Unusual Relationships Between Toner Charge and Toner Concentration

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Abstract

The charging properties of two commercial toners have been investigated by measuring the dependence of their charge-to-mass ratios on toner concentration. By also monitoring the corresponding carrier charge-to-mass ratio we demonstrate that at least three distinct charging regions exist. The unusual charging profiles are inconsistent with the current surface state theories of toner charging. The origin and benefits of such unusual charging relationships are discussed.

Introduction

The copy/print quality generated by electrophotographic systems greatly depends on the magnitude and stability of the toner electrostatic charge. In dual-component electrophotographic systems (most copiers), the charge is generated by agitating the toner particles against a second material called carrier. The toner/carrier mixture is called a developer. Theories have been developed in the past twenty-five years to account for the dependence of the magnitude of the toner charge on the chemistry, the particle size, and the concentration of the toner in the developer.[1,2,3,4,5] The experimental results are not, however, always in agreement with the proposed theories.

Based on linear relationships between the magnitude of the electrostatic charge and Hammet substituent constants[1,6] and work functions,[7] early theories assumed that electrons were solely responsible for the creation of charges on organic materials.[1,2] It has later been proposed, however, that the data supporting electron transfer could also be used in support of ion transfer.[8,9,10] Furthermore, only the transfer of ions has been substantiated by experimental evidences obtained with chemical surface analyses.[9]

Also, surface state theories[2,3,4,5] predict that toner charge-to-mass ratio, Q/M, will be inversely proportional to the toner size. This prediction is not easy to verify experimentally, since variation in the toner surface chemistry with the particle size is well known. In order to prevent this, Guay et al. used a "pure" toner resin and showed that toner Q/M can be independent of material size.[11] The same relationship was obtained for a pseudo-toner made of styrene-acrylic resin and carbon black.[11]

But the strongest argument for the validation of the surface state theories of toner charging is the inverse linear relationship between toner Q/M and toner concentration. Furthermore, the theories predict that the linear relationship between toner mass-to-charge ratio, M/Q, and toner concentration, C_t, will have a non-zero slope and intercept.[2,3,4,5] This is not always the case, however, and linear relationships with *zero slope* have been recently reported by two independent groups.[11,12] The unusual behavior is believed to occur when the total surface sites available to develop an electrostatic charge on the toner, Xt, is smaller than the total surface sites available to develop a charge on the carrier, Xc. Furthermore, a linear relationship with an *intercept equal to zero* has been obtained with a different pseudo-toner, which suggests that Xc < Xt.[11]

In this study, we carefully investigate the charging properties of two commercially available toners designed to work in the same machine. We show that the M/Q vs. Ct relationship of the toners studied can be divided into three regions: 1) M/Q is insensitive to Ct; 2) M/Q follows the theoretically expected relationship, and; 3) M/Q varies linearly with Ct, but with an intercept equal to zero. Charging behaviors of regions "1" and "3" are not consistent with the surface state theories, but can be explained if one considers that Q/M of both toner and carrier is limited by the relative amount of surface charging sites available ("surface limited" charging).

Experimental

Vacuumed-off commercially available OEM developer was used as the carrier. OEM and Nashua toners were used. Both toners are designed to work in the same copy machines. Their chemical compositions are, however, vastly different. The average particle size of the toners was 11 μm. The weight of the carrier used was always 50 grams to which measured amounts of toner were added. The weight ratio of the toner and carrier was defined as Ct. The metal can containing the resulting developer was rolled for a total of 60 minutes. The charge, Q, was determined at different time intervals using the total blow-off method. The toner and carrier Q/M ratios were obtained by dividing the charge, Q, by the weight of toner blown-off and the weight of residual carrier, respectively.

Theory

Current surface state theories of toner charging predict a linear relationship between toner M/Q and Ct.[2,3,4,5] Based on Lee's model,[2] this relationship can be expressed the following way[4]:

$$\frac{M}{Q} = RC_t\left[\frac{\rho_c}{3N_c\Delta\phi e}\right] + r\left[\frac{\rho_t}{3N_t\Delta\phi e}\right] \tag{1}$$

where M/Q, C_t, and *r* are the toner mass-to-charge ratio, concentration, and radius, respectively. *R* is the carrier radius. The bulk density and surface state density are represented by ρ and *N*, respectively. Δϕ is the surface work function difference between the carrier and toner. Thus, for any fixed toner and carrier average particle size, the theory predicts that a plot of toner M/Q vs. Ct will give a linear relationship with a slope and intercept equal to the first and second term in brackets, respectively.

