CHAPTER 2

THEORETICAL BACKGROUND AND LITERATURE REVIEWS

2.1 Theoretical background

2.1.1 Nonimpact printing processes

Early nonimpact printers used technologies of direct printing on specially treated paper for machine simplicity. Later, in order to reduce the operating costs for high volume users, transfer methods were developed to reuse the sensitive material and print on untreated paper similar to plain paper photocopiers. The tendency of research and development is to eliminate the complex transfer step, and print directly on plain paper. Early machines used shaped characters for reasons of technology, cost, or similarity to exist impact printers. As the cost, complexity, and resolution of matrix methods improved and user acceptance increased, the use of matrix methods became more widespread. The advantages of variable character size and shape, special fonts, and full graphics capability have driven most development undertaking in the direction of matrix character printing with resolution requirements sufficient to approach the image quality of fully formed characters. Nonimpact printing process will be classified according to the method of imaging or temporary storage. The largest groups of nonimpact printing methods are electrostatic printing techniques. Electrostatic printing is defined as those methods, which use the interaction of electrostatically charged pigment q and an electric field E to control the deposit of colorant material on a recording substrate. The q * E interaction is a total variation, which occurs as:

$$\Delta(qE) = q\Delta E + E\Delta q \tag{2-1}$$

The first term on the right of the equation represents a process where a latent image field ΔE contains the image information that is developed by uniformly charged particle q. The second term represents a process where the latent image charge Δq contains the image information and the constant electric field E in the developer .[1]

Nonimpact printing processes can be described using the working of conditions shown in the Figure 2-1 for electrographic printing.[1]

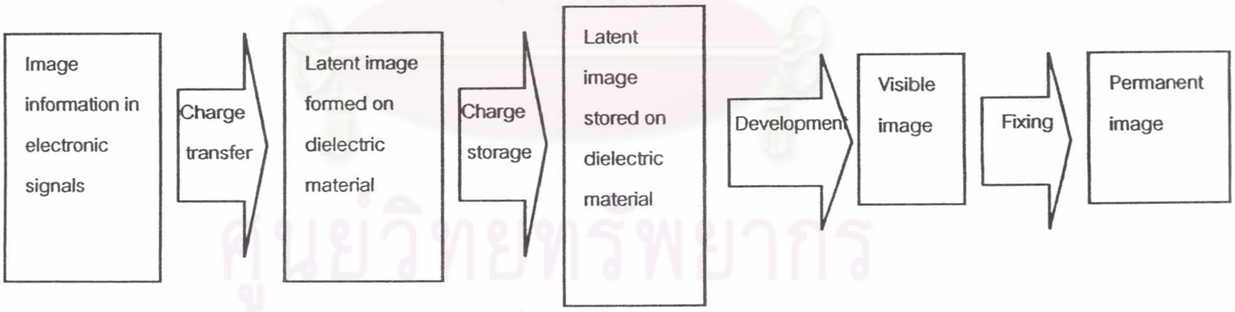


Figure 2-1 Electrography printing functional diagram

Each statement in a box represents a condition in the printing process. The names shown within the arrows are the actions leading to the next condition. Each printing process has a unique set of conditions and actions, however, many of the conditions and actions are used in many different printing processes.

2.1.2 Toner-based printing systems

There are several types of toner, which are used in industry, for example, single component, dual component, magnetic toner, and conductive toner. Conductive toners utilized in some single component and dual component development systems can be formulated by dispersing fine conductive additives on the surface of insulative toner particles. Electrical conductivity of such toners depends not only on intrinsic conductivity of the additives, but also on their dispersion on toner surface. There are five main types of toner printing system. These are electrophotographic, ion deposition, electrostatic, magnetographic and electrographic printing. The most important and wide use of this printing system is electrophotography. [2] Now, toner jet has been developed with the expressed purpose to be faster than ink jet and lower in cost than electrophotographic.

2.1.2.1 The Electrophotographic Process

The active history of electrophotography began with the inventions of Chester Carlson in 1938. He used sulfur as a photoactive material to make images. In 1959, Haloid Corporation (now is Xerox) introduced a 914 automatic copier, which used selenium metal as the photoreceptor and this is regarded as the first commercial negative dry toner using styrene methacrylate copolymers. During the 1970s, IBM and KODAK developed and introduced copiers based on organic photoactive materials and positive charging toners. During the 1980s, Japanese manufacturers, such as Canon and Minolta, produced low speed copiers based on selenium and cadmium sulfide photoreceptors using negative toners. They also introduced dry toner copiers using a single component development, eliminating the use of carrier beads. Since the 1980s, many combinations of single component and two component developments, and positive and negative toners have been used in the industry. A basic structure of electrographic system is shown in Figure 2-2. Electrophotographic process, which is constructed from charging, exposing, developing, transferring and fixing process, forms output images on the paper by each different phenomenon.

