Preparation of Electrically Conductive Particles by Dry Coating and Evaluation of Fine Particle Dispersion

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Abstract

Electrically conductive composite particles were prepared by dry coating of various types of electrically conductive fine powders on insulator resin. The course of composite formation and the state of dispersion were investigated by scanning electron microscope (referred to as SEM observation), X-ray elementary analysis and electrical property characterization.

Combining SEM observation and electrical property characterization determined the course of composite formation. The state of fine particle dispersion of the surface of a single composite particle could be quantitatively evaluated by calculating the coefficient of variance for the fine particles on the basis of elemental analysis of composite particles. Experiments also revealed that composite particles with excellent electric conductivity can be obtained, provided that the state of fine particle dispersion and coating on the core particle is good.

1. Introduction

In recent years, R & D activities have been concentrated on particle design, new materials and functional composite materials. Functional composite materials are characterized by the derivation of new features which cannot be achieved by the starting material bulk powder alone by mixing, kneading, dispersing and otherwise treating several types of powders. Therefore, the function of a composite material often depends upon the state of dispersion of the materials involved.

As an efficient means of composite particle formation and functional composite material design, the mechanofusion system has drawn attention, and a number of reports have been presented.11-15 This system may be characterized by the possibility of particle design based on the dry process rather than by its capability of fine powder processing. In other words, the aim of the mechanofusion system is to design composite particles with the desired function by fixing and coating fine particles on core particles by shearing, compression and tumbling actions in the absence of binders and other additives to obtain an ordered mixture.

In the previous papers16-19, we reported on composite forming studies with the aim of preparing composite particles with excellent electric conductivity by dry coating (dry process), in which various types of electrically conductive fine powders and various sets of coating apparatus operating conditions were tested. Data on the volume specific resistivity, SEM observation and X-ray elemental analysis of the obtained composite particles determined the course of composite formation and the relationship between the state of coating (composite formation) and electric conductivity. Also investigated was the composite formation for an improved flow of fine particles from the viewpoint of SEM observation and charge distribution as well as the basic mechanical prop-
erties. However, quantitative evaluation of the state of dispersion (coating) in composite formation remains unsatisfactory.

In the present study, various types of electrically conductive fine powders were dry coated on insulator resin, in single layers or double layers, to form composite particles. To determine the course of composite formation, SEM observation and electrical property characterization were performed. Also, quantitative evaluation of the state of fine particle dispersion on the surface of composite particles was attempted by calculating the coefficient of variance for electrically conductive fine powders on the basis of elemental analysis of fine particles on composite particles. The function of composite particles was investigated from the viewpoint of their electrical properties and correlated to the state of fine particle dispersion and coating.

2. Apparatus and methods

The compressive mill (Angmill, mechanofusion system, Hosokawa Micron Corp.) shown in Fig. 1 was used to perform dry coating for composite particle formation. Details of the apparatus are described elsewhere. The Angmill used has a casing of 150 mm in diameter and 40 mm in depth.

The powders used in the present study are listed in Table 1. Polymethyl methacrylate (PMMA), an insulator, was used as the core particle material. The electrically conductive fine particles used were Ag particles, Ni particles, Cu particles and Ag-coated TiO₂ (referred to as ATK50) particles.

The experimental conditions of composite formation were as follows: clearance between the inner piece and the casing inside wall was 3.4 mm, rotation rate N was 12.5 to 25 rps, and treatment time t was 600 to 3600 sec.

Table 2 gives specific conditions of complex formation. Samples A1 through A3 were prepared by dry coating one type of electrically conductive fine particles on the surface of PMMA core particles. Samples B1 through B3 were prepared by coating Ni particles or ATK50 particles on A1 through A3 composite particles (core particles). B1 through B3 are thus three-component composite particles consisting of resin and two types of fine particles.

Table 1. Core particle and electrically conductive fine powder

| Material                        | Mean particle size (μm) |
|---------------------------------|-------------------------|
| Core particle                   |                         |
| Polymethyl methacrylate (PMMA)  | 50                      |
| Fine Powder                     |                         |
| Cu                              | 2.5                     |
| Ni                              | 0.02                    |
| Ag coated with TiO₂ (ATK50)     | 0.5                     |
resulting from the coating of core particles with two layers of electrically conductive fine particles. The method of such double coating will be described later. Samples C1 and C2 are also three-component system, but they differ from B1 through B3 in that two types of fine particles have been simultaneously coated on the surface of core particles in a mill. In other words, the core particle is coated with a single layer of a mixture of two types of fine particles.

