CHAPTER 4

RESULTS AND DISCUSSION

4.1 Toner Cloud Confinement condition

The control of the conductive toner motion is important in applications such as the non-impact printing. The conductive toner was sprayed freely on the electrode. When more than a certain value of electric field had been applied between the electrodes, the conductive toner started to move up and down between the electrodes by electrostatic force. Using an electrode dented to a cone shape, the conductive toner was confined between the electrodes in the dented area. As stated earlier, the electrodes used in the experiments are made of a stainless steel plate and the second one, the ITO sputted transparent glass. The ITO glass was used for observing the toner motion. The stainless steel plate was dented to a cone shape.

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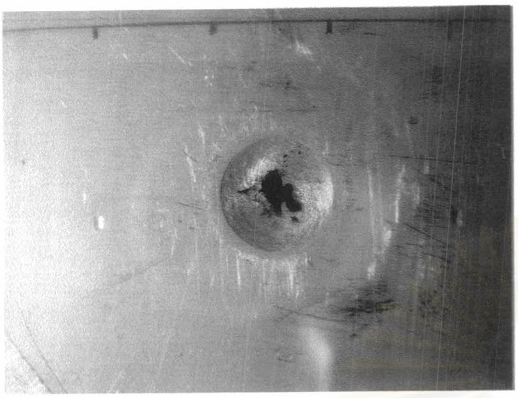
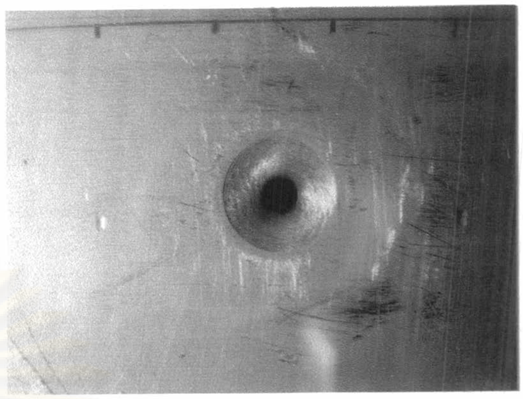
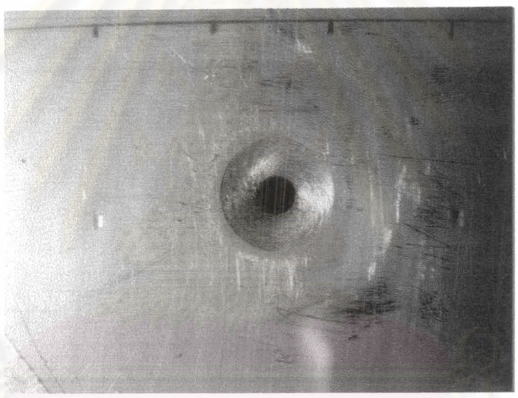
4.1.1 Dependence of toner cloud concentration



a) toner before the cloud state



b) toner at the cloud state



c) toner after the cloud state

Figure 4-1 The photographs of the conductive toner observed by the ITO glass, a) toner before the cloud state, b) toner at the cloud state and c) toner after the cloud state

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Figure 4-1 displays the photographs of the toner before the cloud state, the toner at the cloud state, and the toner after the cloud state. Dispersion or scattering of the conductive toner on the dented electrode was found before the cloud state. After the voltage had been applied to the electrode, the conductive toner started to move up and down between the electrode by the electric force. The conductive toner on the electrode was out of sight and became like a black cloud as shown in Figure 4-1 b). When the applied voltage was stopped, the conductive toner moved down to the dented electrode, which could be observed the ITO glass. It was confined on the dented electrode as shown in Figure 4-1 c). The diameters of the toner cloud, photographed and shown in Figure 4-1, were measured by Image Proplus software. The results of the toner cloud diameter are shown in Tables 4-1 to 4-3.

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Table 4-1 The averaged diameter of the toner cloud for the toner HMT2059-1 having $4.4 \times 10^8\ \Omega$ cm

Voltage (V)	Toner amount (mg)	The toner cloud diameter (mm) at Cone depth of dented electrode (mm)		
		0.2	0.5	1.0
500	0.3	3.82	3.47	3.14
	0.5	4.33	4.13	3.85
	0.8	5.21	4.89	4.24
	1	5.73	5.4	5.27
750	0.3	3.54	3.47	2.99
	0.5	4.26	4.02	3.77
	0.8	5.12	4.81	4.48
	1	5.66	5.2	4.9
1000	0.3	3.35	3.15	2.75
	0.5	4.18	3.94	3.14
	0.8	5.89	4.57	4.47
	1	5.34	5.16	4.83

Average diameter of 3 measurements

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Table 4-2 The averaged diameter of the toner cloud for the toner HMT2059-1 having $5.7 \times 10^7\ \Omega$ cm

Voltage (V)	Toner amount (mg)	The toner cloud diameter (mm) at Cone depth of dented electrode (mm)		
		0.2	0.5	1.0
500	0.3	3.88	3.85	3.55
	0.5	4.32	4.02	3.93
	0.8	5.08	4.65	4.16
	1	5.48	5.23	5.19
750	0.3	3.54	3.48	3.15
	0.5	4.02	3.93	3.7
	0.8	5.04	4.38	4.32
	1	5.81	5.12	4.96
1000	0.3	3.46	3.25	3.07
	0.5	3.98	3.78	3.62
	0.8	4.89	4.32	4.26
	1	5.66	5.23	4.96

Average diameter of 3 measurements

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Table 4-3 The averaged diameter of the toner cloud for the toner HMT2059-1 having $7.4 \times 10^6\ \Omega$ cm

Voltage (V)	Toner amount (mg)	The toner cloud diameter (mm) at Cone depth of dented electrode (mm)		
		0.2	0.5	1.0
500	0.3	3.15	2.98	2.83
	0.5	4.16	3.99	3.94
	0.8	5.04	4.71	4.1
	1	5.5	5.17	5.12
750	0.3	2.92	2.8	2.75
	0.5	3.85	3.84	3.78
	0.8	4.86	4.63	3.78
	1	4.93	4.73	4.71
1000	0.3	2.84	2.74	2.36
	0.5	3.92	3.62	3.46
	0.8	4.78	3.7	3.61
	1	4.89	4.41	4.32

Average diameter of 3 measurements

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As stated previously that the toner was in a cloud state in the dented electrode, which could be postulated that some component in the electric force traveled toward the central axis [6] as shown in Figure 4-2.

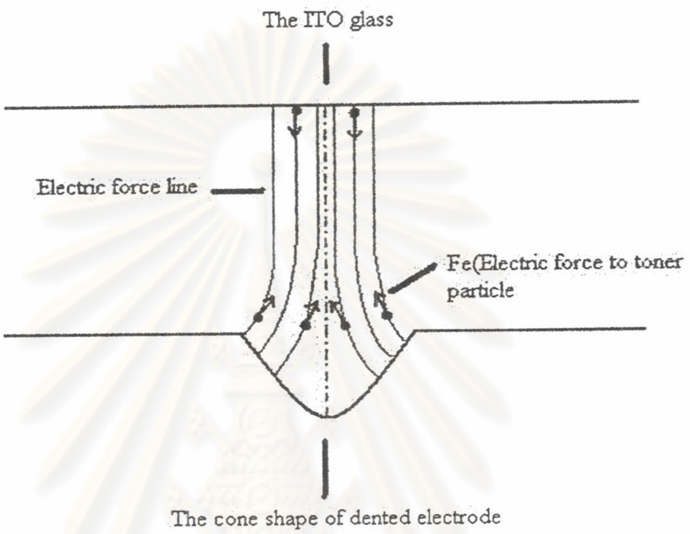


Figure4-2 Schematic explanation the toner motion in the cone shape of dented electrode. ------- Center axis.

Figure 4-2 demonstrates the toner motion and direction as shown by the electric force lines, toward the central axis. The electrostatic field external to the body of a conductor must always be perpendicular to the surface. [13] Therefore, the electric force lines between the electrodes from the cone area of the dented electrode must always be perpendicular to the electrode surface and the ITO glass.

4.1.1.1 Toner cloud extent dependence on the toner concentration

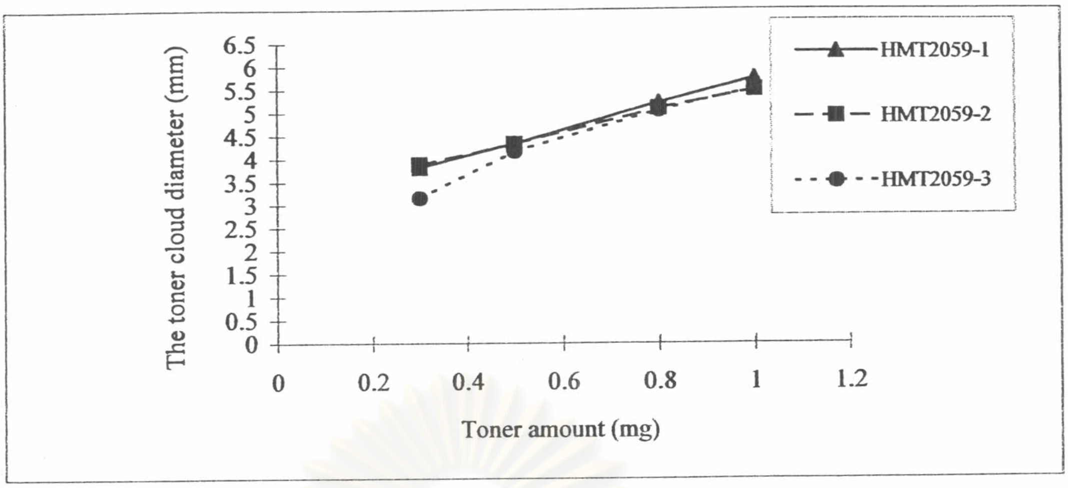
The dependence of the toner cloud extent on the toner concentration was studied using the cone shape dented electrode. Figures 4-3 to 4-13 show the relationship between the conductive toner cloud diameter and the toner amount. The higher amount of the toner produces the larger diameter of the toner cloud during toner jumping, resulting from the greater quantity of toner particles on the dented. Furthermore, the extent of toner cloud also depends on the toner characteristic resistivity, the applied voltage and the cone depth of the dented electrode as follows:

a) Toner characteristic resistivity

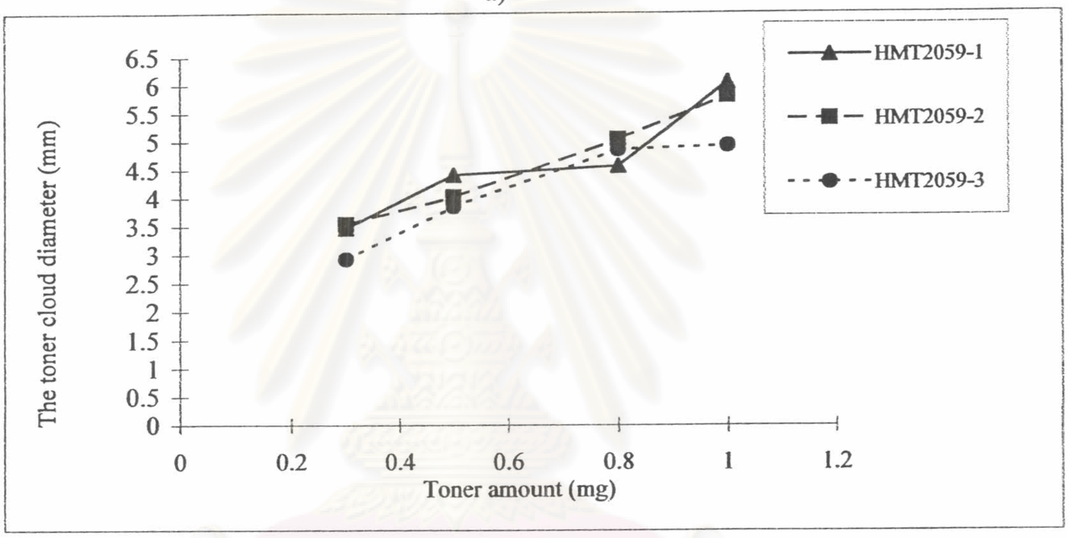
Toners HMT2059-1, HMT2059-2, HMT2059-3 with the resistivity of 4.4×10^8, 5.7×10^7 and 7.4×10^6 Ω cm, respectively, are used for toner cloud study.

Figure 4-3 shows the dependence of the toner cloud diameter on the toner amount in their corresponding resistivity at the fixed cone depth of 0.2 mm. of the dented electrode with different applied voltages of a) 500, b) 750 and c) 1000. The resulting lines show the similar trend, of straight lines with increasing slopes. That is, increasing toner amount increases the diameter of toner cloud.

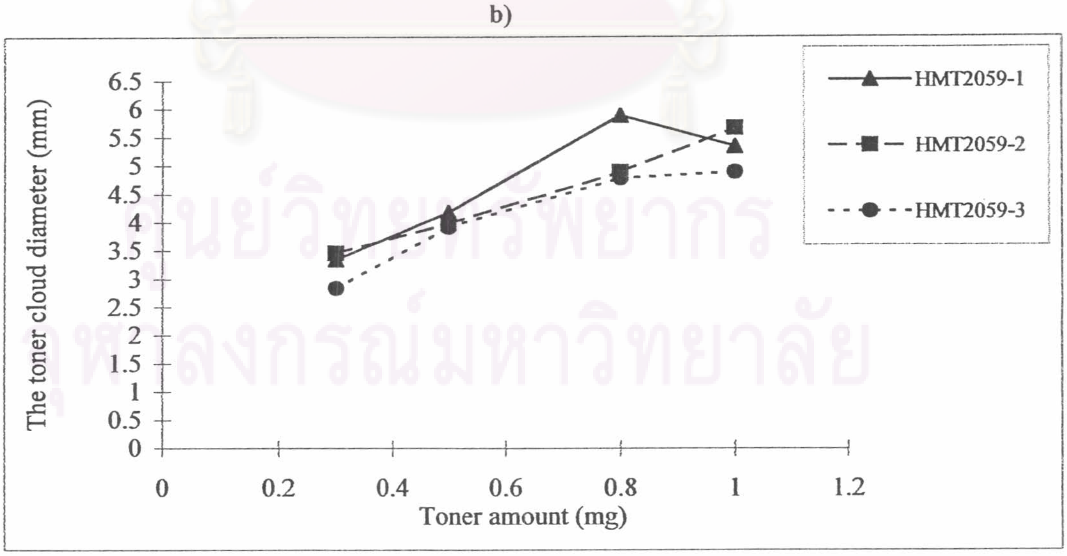
Comparing the level of toner resistivity, the higher the resistivity of the toner, the greater the toner cloud diameters. Therefore, one can observe the longest toner cloud diameter of HMT 2059-1 (4.4×10^8 Ω cm) and the shortest toner cloud diameter of HMT 2059-3 (7.4×10^6 Ω cm.), while the HMT 2059-2 (5.7×10^7 Ω cm.) gives the intermediate length in diameter.



a)



b)



c)

Figure 4-3 Dependence of the toner cloud diameter on the toner amount in their corresponding resistivity at the fixed cone depth of the dented electrode of 0.2 mm with different applied voltages of a) 500 V, b) 750V, and c) 1000V.

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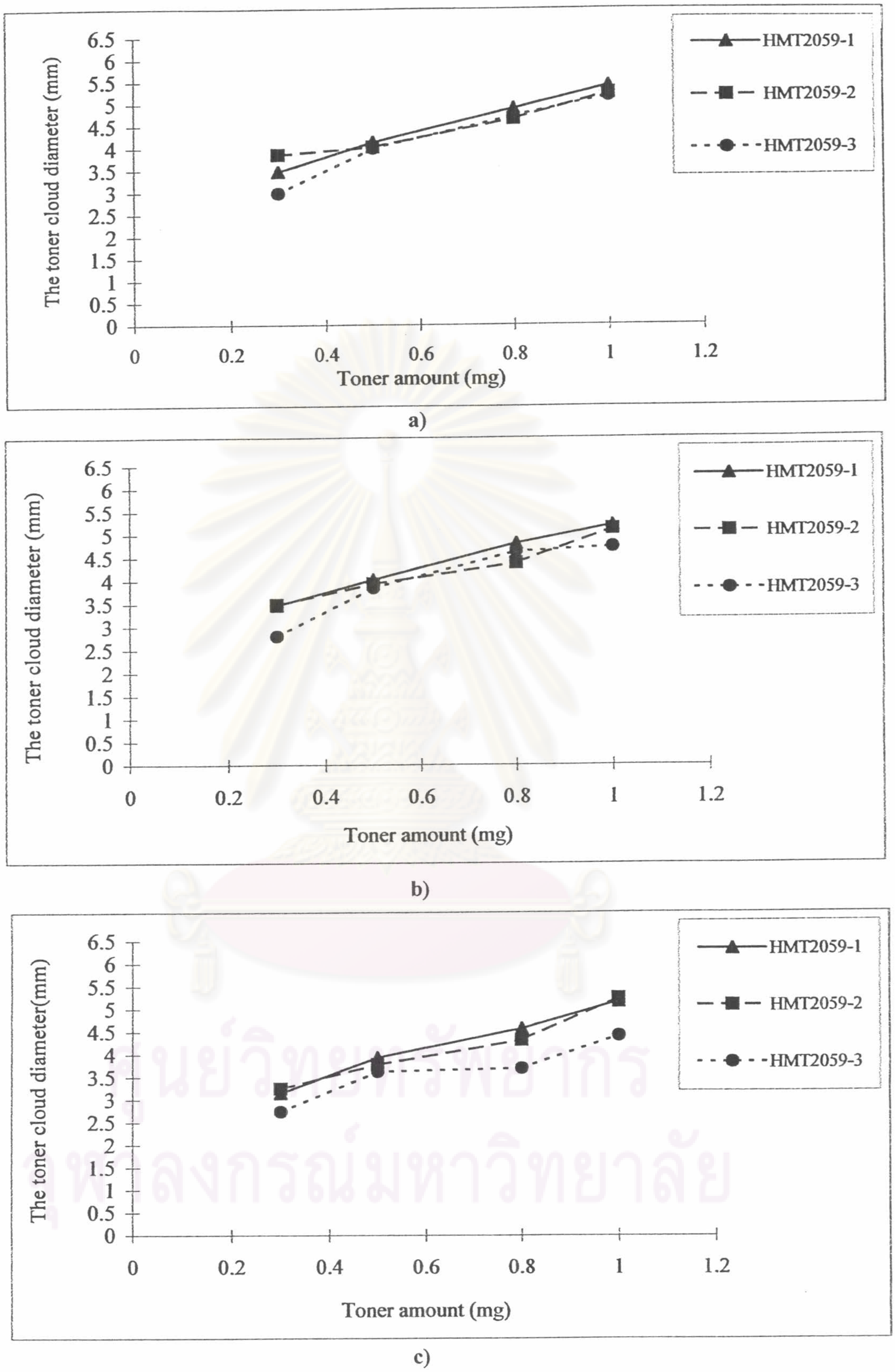

Figure 4-4 Dependence of the toner cloud diameter on the toner amount in their corresponding resistivity at the fixed cone depth of the dented electrode of 0.5 mm with different applied voltages of a) 500 V, b) 750V, and c) 1000V.

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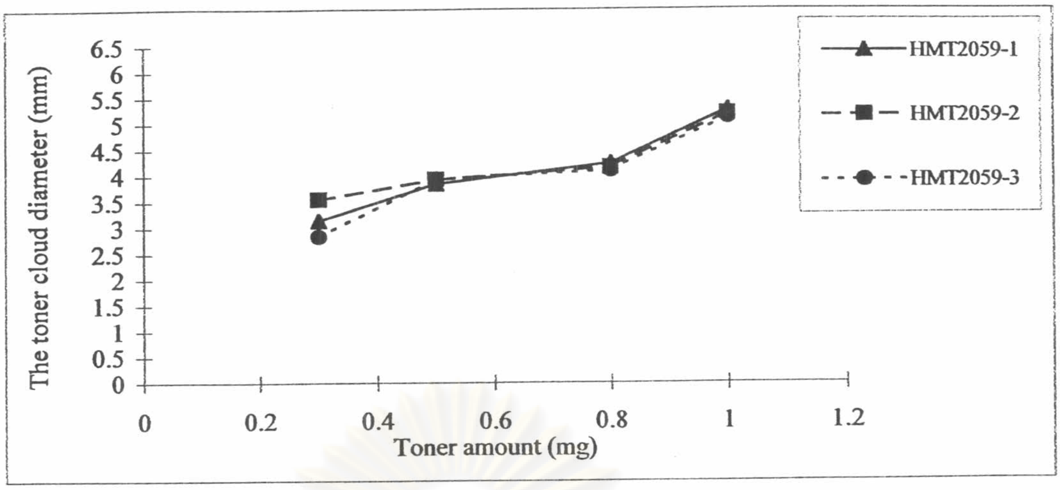
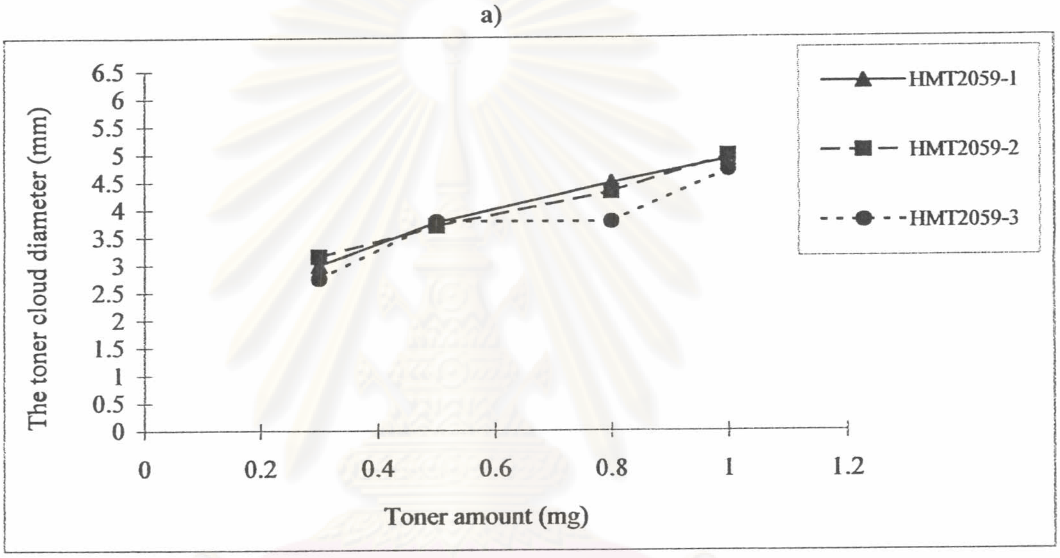
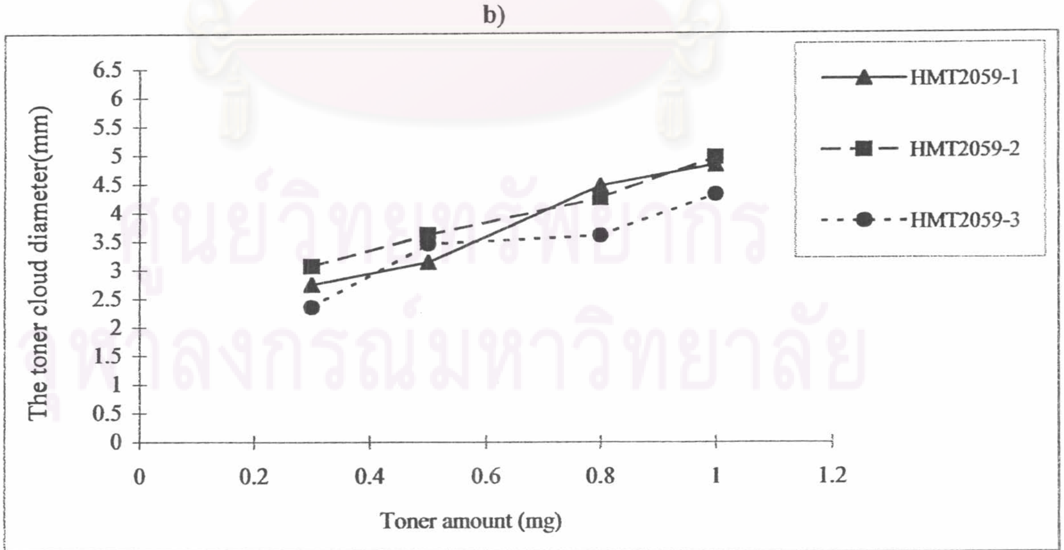


a)



b)



c)

Figure 4-5 Dependence of the toner cloud diameter on the toner amount in their corresponding resistivity at the fixed cone depth of the dented electrode of 1.0 mm with different applied voltages of a) 500 V, b) 750V, and c) 1000V.

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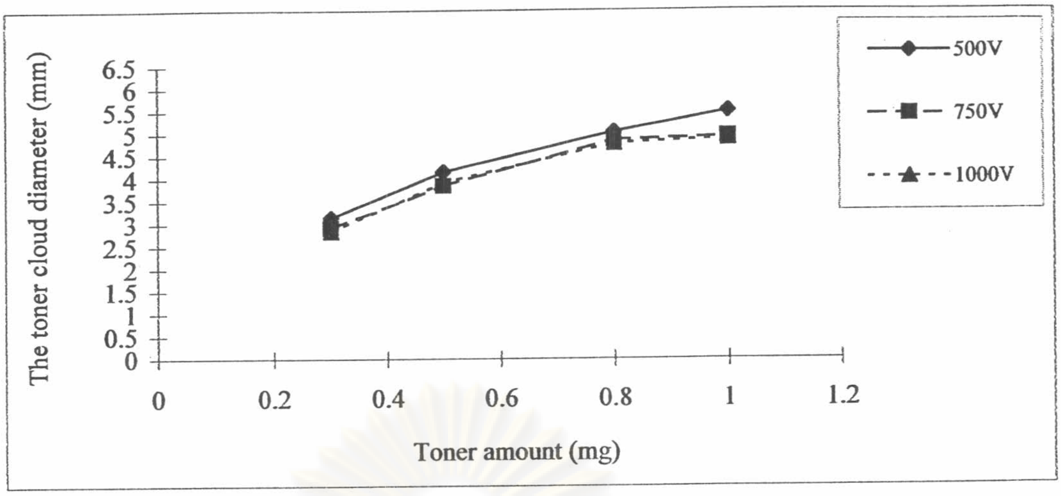
Likewise, when the cone depth of the dented electrode increases, the diameter of toner cloud does not increase significantly. The lines resulting from the effect toner amount on the toner cloud diameter are similar to those at 0.2 mm. depth. The higher toner resistivity (HMT 2059-1, 4.4×10^8 Ω cm) still gives the larger diameter of toner cloud as shown in Figures 4-4 to 4-5. Fukuchi and Takeuchi found the similar trends and explained as follows. The toner having higher resistivity tends to adhere strongly to give the larger threshold voltage. [5] The electric force lines have component towards the central axis of the dented electrode.

b) The applied voltage

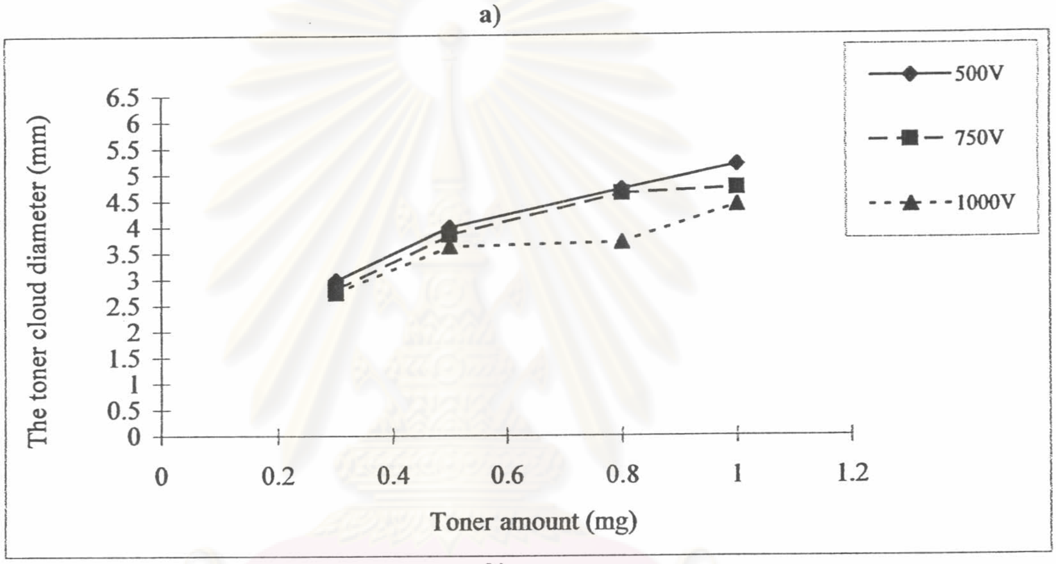
Dependence of the toner cloud extent on the toner amount at three applied voltages of 500, 750, and 1000 V, is shown in Figures 4-6 to 4-8.

