Effect of Magnetic Contact on Macroscopic Permeability of Soft Magnetic Composite

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It is revealed that contact of magnetic particles in soft magnetic composite (SMC) significantly increases the macroscopic permeability. It is shown that Ollendorff's formula which assumes homogenous magnetic particles and insulation layers underestimates the macroscopic permeability of SMC. It is suggested that the excess in the permeability is due to the local contacts among the magnetic particles. The effect of the magnetic contact is evaluated using a magnetic circuit model.

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

I. Introduction

Soft magnetic composite (SMC) which consists of magnetic particles coated with thin insulation layer has been used in electric machines and devices such as motors, inductors and transformers because of its cost effectiveness, isotropy of electromagnetic properties, low eddy current loss and flexibility for manufacturing. The macroscopic magnetic properties of SMC have been evaluated using Ollendorff's formula [1], magnetic circuit method [2] and homogenization method based on finite element method (FEM) [3]-[4]. In particular, Ollendorff's formula has been widely used to evaluate the macroscopic magnetic properties of SMC because of its simplicity. It has been shown in [4] that Ollendorff's formula, magnetic circuit method and the homogenization method based on FEM give almost identical values for macroscopic permeability of SMC under the condition that magnetic saturation is negligible. However, it has been shown in [5] that the permeability evaluated by these methods is far smaller than the measured value.

In this paper, we discuss the reason for the above mentioned discrepancies in macroscopic permeability. We evaluate macroscopic permeability by applying 2D FEM to magnetic particles whose image is taken from a picture of SMC. We remark that this approach has been already reported in [6]. It is revealed from this analysis that contacts among the magnetic particles give rise to significant effects on macroscopic permeability. A magnetic circuit model is introduced to evaluate the effect of magnetic contact.

II. Ollendorff's Formula

Offendorff's formula [1] 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, relative permeability of magnetic particles and coefficient of demagnetization field.

As mentioned above, (1) underestimates the measured permeability. To make the evaluated permeability close to the measured value, the volume fraction is assumed to be greater than the actual value in [5]. For example, let us consider SMC whose cross-sectional picture is shown in Fig. 1, where we find non-uniformly sized particles and insulation thickness. The measured volume fraction is 0.866 and macroscopic relative permeability $\bar{\mu}_r$ is 45. If we evaluate the particle permeability μ_r by substituting these values into (1) and assuming that particles are spherical, that is N=1/3, the resultant μ_r becomes *negative*. Indeed, it can be shown that the macroscopic permeability $\bar{\mu}_r$ evaluated from (1) cannot be greater than 20.4 for any particle permeability [5]. It is difficult to consider the non-uniformity in particle sizes and local contacts among them using (1). The inconsistent results might be due to this limitation.

III. Finite Element Applied to Real Image

To take the effect of non-uniformity in particle size and mutual contact into account, FEM is applied to analysis of magnetostatic field in the magnetic particles in Fig. 1. For simplicity, we assume that the relative permeability of the insulation layer is unit. We analyze the magnetic field without electric current, which is governed by

$$\sum_j A_j \int_S \frac{1}{\mu}\left(\frac{\partial N_i}{\partial x}\frac{\partial N_j}{\partial x} + \frac{\partial N_i}{\partial y}\frac{\partial N_j}{\partial y}\right)\mathrm{d}S = 0 \tag{2}$$

where A_j, μ, N_j are the z component of magnetic vector potential at the j-th node, permeability, scalar interpolation

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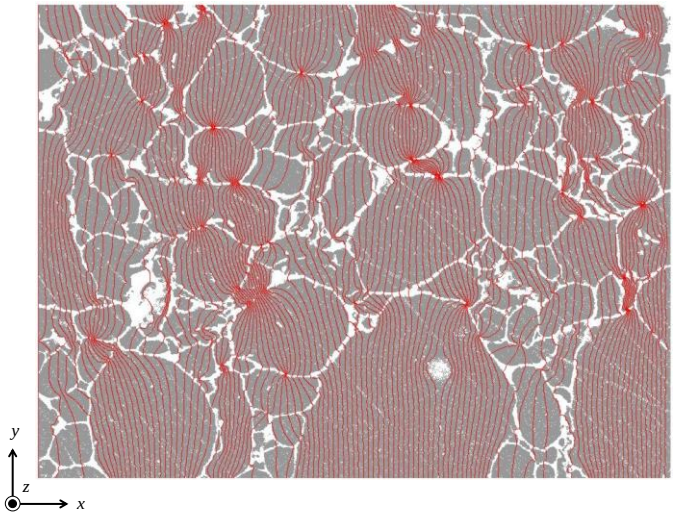