Dry coating of two layers of electrically conductive particles on core particles (composite particle formation) was achieved in the following manner: First, core particles and electrically conductive particles were loaded onto the mill casing, and the casing was tumbled to coat the first layer. After cooling in air, the single coated particles were further coated with electrically conductive fine particles.

As seen in Table 2, the rotation rate, coating treatment time t and fine particle feed rate varied depending on the type of electrically conductive particles charged. This is due to the fact that the conditions shown in Table 2 were developed after dry coating experiments under various sets of conditions. This demonstrates the necessity for suitable conditions for composite particle formation for each powder system.

In the composite formation experiments, dry coating was conducted without premixing the resin and electrically conductive particles, with 70 g of core particles used.

3. Evaluation of composite particle formation

As regards the course of composite particle formation and the function of composite particles, it is critical to evaluate the state of dispersion of electrically conductive fine particles on the surface of composite particles after dry coating. In the present study, composite particle formation was evaluated with an emphasis on the state of fine particle dispersion on the surface of a single core particle (microscopic aspect) and powder bed (formed product) function (macroscopic aspect).

3.1 State of electrically conductive particle dispersion on a single particle

To numerically depict the state of dispersion of electrically conductive particles coated on the surface of a single core particle, elemental analysis (surface analysis) was conducted using an energy dispersive X-ray spectrometer (EDX). On the basis of the analytical data thus obtained, the state of electrically conductive fine particle dispersion was evaluated as schematized in Fig. 2. First, a single composite particle was subjected to surface analysis and photographed. Next, each photographic image was divided into 19 sections, and the luminance L for each section was determined using a color difference meter (CL-100, produced by MINOLTA Corporation). Although the luminance determination should cover the entire surface of the particle, the central portion of the particle surface was especially analyzed to eliminate the problem of strain. The measuring range in each section was a circle of 8 mm in diameter. On the surface analysis images, the presence of a metal element appears as a white dot, which represents an electrically conductive particle.
Fig. 2. Method of luminance determination

conductive fine particles, i.e., luminance is equivalent to the density of coated electrically conductive fine particles. Since the surface analysis images were obtained at x 860 magnification, the actual luminance measuring range was a circle of 9.3 μm in diameter in each section of the surface of composite particles. By calculating the standard deviation $\sigma$ for luminance levels L1 through L19, the state of electrically conductive fine particle dispersion (coating) on the surface of a single core particle can be obtained. For the correction of the sensitivity difference between the target elements, the coefficient of variance CV was calculated for the evaluation of the state of dispersion as follows:

$$\text{CV} (%) = \frac{\sigma}{\bar{L}}$$

(1)

where $\bar{L}$ is the mean of the luminance levels L1 through L19. The uniformity of electrically conductive particle dispersion on the surface of a core particle increases or the state of coating (composite particle formation) is better, as the coefficient of variance CV decreases. There is no previous study of quantitative expression of the state of fine particle dispersion on a single core particles, as far as the author knows.

3.2 Evaluation of the state of electrically conductive particle dispersion based on electrical properties

With respect to the resinmetal composite particles studied, the state of dispersion and coating of electrically conductive fine particles on the insulator resin core particle is believed to affect the electrical properties. The state of electrically conductive fine particle dispersion (coating) was correlated to the volume specific resistivity $\rho$, the reactance X and the dielectric loss tangent $\tan \delta$. Alternating current electrical properties were determined by the LCR method using an impedance analyzer (model 4192A, produced by Yokogawa-Hewlett Packard) with a pressure of 2.9 MPa exerted on a pair of three-terminal parallel plate electrodes energized with composite particles. The determination was made at a frequency f of 100 kHz for a parallel equivalent circuit of resistors, condensers and coils (Fig. 3). The method of determination is schematized in Fig. 4. This method gives dispersed measurements because it is difficult to average all samples with regard to thickness. Dispersion was corrected using the following equations (2) and (3):

$$\text{CV} (%) = \frac{\sigma}{\bar{L}}$$

(1)

$$\text{FIG. 3. Parallel equivalent circuit}$$

$$\text{FIG. 4. Method of electrical property characterization}$$
\[ \rho = R \left( \frac{s}{d} \right)^3 \]  \hspace{1cm} (2)

\[ X' = X \left( \frac{s}{d} \right) \]  \hspace{1cm} (3)

where \( \rho \) is the volume specific resistivity, \( R \) is the resistivity measurement, \( s \) is the sample cross sectional area, \( d \) is the sample thickness, \( X' \) is the corrected reactance value and \( X \) is the reactance measurement.

