Investigation of Factors that Impact Toner Mass Transfer in Electrophotographic Processes Using the Discrete Element Method

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Abstract

Toner mass transfer in the developer nip, an essential part of the electrophotographic imaging printing process, greatly effects print quality. It has long been known that toner particle size and toner particle charge are the two most important factors impacting toner mass transfer in the developer nip. However, there is no quantitative analysis to help determine the effects of these two factors, nor the interaction between them. A third factor, toner particle packing, also influences mass transfer but is typically not considered due to the lack of an effective metric to describe this packing. In this work, distance between particles is used to approximate this factor. The discrete element method (DEM) model developed in previous paper "Simulating Motion of Toner Using the Discrete Element Method" is used here to study effects of these three factors. All three factors (toner particle size, toner charge, and toner packing), and the relationship between these three factors, were investigated using the DEM model in a design of experiments (DOE) format to understand how they influence toner mass transfer. Factors affecting the pile height on the developer roller after mass transfer and the line-width on the developer roller after mass transfer are the same, however, the effect of these factors are different.

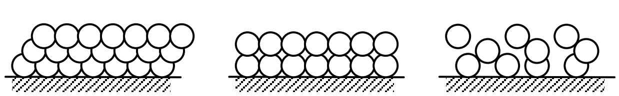
Introduction

In the previous work [1], a DEM model is developed to describe cohesive granular flow, especially toner flow. To validate the model, the overall DEM model is decomposed into three parts: cohesionless DEM model, cohesionless DEM model incorporated with Van der Waals forces, and cohesionless DEM Model incorporated with electrostatic forces. These decomposed sub-models are validated by comparing with experimental results.

The overall model is used to simulate toner mass transfer, one of the most important processes of EP process. The simulation results are compared with Hoffmann's experimental results, and they fit each other very well.

In this paper, factors impacting toner mass transfer are to be studied via this model. Although it is not completely understood what factors have impact on toner mass transfer, it has been observed that particle size and charge are two of the most important factors [2].

Toner packing is another important factor. Toner packing refers to how toner is packed on the first roller surface. However, this factor is very hard to quantify. Several possible packing modes are plotted into Figure 1.



(a) Hexagonal *(b) Quadrate* *(c) Random*

Figure 1. *Toner Packing*

As shown in Figure 1, toner packing can be a regular shape, or it can be random. In order to analysis how this factor impacts toner mass transfer, a quantitative description of this parameter is needed. However, this is not the main focus of this work. To simplify, a quadrate packing is chosen, and the distance between particles is chosen to quantitatively describe this parameter, as shown in Figure 2. It is assumed that $d_x = d_y = d$.

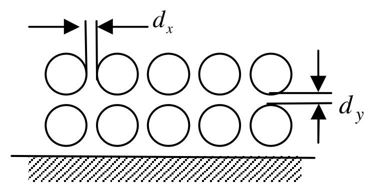


Figure 2. *Quantitative Description of Quadrate Toner Packing*

In this study, statistically designed simulations were conducted to study how size, charge, and toner packing (distance between particles) impact toner mass transfer using design of experiments.

Design of Experiments (DOE) is a structured, organized method to determine the relationships between factors impacting a response [3]. A set of structured tests are designed in such a way that factors are changed on a predefined patterns; thus, it provides an efficient way to study the impact of these factors compared to changing one factor at a time. A one-change-at-a-time method may find that one factor has significant effects on the response, but this change might depend on another factor, i.e., when the second factor is changed, it may alter the effect of the first factor.

Experimental Design

To use DOE, the first step is to identify factors, and the response variables that are to be measured. The second step is to determine a number of levels that defines the range of variables in which the effects of factors are to be studied. The third step is to produce an experimental plan which sets a set of combinations of factors at different levels. The response is to be measured at every experimental run, and these runs are randomly arranged.

Factors are to be studied have been identified in previous section. They are: size, charge, and distance between particles. Two levels of these factors are to be studied, and they are listed in Table 1.