Fig. 1. Cross-sectional picture (70.0 x 52.4μm) of a SMC whose the measured volume fraction is 0.866, the measured macroscopic relative permeability is 45. Red lines are the magnetic fluxes obtained by solving (2).

TABLE I
COMPARISON WITH THE MACROSCOPIC RELATIVE PERMEABILITY OF THE SMC

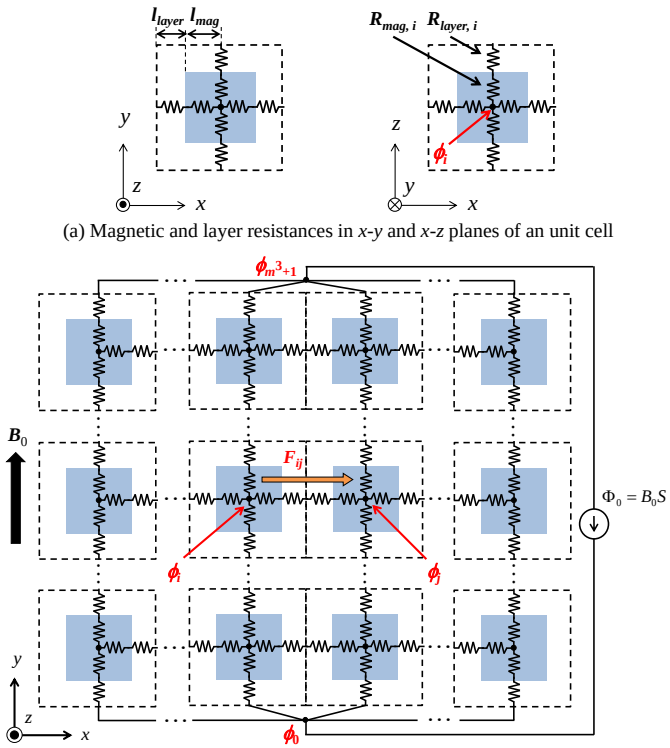
Method	Macroscopic relative permeability
Ollendorff (N=1/3)	17
FE analysis	39
Measured	45

function. The relative permeability μ_r of magnetic particle is assumed to be 100. Assuming a uniform magnetic induction $\boldsymbol{B}_0=B_0\boldsymbol{i}_y$, is applied to SMC, we impose the Dirichlet and Neumann boundary conditions on the both sides and top-bottom boundaries of analysis region in Fig.1, respectively. The image in Fig. 1 is composed of 1280 x 959 pixels, each of which is subdivided into two triangle elements. The whole domain is subdivided into 2,455,040 elements with 1,229,760 nodes so that the thin air gaps and contacts between magnetic particles are expressed with sufficiently fine elements.

The magnetic flux lines obtained by solving (2), shown in Fig. 1, are obviously non-uniform and concentrate on the contact points between neighboring magnetic particles of SMC. Table I compares the measured and computed values of macroscopic relative permeability of SMC. The value in the second row is computed from the magnetic energy [4] resulted from the FE analysis is obviously higher than that obtained from (1). However the result of FEM is still lower than the measured value. This would be due to the fact that three dimensional paths of magnetic flux cannot be considered in the 2D FE analysis [6]. Because it is uneasy to obtain 3D images of SMC, this approach has also limitation.