The dielectric loss tangent \( \tan \delta \) can be expressed as the ratio of the electrical resistance to the reactance using the following formula (4):

\[ \tan \delta = \frac{X}{R} = \frac{X'}{\rho} \]  \hspace{1cm} (4)

4. Results and Discussion

4.1 Course of composite particle formation

Examples of SEM observations of particles obtained by dry coating treatment are shown in Fig. 5. A PMMA-Cu system was treated at a rotation rate of 25 rps. As seen in Fig. 5, fine particles of Cu adhered to the core particle in the form of scales at treatment times of 900 to 2700 sec. This may be associated with the compressive rolling of ductile Cu particles due to interparticle frictional force produced during the dry coating (composite particle formation) process. At a treatment time of 3600 sec, Cu particles were dispersed and coated on the entire surface of the core particle, in which Cu was present in a film form with indefinite borders between particles rather than with the scale form.

Fig. 6 (a) schematizes the course of composite particle formation found by SEM observation. It should be noted, however, that this model is not applicable to all the types of electrically conductive particles used in the study.

The course of composite particle formation for other particle systems was examined.

Using Ni particles and ATK50 particles (fine particles), dry coating was conducted, and the course of composite particle formation was compared with Cu particles. Fig. 7 (a) shows that the PMMA-Ni system (A2) had Ni lumps of 2 to 10 \( \mu \)m thickness adhering to the surface of the core particle even when the coating treatment time \( t \) was changed from 900 sec to 2700 sec. Since the Ni particles used were spherical particles having an average particle size of 0.02 \( \mu \)m (see Table 2), the Ni lumps can be identified as aggregates rather than elongated particles. With respect to this system, it can be said that coating occurred at lower levels of rotation rate \( N \) and treatment time \( t \) (see Table 2) in comparison with the PMMA-Cu system. This suggests that the Ni particles are more likely to adhere to the core particle than Cu particles; Ni aggregates became coated on the surface of the core particle before they were thoroughly disintegrated in the initial stage of dry coating, as shown in the model of Fig. 6 (b).

In the PMMA-ATK50 system shown in Fig. 7 (b), it was seen that ATK50 was coated on the entire surface of the core particle to form a composite particle. ATK50 exhibits no ductility because it is derived from Ag coating on the surface of TiO\(_2\) particles. It can therefore be interpreted that ATK50 particles offer good coating on the core particle without considerable deformation. In this case, the state of fine particle (ATK50) dispersion was better than that in the PMMA-Ni system. The course of composite particle formation for the PMMA-Ni system is modelled as shown in Fig. 6 (c).

Next, the effect of core particle surface condi—
Fig. 6. Model of composite particle formation process

Fig. 7. Composite particle SEM observation

Fig. 8. Composite particle SEM observation (PMMA-Cu-Ni system (B1) or PMMA-ATK50-Ni system (B3)). In these systems, composite particles of the PMMA-Cu system (A1) or the PMMA-ATK50 system (A3), as core particles, were dry coated with Ni particles. As seen in Fig. 8, Ni in the PMMA-Cu-Ni system was coated as aggregates as in the PMMA-Ni
system (Fig. 7 (a)). On the other hand, in the composite particles of the PMMA-ATK50-Ni system, Ni particles were coated in a film form. These findings suggest that Ni aggregates were coated after disintegration into primary particles when the core particle was coated with ATK50.

Although it has thus become possible to visualize the course of composite particle formation and the state of fine particle dispersion and coating, the state of fine particle dispersion cannot be quantified. Thus, quantitative evaluation of the state of electrically conductive particle (fine particle) dispersion on the surface of the core particle was attempted.

