Core losses of ring-shaped \((\text{Fe}_{0.75}\text{B}_{0.20}\text{Si}_{0.05})_{96}\text{Nb}_{4}\) bulk metallic glasses

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Abstract. The soft magnetic properties of ring-shaped \((\text{Fe}_{0.75}\text{B}_{0.20}\text{Si}_{0.05})_{96}\text{Nb}_{4}\) cast bulk metallic glass (BMG) with thickness of 0.3–1.0 mm have been investigated. The BMG specimens exhibit high relative permeability of \((9–29)\times10^3\) at 0.40 A/m and 50 Hz and low coercivity of 4.0 A/m. The core losses of the 0.3 mm thick BMG specimen are lower than those of commercial Fe-6.5 mass% Si steel (6.5Si) with the same thickness, and are comparable to those of the 0.10 mm thick 6.5Si. The low core losses of the BMG originate from the low coercivity and high electrical resistivity.

1. Introduction
The development of new soft materials with lower core losses than that of Si-steels, which are being widely used for power devices, is expected from a viewpoint of energy conservation. It is well known that ordinary Fe-based amorphous alloys exhibit the very low core losses. However, the glass-forming ability (GFA) of the ordinary Fe-based amorphous alloys is low and hence their formation has required extremely high cooling rate, typically \(10^5–10^6\) K/s. Therefore the resultant specimen thickness by an ordinary melt-spinning method has been limited to be less than approximately 50 \(\mu\)m [1].

Since 1995, a new class of Fe-based soft magnetic bulk metallic glasses (BMGs) with a large supercooled liquid region (\(\Delta T_c\)) between the glass transition temperature (\(T_g\)) and the crystallization temperature (\(T_x\)) has been found [2, 3]. The BMGs have high GFA and, therefore, they can be used to prepare bulk amorphous alloys with a thickness of the order of a few millimeters by casting. Furthermore, the soft magnetic properties of Fe-based BMGs are better than those of ordinary amorphous alloys; therefore, these BMGs have wider applications as soft magnetic materials [4–6].

Typical thickness of commercial Si steels is 0.10–0.35 mm. However, the data of soft magnetic properties of the Fe-based BMGs with a thickness comparable to the Si-steels are hardly available. In this study, the soft magnetic properties including the core losses of the \((\text{Fe}_{0.75}\text{B}_{0.20}\text{Si}_{0.05})_{96}\text{Nb}_{4}\) cast BMWG [7] have been investigated.

2. Experimental procedure
The alloy with a nominal composition of \((\text{Fe}_{0.75}\text{B}_{0.20}\text{Si}_{0.05})_{96}\text{Nb}_{4}\) was prepared by arc-melting the mixtures of pure Fe (99.99%), B (99.5%), Si (99.999%), and Nb (99.9%) in an argon atmosphere. The ring-shaped specimens with 10 mm in outer diameter, 6 mm in inner diameter and 1.0 mm in thickness were prepared by copper mold casting in an argon atmosphere. The ring-shaped bulk specimens with 0.30 and 0.50 mm in thickness were prepared by mechanically grinding with emery.
papers. Annealing treatment of the specimens for 600 s at 803 K [8] was carried out with no applied magnetic field in a vacuum by using infrared image furnace. The specimen structures were examined by X-ray diffractometry (XRD) with Cu Kα radiation. The relative permeability (μr), the hysteresis curves and the core loss (Pcm) of the ring-shaped specimens were measured with a vector impedance analyzer, a DC B-H loop tracer under a maximum magnetic field (Hm) of 2.0 kA/m and an AC B-H analyzer, respectively. The saturation magnetization (Js) and the electrical resistivity (ρ) of the annealed melt-spun tapes, prepared by a single-roller melt-spinning apparatus using a part of the same mother alloy, with 1.5 mm in width and approximately 20 μm in thickness were also measured with a magnetic balance under Hm of 0.88 MA/m and a DC four-probe method under a constant DC current density of 0.40 A/mm², respectively. All the measurements were performed at room temperature.

3. Results and discussion

The XRD profiles of the ring-shaped specimen are shown in figure 1. The XRD profile of the as-cast specimen with thickness (t) of 1.0 mm shows an amorphous halo with some superimposed Bragg lines. On the other hand, the profile of the specimen with t = 0.50 mm (both sides of it were removed 0.25 mm each) exhibit a halo pattern. Therefore, the crystalline phases which formed during casting exist only to the vicinity of the surface of the specimens. The 0.30 mm thick specimen also has the fully amorphous structure in an as-cast state and it is maintained after annealing at 803 K.

![Figure 1. X-ray diffraction profiles of ring-shaped bulk specimens.](image)

Table 1. Fundamental properties of (Fe0.75B0.20Si0.05)96Nb4 metallic glass.

| Property                              | Value |
|---------------------------------------|-------|
| Saturation magnetization (T)          | 1.20  |
| Curie temperature (K)                 | 598a  |
| Electrical resistivity (μΩ m)         | 1.45  |
|                                       |       |

a Ref. 7.

