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Fabrication of Fe-based ribbon with controlled permeability by Joule heating under tensile stress

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Abstract

We prepared an Fe-based ribbon with controlled permeability and low magnetic loss by Continuous Stress-Annealing by Joule Heating (CSA-JH) method. The shortest annealing time necessary for the obtaining of the ribbons with completely developed anisotropy was 1 sec, but in order to obtain the sufficiently crystallized ribbons with small saturation magnetostriction it is required to perform annealing longer than 2 sec. A toroidal core was prepared from a long ribbon with controlled permeability and small saturation magnetostriction, and the magnetic loss and relative permeability of the core were evaluated in the frequency range of 0.1 - 3 MHz. The permeability was kept constant up to 2 MHz, and the magnetic loss is lower than that for other types of core with a similar permeability value. These results suggest that the CSA-JH method is a promising method for realizing an Fe-based core with excellent magnetic properties.

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Keywords: Continuous stress-annealing; Stress-induced anisotropy; Joule heating; Controlled permeability; Nanostructure material

1. Introduction

In order to advance high-density-packaging and energy saving of electronic devices, size reduction and improvement in efficiency of magnetic cores are strongly required. Although an Fe-based core prepared from a long ribbon with uniaxial anisotropy developed by stress-annealing [1-4] shows excellent magnetic properties compared with conventional cores with a similar permeability [5-8], the simplification of the annealing process such as reduction in annealing time is required for mass production.

For this purpose, we have proposed the Continuous Stress-Annealing by Joule-Heating method [9, 10]. In this study, the ribbons were prepared by this method focusing on reduction in annealing time and application to toroidal core.

2. Experimental procedure

2.1. Annealing for development of anisotropy

Nanocrystalline Fe-based ribbons with a uniaxial anisotropy perpendicularly to the ribbon-axis were fabricated by Joule-heating amorphous $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ones (Hitachi Metals Ltd., 120 or 500 mm in length, 2 mm in width and 20 μm in thickness) in air under the tensile stress of 100 MPa, referred as the CSA-JH (Continuous Stress-Annealing by Joule Heating) method. The apparatus for the CSA-JH method was described elsewhere [9]. The supplied current density j to the amorphous ribbon was varied from 32.5 to 42.5 A/mm^2. The annealing time t_a was calculated from the distance between electrodes l_e (= 35 mm) and the moving velocity of the ribbon v_m by eq(1).

$$t_a = l_e / v_m. \qquad (1)$$

2.2. Measurements

2.2.1. Hysteresis loop

The dc-hysteresis loop of the annealed ribbon was traced

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with a computer-aided B-H loop tracer (Riken BHS-40, H_m = 4000 A/m, f = 50 mHz). The uniaxial anisotropy energy constant K_u was obtained by numerical integration of $H \bullet \Delta I$ in the first quadrant of the loop.

2.2.2. Estimation of degree of crystallization

For evaluation of the crystallization state in annealed ribbons, thermal analysis was carried out with a differential scanning calorimeter (Seiko Instruments DSC-6200) in Ar flow. The heating rate was fixed at 10 °C /min during an analysis. Figure 1 shows exothermal curves of an amorphous and an annealed ribbon. The exothermic heat peak around 540 °C indicates development of crystallization. The degree of crystallization p was estimated by

$$p = (S_{Amor} - S_{Anneal})/S_{Amor} \times 100, \qquad (2)$$

where S_{Amor} and S_{Anneal} are the area of the heat peaks of the amorphous and the annealed ribbon, respectively. S_{Amor} and S_{Anneal} were obtained by numerical integration of the exothermal curve between 500 and 580 °C.

2.2.3. Elongation

The elongation of the annealed ribbon, $\Delta L/L$, was calculated from

$$\Delta L/L = (L' - L)/L \times 100, \qquad (3)$$

where L and L' are the length of the ribbon before and after stress-annealing, respectively.

2.2.4. Ac-magnetic properties of toroidal core

The annealed 500 mm-long ribbon was formed into a toroidal core with a ceramic bobbin. The relative permeability μ_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 3 MHz.

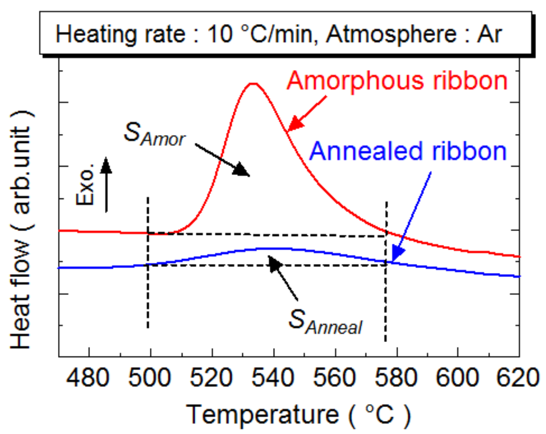

Fig.1 Exothermal curves of amorphous and annealed ribbons. The exothermic heat flow around 540 °C indicates development of crystallization.