Results

OEM and Nashua toners were mixed at different concentrations with 50 grams of carrier. The mixtures were then rolled for a total of 60 minutes and the blow-off charge was measured at different time intervals. Figure 1 shows the toner Q/M as a function of roll time for OEM and Nashua toners at two concentrations. Toner Q/M levels off after 10 minutes for both toner types and concentrations.

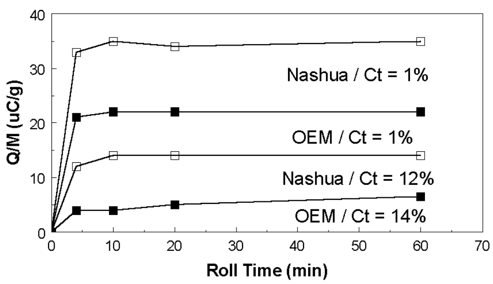

Figure 1. OEM and Nashua toner charge-to-mass ratios, Q/M, as a function of roll time at two different toner concentrations, Ct.

All toner and carrier charge data presented in the following plots correspond to a 20 minute roll time. Figure 2 displays the relationship between toner M/Q and Ct for both OEM and Nashua toners. It appears that M/Q values for both toners scale linearly with Ct. Such relationships have been reported many times and used to validate the current surface state theories.[2,3,4,5]

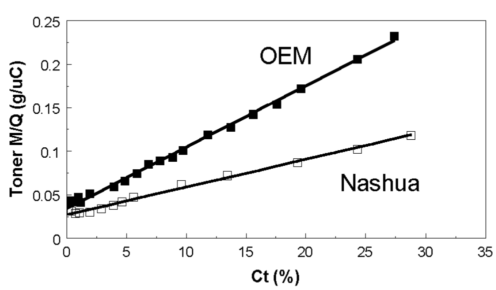

Figure 2. OEM and Nashua mass-to-charge ratios, M/Q, as a function of toner concentration, Ct.

Figure 3 shows toner M/Q and carrier Q/M values for OEM toner as a function of Ct. Carrier Q/M values were calculated using the same blow-off charge used to calculate the corresponding toner M/Q value. As shown in Figure 3, a single line is not appropriate to connect the carrier Q/M data. Instead, it appears that the carrier Q/M data can be divided into three distinct regions. In regions "1" and "2" the carrier Q/M scales linearly with Ct, but with different slopes. In marked contrast, carrier Q/M remains constant in region "3". These three distinct regions suggest transitions in the charging process(es) of the carrier and therefore similar transitions should accompany toner charging. Using the same toner M/Q data, the apparent straight line shown in Figure 2 was divided into three regions. The new toner curves are displayed in Figure 4 along with the carrier Q/M data.

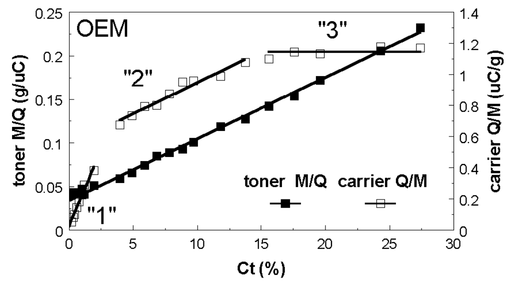

Figure 3. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, Ct.

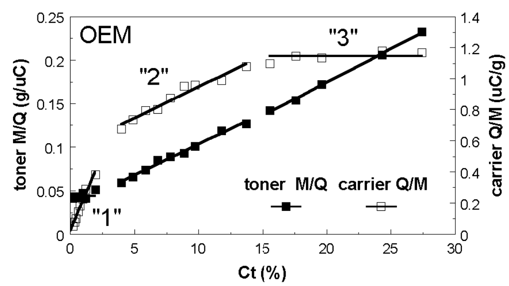

Figure 4. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, Ct.