4.2 State of fine particle dispersion on the surface of a single particle

A model of the state of fine particle dispersion is given in Fig. 9. Conventionally, the state of mixing has often been evaluated on the basis of "complete mixing" or statistical homogeneity, and the target has been a group of particles (powder bed). However, in recent years, particle designing and composite particle formation have been actively investigated with an emphasis on "ordered mixture" or microscopic homogeneity. It is therefore essential to discuss "complete mixing" and "ordered mixture" from the viewpoint of a single particle. First, to examine the state of fine particle dispersion and coating on the surface of a core particle, elemental analysis (surface analysis) was performed using an energy dispersion X-ray spectrometer (EDX). Next, the state of fine particle dispersion was quantitatively evaluated by the method described in section 3.1, on the basis of the results shown in Fig. 2.

Table 3 gives the coefficients of variance CV for Cu, Ni and Ag on the surface of composite particles. These composite particles were obtained with the treatment times shown in Table 2. A low value of coefficient of variance means that fine particles have been uniformly dispersed (coated) on the surface of the core particle, i.e., an "ordered mixture" has been formed. As seen in Table 3, Ag-coated TiO₂ (ATK50) had the lowest value of coefficient of variance CV, indicating a good state of fine particle dispersion, which can be said to represent an "ordered mixture". With respect to the state of dispersion, ATK50 showed the best results followed by Ag and Cu particles, while Ni particles showed the worst results.

These findings suggest that when using Ag-coated TiO₂ particles, which are not liable to deform under shear, compression and other forces, composite particles with the most uniform dispersion of fine particles on the surface of the core particle are formed. This agrees with the SEM observation made in Section 4.1. It can be said that the use of the method described in Section 3.1 enables the evaluation of the state of fine particle dispersion on the sur-

| Sample | Composite particle | First layer Target | CV [-] | Second layer Target | CV [-] |
|--------|--------------------|--------------------|--------|---------------------|--------|
| B1     | PMMA-Cu-Ni         | Cu                 | 8.9    | Ni                  | 10.3   |
| B2     | PMMA-Ni-ATK50      | Ni                 | 11.4   | ATK50               | 4.2    |
| B3     | PMMA-ATK50-Ni      | ATK50              | 1.9    | Ni                  | 7.8    |
|        | PMMA-Cu-Ag         | Cu                 | 8.0    | Ag                  | 6.6    |
4.3 Relationship between the state of fine particle dispersion and coating and electrical properties

Since the resin-metal composite particles studied were prepared by dry coating of electrically conductive particles on the surface of insulator resin core particle, the coating state is apt to affect the electrical properties. Thus, the state of coating was discussed in view of the resistivity, reactance and dielectric loss tangent. Fig. 10 shows the relationship between the alternating current electrical properties (volume specific resistivity $\rho$, reactance $X'$, dielectric loss tangent $\tan \delta$ and treatment time $t$) in composite particles of the PMMA–Cu system (A1). The volume specific resistivity $\rho$ decreased with the treatment time. Since coating of the surface of the core particle by Cu particles proceeds according to the treatment time (see Fig. 5), electrically conductive paths are formed among particles, resulting in a decreased volume of specific resistivity and a good electric conductivity. As seen in Fig. 10, the reactance $X'$ remained almost constant even when the treatment time increased. Thus the dielectric loss tangent $\tan \delta$ as calculated from equation (4), increased with the treatment time $t$. As regards these electrical characteristics, further investigation was made.

First, the volume specific resistivity $\rho$ was investigated on the basis of the $R$ component of the parallel equivalent circuit of Fig. 3. If the resin core particle is the only factor for the determination, the resistance circuit can be represented by the resin’s specific resistance $R_S$, contact resistance $R_C$ and surface resistance $R_L$, as shown in Fig. 11 (a). $R_S$ and $R_C$ are negligible, as $1/R_S$ and $1/R_C$ go zero because the resin is usually an insulator, so that the surface resistance $R_L$ can be regarded as the resistance $R$ of the entire circuit.

When the core particle resin and electrically conductive fine particles remain dispersed without composite particle formation, the electrically conductive (metal particles are present in the core particles; therefore, the electrical resistance is of a serial circuit of core particles and the metal (Fig. 11 (b)). The resistance of the system can be taken as being equivalent to that of the core particle ($R = R_L$), since the resistance of the metal (electrically conductive particles) used is generally much lower than that of the core particle (resin).

