Loss Computation of Soft Magnetic Composite Inductors Based on Interpolated Scalar Magnetic Property

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This paper presents a new loss computation method for soft magnetic composite (SMC), which allows us to evaluate the loss for wide operating conditions. A formula for evaluation of eddy current and hysteresis losses is introduced. The effective volume fraction of the magnetic grain is determined from the sampled measured data. It is shown that the formula provides accurate estimate of the total loss in a toroidal SMC core. Moreover, the loss of SMC inductor is shown to be also accurately evaluated at small computational burden using the proposed method.

***Index Terms*— Anomalous eddy current, eddy current loss, hysteresis loss, inductors, soft magnetic composite.**

I. Introduction

INDUCTOR is one of the components in voltage source circuits. In the development of inductors, there is a strong requirement for increase in both switching frequency and dc-bias current. Due to this requirement, the soft magnetic composite (SMC) has been employed for inductor cores instead of the ferrites [1], [2]. SMC inductors can keep the nominal inductance under the wide bias conditions because the saturated magnetic flux density in SMC is larger than that in the ferrites.

The loss of SMC inductors depends on the operating conditions. Thus, when designing the SMC inductors, we have to consider the inductor loss under the various conditions. The Steinmetz method and its variations are simple but effective approaches to estimate the core-loss [3]. Since the Steinmetz coefficients vary for different dc-bias and operating frequency conditions, we have to measure the SMC losses under various conditions to determine the Steinmetz coefficients. It is, however, time-consuming and laborious to carry out the measurements for different conditions. Furthermore, there is a difficulty in measuring the loss at high frequency due to the limitation of measurement equipment. This is attributed to the fact that, at higher frequency, it is difficult to apply ac field superimposed to the dc bias.

In this paper, we introduce a new method for fast computation for SMC losses. In this method, the eddy current loss in magnetic grains in SMC is analytically evaluated instead of the classical Steinmetz formula. Moreover, the effective volume fraction of the magnetic grain is introduced and its value is determined from the sampled data. We apply the present method to evaluation of the losses in a toroidal SMC and inductor.

II. Loss Computation Method of SMC

SMC consists of magnetic grains coated by electrically insulating and non-magnetic material, as shown in Fig. 1 [4].

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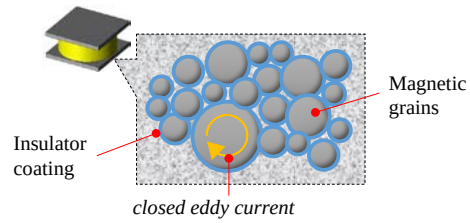


Fig. 1. Structure of soft magnetic composite.

Thus, there do not exist global eddy currents in SMC. However, the eddy current loss arises in each grain when the skin depth is smaller than the grain size at high frequency.

On the other hand, the BH-curves possibly change as operating frequency increases. In this case, it is difficult to estimate the loss at high frequencies only from the BH-curve measured under the dc condition or at a low frequency. To solve this problem, various dynamic hysteresis modeling methods have been proposed, e.g. [5].

For SMC, it is expected that hysteresis and eddy current losses can separately be estimated. We assume that the changes in BH-curve are attributed only to eddy currents. This assumption allows us to estimate the hysteresis loss based on the classical Steinmetz formula. Assuming that SMC consists only of the spherical grains, the eddy current loss of SMC for any conditions can analytically be computed. The loss evaluation method for SMC based on the above estimates will be introduced below.

A. Hysteresis loss

As mentioned above, we compute the eddy current and hysteresis losses separately. The hysteresis loss density is here computed from Steinmetz formula as follows:

$$p_h(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f) = \kappa(B_{\mathrm{dc}}) \times f k_h B_{\mathrm{ac}}{}^{\alpha}, \tag{1}$$

where B_{dc}, B_{ac} denote flux densities for dc-bias and ac field, respectively, f is frequency, k_h, α are the Steinmetz coefficients, and $\kappa(B_{\mathrm{dc}})$ is the correction function for the bias condition. These are determined so as to fit the measured losses at low frequencies.

