Computation of Macroscopic Magnetic Properties of Soft Magnetic Composite Considering Non-uniformity

Y. Ito[1,2], *Member*, *IEEE*, H. Igarashi[1], *Member*, *IEEE*, M. Suzuki[3], Y. Iwazaki[3], K. Kawano[3]

[1]Graduate School of Information Science and Technology, Hokkaido University,
Kita 14, Nishi 9, Kita-ku, 060-0814, Sapporo, Japan, [2]JSPS Research Fellow, [3]Taiyo Yuden Co.
yasuito@em-si.eng.hokudai.ac.jp

It is revealed in this paper that consideration of non-uniformity in the particle size and thickness of the surface insulation layer is essentially important to accurately evaluate the macroscopic permeability of soft magnetic composite (SMC). It is shown that finite element method applied to a real picture image of SMC gives good approximation to its measured value while the homogenization method without considering the non-uniformity has significant errors. Moreover to evaluate the SMC permeability a simple magnetic-circuit method in which the non-uniformity is taken into consideration is proposed.

***Index Terms*—Soft magnetic composite, homogenization, Ollendorff's formula, finite element method, magnetic circuit**

I. Introduction

SOFT MAGNETIC COMPOSITE (SMC) which consists of magnetic particles coated with insulation layer has been used in electric machines and devices such as motors and inductors because of its cost effectiveness, low eddy current loss and flexibility for 3-D modeling. The macroscopic magnetic properties of SMC have been evaluated by using homogenization approaches such as Ollendorff's formula [1], magnetic circuit method [2] and a homogenization method using finite element (FE) analysis [3]. Ollendorff's formula is given by

$$\bar{\mu}_r = 1 + \frac{\eta(\mu_r - 1)}{1 + N(1-\eta)(\mu_r - 1)} \tag{1}$$

where $\bar{\mu}_r$, η, μ_r and N are the macroscopic relative permeability of SMC, volume fraction and relative permeability of magnetic particles, coefficient of demagnetization field. It has been shown that the macroscopic permeability of SMC obtained by the homogenization method based on FE analysis agrees well with those computed by Ollendorff's formula and magnetic circuit if magnetic saturation is negligible. However, it has been shown in [4] that the permeability evaluated by these methods is far smaller than the measured value. To make the evaluated permeability close to the measured value, the volume fraction is assumed to be greater than the actual value in [4]. Let us consider the SMC whose cross-sectional picture is shown in Fig.1. The measured volume fraction is 0.866 and macroscopic relative permeability is 45. If we compute the particle permeability μ_r by substituting these values into (1), the resutant value is negative. Indeed, the macroscopic permeability $\bar{\mu}_r$ evaluated from (1) cannot be greater than 20.4 for any particle permeability.

In this paper, the reason of above discrepancies will be revealed by applying 2-D FE analysis to the actual cross-sectional picture of SMC. It will be shown that the non-uniformity in the particle size and thickness of insulation layer is essentially important to accurately evaluate the macroscopic permeability. Although the real cross-section of SMC is analyzed by FE analysis in [5], importance of non-uniformity is not stressed. Moreover to evaluate the SMC permeability, we propose a simple magnetic-circuit method in which the non-uniformity is taken into consideration.

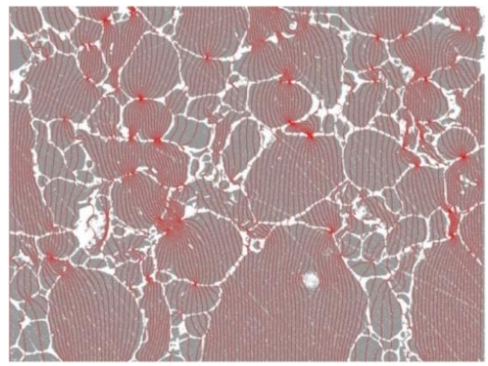

Fig. 1. Cross-sectional picture (70.0 x 52.4μm) of a SMC whose the measured volume fraction is 0.866, the measured macroscopic relative permeability is 45. Red lines are the magnetic fluxes obtained by solving (2).

TABLE I
Comparison with the Macroscopic Relative Permeability of the SMC

Method	Macroscopic relative permeability
Ollendorff (N=1/3)	17
FE analysis	39
Measured	45

II. Finite Element Applied to Real Image

The 2-D FE analysis is applied to the real cross-sectional image of SMC shown in Fig. 1. We analyze the magnetic field without electric current, which is governed by

$$\nabla \times \left(\frac{1}{\mu} \nabla \times \boldsymbol{A} \right) = 0 \tag{2}$$

where μ, $\boldsymbol{A}$ are the permeability and vector potential. The relative permeability μ_r of magnetic particles is assumed to be 100. We assume the Dirichlet and Neumann boundary conditions on the side and top-bottom boundaries of the analysis region, respectively.

