Analysis of Triboelectric Charging Characteristics of Two-Component Developers on Carrier Surface Properties

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Abstract

Recently a new model was proposed to explain the dependence of triboelectric charging characteristics of two-component developers on toner concentration. According to the model, there are three types in dependence of toner charge-to-mass ratio, q/m, on toner concentration.

The dependency of triboelectric charging characteristics on toner concentration is governed by the relative difference of charging site numbers between toners and carriers. The role of the charging site numbers on toner and carrier surface is considered to understand the triboelectric charging mechanisms of two-component developers. The model has been developed quantitatively by experiments. The influence of charging site number on carrier surface with coating materials has been experimentally investigated. The variation of coating materials on carrier surface has been examined by work function, ionization potential and blow-off method. To interpret the results, the proposed model is refined and evidenced.

Introduction

The triboelectric charging behavior of two-component developers is one of the important parameters in electro-photographic systems.The charged toner is consumed in forming the real images from latent images in develop and transfer step of electrophotographic process. The triboelectric charging phenomena has been a long standing challenge.[1-11]

However, the triboelectric charging phenomena of two-component developers has not been cleared in physical modeling. Previous works[3-10] have investigated the dependence of toner charge-to-mass ratio, q/m, on toner concentration. The value of q/m is decreased with increasing toner concentration, C_t, and relation of m/q vs. C_t is linear. It is suggested that the distributed charge of one toner particle on a carrier decreases with increasing toner concentration. It is explained by surface state theory[3-5] and macroscopic Gaussian model.[9-11] However, the result of T. Oguchi et al.[7] is different from those of others. His data by blow-off method shows that the value of q/m is constant with increasing toner concentration. It means that the charge of one toner particle on a carrier is not changed with increasing toner concentration. Recently Kishimoto and Takahashi[1-2] presented a new model of triboelectric charging characteristics of two-component developers and compared model predictions to experimental measurements. According to the new model, the difference of two results, above mentioned, for dependency of toner charge-to-mass, q/m, on toner concentration is clearly explained. The new model have investigated the dependence of toner charge-to-mass ratio, q/m, on toner concentration by number of charging site on toner and carrier. The role of the charging site numbers on toner and carrier surface is considered to understand the triboelectric charging mechanisms of two-component developers.The purpose of the investigation reported here is to extend earlier work.[1-2] The model has been developed quantitatively by experiments. The influence of charging site number on carrier surface with coating materials has been experimentally investigated.

Theoretical Model

The proposed model is based on the difference of number of effective charging sites between toner and carrier and dynamic process of charging mechanism. The triboelectric charging rate of two-component developer is rapid in mixing step and reaches to saturated value in a few minutes. The equilibrium value of triboelectric charge during the mixing process will be determined by the balance of charging and discharging rate. Consequently, the triboelectric charging rate equation can be described quantitatively as follow:

$$dn^+/dt = \alpha(N_c - n^-)(N_t - n^+) - \beta n^+ \qquad (1)$$

where n^+ is the number of triboelectric charged sites at toner of two-component developer, n^- is the number of triboelectric charged sites at carrier of two-component developer and $n^+ = n^-$, N_c and N_t are the maximum number of the triboelectric charging sites of carrier and toner in two-component developer, respectively, α is the charging rate constant and β is the discharging rate constant. The toner charge-to-mass ratio, q/m, is obtained by solving Equation 1 with boundary condition, $\beta \rightarrow 0$ as $t \rightarrow \infty$.

$$n^+ = 2N_cN_t/(N_c + N_t + \sqrt{(N_c - N_t)^2}) \qquad (2)$$

Equation 2 is shown by the charging sites distribution fraction in equilibrium condition of two-component developer. The charged amount is controlled the role of differ-

ence number of effective charging site. Assuming that the exchange of charge is in proportion to difference of effective surface potential energy, DE, between toner and carrier, it is obtained to the toner charge-to-mass ratio, q/m,

$$q/m = e\Delta\, En^{+}/m$$
$$= 2N_cN_te\Delta E/\{m(N_c + N_t + \sqrt{(N_c - N_t)^2})\} \qquad (3)$$

where, e is the charge of the electron and ΔE is difference of effective surface potential energy between toner and carrier. With the difference of amount between N_c and N_t, Equation 3 becomes as follows:

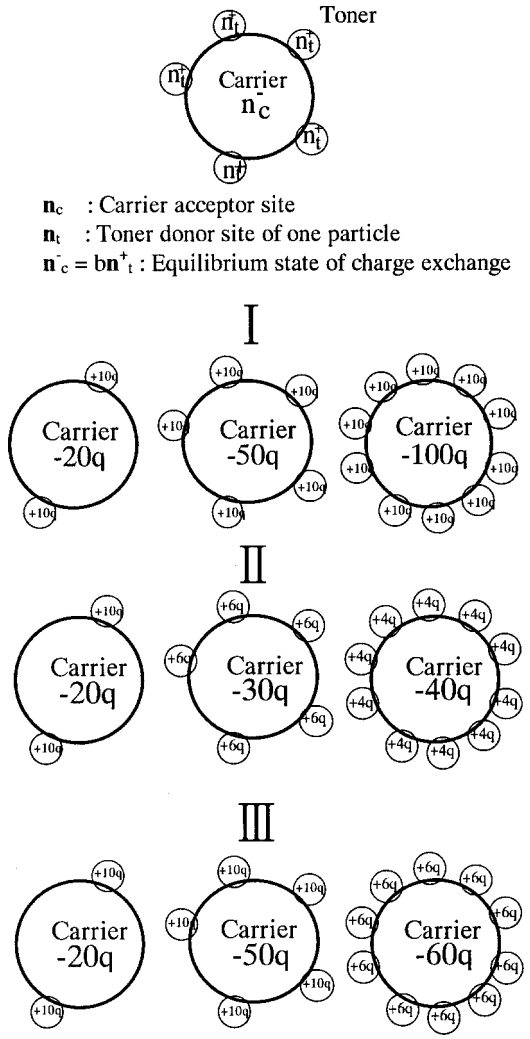

Figure 1. The three patterns of dependence of triboelectric charging characteristics of two-component developers on toner concentration in Equation 3.

- Type I

When $N_c > N_t$, the triboelectric charging amount is controlled by number of toner effective charging site only. Equation 3 is changed to Equation 4,

$$q/m = e\Delta E\, n_t k_t / m_t k_t$$
$$= e\Delta E\, n_t / m_t = \text{constant} \qquad (4)$$

where, m_t is the mass of one toner particle, k_t is total number of toner particles, n_t is the number of charged site of one toner particle. It is expressed that q/m is independent of increasing toner concentration, C_t and the schematic diagram is shown in Figure 1-I. The constant value, $e\Delta E\, n_t / m_t$, shows information of toner side. Let θ denote the covering ratio that is a proportion of covered area of toner on a carrier surface, i.e., θ = 1 means mono layer of toner on a carrier surface. In the neighborhood of θ = 1, the toner triboelectric charge per mass is slightly decreased. As the toner concentration is increasing, a large number of the toner particles are attached to the surface of the carrier and the toners are formed mono layer on carrier surface. At nearby θ = 1, the probability of contact between rest part of the carrier surface and toner is lower. Thereof, because of small probability of contact of developers, unfully charged toner is appeared. As the unfully charged toner is influenced total toner charge. Therefore, the total triboelectric charge of toner is slightly decreased in high toner concentration. In this case, it is called Type I.

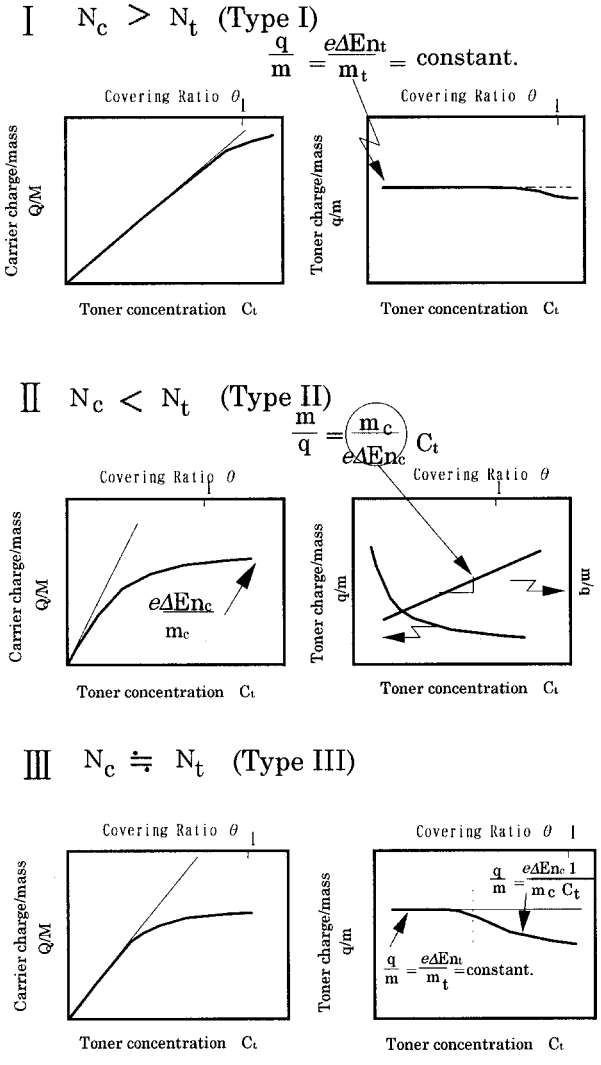

Figure 2. The schematic physical model of dependence of one toner particle charge on toner concentration