B. Eddy current loss

We assume that SMC consists only of the spherical grains

of radius a, as shown in Fig. 2. This assumption makes possible to analytically evaluate eddy currents in the grains immersed in uniform time-harmonic field $B_{ac}e^{j\omega t}$. Note here that the global field B_{ac}, is the spatial average of the local magnetic inductions in the magnetic grain and non-magnetic layer. The former magnetic induction, denoted by B_{loc}, is the field in the vacant sphere which remains after taking a grain out of the SMC. The local magnetic induction B_{loc} is given by [6]

$$B_{\mathrm{loc}} = \mu_0 B_{\mathrm{ac}} \Big/ \mu\left\{1 - \frac{\eta N(\mu_r - 1)}{1 + N(\mu_r - 1)}\right\}. \tag{2}$$

where μ_r is the relative permeability of the grain, and N is demagnetizing factor of the grains. Since we assume spherical grains, N is set to 1/3. Moreover, η denotes the volume fraction of SMC.

Now, let us consider the following equations:

$$\nabla^2 \boldsymbol{A} - j\omega\mu\sigma\boldsymbol{A} = 0, \quad \text{in sphere}, \tag{3}$$

$$\nabla^2 \boldsymbol{A} = 0, \quad \text{otherwise}, \tag{4}$$

where σ denotes the grain conductivity. From symmetry, the solutions to (3) and (4) can be written in the spherical coordinate as follows:

$$A = p i_1(kr)\sin\theta, \tag{5}$$

$$A = \left(q/r^2 + B_{\mathrm{loc}} r/2\right)\sin\theta, \tag{6}$$

where A is the azimuthal component of $\boldsymbol{A}$, $i_1(kx)$ is the modified spherical Bessel function of first order, and $k=(1+j)/\delta$ where δ represents the skin depth, and p and q are constants. By imposing the boundary conditions to the tangential component of magnetic field and the normal component of magnetic induction on the surface of the grain, we obtain

$$\begin{bmatrix} i_1(ka) & -a^{-2} \\ \dfrac{1}{\mu_r}\dfrac{di_1(kr)}{dr}\Big|_{r=a} & a^{-2} \end{bmatrix} \begin{bmatrix} p \\ q \end{bmatrix} = \frac{B_{\mathrm{loc}} a}{2} \begin{bmatrix} 1 \\ 2 \end{bmatrix}. \tag{7}$$

The eddy current $J(r)$ and loss in one grain $P_e(a)$ are obtained by solving (7) as follows:

$$J(r) = j\omega\sigma p i_1(kr)\sin\theta, \tag{8}$$

$$\begin{aligned} P_e(a) &= \frac{1}{2\sigma}\iiint_V J(r)J^*(r)\,\mathrm{d}V \\ &= \frac{4\pi\sigma\omega^2 p^2}{3}\int_0^a r^2 i_1(kr) i_1^*(kr)\,\mathrm{d}r, \end{aligned} \tag{9}$$

where superscript * denotes complex conjugate.

The SMC actually consists of the different sized grains. Thus, the mean eddy current loss density in SMC, p_e, is computed from the expected value as follows:

$$p_e = \eta \frac{\int_0^\infty f(a)P_e(a)\,\mathrm{d}a}{\frac{4\pi}{3}\int_0^\infty f(a)a^3\,\mathrm{d}a}, \tag{10}$$

where $f(a)$ is the probability density function of the grain radius. The eddy current loss density p_e depends on frequency f and the amplitude B_{loc} which is determined from B_{ac} by (2). Because μ_r depends on B_{dc} in actual grains due to magnetic saturation, we assume that $p_e = p_e(B_{dc}, B_{ac}, f)$.

Consequently, the total loss density of SMC, $p(B_{dc}, B_{ac}, f)$ (W/m^3), is computed from the formula

$$p(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f) = p_h(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f) + p_e(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f). \tag{11}$$

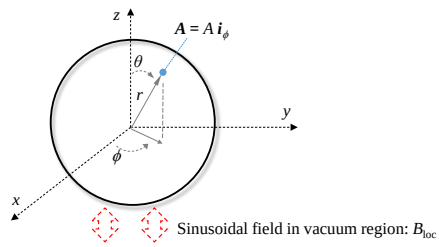


Fig. 2 Eddy current in a sphere immersed in uniform field.

