Theoretical Analysis of Conductivity for Composite Bipolar Plate

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Abstract: Conductive composite bipolar plate is made of composite materials filled with high content conductive filler. The conductivity of this bipolar plate is influenced by many factors. It is difficult to use a formula to accurately calculate its conductivity, and current models have certain defaults. In this paper, in view of the contact resistance, a model is established and the conductivity formula has been educed. The conductivity formula reveals some factors that influence the conductivity, especially the particle size and pressure. Several ways to improve the conductivity of the composite material are discussed.

Keywords: Bipolar plates, Conductive composite material, Contact resistance, Aggregate.

1. INTRODUCTION

Conductive composite bipolar plate is the mainstream development direction of bipolar plate. The composite materials consisting of conductive graphite filler and resins adhesives can be produced into bipolar plates with flow field through compression moulding or injection moulding technology, which is high production efficiency and easy to be mass produced, and it is a significant decline in costs. Polymer composite bipolar plate has the same performance of corrosion resistance as graphite bipolar.

Graphite polymer composite bipolar plates are made of composite materials filled with high content conductive filler. The high conductivity of bipolar plate demands for high content of graphite. But the mechanical performance will decrease if the content of graphite is much too high. So, the key problem of how to meet the requirement of conductivity of a composite bipolar plate with the addition of a small amount of conductive fillers is needed to be resolved. Theoretical analysis is necessary on the basis of the conductive mechanisms of the composite materials. There are many kinds of theories about the electric conductivity mechanism which is the result of the combination of those theories in general view. However, most of the theories are suit for composite materials filled with low content conductive filler. For those filled with high content, we argues that the mutual contact of the filler particles is the main contribution to the conductivity of composite materials, while the effect of the tunnel current on the conductivity is so little that it can be negligible.

The conductive of composite materials filled with high content conductive filler are affected by many factors, such as the content of the filler, shape, conductivity and particle distribution [1]. Therefore, it is difficult to accurately calculate the conductivity by using a certain formula, and there are certain defaults about most of the existing models [2, 3]. There is no unified theory about the studying in this field. At present, though many interpolation formulas based on the model have been proposed to fit experimental data, no strict analytical solutions are available for calculation of conductivity in this case [4]. The most appropriate ones are very complicated, therefore, not convenient for practical use [5, 6]. Some experiments show that the conductivity of composite bipolar plate increases with the increasing of conductive filler size [7-10]. But there is no reasonable explanation about this phenomenon. To study the effect of filler size, shape, mould pressuring on the conductivity of bipolar plates, a simplified model is established, and the theoretic analysis is given in this paper.

2. ESTABLISHING MODEL AND EDUCING CALCULATION FORMULA

For the composite materials filled with high content of conductive filler, we assume that conductive filler particles are spheroid with the same size and pile up closed, polymer adhesive is filled in the voids of the conductive filler when the filler is mixed evenly. The contact between conductive filler particles forms conductive channels, which is the main reason for electric conductivity. The calculation formula of conductivity can be educed from the perspective of circuit. The conductive is inevitably affected by contact resistance as conductive filler particles contact in large quantity. Contact resistance is an important factor which must be considered in the calculation formula.

2.1. Closed Pile Up Model

The sizes of bipolar plates are supposed to be marked with thickness L_a, width L_b and length L_c. The inner structure is described as follows: the number of conductive filler arranging along L_a, L_b and L_c is a, b, c respectively. And r represents the radius of spherical particle. The shape and the inner structure for conductive filler pileup of bipolar plates are shown in Fig. (**1**).

