Theoretical relationship among electrical resistivity, insulator volume content and powder coating rate of soft magnetic composite

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In present work, two related models of SMC (microstructure model and electric circuit model) were built, and the relationship among electrical resistivity (ρ), insulator volume content (γ) and powder coating rate (α) was derived and discussed. From the obtained relationship, the coating rate could be quantified and be comparable during preparation. The calculation indicates that both increase of insulator volume content and powder coating rate could improve the electrical resistivity. Moreover, significant improvement of electrical resistivity could only be obtained at very high coating rate (above 99.5%) at a constant insulator volume content (15 vol.%). Therefore, comprehensive consideration of electric and magnetic properties, more effort should be expended to explore effective processing method to obtain iron powders with high coating rate.

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1. Introduction

Soft magnetic composites (SMC) are composed of surface-insulated iron powder particles, which are compacted to form uniform isotropic components with complex shapes in a single step [1-3]. They possess several advantages over traditional soft magnetic materials including (i) isotropic magnetic property, (ii) very low eddy current loss and (iii) relatively low total core loss at medium to high frequencies [4-6]. Moreover, a distinct advantage of SMC is that three-dimensional magnetic devices with net shape and tight tolerance can be prepared by various powder metallurgy compaction techniques, which satisfies the precision and miniaturization for special components [6]. SMC is challenging traditional material (soft magnetic ferrites and electrical steels) in electromagnetic applications, such as core materials in inductors, stators and rotors for electrical machines, actuators, sensors and transformer cores [7-10].

The current researches on SMC are mainly focus on effect of iron powders [11-13], new insulators [14,15], iron powder content [16,17], preparation method [18-20] and heating treatment [16] on their magnetic properties. Although it is well known that iron powder coating rate (α) has great influence on electrical resistivity (ρ), eddy current loss (P_e) and demagnetization behavior [17], the relationship among these parameters has rarely been investigated due to lack of effective method to evaluate covering.

Therefore, a model to describe the relationship among electrical resistivity (ρ), insulator volume content (γ) and powder coating rate (α) was suggested in present work. It will be helpful for better understanding of core loss behavior of SMC, and will be beneficial for developing new SMC.

2. Theoretical models and derivation

The typical microstructure of iron powders and SMC are shown in Fig. 1a and b, respectively. Most of the iron powders are in irregular sharp [11-17]. In SMC, the iron powders distribute in the continuous insulator. However, it is hard to distinguish whether the iron particles are connected with each other or not. The model should reveal the relationship between microstructure and electrical resistivity (ρ). Moreover, the model should be of physical sense. Therefore, two related models of SMC were suggested in present work: a microstructure model and another electric circuit model. These two models were related by calculation below.

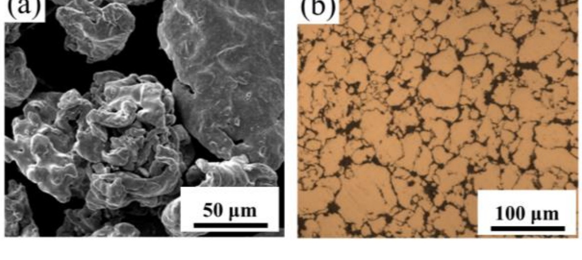

Fig. 1. The typical microstructure of iron powders and SMC.

In present work, the sharp of iron powders was simplified to cube, and the connecting part between them was in cuboid, as shown in Fig. 2. Although the connecting parts may be more than one area (Fig. 3a), the following calculation can demonstrate that all these parts could be equivalent to a zone whose area is equal to the sum of all connecting parts (Fig. 3b).

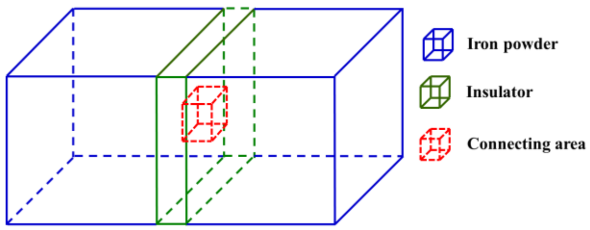

Fig. 2. The geometric model of SMC.