- Type II

When $N_c < N_t$, Equation 3 is transformed to Equation 5.

$$q/m = e\Delta E\, n_c k_c / m_t k_t = e\Delta E\, n_c / m_c * 1/(m_t k_t / m_c k_c) = e\Delta E\, n_c / m_c * (1/ C_t) \quad (5)$$

where, m_c is the mass of one carrier particle, k_c is total number of carrier particles, n_c is the number of charged site of one carrier particle. The triboelectric charging amount is controlled by number of carrier effective charging site only. It is expressed that the value of q/m is dependent of toner concentration, C_t. (Figure 1-II) The value of q/m is decreased with increasing toner concentration and the inverse of q/m, i.e., m/q, is linear with increasing toner concentration. It is expressed as follow:

$$m/q = (m_c / e\Delta E n_c)\, C_t \quad (6)$$

The coefficient of Equation 6, i.e., $(m_c / e\Delta E n_c)$, shows information of carrier side. In this case, it is called Type II.

- Type III

When $N_c \cdot = \cdot N_t$, the triboelectric charging amount is controlled by number of toner effective charging site (lower toner concentration) and number of carrier effective charge site (higher toner concentration). Equation 3 is shown to be

$$q/m = e\Delta E\, n_t / m_t \text{ or } e\Delta E\, n_c / m_c * (1/ C_t) \quad (7)$$

It is described by mixed characteristics of Type I and Type II (Figure 1-III). In this case, it is called Type III.

When the one toner particle on carrier surface is focused, the schematic physical model of charge exchange phenomena between toner and carrier is shown in Figure 2. The top side of Figure 2 shows the attached toner particles in one carrier particle. Let n_c denote number of acceptor site on surface of a carrier particle, n_t denote number of donor site on surface of a toner particle. At equilibrium state of charge exchange, $n_c^- = bn_t^+$,where b is number of attached toner particles on carrier.

Figure 2-I shows the case of Type I. According to $N_c > N_t$, the donor capacity of toner is totally ionized or activated, $n_t^+ = n_t$, when the surface of carrier is contacted and attached by toner. In the carrier acceptor site, a part of acceptor capacity on carrier surface is ionized, n_c^-, but the surface condition of carrier, $n_c >> n_c^-$, is still remained. As the attached toner on carrier is increased with the toner concentration, the toner charge is constant. For example, let n_t = 10q and toner is saturated by totally ionized. It is enough to increasing toner concentration that the remained acceptor capacity on carrier surface is able to be ionized by triboelectrification. If the Type I combination of toner and carrier is chosen, the obtained triboelectrification system with independent toner concentration is reliable for hardcopy machine.

Figure 2-II shows the case of Type II. It is opposited to Type I. According to $N_c < N_t$, the donor capacity of toner is not enough to be ionized or activated, $n_t^+ < n_t$, when the surface of carrier is contacted and attached by toner. The acceptor capacity of the carrier side is smaller than the donor capacity of the toner side. Then the triboelectric charge of one toner is decreased with toner concentration. But, at the case of small toner concentration, all of the donor capacity of toner is ionized because the number of toner particle is small and the capability of ionization is enough in carrier site.

Figure 2-III shows the case of Type III. It shows the mixed characteristics between Type I and Type II. In the case of lower toner concentration, it is similar to Type I. In the case of higher toner concentration, it is similar to Type II but the capability of ionization of Type III is higher than those of Type II. Therefore, the constant region of triboelectric charge of toner to mass in Type III is longer than those of Type II.

Experimental

Developers (Toner and Carrier)

- Toner: Four types of toners were used in this experiment. Two toners were positive toner (P2, P3) with a mean diameter of 10μm. The others were negative toner (M1, M4) with a mean diameter of 10μm.
- Carriers: Tree types of carriers were used. One was coated spherical ferrite carrier (FFM, FFP, FPC carrier) with a mean diameter of 80μm, another was un coated spherical ferrite carrier (FUC) with a mean diameter of 80μm and the other was uncoated spherical iron carrier (IUC) with a mean diameter of 80μm.
- Developers: The mixture of toner and carrier was fully mixed up by mixer.