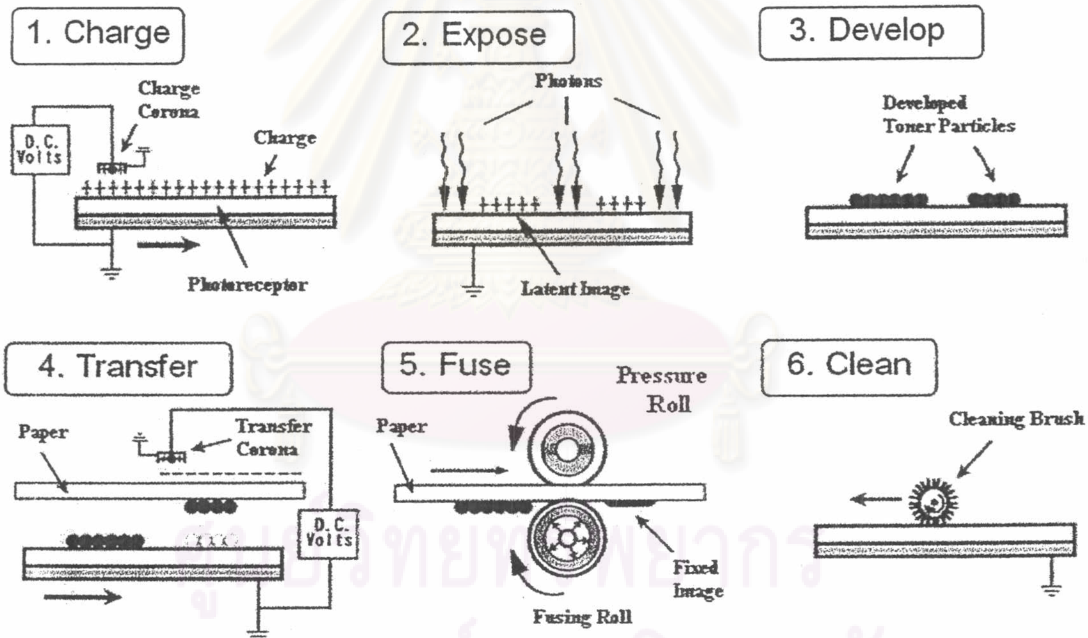


Figure 2-2 Schematic diagram of the electrophotographic process

In the charging step, the photoreceptor is covered with ions of the appropriate polarity through the use of a wire or grid bias to high voltage. In the exposure step, an optical system forms an image of the document on the photoreceptor. When the document is white, there is sufficient light to cause the photoreceptor to conduct charge and neutralize the image, but the dark lines of the text leave the charge undistributed when imaged on the photoreceptor. This step forms a latent image of charges, duplicating the original document. In the development step, a toner of the opposite sign from the latent image is typically brought into contact with this image. In the transfer step, a piece of paper is brought onto the photoreceptor, and the backside of the paper is charged with ions opposite in polarity from the toner. This attaches the great majority of the toner particles to the paper. The paper is then removed from the photoreceptor and passed through the fuser. In the fusing step, the toner is molten onto the surface of the paper. In the cleaning step, the small amount of toner remaining on the photoreceptor, after being transferred, is removed by an electrostatic brush or a conformable rubber blade.

2.1.2.2 Toner jet

Toner jet is a printing technology, which was invented and developed by Array Printer AB in 1986. Toners jet is a direct print process that easily achieves, extremely good and stable color registration at low manufacturing cost. The dot registration can be controlled by a feedback loop that measures the print media position.[3] The speed and performance of the print process have improved when implementing a chemical toner. Toner particles are applied in the thin layer on feeding steel roller by a brush. The brush charges the surface of the plastic particle electrostatic. Mirror forces holds the charged particles to the roller surface. Figure 2-3 shows the schematic of the toner transport by toner jet method. A flexible printed circuit board (called FPC) is mounted in the area between the feeding roller and the print media. The FPC contains an array of apertures. The electrode that can be controlled surround each aperture as shown in Figure 2-4. Applying the voltage on the electrode can modulate the electric field between the feeding roller and the back electrodes. The forces acting on the toner particles consist of the electrical field force, coulomb forces, mirror force, collision forces, friction force, and air draught forces.

