Prediction method of inhomogeneous thermal flux loss in a magnet

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Thermal flux loss (FL) is one of the important properties in applications of Nd–Fe–B magnets to electrical and electronic devices. FL is expected to occur inhomogeneously in magnets with a complex shape, because it depends on the strength of the local demagnetizing field. Thus, in terms of their applications, we need to predict the inhomogeneous FL from basic magnetic properties measured for a magnet with a simple shape such as a sphere. In this contribution, we propose a method of predicting inhomogeneous initial flux loss, FL_{int}, in a magnet with a complex shape, and compare the predicted values of FL_{int} with the measured ones for a model magnet. Consequently, the predicted and measured distributions agreed with each other. This result suggests that the proposed method can be applied to the prediction of FL_{int} in magnets with a complicated shape used in electrical and electronic devices. [DOI: 10.1063/1.2173961]

I. INTRODUCTION

Nd–Fe–B magnets have high remanence and coercivity at room temperature, and have been applied to the electrical and electronic devices such as motors. In such applications, a Nd–Fe–B magnet is exposed to an elevated temperature, which causes a reduction of its magnetization. Thus, the flux generated by the magnet is also decreased. This phenomenon is called flux loss (FL). FL is categorized into three types, the permanent, initial, and long-term flux losses. The three types of FL originate from metallurgical change, decrease in coercivity, and magnetic aftereffect at an elevated temperature, respectively.[1] Generally, the initial flux loss FL_{int} is particularly significant, because it indicates a large reduction of flux in a short time.

As the Curie temperature of $Nd_2Fe_{14}B$, 312 °C,[2] is much lower than those of $SmCo_5$ and Sm_2Co_{17} (727 and 920 °C, respectively),[3] Nd–Fe–B magnets have a tendency of exhibiting a large FL value when they are exposed to an elevated temperature. Thus, an evaluation of FL has increased in importance significantly in many applications such as motors used in vehicles.

In many cases, the FL of a magnet has been evaluated for a magnet with a simple shape.[4] In applications of a magnet to devices, however, a magnet is processed to a complex shape such as a block, a segment, or a ring. Therefore, it was difficult to predict FL of a magnet used in a real device and to evaluate deterioration of the characteristics of the device, and it is necessary to develop a prediction method of FL in a magnet with a complex shape from its basic magnetic properties.

Previously, a method of predicting FL was proposed by some researchers.[5,6] In that method, however, it is necessary to measure FL for magnets with a simple shape and various permeance, and to obtain the FL vs Δ curve, where Δ is the difference between coercivity and the demagnetizing field. In addition, the theoretical background of this method is not clear.

In this contribution, we propose a method of predicting FL_{int}, which occurs in a short time by exposure to an elevated temperature. The proposed method is based on physical consideration of FL process, and enables us to predict FL_{int} from the demagnetizing curves at room and elevated temperatures by taking advantage of the finite element analysis. We predicted the distribution of FL_{int} in a cylindrical model magnet by the proposed method, and compared it with that obtained experimentally. Consequently, the predicted and measured distributions of FL_{int} agreed with each other, which suggests that the proposed method can be applied to the prediction of FL_{int} in a magnet with a complex shape used in electrical and electronic devices.

II. CALCULATION METHOD

Figure 1 shows the distribution of the direction of the magnetization in an isotropic magnet schematically. The hexagons in the figure indicate grains. The directions of the magnetization at room temperature are assumed as shown in Fig. 1(a), tentatively. When a magnet is exposed to an elevated temperature T_{ex}, the coercivity decreases in magnitude and the magnetization reversal occurs in a part of the magnet, as shown in Fig. 1(b). Thus, the magnetization of the magnet decreases from $I_w(T_{rt})$ to $I_w(T_{ex})$. When the temperature is decreased to T_{rt} again, the magnetization increases to

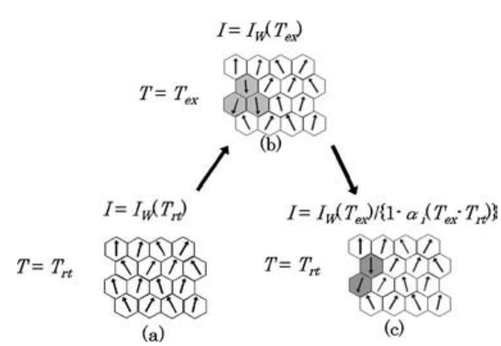

FIG. 1. Schematic representation of flux loss due to exposure at an elevated temperature.