Figure 4-6 shows the dependence of the toner cloud diameter on the toner amount at the applied voltages for at the toner resistivity of 4.4×10^8 Ω cm. with different cone depths of the dented electrode of 0.2, 0.5 and 1.0 mm, respectively. The toner cloud diameter increases, when the toner amount increases.

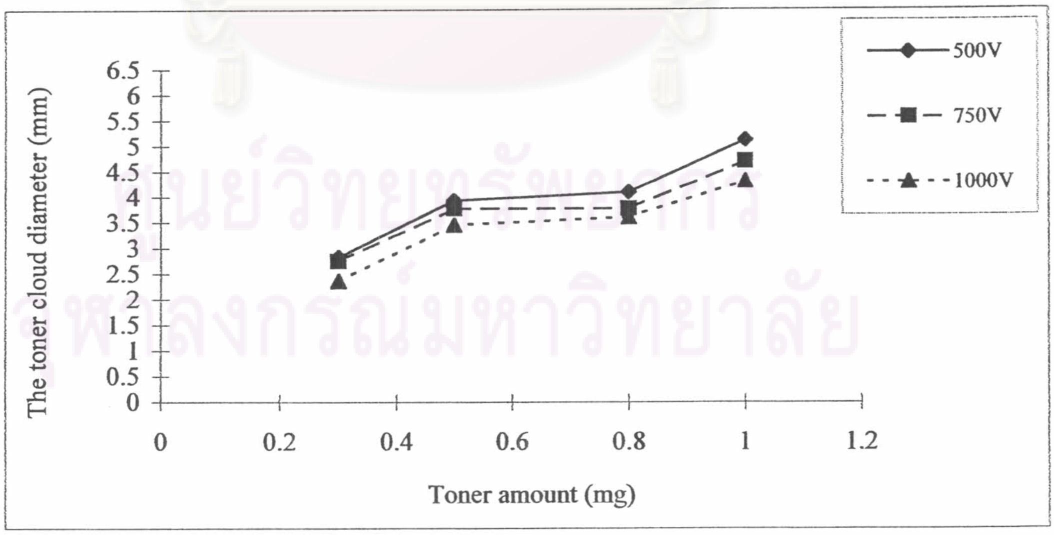
Considering the influencing factor of applied voltage on the diameter of toner cloud, the lowest applied voltage (500 V) produces the longest diameter whereas the 1000 V gives the smallest diameter size of the toner cloud.



a)



b)



c)

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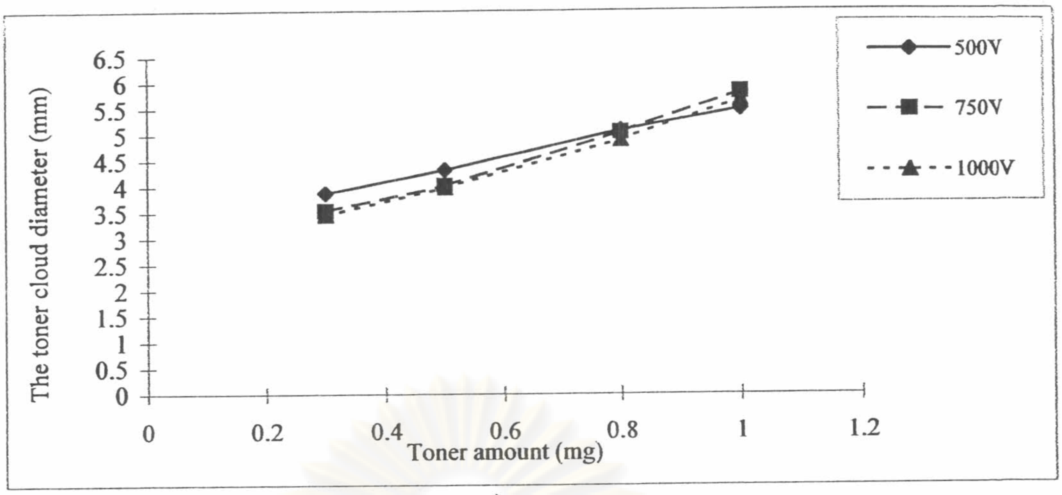
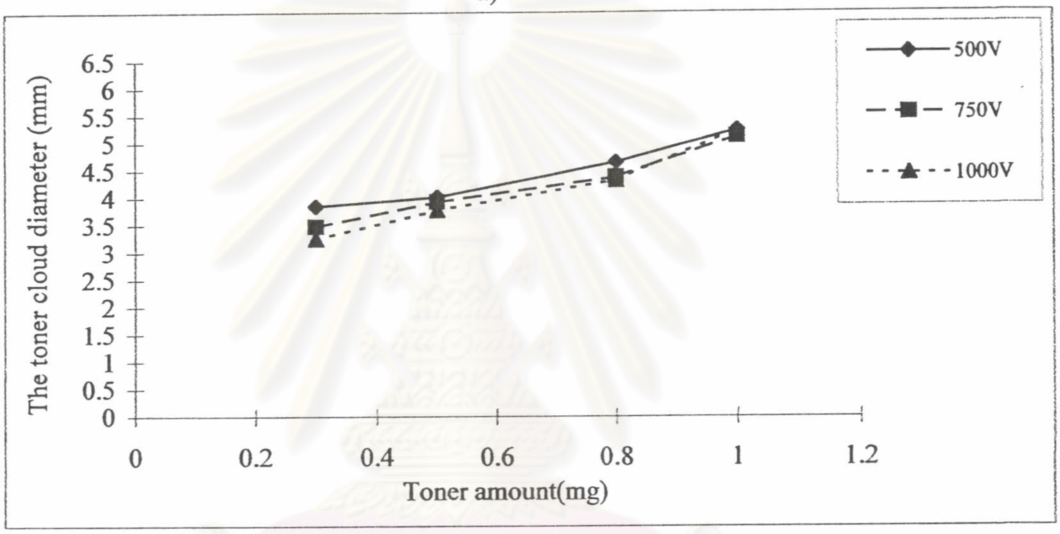
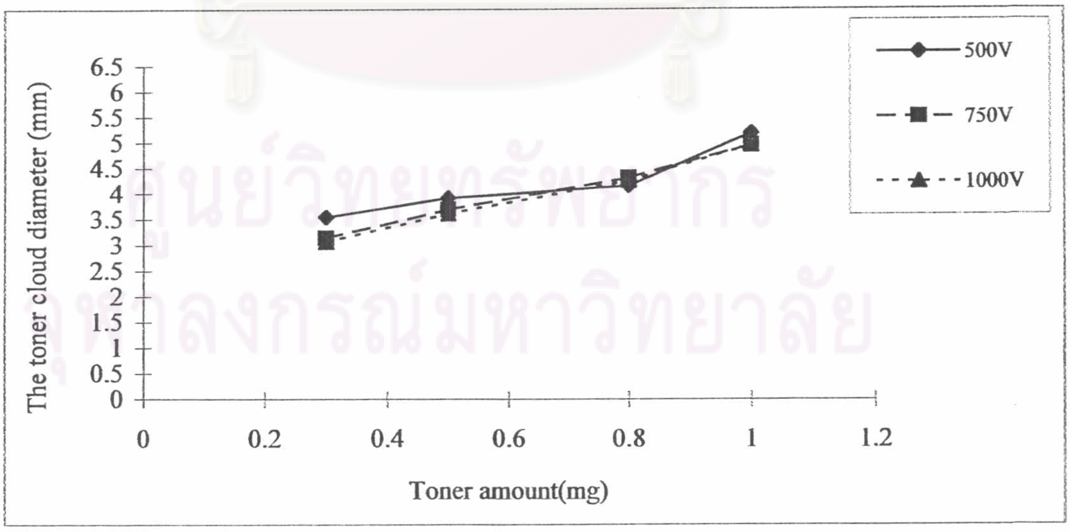
Figure 4-6 Dependence of the toner cloud diameter on the toner amount at three applied voltages for toner HMT2059-1 at the cone depths of dented the electrode of a) 0.2, b) 0.5, and c) 1.0 mm.



a)



b)



c)

Figure 4-7 Dependence of the toner cloud diameter on the toner amount at three applied voltages for toner HMT2059-2 at the cone depths of dented the electrode of a) 0.2, b) 0.5, and c) 1.0 mm.

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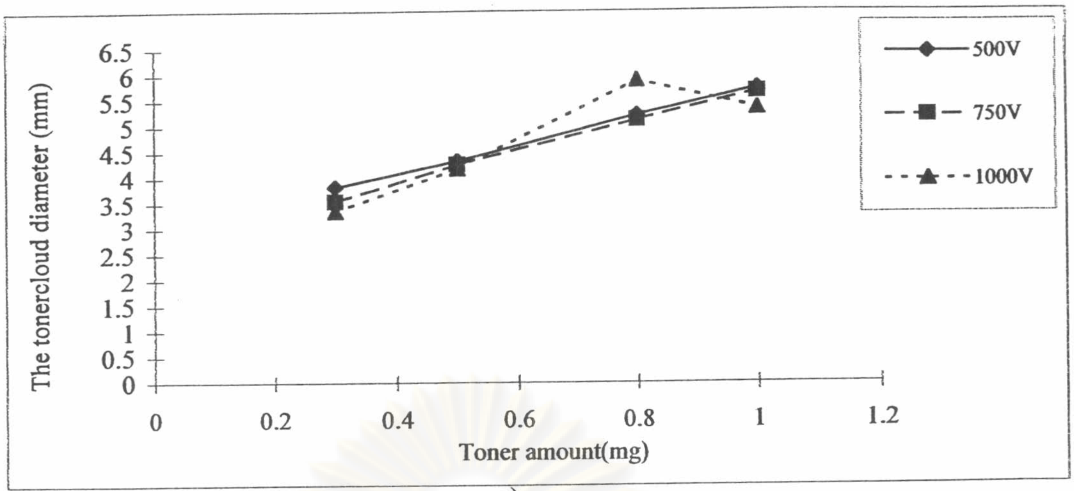
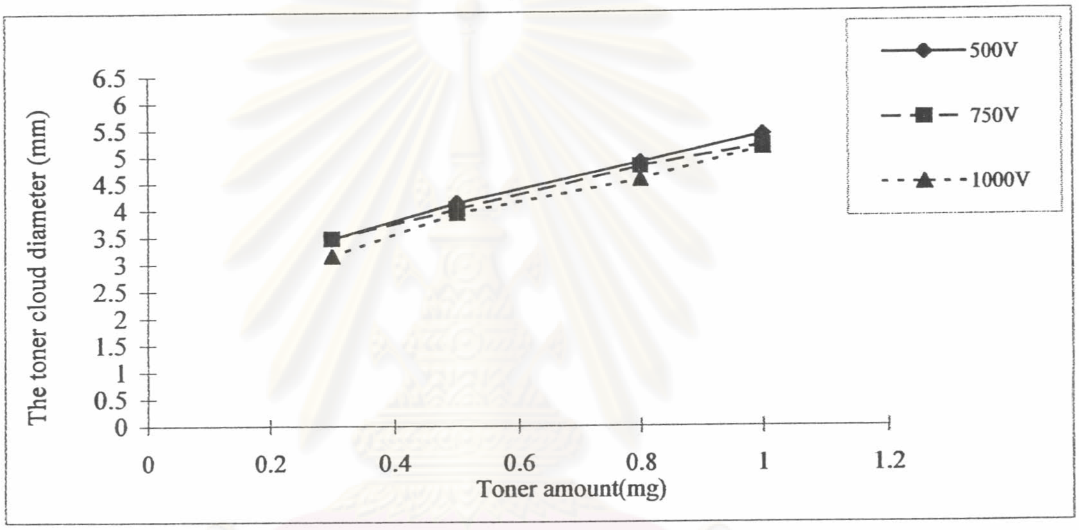
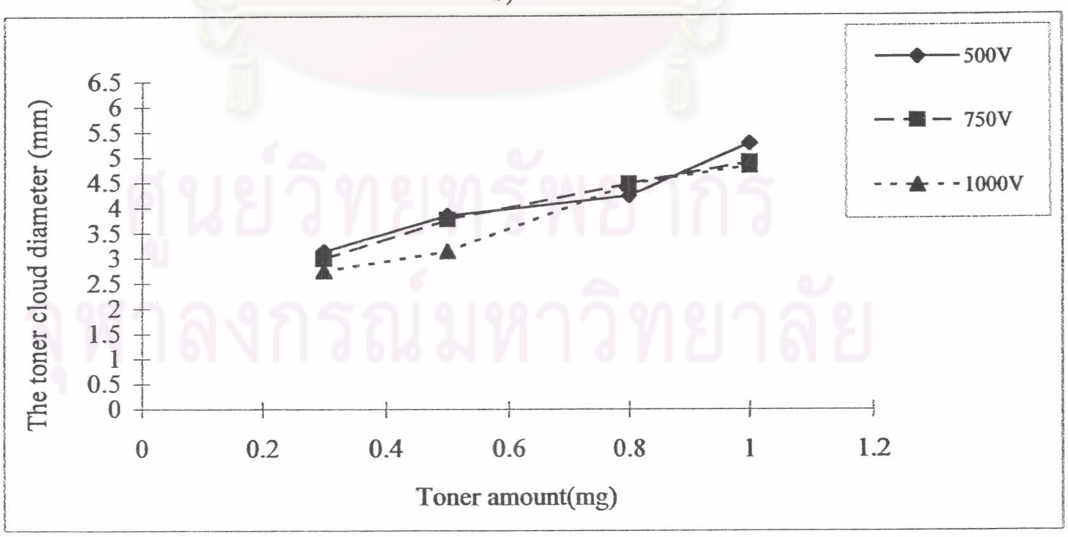


a)



b)



c)

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Figure 4-8 Dependence of the toner cloud diameter on the toner amount at three applied voltages for toner HMT2059-3 at the cone depths of dented the electrode of a) 0.2, b) 0.5, and c) 1.0 mm.

Similarly, Figures 4-7 to 4-8 show the dependence of toner cloud diameter on the toner amount at the applied voltages and the toner resistivity of 5.7 x 10^7 and 7.4 x 10^6 Ω cm, at the cone depths of the dented electrode of 0.2, 0.5 and 1.0 mm. The toner cloud diameter increases with increasing toner amount in the same manner of that in Figure 4-6. The lower applied voltage (500V) is found to givethe larger toner cloud diameter than that at 1000 V, which produces the smaller diameter compared with that in Figure 4-6.

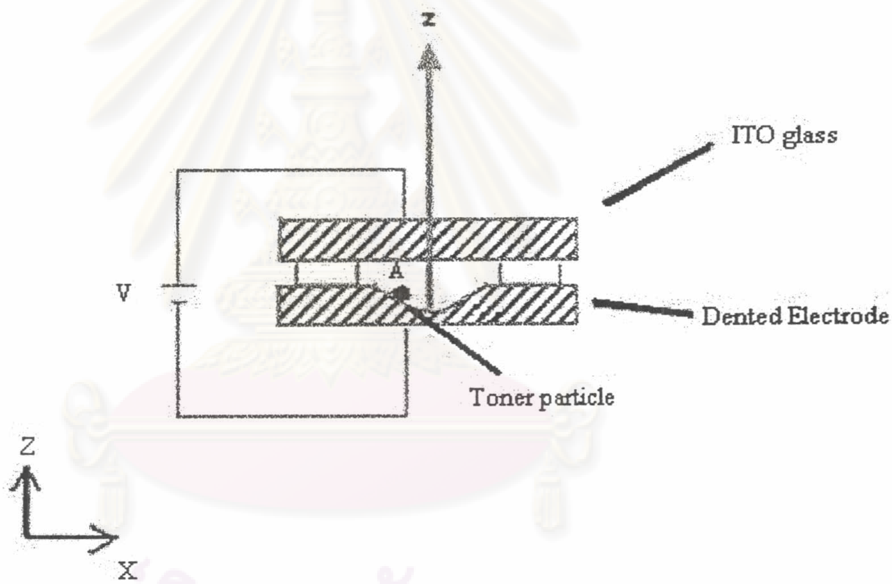

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Figure 4-9 Schematic diagram of the electrode arrangement

When the voltage was applied to the electrodes, the toner particles were charged and then moved between the electrode due to the electrostatic force. The applied voltages are 500, 750, and 1000 V.

The electric force acting on the toner particle can be calculated by the following equation:

$$\vec{F}_e = q\vec{E} \qquad (4\text{-}1)$$

Because of F = ma = mdv/dt, while $\vec{v}$ is the velocity of the toner particle and x is the displacement of the toner particle, Equation (4-1) can be derived in the second derivative equation along the x and z directions as follows:

$$\frac{d^2x}{dt^2} = \frac{q}{m}E_x \qquad (4\text{-}2)$$

$$\frac{d^2z}{dt^2} = \frac{q}{m}E_z \qquad (4\text{-}3)$$

Considering the displacement of the toner particle along the x and z directions, which indicate the toner cloud extent. By using integrated Equations (4-2) and (4-3), here, the charge q and the mass m are assumed to be constants on the position A, and the displacement of the toner particle from the position A is then obtained. When the time is a constant, the displacements then depend on the electric field. As a rule of thumb, $\vec{E} = -\vec{\nabla}V$, [14] hence, when the higher voltage was applied, the displacement of the toner particle is longer and more towards the central axis of the dented electrode. So, the higher applied voltage (1000 V) is found to give the shorter cloud diameter than that at 500 V as previously.

c) The cone depth of the dented electrode

Dependence of the toner cloud extent on the toner amount at the cone depths of the dented electrode of 0.2, 0.5 and 1.0 mm are shown in Figures 4-10 to 4-12

The results in Figure 4-10 show that the toner cloud diameter increases when the toners amount increases. For the effect of the cone depth of the dented electrode on the toner cloud diameter, the cone depth of the dented electrode of 0.2 mm gives the biggest diameter while that of 1.0 mm produces the smallest diameter.

In the same manner as shown in Figures 4-11 to 4-12, regardless of the magnitude of applied voltage, the smaller depth of the dented electrode produces the largest toner cloud diameter at any toner amount. The largest depth (1.0 mm) of the dented electrode gives the smallest diameter of toner cloud while the 0.5 mm depth of the dented electrode yields the intermediate value of diameter.

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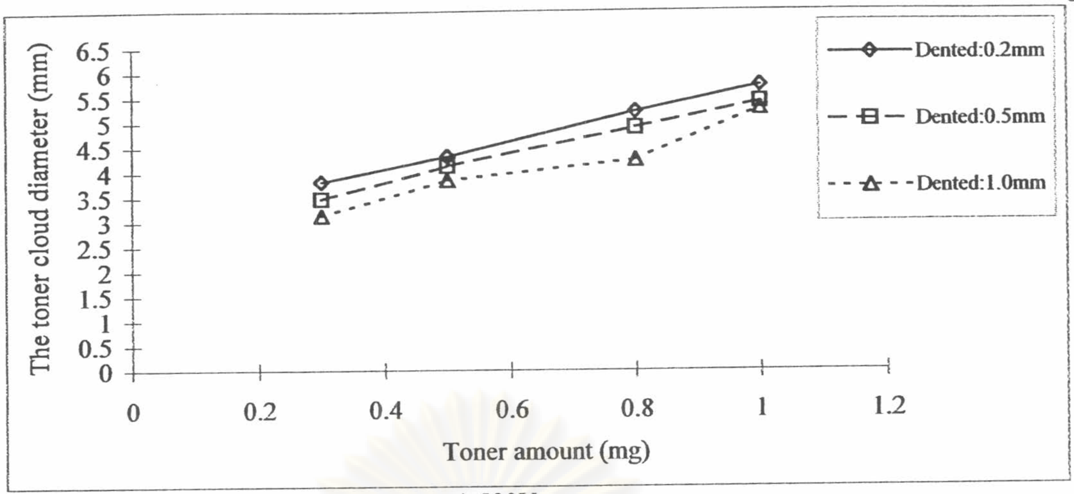
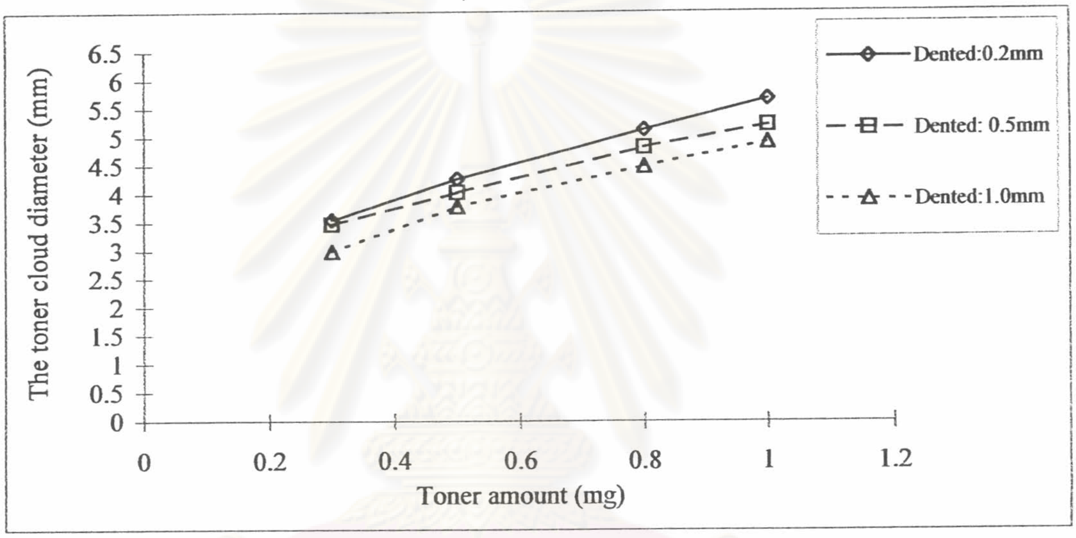
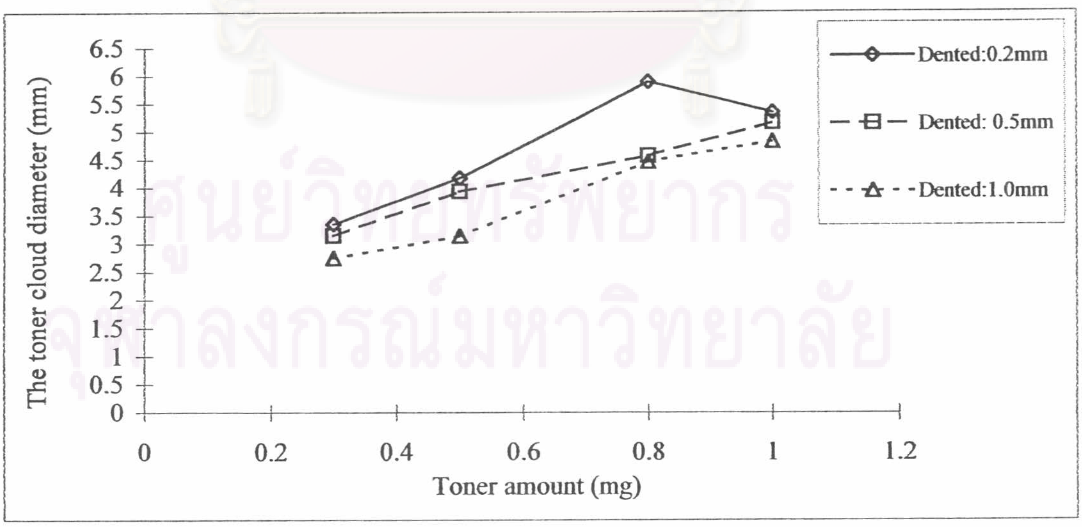


a) 500V



b) 750V



c) 1000V

Figure 4-10 Dependence of the toner cloud diameter on the toner amount for the cone depth of the dented electrode of the toner HMT2059-1 with 500, 750, and 1000V.

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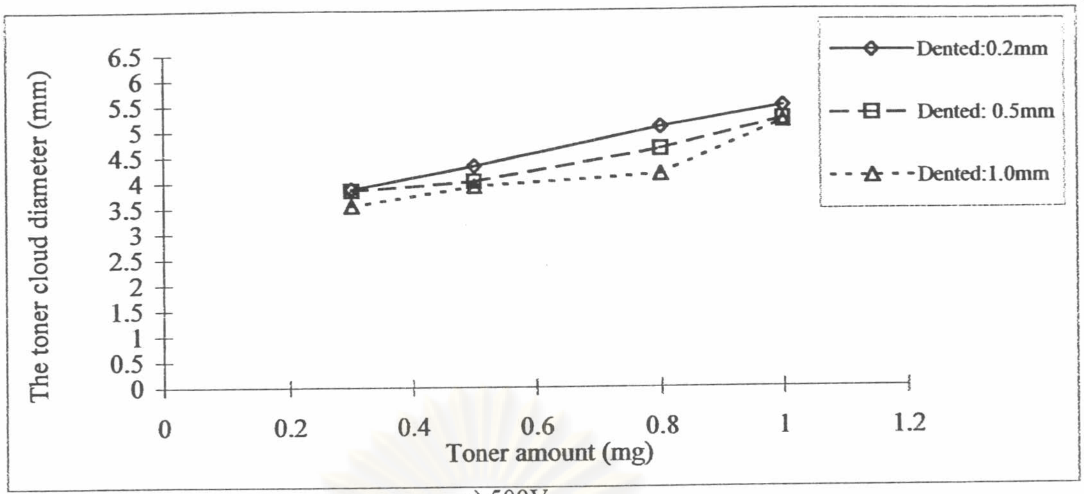
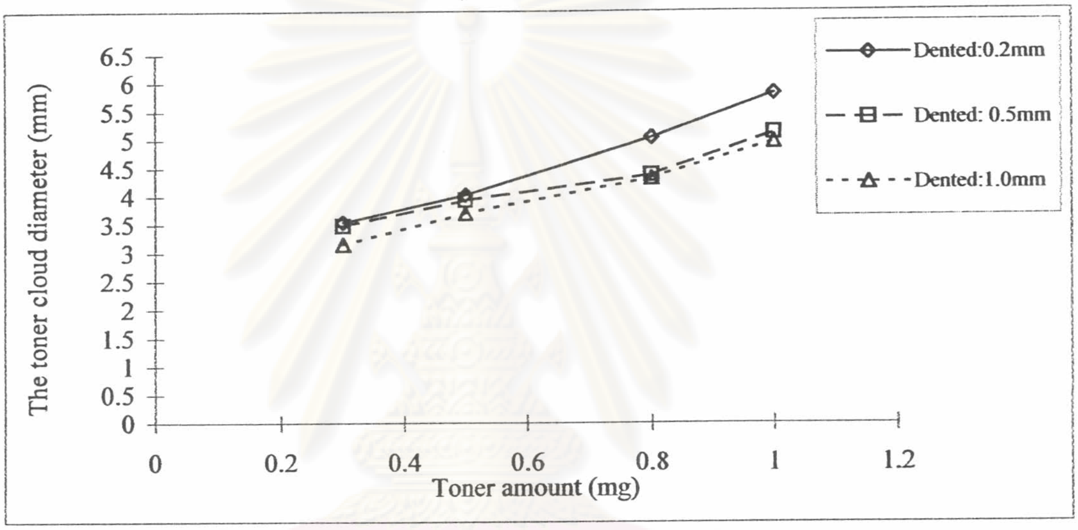
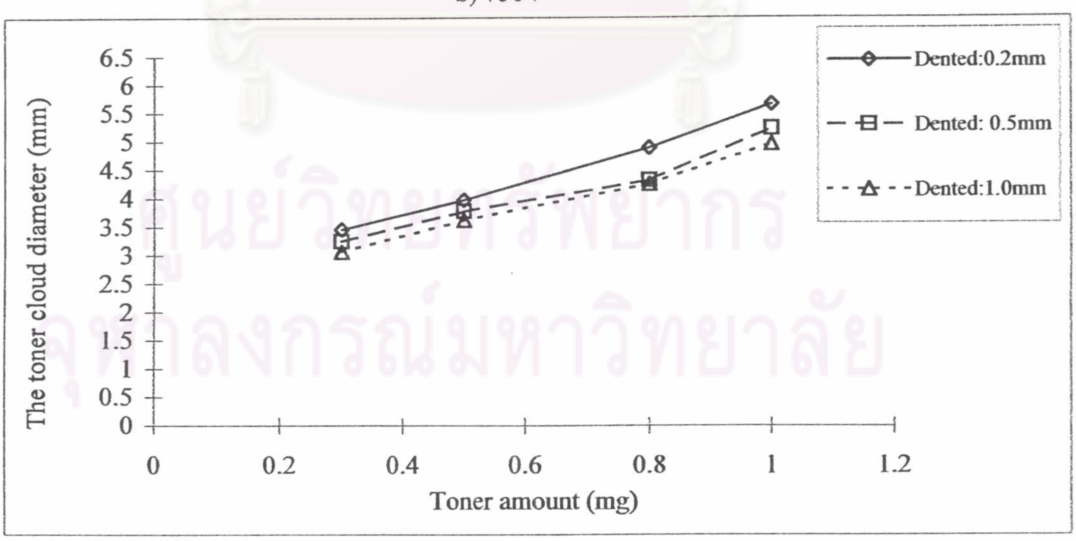