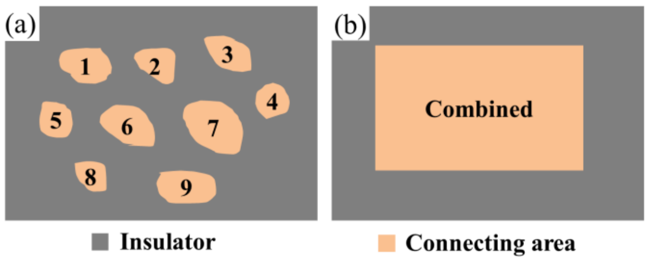

Fig. 3. Dispersed connecting area (a) and combined connecting area (b) in the interface between two adjacent iron powders.

The electrical resistance (R) of each part could be calculated by Eq. (1):

$$R = \frac{\rho \times d}{S} \quad (1)$$

where d is the average thickness of insulator and the connecting parts, and S is the value of their area.

The insulator and connecting parts are in parallel connection, and the total electrical resistance (R_T) could be obtained by Eq. (2):

$$\begin{aligned} \frac{1}{R_T} &= \frac{1}{R_I} + \frac{1}{R_{C1}} + \frac{1}{R_{C2}} + \cdots + \frac{1}{R_{Cn}} \\ &= \frac{S_I}{\rho_I \times d_I} + \frac{S_{C1}}{\rho_C \times d_{C1}} + \frac{S_{C2}}{\rho_C \times d_{C2}} + \cdots + \frac{S_{Cn}}{\rho_C \times d_{Cn}} \end{aligned} \quad (2)$$

where subscripts T, I and C refer to the unit cell, insulator and connecting parts, respectively. The subscript numbers 1 to n represent the number of connecting parts, respectively.

Furthermore, the thicknesses of insulator and the connecting parts are same in present model, and area of connecting part in Fig. 3b is equal to the sum of area in Fig. 3a. Thus, Eq. (2) could be derived as:

$$\begin{aligned} \frac{1}{R_T} &= \frac{S_I}{\rho_I \times d_I} + \frac{\sum_{m=1}^{n} S_{Cm}}{\rho_C \times d_C} \\ &= \frac{S_I}{\rho_I \times d_I} + \frac{S_C}{\rho_C \times d_C} \end{aligned} \quad (3)$$

Therefore, all the connecting parts with irregular sharp could be equivalent to a regular sharp zone whose area is equal to the sum of them.

Cross-section of Fig. 2 is shown in Fig. 4a. The structure of unit cell is shown in Fig. 4b. The length of iron powder cube and connecting area and the thickness of insulator are l_0, l_1 and d, respectively, as shown in Fig. 4b. It should be noted that the electrical resistances of insulators are usually severe power (more than 10) of ten higher than that of iron powder and connecting parts [16]. Actually, the electrical resistance of iron powder is same to that of connecting parts. Therefore, electrical resistances of the unit cell (R_{cell}) could be simplified to

$$\begin{aligned} R_{cell} &= \frac{\rho_P l_0}{S_P} + \frac{\rho_C \frac{d}{2}}{S_C} + \frac{\rho_C \frac{d}{2}}{S_C} \\ &= \frac{\rho_P l_0}{l_0^2} + \frac{\rho_P d}{l_1^2} \end{aligned} \quad (4)$$

where subscripts P refers to the iron powder.

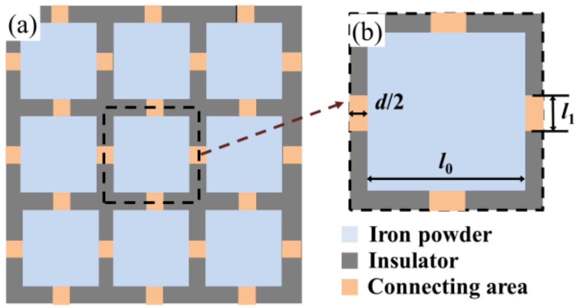

Fig. 4. Cross-section of geometric model (a) and unit cell of cross-section.