The magnetic flux lines obtained by solving (2), shown in Fig. 1, are obviously non-uniform because of highly non-uniform particle sizes and insulation thickness. Moreover there are many nearly contact points through which magnetic fluxes easily penetrate into magnetic particles. Table I compares the macroscopic relative permeability of the SMC calculated by (1) in which non-uniformity is not considered with that obtained in the above-mentioned analysis. From these results, it is concluded that non-uniformity gives significant contribution to the large permeability of SMC.

III. MAGNETIC CIRCUIT CONSIDERING NON-UNIFORMITY

We want to establish a simple method to evaluate the permeability of SMC without analyzing the real picture. To do so, we employ the magnetic circuit method. First, to test validity of this method, we will compare the macroscopic permeability computed by this method without considering non-uniformity with that computed from (1). Then we will introduce non-uniformity into the present method.

We consider a magnetic circuit with lattice structure shown in Fig.2. The magnetic resistance includes those for magnetic particle and insulation layer, that is, $R=R_{mag}+R_{layer}$. The magnetic circuit contains m^2 unit domains as shown in Fig. 2. The Dirichlet and Neumann boundary conditions are imposed on the side and top-bottom boundaries of the magnetic circuit, respectively. From Kirchhoff's first law for magnetic flux Φ, the circuit equations for magnetomotive force F_i can be obtained. By solving the circuit equations, the macroscopic relative permeability of SMC is computed from [2]

$$\bar{\mu}_r = \frac{l\Phi}{\mu_0 S \Delta F} \quad (3)$$

where S and l are the considered area in x-z plane and length of the whole circuit in y direction, and $\Delta F = F_{m^2+1} - F_0$ denotes the magnetomotive force imposed to the magnetic circuit.

To test the validity of the considered magnetic circuit, we compare $\bar{\mu}_r$ obtained from (3) with that calculated by (1) in which N=1/2 is assumed. In the analysis, we assume the following sizes: $d_x=d_y$=30.0μm, $\delta_x=\delta_y$=1.118μm, so that the volume fraction is given by $\eta=d_xd_y/((d_x+2\delta_x)(d_y+2\delta_y))$=0.866. The relative permeability μ_r of magnetic particles is assumed to be 100 and m=100. The magnetic resistances are given by $R_{mag}=d_x/(\mu_r\mu_0 d_y d_z)$, $R_{layer}= \delta_x/(\mu_0 d_y d_z)$, where $d_z=d_x=d_y$. The resultant values of macroscopic relative permeability calculated by (1) and (3) are 12.23, 11.83, which are in good agreement.

Next we consider the non-uniformity in the particle size and thickness of the insulation layer in the present method. To do so we introduce the distributed layer thickness whose probability density function, obeying logarithm normal distribution LN(1.118μm, σ^2), is shown in Fig. 3. To consider the distributed particle size in the magnetic circuit, we introduce the probabilistic number of adjacent particles because the number of adjacent particles depends on the particle size as shown in Fig.1. In actual computation, we

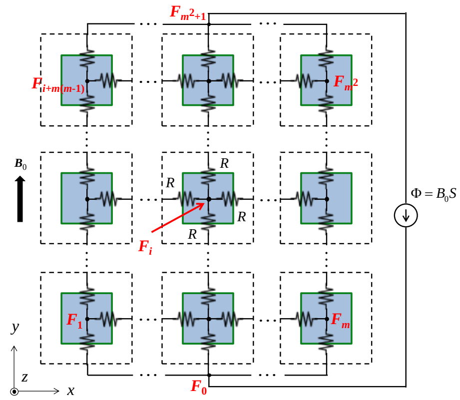

Fig. 2. Magnetic circuit of the m^2 unit domains

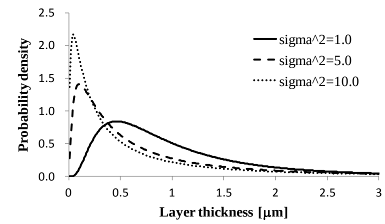

Fig. 3. Distribution of layer thickness

TABLE II
RESULTS COMPUTED BY THE PRESENT METHOD

	Macroscopic relative permeability		
	σ^2=1.0	σ^2=5.0	σ^2=10.0
P_{th}=0.4	18.74	25.08	29.41
P_{th} =0.3	24.65	33.47	39.41
P_{th} =0.2	30.24	41.50	49.03

assume eight neighboring particles for each particle, and connectivity in flux between two neighboring particles are determined by generating uniform random numbers $0 \le P \le 1$ so that the magnetic resistance between the two adjacent particles are infinite if $P<P_{th}$.

Table II shows the results from which it is found that the macroscopic relative permeability obtained by the present method increases with σ^2. Also when P_{th} becomes lower, the macroscopic relative permeability obtained by the present method also increases. In particular, when σ^2 =5.0, 10.0, P_{th}=0.2, the computed results are close to the measured value. In the long version, we will discuss how to determine appropriate values of σ^2 and P_{th}.

IV. REFERENCES

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