# Magnetic properties of Fe-based toroidal cores prepared by continuous Joule heating under tensile stress

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Fe-based toroidal cores with a permeability value of several hundreds were prepared by the continuous Joule heating method under tensile stress at a high moving velocity of 120 cm/min, corresponding to an effective annealing time of approximately 1.8 s, and their magnetic properties were evaluated. The prepared core showed a constant permeability value up to 2 MHz and a low magnetic loss compared with those for conventional cores with controlled permeability. An investigation of dc-bias properties of the core suggested that the core has constant and good magnetic properties below the dc-bias field of 1 kA/m which is approximately 50% of the anisotropy field. Consequently, the continuous Joule heating under a tensile stress method at high moving velocity enables us to prepare a long annealed ribbon in a short time with simple equipment and improves productivity for the fabrication process of high performance Fe-based toroidal cores with controlled permeability.  [DOI: 10.1063/1.2712947]

## I. INTRODUCTION

Soft magnetic cores with controlled permeability such as choke coils and reactors are widely used in electronic devices. In order to advance high-density packaging and energy saving of the devices, size reduction and improvement in efficiency of the cores are strongly required. We, therefore, proposed several kinds of Fe-based toroidal cores with controlled permeability and showed their applicability to choke coils.[1,2] In particular, an Fe-based magnetic core with nanostructure and uniaxial anisotropy developed by stress annealing[3–6] has excellent magnetic properties in the proposed cores.[2,7–9]

From the viewpoint of improving the control over permeability, we have reported on several methods of the stress annealing such as the continuous stress annealing with a furnace (CSA-F),[10–12] the Joule heating (JH) under tensile stress[13–16] and the continuous stress annealing by Joule heating (CSA-JH).[17] For industrial production of a toroidal core, we need to reduce the annealing time and prepare a long ribbon in a short time with simple equipment. The CSA-JH method, which combines productive advantages of the CSA-F and JH methods, is one of the attractive techniques for production of high performance toroidal cores with controlled permeability.

In this study, a toroidal core was prepared by the CSA-JH method focusing on reduction in annealing time, and then their magnetic properties were evaluated.

## II. EXPERIMENTAL PROCEDURE

### A. Annealing for development of anisotropy

An amorphous $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbon (500 mm $\times$2 mm$\times$20 $\mu$m) was Joule annealed continuously in air under tensile stress of 50 or 100 MPa, referred to as CSA-JH method. The apparatus for CSA-JH method was described in Ref. 17. Rotatable Cu tubes were used as electrodes, and a dc was supplied to the ribbon though the electrodes by a computer-aided dc power supply. The supplied current density $j$ was set at 37.5 A/mm$^2$ considering the result for optimization of CSA-JH conditions in Ref. 17. The moving velocity $v_m$ of the ribbon was varied from 1 to 150 cm/min by change in the rotational speed of a roll-up motor.

Uniaxial magnetic anisotropy is developed perpendicularly to the ribbon axis by the stress annealing and reduces hysteresis loss.

### B. Measurements

In order to evaluate the crystallization state of annealed ribbons, differential scanning calorimetry (DSC) analysis was carried out with a differential scanning calorimeter (Seiko Instruments DSC-6200) in Ar. The heating rate was fixed at 10 °C/min, and DSC curve was traced in a temperature range from 480 to 600 °C.

The annealed 500-mm-long ribbon was formed into a toroidal core using a ceramic bobbin. We traced the dc-hysteresis loop of the prepared core with a computer-aided $B$-$H$ loop tracer (Riken BHS-40). The maximum exciting field and exciting frequency were approximately 4000 A/m and 50 mHz, respectively. The saturation magnetization $I_s$, the uniaxial anisotropy energy constant $K_u$, and the aniso-

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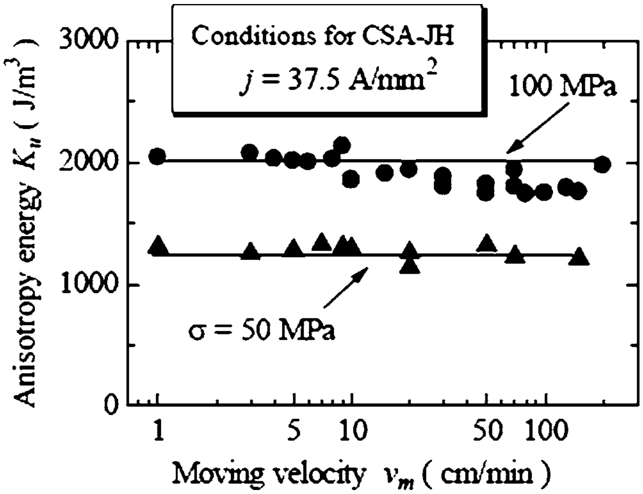


FIG. 1. Anisotropy energy $K_u$ of ribbons prepared by continuous stress-annealing by Joule heating (CSA-JH) as a function of moving velocity $v_m$. The current density $j$ was set at 37.5 A/mm$^2$. The ribbons were annealed under the tensile stress of 50 or 100 MPa.