III. Loss Evaluation from Present Method

We estimate the loss of SMC from the measurement data shown in Fig. 3 which was measured using a toroidal core at 800kHz. The dc and ac magnetic properties of SMC are shown in Fig. 4, and the distribution of grain size is shown in Fig. 5. The measured volume fraction η of the SMC is 81.9%.

A. Determination of effective volume fraction

To compute (2) and (7), μ_r of the magnetic grains must be determined. Because the direct measurement of μ_r is difficult, we indirectly evaluate μ_r from the Ollendorf formula

$$\mu_r = 1 + \frac{\left(2\eta - \frac{1}{N}\right)\mu_{\mathrm{smc}} - \left(2\eta + \frac{1}{N}\right)}{(1-\eta)\mu_{\mathrm{smc}} + \left(1 - \frac{1}{N}\right)\eta - 1}, \tag{12}$$

where μ_{smc} is the relative permeability of SMC which is measured as shown in Fig. 4(b).

Here, we introduce the effective volume fraction η_e because of the following reasons:

a) If η is assumed 81.9%, the value of μ_r becomes negative for weak applied field. For positive μ_r, η must be set greater.

b) The thickness of the non-magnetic layers around the grains in SMC is far from uniform: the grains seem to be surrounded by much thinner layers than the average while there are spherical non-magnetic regions surrounded by the grains [e.g. 7]. Because the magnetic flux would mainly pass through the thin layers, the effective value of η is larger than

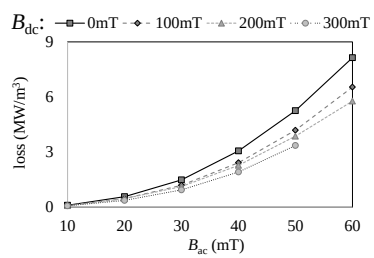
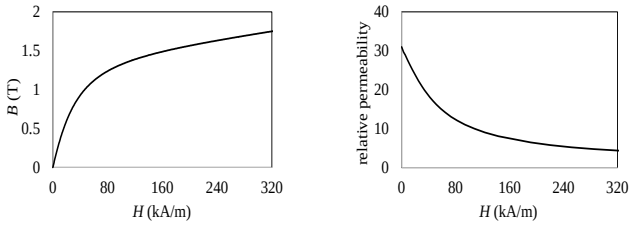


Fig. 3 Measured losses of SMC at 800kHz.



(a): dc property (b): ac property

Fig. 4 Magnetic properties of target SMC.

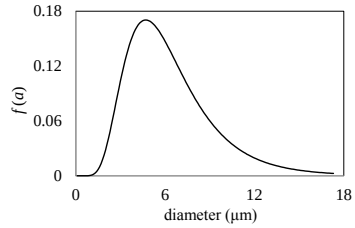
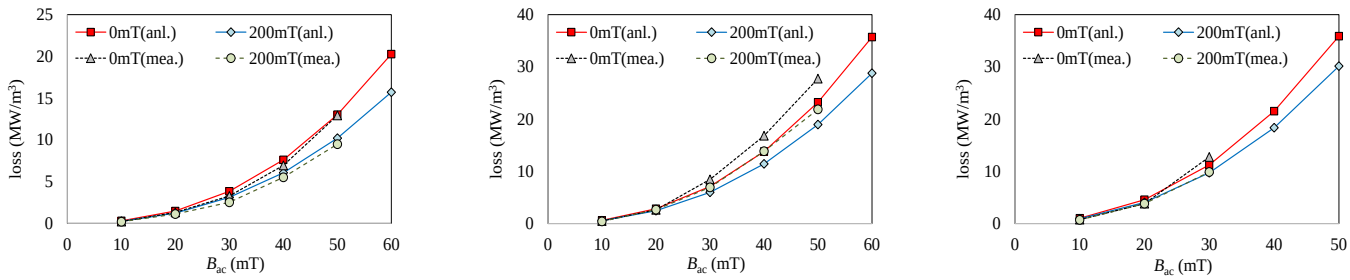


Fig. 5 Distribution of grain size.