a) 500V

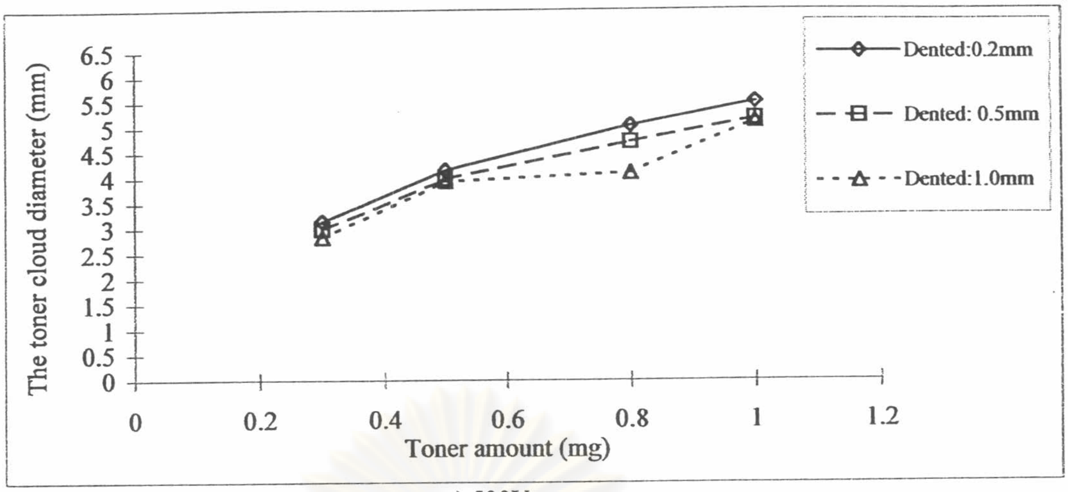


b) 750V

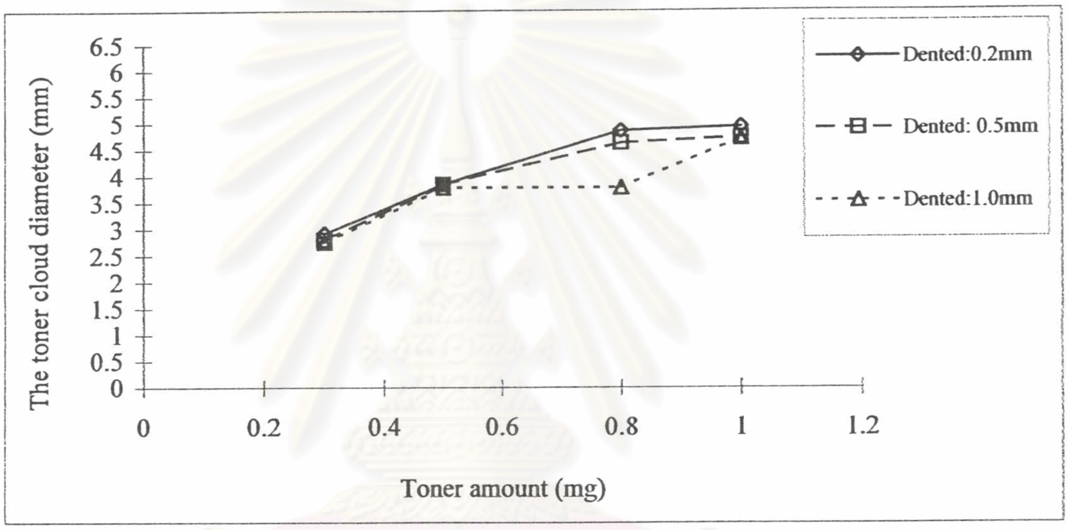


c) 1000V

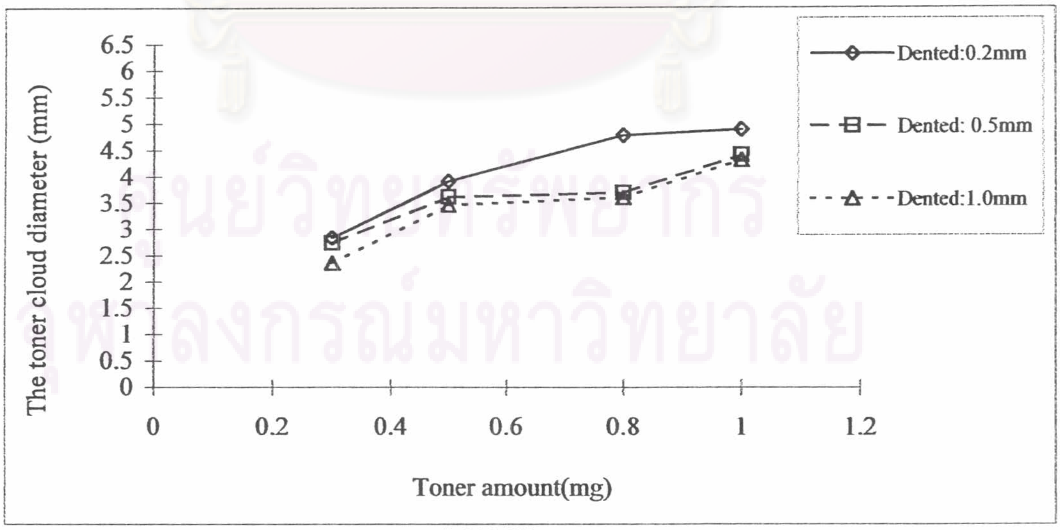
Figure 4-11 Dependence of the toner cloud diameter on the toner amount for the cone depth of the dented electrode of the toner HMT2059-2 with 500, 750, and 1000V.



a) 500V



b) 750V



c) 1000V

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Figure 4-12 Dependence of the toner cloud diameter on the toner amount for the cone depth of the dented electrode of the toner HMT2059-3 with 500, 750, and 1000V.

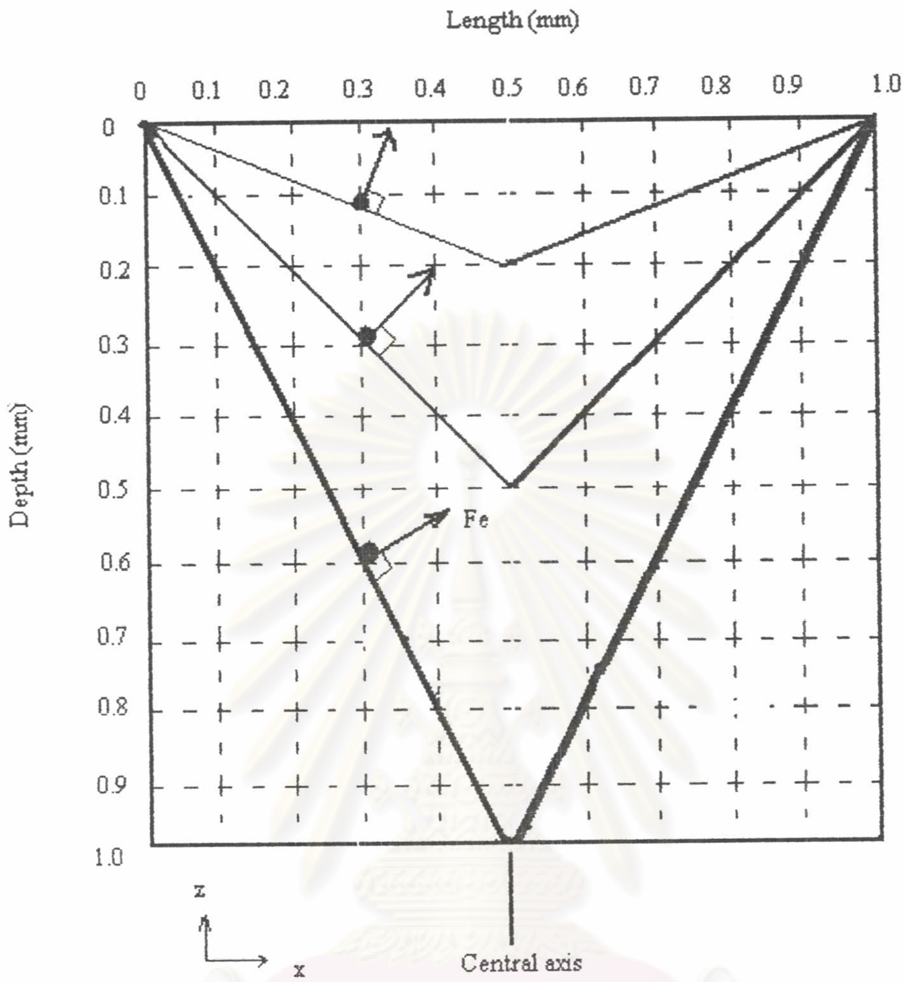

Figure 4-13 Schematic diagram of the cross-section of the dented electrode at three depths of 0.2, 0.5 and 1.0 mm

The cross-section of the cone shape of dented electrode at three depths are shown in Figure 4-13. The slope (m) of the cone depth of the dented electrode were obtained. The slope of the depth of the dented electrode of 0.2, 0.5, and 1.0 m. are 0.4, 1, and 2, respectively. Since the slope of the depth of the dented electrode is known, the position of z could be determined using the linear equation (z = mx). The linear equations for the cone shape of the dented electrode at three depths can be written as follows:

$$z_{0.2\,mm} = 0.4\,x \qquad (4\text{-}4a)$$

$$z_{0.5\,mm.} = x \qquad (4\text{-}4b)$$

$$z_{1.0\,mm} = 2\,x \qquad (4\text{-}4c)$$

Here, the position X of the toner one particle was assumed to be 0.3 mm. The displacement along the Z direction is $z_{0.2\,mm} = 0.12$, $z_{0.5\,mm} = 0.3$, and $z_{1.0\,mm} = 0.6$ mm. The positions x and z is plotted in Figure 4-10.

The electric force (F_e) from the surface of the dented electrode, which imposes to the toner particles is shown in Figure 4-13. The electric force line must always be perpendicular to the surface. So, the electric force line of the dented electrode at three depths has the component towards the central axis of the dented electrode.

Because the electric force line of the deeper cone depth of the dented electrode can carry more component towards the central axis of the dented electrode, therefore, the deeper the cone depth of the dented electrode, the smaller the toner cloud.

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4.1.2 Dependence of toner jumping current

The toner jumping current is normally measured by the toner cloud generation method, the conductive toner particles are sprinkled over on the cone shape, dented electrode. The dc voltage applied to the electrodes and the occurrence of the toner jumping to generate the toner cloud can be observed and quantized by measuring the current flow between the electrodes. The toner jumping current can also be detected by the electrometer.

Considering the current caused by the toner jumping between the electrode, as a rule of current flow parallel to $\bar{E}$, the current I_t can be written as shown in Equation (4-5)

$$I_t = nqbE(t) \quad (4\text{–}5)$$

[7]

where n is the number of the toner particles, q is the electrostatic change on the toner, b is the electrical mobility (particular velocity per unit electric field), and E (t) is the applied electric field to the electrodes.

Toner cloud confinement is detected by measuring the current flow between the electrodes, at certain electric fields, to provide information yielded by the cone shape, dented electrode on the applied voltage, toner amount, and the characteristics toner resistivity.

4.1.2.1 Dependence of toner jumping current on the toner amount

Dependence of the toner jumping current on toner amount was studied using the cone shape dented electrode. Three types of conductive toner namely HMT2059-1, HMT2059-2, and HMT2059-3 with the corresponding resistivity of 4.4×10^8, 5.7×10^7 and 7.4×10^6 Ω cm were sprinkled over the electrode. The amounts of the toner are 0.3, 0.5, 0.8 and 1.0 mg. The applied voltages of 500, 750 and 1000 V were each given to the electrodes. When the threshold voltage or higher is applied between the electrodes, the conductive toners move up and down between the electrodes. This is because the toners are charged by conduction from the electrode under the electric field applied, and the electric force works on the toners. The current on the toner amount from which the beginning voltage for the toners to jump and the magnitude of the electrical current due to toner jumps could be obtained. Tables 4-4 to 4-6 show the results of the toner jumping current at several experiment conditions.

Table 4-4 The averaged toner jumping current of the toner HMT2059-1

Voltage (V)	Toner amount (mg)	Toner jumping current (nA) at cone depth of dented electrode (mm)		
		0.2	0.5	1.0
500	0.3	42	34	20
	0.5	45	36	25
	0.8	75	56	41
	1	108	70	58
750	0.3	188	114	62
	0.5	192	143	85
	0.8	364	189	95
	1	387	241	157
1000	0.3	472	241	158
	0.5	544	271	248
	0.8	803	456	236
	1	898	568	307

Average toner jumping current is the mean of 3 measurements

Table 4-5 The averaged toner jumping current of the toner HMT2059-2

Voltage (V)	Toner amount (mg)	Toner jumping current (nA) at cone depth of dented electrode (mm)		
		0.2mm	0.5mm	1.0mm
500	0.3	109	30	15
	0.5	189	45	37
	0.8	334	75	109
	1	453	80	114
750	0.3	491	145	100
	0.5	517	221	147
	0.8	694	300	224
	1	959	314	263
1000	0.3	575	309	226
	0.5	789	483	400
	0.8	1020	590	556
	1	1356	885	673

Average toner jumping current is the mean of 3 measurements

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Table 4-6 The averaged toner jumping current of the toner HMT2059-3

Voltage (V)	Toner amount (mg)	Toner jumping current (nA) at cone depth of dented electrode (mm)		
		0.2mm	0.5mm	1.0mm
500	0.3	193	81	55
	0.5	291	115	82
	0.8	454	215	109
	1	553	224	114
750	0.3	569	267	216
	0.5	1036	407	234
	0.8	1536	673	344
	1	2194	964	441
1000	0.3	803	500	419
	0.5	1993	732	598
	0.8	3401	1520	823
	1	4008	1988	973

Average toner jumping current is the mean of 3 measurements

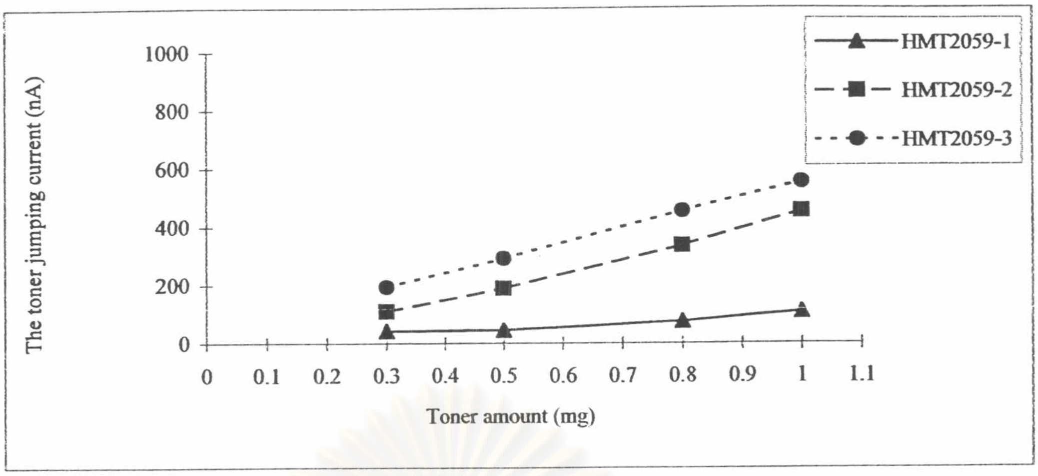
Figures 4-14 to 4-22 show the relationship between the toner jumping current and the toner amount of the toner characteristic resistivity. The higher the toner amounts, the higher the toner jumping current. When the high amount of the conductive toner was used, the toner particles charged by the electric field between the electrodes also increased. From Equation (4-5), the amount of current should depend on the number of the toner particles. When the number of the charged toner particles increased and started to move, the toner jumping current increased in conjunction with the increasing numbers. Because electric current is caused by a flow of the electric charge, thereby, the increase in the electric current of the toner jumping is the result of the increase in the volume of the flow of the electrical charges during the toner jumping.

a) On the toner amount at different toner resistivity

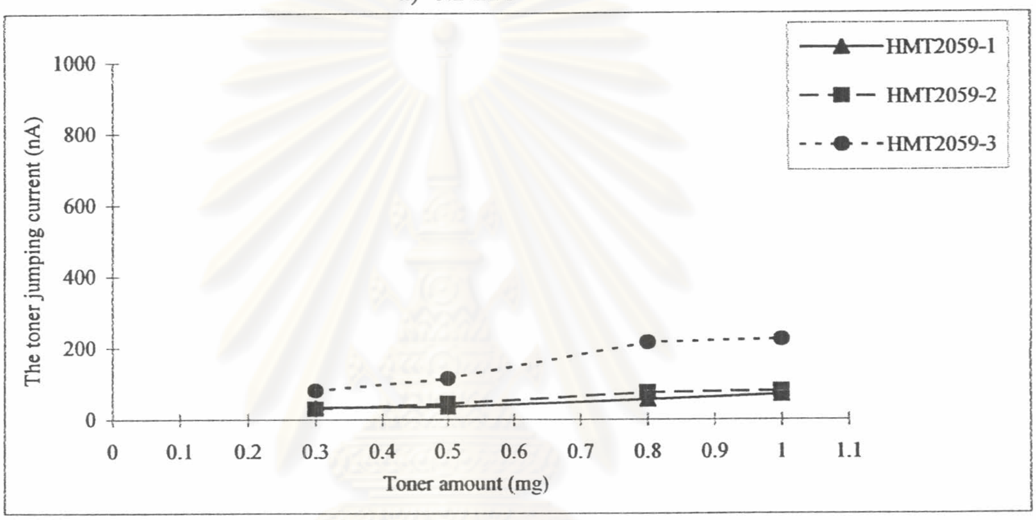
The toner jumping current at several toner resistivity of 4.4×10^8, 5.7×10^7 and 7.4×10^6 Ω cm depended on the toner amount of 0.3, 0.5, 0.8 and 1.0 mg. The applied voltages used in this experiment are 500, 750 and 1000 V. The results are shown in Figures 4-14 to 4-18.

The toner jumping current in Figure 4-14 increases with an increase in the toner amount from 0.3, 0.5, 0.8 to 1.0 mg. The straight lines with the position slopes are all obtained for the toner jumping currents of all three toners.

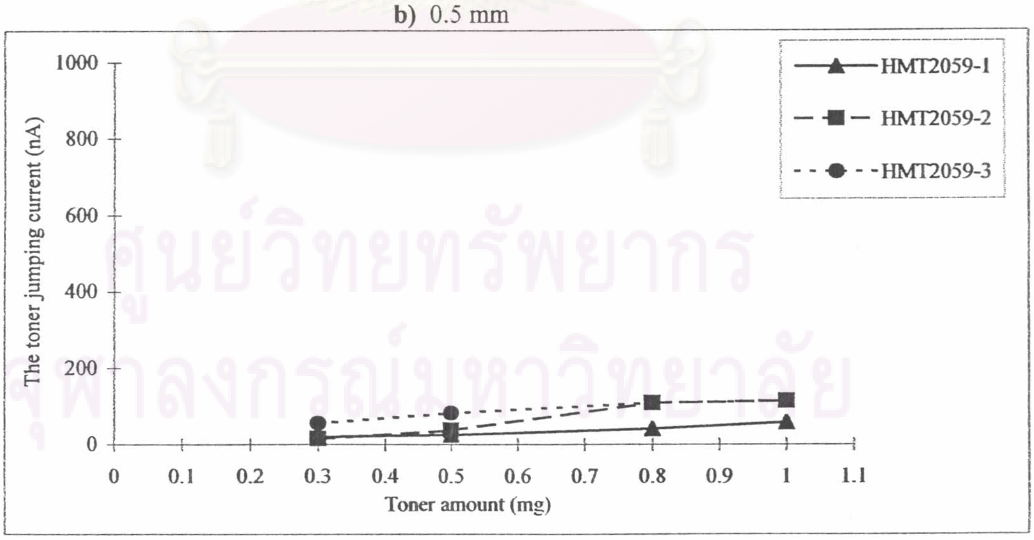
Figures 4-15 and 4-16 show the relationship between the toner jumping current and the toner amount and the toner characteristics resistivity at the applied higher voltages of 750 and 1000 V. The similar trend is found for both resistivity as that the lower toner resistivity gives the higher jumping current.



a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

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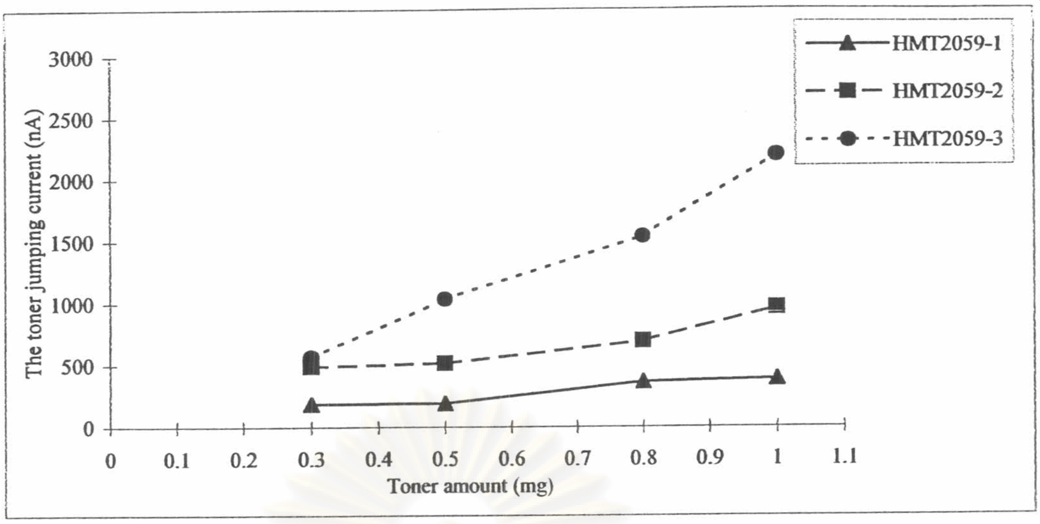
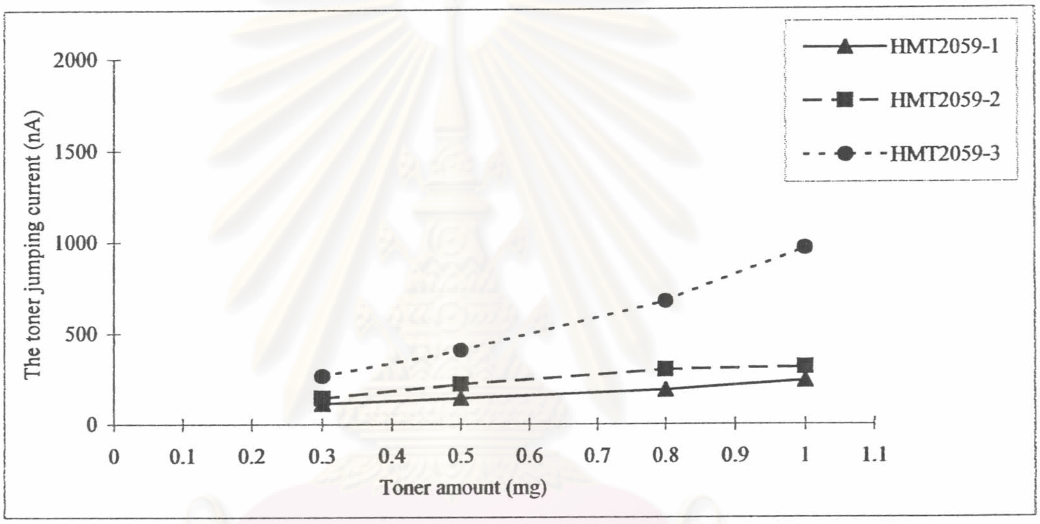
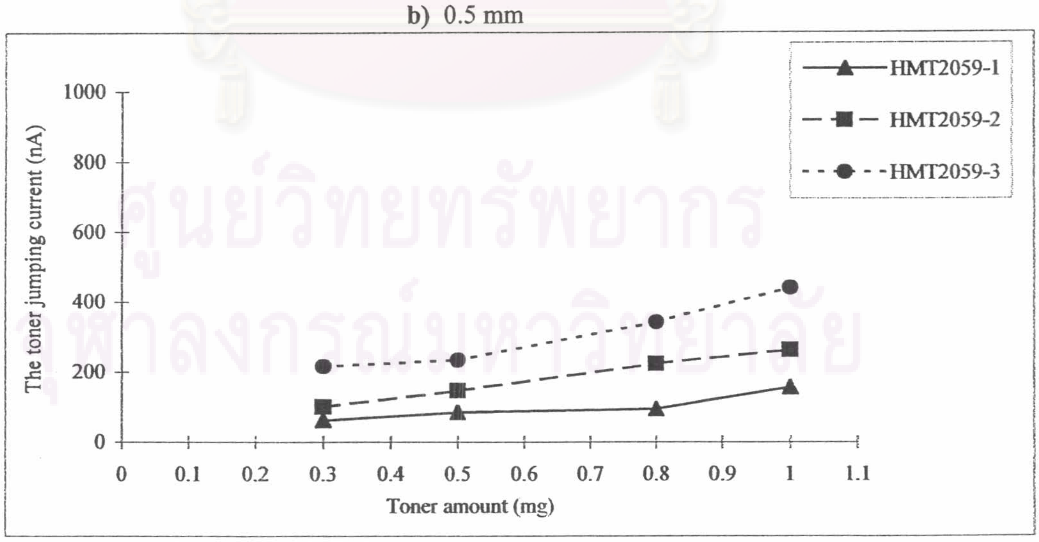
Figure 4-14 Relationship between the toner jumping current and the toner amount for the different toner resistivity at the applied voltage of 500 V and the cone depths of the dented electrode at a) 0.2, b) 0.5, and c) 1.0 mm.



a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

Figure 4-15 Relationship between the toner jumping current and the toner amount for the different toner resistivity at the applied voltage of 750 V and the cone depths of the dented electrode at a) 0.2, b) 0.5, and c) 1.0 mm.