Table 1. Factors for Toner Mass Transfer

Factors	Symbol	Units	Levels	
			+	-
A: Diameter	D	micron	10.0	6..0
B: Charge/ Particle	Q	C	-8.0E-15	-1.0E-15
C: Distance between particles	d	m	0.8E-9	0.4E-9

In general, factorial designs are most efficient to study effects of two or more factors [3]. With a full factorial design, all possible combinations of the levels of the factors are investigated. The factorial designs have several advantages: 1) They are more efficient than one-factor-at-a-time experiments; 2) A factorial design is necessary when interaction may be present, and conclusions draw from one-factor-at-a-time experiments are misleading in the case where interactions are present; 3) Factorial designs allow the effects of one factor to be investigational at different levels of other factors, which can provide valid conclusions over a wide range of experimental conditions.

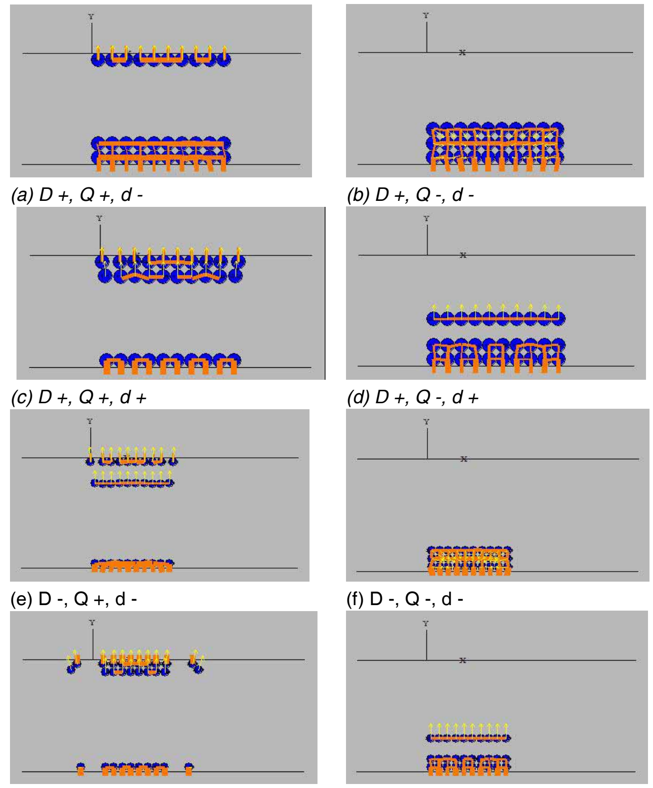
Since there are only three factors, a full two-level factorial design is used. Thus, all possible combinations of all three factors at two different levels are studied. Table 2 shows all possible combinations of these three factors at different levels.

Table 2. Experimental Design Matrix

Order	Diameter (D)	Charge (Q)	Distance (d)
1	+	+	-
2	+	-	-
3	+	+	+
4	+	-	+
5	-	+	-
6	-	-	-
7	-	+	+
8	-	-	+

Results

Each designed experimental run is simulated using the DEM model developed in previous work [1]. For every 5000 cycles, a picture is saved and all pictures saved during the simulation are combined into a video file. The last pictures of these simulation runs, which are taken after a total 400000 cycles for each simulation run, are given in Figure 3.



(a) D +, Q +, d - *(b) D +, Q -, d -* *(c) D +, Q +, d +* *(d) D +, Q -, d +* *(e) D -, Q +, d -* *(f) D -, Q -, d -* *(g) D -, Q +, d +* *(h) D -, Q -, d +*

Figure 3. *Simulation Results after 400000 Cycles*

It can be seen from these graphs in Figure 3 that toner mass transfers at these eight different situations are very different. To quantify the effects of these factors, results are analyzed with design-expert DOE analysis software. The positions of the representing particle, as shown in Figure 4, are documented. The absolute value of change in x direction and the y position of this representing particle at the end of simulation are chosen as two response variables. They are analyzed below.