(a): 1.6MHz (b)2.4MHz (c): 3.2MHz

Fig. 6 Loss of SMC, where solid and broken lines represent the computed and measured losses, respectively.

the average.

c) In addition to the classical eddy current loss, there exists the anomalous eddy current loss. The latter is proportional to f^2 in the same way as the classical eddy current loss when the domain size in the grains is so small that a grain has one domain boundary [8]. This effect can be included by determining the value of η_e so that the total loss agrees with the measured result.

In this work, the value of η_e is determined to be 94% so as to fit the measurement data. When computing B_{loc} from (2) and μ_r from (12), η is replaced with η_e. Note that once η_e is determined, we can make accurate estimation of the total loss from (11) also for the conditions under which measurement is not carried out, as will be shown below.

B. *Material loss estimation*

First, we subtract $p_e(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f)$ from the measured loss shown in Fig. 3. The resultant loss is assumed to be the hysteresis loss for the dc condition. From the resultant hysteresis loss for no bias, k_h and α are determined to be 15038 and 2.669, respectively. Then, the reduction ratio for dc-bias is determined from the resultant hysteresis loss. To smoothly fit them, $\kappa(B_{\mathrm{dc}})$ is constructed using Akima's interpolation method [9].

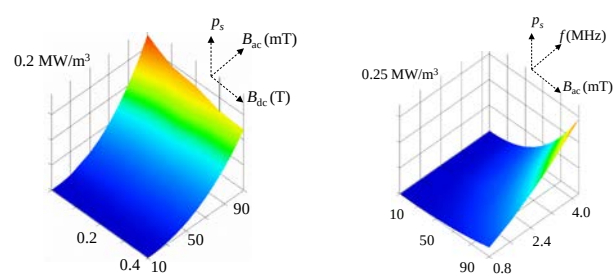
Figure 6 shows the analysis and measurement results. We can see that the analysis results are in almost agreement with the measurement results. At 3.2MHz, there are small numbers of measurement data. This is due to the limitation of the measurement equipment. The present method can estimate the loss for such conditions. These results show that the present method can effectively estimate the loss of SMC for wide conditions.

C. *Construction of fast loss estimation formula*

Because computation of (10) involves numerical integration in (8), it is time-consuming to evaluate p_e over the inductor region. On the other hand, we have the limited measurement results. For this reason, to perform fast evaluation of total loss in the inductor, we construct interpolated loss surfaces from the measured and computed losses using the Akima method [9] as follows:

$$p_s(B_{\mathrm{dc}}, B_{\mathrm{ac}}, f) = \sum_{s=0}^{3}\sum_{t=0}^{3}\sum_{u=0}^{3} k(s,t,u) \times (B_{\mathrm{dc}} - B_{\mathrm{S}})^s (B_{\mathrm{ac}} - b_{\mathrm{S}})^t (f - f_{\mathrm{S}})^u, \tag{13}$$

where (B_{S}, b_{S}, f_{S}) is the sampling point nearest to (B_{dc}, B_{ac}, f), and $k(s, t, u)$ is the interpolation coefficient which is determined from the sampled data which are obtained from the measurement and computed data using (11). The sampling points for B_{dc} and B_{ac} are placed with interval of 0.1T and 10mT over 1T and 100mT, respectively. The same points along the frequency axis are taken over 4.8MHz at intervals of 0.8MHz. The computed losses are used in the domain where no measurement data present. Over 4MHz, the computed data are used for all points. The constructed loss characteristic is shown in Fig. 7, from which it can be seen that smooth loss surface is obtained.



(a): (B_{dc}, B_{ac}) map at 3.2MHz (b): (B_{ac}, f) map for no bias

Fig. 7. Loss surface constructed by Akima method.

IV. Inductor Loss Estimation

The core-loss in an inductor shown in Fig. 8 is computed from (13). The distributions of B_{dc} and B_{ac} in the core are computed by the finite element method (FEM) as follows [10]:

1. The operating points of each FE for dc-bias current are

computed by nonlinear FEM using the dc-property shown in Fig. 4(a), and simultaneously, B_{dc} for FEs is obtained.

2. The permeability of FEs for the operation points is determined from the ac-property shown in Fig. 4(b). Then, linear FE analysis for ac-current is performed. As a result, B_{ac} is obtained.