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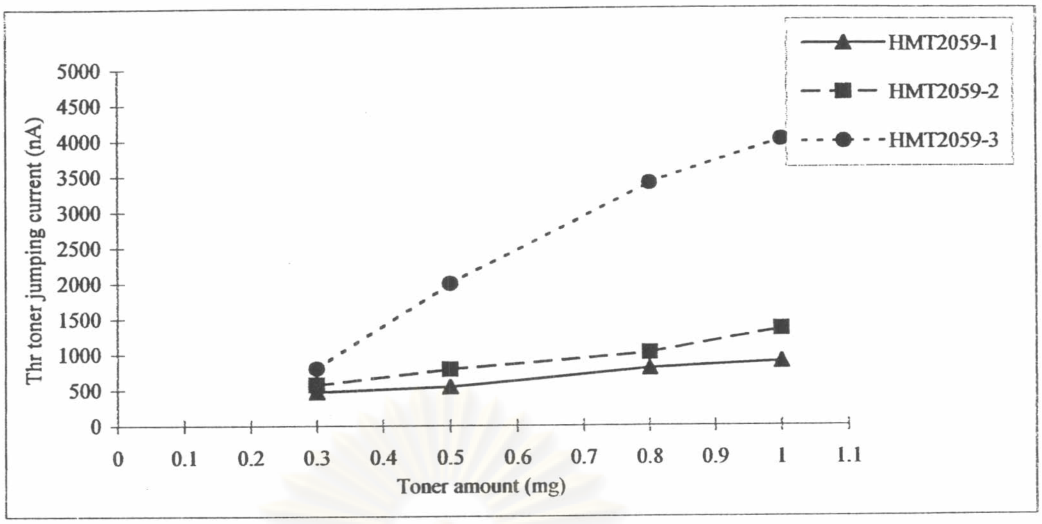
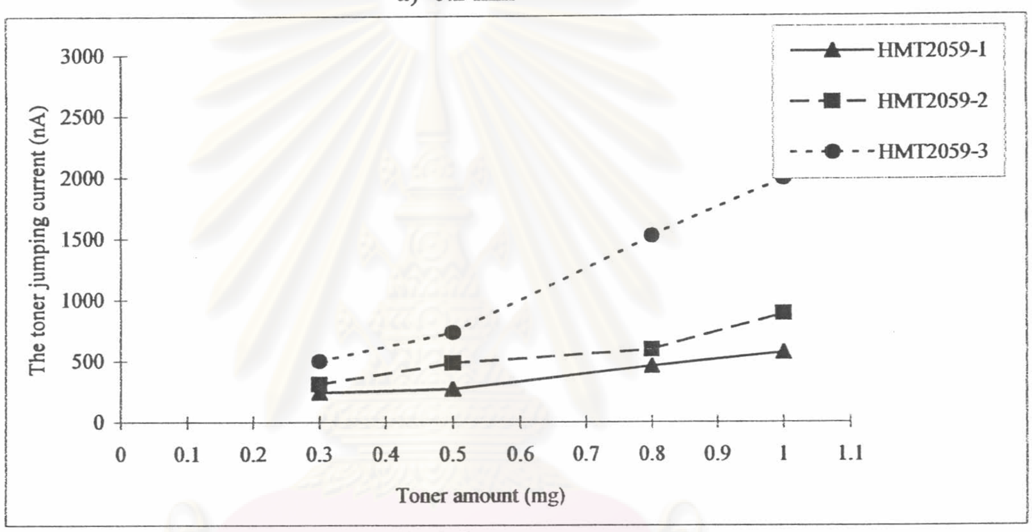
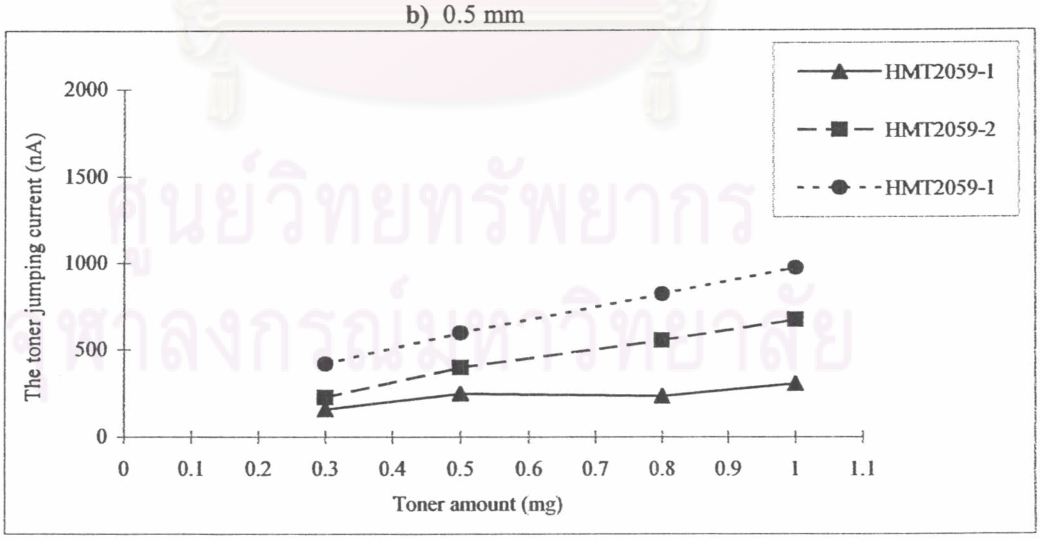


a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

Figure 4-16 Relationship between the toner jumping current and the toner amount for the different toner resistivity at the applied voltage of 1000 V and the cone depths of the dented electrode at a) 0.2, b) 0.5, and c) 1.0 mm.

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As a rule of thumb, the following relationship has long been established:

$$\vec{E} = \vec{J}\rho \qquad (4\text{-}6)$$

Equation (4-6) is Ohm's law recast,[15] where J is current density (A/cm^2), ρ is the resistivity (Ω cm). It is customary to introduce the conductivity (σ), which is inversely proportional to the resistivity (σ = 1/ρ), for further evaluation and can be written:

$$\vec{J} = \sigma\vec{E} \qquad (4\text{-}7)$$

For this case, J is the toner jumping current per unit area. The conductivity of the toner three types of conductive toner (HMT 2059-1, HMT 2059-2, HMT 2059-3) can be calculated by σ = 1/ρ to give 2.27×10^{-9}, 1.75×10^{-8} and 1.35×10^{-7} $(\Omega\ cm)^{-1}$, respectively. Therefore, at the fixed electric field, the higher the conductivity renders the greater toner jumping current.

b) On the toner amount at the applied voltage

The dependences of the toner jumping current on the toner amount (0.3, 0.5, 0.8 and 1.0 mg) at 500, 750 and 1000 V are shown in Figures 4.15 to 4.17

Since the extent of toner jumping current depends largely on the depth of the dented electrode, the relationship between toner jumping current and toner amount is then undoubtedly controlled by the amount of toner filled in the depth of the dented electrode. The toner jumping current increases when the toner amount increases. As the applied voltage is an effective factor controlling the toner jumping current in a direct proportional manner, then the higher the applied voltage, the greater the toner jumping current. The lines of toner jumping current are similar in all depths of the dented electrode.

The same manner is found for other toner amounts. Because the amount of current should depend on the electric field (E), and E depends on the voltage (V)[11]. Based on Equation (4-5), the toner jumping current depends on the applied electric field, and the applied voltage. Hence, $I_t \propto V$, therefore, the higher the voltage, the greater the jumping current of toner. Hence, $I_t \propto V$.

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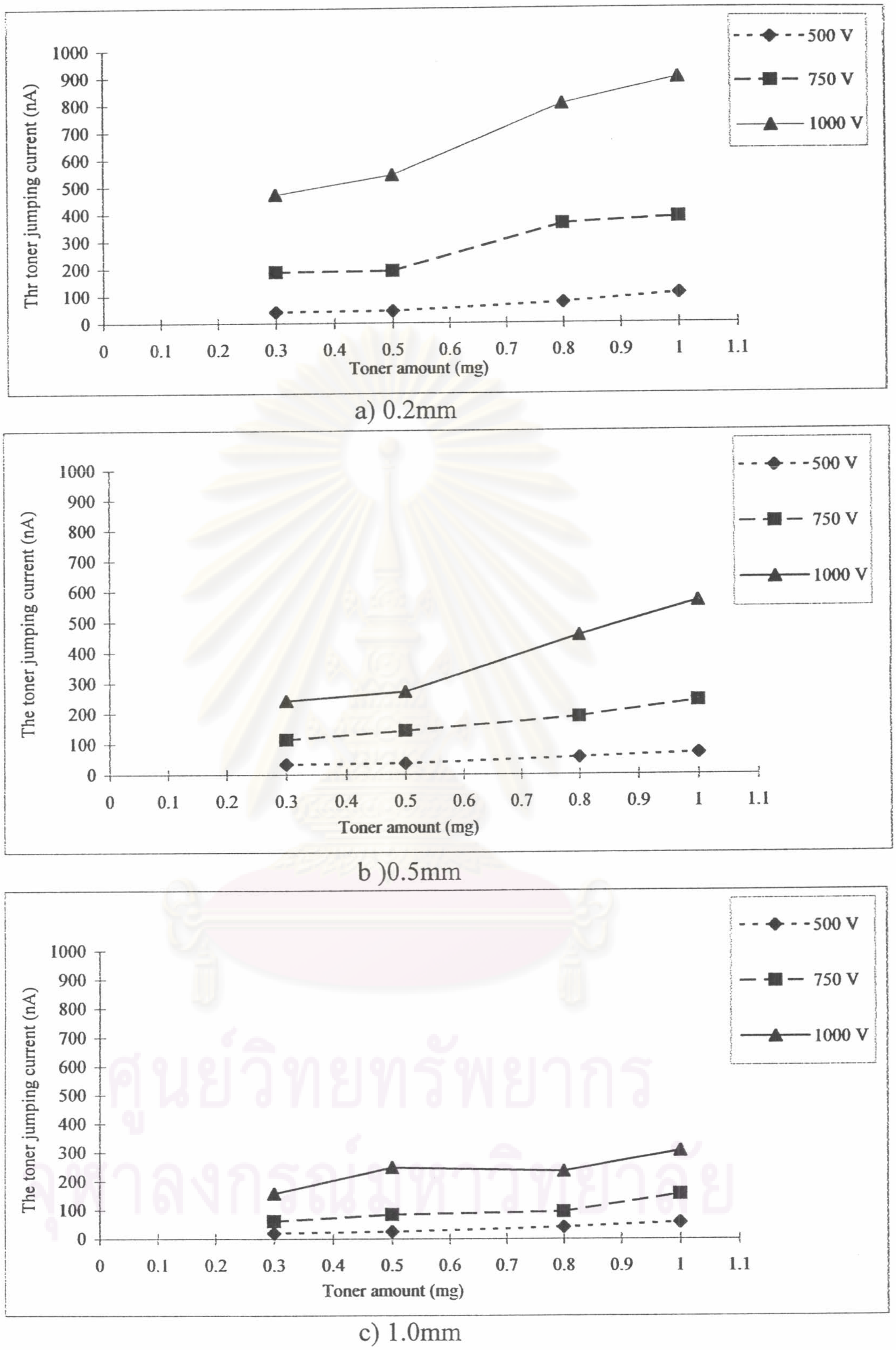
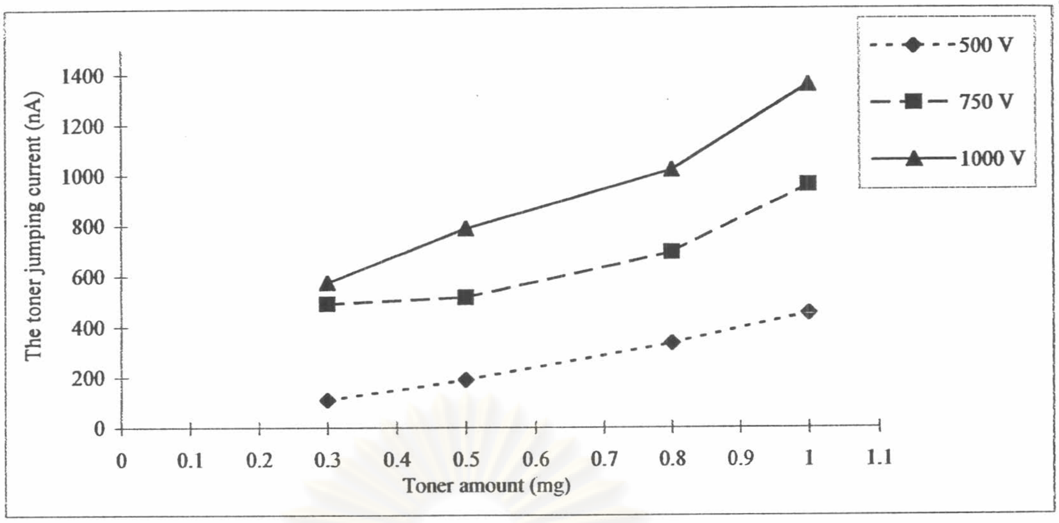


a) 0.2mm

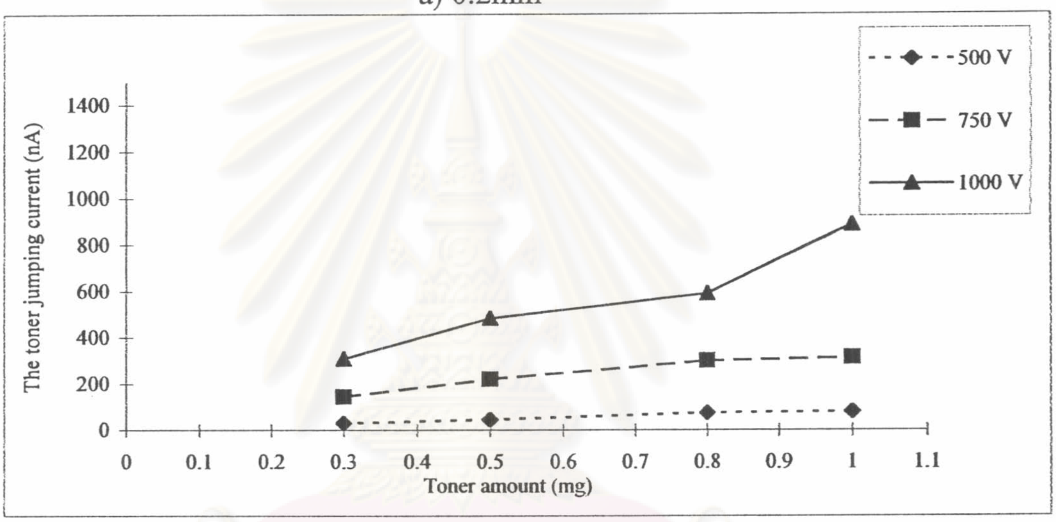
b)0.5mm

c) 1.0mm

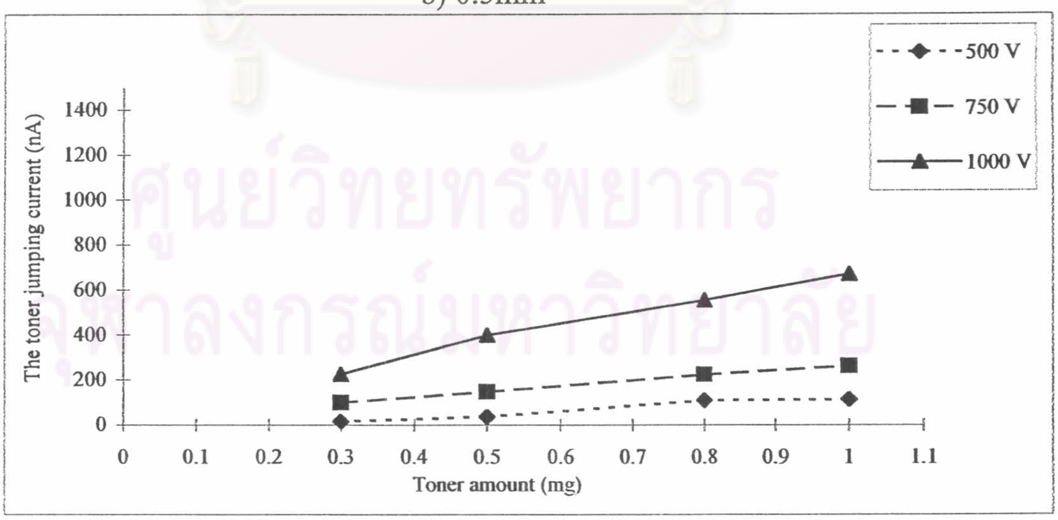
Figure 4-17 Relationship between the toner jumping current and the toner amount at three applied voltages for the toner HMT2059-1 at the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.



a) 0.2mm



b) 0.5mm



c) 1.0mm

Figure 4-18 Relationship between the toner jumping current and the toner amount at three applied voltages for the toner HMT2059-2 at the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.

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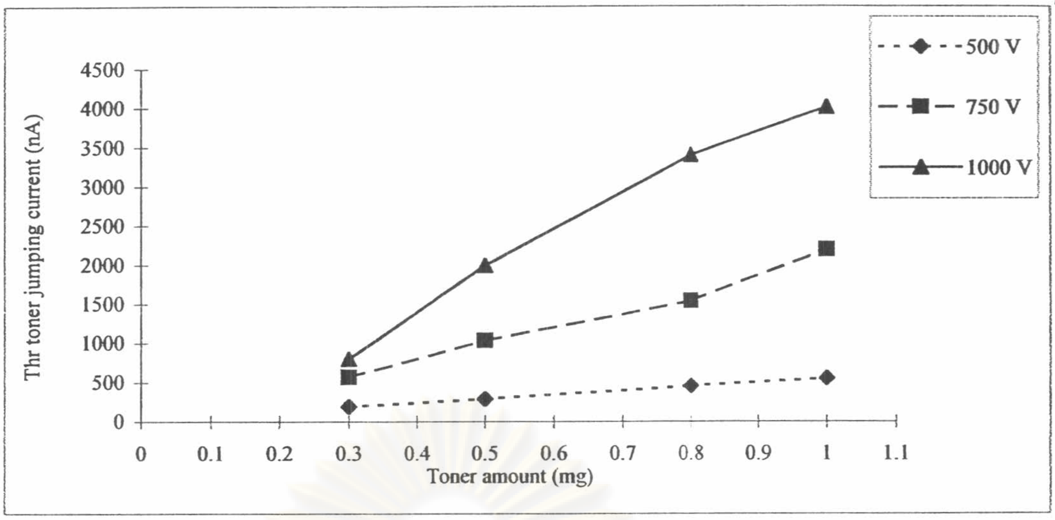
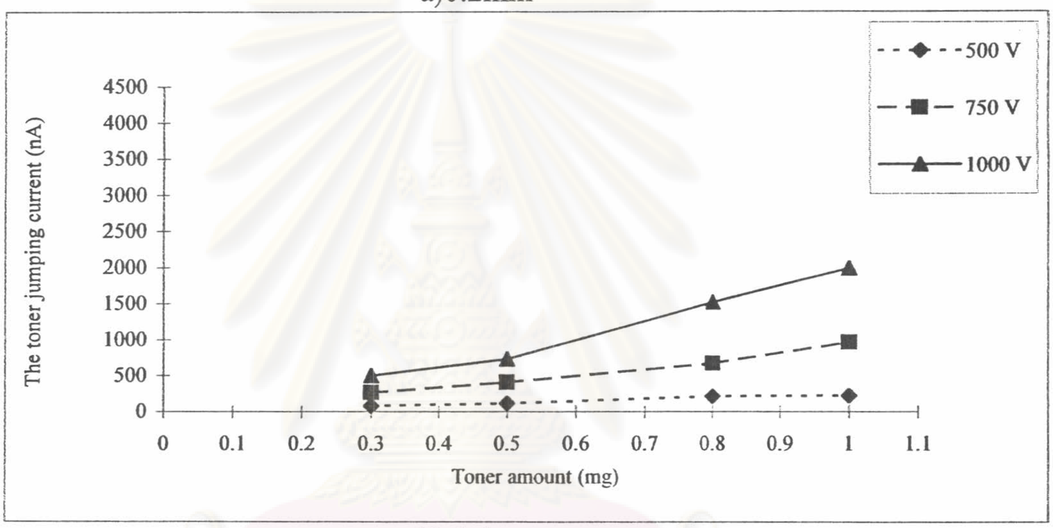
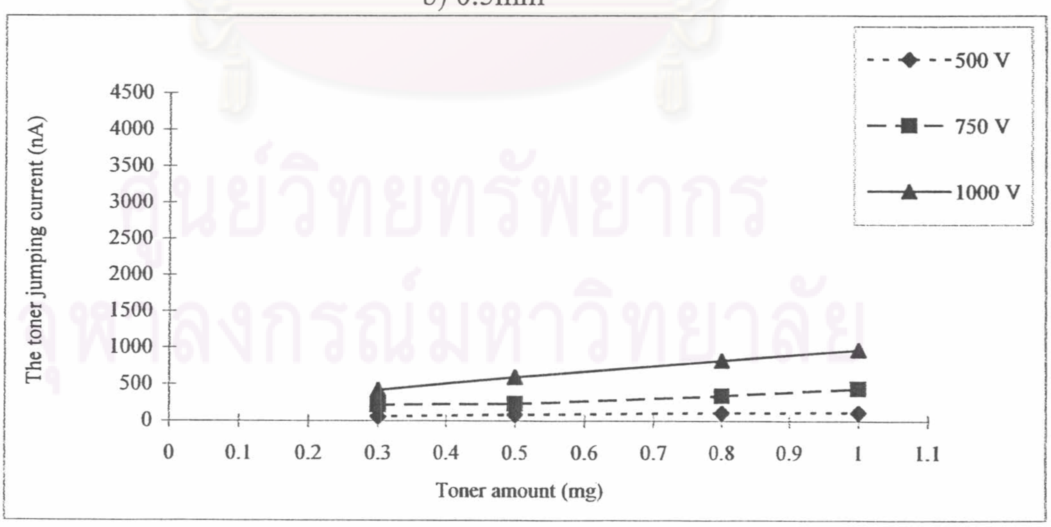


a)0.2mm



b) 0.5mm



c) 1.0mm

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Figure 4-19 Relationship between the toner jumping current and the toner amount at three applied voltages for the toner HMT2059-3 at the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.

c) On the toner amount at the cone depth of the dented electrode

The effect of the depth of the dented electrode on the toner jumping current is shown in Figures 4-20 to 4-22.

Since the amount of toner is the controlling factor for toner jumping, therefore, it is a logistic way to relate the current with the amount of toner at several depths. These results in these figures show that the toner jumping current increases when the toner amounts increases. At the fixed toner resistivity and applied voltage, the jumping current increases linearly with the toner amount. Its effect becomes significantly at the higher voltage applied. The lower depth of the dented electrode allows the greater toner jumping current and vice versa. When decreasing the toner, the jumping current increases clearly as shown in Figures 4-21 and 4-22.

We anticipated that the distance from the dented electrode to the lower electrode might be the controlling factor. The shallower the cone depth of the dented electrode, the higher toner jumping current. The toner particles at the shorter distance between the two electrodes can move up much easier to achieve the higher jumping current.

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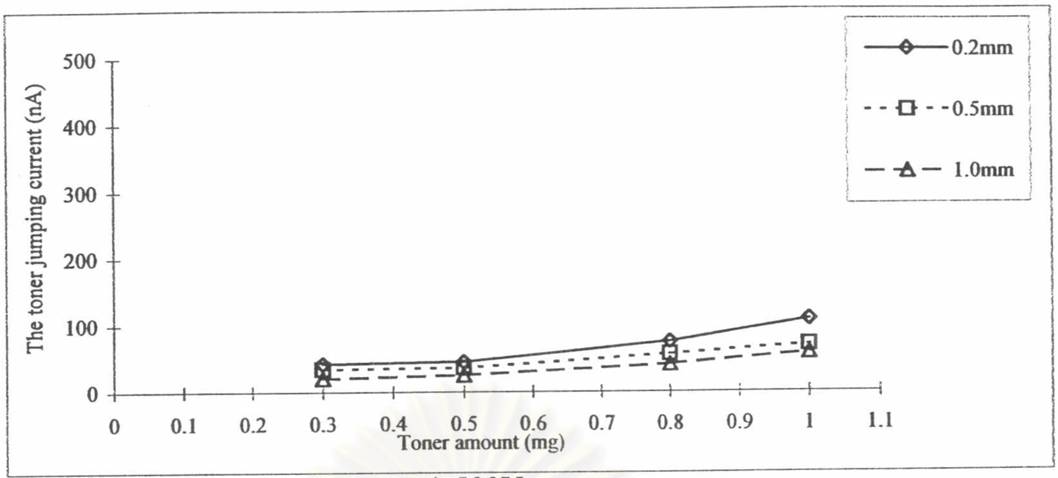
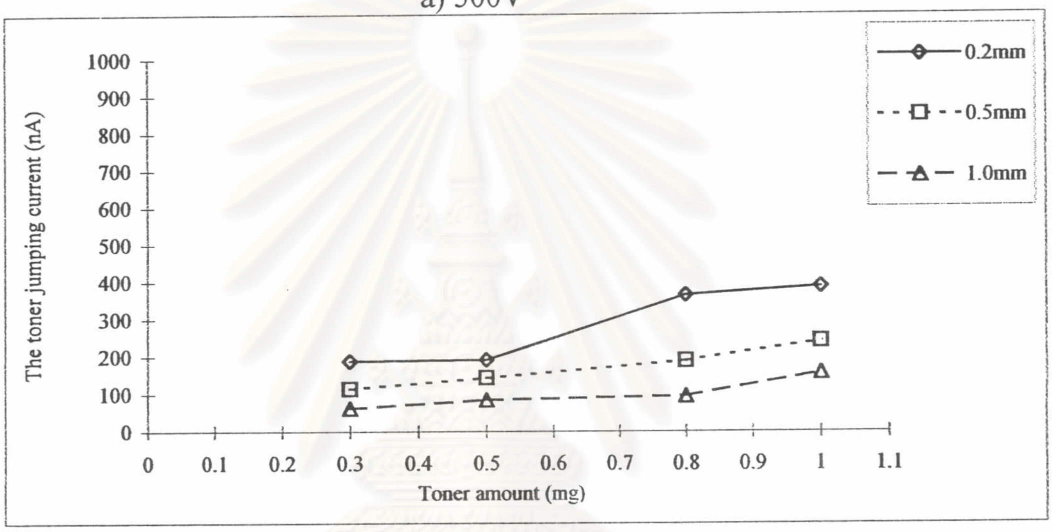
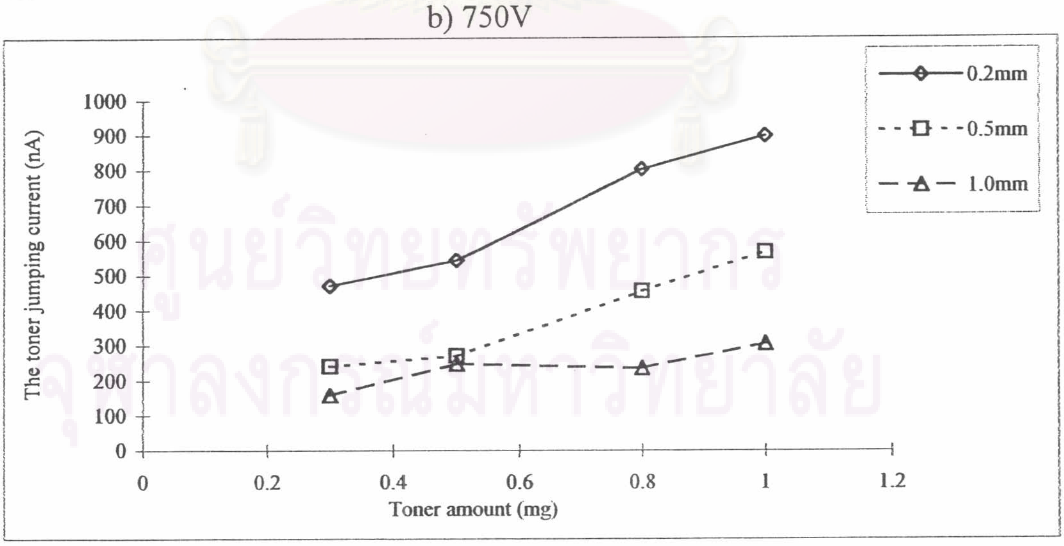


a) 500V



b) 750V



c) 1000V

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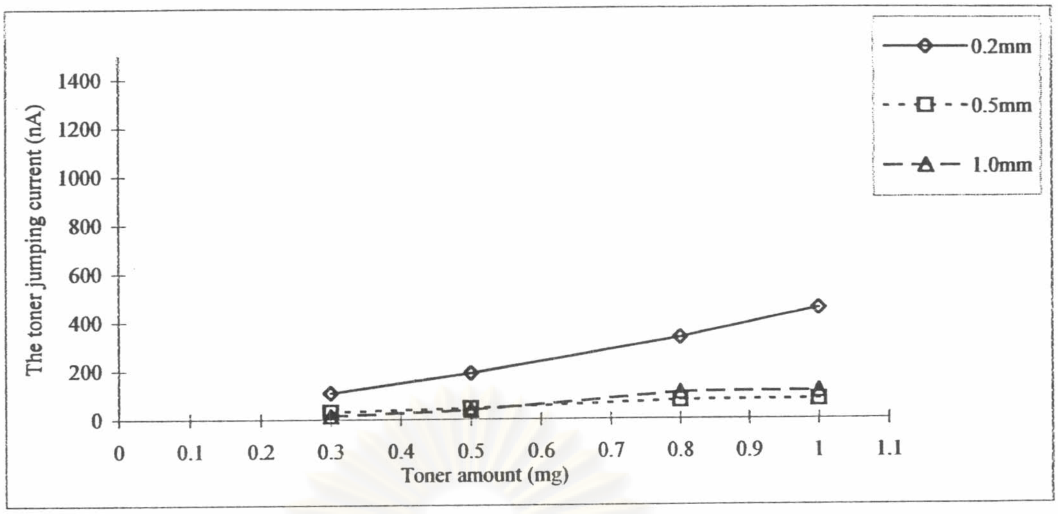
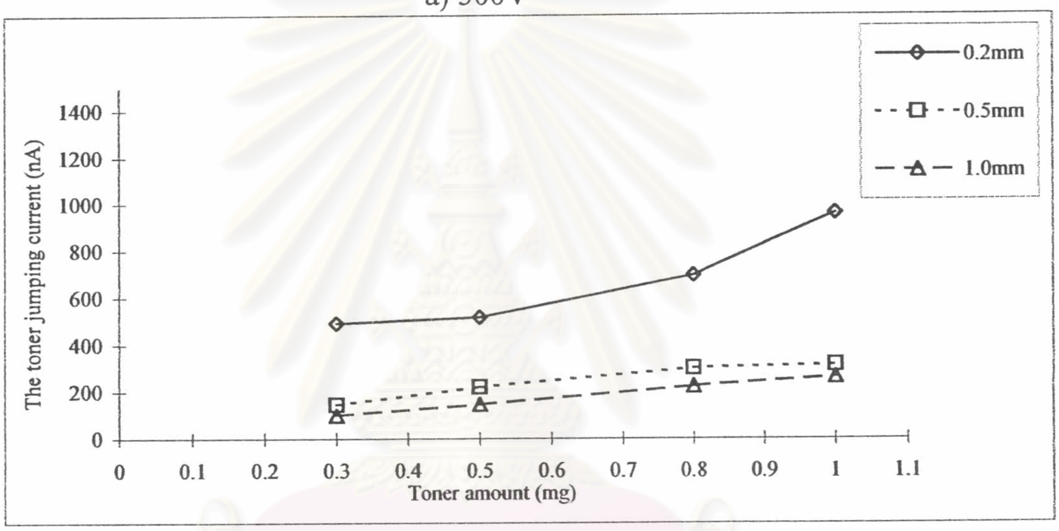
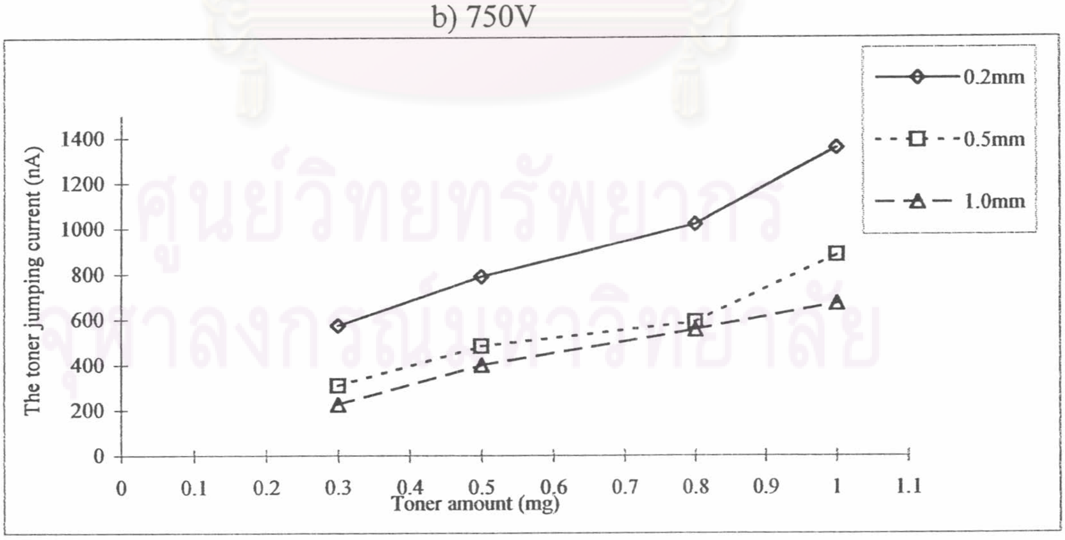
Figure 4-20 Relationship between the toner jumping current and the toner amount for the cone depth of the dented electrode three hollows of the toner HMT2059-1 at the applied voltages of 500, 750, and 1000V.



a) 500V



b) 750V



c) 1000V

Figure 4-21 Relationship between the toner jumping current and the toner amount for the cone depth of the dented electrode three hollows of the toner HMT2059-2 at the applied voltages of 500, 750, and 1000V.