The electric circuit model of SMC is shown in Fig. 5. The unit cell is a resistance. The green lines mean the path that electric current could pass. However, there is no electric current perpendicular to the voltage direction due to equipotential, and they are marked in red lines. Therefore, the resistances parallel and perpendicular to the voltage direction are in series and parallel connection, respectively. The number of unit cells (x) in the plane perpendicular to the voltage direction, which are in parallel connection, could be obtained by Eq. (5):

$$x = \frac{S_{SMC}}{(l_0 + d)^2} \tag{5}$$

where S_{SMC} is the area of the plane, as shown in Fig. 5.

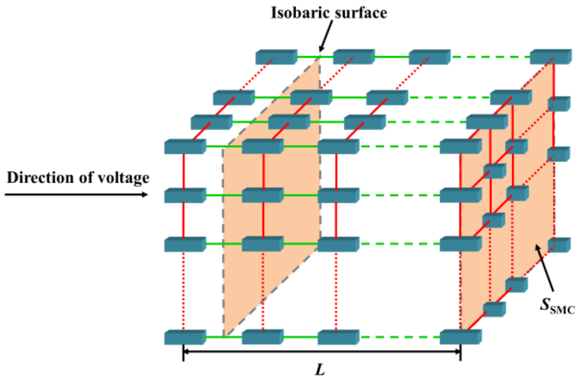

Fig. 5. The electric circuit model of SMC.

Moreover, the number of unit cells (y) in the plane parallel to the voltage direction, which are in series connection, could be calculated by Eq. (6):

$$y = \frac{L}{l_0 + d} \tag{6}$$

Therefore, the electrical resistance of SMC (R_{SMC}) could be derived as Eq. (7):

$$\begin{aligned} R_{SMC} &= R_{cell} \times \frac{y}{x} \\ &= R_{cell} \times \frac{L}{l_0 + d} \times \frac{(l_0 + d)^2}{S_{SMC}} \\ &= \rho_P \times (\frac{l_0}{l_0^2} + \frac{d}{l_1^2}) \times (l_0 + d) \times \frac{L}{S_{SMC}} \end{aligned} \tag{7}$$

The electrical resistance of SMC (R_{SMC}) could also be expressed as Eq. (8):

$$R_{SMC} = \rho_{SMC} \times \frac{L}{S_{SMC}} \tag{8}$$

Thus:

$$\rho_{SMC} = \rho_P \times (\frac{l_0}{l_0^2} + \frac{d}{l_1^2}) \times (l_0 + d) \tag{9}$$

Furthermore, the coating rate (α) and insulator volume content (γ) could be given as Eq. (10) and (11), respectively.

$$\alpha = 1 - \frac{S_C}{S_P} = 1 - \frac{6l_1^2}{6l_0^2} = 1 - \frac{l_1^2}{l_0^2} \tag{10}$$

$$\gamma = \frac{V_T - V_P - V_C}{V_T} = \frac{(l_0 + d)^3 - l_0^3 - 6 \times \frac{d}{2} \times l_1^2}{(l_0 + d)^3} \tag{11}$$

where V and S refer to volume content and area, and subscripts T, P and C refer to the total unit cell, iron powder and connecting parts, respectively.

The square and cube of d/l_0 could be neglected since the thickness of insulator (d) is generally much thinner than the size of iron powders (l_0). Combining Eq. (10) and (11), the insulator volume content (γ) could be written as:

$$\gamma \approx \frac{3d\alpha}{l_0 + 3d} \tag{12}$$

Combining Eq. (9), (10) and (12), relationship among electrical resistivity (ρ), insulator volume content (γ) and coating rate (α) could be established as:

$$\rho_{SMC} = \rho_P \times [1 + \frac{\gamma}{3(\alpha - \gamma)(1 - \alpha)}] \times [1 + \frac{\gamma}{3(\alpha - \gamma)}] \tag{13}$$

3. Discussion

Actually, the electrical resistivity of composites (ρ_{SMC}) could be measured by Kelvin (4-wire) resistance method. The insulator volume content could be obtained via measuring microstructure of polished samples or density of prepared SMC. Therefore, the powder coating rate could be quantified from the Eq. (13). It will be very useful for comparing the coating quality during preparation.