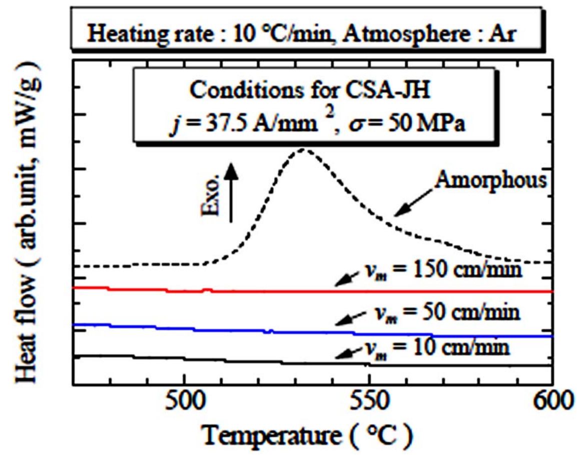


FIG. 2. (Color online) DSC curves of ribbons prepared under the varied moving velocities of 10, 50, and 150 cm/min. The measurement was carried out in a temperature range from 480 to 600 °C, and the heating rate was fixed at 10 °C/min.

tropy field $H_A$ were determined from the measured loop. $K_u$ was obtained by numerical integration of $H \cdot \Delta I$ in the first quadrant of the loop.

The relative permeability $\mu_r$ and the magnetic loss per cycle $P_{cv}/f$ of the prepared core at $B_m$=0.1 T were evaluated with a $B$-$H$ analyzer (Iwatsu SY-8232) in the frequency $f$ range from 0.1 to 2 MHz.

Magnetic properties under dc-bias field are important in applications to a choke coil. Thus, we also evaluated dc-bias properties of the prepared core at $B_m$=0.1 T and $f$ =0.5 MHz. The dc-bias field $H_{dc}$, was varied from 0 to 2000 A/m.

## III. RESULTS AND DISCUSSIONS

### A. Dependence of anisotropy energy on moving velocity

In the case of continuous annealing, increase in moving velocity $v_m$ is one of the effective factors for reducing annealing time. We, therefore, evaluated dependence of anisotropy energy $K_u$ on $v_m$.

Figure 1 shows the dependence of $K_u$ on $v_m$. The tensile stress $\sigma$ during CSA-JH was set at 50 or 100 MPa. As seen in the figure, $K_u$ did not depend on $v_m$ in the wide range of $v_m$ from 1 to 150 cm/min. Taking advantage of this result, we found that the annealing time can be reduced by increasing $v_m$.

When an annealed ribbon is formed into a toroidal core, mechanical stress induces a magnetic anisotropy through its magnetostriction. As this anisotropy may cause deterioration of magnetic properties such as an increase in magnetic loss, the annealed ribbon is desired to have a small saturation magnetostriction value. Magnetostriction in the $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbon varies with the crystallization state from ≈+20 ppm for the amorphous state to nearly zero for the sufficiently crystallized state.[18–20] Thus, we investigated the state of crystallization for the annealed ribbons taking advantage of DSC analysis.

Figure 2 shows DSC curves of ribbons prepared at $v_m$ =10, 50, and 150 cm/min, together with the result for an amorphous ribbon. Although exothermic heat flow around 530 °C, indicating development of crystallization, was observed in the amorphous ribbon, the flow did not happen in any of the annealed ones. From this result, we confirmed that the ribbon prepared under a high moving velocity of 150 cm/min was crystallized sufficiently.

The highest moving velocity, which enables us to obtain a long ribbon sufficiently crystallized with completely developed anisotropy, was 150 cm/min in our equipment. This value of $v_m$ corresponds to an effective annealing time of approximately 1.4 s, which is 50% as short as that for CSA-F.[12]

### B. dc magnetic properties of prepared core

A toroidal core with the inner diameter $D$ of 20 mm was prepared from a 500-mm-long annealed ribbon ($j$ =37.5 A/mm$^2$, $v_m$=120 cm/min, and $\sigma$=50 MPa).