The samples of developer (toner and carrier) are given in Table 1.

Table 1. Samples of Developer (Toner and Carrier)

Developer	FUC carrier	IUC carrier	FPC carrier	FFP carrier	FFM carrier
P2 toner	T1C1	T1C2	T1C3	T1C4	T1C5
P3 toner	T2C1	T2C2	—	—	—
M1 toner	T3C1	T3C2	T3C3	T3C4	T3C5
M4 toner	T4C1	T4C2	—	—	—

Modified Blow-off Method

Triboelectric charge of toner was measured with a specially constructed blow-off type Faraday cage. In the conventional blow-off method, after the measurement, the small parts of toner is attached to the Faraday cage's wall. It is affected to real toner charge by adding its charge. As the blow-off gas is higher, the carrier is charged by the mesh during the gas is blown. Thereof, the triboelectricity between the developer and mesh adversely influences the measured value, resulting in the conventional blow-off method not being able to give accurate value for toner charge.

We have accordingly studied a modified blow-off method which does use a vacuum system with inlet air gap. An apparatus of the modified blow-off method is shown in Figure 3. In this method, a screen mesh holds the sample developer (toner and carrier) and toner is driven from the carrier through the mesh by compressed N_2 and vacuum force with inlet air gap. The vacuum force acts on measurement of accurate toner charge and on decreasing the

blow-off gas which can be operated with small tribo-electrification between the developer and the mesh. The compressed N_2 is released through a nozzle 1.2 mm dia-meter at a pressure of 0.2 kg/cm^2. The vacuum pipe is placed 1mm below the Faraday cage. The gap between Faraday cage and vacuum pipe, i.e., inlet air gap, is elimi-nated attached toner on the Faraday cage's wall (part 1 in Figure 3). The vacuum force with inlet air gap is also prevented the toner from attaching to the Faraday cage's inner wall (part 2 in Figure 3).

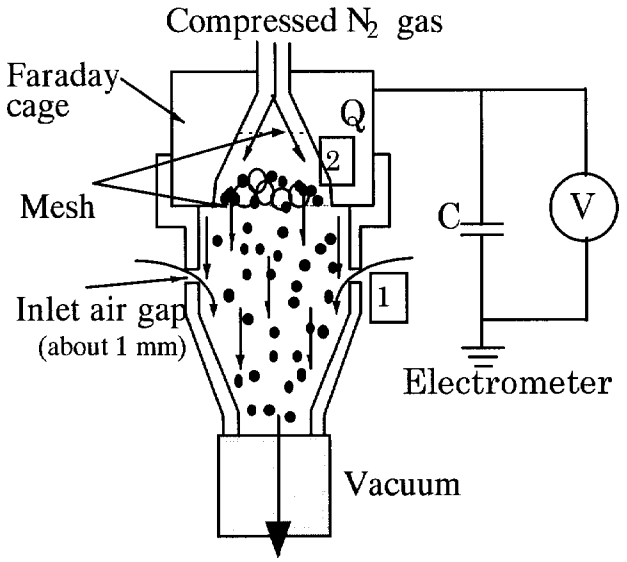

Figure 3. Apparatus of modified blow-off method.

Work Function and Ionization Potential

The work function of carriers was measured by Kelvin-Zisman method (difference of contact potential voltage), which was specially developed in our laboratory. The ionization potential of carriers was measured with photoelectric emission equipment (AC-1, manufactured by Riken Keiki Inc.).

Results and Discussion

We have found that there are three types in dependence of q/m on toner concentration at the developers used in this experiments.

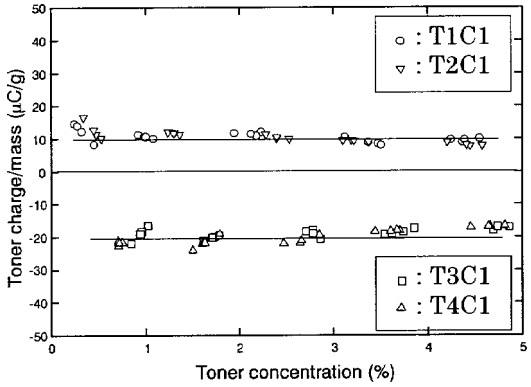

Figure 4. Dependence of toner charge-to-mass ratio, q/m, on toner concentrations, C_t , by combination of toner (minus and plus) and uncoated ferrite carrier.