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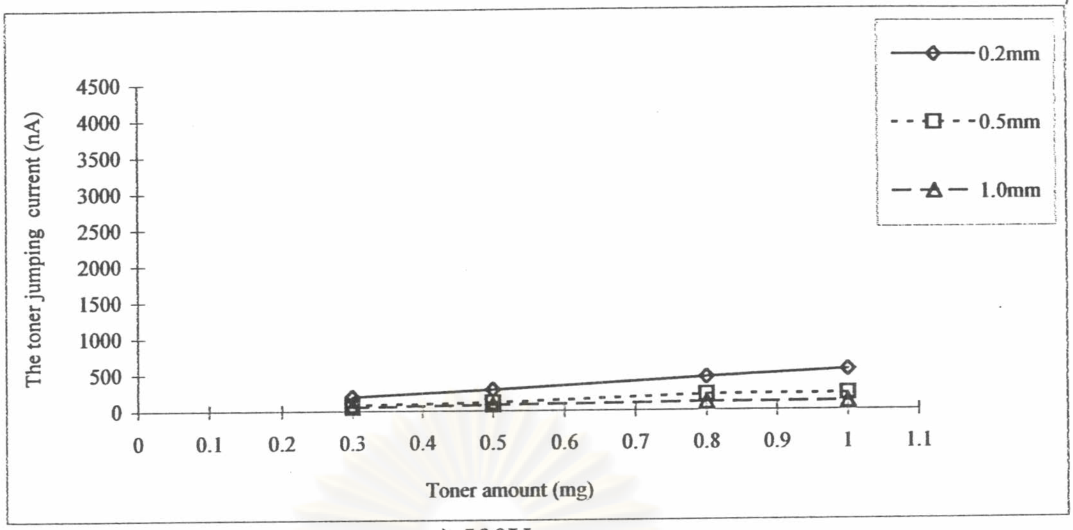
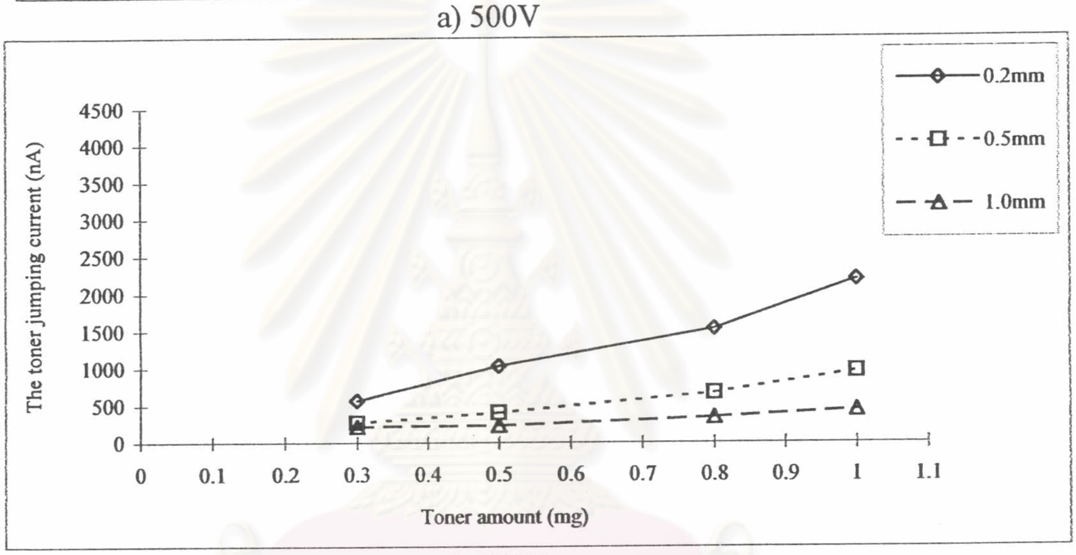
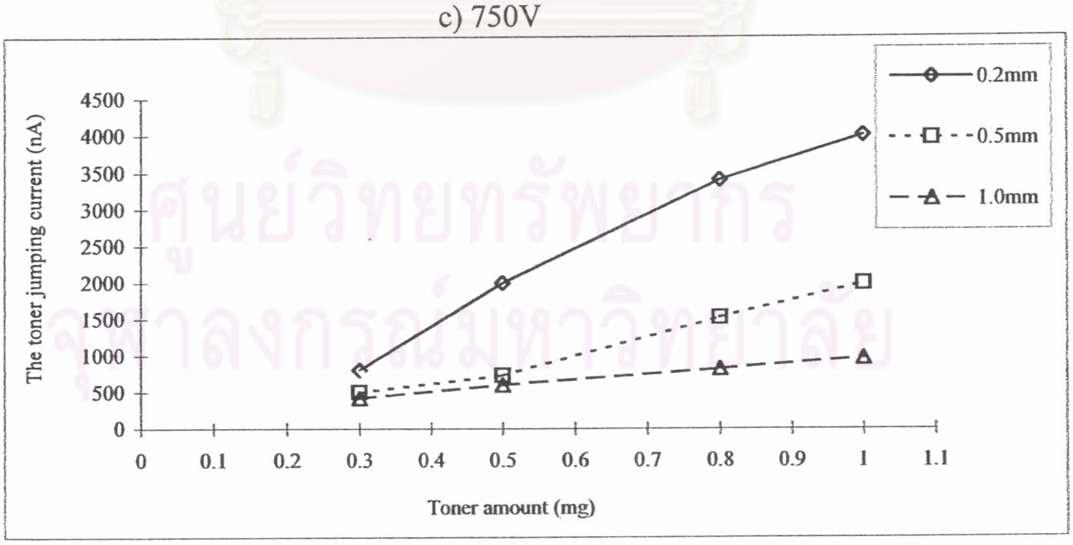


a) 500V



c) 750V



c) 1000V

Figure 4-22 Relationship between the toner jumping current and the toner amount for the cone depth of the dented electrode three hollows of the toner HMT2059-3 at the applied voltages of 500, 750, and 1000V.

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From Equation (4-5), one can see that n, q and b can be fixed as the material constants, then $I_t \alpha E(t)$, or the toner jumping current depends significantly on the applied electric field to the electrode.

As the electric field was approximated by the ELFIN software, we found that the electric field depends on the cone depth of dent electrode as shown in Table 4-7

Table 4-7 The magnitude of the electric field from ELFIN software

Voltage (V)	The cone depth of dented electrode (mm)	The magnitude of the electric field (V/m)
500	0.2	1.91×10^5
	0.5	4.37×10^5
	1	2.96×10^2
750	0.2	6.26×10^5
	0.5	6.56×10^5
	1	3.42×10^5
1000	0.2	8.35×10^5
	0.5	4.37×10^5
	1	4.07×10^5

It was found in Table 4-7 that the the shallower the dented electrode depth, the more magnitude of the electric field, therefore, the shallower depth of the dented electrode produce the higher jumping current.

4.1.2.2 Dependence of toner jumping current on applied voltage

After a certain level of voltage was applied between the electrodes, the conductive toner moves up and down between the electrodes because the electric field approaches a threshold value. Therefore, a detachment of the conductive toner particles from the dented electrode was obtained. When the electric field exceeds the threshold value, the conductive toner starts to increase the current significantly [7]. The toner jumping current was detected by the electrometer. Tables 4-8 to 4-10 show the dependency of the toner jumping current on the applied voltage for the conductive toners HMT2059-1, HMT2059-2, and HMT2059-3, respectively. The relationship between the toner jumping current and voltage at three depths of the dented electrode is shown in Figures 4-23 to 4-26.

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Table 4-8 Dependence of toner jumping current for HMT 2059-1 on the applied voltages at various toner amounts and depths of the dented electrode.

Voltage (V)	The toner jumping current (nA)											
	Toner amount: 1.0 mg			Toner amount: 0.8 mg			Toner amount: 0.5 mg			Toner amount: 0.3 mg		
	The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode		
	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm
0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0
200	5	4	2	3	2	1	5	6	3	3	2	1
300	12	10	8	11	9	7	12	6	7	12	7	6
400	32	15	14	26	13	9	25	14	14	22	15	13
500	108	25	38	76	26	14	45	16	21	42	32	20
600	117	62	45	125	55	23	62	32	27	54	37	24
700	256	78	83	188	132	33	126	75	64	125	65	37
800	498	266	191	476	270	139	256	141	119	258	157	87
900	718	372	267	712	389	188	359	195	159	359	184	99
1000	898	607	307	880	560	236	544	323	248	472	260	180

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Table 4-9 Dependence of toner jumping current for HMT 2059-2 on the applied voltages at various toner amounts and depths of the dented electrode.

Voltage (V)	The toner jumping current (nA)											
	Toner amount: 1.0 mg			Toner amount: 0.8 mg			Toner amount: 0.5 mg			Toner amount: 0.3 mg		
	The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode		
	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm
0	0	0	0	0	0	0	0	0	0	0	0	0
100	0	0	0	0	0	0	0	0	0	0	0	0
200	5	3	1	2	1	0	2	1	0	1	1	0
300	15	9	7	13	11	1	14	9	8	8	7	5
400	136	37	18	92	34	16	28	25	20	58	16	15
500	293	56	24	207	57	40	80	48	37	109	31	46
600	338	117	73	229	117	98	102	89	49	173	63	61
700	531	251	145	382	214	121	186	141	102	282	126	71
800	1144	434	352	868	401	318	407	261	214	323	209	138
900	1520	678	471	1165	587	438	523	452	274	405	326	172
1000	1644	836	585	1313	743	548	575	581	400	489	462	220

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Table 4-10 Dependence of toner jumping current for HMT 2059-3 on the applied voltages at various toner amounts and depths of the dented electrode.

Voltage (V)	The toner jumping current (nA)											
	Toner amount: 1.0 mg			Toner amount: 0.8 mg			Toner amount: 0.5 mg			Toner amount: 0.3 mg		
	The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode			The cone depth of dented electrode		
	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm	0.2 mm	0.5 mm	1.0 mm
0	0	0	0	0	0	0	0	0	0	0	0	0
100	2	0	0	1	0	0	0	0	0	0	0	0
200	5	4	3	3	2	1	2	1	0	1	0	0
300	41	22	15	35	16	10	26	7	5	15	9	5
400	338	145	49	205	50	31	162	42	26	43	27	20
500	605	204	114	554	113	109	291	68	52	91	42	38
600	828	290	189	747	186	136	417	108	111	100	80	69
700	1480	386	253	1065	336	213	589	288	183	151	144	130
800	2259	531	521	2157	565	418	1262	402	313	323	249	186
900	2683	894	661	2549	742	556	1749	505	398	378	322	222
1000	3217	1078	973	3147	920	823	1993	622	588	401	386	361

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a) On the applied voltage at the toner characteristics resistivity

The dependence of the toner jumping current on the applied voltage for the three HMT2059-1, HMT2059-2, and HMT2059-3, which have the resistivity values of 4.4×10^{8}, 5.7×10^{7} and $7.4\times10^{6}\Omega$ cm, respectively, was investigated. The results are shown in Figures 4-23 to 4-26.

The toner amount of 1.0 mg and the cone depths of the dented electrode of 0.2, 0.5 and 1.0 mm were studied for the toner jumping current as shown in Figure 4-23. When the applied voltage was increased and approached a threshold value, the toner jumping current increases gradually. The higher the applied voltage, the greater the toner jumping current. Considering the toner characteristic resistivity, the toner HMT2059-3 (7.4×10^{6} Ω cm) gives the higher jumping current than the toners HMT2059-2 and HMT2059-1, respectively. Figures 4-24 to 4-26 show the dependence of the toner jumping current on the applied voltage at the toner amounts of 0.8, 0.5 and 0.3 mg at the cone depths of the dented electrode of 0.2, 0.5 and 1.0 mm. Similar results are obtained, i.e. the applied voltage is increased and approaches a threshold value, the toner jumping current increases gradually. The higher the applied voltage, the greater the toner jumping current. The lower characteristic resistivity toner gives the higher toner jumping current.

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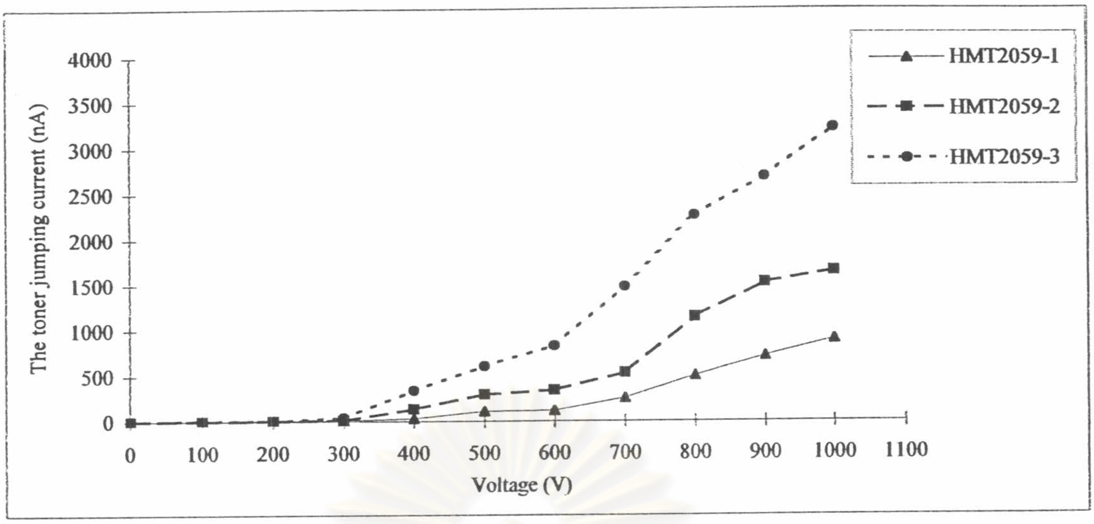
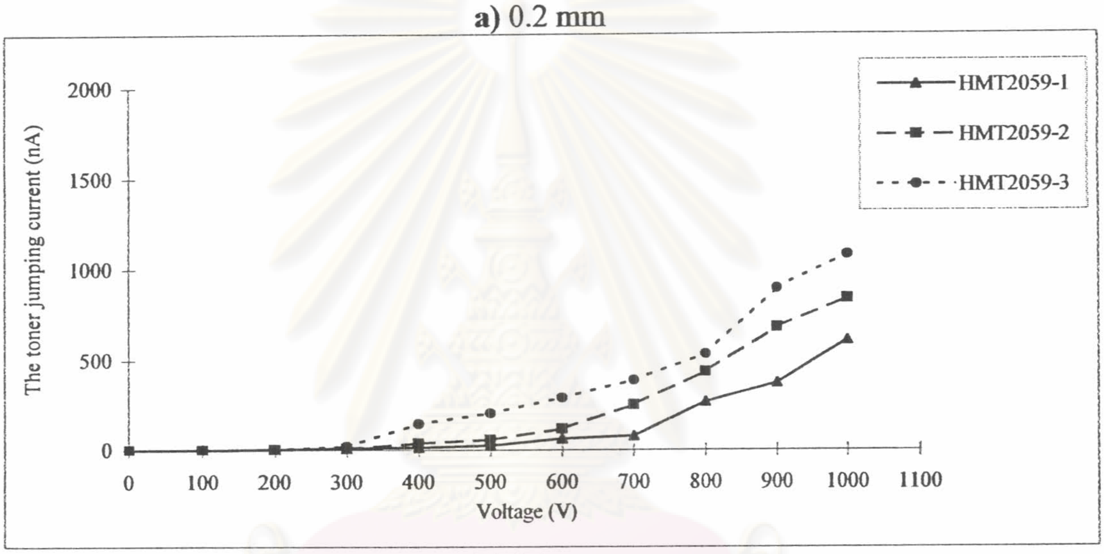
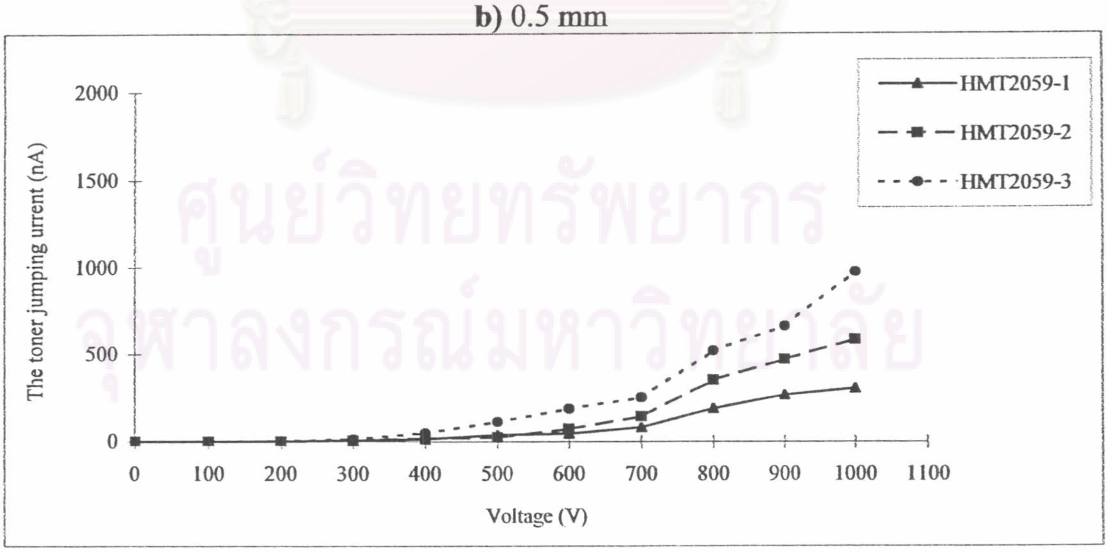


a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

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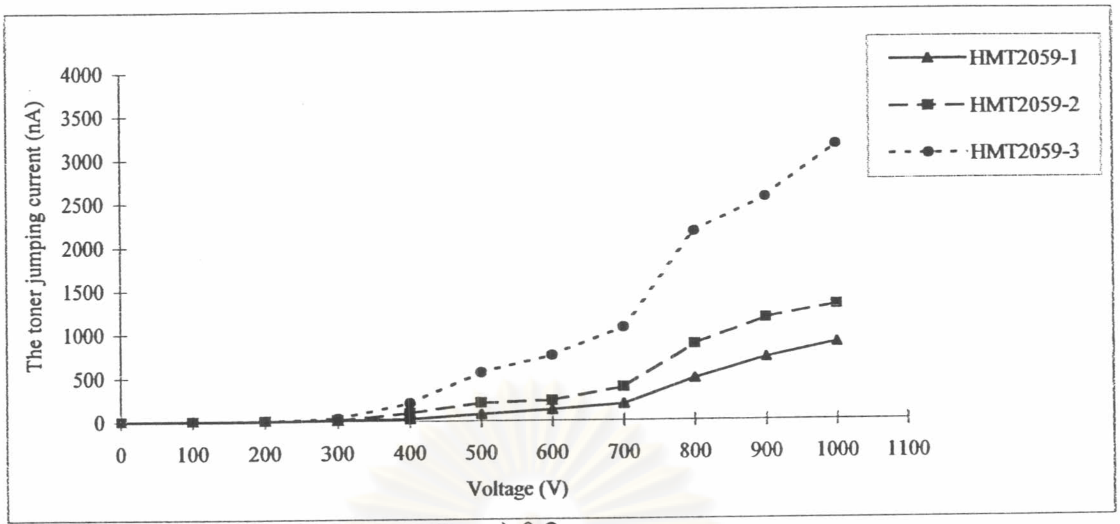
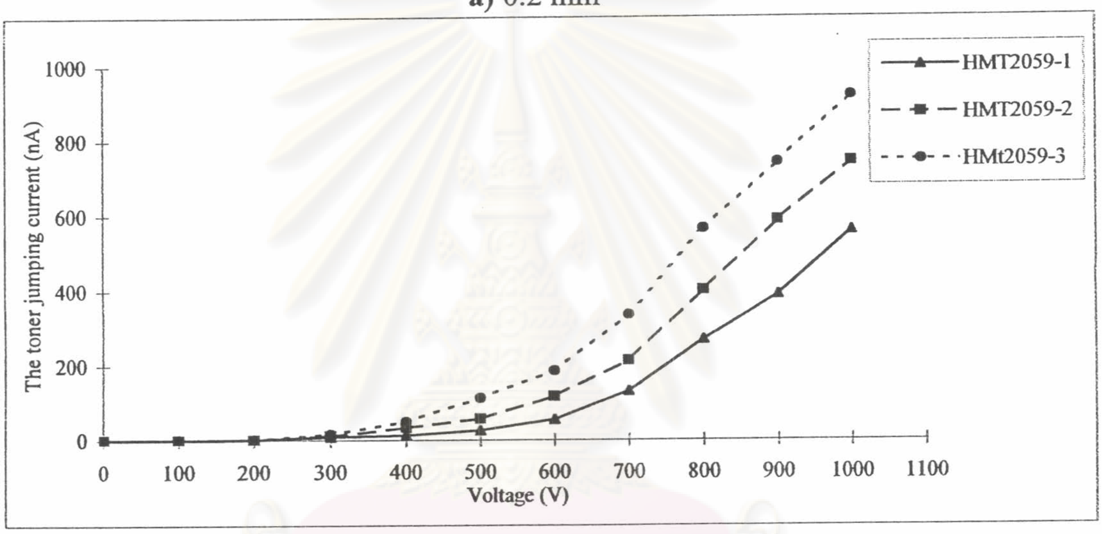
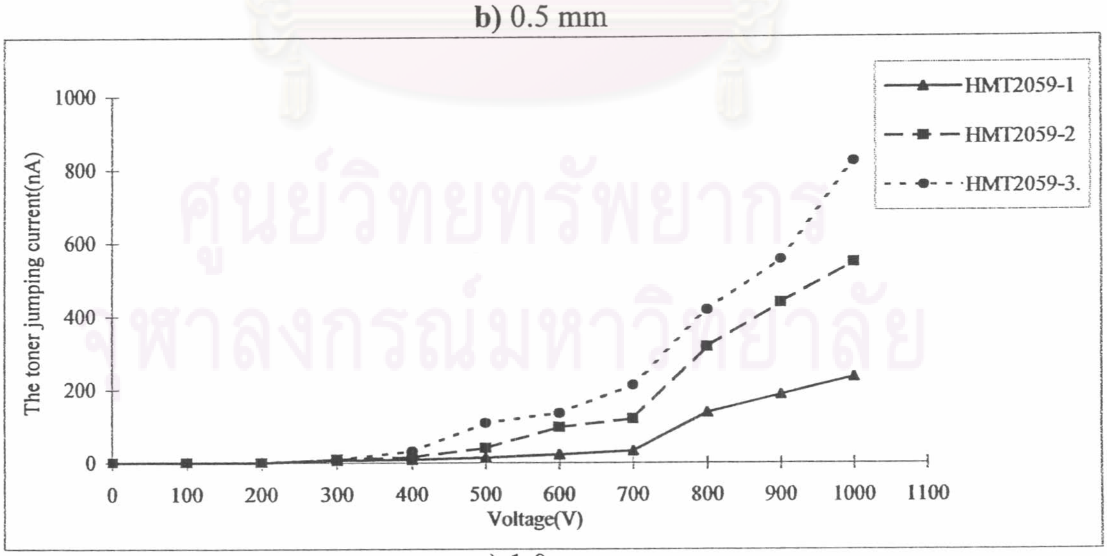
Figure 4-23 Dependence of the toner jumping current on the applied voltage at the toner resistivity and the toner amount of 1.0 mg with the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.



a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

Figure 4-24 Dependence of the toner jumping current on the applied voltage at the toner resistivity and the toner amount of 0.8 mg with the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.

