Preparation of ring-shaped composite bonded magnets with continuously controlled anisotropy distribution for internal space

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Abstract. We have already reported an advanced method for producing a radially-anisotropic rare earth composite bonded magnet with continuously controlled direction of anisotropy. The magnet has been applied to an inner rotor as a practical usage. In this study, the outstanding preparation method was adopted into the preparation of a magnet applied for an outer rotor. An optimized condition of extrusion and compaction at an elevated temperature could be obtained. In addition, a low pressure configuration to the ring-shaped magnet from plural preformed magnets was carried out, which had specific distribution of magnetic anisotropy for internal space for a small motor, by using self recoverability based on the viscous deformation without an alignment field. No deterioration of magnetic properties was detected through the process even if those magnets were miniaturized. Resultantly, the $(BH)_{max}$ of a ring-shaped magnet with the continuously controlled direction of magnetic anisotropy attained the value of 186 kJ/m^3, and we obtained sine-wave magnetic anisotropy distribution, even if those magnets were miniaturized.

1. Introduction

Further improvements in performance of small motors are strongly required from the standpoints of environment protection and saving of resources. In order to realize a high efficiency motor, a miniaturized magnet with excellent magnetic properties is indispensable.

This contribution reports an optimized preparation process for an arc-shape magnet with continuously controlled direction of anisotropy by taking advantage of the previously reported technique [1] in order to apply it to an outer rotor. The magnetic properties of the arc-shaped magnets did not degrade through the process. It was also clarified that the direction of anisotropy in the ring-shaped magnets can be controlled continuously under an application of an alignment field with one direction together with a mechanical design of preformed magnets before deformation. Finally, we succeeded in obtaining a 12 pole ring shaped magnet with $(BH)_{max}$ and remanence values of 186 kJ/m^3 and 1.03 T, respectively, and static magnetic field for internal space can be detected.

2. Experimental procedure

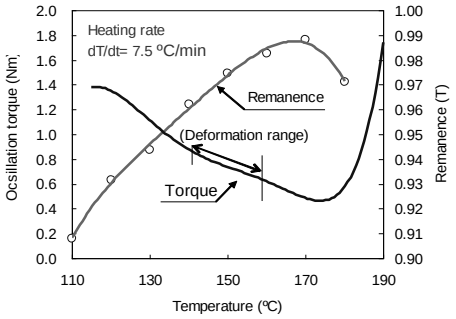

Figure 1. Thermo mechanical behaviour of oscillating torque and remanence of the compound. The oscillating torque was measured by curelast-meter method. The alignment field was 1.4 MA/m.

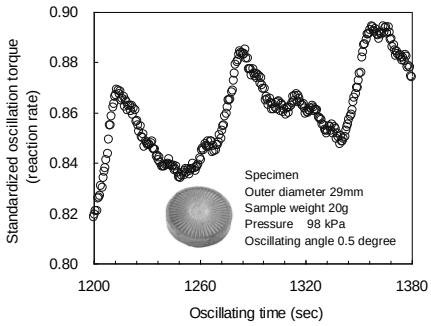

Figure 2. Changes in oscillation torque by self-recoverability during cross-linking reaction. The oscillating angle and temperature were ±0.5º and 170 ºC, respectively.

Detailed preparation process of the magnets is as follows. We utilized RD (Reduction and diffusion) -Sm-Fe-N [2] (1.29 T of remanence, 0.82 MA/m of coercivity) and HDDR (Hydrogenation, Disproportionation, Desorption, and Recombination) -Nd-Fe-B [3] (1.34 T of remanence, 0.98 MA/m of coercivity) powders as starting materials and coated them with solid epoxy-oligomer. Then, they were mixed with poly-amide, and slip-agent. The particle size of the granular compound was adjusted to 500 μm or less by crushing and sieving-classification.

The obtained compound with the weight of approximately 150 mg was compacted into an arc-segment type preformed magnet with 1.1 mm in thickness under a pressure of 50 MPa at 160 °C. During the compaction, the magnetic powders in the compound were aligned to one direction by applying a magnetic field of 1.4 MA/m. As shown in Fig. 1, the remanence and torque showed the opposite tendency with increasing the compacting temperature in the temperature ranging from 120 to 160 °C, and the remanence value showed approximately 0.98 T at 160 °C. The majority of macromolecular-chains were not in the gelation state. Subsequently, the above preformed magnets were extruded and compressed into ring-shaped magnets at 140-160 ºC by using rheology based on the viscous deformation of the macromolecular-chains without an alignment field. The values of torque for the arc-shaped and ring-shaped magnets were almost the same between 140 and 160 °C. (see Fig. 1) The direction of anisotropy for the ring-shaped magnet could be controlled continuously, and the anisotropic phenomenon agreed with the result obtained in previous reports [4]. Namely, H_θ, which is the specific aligned angles to tangential direction, is almost equal to the direction of anisotropy, M_θ, which is the angle between the direction of the easy magnetization and the tangent of the magnet. In the final step of the preparation process, cross-linking reaction of binder was carried out through the heating process at 170 ºC for 20 min in air. Figure 2 shows the changes in oscillation torque by a self-recoverability of the magnet during cross-linking reaction at 170 ºC. The rigid ring-shaped magnet could be prepared from preformed magnets including their fractured surface by using self-recoverable phenomenon.