The Case of Uncoated Ferrite Carrier

The toner charge-to-mass ratio, q/m, for uncoated ferrite carrier (FUC) and toner (positive-P2, P3 and negative-M1, M4) is plotted with toner concentration, C_t, in Figure 4. The value of q/m is constant with increasing C_t. It shows a independent relationship between the charge of one toner particle on a carrier surface and toner concentration. In the case of uncoated ferrite carriers, it is all exhibited to Type I for positive toner and negative toner.

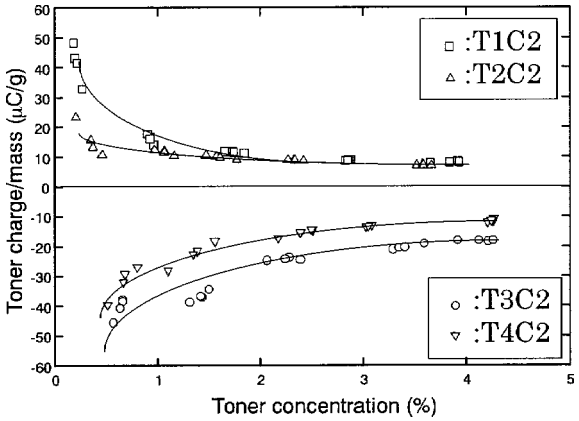

Figure 5. Dependence of toner charge-to-mass ratio, q/m, on toner concentration, C_t , by combination of toner (minus and plus) and uncoated iron carrier.

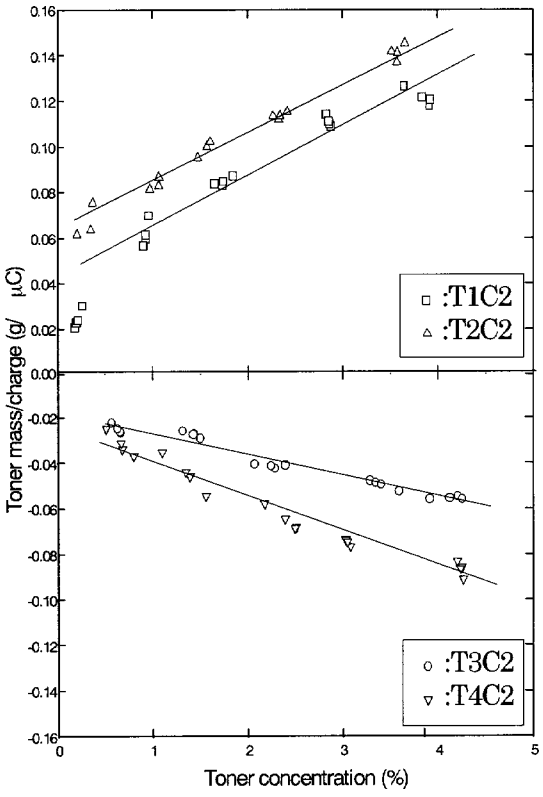

Figure 6. Dependence of toner mass-to-charge ratio, m/q, on toner concentration, C_t, by combination of toner (minus and plus) and uncoated iron carrier.

The Case of Uncoated Iron Carrier

The toner charge-to-mass ratio, q/m, for toner (positive-P2, P3 and negative-M1,M4) and uncoated iron car-

rier (IUC) with toner concentration, C_t, is shown in Figure 5. The value of q/m rapidly decreases with increasing toner concentration, C_t. The relationship between m/q and C_t is linear, in Figure 6. In this case, the slope of the Figure 6 is indicated characteristics of the carrier side. According to using of the same carrier (IUC), the effective charged site of carrier surface is unchanged. Therefore, the slope of m/q to C_t in Figure 6 is same value, because this is indicated same characteristics of carrier.

Lee[3] and Anderson[4] have reported similar results. But Lee only found that m/q of the toner was a linear function of toner concentration, C_t. Anderson also found that the linear relationship between m/q and toner concentration, Ct. For example, Figure 7 shows the dependence of m/q on toner concentration, Ct, with size variation of the same toner formulation (Figure taken from Reference 3). In Figure 7, with the variation of the toner particle size, the slope remains unchanged. Because the toner charge site per toner surface area is same, the slop is not changed. The slope shows information of carrier side. If the carrier is changed, the slope of m/q on toner concentration will be changed. Because the surface properties of carrier is changed, the effective charged site of carrier surface is changed. In the case of uncoated iron carriers, it is all exhibited to Type II.