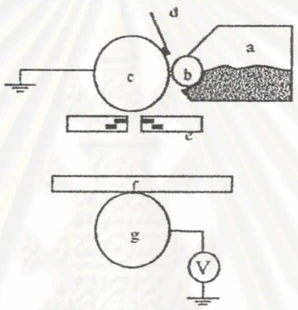


Figure 2-3 Schematic layout of the toner transports by toner jet method: a) toner container, b) brush, c) feed roller, d) FPC, e) print media, and f) back electrode.

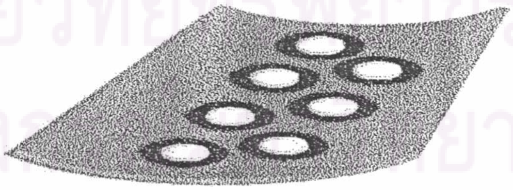


Figure 2-4 Flexible printed circuit board with two rows of apertures and ring electrode.

Toner Jet is now the print technology that combines color printing at a high speed, good print quality and a low manufacturing cost. The print media is paper or an intermediate image transfer belt. Figure 2-5 shows a printer model with four print heads, one for each color, using a transfer belt as print media. [3]

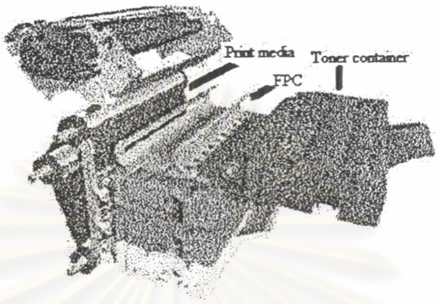


Figure 2-5 Toner jet printer with four print heads, CMYK, using a transfer belt as print media

The toner particles (negatively charged) are attracted to the print media by the electrostatic forces. The electrostatic forces generated by a potential difference between a toner supply sleeve and a back electrode. The back electrode is located behind the print media and has a higher potential than the toner supply sleeve. The potential difference creates the electric field that transfers the toner particles from the toner sleeve to the print media. The FPC is mounted in this electric field, which has an array of small apertures as shown in Figure 2-6.[3]

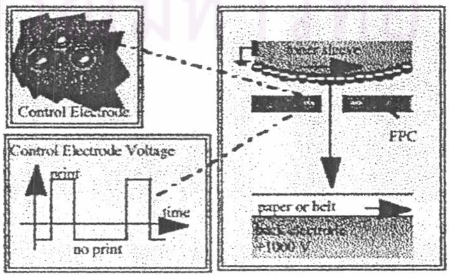


Figure 2-6 The control electrode in the Flexible Printed Circuit

The dots on the print media created by the toners that pass through these apertures. The potential of the control electrodes controls the toner transport to the print media. So, the toner particles can pass through the aperture and form a dot by used the control electrodes. Figure 2-6 shows how the control electrode potential is pulsed to a print voltage that allows toner transport to the print media.

2.1.3 Toner components

Dry electrophotographic toners consist mainly of a colorant in a binder resin. Besides these essential ingredients, a particular toner design may contain charge control additives, surface additives, magnetic additives and other additives such as wax.

2.1.3.1 Resin

The role of resin in a toner is to bind the pigment to the paper or transparent material to form a permanent image. The selection of the polymer depends on the fusing or melting properties and the fusing method, which can be subdivided as follows :

a) Cold pressure method

The materials for this method are typically lower molecular weight polypropylenes, polyethylenes, ethylene-vinyl acetate copolymers, and mixture of these materials. These cold pressure fix materials have the advantage of requiring low power in operation and no standby power.

b) Continuous radiant source

Using a quartz lamp or heated coil to melt the toner into the paper fibers. The viscosity of the toner usually reaches quite low melt viscosity in flowing into the paper. The polymers such as polyester and epoxies, which have a molecular weight ranging from 5,000 to 50,000 and glass transition temperature from 50 to 60 ° C, are often used.

c) Flash fusing

The toner is melted into the paper by a very short, high intensity flash of light lasting less than 5 ms. Styrene copolymers, epoxies, and polycarbonates have been used in this fusing technique for fixation of toner images.

d) Roll fuser

The paper with the unfused toner passes through a nip formed by a heated roll and a backup roll forced against the heated roll at fairly high pressures. The polymers used are styrene copolymers such as styrene acrylates, methacrylates, and butadienes, which have molecular weights ranging 30,000 to 100,000 and glass transition temperatures ranging from 50 to 65 °C.