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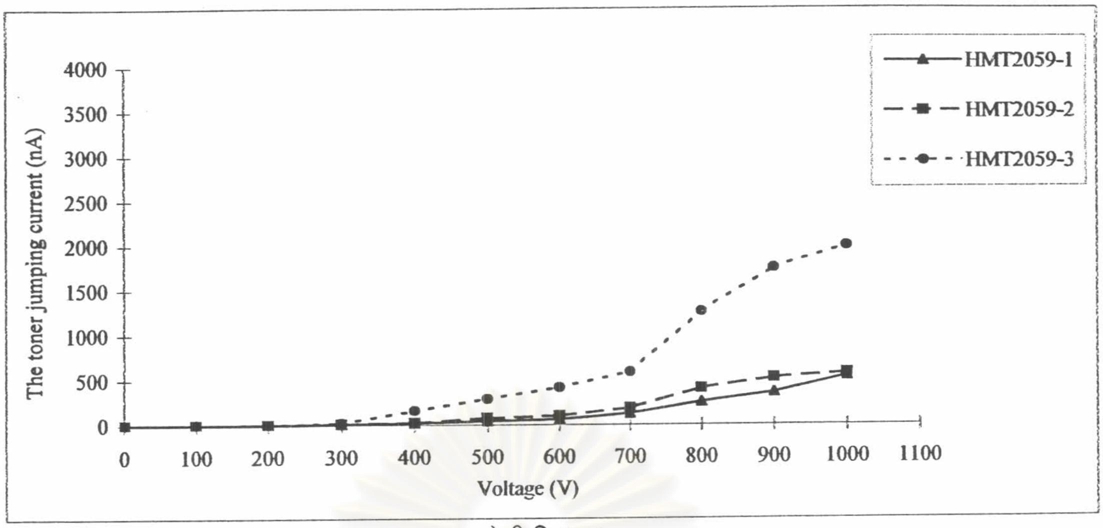
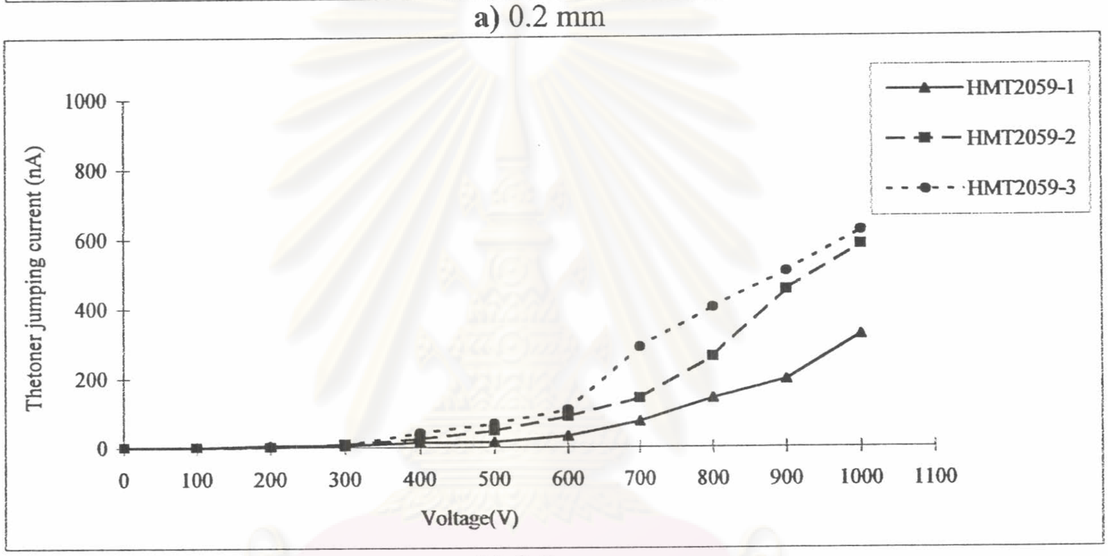
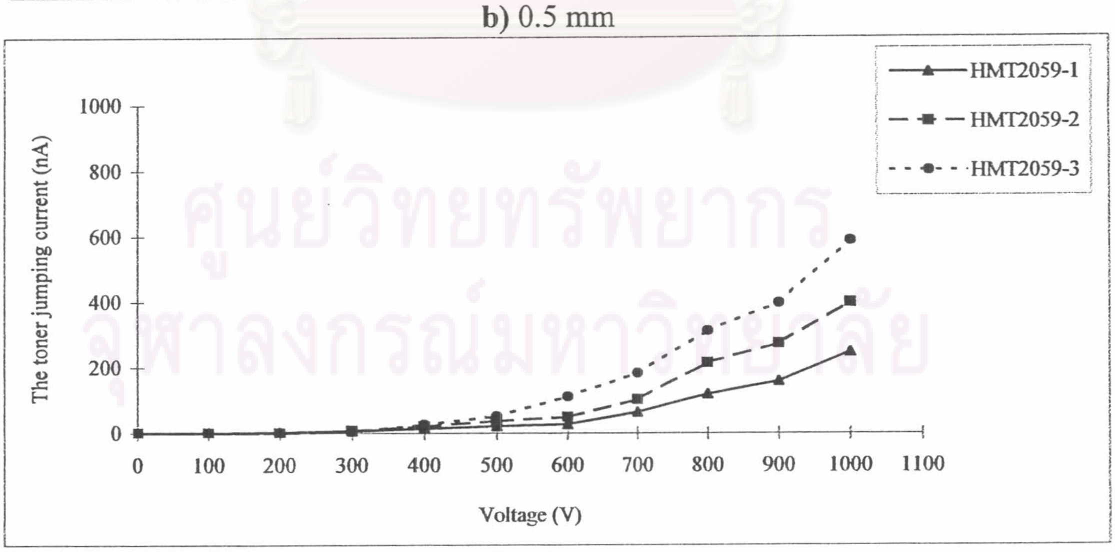


a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

Figure 4-25 Dependence of the toner jumping current on the applied voltage at the toner resistivity and the toner amount of 0.5 mg with the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.

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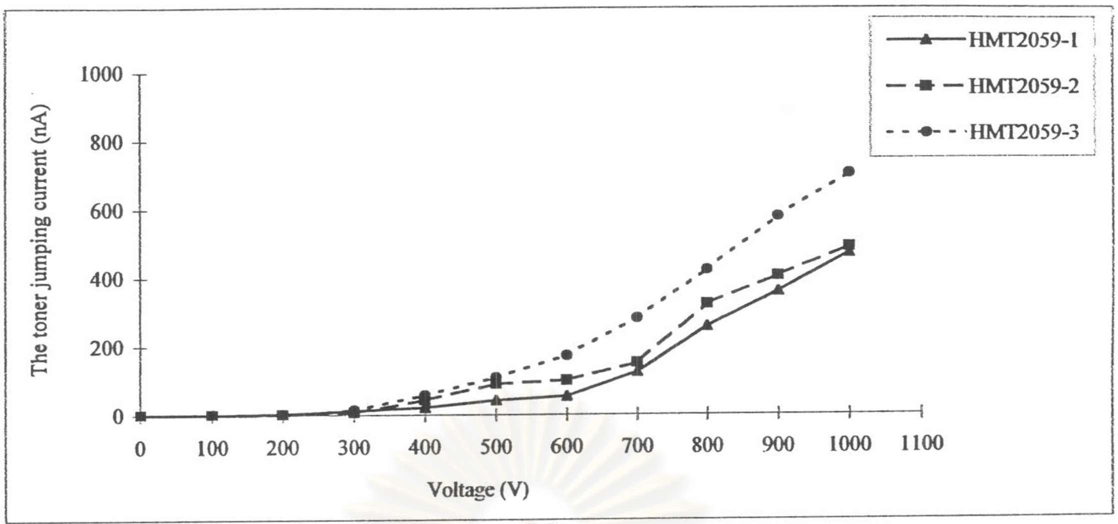
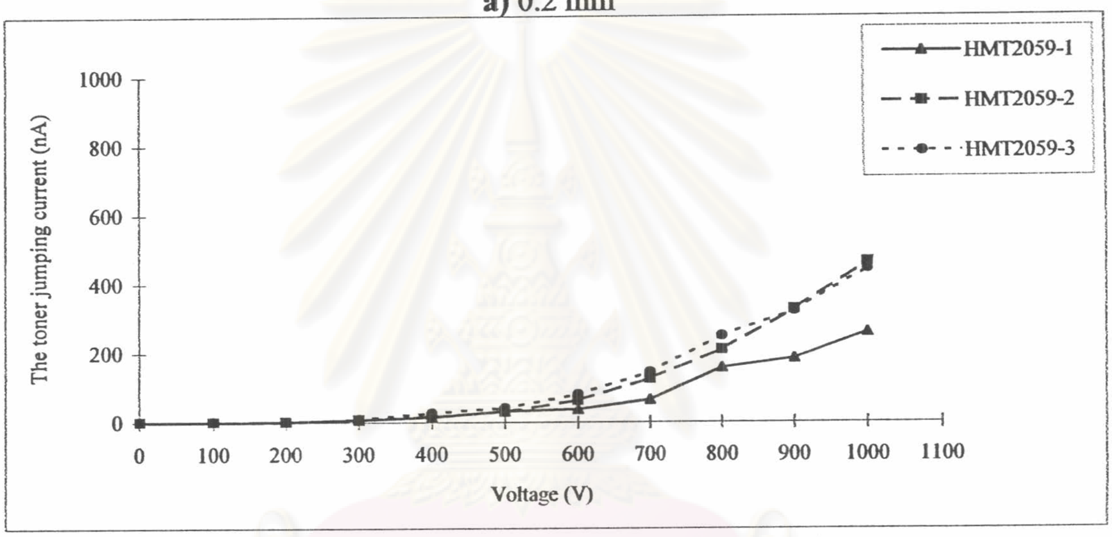
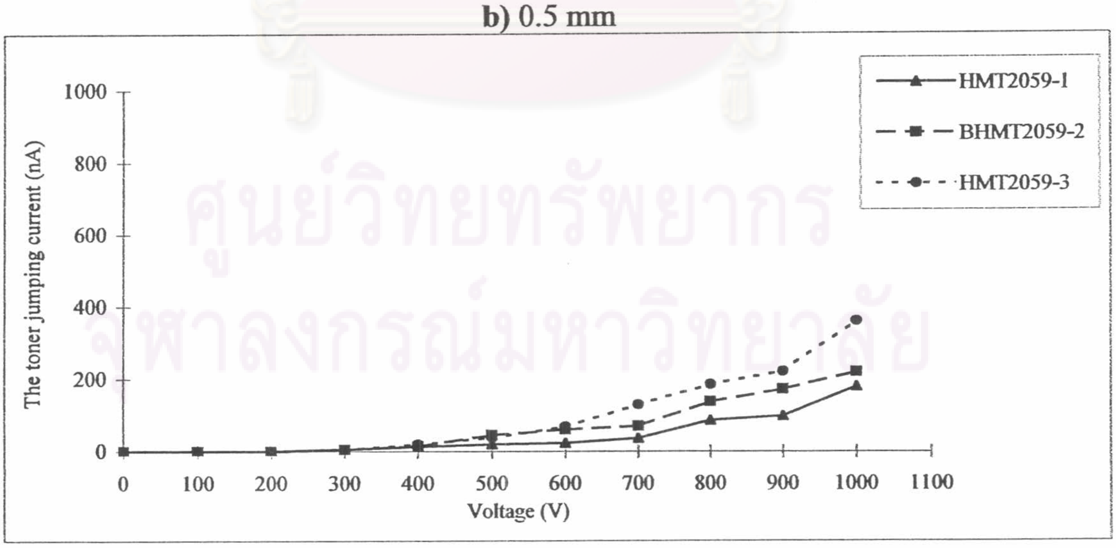


a) 0.2 mm



b) 0.5 mm



c) 1.0 mm

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Figure 4-26 Dependence of the toner jumping current on the applied voltage at the toner resistivity and the toner amount of 0.3 mg with the cone depths of the dented electrode of 0.2, 0.5, and 1.0 mm.

Figures 4-23 to 4-26 show the dependence of the toner jumping current on the applied voltage for three types of toner characteristic resistivity. We can estimate the threshold voltage for the toner jumping current as shown in Figures 4-23 to 4-26. We can determine the range of threshold voltage, at which the toners start jumping. For the toner HMT 2059-3 with $7.4 \times 10^6\ \Omega$ cm, the threshold voltage is 400 to 500 V. We also found the higher threshold voltages for the toner HMT2059-1 and HMT2059-2 having the higher resistivity of 4.4×10^8 and $5.7 \times 10^7\ \Omega$ cm, respectively. As mentioned earlier, conductivity is inverse proportional to resistivity. The higher conductivity of the toner can move the toners up to the upper electrode.

When the voltage exceeds a threshold value, the toner jumping starts to increase the current. The process of the toner jumping continues. The rates of induction changing of the conducting toner will depend upon the charging time constant or the relaxation time. The charging time constant can be expressed as: [6, 7].

$$\tau_c = C_{tc} R_t \tag{4-8}$$

where C_{tc} is the capacitance between the toner surface and the upper electrode and R_t is the resistance of the toner layer. Whether or not a material obeys Ohm's law, its resistance can be described in terms of its bulk resistivity. The charging time constant is a measure of how fast the conducting approaches electrostatic equilibrium. [13] The charging time constant for the toner HMT 2059-1, HMT 2059-2, and HMT 2059-3 depend on the resistivity of these toners. The relaxation time of the toner HMT 2059-1 is the longest time, therefore the toner moves up to the upper electrode with the larger threshold voltage.

b) On the applied voltage at the cone depth of the dented electrode

The dependence of the toner jumping current on the cone depths of dented electrode of 0.2, 0.5 and 1.0 mm are shown in Figures 4-27 to 4-29.

Figure 4-27 shows the dependence of the toner jumping current on the cone depth of dented electrode for the toner HMT2059-1 and the toner amounts of 1.0, 0.8, 0.5 and 0.3 mg. When the applied voltage is increased to approach a threshold value, after which the jumping current increases. The higher the applied voltage, the higher the toner jumping current.

Similar results are obtained as shown in Figures 4-28 and 4-29. Moreover, the higher toner jumping current is obtained when the depth of the dented electrode is shallow, therefore, the shorter distance between the two electrodes can produce the higher toner jumping current.

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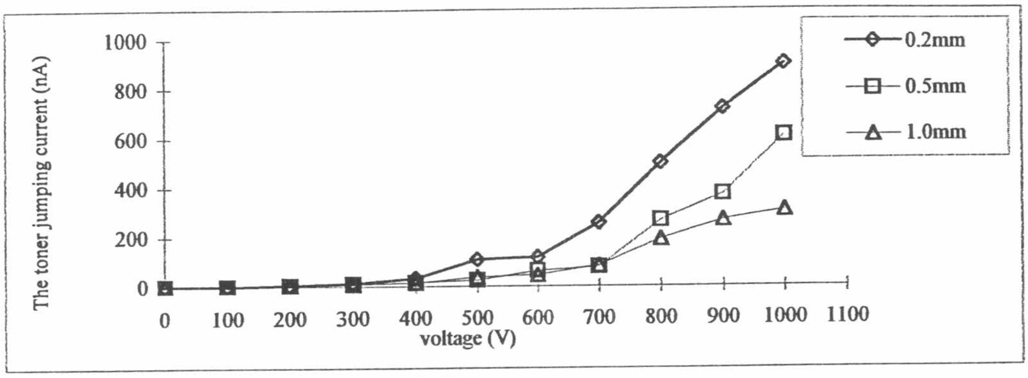
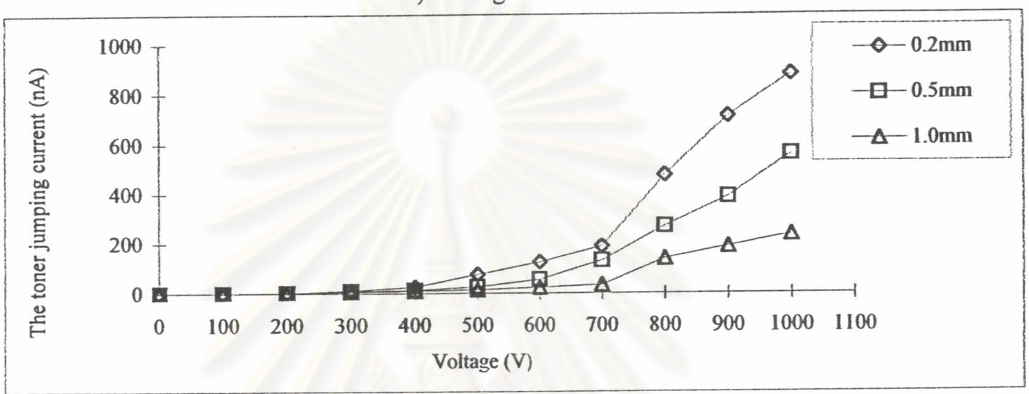
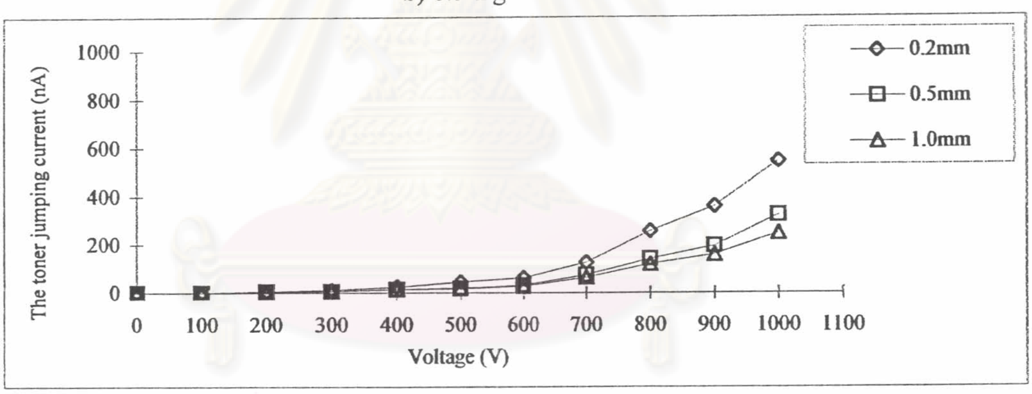


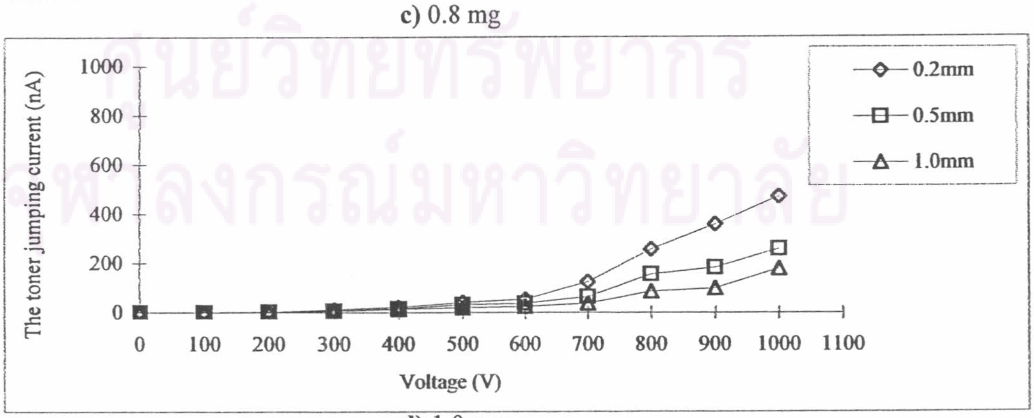
a) 0.3 mg



b) 0.5 mg



c) 0.8 mg



d) 1.0 mg

Figure 4-27 Dependence of the toner jumping current on the applied voltage at the cone depths of the dented electrode for the toner HMT2059-1 and the toner amounts of 1.0, 0.8, 0.5, and 0.3 mg.

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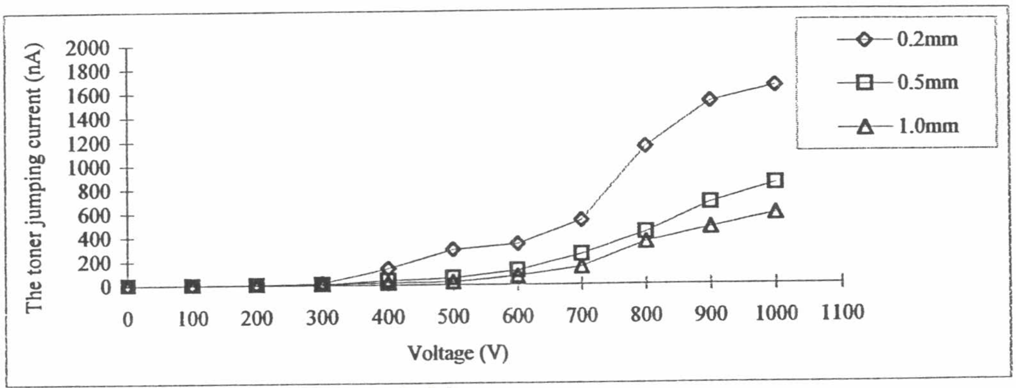
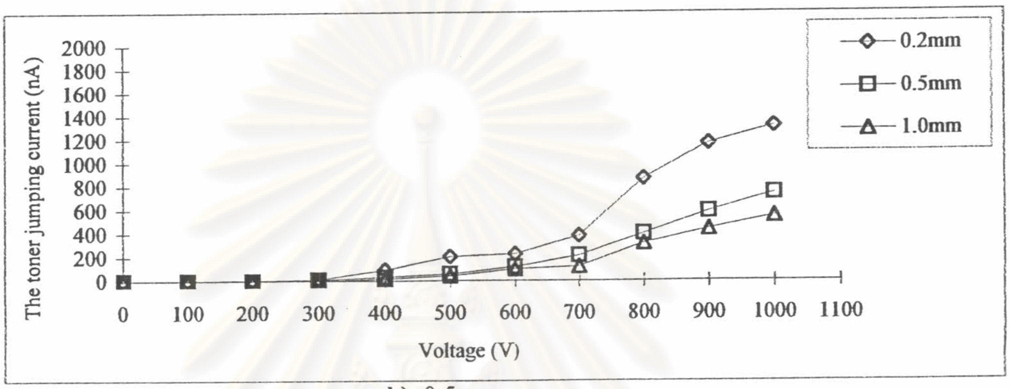
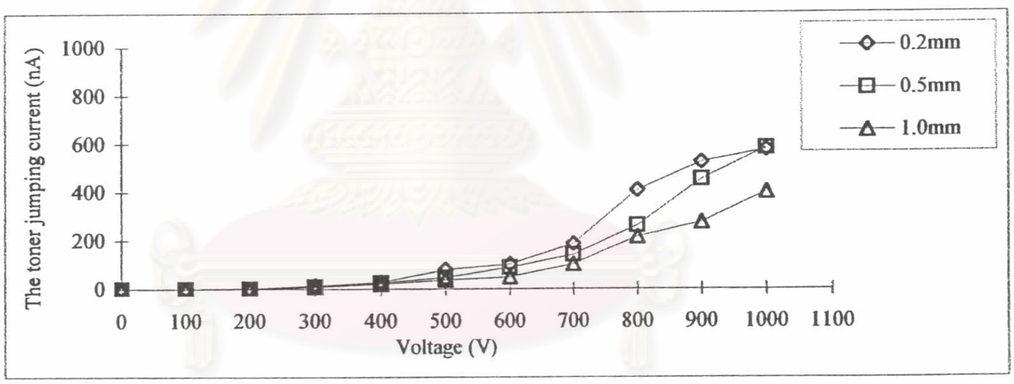


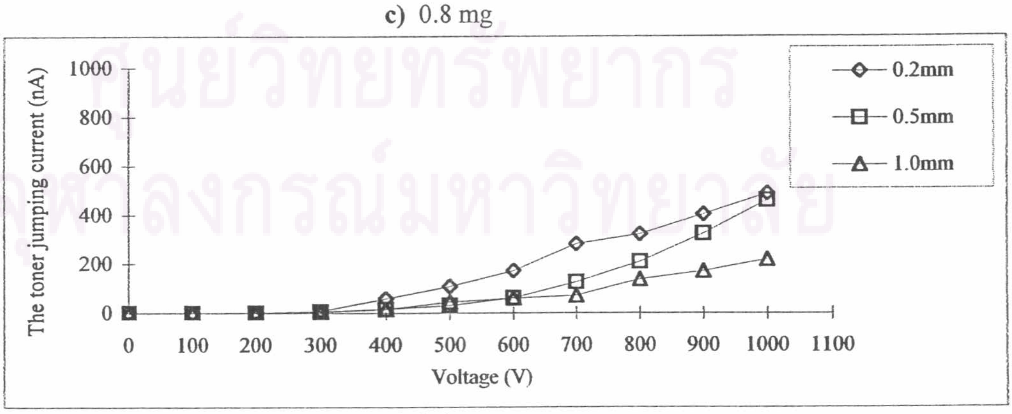
a) 0.3 mg



b) 0.5 mg



c) 0.8 mg



d) 1.0 mg

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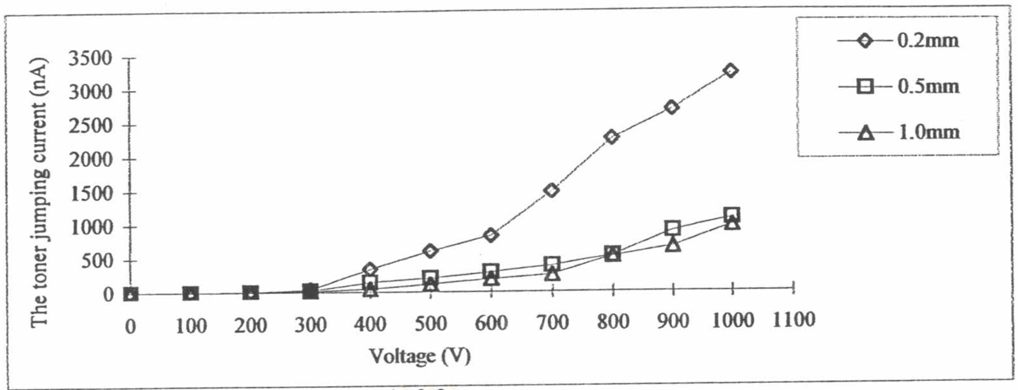
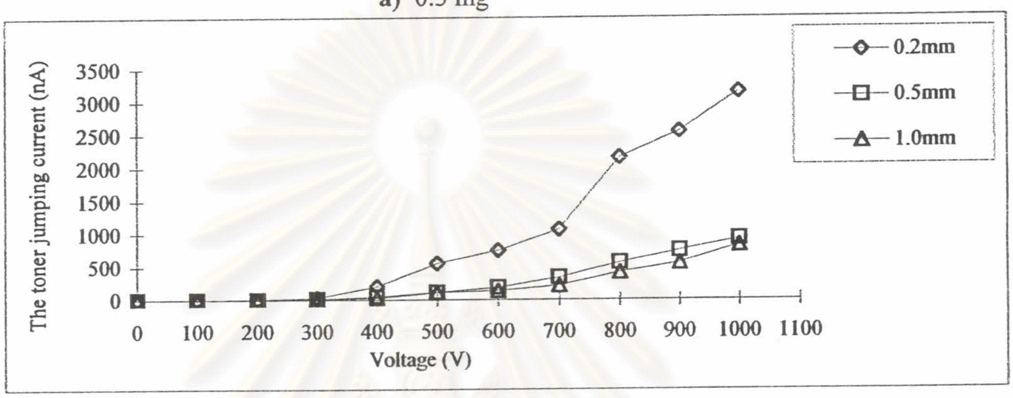
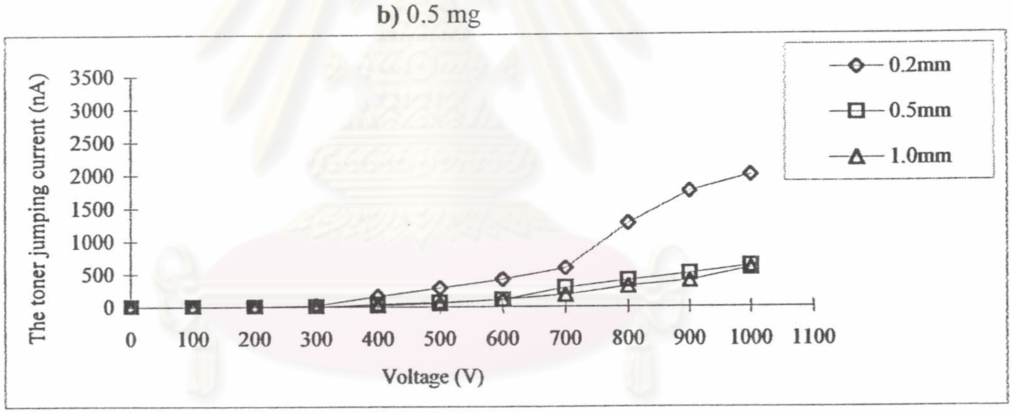
Figure 4-28 Dependence of the toner jumping current on the applied voltage at the cone depths of the dented electrode for the toner HMT2059-2 and the toner amounts of 1.0, 0.8, 0.5, and 0.3 mg.