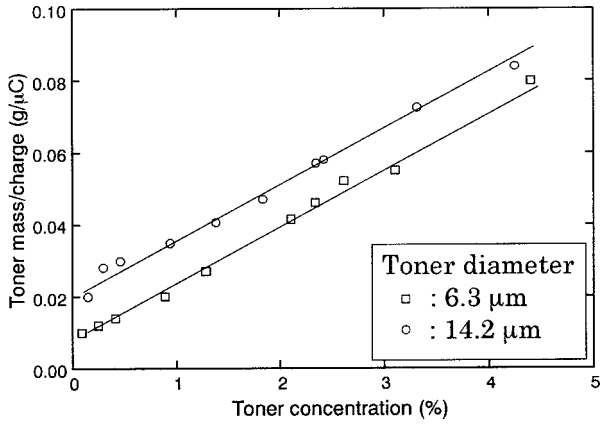

Figure 7. Dependence of toner mass-to-charge ratio, m/q, on toner concentration, C_t, with different toner sizes, same steel carrier and same toner formulation. (Figure taken from Reference 3).

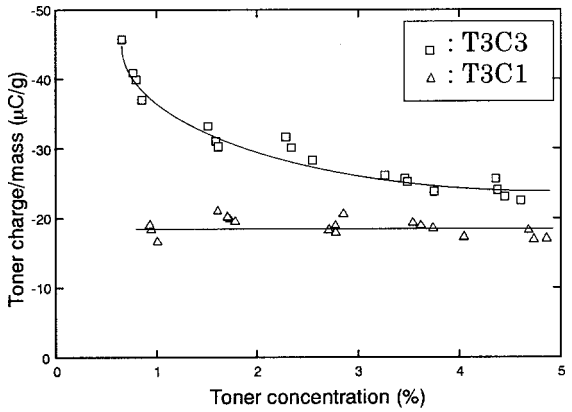

Figure 8. Dependence of toner mass-to-charge ratio, q/m, on toner concentration, C_t, by combination of negative toner and two types of carrier (uncoated ferrite carrier and silicone coated ferrite carrier).

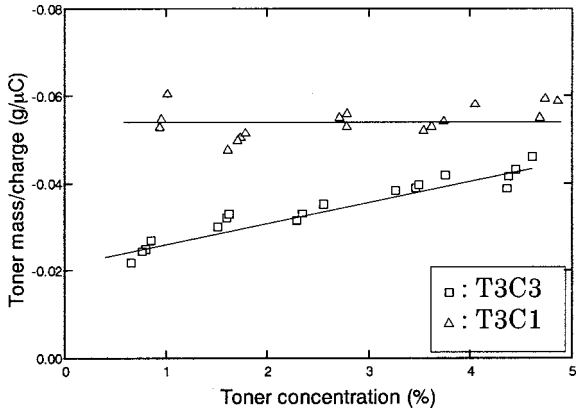

Figure 9. Dependence of toner mass-to-charge ratio, m/q, on toner concentration, C_t, by combination of negative toner and two types of carrier (uncoated ferrite carrier and silicone coated ferrite carrier).

The Case of Coated Ferrite Carrier

Figure 8 shows the toner charge-to-mass ratio, q/m, for negative toner-M1 and two types of carriers (uncoated ferrite carrier-FUC and silicone coated ferrite carrier-FPC) with toner concentration, C_t. The coating materials on carrier surface is influenced to change the characteristics of effective charging site. As the results, Type I (used uncoated ferrite carrier) is changed to Type II (used silicone coated ferrite carrier). The inverse of q/m, i.e., m/q, vs. toner concentration is shown in Figure 9. In case of FPC, the value of m/q is linear with increasing toner concen-tration. From the Figure 8, Equation 4, Figure 9 and Equation 5, we have calculated the number of charged site on toner and carrier, numerically. The following values are used for the calculation.

$$\rho_t = 1.1 \text{ g/cm}^3$$
$$d_t = 10 \times 10^{-4} \text{ cm}$$
$$e = 1.6 \times 10^{-19} \text{ C}$$
$$\rho_c = 5.5 \text{ g/cm}^3$$
$$d_c = 80 \times 10^{-4} \text{ cm}$$

- The case of the uncoated ferrite carrier (FUC):

at q / m = 18 μC/g and ΔE = 1 eV

Then

$$q/m = en_t/m_t = 18 \text{ μC/g}$$
$$n_t = \{(18 \times 10^{-6})(1.1)(4\pi/3)(5 \times 10^{-4})^3\} / (1.6 \times 10^{-19})$$
$$= 6.48 \times 10^4 \text{ charged site/toner}$$