2.1.3.2 Colorants

The most common colorant for electrophotographic toners is carbon black. Important properties of carbon blacks for applications are their dispersibility in the polymer resin and their tendency to charge either positively or negatively. Carbon black is usually used in toners at 5 to 15% loading. Besides carbon black, there are other materials that can be used to make black toners, for instance, magnetite is used to control magnetic properties of toner, and nigrosine is used as charge control agent as well as black pigment. For full color electrophotography, the organic pigments are usually used, such as, copper phthalocyanines are used for cyans and blues, azo pigments for yellows, and quinacridones or rhodamines for magentas and reds.

2.1.3.3 Charge control additives

Charge control additives, CCA, are added to the toner when the pigment blended into the polymer does not give an adequate charge level or rate of charging. For positive images, the quaternary ammonium salts are usually used in color toners because they are colorless. The other is nigrosine, which is black and used in black toners. For negative applications, acidified carbon blacks, fumed silicas and metal complexes are used.

2.1.3.4 Surface additives

Surface additives, such as fumed silicas are added to the toner surface to improve flow properties, transfer efficiency of the toner from the photoreceptor to paper by decreasing the adhesion of the toner to the photoreceptor, and improving the charge stability of the toner and carrier mixture. The fumed silicas also decrease the toner agglomeration.

2.1.3.5 Other additives

These additives are used in a specific application, such as silicone oil, which is used as a release agent for the fuser roll.

2.1.4 Toner Characterization

2.1.4.1 Rheology

The rheological characteristic of a toner especially affects fixing behavior. There are three significant temperatures necessary to characterize the toner-fixing behavior.

a) The minimum fixing temperature is an adequate temperature at which the image is fixed to the paper.

b) The hot offset temperature is higher than the minimum fixing temperature at which the toner is so fluid that it simply splits apart when the paper leaves the fuser roll, leaving traces of the image on the fuser roll to undesirably contaminate the next sheet.

c) The blocking temperature is the temperature at which significant sintering occurs.

Besides these, a commonly measured characteristic of a polymer is its glass transition temperature, Tg, where the polymer changes from a hard glass to a rubbery state. This is measured in a differential scanning colorimeter, which looks for the change in heat capacity at the transition. For adequate blocking, toners generally should have a Tg value above 50°C. [4]

2.1.4.2 Colorimetrics

For the black toner, the primary consideration is its ability to generate high optical densities. For highlight color toners, there should be able to develop an optical density of the color with the tinting strength or chroma of color and pleasing hue. For process color developers, the goal is to generate as wide a color spectrum as possible, which depends on the detailed spectral absorption of the various pigments.

2.1.4.3 Particle Size

Toner particle sizes are generally in the range of about 10 to 20 μm in diameter. The particle sizes larger than these usually produce ragged lines and dots. The smaller particle sizes than this range improve color reproduction and noise reduction. However, the smaller particle sizes require longer times in manufacturing, hence are more expensive to produce. Also smaller sizes tend to produce more dirt at a given charge-to-mass ratio and to cause more rapid developer degradation.

2.1.4.4 Charging

The charge on the toner is controlled by the selection of its carrier chemical nature and the mixing condition. When the toner and the carrier are rubbed together, the triboelectric series, which depends on a work function of them are generated. The one lower on the work function series becomes the electron acceptor or negative charge, and the one higher on the work function series becomes the electron donor or positive charge. There are two quantities of the toner charge measured by Blow-off method. For the toner particle size of around 10 μm, the useful range of charge-to-mass ratios is from 10 to 30 μC/g. Toner particles with a higher charge are difficult to strip from the carrier and also deposit little mass for a given amount of charge image density. The q/m values below 10 μC/g generally lead to both a dirty environment in the machine and background density on the copy. [4]

2.1.5 Toner cloud generation

Toner jumping phenomena generates toner clouds. When one of the conductive toner particles is jumping from the lower electrode to the upper electrode, the following relationship can be written as below, and its setup is illustrated in Figure 2-7.[6]

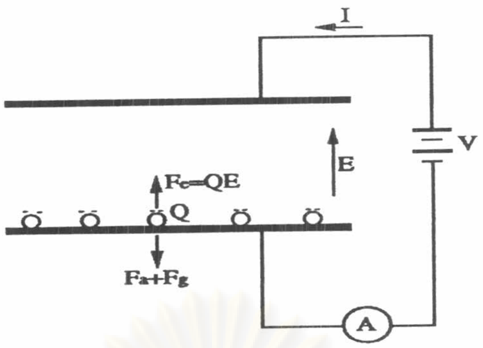


Figure 2-7 Schematic diagram of the setup for toner jumping method

$$F_e = F_a + F_g \tag{2-2}$$

where F_e is the electrostatic force, F_a is the adhesion force between the toner particle and the substrate and F_g is the gravitation force. Then, the adhesion force of a conductive toner particle can be written as shown in equation 2-3, [5]

$$F_a = F_e - F_g \tag{2-3}$$

Two conducting parallel plates are used across to which an electric voltage is applied. Conductive toner particles are first deposited on the top surface of the bottom electrode. The total current, I can be written as:

$$I = I_C + I_t \tag{2-4}$$

where I_C is the current though the parallel plate capacitor and I_t is the current caused by the toner jumping.

$$I_t = c\,(dV/dt) = C\beta \tag{2-5}$$

if we express

$$V(t) = \beta t \tag{2-6}$$

where V is the applied voltage and β is the rate of increase of voltage in V/s.