The prepared magnets were magnetized under a pulsed field of 2.4 MA/m. The rheology, magnetic properties, and distribution of anisotropy direction were evaluated, respectively.

3. Results and discussion

3.1 Rheology

Figure 3 (a) shows a SEM micrograph of the fractured surface of a preformed magnet, together with the fraction of Nd-Fe-B particles and matrix in the magnet. The particles were distributed separately by the matrix including Sm-Fe-N fine powder, suggesting that the Nd-Fe-B particles were consolidated together with the Sm-Fe-N ones in a good hybridization. In addition, the molten state of

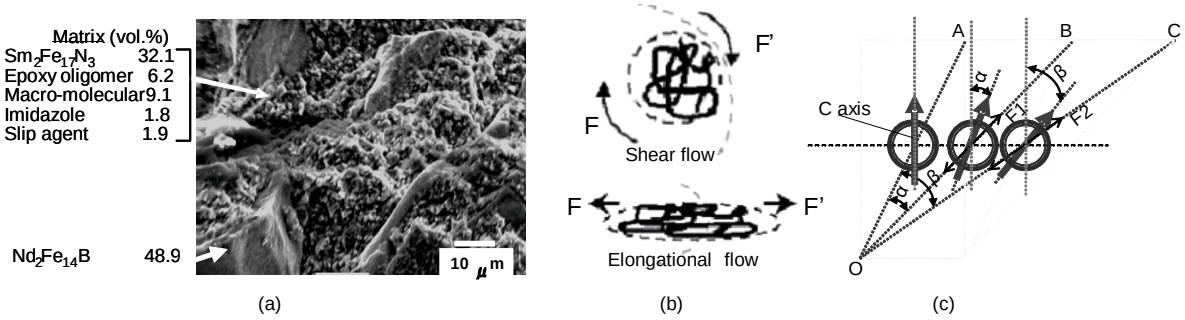

Figure 3. (a) SEM micrograph of fractured surface of the preformed magnet prepared from granular compound. (b) Schematic representation of two kinds of flow pattern for macromolecular-chain in the matrix during viscous deformation at elevated temperature. The symbols of F and F' denote the direction of the force during deformation. (c) Mechanism of the controlled anisotropy directions.

macromolecular-chain in the matrix has flow patterns such as a shear-flow and an elongational-flow during viscous deformation as shown in Fig.3 (b). When diagonal *OA* moves to *OB* and *OC* in order to transform by the shear-flow, a magnet powder which exists in the diagonal rotates with corresponded tension *F1* and *F2* as shown in Fig. 3 (c). Thus, the angle change of c-axis according to the rotation of magnet powders is almost proportional to diagonal angle-α and angle-β corresponding to viscous deformation by the shear-flow. On the other hand, when the deformation occurred by the elongational-flow, a magnet powder does not rotate, as well as c-axis direction does not change.

The direction of the magnetic anisotropy, therefore, can be continuously controlled by mechanically controlling the rotation of magnet powders in a preformed magnet by using the both of shear-flow and elongational-flow during the viscous deformation.

3.2 Magnetic properties

We investigated the magnetic properties and the direction distribution of magnetic anisotropy for the prepared ring-shaped magnet. (see Fig.4) In order to evaluate magnetic properties with a B-H tracer, cubic specimens with 7 mm in size were fabricated by using the same process for the ring-shaped magnet. Typical magnetic properties of the cubic magnets are shown in Fig. 5. Demagnetization and B-H curves of an isotropic magnet are also displayed. We could obtain a sample with 186 kJ/m^3 in $(BH)_{max}$, 1.03 T in remanence, 0.88 MA/m in coercivity, and 6.2 g/cm^3 in density, respectively.