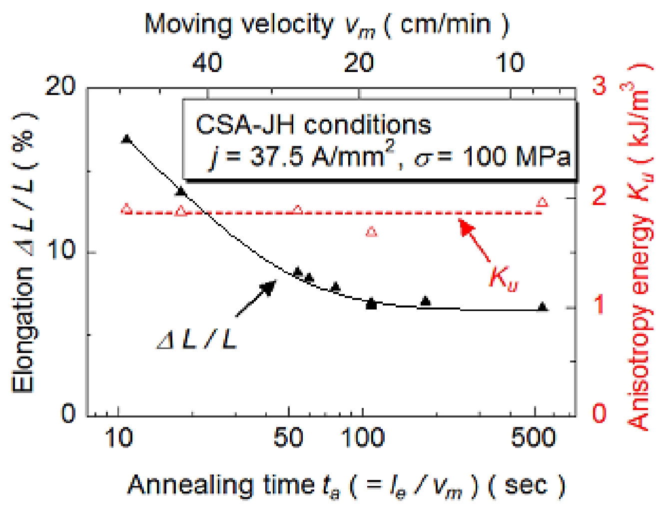

Fig.2 Elongation $\Delta L/L$ and anisotropy energy K_u of annealed ribbons as a function of annealing time t_a.

3. Result and discussion

3.1. Dependence of elongation and of anisotropy energy on annealing time

Figure 2 shows the dependence of elongation $\Delta L/L$ and of anisotropy energy K_u on annealing time t_a. As seen in the figure, K_u did not depend on t_a in the wide range of t_a from 10 to 500 sec. On the other hand, $\Delta L/L$ is large at $t_a \leq 50$ sec. This phenomenon suggests that the large elongation, which is observed at $t_a \leq 50$ sec, did not affect a magnitude of K_u. As a wasteful elongation has a tendency of mechanical break of the ribbon during annealing, we need to pay attention to restrain the wasteful elongation.

3.2. Reduction in annealing time

Figure 3 shows a relationship among the development states of anisotropy, current density j and annealing time t_a, together with the result for JH method [11]. The JH method corresponds v_m = 0 cm/min for the CSA-JH method. The development states of anisotropy were categorized into 5 ones from hysteresis loops of annealed ribbons. Symbols, "○", "Δ", "/", "+", and "×", indicate "completely developed", "under development", "not developed", "magnetically-deteriorated", and "mechanically broken during annealing", respectively. The completely developed anisotropy could be obtained stably in the range of t_a = 1-200 sec at j = 37.5 A/mm^2. In our equipment, the shortest annealing time t_{amin} which enabled the fabrication of a ribbon with completely developed anisotropy, was approximately 1 sec. This value of t_{amin} was almost the same as that for the JH method one (0.5 sec).

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

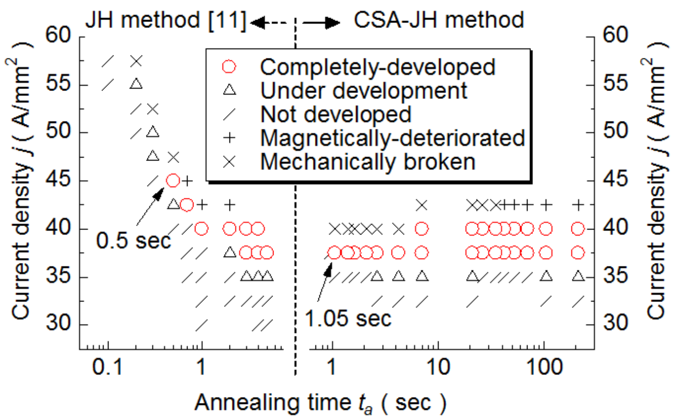

Fig.3 Relationship among development state of anisotropy, current density j and annealing time t_a. "○", "Δ", "/", "+", and "×" indicate "completely developed", "under development", "not developed", "Magnetically-deteriorated", and "mechanically-broken during annealing", respectively.

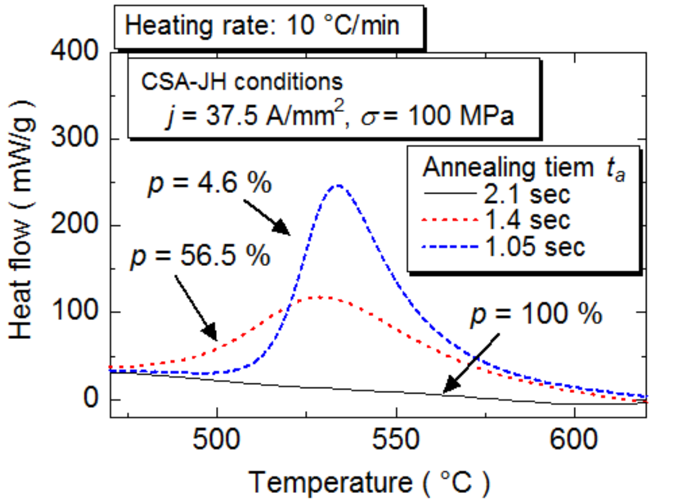

Fig.4 Exothermal curves of ribbons prepared at t_a = 1.05, 1.4 and 2.1 sec. The measurement was carried out in a temperature range from 470 to 620 °C.

of magnetic properties, the annealed ribbon is desired to have a small saturation magnetostriction value. As a magnetostriction in the sufficiently crystallized $Fe_{73.5}Cu_1Nb_3Si_{15.5}B_7$ ribbon is nearly zero [12-14], sufficiently crystallization is important for size reduction of the cores with excellent magnetic properties. Thus, we investigated the crystallization state for the annealed ribbons.

