Magnetic Properties of Fe-Based Ribbons and Toroidal Cores Prepared by Continuous Joule Heating Under Tensile Stress

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Nanocrystallized $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbons with controlled permeability were prepared by using continuous stress-annealing by Joule heating (CSA-JH) method. An optimization of the annealing conditions revealed that a completely developed anisotropy perpendicular to the ribbon axis can be obtained stably in the moving velocity range from 1 to 200 cm/min at the current density of 37.5 A/mm^2. In particular, the highest velocity of 200 cm/min achieved the significant reduction in effective annealing time. The core made from the above-mentioned ribbon had good ac-magnetic properties such as constant permeability up to 2 MHz and low magnetic loss compared with those for different types of cores with controlled permeability.

Consequently, it was clarified that the CSA-JH method is one of effective techniques for production of high performance toroidal cores with controlled permeability.

Index Terms—**Continuous stress-annealing, controlled permeability, Joule heating, magnetic toroidal core, nano-crystalline, stress-induced anisotropy.**

I. Introduction

In order to advance the high-density packaging and energy saving of electric devices, size reduction and improvement in efficiency of magnetic cores are strongly required. We, therefore, proposed several kinds of Fe-based toroidal cores with controlled permeability and low loss, and showed that they could be applicable to choke coils [1]–[4].

A choke coil operates under dc-bias field and we need to control its permeability at several hundreds, because it operates under dc-bias field. For preparation of a high performance magnetic core with controlled permeability, we used a uniaxial magnetic anisotropy developed perpendicularly to the ribbon axis by stress-annealing, because the perpendicular anisotropy leads the magnetization rotation mode and reduces magnetic loss. From the viewpoint of improving the controllability of the permeability, we have reported several methods of stress-annealing such as the continuous stress-annealing with a furnace (CSA-F) [5]–[7] and the Joule-heating under tensile stress (JH) [8]-[11]. Although both the methods are hopeful candidates for obtaining a ribbon with controlled permeability, the CSA-F method needs a furnace and the JH method had difficulty in obtaining a long ribbon efficiently.

We, therefore, developed a fabrication method which combines the advantages in each method. This contribution reports the developed method, which was called the continuous stress-annealing by Joule-heating (CSA-JH) method, with the potential for high productivity.

Digital Object Identifier 10.1109/TMAG.2006.880078

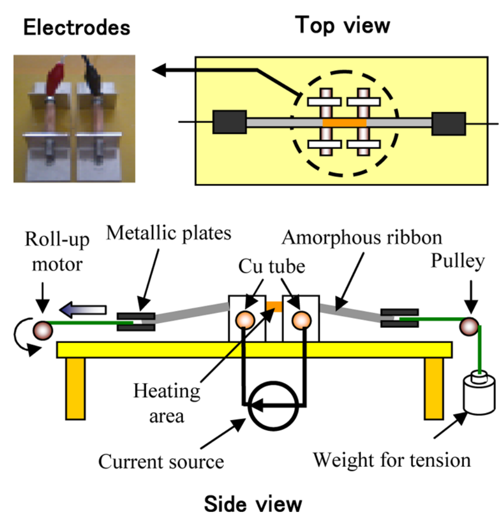

Fig. 1. Schematic representation of apparatus for continuous stress-annealing by Joule heating. (Color version available online at http://ieeexplore.ieee.org.)