I_t is the current caused by the toner jumping between the two parallel plates. I_t can be written as:

$$I_t = nqbE \tag{2-7}$$

where n is the number of particles, q is the electrostatic charge on the toner, b is the electrical mobility, and E is the magnitude of the applied electric field. Conducting toners are used so that the effect of triboelectric charging of the toners on the electrostatic force balance can be eliminated. Conducting toner particles resting on the bottom grounded electrode will acquire induced charge due to the applied electric field E. The polarity of the induced charge will be opposite to the polarity of the applied voltage at the top electrode. The magnitude of the charge for spherical particles is given by:

$$q = K_1 \pi\varepsilon_0 r^2E \tag{2-8}$$

where ε_0 is the permittivity of free space, r is the radius of the toner particles, K_1, is a numerical constant, and E is the applied electric field at any instant. For a given electric field E, the force of detachment experienced by a toner particle is given by:

$$F_d = qE = K_1SE^2 \tag{2-9}$$

where S is the effective projected surface area of the toner particle, which means the cross section of an electric flux reaches the toner as shown in Figure 2-8.[6] When the shape of the toner is spherical, the area S becomes $1.65\times4\pi r^2$. [6]

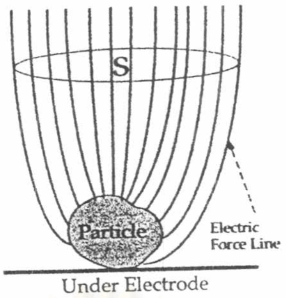


Figure 2-8 Relation between toner shape and the area S.

The forces of adhesion between the substrate have three components: 1) electrostatic image force (F_i), 2) the van der Waals force (F_{vdw}), and 3) gravitational force (F_g). The total force of adhesion

$$F_a = F_i + F_{vdw} + F_g \tag{2-10}$$

When the electric field approaches a threshold value, we have a detachment of particles. The detachment force is

$$F_d \geq F_a \tag{2-11}$$

As the conducting toner particles carry charges from the bottom plate to the top plate, they lose their charge and acquire an electrostatic charge of opposite polarity due to induction. The particles then leave the top plate and reach the bottom plate.[7]

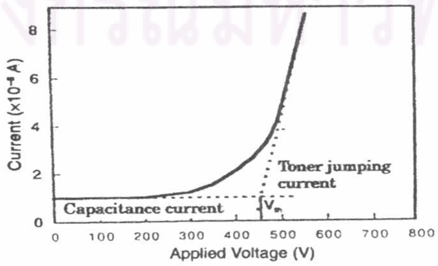


Figure 2-9 Determination of threshold voltage for toner jumping across the parallel plates.

Figure 2-9 shows a typical current voltage relationship. As the applied voltage is increased, there is a constant capacitive current and when the voltage exceeds a threshold value, there is a significant increase in the current.[7] The threshold voltage is determined, as shown in Figure 2-9, so that the initial rise of current that might be caused by dust and fine particles can be neglected.

2.1.6 Toner Cloud Confinement Condition

The toner, which is in a powder form for toner image, plays an important role in controlling the powder motion in every application of toner printing.

The electrodes used as shown in Figure 2-7 in the experiments are a brass plate and an ITO (Indium Tin Oxide). The brass plates are prepared, one is flat and the other is dented to a thin lens shape as shown in Figure 2-10.[6]

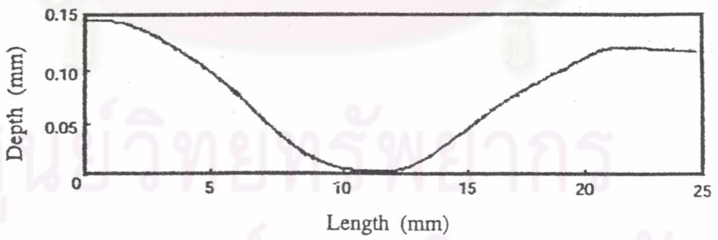


Figure 2-10 Cross section of the dented shape electrode.