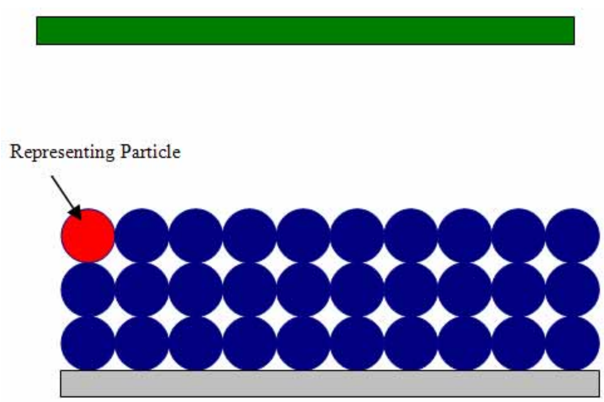


Figure 4. *Representing Particle*

Response 1: Absolute Change in X Direction

The absolute change in X direction between before and after transfer is a good indicator for the location after transfer. The bigger this response is, the worse the location of particles is after transfer. The effects of factors and their combinations are plotted into Figure 5.

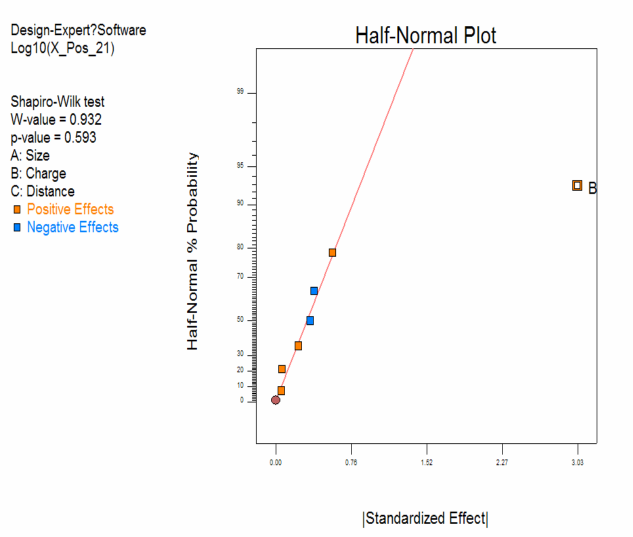


Figure 5. *Response Variable 1: Half-Normal Plot*

Figure 5 is the half-normal plot for the response variable 1, the absolute change in X direction of the representing particle. Factors that fall into the straight line, the orange line shown in Figure 5, are non-significant factors, while factors that lie away from the straight line are significant. The further the factor is away from that line, the bigger the effect is.

As we can see from Figure 5, factor B (charge) is the only significant factor. The Analysis of Variance Table (ANOVA) for this response variable (absolute change of X position for the representing particle) listed in Table 3 also confirmed this result.

Table 3. ANOVA for Response 1

Source	Sum of Squares	df	Mean Square	F Value	p-value
Model	97.43	1	97.43	84.12	< .0001
B-Charge	97.43	1	97.43	84.12	< .0001
Residual	6.95	6	1.16		
Cor Total	104.38	7			

However, this conclusion is valid only when the consumption of "normally and independently distributed errors" can be satisfied. This assumption can be checked via the normal plot of residuals, showed in Figure 6.

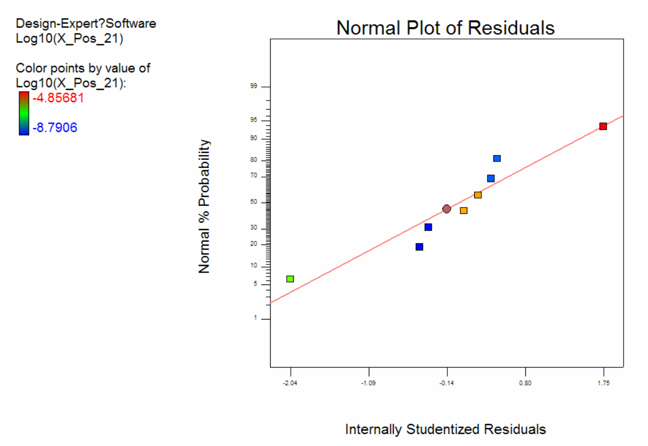


Figure 6. *Response Variable 1: Normal Plot of Residuals*

From the normal plot of residuals for response, it can be seen that residuals fall into one straight line. This indicates that the "normally distributed residuals" assumption is satisfied.