II. Experimental Procedure

A. Annealing for Development of Anisotropy

Amorphous ribbons (Hitachi Metals *Ltd.*), 200 or 500 mm in length, 2 mm in width, and 20 μm in thickness, were annealed under tensile stress, σ, from 50 to 175 MPa by the CSA-JH method in air. The apparatus used for the annealing is shown in Fig. 1. Rotatable Cu tubes connected with a dc-current source were used as electrodes, and the ribbon was kept contact with the electrodes under CSA-JH. The supplied current density, j, and the moving velocity, v_m, of the ribbons were varied from 32.5 to 42.5 A/mm^2 and from 1 to 200 cm/min, respectively. Magnetic anisotropy was developed perpendicularly to the ribbon axis through the stress-annealing, which changes the magnetization mode to the rotation mode from the domain wall displacement one [12]–[15]. Details of the origin of anisotropy de-

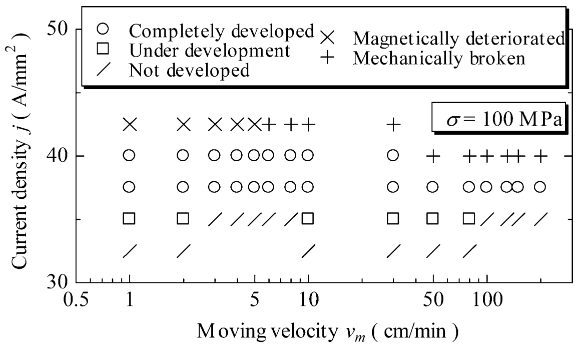

Fig. 2. Relationship among development state of anisotropy, current density, j, and moving velocity, v_m. "◯", "☐", "/", "×", and "+" indicate "completely developed", "under development", "not developed", "magnetically deteriorate", and "mechanically broken during annealing", respectively.

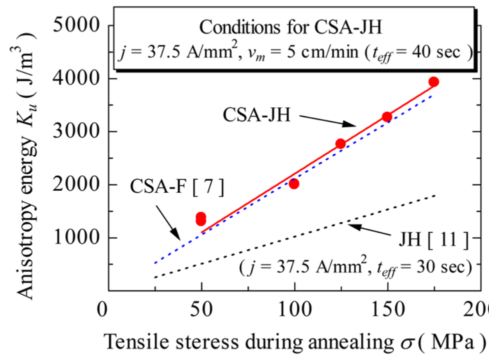

Fig. 3. Anisotropy energy of ribbons prepared by CSA-JH as a function of tensile stress during annealing. The results obtained by CSA-F and JH methods were also shown in the figure [7], [11] (Color version available online at http://ieeexplore.ieee.org.).

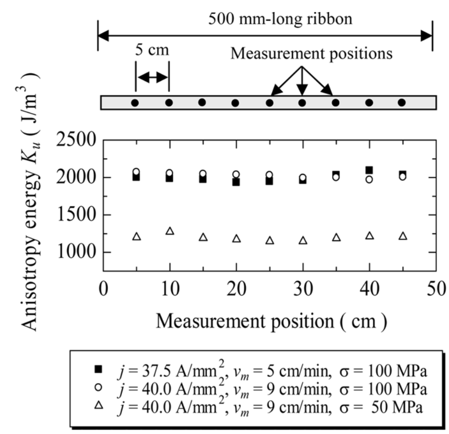

Fig. 4. Distribution of anisotropy energy, K_u, in a 500-mm-long ribbon prepared by CSA-JH method.

veloped by stress-annealing in nanocrystallized Fe-based ribbon were reported by Ohnuma *et al.* [16], [17].

B. Measurements

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

The annealed 500-mm-long 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 evaluated with a B-H analyzer (Iwatsu SY-8232) in the frequency, f, ranging from 0.1 to 2 MHz.