When the applied voltage overcomes the sum of the adhesion force and the gravitational force, the toner starts to move up and down between the electrodes with electrostatic force, when the applied voltage overcomes the sum of the adhesion force and the gravitational force. The toner jumping current rises from zero due to the electric charge carried by the toner. So, the toner is charged within a certain relaxation time, which is controlled by the applied voltage. Figure 2-9 shows the typical current versus the ramp voltage applied between the electrodes.[7] Therefore, the dented electrode is effective in confinement of the jumping toner.

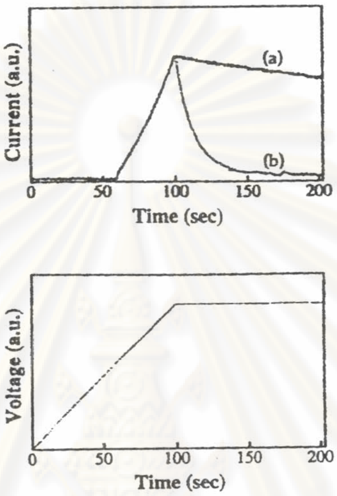


Figure 2-11 Current waveform versus applied voltage. (a) dented electrode. (b) flat electrode.

Figure 2-11 shows the typical current wave form versus ramp voltage applied between electrodes. Current wave forms (a) and (b) correspond to the dented electrode and flat electrode, respectively.[6] The amplitude of current has a linear relation to the amount of jumping toner in the condition of same electric field as shown in Figure 2-12. It is understood that the dented electrode is effective in confining the jumping toner. The confinement is also confirmed by observing the toner motion through the upper transparent electrode, which is covered by the thin layer of ITO. When the toner starts jumping, the toner on the electrode goes out of sight and becomes like a black cloud in the dented area.[6] The phenomenon is believed to be due to the fact that the electric force has the component toward the central axis as shown in Figure 2-12,[6] and by the momentum of the collision under dented electrode with electric force lines toward the central axis.

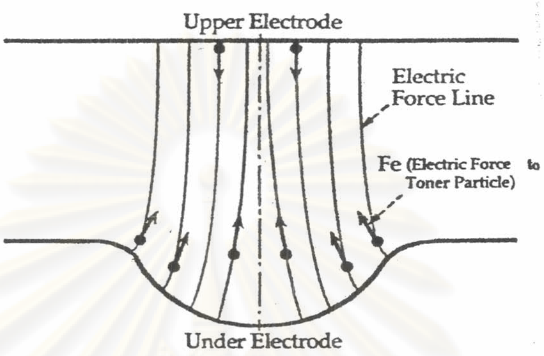


Figure 2-12 Schematic illustration of toner motion in the case of dented electrode ------- (for the central axis).

Figure 2-13 shows the typical relationship between the current and the applied voltage. The current begins to increase at a certain voltage and drops at another certain voltage. Figure 2-13[6] also shows the method of obtaining the voltages, at which the toner begins jumping and stops jumping. There are slight differences between these voltages. such differences are caused by the disparity between the adhesion force, which sometime has elapsed and sometime the adhesion force is just enough to adhere. Jumping conductive toners are confined between electrodes, one of which is dented to a thin lens shape. So, the start and stop toner jumping characteristics are then measured by the increasing and decreasing ramp voltages.

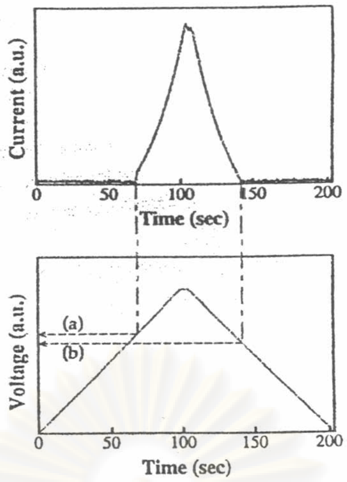


Figure 2-13 Current versus voltage, when the voltage waveform is trapezoid. The marks (a) and (b) mean the voltage of jump at begin and at stop, respectively.

