Performance Improvement of a 10 kW-class Halbach Array Permanent Magnet Synchronous Motor using NdFeB Laminated Permanent Magnets with Optimal Insulation Structure

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ABSTRACT: Achieving high efficiency and high power density characteristics in automobile traction motors is an important research and development issue. We have investigated the characteristics of a 10 kW-class permanent magnet motor with a Halbach structured permanent magnet rotor using NdFeB laminated magnets. First, we optimized the insulation layer of the NdFeB laminated permanent magnet through experiments and 3D electromagnetic field analysis. Then, we used the laminated permanent magnets with the above-mentioned optimized insulation layer and performed 3D electromagnetic field analysis of the 10 kW-class Halbach motor of which the experimental results have already been reported. The analysis results show that the introduction of NdFeB laminated permanent magnets improves both the efficiency and output of the Halbach permanent magnet motor.

KEY WORDS: eddy current loss, electric vehicle, electromagnetic magnetic field analysis, halbach array, NdFeB laminated permanent magnet, permanent magnet synchronous motor,

1. INTRODUCTION

Automotive drive motors are required to have high power density at start-up and high efficiency while driving, including during acceleration and deceleration. We have been investigating a permanent magnet motor with a Halbach structure to achieve high power density and high efficiency.[(1)] In this study, we investigated the use of laminated permanent magnets in order to further improve the efficiency of the above motor.

2. OPTIMAL INSULATING LAYER STRUCTURE OF LAMINATED NDFEB PERMANENT MAGNET

2.1. Eddy current loss of laminated permanent magnet

NDFEB Corporation is working on laminating NdFeB magnets by means of so-called Hot Press (HP) method, with the aim of applying them to high-speed motors. [(2)] In this method, a temporarily joined laminated body of sintered magnets is pressed at high temperature, making it possible to produce laminated magnets at low cost. The main purpose of laminating NdFeB magnets is to reduce their eddy current loss, which requires optimizing the structure of the insulating layer. It is necessary to increase the thickness of the insulation layer in order to reliably reduce eddy current loss, but on the other hand, a thicker insulation layer leads to a reduction in the total magnetic flux. Therefore, the optimal insulation layer thickness, taking into account the electrical resistivity of the insulation layer, was determined by three-dimensional electromagnetic field analysis.

2.2. Analysis

2.2.1. Method

A 3D electromagnetic field analysis of eddy current loss in a laminated permanent magnet was performed using JMAG-

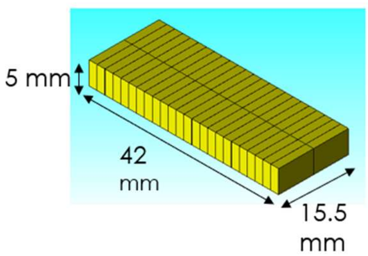


Fig. 1 3D model of laminated NdFeB permanent magnet.

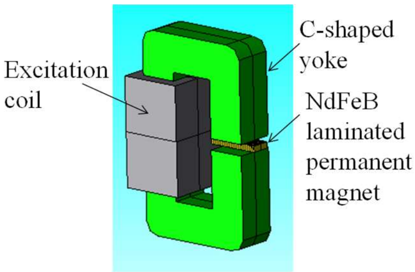
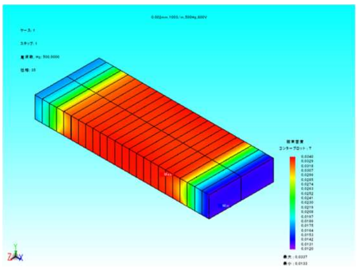
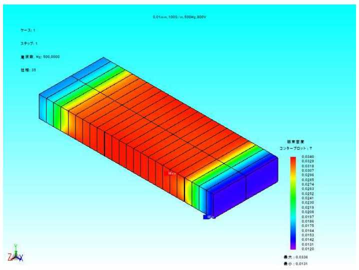


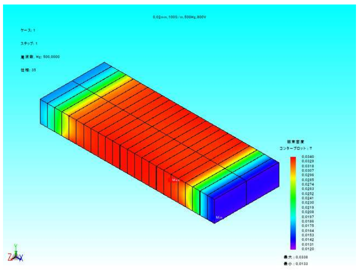
Fig. 2 3D model of overall 3D analysis model.