Figure 4 shows exothermal curves of ribbons prepared at t_a = 1.05, 1.4 and 2.1 sec. Although the exothermic heat flow was observed in the ribbons with t_a = 1.4 sec and 1.05 sec, the flow did not happen in the annealed one with t_a = 2.1 sec. This result suggests that the ribbon prepared at $t_a \leq$ 1.4 sec deteriorates their magnetic properties during formation of a toroidal core.

The shortest annealing time which enables us to obtain a ribbon crystallized sufficiently was 2.1 sec in our equipment. This value is 25 % as short as that for Continuous Stress-Annealing with a Furnace (CSA-F) method [15].

3.3. Magnetic properties of toroidal core

As we confirmed that the ribbon prepared under a short annealing time of 2.1 sec was crystallized sufficiently and has anisotropy developed completely, a toroidal core with the inner diameter D_{in} of 15 mm was prepared and its ac magnetic properties were evaluated.

Figure 5 shows the frequency dependencies of relative permeability μ_r (a) and magnetic loss per cycle P_{cv}/f (b) of the prepared core, respectively. Magnetic losses at f = 0.1 MHz for conventional cores with a similar permeability reported by Endo *et al.* [16] are also shown in the figure 5 (b). The prepared core had kept the permeability constant up to 2 MHz and the low value of magnetic loss compared with those for the conventional ones. These properties were almost the same as those for the previously reported ones [5].

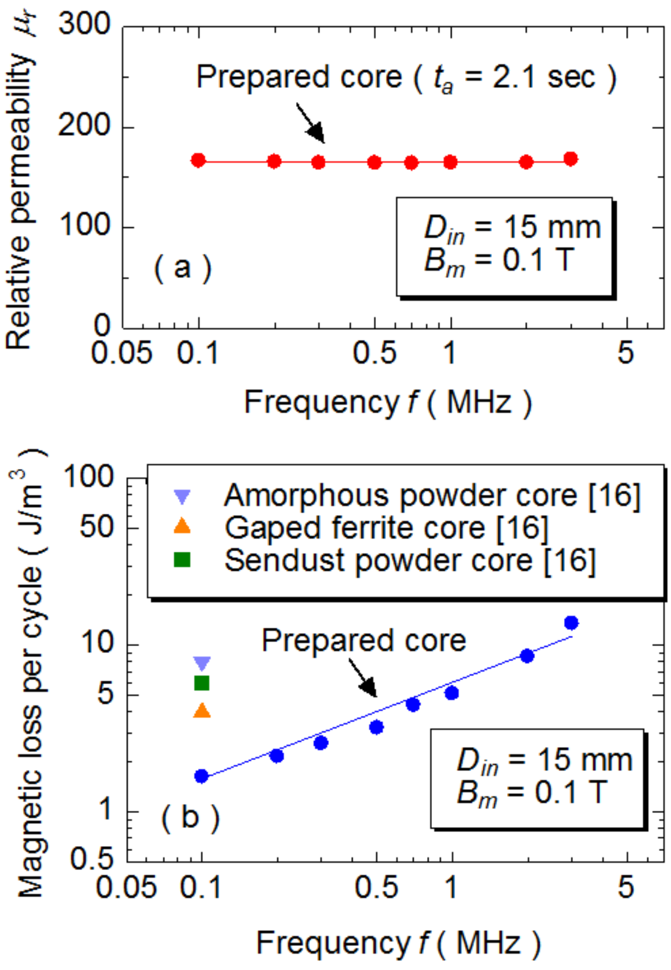

Fig.5 Relative permeability μ_r (a) and magnetic loss per cycle P_{cv}/f (b) of a developed core as a function of frequency. Magnetic losses at f = 0.1 MHz for different types of cores with a similar permeability were shown in the Fig.5 (b) [16].

4. Conclusion

We prepared the Fe-based ribbons sufficiently nanocrystallized with controlled permeability focusing on reduction in annealing time and the application to a toroidal core by the CSA-JH method. The obtained results are summarized as follows;

(1) We achieved a reduction in an annealing time compared with that of the CSA-F method. Resultantly, we can obtain an Fe-based ribbon with completely developed anisotropy and small saturation magnetostriction in a short time of 2.1 sec.
(2) A toroidal core prepared from the long ribbon with small magnetostriction value had constant permeability up to 2 MHz and showed lower magnetic loss than those for different types of cores with a similar permeability.

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