IV. MAGNETIC CIRCUIT MODEL

We aim to establish a simple method to evaluate the permeability of SMC without analyzing particle models taken from real images. To do so, we employ the magnetic circuit method. Let us consider SMC which consists of m^3 unit cells, where a magnetic particle coated by insulation layer exists,



(a) Magnetic and layer resistances in x-y and x-z planes of an unit cell

(b) Magnetic circuit of SMC in x-y plane

Fig. 2. Definition of magnetic and layer resistances and cross section of 3D magnetic circuit model of SMC.

with periodic configuration as shown in Fig. 2. We assume the brick-shaped particles of the same size for simplicity. The uniform magnetic induction B_0 is applied to SMC in y-direction. Magnetic fluxes Φ_i satisfy

$$\sum_i \Phi_i + \Phi_0 = 0 \tag{3}$$

which is equivalent to div$\boldsymbol{B}$=0, where $\Phi_0=B_0S$, and S denotes the area of a square surface of the cubic-shaped 3D circuit.

We consider magnetic resistance $R_{mag,i}$, $R_{layer,i}$ of particle and insulation layer on each surface in i-th unit cell as shown in Fig. 2(a). Magnetomotive force F_{ij} which is a line integral of magnetic field can be expressed by magnetic scalar potential as follows:

$$F_{ij} = \int_{C_{ij}} \boldsymbol{H}\cdot d\boldsymbol{l} = \phi_i - \phi_j \tag{4}$$

It can also be expressed as

$$F_{ij} = \int_{C_{ij}} \boldsymbol{H}\cdot d\boldsymbol{l} \approx 2\left(\frac{l_{mag}}{\mu_{mag}S} + \frac{l_{layer}}{\mu_{layer}S}\right)\Phi_{ij} \equiv 2R_{ij}\Phi_{ij} \tag{5}$$

where μ_{mag}, μ_{layer} denote the permeability of magnetic particle and insulation layer, and $R_{ij}=R_{mag,i}+R_{layer,i}+R_{layer,j}+R_{mag,i}$. From

(3)-(5), we obtain the circuit equation

$$\sum_{j=1}^{6} \frac{\phi_i - \phi_j}{R_{ij}} + \Phi_0 = 0 \tag{6}$$

which corresponds to Kirchhoff's first law can be derived. By solving (6), the macroscopic relative permeability of SMC is computed from [2]

$$\bar{\mu}_r = \frac{LB_0}{\mu_0(\phi_0 - \phi_{M+1})} \tag{7}$$

where $L=2(l_{mag}+l_{layer})m$, m is the number of unit cells in one direction so that the total number of unit cells is $M=m^3$.

V. Numerical Results

We assume that l_{mag}=3.0μm, l_{layer}=0.147μm, i.e. the volume fraction of SMC is 0.866, μ_{mag}/μ_0=100 and m=100.

A. Uniform layer thickness without contacts

To test the validity of present method, we compare the macroscopic permeability computed by the magnetic circuit with that computed from (1) in which N=1/3 is assumed. In this computation, it is assumed that both particle size and magnetic layer are uniform and there are no magnetic contacts. The resultant values of macroscopic relative permeability calculated by (1) and (7) are 16.85, 16.24, which are in good agreement.

B. Non-uniform layer thickness without contacts

We next consider the influence of non-uniformity in thickness of insulation layer neglecting magnetic contacts. To do so, we introduce the distributed layer thickness whose probability density function obeys the uniform distribution. The volume fraction of a unit cell is kept to 0.866. In the computation, a random number λ obeying uniform distribution satisfying $0 < \lambda < 2l_{layer}$ is generated. Then the thickness of the insulation layers in a unit cell is set to λ and $2l_{layer}-\lambda$. The thickness is determined in this way for six directions. The resistance R_{ij} can be calculated after this process.

When (6) is solved under this condition, the resultant value of macroscopic relative permeability is found to be 17.423, which is far smaller than the measured value. From this result, it is concluded that the non-uniformity in the insulation-layer thickness gives no significant contribution to the macroscopic permeability.

C. Effect of magnetic contact

We consider here the effect of the contact between the magnetic particles. To do so, we introduce the parallel circuits between two neighboring unit cells as shown in Fig. 3. In this analysis, the magnetic resistance between i-th and j-th unit cells is given by

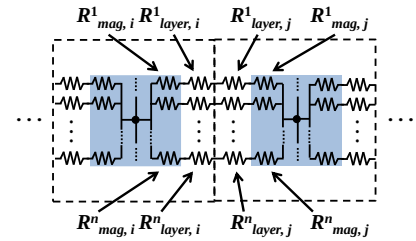


Fig. 3. Parallel circuits of between two neighboring unit cells.