For the conductive filler along the plane $P_{x,y}$ direction, the number of spherical particle arranging along the direction x is marked with a, and the number of layers arranging along

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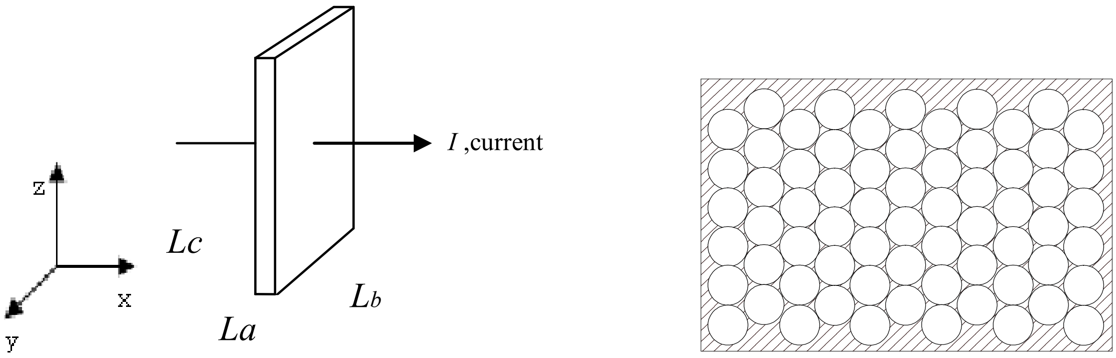

(a) (b)

Fig. (1). The shape (**a**) and inner structure (**b**) of bipolar plates.

the direction *y* is marked with *b*. Every adjacent spherical particle contacts with each other, as show in Fig. (**2**).

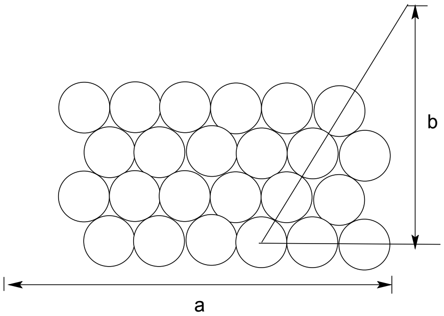

Fig. (2). The arrangement drawing of spherical particle in plane $P_{x,y}$ direction.

It is easy to obtain the following relations,

Thickness $L_a = 2ar$

width $L_b = \sqrt{3}\,br$

The number of layers piling up along the direction *z* is marked with *c*, and every layer follows the arrangement way as shown in Fig. (**2**).The distance between the layers is illustrated as Fig. (**3**).

According to the geometry relations, L_c can be calculated as follows.

$$\text{Length } L_c = \frac{2\sqrt{2}}{\sqrt{3}}\,cr$$

2.2. Calculation Formula of Conductivity

Each spherical particle contacts with *12* others around, and the average number of contact points is *6*, of which the contact resistance in *3* contact points can be regarded as parallel connection with spherical particle, while the other *3* can be regarded as connection in series with spherical particle. The circuit for a conductive monomer is shown in Fig. (**4**).

The resistance of a conductive monomer can be expressed as

$$R' = \left(\frac{1}{3R_c} + \frac{1}{R_f} + \frac{1}{R_m}\right)^{-1} + 3Rc$$

where R_c, R_f, and R_m are the resistance of contact, filler and polymer, respectively.

The effect of R_m can be ignored, for the relation $R_m >> R_f$

In the circuit of the whole bipolar plate, conductive monomer arranging along the plane $P_{y,z}$ direction can be regarded as parallel connection which are then connected in series *a* times.

So the resistance of the whole bipolar plate can be expressed as

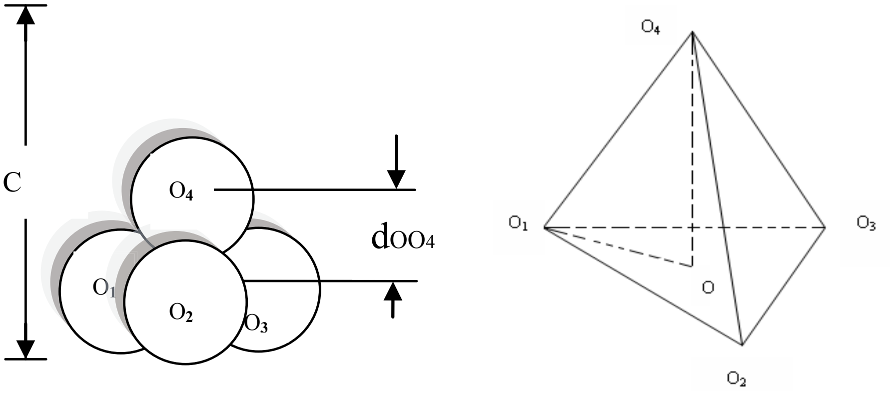

Fig. (3). The distance between the layers piling up along the direction *z*.