Assuming the number of toner particles per carrier is 250 toner particles/carrier (monolayer), then

$$n_c = 250 \times 6.48 \times 10^4$$
$$= 1.62 \times 10^7 \text{ charged site/carrier}$$

- The case of the silicone coated ferrite carrier (FPC):

at m / q = 5.22×10^{-1} g/μC and ΔE = 1 eV

Then

$$m/q = m_c/en_c = 5.22 \times 10^{-1} \text{ g/μC}$$
$$n_c = \{(5.5)(4\pi/3)(40 \times 10^{-4})^3\} / \{(1.6 \times 10^{-19})(5.22 \times 10^5)\}$$
$$= 1.76 \times 10^7 \text{ charged site/carrier}$$

Assuming the number of toner particles per carrier is 250 toner particles/carrier (monolayer), then

$$n_t = 1.76 \times 10^7/250$$
$$= 7.04 \times 10^4 \text{ charged site/toner}$$

As the results of calculation, it is found that the numbers of charged site of coated ferrite carrier and uncoated ferrite carrier are same order. The numbers of charged site of toner side is same order, too. It means that the number of charged site on toner and carrier is same value at mono layer and same toner. But, there are different to the situation of carrier acceptor site. In FUC case, the number of acceptor site on surface of a carrier particle is larger than the number of ionized acceptor site, $n_c > n_c^-$. In FPC case, the number of acceptor site on surface of a carrier particle is almost same to the number of ionized acceptor site, $n_c \cdot = \cdot n_c^-$.

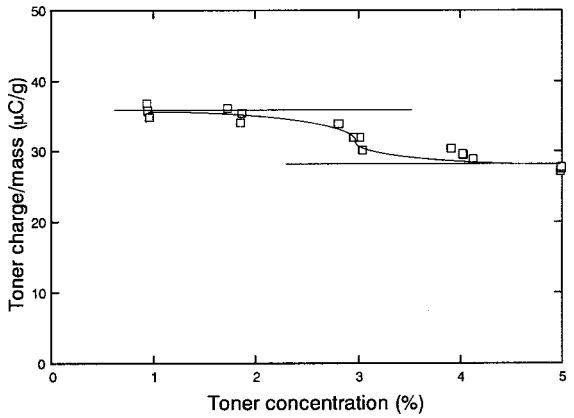

Figure 10. Dependence of toner charge-to-mass ratio, q/m, on toner concentration, C_t, by combination of positive toner-P2 toner and fluorine coated ferrite carrier-FFP carrier.

Figure 10 shows the toner charge-to-mass ratio, q/m, for positive toner-P2 and fluorine coated ferrite carrier-FFP with toner concentration, C_t. It shows mixed characteristics of Type I and Type II, so called Type III. The toner charge-to-mass ratio, q/m, for negative toner-M1 and silicone coated ferrite carrier-FFM with toner concentration, Ct, is shown in Figure 11. It is expressed that the value of q/m is constant, i.e., Type I.

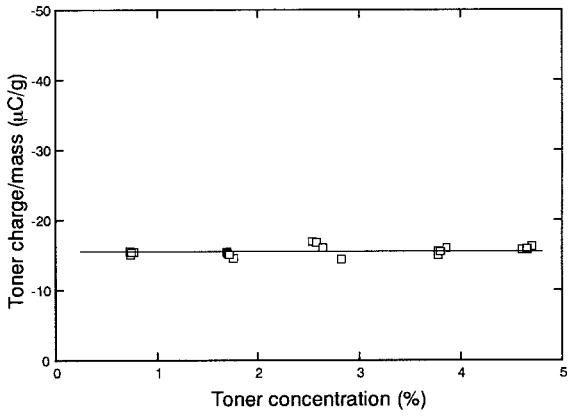

Figure 11. Dependence of toner charge-to-mass ratio, q/m, on toner concentration, C_t , by combination of negative toner-M1 toner and silicone coated ferrite carrier-FFM carrier.

As the result of experiment by used coated ferrite carrier, there are exhibited all Types, i.e., Type I, Type II and Type III. The toner charge, required system which is image stability and reliability, etc., can be obtained by a choice of the coating materials. It is desirable for a hardcopy machine to use the Type I developer which the value of q/m is independent of C_t.