After identifying significant factors to the representing particle absolute position change in X direction, we can study how the significant factor impacts this response. Figure 7 shows the effect of factor B (charge).

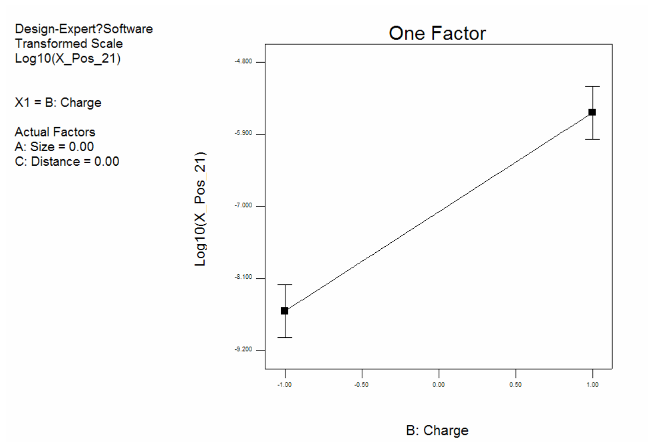


Figure 7. *Response Variable 1: Effect Plot of Factor B (Charge)*

It can be seen from Figure 7 that to achieve a desired location of this particle, that is to say, to get a small change in x direction, a smaller charge is desired.

Response 2: Y Position of Particle 21

The y position of the representing particle after 400000 cycles is chosen as another response variable. It can provide a good indication on the time needed for the particle to be transferred from the developer to the OPC.

Figure 8 shows the half-normal plot for response variable 2. This shows that for this response variable, only factor B (charge) has significant impact.

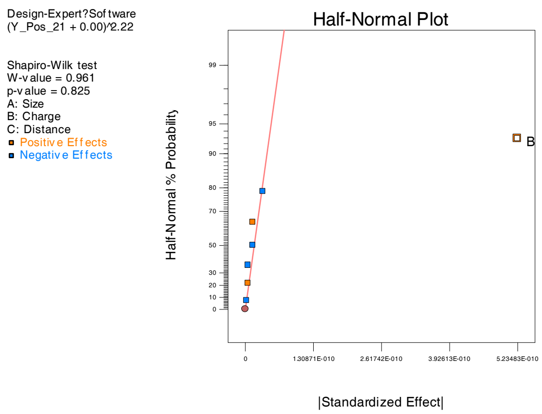


Figure 8. *Response Variable 2: Half-Normal Plot*

The very small p value in the ANOVA analysis listed in Table 4 also confirms this result.

Table 4. ANOVA for Response 2

Source	Sum of Squares	df	Mean Square	F Value	p-value
Model	5.481E-019	1	5.481E-019	1041.86	< .0001
B-Charge	5.481E-019	1	5.481E-019	1041.86	< .0001
Residual	3.156E-021	6	5.260E-022		
Cor Total	5.512E-019	7			

Figure 9, the diagnostic normal plot of residuals, shows that the assumption is satisfied.

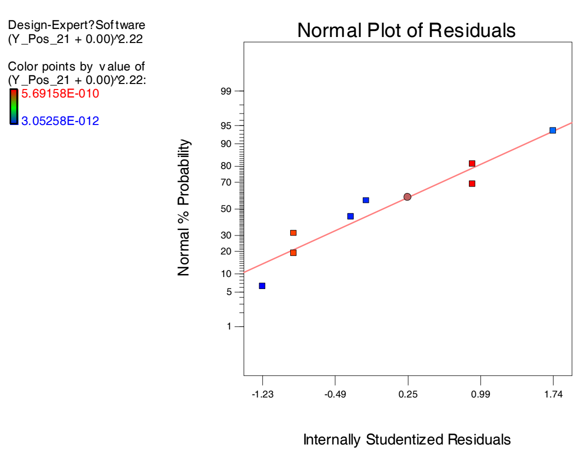


Figure 9. *Response Variable 2: Normal Plot of Residuals*

Figure 10 shows the effect of charge on the time needed for toner to be transferred. It can be seen from this graph that the y-position of the representing particle will increase as the charge of this particle increases, that is to say, it takes less time for this toner particle to be transferred to the OPC if it gets charged more.