When composite particles are prepared by accelerated dry coating, the metal particles coating of the surface of the core particle in an elongated form, as stated above. Therefore, the resulting composite particle system is characterized by surface contact (Fig. 11 (c)). In this case, in addition to the serial circuit of the resistance $R_L$ of the core particle and the resistance $R_M$ of the metal, the parallel circuit should be considered. As seen in Fig. 11 (c), the surface resistance $R_{L_2}$ of the core particle forms a parallel circuit with the metal resistance $R_M$ in the area covered by electrically conductive particles. Since $R_M$ is much lower than $R_L$, the resistance of the parallel circuit is equivalent to $R_M$; this system forms a serial circuit of $R_{L_1}$ and $R_M$. Because the $R_M$ of the serial circuit is negligible, the resistance $R$ of the composite particle system can be expressed as the surface resistance $R_L$ of the core particle in the area not covered by electrically conductive particles. This means that the volume specific resistivity $\rho$ decreases as the core particle surface area covered by Cu particles increases. This supports the finding that the volume specific resistivity $\rho$ of the PMMA–Cu system (A1) decreased (electric conductivity
Next, the reactance $X'$ is discussed. In a circuit of reactance $X'$, interparticle spaces, as well as the resin core particle and electrically conductive fine particles, should be considered. In this case, the system can be regarded as a system in which electrically conductive particles of inductance $L$ are dispersed in two different media with different values of static capacity $C$. Therefore, the reactance of this system can be expressed in a circuit of the static capacity (condenser) of the core particle and the interparticle spaces and the inductance of electrically conductive particles. However, in the present experiment, the volume fraction of electrically conductive particles is about 1 to 5 vol%, as seen in Table 2. This level appears to have no significant effect on $X'$. Fig. 12 shows the relationship between the reactance $X'$ and the volume specific resistivity $\rho$ of composite particles obtained in the present experiment. Unlike the volume specific resistivity, the reactance $X'$ remains almost constant without any marked change, even when the type, feed rate and treatment time of electrically conductive particles were changed. The same applies to the results shown in Fig. 10. As seen in Fig. 12, it was the PMMA–ATK 50–Ni (B1) system which had highly electrically conductive composite particles with a small value of volume specific resistivity $\rho$ followed by particles of the PMMA–Ni–ATK50 (B2) system and of the PMMA–Cu–Ni (B3) system.

These findings demonstrate that the state of dispersion and coating of electrically conductive fine particles on the surface of the core particle can be evaluated in terms of the volume specific resistivity $\rho$ rather than the reactance.

Fig. 11. Relationship between composite particle dispersion and coating state and electrical resistance circuit.

Fig. 12. Relationship between composite particle volume specific resistivity and reactance.
X'. Also, when the reactance X' has a constant value as in composite particles prepared in the present experiment, the state of coating can be evaluated even on the basis of the dielectric loss tangent \( \tan \delta \) since the numerator of equation (4) is a constant so that equation (5) is obtained as follows:

\[
\tan \delta = \frac{A}{\rho} \quad (A \text{ is constant})
\]  (5)

Equation (5) shows that dry coating accelerates as \( \tan \delta \) increases. There are some cases where the use of \( \tan \delta \) is advantageous. This is because \( \tan \delta \) can be expressed as the ratio of resistance \( R \) and reactance \( X' \) as in equation (4) so that it is unnecessary to determine the cross sectional area and thickness of the sample. Thus the dielectric loss tangent \( \tan \delta \) was used as the basis for the evaluation of the state of dispersion and coating.

Composite particles were prepared with different treatment time \( t \). The results are shown in Fig. 13 as a function of dielectric loss tangent \( \tan \delta \) and treatment time \( t \). In the resin-ATK50 system, it appears that the model of Fig. 11 (b) is applicable, since ATK50 particles are fixed on the surface of the core particle without definite deformation, as described in the previous section. However, experimentation revealed that in all the systems examined, the dielectric loss tangent \( \tan \delta \) increases to some extent with the treatment time, i.e., the model of composite particle system shown in Fig. 11 is applicable. When using ATK50 fine particles, some are embedded in the core particle\(^9\), whereby the composite particle system model is formed. The \( \tan \delta \) of the composite particles B2 (PMMA-Ni-ATK50 system) can be said to be greater than that of the composite particles C2 (PMMA-Ni-ATK50 system). In other words, the former presents a better condition for coating. According to the SEM observation shown in Fig. 8, there is no clear difference between these two systems with respect to composite particle surface condition. However, the measurements of the dielectric loss tangent \( \tan \delta \) revealed that there is a clear difference in the state of coating between double coating (two types of fine particle subjected to dry coating one by one) and single coating (two types of fine particles are simultaneously treated as a mixture). This means that double coating offers better electrical properties.