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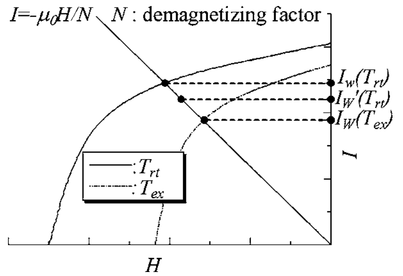

FIG. 2. Demagnetization curves and definition of $I_w(T_{rt})$, $I'_w(T_{rt})$, and $I_w(T_{ex})$. $I'_w(T_{rt})$ is the magnetization at room temperature after an exposure at T_{ex}.

$I_w(T_{ex})/[1-\alpha(T_{ex}-T_{rt})]$, where α is the temperature coefficient of the remanence. This value of the magnetization is, however, smaller than $I_w(T_{rt})$, because a part of the magnetization reversed at T_{ex} does not return to the original direction as shown in Fig. 1(c). Resultantly, the magnetization of the magnet decreases on the work line as shown in Fig. 2, where the magnetization at room temperature after the exposure is shown by $I'_w(T_{rt})$.

When the exposure time is short and the magnetic aftereffect can be disregarded, the flux loss, FL_{int}, which is called the initial flux loss, is given[4] as

$$(FL)_{int} = 1 - I_w(T_{ex})/\{I_W(T_{rt})[1-\alpha(T_{ex}-T_{rt})]\}, \qquad (1)$$

where $I_w(T_{rt})$ and $I_w(T_{ex})$ are the magnetization values at the operating points at room temperature T_{rt} and an exposure temperature T_{ex}, respectively, and α is the temperature coefficient of the remanence. In general, $I_w(T_{rt})$ and $I_w(T_{ex})$ distribute in a magnet, because the demagnetizing field is not constant in a magnet, and the operating point depends on the demagnetizing field.

In order to calculate the spatial distribution of FL_{int}, we divided the model magnet into small elements, and $I_w(T_{rt})$ and $I_w(T_{ex})$ values in each element were calculated by the finite element method (FEM). The calculation of magnetization in a magnet by FEM is a well-established technique, and we used a commercially available FEM program (ANSYS). In the analysis, we carried out the axially symmetric three-dimensional analysis with consideration to the demagnetizing curves of the model magnet. The utilization of the axially symmetric analysis reduces the number of elements drastically.

The FEM analysis gives us the flux density and magnetic field in each element at a temperature T. As no external field is applied to the model magnet, we can determine the local demagnetization field and the magnetization $I_w(T)$ in each element from the results of FEM. Subsequently, the flux loss in each element was determined from Eq. (1).

III. CALCULATION MODEL

The calculation model assumed in this study is shown in Fig. 3. The model magnet is a resin-bonded magnet with a cylindrical form, 5 mmΦ × 4 mmH, and is assumed to be prepared from the MQP-B powder. For the calculation by FEM, we assumed the vacuum portion (20 mmΦ × 20 mmH) outside the magnet and the infinite boundary elements outside the vacuum portion. The assumption of the infinite boundary elements suppresses the effect of the finite size of the analyzed space.

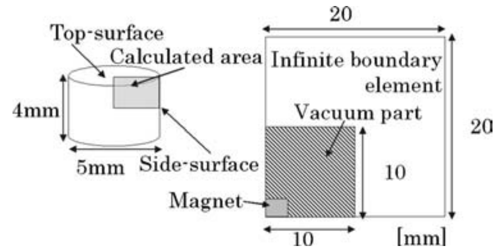

FIG. 3. Calculation model.

Considering the symmetry of the magnet, we analyzed a quarter part of the magnet, and divided the magnet and vacuum portion into 320 and 2551 elements, respectively. The accuracy of the FEM analysis depends on the element size. As our element size for the magnet is 0.125 × 0.125 mm^2, and small enough compared with the magnet size, it was assumed that the FEM result given would be of a sufficiently high technical accuracy.

In the calculation, we need the demagnetization curves and the values of α at elevated and room temperatures. These basic material parameters were determined by measurements for a spherical specimen made from MQP-B powder under the assumption of $N=1/3$, where N is the demagnetizing factor. The demagnetization curves used in this study are shown in Fig. 4.

IV. MEASUREMENT OF FLUX LOSS

We prepared cylindrical magnets with the same dimension as the model magnet from MQP-B powder, magnetized them by a pulse field of 6.4 MA/m, and exposed them for 1 h at 80, 100, and 120 °C. After an exposure, FL_{int} averaged over the whole magnet was evaluated by pulling out the corresponding magnet from a pickup coil. The flux loss at the top surface was also evaluated with Hall equipment.