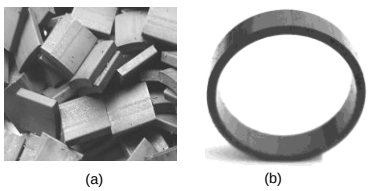

Figure 4. (a) External view of preformed magnets. The weight of a preformed magnet was approximately 150 mg. (b) A multi-polarly magnet for an outer magnet rotor.

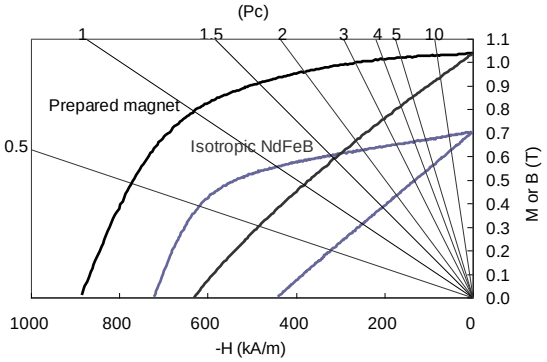

Figure 5. Demagnetization and B-H curves of a prepared magnet measured with a DC-BH tracer, together with those of an isotropic Nd-Fe-B bonded magnet. The maximum field H_m is 2.4 MA/m.

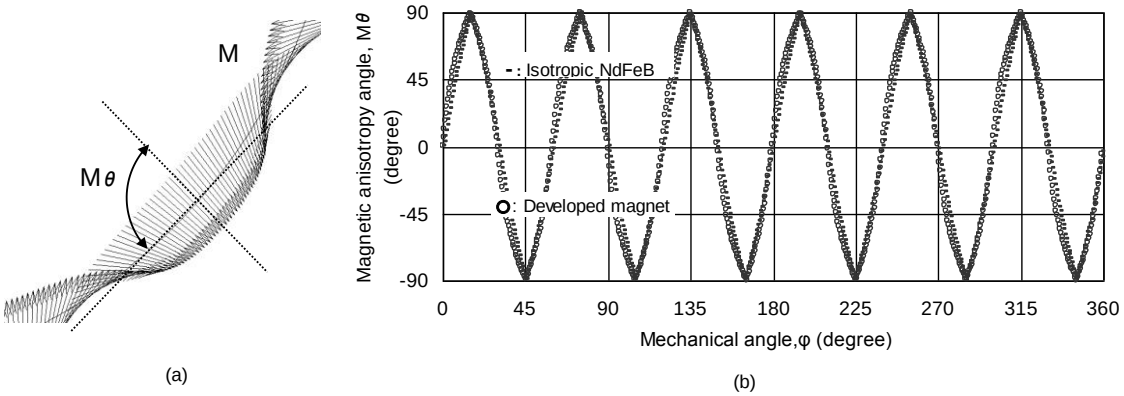

Figure 6. (a) An arrow indicates a direction of a magnetic vector, M, of a prepared magnet, and distribution of magnetization vector in an inner space, (b) A sine-wave of a ring-shaped magnet outer rotor together with that for an isotropic Nd-Fe-B bonded magnet rotor with the same dimension. The outer diameter, thickness, and density of a magnet are approximately 19 mm, 1.1 mm, and 6.1 g/cm^3, respectively. The magnetic vectors, M, denote every 0.5 degrees in the mechanical angle φ and M_θ denotes the specific anisotropy angles to tangential direction.

3.3 Magnetic anisotropy distribution of a prepared rotor

We, further, evaluated the controllability of the direction of anisotropy for an outer magnet rotor with an iron frame.

Figure 6 shows the magnetizing vector distribution of a prepared magnet. As a result, an anisotropy distribution for sine-wave of a prepared magnet is better than that of an isotropic Nd-Fe-B magnet with the same dimension, and a flux value could be improved by 140 %, which suggests that the developed method is effective to prepare outer small rotors. We, further, indicated that the direction of anisotropy can be controlled continuously by using a fixed alignment field together with a mechanical design of the preformed magnets, and their self-recoverability.

4. Conclusion

We have developed a new technique which enables us to prepare a highly dense radially-anisotropic composite bonded magnet with 186 kJ/m^3 in $(BH)_{max}$ as well as to control continuous anisotropy directions by using self-recoverability. In order to investigate the characteristics for the above-mentioned magnet rotor, we evaluated a magnetic anisotropy distribution together with a flux value. Resultantly, the anisotropy of the developed rotor has a sine-wave distribution which is similar to a sine-wave for a magnetized isotropic Nd-Fe-B one with 80 kJ/m^3 in $(BH)_{max}$. The flux value of the obtained rotor with the sine-wave magnetic anisotropy distribution was improved by 140 % compared with that of a conventional isotropic Nd-Fe-B one with the same dimension.

Acknowledgement

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