III. Results and Discussions

A. Optimization of Annealing Conditions

In order to determine suitable annealing conditions for CSA-JH method, amorphous ribbons were annealed under various conditions, and then relationship among the development states of anisotropy, j and v_m was evaluated. Fig. 2 shows the results for the development state of anisotropy. The states were categorized into 5 ones based on the shape of hysteresis loops for the annealed ribbons. Symbols, "◯", "☐", "/", "×", and "+", indicate "completely developed", "under development", "not developed", "magnetically deteriorated", and "mechanically broken during annealing", respectively. The completely developed anisotropy could be obtained stably at $v_m = 1 - 200$ cm/min and $j = 37.5$ A/mm^2. The highest moving velocity of 200 cm/min in our equipment corresponds to effective annealing time of approximately 1 sec, and enables us to reduce effective annealing time by 75% compared with that for the CSA-F method [7]. However, a ribbon annealed at high v_m tended to wrinkle mechanically. From the viewpoint of forming the annealed ribbon into a toroidal core, the wrinkles should be improved in the future. In this experiment, we could obtain the ribbons with completely developed anisotropy and good mechanical stability below $v_m = 10$ cm/min.

Fig. 3 shows the dependence of anisotropy energy, K_u, on σ, together with results for the CSA-F [7] and JH [11] methods. The slope of the K_u vs σ curve for the ribbons prepared by CSA-JH method was 2 times as large as that for JH method, indicating that a required σ value can be reduced.

From the above results, we concluded that the CSA-JH method has high productivity compared with those for the CSA-F and JH methods.

B. Distribution of Anisotropy in Annealed Ribbons

In order to apply the long ribbon with controlled permeability to a toroidal core, K_u of 500-mm-long ribbons was evaluated every 50 mm in length. The measurement was carried out using single-sheet tester (SST). The long ribbon inserted into pick-up coil, and then excited at $f = 50$ mHz. Lengths of an exciting coil and pick up one are 50 and 3 cm, respectively. The exciting coil is long enough to guarantee a uniform magnetic field in the pick up coil. An error of the measurement is less than 5%. Fig. 4 shows the measured K_u at each measurement point. The K_u value was almost constant in each point, and we could confirm that the CSA-JH method enables us to fabricate long ribbons with homogeneous anisotropy.

C. AC 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 ($j = 40$ A/mm^2,

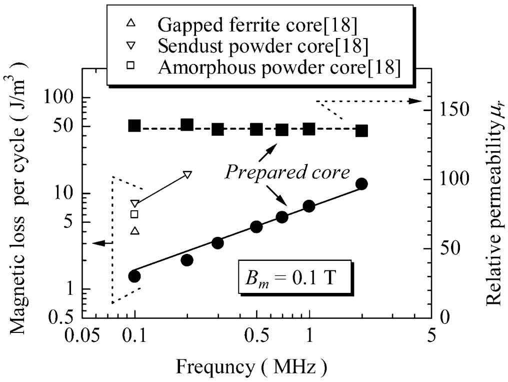

Fig. 5. Relative permeability, μ_r, and magnetic loss of a developed core as a function of frequency, together with those for different types of cores with controlled permeability [18].

$v_m = 9$ cm/min and $\sigma = 100$ MPa), and its ac magnetic properties were evaluated at $B_m = 0.1$ T in the frequency range from 0.1 to 2 MHz.

Fig. 5 shows relative permeability, μ_r, and magnetic loss per cycle of the prepared core as a function of frequency, together with those for conventional cores with controlled permeability [18]. The prepared core had the low value of magnetic loss compared with those for the conventional ones, and also kept the permeability constant up to 2 MHz. These properties were almost the same as those for the previously reported ones [1]–[4].

IV. CONCLUSION

We developed a fabrication method of continuous stress-annealing by Joule-heating (CSA-JH) which combined some productive advantages of the continuous stress-annealing with a furnace (CSA-F) and the Joule-heating (JH) methods for obtaining a magnetic ribbon with controlled permeability. The obtained results are summarized as follows;

1) The CSA-JH method achieved a significant reduction in an effective annealing time compared with that of the CSA-F method.
2) In the CSA-JH method, the magnitude of tensile stress during annealing for obtaining a suitable anisotropy energy value could be reduced compared with the JH method.
3) A toroidal core prepared from the ribbon obtained by the CSA-JH method had constant permeability up to 2 MHz and showed lower magnetic loss than those for different types of cores with controlled permeability.

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