2.1.7 Toner Cloud Beam

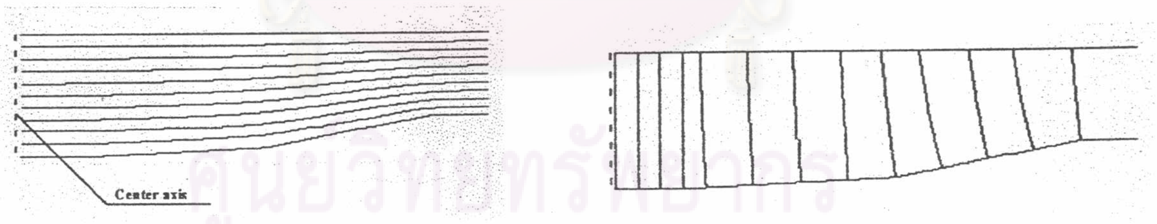
The control of toner motion is significant for evaluation of nonimpact printing. Main evaluation items of the printing process are print quality, printing speed and simplicity of printing mechanism. The print quality is controlled by the precision of position where a toner particle is attached to a paper and the controllability of an amount of attaching toner particles.

Although the printing mechanism of electrophotography is very complex but print quality and speed are excellent. So, the electrophotoghaphy is used as one of major non-impact printing technologies. In order to reduce the operating costs for printing mechanism, Toner jet is one of important attempts. Toner is selectively conveyed to paper. The printing mechanism is simplified compared with the electrophography.

The dot formation method as "Toner Cloud Beam (TCB)" is a printing technology, which has characteristics of simpler printing mechanism, higher printing quality, higher printing speed, and/or better stability and maintainability. The TCB method is that toner beam is extracted from toner cloud generated by electric field applied between electrodes and the toner beam is then projected to paper.

The conductive toners start move up and down between the electrodes because the conductive toners are charged by conduction from the electrode under the electric field applied and electric force (toner charge × electric field) works on the toners. The conductive toners can be confined between electrodes using the dented electrode. This confinement is realized by electric field toward the central axis of the dented electrode. Figure 2-14 shows an example of the electric field analysis.[8]

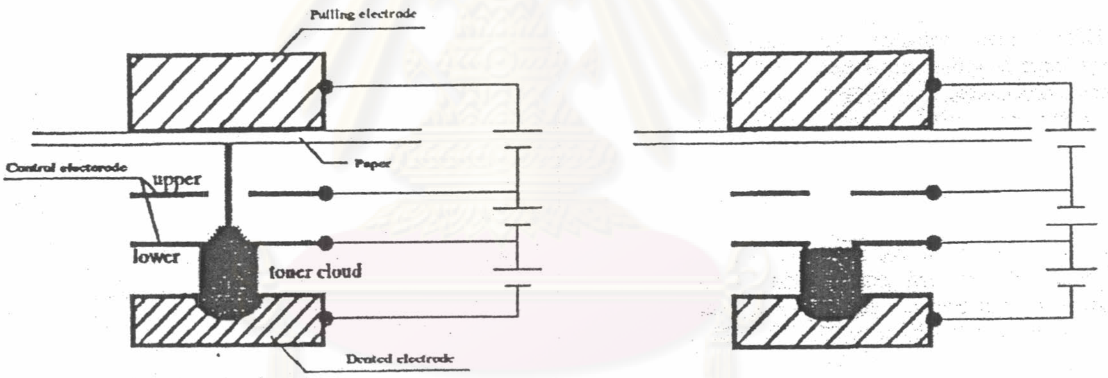
When the toner moves upward, the force toward the control axis worked on toner is more effective comparing with the force moving downward.



a) Equal-potential line b)Electric force line

Figure 2-14 Results of electric field analysis.

The generation of toner beam is controlled as shown in Figure 2-15 that (a) shows the toner beam at the "on", state and Figure 2-15 (b) shows the toner beam at the "off" state.[8] From the dented electrode, the negatively charged toner moves upward. When a higher voltage is applied to the upper control electrode than to the lower control electrode, the toner moving upward can pass through the control electrode. When the voltage of the upper electrode is less than the lower electrode, the toner can not pass the control electrode, because the direction of electric field in the aperture of control electrode become blocking. [8]



(a) "on" state (b) "off" state

Figure 2-15 Toner beam control mechanism.

When the voltage of the upper control electrode increases, the toner passing area of a cross section aperture increases, therefore, the amount of toner also increases as the voltage increases. The toner passes through the aperture when the potential of upper electrode is negative by the electric field within the aperture. The electric fields between the pulling electrode and the upper control electrode, and also the electric field between the dented electrode and the lower control electrode influence the electric field within the aperture.