The dc hystresis loop of the prepared core was traced and shown in Fig. 3. As seen in the figure, stress annealing

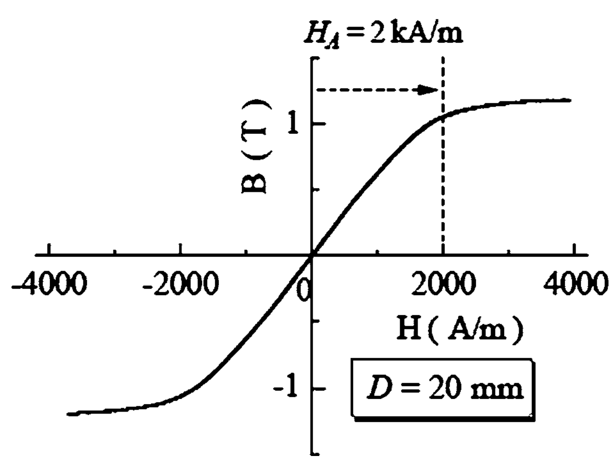


FIG. 3. dc hysteresis loop of a prepared core made from a 500-mm-long ribbon. The long ribbon was fabricated by high speed CSA-JH method ($j$ =37.5 A/mm$^2$, $v_m$=120 cm/min, and $\sigma$=50 MPa).

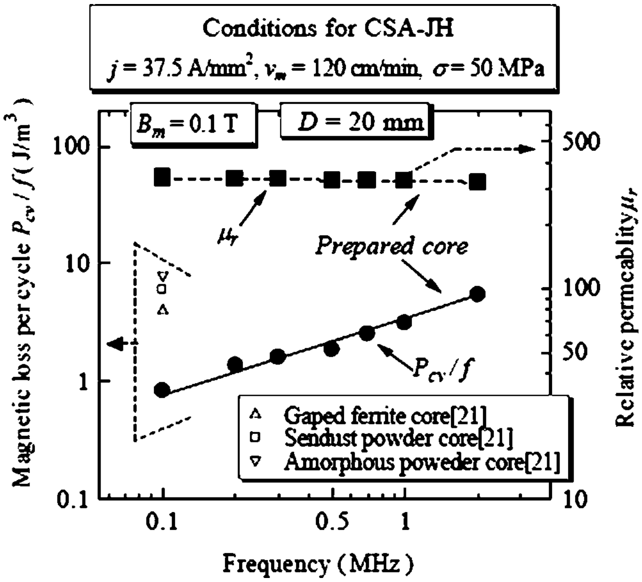


FIG. 4. Relative permeability $\mu_r$ and magnetic loss per cycle $P_{cv}/f$ of a developed core as a function of frequency, together with those for different types of cores with controlled permeability (Ref. 21).

induces uniaxial magnetic anisotropy and reduces permeability without an increase in coercivity ($H_c < 10$ A/m). From the loop, the anisotropy field $H_A$ of the prepared core was determined to be 2 kA/m.

### C. ac magnetic properties of prepared core

Figure 4 shows the relative permeability $\mu_r$ and magnetic loss per cycle $P_{cv}/f$ of the prepared core at $B_m$=0.1 T as a function of frequency $f$ together with those for conventional cores with controlled permeability.[21] The magnetic loss of the prepared core was approximately 1.2 J/m$^3$ at $f$ =0.1 MHz and the lowest in the cores shown in the figure. The permeability of the prepared core was kept constant up to 2 MHz. These properties were almost the same as those for the previously reported ones,[1,2,16] and we found that a toroidal core with controlled permeability and low magnetic loss could also be obtained by high speed CSA-JH method.

### D. dc-bias properties of prepared core

Figure 5 shows dependence of relative permeability $\mu_r$ and magnetic loss per cycle $P_{cv}/f$ on dc-bias field $H_{dc}$. Both $\mu_r$ and $P_{cv}/f$ were almost constant up to $H_{dc}$=1 kA/m. Considering that an anisotropy field $H_A$ of the core was approximately 2 kA/m (Fig. 3), the prepared core keeps its good magnetic properties up to the dc-bias field of $H_A/2$.

## IV. CONCLUSION

We fabricated an Fe-based toroidal core with controlled permeability by continuous Joule heating under stress annealing at high moving velocity and evaluated its magnetic properties. The results obtained are summarized as follows.