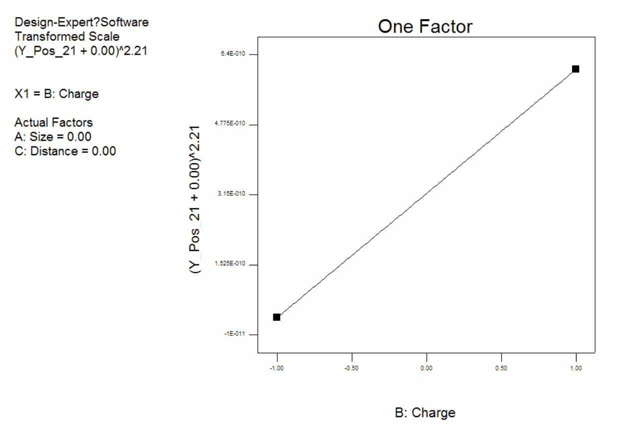


Figure 10. *Response Variable 2: Effect Plot of Factor B (Charge)*

Although it shows that the higher charge will help toner particles to be transferred to the right location in less time, this statement is only valid for the range which has been studied in this research. There might be some risks if toner particles are overcharged. More research is needed to determine that.

For the desired position after transfer, a smaller charge is desired while a higher charge is desired to transfer toner at a less time. That is to say, a trade off has to be made to transfer toner to the desired position as quickly as possible.

Summary

In this work, an example illustrated how to use the model developed in previous work [1] to conduct analysis. DOE was used to design a set of DEM simulations to study the effects of three critical factors on toner mass transfer: toner particle size, particle charge, and the distance between particles packed on the developer surface. The left-most particle on the top layer was chosen as an example to quantitatively study the effects. The absolute position change of this particle in X direction, and the position of this particle in Y direction are chosen as two response variables. For both response variables, Factor B (charge) is the only significant factor. However, the effects of this factor are different. To achieve a desired position after transfer, a smaller charge is needed. To transfer toner more quickly to the desired position, a higher charge is needed. That is to say, a trade off has to be made.

References

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[2] R. Hoffmann, “Modeling and Simulation of an Electrostatic Image Transfer”, Dissertation, Technische University Munchen, (2004).

[3] D. C. Montgomery, “Design and Analysis of Experiments”, Wiley, (2000).

Author Biography

Hong Ren: She received her MS degree in Mechanical Engineering from Southwest Jiaotong University (1999), and will receive her PhD degree in Mechanical Engineering this coming Aug from University of Idaho. She is currently working at Hewlett-Packard Company as a hardware development engineer.

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Thom Ives, Ph.D.: He has worked at HP for 9 years and has performed a variety of research, development and engineering tasks. He has 21 U.S. patents. He teaches occasionally at local universities. He received his Ph.D. in 1997 from Texas A&M University where he modeled and researched hybrid-electric-vehicle power plants. His 1995 M.S. was also from Texas A&M with research in robotics. His B.S. was received from The University of Texas in 1984. All these degrees are in Mechanical Engineering.

Santiago Rodriguez: He has worked at HP for 20 years in many different areas of product generation such as manufacturing of circuit boards, development of "Surface Mount processes", design of circuit boards, ASIC packaging design, LaserJet product development management. The last seven years he has worked as an Electro photographic engineer responsible for Laser Jet development of monochrome and color consumables. He received his M.S. in 1987 from SDSU, and B.S. from the University of Puerto Rico.