The Relationship Between Toner Charge-to-Mass and Work Function and Ionization Potential

In Figure 12, it is found that the relationship between work function and ionization potential is linear. But the value is small difference between work function and ionization potential. It is expressed that the value is according to a band model. The work function or ionization potential is changed by coating materials on carrier surface. Figure 13 and Figure 14 show the relationship between toner (positive toner-P2 and negative toner-M1) charge-to-mass ratio, q/m, and ionization potential at 5 wt% toner concentration, uncoated carrier and coated carrier, respectively. It shows the dependence of toner charge properties on the characteristics of carrier surface. In general, the work function or ionization potential is great side, the acceptor site itself is changed easily. As shown in Figure 13 and Figure 14, it is not dependent on general rule. Therefore, probably, the driving force of triboelectrification is not work functions or ionization potentials on surface of developer but the difference of effective surface potential energy including the difference of the number of effective charging site.

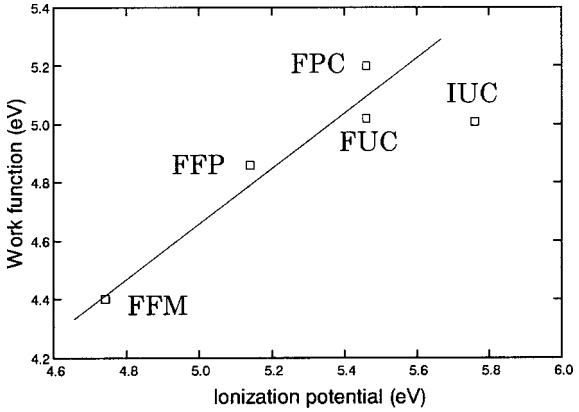

Figure 12. Related to work function and ionization potential.

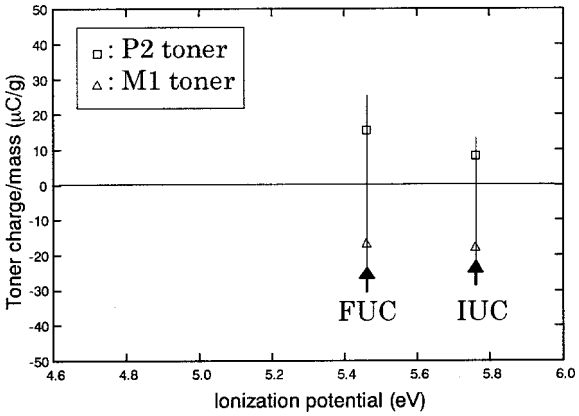

Figure 13. The relationship between toner charge-to-mass ratio, q/m, and ionization potential at 5 wt% toner concentration and uncoated carrier (FUC, IUC).

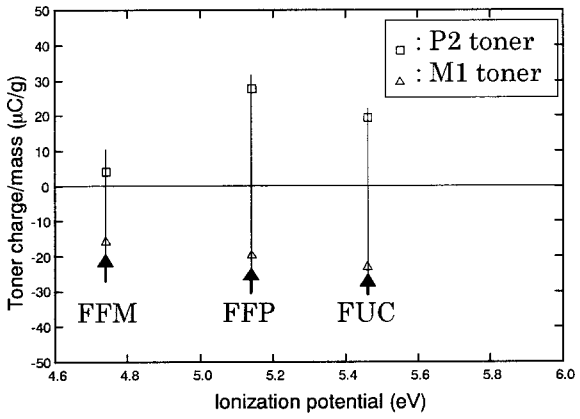

Figure 14. The relationship between toner charge-to-mass ratio, q/m, and ionization potential at 5 wt% toner concentration and coated carrier (FFM, FFP, FPC).

Conclusions

It is found that the triboelectricity between toner and carrier is one of three types depending upon toner concentration. The results of experiment are in good agreement with the proposed triboelectric charge model of earlier study.[1-2] The results of uncoated ferrite carrier are indicated Type I and uncoated iron carrier are indicated Type II. In the case of coated carrier, there are exhibited all Types (Type I, Type II and Type III). The toner charge, required for system image stability and reliability, etc., can be obtained by a choice of the coating materials. It is desirable for an electrophotographic machine to use the Type I developer in which the value of q/m is independent of C_t.

It is clear from the analysis of triboelectric charging characteristics of two-component developers that the concept of the number of effective charging sites on surface of developer is very important and useful for the analysis of microscopic behavior of two-component systems. For this reason it would be desirable to find a more accurate way of determining the number of effective charging sites on the surface of developer.

It is found that the work functions and ionization potentials of carriers are changed by coated materials. The work functions and ionization potentials of several carriers are not available for comparison with triboelectrification. The driving force of triboelectrification is probably not work functions or ionization potentials on surface of developer but the difference of effective surface potential energy including the difference of the number of effective charging sites.

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