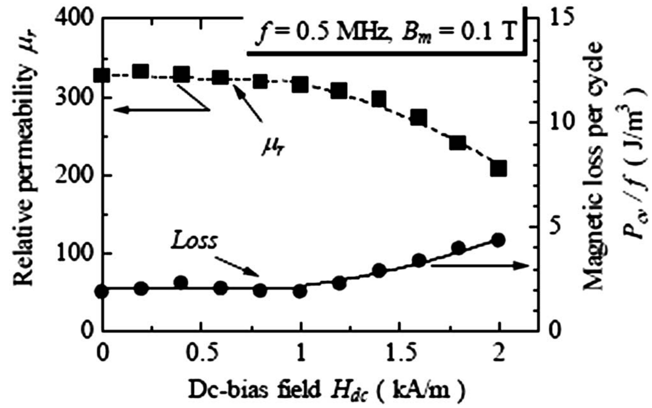


FIG. 5. Dependence of relative permeability $\mu_r$ and magnetic loss per cycle $P_{cv}/f$ on dc-bias field, $H_{dc}$. The measurement was carried out at $f$ =0.5 MHz and $B_m$=0.1 T.

(1) A long ribbon sufficiently nanocrystallized with completely developed anisotropy could be prepared in a short annealing time of approximately 1.4 s with simple equipment.

(2) The prepared core has good magnetic properties up to 2 MHz and keeps its good magnetic properties up to the dc-bias field of $H_A/2$.


[1] H. Fukunaga, H. Tanaka, T. Yanai, M. Nakano, and J. M. Song, J. Magn. Magn. Mater. **254–255**, 519 (2003).
[2] H. Fukunaga, N. Furukawa, H. Tanaka, and M. Nakano, J. Appl. Phys. **87**, 7103 (2000).
[3] L. Kraus, K. Závěta, O. Heczko, P. Duhaj, G. Valsák, and J. Schneider, J. Magn. Magn. Mater. **112**, 275 (1992).
[4] N. Murillo, J. González, J. M. Blanco, and M. Vázquez, J. Appl. Phys. **74**, 3323 (1993).
[5] G. Herzer, IEEE Trans. Magn. **30**, 4800 (1994).
[6] B. Hofmann and H. Kronmüller, Nanostruct. Mater. **6**, 961 (1995).
[7] H. Fukunaga, H. Tanaka, T. Yanai, M. Nakano, K. Takahashi, Y. Yoshizawa, K. Isiyama, and K. Arai, J. Magn. Magn. Mater. **242–245**, 279 (2002).
[8] H. Fukunaga, T. Yanai, H. Tanaka, M. Nakano, K. Takahashi, Y. Yoshizawa, K. Ishiyama, and K. I. Arai, IEEE Trans. Magn. **38**, 3138 (2002).
[9] T. Yanai, M. Yamasaki, K. Takahashi, M. Nakano, Y. Yoshizawa, and H. Fukunaga, IEEE Trans. Magn. **40**, 2721 (2004).
[10] F. Alves, J. B. Desmoulins, D. Hérisson, J. F. Rialland, and F. Costa, J. Magn. Magn. Mater. **215–216**, 387 (2000).
[11] G. Herzer and N.-C. Liu, U.S. Patent 6,645,314, (2003).
[12] T. Yanai, T. Ohya, K. Takahashi, M. Nakano, and H. Fukunaga, J. Magn. Magn. Mater. **290–291**, 1502 (2005).
[13] J. González, N. Murillo, J. M. Blanco, J. M. González, and T. Kulik, J. Appl. Phys. **76**, 1131 (1994).
[14] C. Miguel, A. P. Zhukov, and J. González, Phys. Status Solidi A **194**, 291 (2002).
[15] F. Alves and R. Barrué, J. Magn. Magn. Mater., **254–255**, 155 (2003).
[16] T. Yanai, M. Yamasaki, K. Takahashi, M. Nakano, H. Fukunaga, and Y. Yoshizawa, *Conference Proceedings of SMM 16*, 2004 (unpublished), Vol. 2, pp. 737–741.
[17] T. Yanai, A. Shimada, K. Takahashi, M. Nakano, Y. Yoshizawa, and H. Fukunaga, IEEE Trans. Magn. **42**, 2781 (2006).
[18] K. Twarowski, M. Kuźmiński, A. Ślawska-Waniewska, H. K. Lachowicz, and G. Herzer, J. Magn. Magn. Mater., **140–144**, 449 (1995).
[19] K. Twarowski, M. Kuźmiński, A. Ślawska-Waniewska, H. K. Lachowicz, and G. Herzer, J. Magn. Magn. Mater. **150**, 85 (1995).
[20] L. Kraus, V. Hašlar, O. Heczko, and K. Závěta, J. Magn. Magn. Mater., **157–158**, 151 (1996).
[21] I. Endo, H. Tatsumi, I. Otsuka, H. Yamamoto, A. Shintani, H. Koshimoto, M. Yagi, and K. Murata, IEEE Trans. Magn. **36**, 3421 (2000).