2.2 Literature Reviews

The measurement of van der Waals force of toner adhesion between various substrates and different particle sizes of toner, which involves the measurement of the detachment force by toner jumping between the parallel plates. This method was proposed by Hoshino et. al [7]. In their experiment, three difference sizes of toner including small, medium and large size were used. These toners are derived from the same source of material, which was classified into three sizes. Three types of substrates namely stainless steel, silicon wafer and PPC paper were used. According to their experiment, the conductive toners were first sprayed on the top surface of the bottom plate, then the ramped voltage to the two parallel plates at a constant rate was applied. When the electrostatic force of detachment exceeds the forces of adhesion between the toners and substrate, there was a significant increase of the current between the two parallel plates due to the toners jump from the bottom plate and reaching the upper electrode. Moreover, they found that the threshold voltage for detachment of toners from the substrate, decreases with increasing particle size. The threshold voltage for toner jumping remains essentially the same for both stainless and silicon wafer. They found that the threshold voltage had to be significantly higher for toner jumping to start when the moist papers were used.

In the experiment of Kiatkamjornwong et. al,[9] they applied the toner jumping method to estimate toner adhesion force by electric field activated toner jumping, by which various substrates and toner particle size were used. Four conductive toner sizes were performed including G2G (14.6 μm), G2M (12.25 μm), M2G (9.43 μm), and M2M (14.6 μm). The lower electrodes used were a crystalline silicone wafer, Organic Photoconductor (OPC), Indium Tin Oxide (ITO) coated glass, and stainless steel, while the upper electrode was stainless steel. In addition, several toner application methods were tried including free falling, wipe-on using Kim-wipe and magnetic brush. According to this experiment, the toners were made conductive by the inclusion of carbon black and silica for improving flow property and the conductive toner was sprayed on one of a pair of electrodes. Then the voltage was applied to the electrode at a constant rate and toner jumping started at the voltage where the electric force overcomes adhesion and gravitation forces. From the toner jumping voltage or the threshold voltage, the adhesion force was estimated. From this experiment, the adhesion force of toner jump f_{adh} was calculated.

The following equation can be used :

$$f_{adh} = \varepsilon_0 S E_{th}^2 \qquad (2\text{-}12)$$

where

E_{th} = electric field when V_{th} is applied

ε_0 = permitivity of the free space, 8.85×10^{-12} F/m

S = effective cross section of toner particle (m^2)

So, f_{adh} can be written as follows :

$$f_{adh} = 8.85 \times 10^{-12} \times 4\pi^{1/3}(3\ V/4)^{2/3}[V_{th}/0.6 \times 10^{-3}]^2 \qquad (2\text{-}13)$$

The adhesion force was calculated by Equation 2-13. They found the results of V_{th} and E_{th} are in inverse relationship with the size of the toner. The conductive glass shows significantly different jumping voltages of the toner whereas the amorphous silicon film was inactive to the voltage applied and toners cannot jump. Moreover, when using the magnetic brushing technique, the threshold voltage is higher than Kim-wipe rubbing and free falling, respectively.

The influence of electrostatic and van der Walls force to toner adhesion by comparing results of the toner jumping method and centrifugal method, was carried out by Fukuchi and Takeuchi.[5] In this experiment, the toner adhesion force was estimated from the voltage at the occurrence of the toner jumping. They used low resistivity toners and the applied dc voltage to the electrodes was increased at a constant rate. The numbers of toner particles, which have a certain adhesion force were estimated. They found the toner adhesion forces were distributed from 10^{-11} to 10^{-17} N and the adhesion force of the smaller toner was smaller than that of the larger one. Moreover, they found that the toners of higher resistivity tend to show the lager adhesion force. Fukuchi and Takeuchi[5] concluded that the results of the toner adhesion force measurements by the toner jumping method agree well with those by the centrifugal method. Later, they studied the particle adhesion force measurements by the toner jumping method.[10] In this study, the conductive toner as well as conductive polymer particles were used.

The control of conductive powder cloud by applying the toner jumping method, using the dented electrode was proposed and developed by Hoshino et. al.[6] The conductive cloud generation and its cloud confinement between the electrodes using the electrode, dented to a thin lens shape were found. There are three different sizes of the conductive toners of 8.5, 10.71, and 12.85 μm were used. When the conductive toner was charged and controlled by the capacitance of the lower electrode and the conductivity of substrate to the toner for a period corresponding to the toner relaxation time. The toner jumping current between the electrodes is measured. The amplitude of current has a linear relation to the amount of jumping toner at the same electric field. The confinement of toner cloud was confirmed by observing the toner motion through the upper transparent electrode, which is covered by a thin layer of ITO. The confining technique is expected to be useful in such application as Toner Cloud Beam (TCB), which is a new dot formation method. The TCB method was also invented by Hoshino et. al,[8] which the experimental setup for this method includes the dented electrode, lower control electrode, upper control electrode and pulling electrode being placed parallel, respectively. They can confined the toner cloud between the electrodes by the applied voltage could then be confined as a dot formed on a substrate. The toner beam is extracted from the toner cloud and projected to the substrate.