(a) Insulation layer thickness: 2 μm



(b) Insulation layer thickness: 10 μm

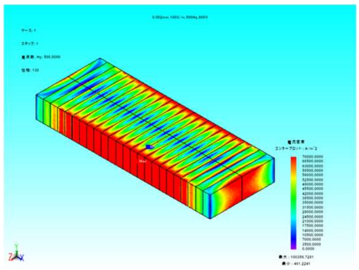


(c) Insulation layer thickness: 20 μm

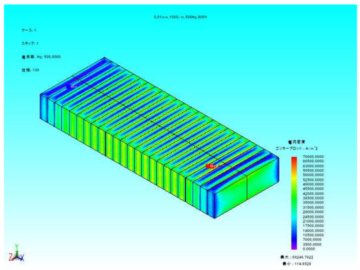
Fig. 3 Analysis results of magnetic flux density contour (f= 500 Hz, $\sigma_{\mathrm{I}} = 1{\times}10^2$ Sm^{-1}).

Designer®. An analytical model was created that faithfully reproduced the experimental setup in order to enable quantitative comparison with the experimental results.

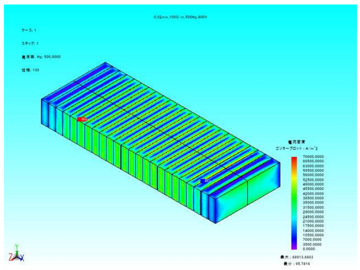
Fig. 1 shows a 3D model of laminated permanent magnet. The electrical conductivity of the permanent magnet (σ_{P}) was set to $7{\times}10^5$ Sm^{-1}. Fig. 2 shows the overall 3D analysis model. The excitation coil was excited by an AC voltage source, and the eddy current loss of the permanent magnet was analyzed. The analysis was performed for different frequencies (f), magnetic field strengths, electrical conductivities of the insulating layer (σ_{I}), and insulating layer thicknesses.



(a) Insulation layer thickness: 2 μm



(b) Insulation layer thickness: 10 μm



(c) Insulation layer thickness: 20 μm

Fig. 4 Analysis results of eddy current density contour (f= 500 Hz, $\sigma_{\mathrm{I}} = 1{\times}10^2$ Sm^{-1}).

2.2.2. Result

Fig. 3 shows analysis results of magnetic flux density contour at f= 500 Hz, $\sigma_{\mathrm{I}} = 1{\times}10^2$ Sm^{-1}. The magnetic flux density contours in the figure do not reveal any differences in the insulation layer thickness. On the other hand, Fig. 4 shows the eddy current density contours corresponding to Fig. 3. As shown in the figure, when the insulation layer thickness is 2 μm (Fig. 4(a)), large eddy currents are induced around the edge of the magnet, which means that the effect of lamination is weakened. Furthermore, when the insulation layer thickness is about 10 μm or more, the eddy currents are localized by the insulation layer, which means that the effect of lamination appears to be apparent (Fig. 4(b) and (c)).

Figure 5 shows the analysis results of the eddy current loss for different insulation layer thicknesses. Since σ_{I} has not been identified, it was used as a variable in the analysis. As shown in the figure, in laminated magnets with an insulation layer thickness of 10 μm or more, the eddy current loss is effectively reduced

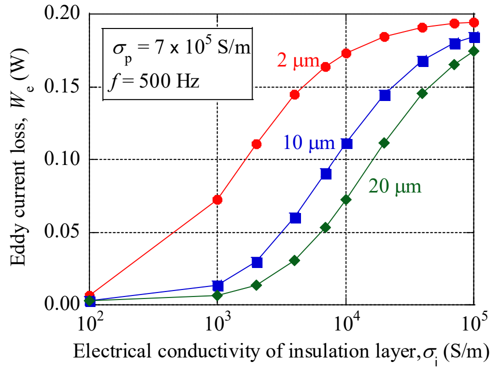


Fig. 5 Typical analysis results of eddy current loss (f= 500 Hz).