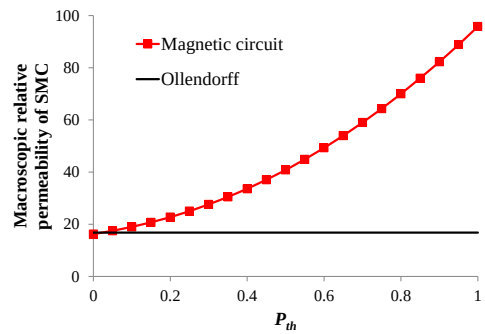
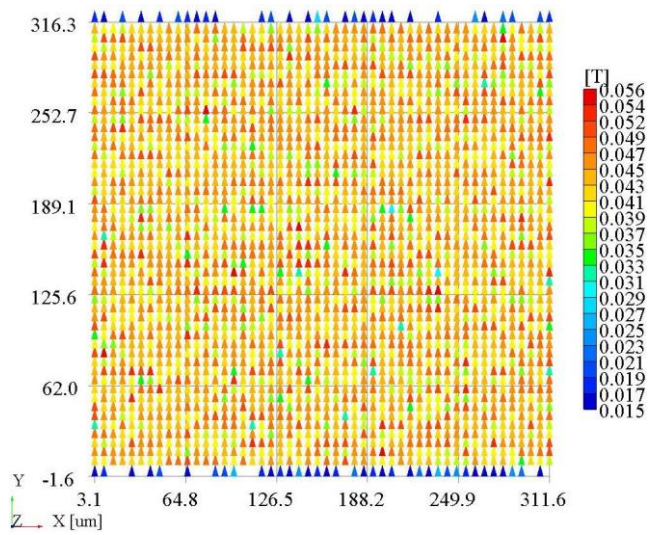
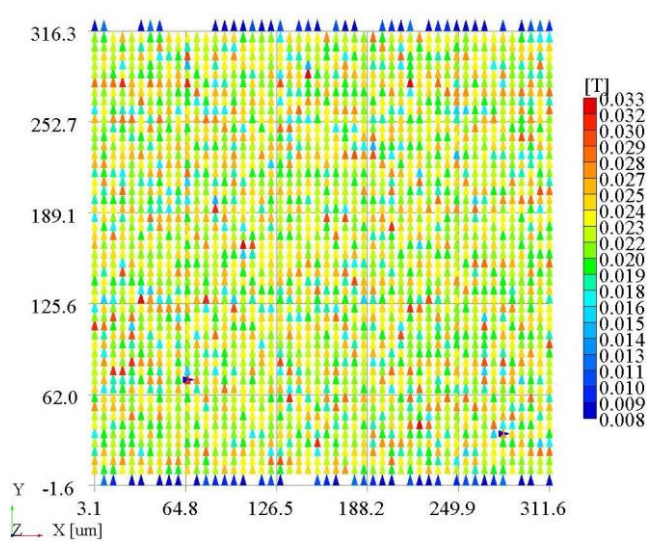


Fig. 4. Macroscopic relative permeability of SMC with n=10 and $0 < P_{th} < 1$.



(a) P_{th}=0.2



(b) P_{th}=0.55

Fig. 5. Magnetic induction on a cross section of magnetic circuit.

$$R_{ij} = \frac{1}{1/R_{ij}^{1} + 1/R_{ij}^{2} + \cdots + 1/R_{ij}^{n}} \tag{8}$$

where $R_{ij}^{k} = R_{mag,i}^{k} + R_{layer,i}^{k} + R_{layer,j}^{k} + R_{mag,j}^{k}$, $1 \le k \le n$. In the computation, a random number P which obeys the uniform distribution satisfying $0 < P < 1$ is generated for $R_{layer,i}^{k}$, $1 \le i \le m^3$. Then the particles are judged to have magnetic contacts if P is smaller than a threshold, that is, $R_{layer,i}^{k}$ =0 if $P < P_{th}$.