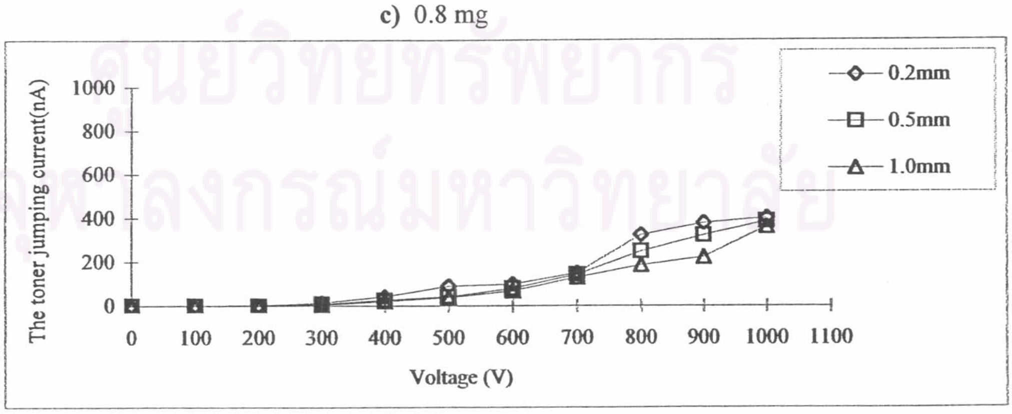
a) 0.3 mg



b) 0.5 mg



c) 0.8 mg



d) 1.0 mg

Figure 4-29 Dependence of the toner jumping current on the applied voltage at the cone depths of the dented electrode for the toner HMT2059-3 and the toner amounts of 1.0, 0.8, 0.5, and 0.3 mg.

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On the other hand, the range of threshold voltage is also found in a similar manner. When the deeper depth of the dented electrode (0.5 and 1.0 mm) is used, the threshold voltage is in ranges of 500 to 700 V.

From Figure 4-13, we can found the distance between the electrodes and the slope of the cone depth of the dented electrode at three depths. The cone depth of dented electrode of 0.2 mm shows the short distance and the slope of depth is 0.4 while the cone depth of the dented electrode of 0.5 and 1.0 mm show the longer distance between the electrode and the slope of the depth is 1 and 2, respectively.

From Table 4-7, the magnitude of the electric field was approximated, which depends on the cone depth of dented electrode. Again the adhesion force can be estimated as shown in Equation (4-8).

$$f_{adh} = \varepsilon_0 S E_{th}^2 \qquad (4\text{-}8)$$

where ε_0 and S are the constant, the adhesion force of the toner jump, f_{adh} increased by the higher electric field.

Therefore, the shallower depth of the dented electrode reduces the threshold voltage.

4.2 Calculation of the toner jumping trajectory

The ELFIN software simulates the movement of the conductive toner particles in the electric field. The conductive toner particles move up from the dented electrode to the pulling electrode (ITO glass). The electrical field forces and the air draught forces affect the simulated particles.

The first step, the element data was created. At this point, the position, length and field strength of each element has to be provided. Then, the initial conditions need to be given. Using this information, the toner particle trajectories are computed. The initial conditions consist of the charge of particle of $-2\text{x}10^{-16}$ C, the mass of particle of 5.24×10^{-13} kg, k constant of 1.71×10^{-9} kg/ sec. The applied voltage and the cone depth of dented electrode for initial conditions are given in Table 4-10.

Table 4-11 The initial conditions for the calculation of the toner jumping trajectory

Depth of dented Electrode (mm)	Voltage (V)
0.2	500
0.5	750
1.0	1000

The etest.mai program in Appendix B was used to calculate and analyze the electric field and the W_{map} (etest) calculated the electric field and the electric force line as shown in Figures 4-30 to 4-32.

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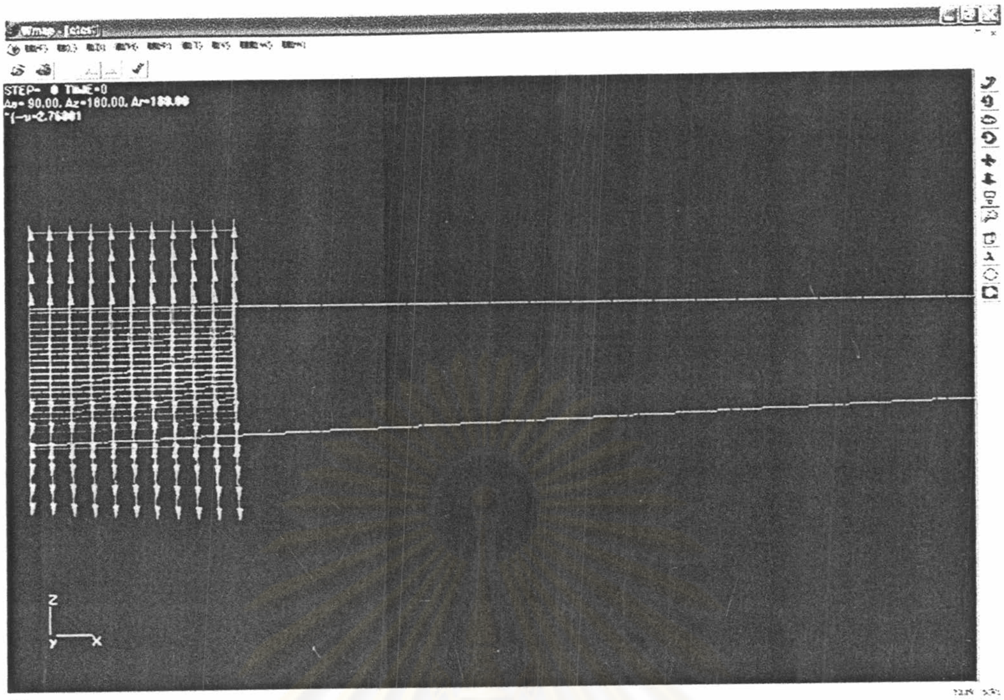

Figure 4-30 The electric force lines at the cone depth of dented electrode of 0.2 mm and applied voltage of 1000 V

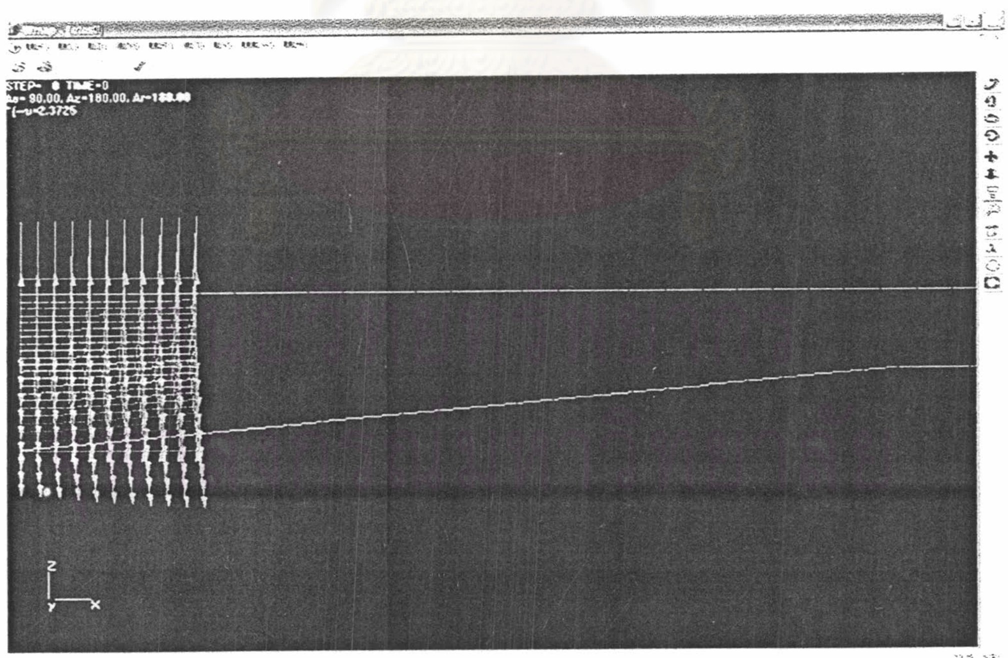

Figure 4-31 The electric force lines at the cone depth of dented electrode of 0.5 mm and applied voltage of 1000 V

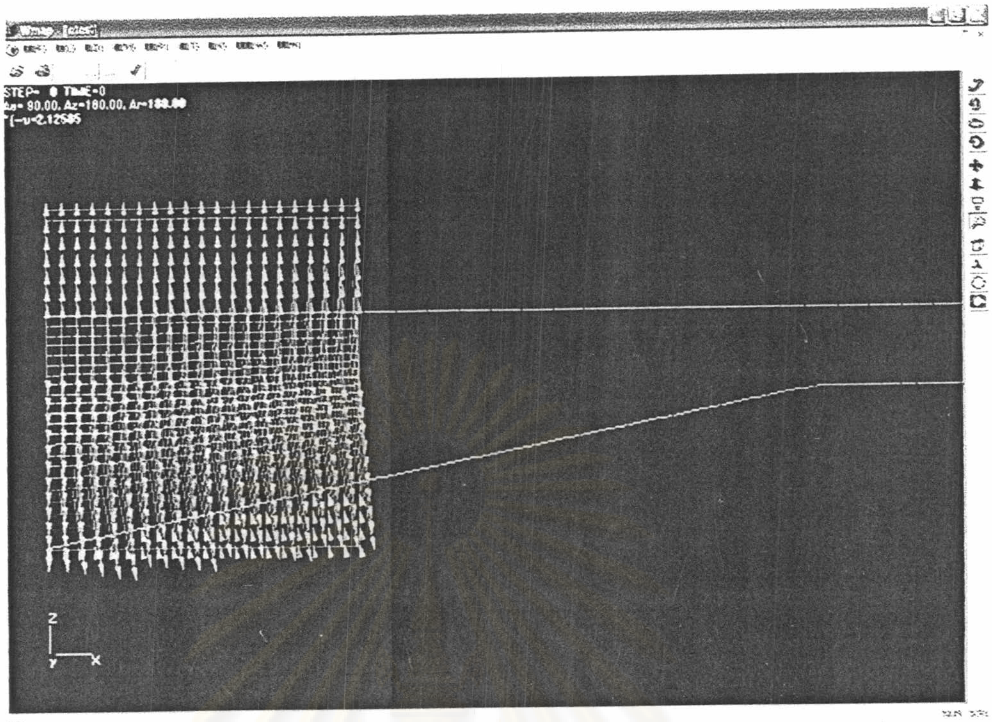

Figure 4-32 The electric force lines at the cone depth of dented electrode of 1.0 mm and applied voltage of 1000 V

These results can confirm the direction of the electric force line, which carries components directly toward to the central axis. It was confirmed that the cone shape of the dented electrode is effective in confining the conductive toner cloud. The Coulomb's law [16] and Maxwell's Stress [17] in Appendix A are used to calculated this phenomenon.

When the toner jumping trajectory computation had been finished by the ELFIN/Bench, the Wmap then showed the toner jumping particle trajectory of one particle, as shown in Figure 4-33.

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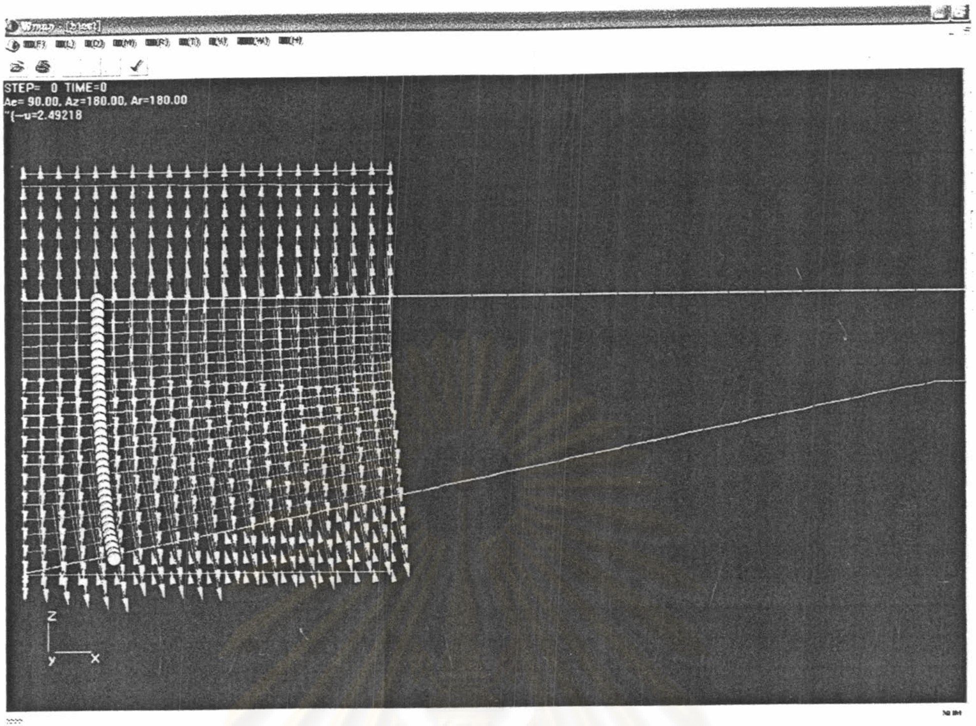

Figure 4-33 One toner particle jumping trajectory

The results of the computation by the ELF/Bench show the toner jumping trajectory and either for the position of the tone on the coordinates X, Y, and Z as shown in Appendix C. This research determined the toner jumping trajectory by plotting the positions X and Z as shown in Figures 4-34 to 4-42.

Figure 4-34 shows the motion of the toner for the case of the cone depth of dented electrodes of 0.2 mm diameter at the voltage of 500V. The trajectory of the toner particle moving up and down between the electrodes is shown in Figure 4-34. The distance between the electrodes is 0.7 mm. From Figure 4-34, the graph was plotted between the positions of the toner particle in Z-axis and X-axis. The relation shows that the particle trajectory is in the direction of the electric force line, which moves toward the central axis. This simulation illustrates the toner trajectory that

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moves up and down three times to generate the steps of moving up and moving down. This toner trajectory has 18 moving-up steps and 16 moving-down steps for the move up and moves down motions for three times of double direction (up and down). The values of the positions and distance in each step are shown in Appendix C. Moreover, the position X of the maximum toner moving up and the minimum toner moving down are presented in Table 4-12.

Figures 4-35 and 4-36 show the motion of the toner at the voltage of 500V for the cone depth of the dented electrode 0.5 and 1.0 mm, respectively. Figures 4-37 to 4-39 show the motion of the toner at the voltage of 750V for the cone depths of dented electrode of 0.2, 0.5 and 1.0mm. Figures 4-40 and 4-42 show the motion of the toner at the voltage 1000V for the cone depths of dented electrode of 0.2, 0.5 and 1.0 mm. The results from Figures 4-33 to 4-40 are similar to that of the Figure 4-34. The distance between the two electrodes in Figures 4-35, 4-38 and 4-41 is 1.0 mm; for Figure 4-37 and 4-40 is 0.7 mm, and for Figures 4-36, 4-39 and 4-42 is 1.5 mm. All the toner trajectory lines are in the direction of the electric force line towards the central axis. The values of the position and distance in each step are shown in Appendix C. The numbers of the moving-up step and the moving-down step of each condition are shown in Appendix C. Moreover, the positions X of the maximum toner moving up and the minimum toner moving down are also presented in Table 4-12.

Table 4-12 The positions X of the maximum toner moving up and the minimum toner moving down for all conditions

The applied voltage (Volt)	The cone depth of of dented electrode (mm)	Start step	Moving up step			Moving down step		
		0	1	3	5	2	4	6
500	0.2	0.499379	0.488116	0.487247	0.486476	0.498752	0.498314	0.497495
	0.5	0.498945	0.464247	0.462699	0.461205	0.497861	0.497110	0.495036
	1	0.498783	0.415123	0.416051	0.414262	0.500702	0.499590	0.498062
750	0.2	0.499061	0.487877	0.486685	0.485491	0.497040	0.495870	0.494697
	0.5	0.498409	0.463776	0.461557	0.459414	0.494995	0.492137	0.490114
	1	0.498167	0.414614	0.411776	0.409023	0.496148	0.492870	0.489628
1000	0.2	0.498743	0.487811	0.486163	0.484519	0.497494	0.495882	0.494969
	0.5	0.497874	0.463342	0.460466	0.457933	0.493378	0.490659	0.488267
	1	0.497551	0.414168	0.410301	0.406527	0.494950	0.491551	0.487095

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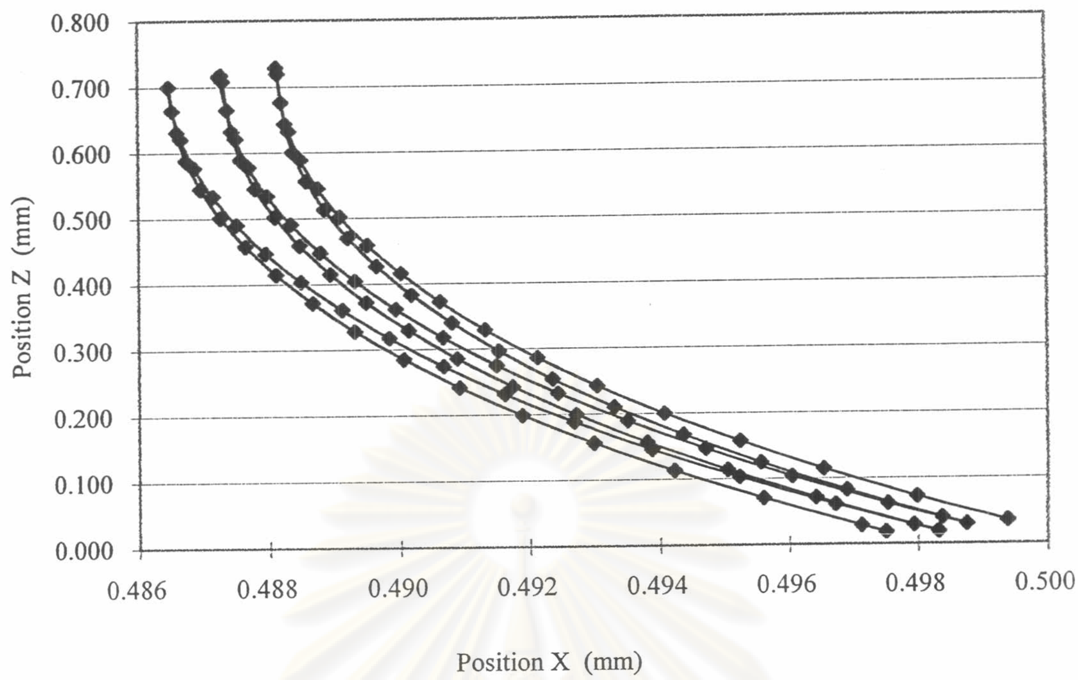

Figure 4-34 Motion of the toner for the depth of a dented cell of 0.2 mm (500V)

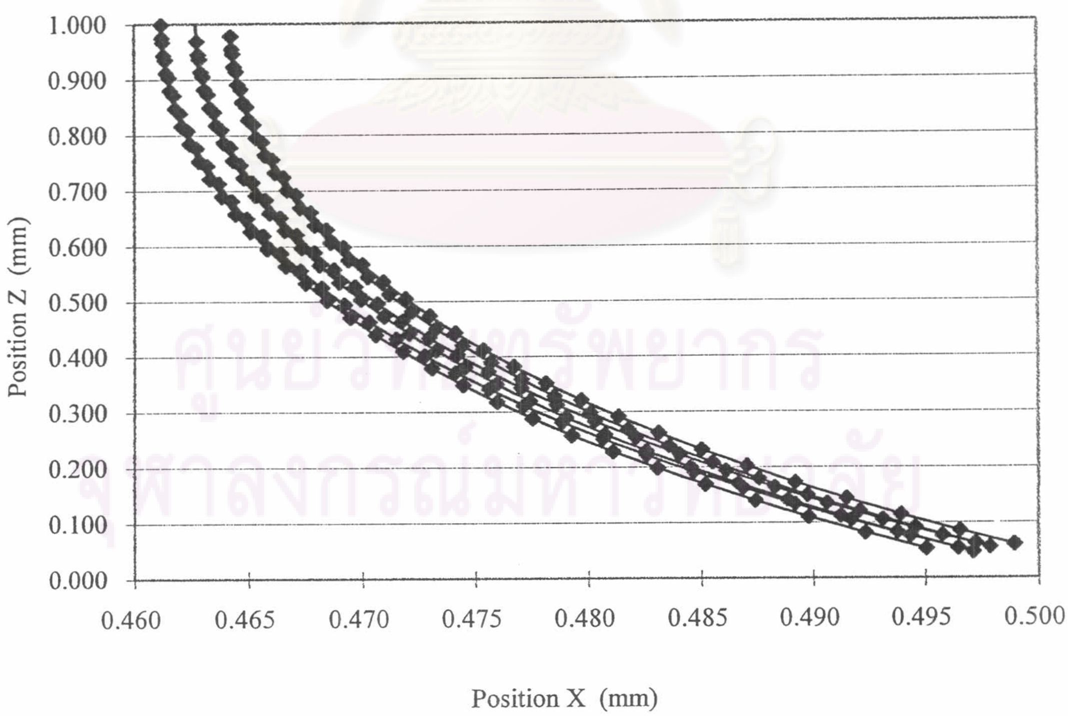

Figure 4-35 Motion of the toner for the depth of a dented cell of 0.5 mm (500V)

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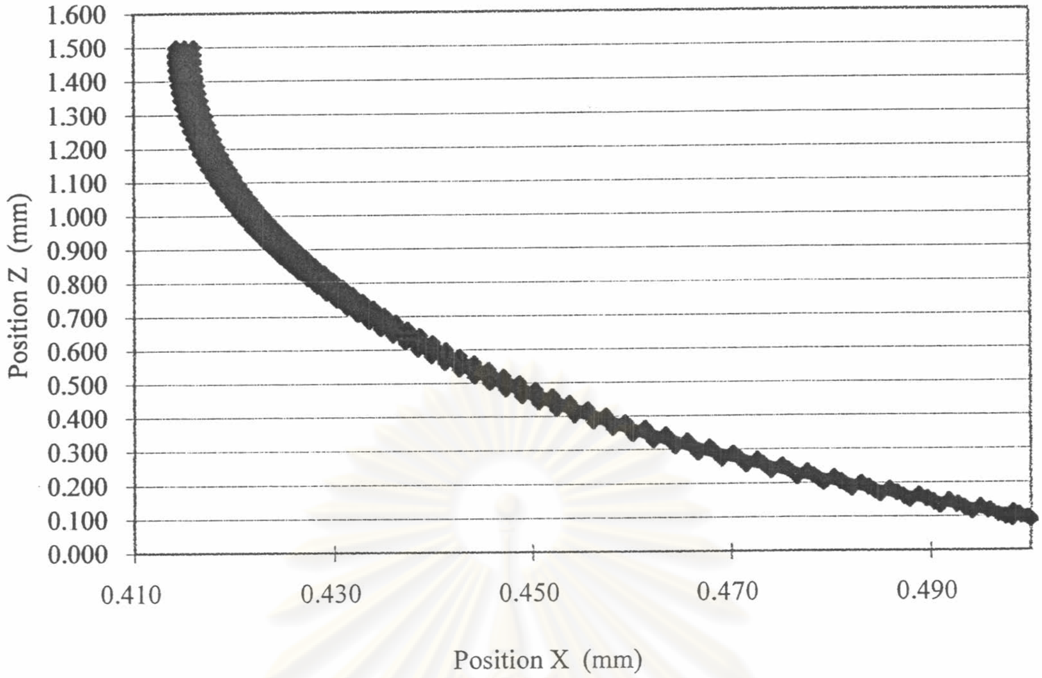

Figure 4-36 Motion of the toner for the depth of a dented cell of 1.0 mm (500V)

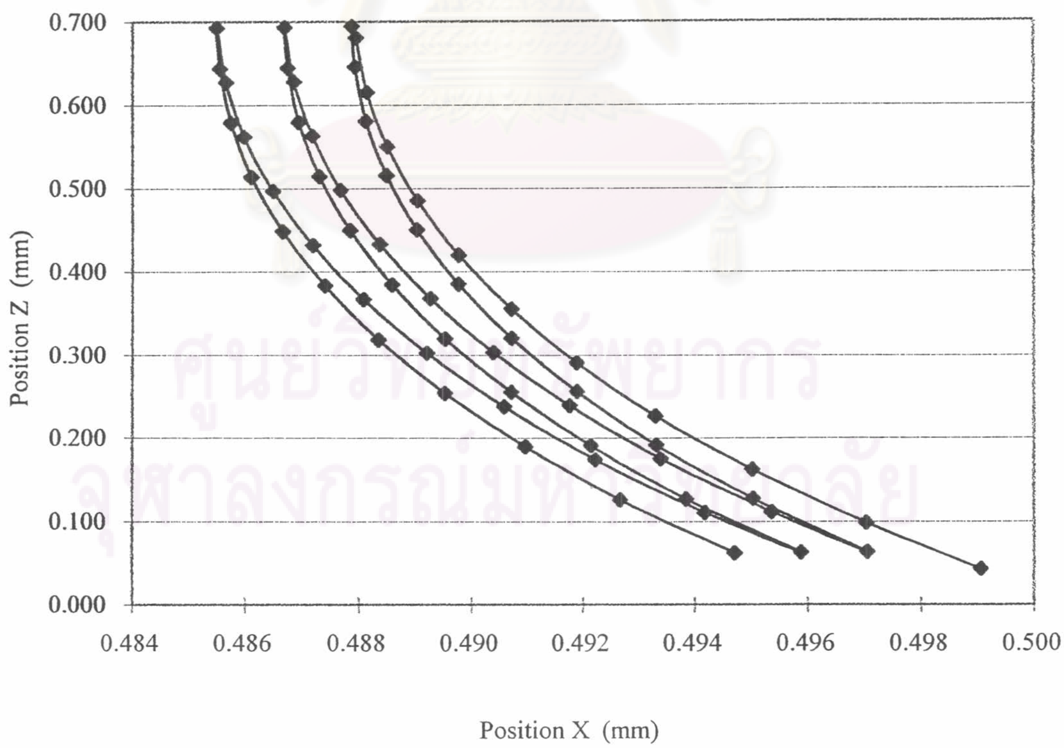

Figure 4-37 Motion of the toner for the depth of a dented cell of 0.2 mm (750V)

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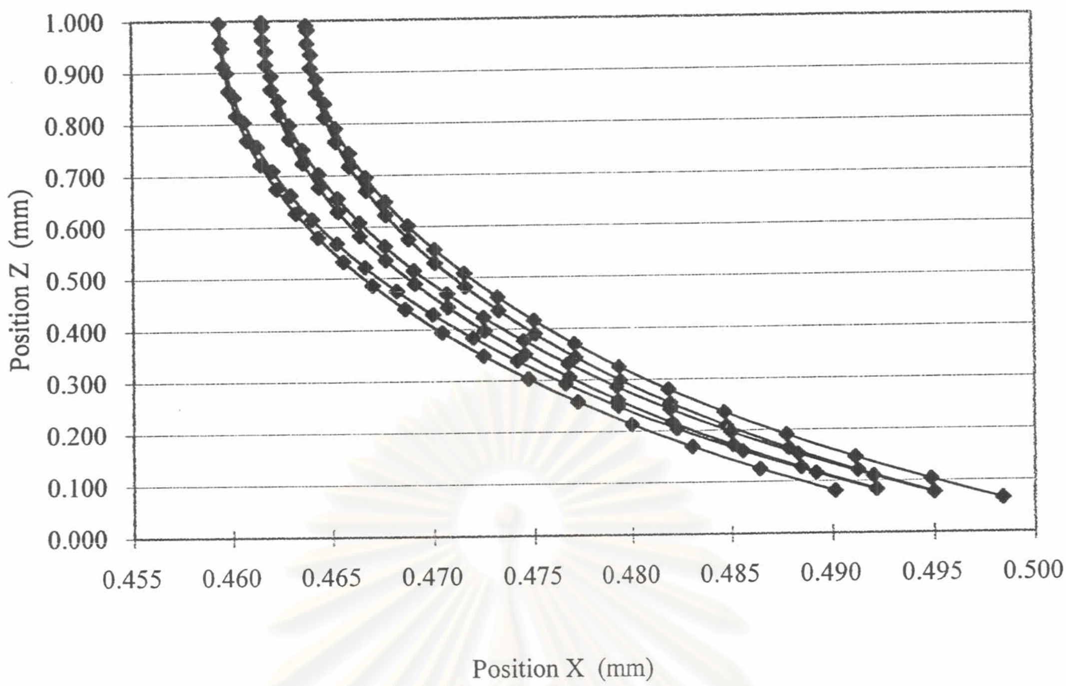