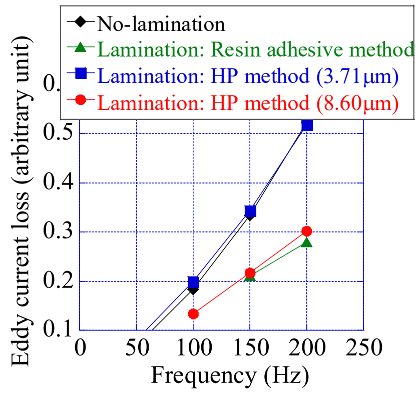


Fig. 7 Experimental results of eddy current loss of NdFeB laminated permanent magnet.

Fig. 6 Photograph of an experimental set-up of eddy current loss of NdFeB laminated permanent magnet.

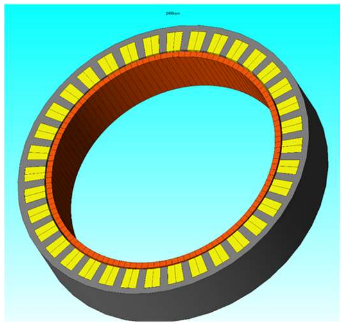


Fig. 8 3D electromagnetic field analysis model of a 10 kW class Halbach motor.

regardless of σ_i. In other words, the optimal insulation layer thickness is thought to be about 10 μm.

2.3. Experimental validation

2.3.1. Method

Fig. 6 shows a photograph of the experimental setup for eddy current loss in laminated permanent magnets. The setup is identical to that shown in Fig. 2.

2.3.2. Result

The measurement results of the eddy current losses in the permanent magnets are shown in Fig. 7. The samples used for the measurement were a non-laminated magnet, a completely insulated resin-impregnated laminated magnet, and two types of laminated magnets produced by the HP method (average thickness of the insulation layer: 3.71 μm, 8.60 μm).

As shown in the figure, the eddy current loss of the thin HP magnet (3.71 μm) has almost the same loss characteristics as a non-laminated magnet, which means that there is almost no effect of laminations. On the other hand, the eddy current loss of the thicker HP magnet (8.60 μm) has the same loss characteristics as a resin-impregnated magnet, in which the eddy current loss is reliably reduced by complete lamination. In other words, a laminated magnet with an insulation layer of this thickness can reduce eddy current loss. The above result is almost consistent with the optimal insulation layer thickness (approximately 10 μm) obtained from the analysis results in Section 2.2.2.

3. ANALYSIS OF A HALBACH MOTOR

3.1. Analysis model and method

Fig. 8 shows a three-dimensional electromagnetic field analysis model of a 10 kW class Halbach motor. Rotational characteristics were analyzed using JMAG-Designer®. In the analysis using the laminated magnet, the insulation layer thickness was set to 20 μm and the electrical conductivity was set to 100 Sm^{-1}.

3.2. Results and discussion

The analysis results of the torque characteristic at a rotation speed of 2400 rpm (f = 800 Hz) are shown in Fig. 9. As shown in the figure, the torque characteristics were improved by laminating the permanent magnets. The exact relationship between magnet lamination and torque increase is currently under investigation, but

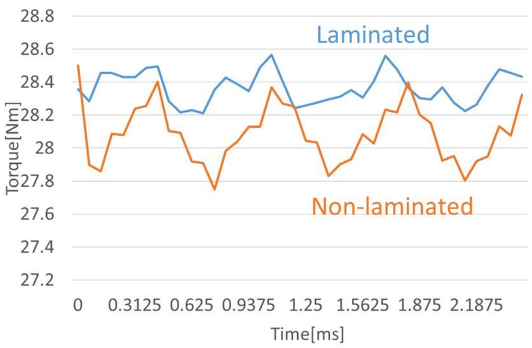


Fig. 9 Analysis results of a toque characteristic in a 10 kW class Halbach motor (rotation speed= 2400 rpm, *f*= 800 Hz).

the reason is believed to lie in the fact that magnet lamination reduces torque ripple and increases average torque.

4. CONCLUSIONS

Based on a three-dimensional electromagnetic field analysis, we investigated the optimal insulation layer thickness of the NdFeB laminated permanent magnet from the viewpoint of eddy current loss and total magnetic flux. We have shown that it should be approximately 10 µm. We also verified the above analytical results by experiment. Furthermore, we performed an analysis of the rotation characteristics of a 10 kW-class Halbach motor using the above laminated magnet, and demonstrated that the characteristics were improved. As a next step, we plan to prototype the above-mentioned Halbach motor and conduct experimental verification.

REFERENCES

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(2) unpublished