V. CALCULATION RESULT AND DISCUSSION

Figure 5 shows the distribution of the ratio $I_w(T_{ex})/I_w(T_{rt})$ in the model magnet at 80, 100, and 120 °C. The ratio was calculated by FEM, as explained in Sec. II. The bar at the bottom of the figure indicates the value of $I_w(T_{ex})/I_w(T_{rt})$. It is seen that the value of $I_w(T_{ex})/I_w(T_{rt})$ becomes smaller with increasing T_{ex}. For all the temperatures studied, the value of $I_w(T_{ex})/I_w(T_{rt})$ is small at the center of

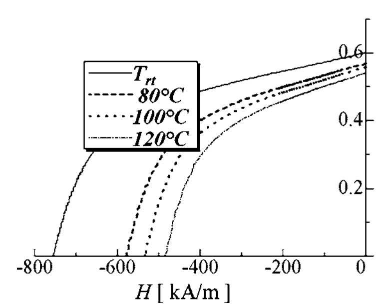

FIG. 4. Demagnetization curves used for calculation.

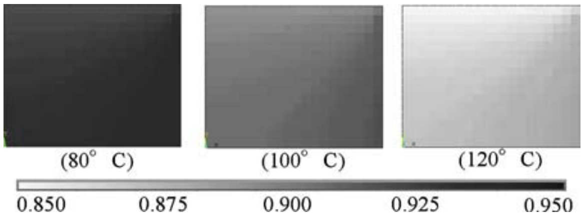

FIG. 5. Calculated distribution of $I_w(T_{ex})/I_w(T_{rt})$ in model magnet.

the top surface, and large at the center of the side surface. This result can be attributed to the distribution of demagnetizing field in the magnet, because $I_w(T)$ is determined from the demagnetization curves and demagnetizing field at a temperature T.

The distributions FL_{int} were determined from Eq. (1) by using the results shown in Fig. 5, and are shown in Fig. 6. It is seen that an increase in temperature results in an increase in FL_{int}. As for the distribution of FL_{int}, a large FL_{int} value was expected at the center of the top surface, although FL_{int} is small at the center of the side surface. This distribution is the reflection of that of $I_w(T_{ex})/I_w(T_{rt})$ shown in Fig. 5. As the values of FL_{int} averaged over the magnet are 1.94%, 2.48%, and 3.82% at 80, 100, and 120 °C, respectively, the differences between the largest and smallest FL_{int} values in the magnet are deduced as 102%, 109%, and 95.5% of the averaged values at 80, 100, and 120 °C, respectively. The calculated large distribution of FL_{int} in magnitude suggests the importance of its prediction in applications of a magnet.

In order to confirm the validity of the proposed method, the FL_{int} values at some points in the magnet were compared with those obtained experimentally. The comparison was carried out for the averaged value and the value at the center of the top surface, the results of which are shown in Fig. 7. In the figure, open and closed symbols show the results for the center of the top surface and the whole magnet, respectively. As seen in the figure, the calculated and measured flux loss values agreed with each other, which suggests that the proposed method can be applied to the prediction of a distribution of FL_{int} in a magnet with a complex shape.

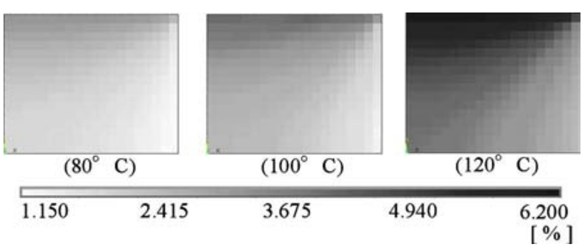

FIG. 6. Calculated distribution of initial flux loss in model magnet.

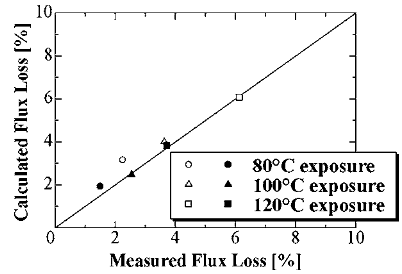

FIG. 7. Comparison of initial flux loss values obtained by experiment and calculation. The open and closed symbols show the results for the center of the top surface and the whole magnet, respectively.

VI. CONCLUSIONS

We proposed a method of predicting a distribution of initial flux loss in a magnet. The proposed method is composed of the finite element analysis and the analytical calculation of the flux loss utilizing the result of the finite element analysis, and enables us to predict the distribution from the demagnetization curves at room and exposed temperatures. We applied this method to a cylindrical magnet and predicted a distribution of initial flux loss. The predicted distribution agreed with the experimental one, which suggests that the proposed method can be applied to prediction of a distribution of initial flux loss in a magnet with a complex shape.

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