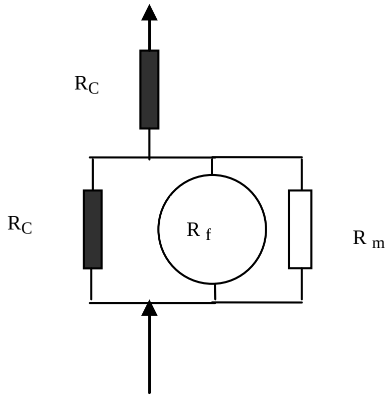

Fig. (4). The circuit drawing for a conductive monomer.

$$\mathrm{R}=\frac{a}{bc}\left[\left(\frac{1}{3R_c}+\frac{1}{R_f}\right)^{-1}+3Rc\right] \tag{1}$$

The spheroid resistance formula can be educed by integral, the drawing of integral for sphere resistance is shown in Fig. (**5**).

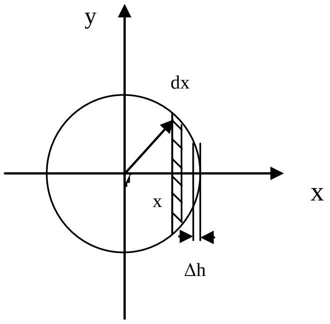

Fig. (5). The drawing of integral for sphere resistance.

$$R_f=\rho_f\frac{l}{s},\ dR_f=\rho_f\frac{\mathrm{dx}}{\pi\left(r^2-x^2\right)}$$

$$R_f=2\int_0^{r-\Delta h}\rho_f\frac{1}{\pi\left(r^2-x^2\right)}\mathrm{dx}=\frac{\rho_f}{\pi r}\ln\left(\frac{2r}{\Delta h}-1\right)$$

$$R_f=\frac{1}{\delta_f\pi r}\ln\left(\frac{2r}{\Delta h}-1\right) \tag{2}$$

where $\Delta h=r-\sqrt{r^2-\alpha^2}$

When the contacting materials are the same, the contact resistance can be expressed as [11]

$$Rc=\frac{\rho_f}{2\alpha} \tag{3}$$

Where α is the radius of contact point, of which the magnitude is determined by the surface deformation generated by mutual contacts.

According to Hertz elastic deformation formula,

$$\alpha=\left(\frac{3}{4}Fr\frac{1-\mu^2}{E}\right)^{\frac{1}{3}}$$

Where F is the pressure on sphere, μ is the Poison's ratio, E is the elastic module

According to the definition, it can be obtained that

$$\mathrm{R}=\rho\frac{l}{s}=\frac{l}{\delta \mathrm{s}}=\frac{L_a}{\delta\ \mathrm{L_bL_c}}, \tag{4}$$

Substituting Eq. (2, 3, 4) into Eq. (1), we can get

$$\frac{2\mathrm{ar}}{\delta\sqrt{3}\mathrm{br}\frac{2\sqrt{2}}{\sqrt{3}}cr}=\frac{a}{bc}\left[\left(\frac{2}{3}\delta_f\alpha+\frac{\delta_f\pi r}{\ln\left(\frac{2r}{\Delta h}-1\right)}\right)^{-1}+\frac{3}{2\delta_f\alpha}\right] \tag{5}$$

Namely

$$\delta=\frac{2\sqrt{2}}{9}\left[\frac{1}{\frac{\alpha}{r}+\frac{3\pi}{2\ln\left(\frac{2r}{\Delta h}-1\right)}}+\left(\frac{\alpha}{r}\right)^{-1}\right]^{-1}\delta_f \tag{6}$$

3. RESULT AND DISCUSSION

Concrete discussions as follows:

(1) The effect of r on δ

$$\frac{\alpha}{r}=Kr^{-\frac{2}{3}}, \tag{7}$$

where $K=\left(\frac{3}{4}F\frac{1-\mu^2}{E}\right)^{\frac{1}{3}}$

$\frac{\alpha}{r}$ is the decreasing function of r

$$\frac{r}{\Delta h}=\frac{1}{1-\sqrt{1-K^2r^{-\frac{2}{3}}}}=\frac{r^{\frac{4}{3}}\left(1+\sqrt{1-K^2r^{-\frac{4}{3}}}\right)}{K^2} \tag{8}$$

We can know that $\frac{r}{\Delta h}$ is the increasing function of r

Analysis of Eq. (6) shows that δ is the decreasing function of r

(2). The effect of K on δ

It is not difficult to find that $\frac{\alpha}{r}$ is the increasing function of K, $\frac{r}{\Delta h}$ is the decreasing function of K. Analysis of Eq. (6) shows that δ is the increasing function of K

Therefore the conductivity increases with the decreasing of particle size, and the increasing of pressure. In order to increase the conductivity we must choose smaller particles in size. On the other hand, the smaller are easy to aggregate than the bigger. The density of the composite bipolar plate decreases with decreasing graphite size, and the porosity increases with decreasing in graphite size [7]. That is the evidence of aggregation behavior and existing voids in composite material. In that case, conductive filler can not be mixed evenly with polymer adhesive, thus the composite material filled with small conductive particles exists more voids, while the redundant polymer cut off the contact of conductive particles. Some experiments reveals that the conductivity decreases with the decreasing of filler particle size [7-10].

So we must use appropriate disperse technologies to enable graphite particles evenly mixed with the polymer. Graphite particles piles up closely filled with polymer in the voids, in this case, polymer only play the role of cohesive action and not to hinder the formation of conductive path. So the conductivity is not affected by polymer, and is compared with the pure graphite bipolar plate. The polymer-filler interaction impacts on the conductivity of composite. Choosing the appropriate polymer adhesive can also improve the dispersing of filler.

REFERENCES

[1] Scarisbrick, R. M. Electrically conducting mixtures. *J. Phys. D Appl. Phys*., **1973**, *6*, 2098-2110.

[2] Zeng, R.; Zeng, H.M. Formation of the conductive path in conductive polymer composite. *J. Mater. Eng*., **1997**, *10*, 9-13.

[3] Wan, Y.; Wen, D.J. Polymer composites and their special effects. *Chin. J. Nat*., **1999**, *21*, 149-53.

[4] Lux, F. Models proposed to explain the electrical conductivity of mixtures made of conductive and insulating materials. *J. Mater. Sci*., **1993**, *28*, 285-301.

[5] McLachlan, D.S.; Blaszkiewicz, M.; Newnham, R.E. Electrical resistivity of composites. *J. Am. Ceram. Soc*., **1990**, *73*, 2187-203.

[6] Banhegyi, G. Comparison of electrical mixture rules for composites. *Colloid Polym. Sci*., **1986**, *264*, 1030-50.

[7] Hsu-Chiang, K.; Chen-Chi M.M.; Ke, H.C.; Shih-Ming, C. Preparation,electrical, mechanical and thermal properties of composite bipolar plate for a fuel cell. *J. Power Sources*, **2004**, *134*, 7-17.

[8] Jianhua, H.; Donald, G. B.; James, E. M. Highly conductive thermoplastic composites for rapid production of fuel cell bipolar plates. U.S. Patent 7,365,121, April 29, 2008.

[9] Zhang, J.; Zou, Y.W.; He, J. Influence of graphite particle size and its shape on performance of carbon composite bipolar plate. *J. Zhejiang Univ. Sci*., **2005**, *6A*, 1080-83.

[10] Liu Z.H.; Wang Y.X. Influence of particle grade on the electrical conductivity and gas-tightness of graphite/polymer composite. *Chin. J. Power Sources*, **2006**, *30*, 48-50.

[11] Mikrajuddin, A.; Shi, F. G.; Kim, H. K.; Okuyama K. Size dependent electrical constriction resistance for contacts of arbitrary size from Sharvin to Holm limits. *Mater. Sci. Semiconduct. Proces*., **1999**, *2*, 321-27.

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