The fundamental properties of the (Fe0.75B0.20Si0.05)96Nb4 metallic glass are summarized in table 1. Figure 2 shows the enlarged hysteresis curves (~200 ≤ H ≤ 200 A/m) of the specimens with 0.30 and 1.0 mm in thickness after annealing, respectively. Both the specimens exhibit low coercivity (Hc) of 4.0 A/m. The magnetic flux density of the 0.30 mm thick specimen reaches to 1.18 T at 2.0 kA/m. However, the 1.0 mm thick specimen is not easily magnetized (1.06 T at 2.0 kA/m) because of the magnetic anisotropy induced by the surface crystallization. The frequency (f) dependence of the permeability at Hm of 0.40 A/m after annealing is shown in figure 3. Among the three specimens, the 1.0 mm thick one exhibits lowest permeability. This due to pinning of magnetic domain wall displacements and/or magneto-elastic anisotropy caused by the surface crystallized layers. In the low frequency region below 150 Hz, the real part of the relative permeability (μr') of the 0.30 mm thick
specimen is lower than that of the 0.50 mm thick one because the pinning of magnetic domain wall displacements by surface ruggedness becomes remarkable with decreasing the specimen thickness [9].

![Hysteresis curves](image)

**Figure 2.** Hysteresis curves of 0.30 and 1.0 mm thick specimens after annealing.

![Relative permeability](image)

**Figure 3.** Frequency dependence of relative permeability at 0.40 A/m after annealing.

Figure 4 shows the cycle losses ($P_{cm}/f$) after annealing as a function of the frequency. The classical eddy current loss ($P_e$) for sheets at a frequency $f$ and a maximum magnetic induction $B_m$ are given by [10]

$$P_e = \frac{3 \sin x - \sin x \left(\frac{\pi tf B_m}{6\rho}\right)^2}{x \cosh x - \cos x}$$  \hspace{1cm} (1)

with $x = 2\sqrt{f/f_w}$, where $f_w = 4\rho/\left(\pi \mu_0 \mu_i \tau^2\right)$ is the limiting frequency above which the magnetic field no longer fully penetrates the specimen and $\mu_i$ is the initial permeability. The dashed lines in figure 4 represent the estimated $P_e$. The observed $P_{cm}$ is two times or more as large as $P_e$ due to anomalous eddy current contributions as well as other many soft magnetic materials.
Figure 4. Cycle loss ($P_{cm}/f$) at 0.20 T as a function of frequency ($f$). The dashed lines represent estimated classical eddy current losses.

The core losses at 50 Hz–10 kHz of the 0.30 mm thick specimen after annealing as a function of $B_m$ are shown in figure 5. The data for commercial Fe-6.5 mass% Si steel (6.5Si, $t = 0.10$ and 0.30 mm) are also shown for comparison [11]. In the low frequency region of 50–400 kHz, the BMG with $t = 0.30$ mm exhibits the lower $P_{cm}$ than that of the 6.5Si steel with $t = 0.10$ mm. It should be noted that the low $P_{cm}$ of the BMG is maintained to high $B_m$ up to 0.9 T though the saturation magnetization is only 2/3 times as large as that of the 6.5Si steel. The core loss of the 0.3 mm thick BMG increases more rapidly than that of the 6.5Si steel with increasing frequency, and exceeds that of the 6.5Si steel at 10 kHz. However, the BMG maintains the low loss compared with the 6.5Si steel with the same thickness.

Figure 5. Core loss ($P_{cm}$) at 50 Hz–10 kHz of 0.30 mm thick specimen as a function of maximum induction ($B_m$). The data for commercial Fe-6.5 mass% Si steel ($t = 0.10$ and 0.30 mm) are also shown for comparison [11].
4. Summary
It has been confirmed that the ring-shaped \((\text{Fe}_{0.75}\text{B}_{0.20}\text{Si}_{0.05})_{96}\text{Nb}_{4}\) cast BMG specimens with thickness of \(0.30 \sim 1.0\) mm exhibit the high permeability, the low coercivity and the low core loss. The low core loss of the BMG originates from the low coercivity and the high electrical resistivity. It should be paid attention that the low loss characteristic of the BMG is maintained up to high magnetic induction of approximately \(0.9\) T that is comparable to the commercial Fe-6.5 mass% Si steels. If thin sheets of Fe-B-Si-Nb BMGs are prepared directly, the saturation magnetization could be improved in exchange for decrease in GFA, e.g., decrease in Nb content. Therefore, it can be concluded that the Fe-B-Si-Nb BMGs have potential for development as a core material for power devices.

Acknowledgement
This work was partly supported by Japan Society for the Promotion of Science (JSPS), Grant-in-Aid for Scientific Research (C) (KAKENHI), Nos. 17560585 and 21560690.

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