the measured temperature range, which is also consistent with the observation that magnetic loss did not increase up to 523 K.

Relative permeability was not affected by operating temperature as shown in Fig. 3. Relative permeability of a magnetic material with uniaxial anisotropy is given as

$$\mu_r = \frac{I_s}{\mu_0 H_A} = \frac{I_s^2}{2\mu_0 K_{uc}} \tag{2}$$

where H_A is the anisotropy field. Thus, the temperature-independent permeability suggests that K_{uc} is proportional to I_s^2. The measured K_{uc} is plotted in Fig. 4 as a function of I_s. Actually, K_{uc} was proportional to I_s^2 in the core.

Consequently, we found that our proposed cores with $D/D_{c/\mathrm{RT}} > 1$ can be used up to 523 K without magnetic property deterioration and have superior high temperature properties.

C. Cores With $D/D_{c/\mathrm{RT}} < 1$

Fig. 5 shows ac magnetic loss and relative permeability of the core with $D/D_{c/\mathrm{RT}} < 1$ at $B_m = 0.1$ T as a function of operating temperature. The relative permeability was almost

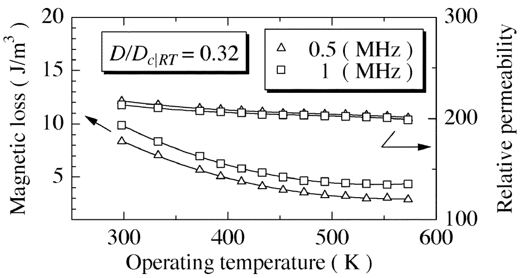

Fig. 5. Magnetic loss and relative permeability of the prepared core with $D/D_c < 1$ at $B_m = 0.1$ T as a function of operating temperature.

constant up to 573 K. However, magnetic loss decreased with increasing operating temperature, approaching the value of the core with $D/D_{c/\mathrm{RT}} > 1$. This decrease can be attributed to increasing D/D_c with increasing operating temperature as discussed in section Section III-A.

Consequently, we found that the magnetic properties of cores with $D/D_{c/\mathrm{RT}} < 1$ and $D/D_{c/\mathrm{RT}} > 1$ did not deteriorate up to 523 K.

D. Origins of Creep-Induced Anisotropy

From Figs. 2 and 4, K_{uc} was proportional to λ_s and I_s^2. Induced anisotropy is proportional to λ_s in the back-stress model proposed by Herzer [2] and I_s^2 in the pair-ordering model [18] proposed by Hofmann *et al.* [4], respectively. Thus, our experimental results on temperature dependence of K_{uc} are consistent with both the models.

IV. Conclusion

In order to investigate the high temperature properties of toroidal cores prepared from Fe–Cu–Nb–Si–B ribbon with creep-induced anisotropy, we evaluated ac magnetic loss and relative permeability at $B_m = 0.1$ T in the frequency of 0.5–1 MHz and temperature range from room temperature to 523 K, respectively.

1) $D > D_{c/\mathrm{RT}} (K_{uc} > K_{um})$
   Both magnetic loss and relative permeability were constant up to 523 K. Temperature-independent permeability suggests that the anisotropy energy constant is proportional to the square of the saturation magnetization.
2) $D < D_{c/\mathrm{RT}} (K_{uc} < K_{um})$
   Although relative permeability did not depend on operating temperature, magnetic loss decreased with increasing operating temperature. This decrease can be attributed to an increase in D/D_c with increasing operating temperature.
3) From the above results, it was demonstrated that our proposed cores with $D/D_{c/\mathrm{RT}} > 1$ have superior high temperature properties and can be used under high temperatures exceeding the maximum operating temperature for conventional ferrite cores.

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