For sake of clarity, region "1" data are displayed in Figure 5 using a smaller Ct scale. Figure 5 shows that toner M/Q is constant and carrier Q/M increases proportionally with Ct between 0.2 and 1.9%. Also, the intercept of the carrier Q/M curve is, within the experimental error, equal to zero. These results suggest that the electrostatic charges on the toner and carrier particles are limited by the surface charging sites of the toner, and Xt < Xc. Similar results have previously been reported,[11,12] but with very limited data in one study.[12] Interestingly, the insensitivity of toner M/Q to Ct is not reconcilable with the surface state theories since they all predict an increase in toner M/Q as a function of Ct.

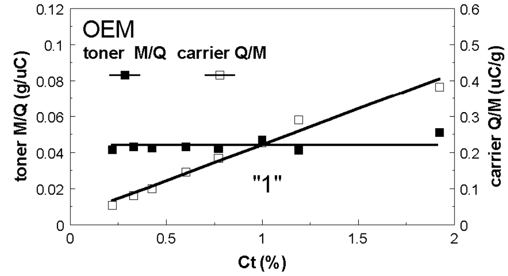

Figure 5. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, Ct, in region "1".

In Figure 4, region "3" shows that toner M/Q increases and carrier Q/M is constant for Ct ranging from ca. 15-28%, in marked contrast with region "1". The charging profiles of region "3" suggest that the electrostatic charge on the toner and carrier are limited by the surface charging sites of the carrier, and Xc < Xt. The intercept of the toner curve is not expected to be zero, but the experimental value is 0.01 ± 0.02 g/µC. Once more, the results are not consistent with surface state theories. Similar toner and carrier charging behaviors have also been previously reported for pseudo-toners.[11] It is also interesting to note that the way the toner concentration is calculated can affect the slope and the intercept of the toner charge curve exhibited in region "3". Indeed, for Ct values greater than 10%, the "real" toner concentration values (TC), defined by the weight ratio of toner to the total weight of toner and carrier in the developer, are significantly smaller than Ct values, defined by the weight ratio of toner and carrier in the developer. Figure 6 shows the same toner M/Q and carrier Q/M values as in Figure 4, but as a function of TC. Comparison of Figures 4 and 6 reveals that the slope and intercept of the toner M/Q curve in region "3" are significantly different, and the latter is equal to -0.02 ± 0.02 g/µC. As expected, the slopes and intercepts of regions "1" and "2", where TC is smaller than 10%, are practically unchanged. Therefore, it is more appropriate to use TC to represent the toner concentration.

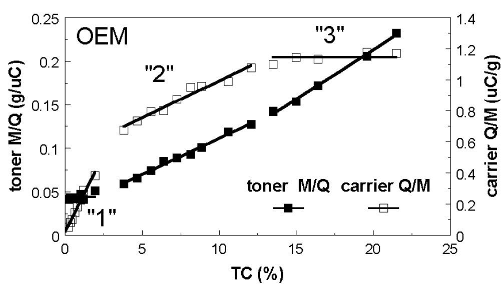

Figure 6. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, TC.

In Figure 6, region "2" shows that toner M/Q and carrier Q/M increase linearly with TC. The relationship between toner M/Q and TC in region "2" is consistent with the surface state theories. Comparison of regions "2" and "3" indicates that the toner charging profiles are similar, whereas the charging profiles for the carrier are quite different.

Figure 7 shows Nashua toner M/Q and corresponding carrier Q/M as a function of TC. Three distinct regions can again be identified from the carrier Q/M data. The toner M/Q data displayed in Figure 7 are the same as in Figure 2, only the line going through the data was rearranged. Region "1" for Nashua toner is also displayed in Figure 8 using a different TC scale. Figure 8 shows that Nashua toner M/Q values are constant from 0.2 to 3.0%, whereas the carrier Q/M is proportional to TC, with an intercept equal to zero. These results suggest that the electrostatic charges on the toner and carrier particles are limited by the surface charging sites of the toner, and Xt < Xc. Region "3", displayed in Figure 7, shows that the carrier Q/M has leveled off, whereas toner M/Q data are proportional to TC and have an intercept equal to zero. Toner and carrier data in region "3" suggest that the electrostatic charge on both materials is limited by the surface charging sites of the carrier, and Xc < Xt. Charging behaviors of Nashua toner in regions "1" and "3" are not in line with the surface state theories. In region "2", toner and carrier charge data have parallel slopes. The data displayed in region "2" is in agreement with the surface state theories.