Fig. 4 shows the resultant macroscopic relative permeability of SMC for different values of P_{th} where η=0.866, n=10. When P_{th}=0.0, i.e. there are no magnetic contacts, the resultant value is close to that computed by (1), as expected. When P_{th}=1.0, i.e. domain is covered by magnetic particles without insulation layers, the result is close to 100. The computed value for P_{th}=0.55 at η=0.866 is close to the measured value. Fig. 5 shows the distribution of magnetic induction on a cross section of the magnetic circuit. When P_{th}=0.2, magnetic induction has nearly uniform distribution. On the other hand, when P_{th}=0.55, non-uniformity in the magnetic induction becomes more apparent. Fig. 6 shows dependence of macroscopic permeability on the volume fraction and P_{th}. When P_{th}=0.2, the macroscopic permeability is near to that computed from (1). However, as P_{th} increases, then it becomes much larger than that computed from (1) especially when η is not close to 1. This tendency can be clearly observed in Fig. 7 which shows the ratio of macroscopic permeability computed by (1) to that obtained from (7).

We have evaluated the macroscopic permeability which is parametrized by P_{th}. It would be possible to determine the value of P_{th} from the measured macroscopic permeability of SMC. It would be also possible to determine it from the picture images like Fig.1.

It is also expected that the eddy current loss increases due to the electric contacts among the magnetic particles. The eddy current distribution would be highly complicated when there are such contacts. The excess eddy current losses due to the electric contact could be evaluated using the circuit model proposed in this paper. This remains as an open question.

VI. Conclusion

In this paper, it has been pointed out through FE analysis of SMC image and magnetic circuit model that the magnetic contacts among the magnetic particles give significant effects on the macroscopic permeability. When P_{th} is 0.55, the computed macroscopic permeability is close to the measured value. Excess eddy current losses due to electric contacts could also be evaluated using the proposed circuit model. This remains as a future work.

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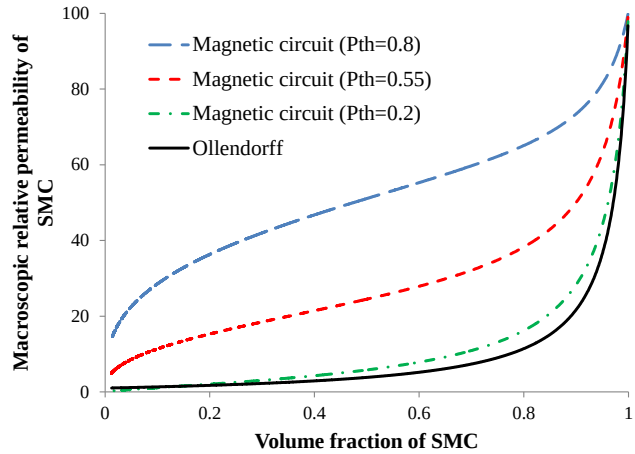

Fig. 6. Relationship between the volume fraction and macroscopic relative permeability of SMC when n=10.

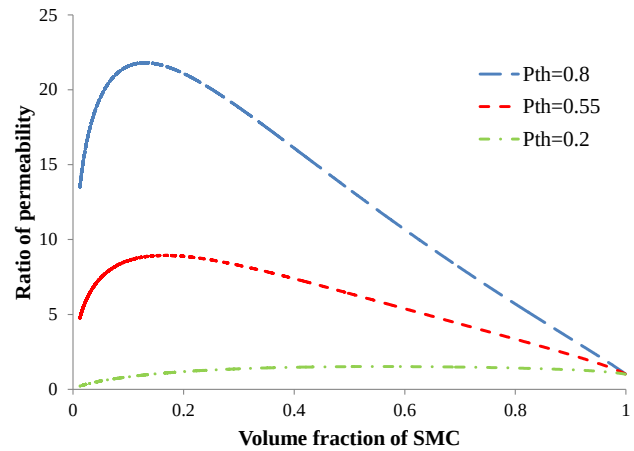

Fig. 7. Ratio of macroscopic permeability computed by (1) to that computed by (7).

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