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Multi-polarly micro rotor prepared from isotropic nanocrystalline films with self-bonding layer

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Abstract. A magnetized micro rotor such as 1.6 mm in outer diameter was prepared from a laminated isotropic nanocrystalline film with an optimized self-bonding layer. A relative density(RD) higher than 85 % in perpendicular direction of the above film could be obtained, and an estimated permeance coefficient, B/μ₀H, exceeded 20 by 3-D finite element method. Furthermore, an enhancement of magnetic torque and relative torque constant, dT/dH-gradient, of the above-mentioned sample with the single pole pair could be achieved. Consequently, it was found that use of laminated isotropic film with optimized self-bonding layer is effective in obtaining a multi-polarly magnetized micro rotor with highly dense torque compared with those of a bonded magnet prepared from consolidated flake with the same materials.

1. Introduction

The film magnets with the thickness range between 10 - 300 microns are indispensable for advancing a size reduction in millisize-motors and micro-actuators [1]. In particular, further improvement in the rotating torque of the above motor and actuator is required for practical applications. We have already investigated laminated films such as Fe₃B/Nd₂Fe₁₄B nanocomposite material [2] with double pole-pairs for highly dense torque compared with that of conventional anisotropic bulk magnet with single pole-pair [3].

In this contribution, an enhancement in the torque for a multi-polarly micro cylindrical magnet rotor was achieved by using isotropic nanocrystalline films with an optimized self-bonding layer. An approximately 45 µm-thick and 2 mm-width isotropic nanocrystalline film with self-bonding layer was used as a starting material. A relative density, RD, in perpendicular direction of the above film exceeded 85 %, and the estimated value of permeance coefficient, B/μ₀H, showed higher than 20 by using a 3-D finite element. Namely, the magnetic torque and relative torque constant, dT/dH-gradient, of the obtained sample could be improved compared with that of a conventional bonded magnet rotor. The superior magnetic torque of the obtained rotor is attributed to a use of the shape-magnetic-anisotropy in the plane together with the improvement of relative density into perpendicular direction. Consequently, the usage of isotropic nanocrystalline films with optimized self-bonding layer is expected to be suitable to multi-polarly magnetized micro rotor for highly dense torque millisize-motors and micro-actuators.
2. Experimental procedure

2.1. Preparation processes
In the section, the detailed preparation processes of a nanocrystalline film, a laminated film and a bonded magnet, respectively, were described (see Fig.1).

Nd_{4.5}Fe_{80}Co_{5}B_{12.5}Cr_{3} molten alloy was melt spun into an amorphous ribbon with approximately 45 μm in thickness and 2 mm in average width using a Cu wheel in Ar atmosphere at the pressure of 10 kPa. In the melt-spinning process, the ejection pressure of 50 kPa by Ar gas, the orifice of 0.7 mm in the quartz crucible, and the wheel speed of 30 m/s, respectively, were used. The amorphous ribbons were cut to 50 mm or less in length and were crystallized at the elevated temperature of 680 °C for 10 min with heating rate of 200 °C/min under the vacuum pressure of 10^{-2} Pa. After cooling them to room temperature, the Cr-Co-doped Fe_{3}B/Nd_{2}Fe_{14}B nanocrystalline films were coated with approximately 5 µm-thick or less self-bonding layers including amino active hydrogen in macromolecule chain and blocked-isocyanate as seen in Fig.2.

Figure 1, further, shows a laminated film fabricated from the above-mentioned films. Each film was pierced into a hollow disc shape under a pressure up to 50 kN. The intended dimensions are 1.6 mm in outer diameter and 0.7 mm in inner diameter. In addition, the laminated film was prepared into several specific lengths such as approximately 1.0 - 1.5 in L/D ratio (L: length, D: diameter) in the punching. Namely, the laminated film was solidified under a pressure of 50 MPa at the temperature of 180 °C for 5 min. In the cross-linking to obtain a rigid laminated film, the blocked-isocyanate dissociated at elevated temperature. Subsequently, the generated isolation isocyanate reacted to amino active hydrogen in the macromolecule chain including in a self-bonding layer (See Fig.2). The laminated film was magnetized to an in-plane direction under the pulsed magnetic field of 4.8 MA/m.