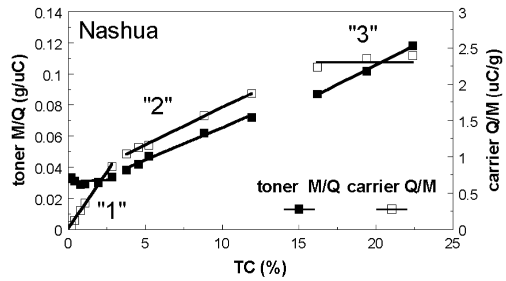

Figure 7. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, TC.

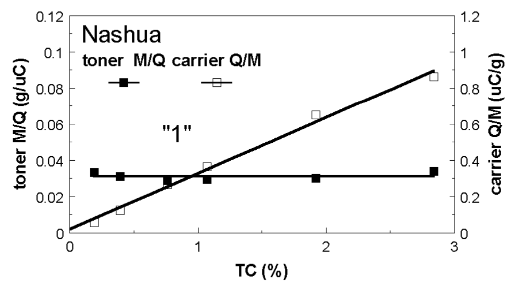

Figure 8. OEM toner mass-to-charge (M/Q) and carrier charge-to-mass (Q/M) ratios as a function of toner concentration, TC, in region "1".

Discussion

The charging profiles of OEM and Nashua toners display three distinct regions as shown in Figures 6 and 7, respectively. In region "1", toner Q/M values are the largest and are also insensitive to toner concentration. Therefore, the charge of the toner in that region will be called "saturated". In regions "2" and "3", the toner charge decreases as the toner concentration increases. Thus, the toner charge is "unsaturated" in these regions.

The three charging regions observed for OEM and Nashua toners are not brought about by a unique chemistry, since both toners are made with raw materials chemically different. Thus, similar charging profiles should also be observed for other toners and pseudo-toners. Despite numerous studies on the relationship between M/Q and Ct, only a few have reported charge data similar to regions "1" and "3".[11,12] This is likely due to the fact that in most studies, Ct range examined is narrow, insufficient Q/M data are generated for Ct range studied, and carrier Q/M data is ignored (regions "2" and "3" can hardly be differentiated when only toner Q/M data are used). Other factors may also prevent the observation of a saturated charge. Indeed, when excessive rolling times are used to determine the relationship between toner charge and toner concentration, the carrier surface often becomes contaminated. From a surface area ratio standpoint, the contamination of the carrier is equivalent to increasing the toner concentration, which, as depicted in Figures 6 and 7, will lead to unsaturated charge values. In other words, the toner concentration range corresponding to region "1" could be reduced to the extent that only region "2" will be observed. Modifications to the surface chemical composition of the toner can also occur after prolonged developer agitation and lead to the same effect. Considering all the arguments previously presented, it is not surprising to find that region "2" is the most commonly observed and reported region.

From a practical standpoint, region "1" is the most interesting due to the fact that a saturated toner charge can be maintained over a functional range of toner concen-trations. The magnitude and stability of the toner charge are essential in maintaining adequate copy/print quality in electrophotographic systems. Even though sophisticated sensors and complex electronics have been added to copiers and printers to monitor and compensate for toner charge changes occurring throughout the operating life of the developer in the machines, our functional test results suggest that toner alone may greatly enhance robustness. Indeed, after multiple life and environmental tests in several machines, the results show that Nashua toner has greater stability for: 1) toner charge and concentration, 2) optical density, and 3) background toner. We believe that Nashua toner is more robust than OEM because the "saturated" charge extends to a higher toner concentration value, as shown by comparing Figures 5 and 8. Also, the fact that Nashua toner charge decreases at half the rate of that of OEM toner in region "2" (see figures 6 and 7) may also contribute to the more robust performances obtained with Nashua toner.† These results suggest that toner can be designed to provide absolute charge stability with regard to toner concentration and lead to greatly improved copy/print quality robustness. Interestingly, current surface state theories[2,3,4,5] predict that a "saturated" toner charge cannot exist.

Conclusion

We showed that at least three distinct relationships exist between toner charge and toner concentration. These relationships can easily be mistaken for a single one if the Ct studied is too narrow, not enough data are collected, the carrier charge-to-mass ratio is not monitored. One of these three regions is of special interest since the toner charge is "saturated", i.e. insensitive to toner concentration. Machine test results show that copy quality is more robust for the toner that maintains a saturated charge over a wider range of toner concentrations. These results suggest that absolute toner charge stability can be achieved by design and lead to significant copy/print quality benefits.

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