Next, the use of fine Ni particles is discussed. Fig. 14 shows measurements of \( \tan \delta \) of the PMMA-Ni system and other systems. Since the \( \tan \delta \) of the PMMA-Ni system remained almost constant even when the treatment time \( t \) was...
changed from 900 to 2700 sec, the state of dispersion and coating appears to be constant. As seen in Fig. 8, the SEM observation of the PMMA-Ni system reveals that Ni was covered with aggregates at t = 900 sec, while the composite particle surface condition remains constant even at t = 2700 sec. It can therefore be speculated that dry coating can be completed at t = 900 sec. The same applies to composite particles of the PMMA-Cu-Ni system (B3). The \( \tan \delta \) of the PMMA-Cu-Ni system, represented by the symbol C1, increased to some extent with the treatment time t, demonstrating a gradual progress of coating. These changes in \( \tan \delta \) are similar to those found in the PMMA-Cu system rather than in the PMMA-Ni system, i.e., the course of composite particle formation of the PMMA-Cu-Ni system is strongly affected by Cu particles.

5. Conclusion

It has been demonstrated that electrically conductive composite particles can be obtained by dry coating electrically conductive fine powders on the surface of insulator particles. The course of composite particle formation, function etc. have been discussed on the basis of SEM observations, electrical properties and electrical resistance circuits. The method for evaluating the state of fine particle dispersion and coating on the surface of a single core particle has been investigated. The present findings can be summarized as follows:

1) The state of fine particle dispersion on the surface of a single composite particle can be evaluated by calculating the coefficient of variance of the target particle on the basis of data of the elemental analysis of fine particles on the composite particle. In other words, the state of dispersion can be quantitatively evaluated. The use of this evaluation method appears to ease the comprehension of the state of “ordered mixture” on the surface of a single particle.

2) The state of fine particle dispersion can be evaluated on the basis of the volume specific resistivity and dielectric loss tangent. The course of composite particle formation can be elucidated by measurements of these parameters and SEM observations. The state of dispersion and coating of electrically conductive fine particles improves as the volume of specific resistivity decreases or the dielectric loss tangent increases.

3) When using two types of electrically conductive particles to obtain composite particles with excellent electric conductivity, double coating (the two types are coated one by one) is better than single coating (the two types are simultaneously coated as mixture).

References

1) Alonso M., M. Sato and K. Miyamami: Powder Technol., 59, 45 (1989)
2) Alonso M., M. Sato, K. Miyamami, K. Higashi and T. Ito: Powder Technol., 63, 35 (1990)
3) Tanno K.: Funsai, No. 33, 81 (1989)
4) Naito M., M. Yoshikawa and T. Yotsuya: J. of the Japan Soc. of Powder and Powder Metallurgy, 37, 131 (1990)
5) Tanno K.: KONA, No. 8, 74 (1990)
6) Tanno K., T. Yokoyama and K. Urayama: J. of the Soc. of Powder Technol. Japan, 27, 153 (1990)
7) Mizota K., S. Fujiwara and M. Senna: J. of the Soc. of Mat. Sci., and Eng., B10, 139 (1991)
8) Terashita K., K. Umeda and K. Miyamami: J. of the Soc. of Powder Technol. Japan, 27, 457 (1990)
9) Higashi M., K. Terashita and K. Miyamami: J. of the Soc. of Mat. Sci. Japan, 40, 417 (1991).

Nomenclature

\( A \) = constant \([-]\)
\( C \) = static capacity \([F]\)
\( CV \) = coefficient of variance \([\%]\)
\( d \) = sample thickness \([m]\)
\( f \) = frequency \([Hz]\)
\( L \) = luminance levels \([-]\)
\( \bar{L} \) = mean of luminance levels \([-]\)
\( N \) = rotation rate \([rps]\)
\( s \) = sample cross sectional area \([m^2]\)
\( t \) = treatment time \([s]\)
\( \tan \delta \) = dielectric loss \([-]\)
\( X \) = reactance measurement \([\Omega]\)
\( x' \) = corrected reactance value \([\Omega m]\)
\( \sigma \) = standard deviation for luminance levels \([-]\)
\( \rho \) = volume specific resistivity \([\Omega m]\)