We also prepared a bonded magnet by using the above-mentioned nanocrystalline film. The particle size of the compound was adjusted to 350 μm or less by crushing and sieving-classification. The obtained compound was compacted into specific shape with 1.6 mm in outer diameter under a pressure of 1000 MPa at 180 °C. Through the compaction, a rigid bonded magnet could be obtained by cross-linking reaction of self-bonding material.

2.2. Evaluations
A magnetization reversal rate and magnetic torque in a different rotating field were measured with a VSM and a magnetic torque meter, respectively, and a permeance coefficient, B/μoH, was estimated by a 3-D finite element model (EFM).
3. Results and Discussion

3.1. Improvement in permeance coefficient, B/μ₀H
The typical magnetic properties of obtained film are 1.1 T in remanence, 330 kA/m in coercivity, 95 kJ/m³ in (BH)ₘₐₓ, respectively.

Figure 3 shows the permeance coefficient, B/μ₀H, of an above-mentioned laminated film with specific shape such as L/D=1.5. The maximum value of B/μ₀H could be obtained as the relative density into perpendicular direction became approximately 90 %. From a outer side view of B/μ₀H distribution, B/μ₀H little by little decreasing with the relative density of the laminated film can be observed (see Fig. 4). The decrease is attributed to the thickness of the self-bonding layer into perpendicular direction of a film seen in Fig.3. These results indicate that the use of a shape-magnetic-anisotropy together with a high relative density into perpendicular direction of approximately 90 % is effective to obtain an isotropic multi-polarly miniaturized rotor with approximately 1.6 mm in outer diameter. Consequently, a relative density into perpendicular direction by using optimized self-bonding layer could exceed 85 % (see Fig.3).

3.2. Magnetic torque
A magnetic torque of an isotropic laminated film for a miniaturized rotor was evaluated.

A relational expression of motor torque is denoted by

\[ T = P_n \times \Phi_a \times I_q + P_n \times (L_d \pm L_0) \times I_d. \]

In the right side of the equation, the clauses 1 and 2 show magnetic and reluctance torques, respectively. Each symbol of \( P_n, \Phi_a, I, \) and \( L \) denote the number of pole pair, interlinkage flux, current, and inductance, respectively. In addition, the subscripts \( q \) and \( d \) show the axis of different direction of magnetic circuit design of a motor. In the generated torque by the interaction between each magnetic field and the obtained magnetized specimens, the reluctance torque does not occur.

The magnetic torque of a magnetized laminated film after magnetization was examined with a magnetic torque meter because the measured magnetic torque was applicable compared with general S-T equipment in the micro rotor with a single pole pair.

Figure 5 shows a magnetic torque curve of a disc shaped film with single pole pair compared with that of an amorphous film with the same alloy composition. The intended dimensions of samples are 1.6 mm in outer-diameter and 45 μm in average thickness, respectively.
As the rotating field range became between 0 and 80 kA/m, good correlation coefficient of a magnetic torque as well as magnetization reversal rate could be observed as shown in Fig.6. These results suggest that the small magnetic torque in the small rotating field for a miniaturized rotor can be evaluated clearly.

Table 1 and Figure 7 show the magnetic torques and dT/dH-gradients, respectively, in laminated films and consolidated flake as a function of L/D ratio. In the laminated films with the single pole pair magnetization to in plane direction, an enhancement in magnetic torque occurs compared with that of a bonded magnet preparing consolidated flake with the same materials and dimensions. It is clarified that a usage of the shape-magnetic-anisotropy to the in-plane and the relative density higher than 85 % into perpendicular direction are effective.

From the above-mentioned results, the values of dT/dH-gradient for a laminated film magnet (L/D=1) could be improved by 121 % compared with that of a bonded magnet. We also considered that the above dT/dH-gradient is corresponding to a torque constant of a micro DC brushless motor. In particular, as their L/D ratio increased, the superior magnetic torque and the dT/dH-gradient of the laminated film due to a use of the shape-magnetic-anisotropy could be achieved.

4. Conclusion

In a miniaturized rotor comprising an isotropic nanocrystalline film with the optimized self-bonding layer, highly dense torque and relative torque constant, dT/dH-gradient, could be achieved by taking advantage of a shape-magnetic-anisotropy and an improved relative density into perpendicular direction.

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