Moreover, the Eq. (13) also is very helpful as guideline of coating preparation. In case of pure iron powder (ρ_P= 1×10^{-7} Ω•m), the electrical resistivity of composites would increase with insulator volume content and coating rate, as shown in Fig.6a. More specifically, the relationship between electrical resistivity and coating rate at a constant insulator volume content (15 vol.%) is exhibited in Fig. 6b, and the relationship between electrical resistivity and insulator volume content at high coating rate (97%, 98% and 99%, respectively) is displayed in Fig. 5c, respectively.

Although beneficial for improvement of electrical resistivity (Fig. 6c), higher insulator volume content, which implies lower iron amount, will result in decline of saturation magnetic flux density and permeability. On the other hand, significant improvement of electrical resistivity could only be obtained at very high coating rate (above 99.5%) at a constant insulator volume content (15 vol.%) (Fig. 6b). However, it should be noted that a slight increase of coating rate above 99.5% will lead to apparent improvement in electrical resistivity. Therefore, comprehensive consideration of electric and magnetic properties, more effort should be expended to explore effective processing method to obtain iron powders with high coating rate.

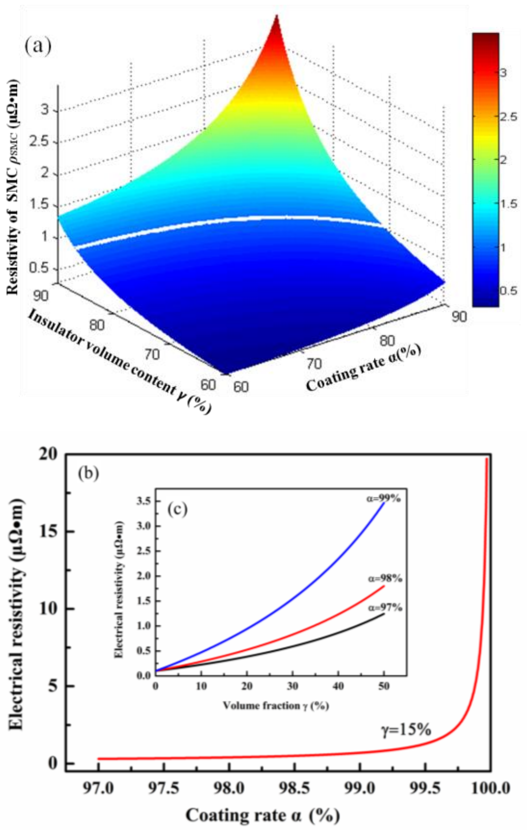

Fig. 6. (a) the relationship among electrical resistivity, insulator volume content and coating rate; (b) the relationship between electrical resistivity and coating rate at a constant insulator volume content (15 vol.%); (c) he relationship between electrical resistivity and insulator volume content at high coating rate (97%, 98% and 99%, respectively).

4. Conclusions

In present work, two related models of SMC (microstructure model and electric circuit model) were suggested, and the relationship among electrical resistivity (ρ), insulator volume content (γ) and powder coating rate (α) was derived and discussed. From the obtained relationship, the coating rate could be quantified and be comparable during preparation. Both increase of insulator volume content and powder coating rate could improve the electrical resistivity. However, higher insulator volume content, which implies lower iron amount, will result in decline of saturation magnetic flux density and permeability. Moreover, significant improvement of electrical resistivity could only be obtained at very high coating rate (above 99.5%) at a constant insulator volume content (15 vol.%). Therefore, comprehensive consideration of electric and magnetic properties, more effort should be expended to explore effective processing method to obtain iron powders with high coating rate.

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