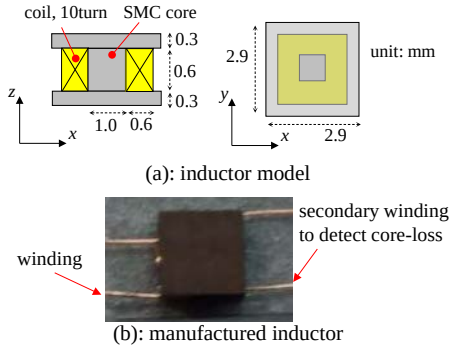
From these results, the loss in each FE is computed from $V_e p_s(B_{dc}, B_{ac}, f)$, where V_e is the volume of element e. The computed and measured inductance are shown in Table I, in which we can find that they are almost identical.

The core-loss is measured through the secondary winding, as shown in Fig. 8(b). This is because the resistance of primary winding increases due to the Joules loss caused by large bias current. The losses for three frequencies against the bias current are shown in Fig. 9(a). We can see that the results computed by (13) well agree with the measurement data. At 0.8MHz, they are almost identical because the loss surface for these conditions are constructed almost only from the measured losses. It is seen that, at 2MHz, the analysis results are also in good agreement although those are computed from the fully interpolated value for all components. The losses against frequency are shown in Fig. 9(b). It is found that there are also in good agreement, while there is no measured data at 4MHz. The distributions of B_{dc} and loss are shown in Fig. 10, where the bias current is set to 2A at 3.2MHz. We can see that B_{dc} is over 0.2T in the inductor axis. Although we have no measured data for such strong magnetic inductions, the present method can compute the core-loss as shown in Fig. 10(b).

From these results, we conclude that the core-loss can be estimated using present interpolation formula which is constructed from both measured and computed data.

V. Conclusion

The loss computation method for SMC has been presented. It has been shown that the computed losses are in almost agreement with measurement results when assuming appropriate effective volume fraction. The constructed formula can give accurate estimate of the total loss of inductors.



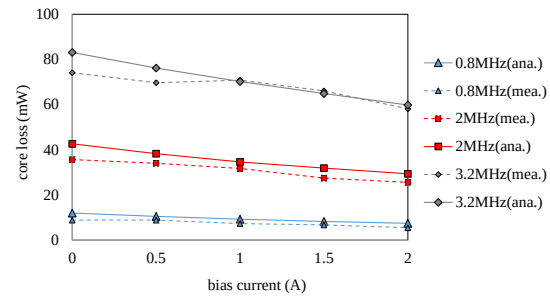
(a): inductor model

(b): manufactured inductor

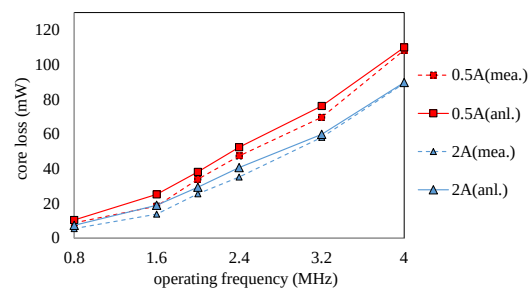
Fig. 8. SMC inductor for test.

TABLE I
Inductance value of SMC inductor

bias current	0.5A	1.0A	1.5A	2.0A
analysis	1.22μH	1.21μH	1.18μH	1.16μH
measurement	1.22μH	1.22μH	1.20μH	1.19μH

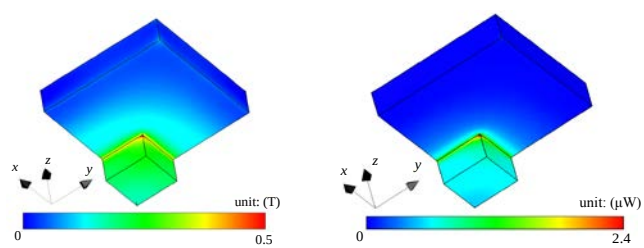


(a): against bias current



(b): against manufactured inductor

Fig. 9. Computed and measured losses when ac current is 0.5A.



(a): distribution of B_{dc} in FEs (b): distribution of loss in FEs

Fig. 10. Distributions of B_{dc} and loss when bias current is 2A at 3.2MHz.

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