Figure 4-38 Motion of the toner for the depth of a dented cell of 0.5 mm (750V)

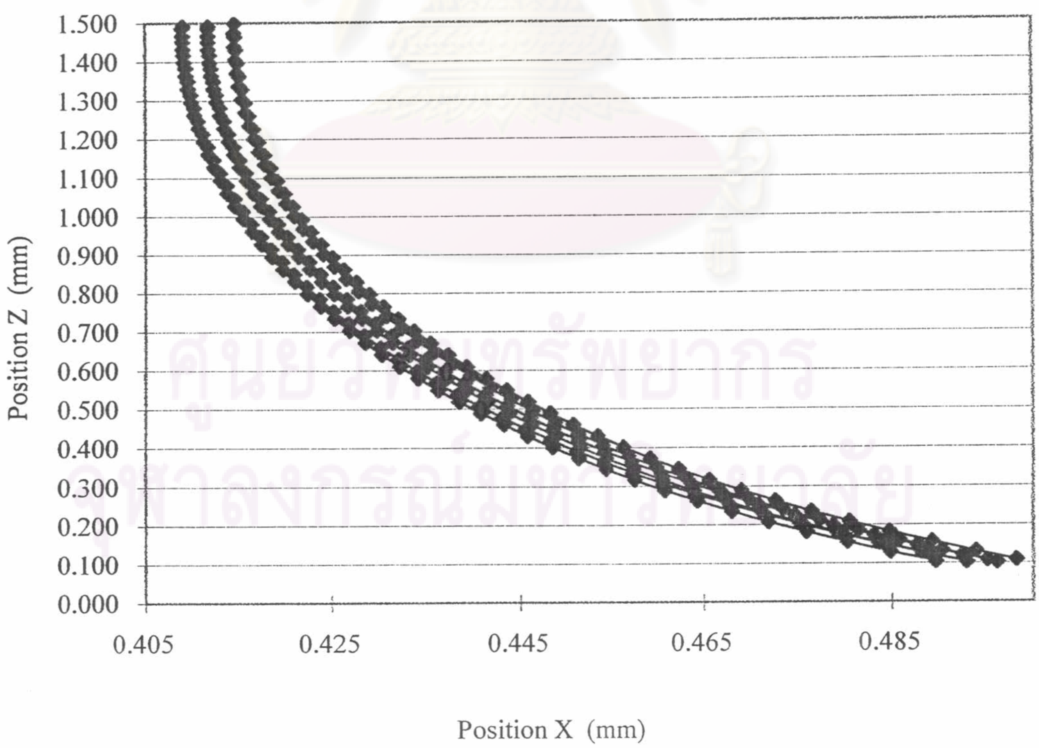

Figure 4-39 Motion of the toner for the depth of a dented cell of 1.0 mm (750V)

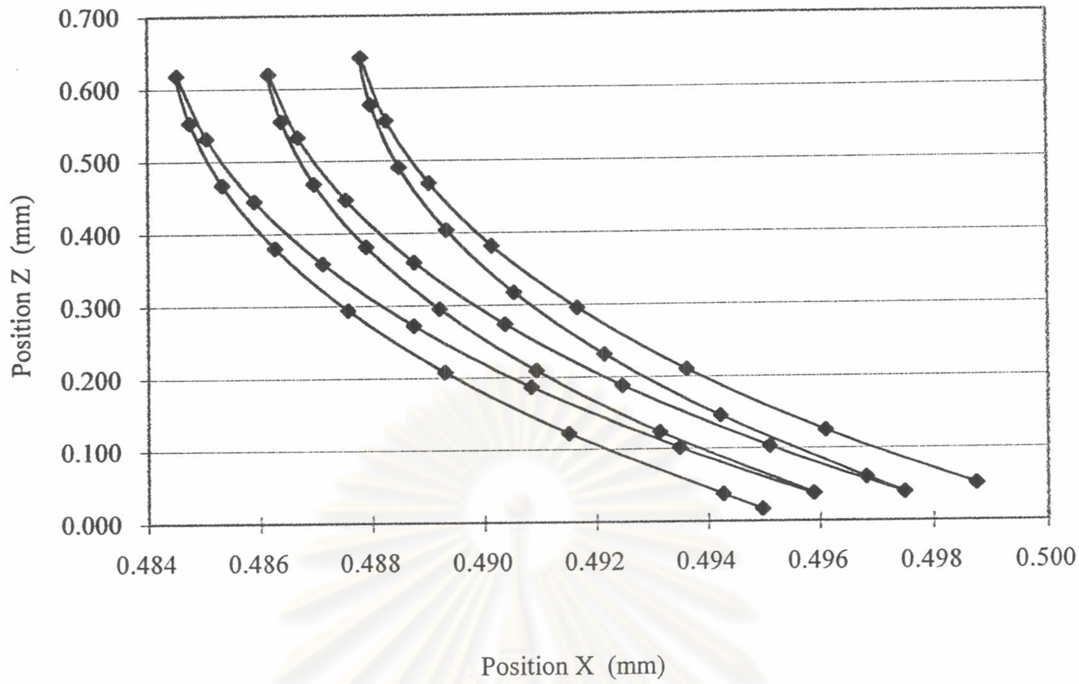

Figure 4-40 Motion of the toner for the depth of a dented cell of 0.2 mm (1000V)

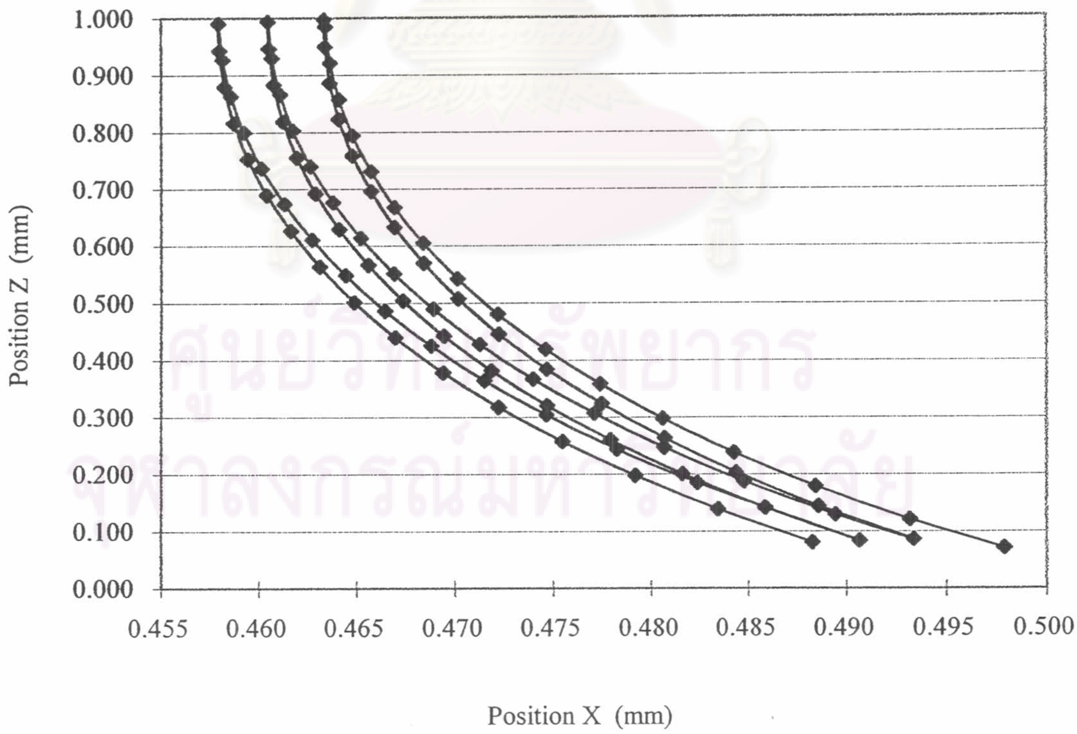

Figure 4-41 Motion of the toner for the depth of a dented cell of 0.5 mm (1000V)

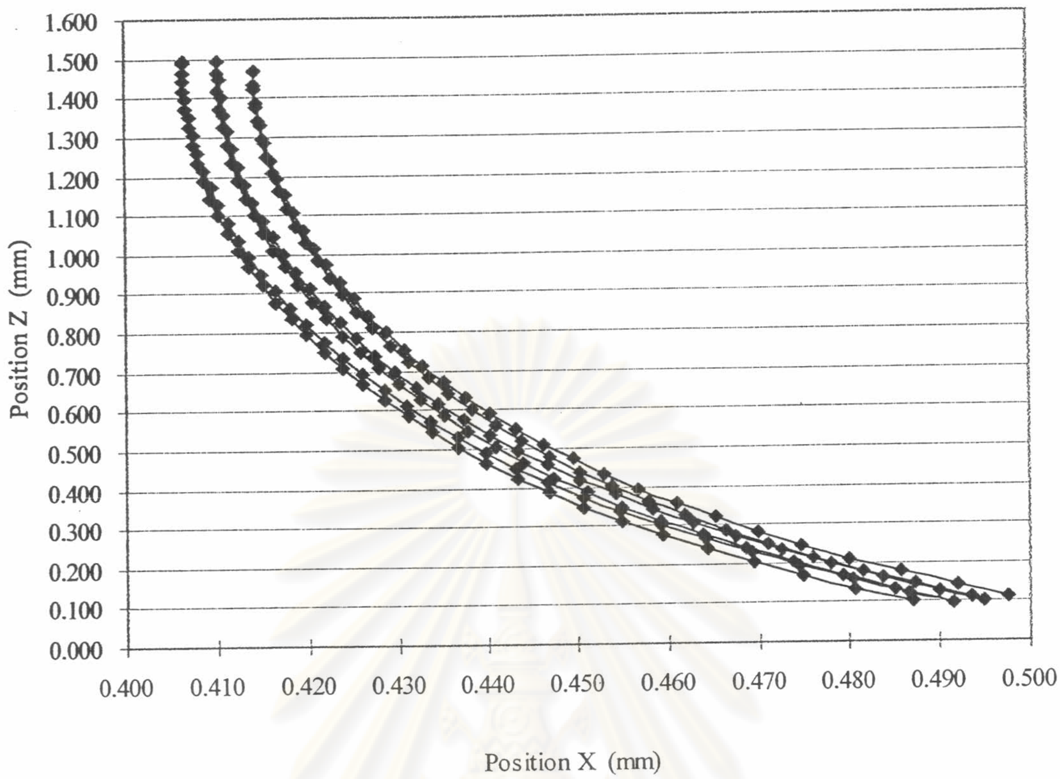

Figure 4-42 Motion of the toner for the depth of a dented cell of 1.0 mm (1000V)

The numbers of the moving-up step and the moving-down step of the toner particles refer to the time for which the toner particles travel between the electrodes. The results from Appendix B showing the numbers of the moving-up and down steps found in the cone depth of dented electrode of 1.0 mm by the applied voltage of 1000 V have the maximum number of the moving up and the moving down steps. So, the time of the toner movement between the electrodes is of course longer. This observation is caused by the wider distance between the electrodes and the higher voltage.

The results in Figures 4-34 to 4-42 and Table 4-12 so obtained indicate the positions X of the toner particles and its movement in the up and down directions. So we can determine the tendency of the toner cloud extent, which depends on the cone depth of the dented electrode and the applied voltage by plotting the positions X and Z in all conditions. The comparison of the toner jumping trajectory dependence on the cone depth of dented electrode in the toner cloud state is shown in Figures 4-43 to 4-45.

Figure 4-38 shows the toner jumping trajectory dependence on the cone depth of the dented electrode at the applied voltage of 500V. The toner motion for the cone depth of the dented electrode of 1.0 mm has the trajectory lines towards the central axis. Since the toner particles are moved by electric force line, so, the electric force carries the components toward the central axis too. Therefore, the deeper the cone depth of dented electrode, the smaller the toner cloud extent.

Likewise, Figures 4-44 and 4-45 show the toner jumping trajectory dependence on the cone depth of the dented electrode at the applied voltage of 750V and 1000V. The results are similar to that in Figure 4-43. Therefore the toner jumping trajectory in the cloud state depends on the applied voltage as shown in Figures 4-46 to 4-48.

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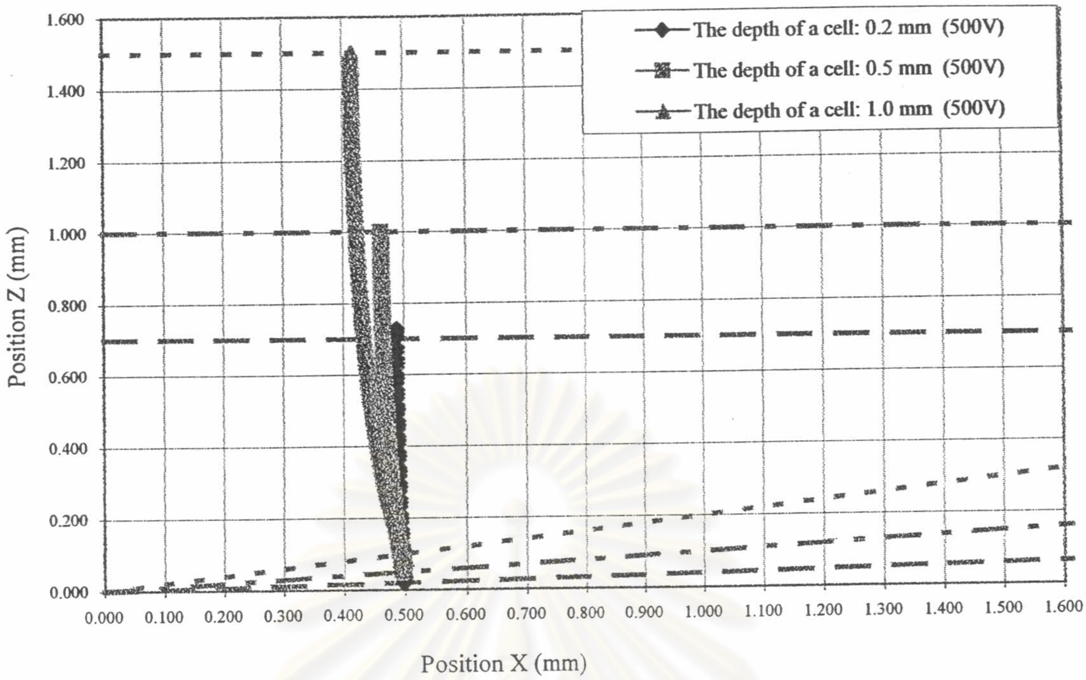

Figure 4-43 The toner jumping trajectory dependence on the cone depth of the dented electrode at the applied voltage of 500V

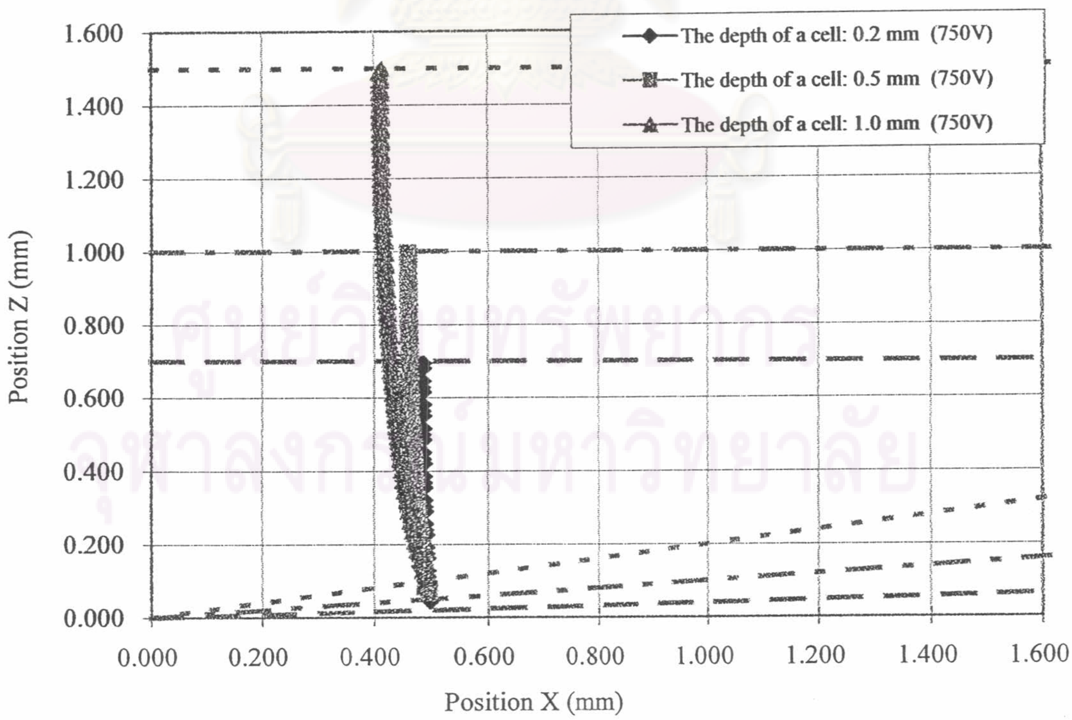

Figure 4-44 The toner jumping trajectory dependence on the cone depth of the dented electrode at the applied voltage of 750V

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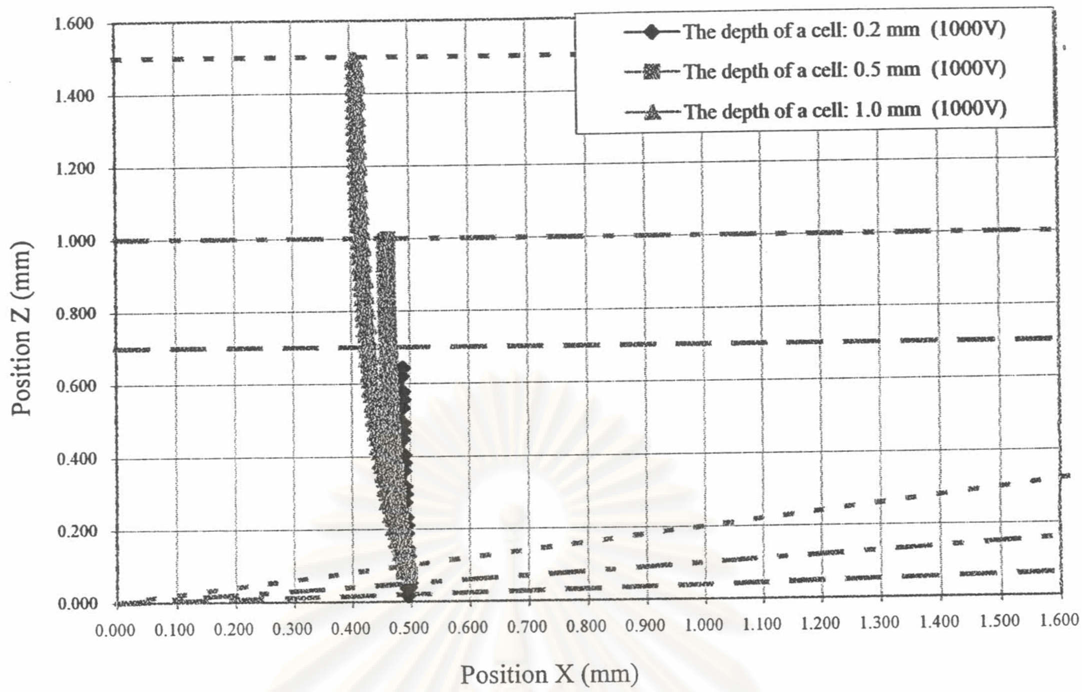


Figure 4-45 The toner jumping trajectory dependence on the cone depth of the dented electrode at the applied voltage of 1000V

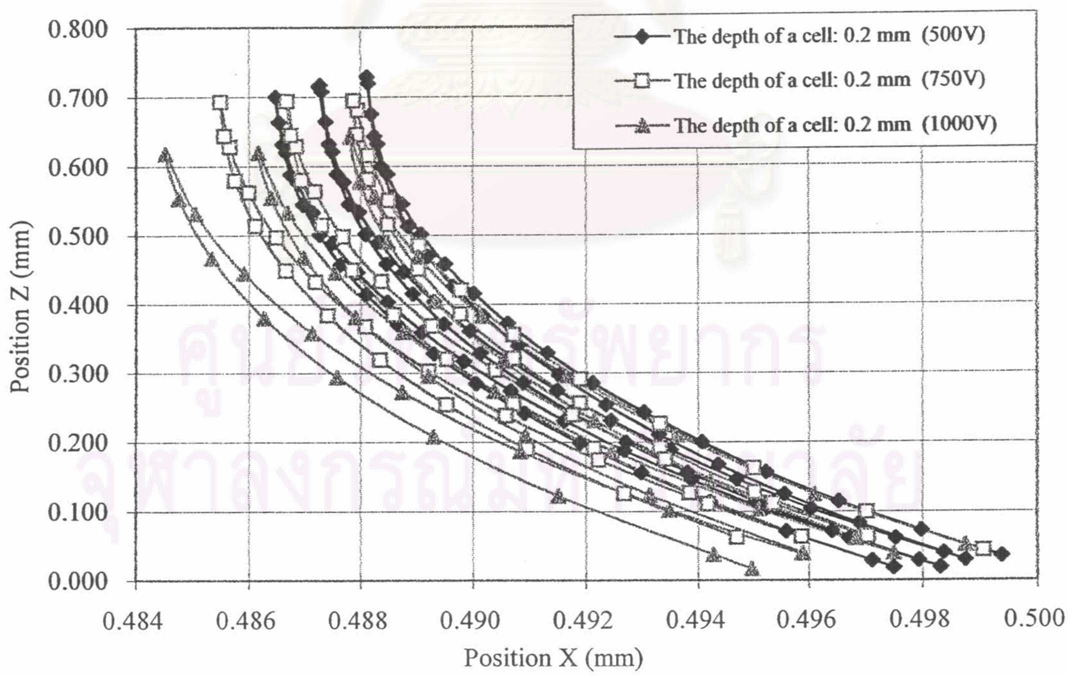


Figure 4-46 The toner jumping trajectory dependence on the applied voltage at the cone depth of dented electrode of 0.2 mm

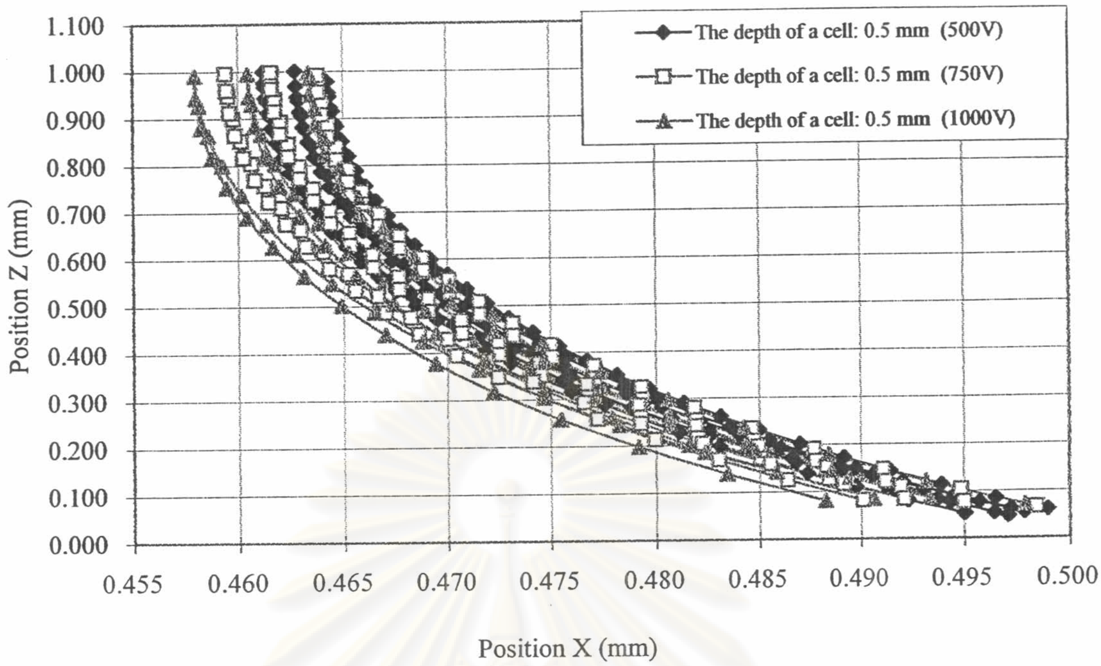


Figure 4-47 The toner jumping trajectory dependence on the applied voltage at the cone depth of dented electrode of 0.5 mm

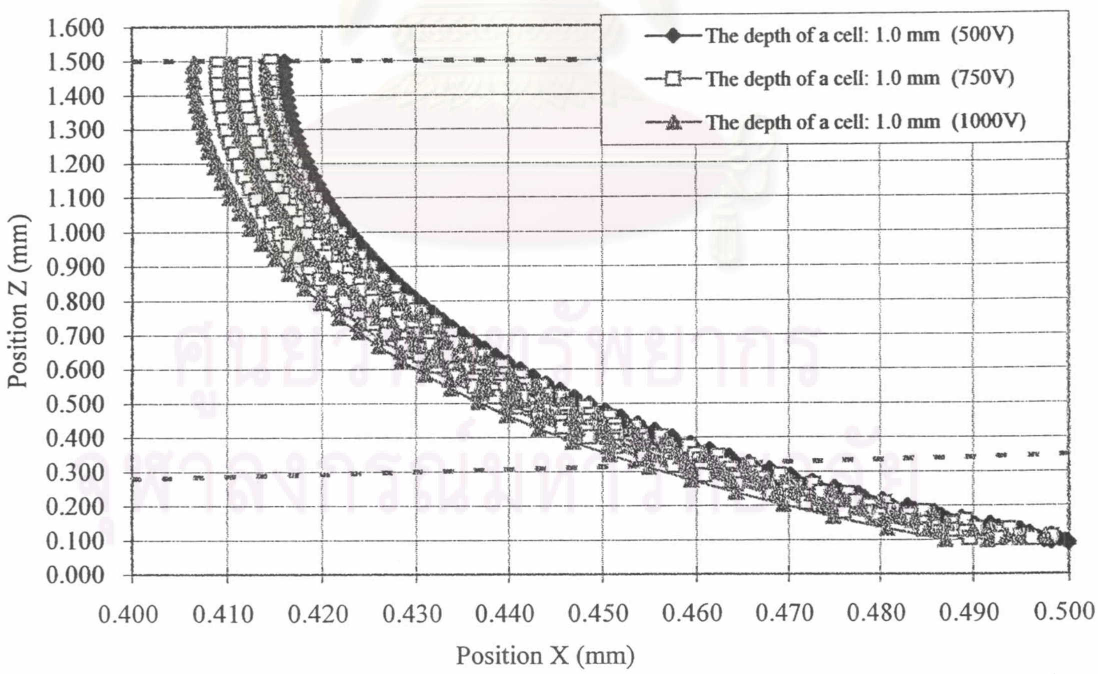
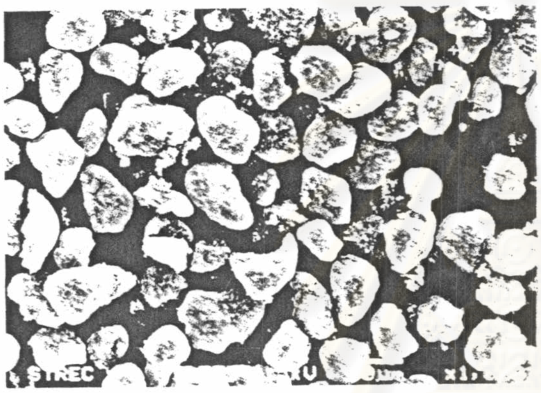


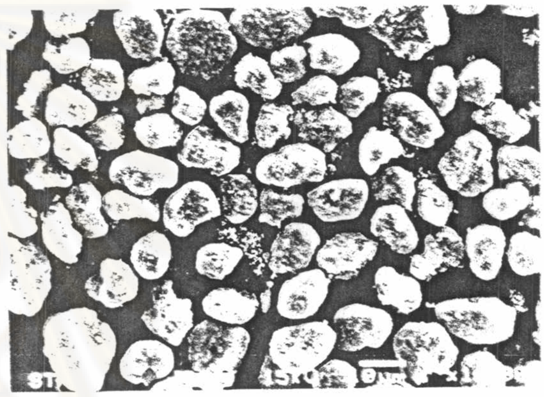
Figure 4-48 The toner jumping trajectory dependence on the applied voltage at the cone depth of dented electrode of 1.0 mm

4.3 Morphology of the conductive toner

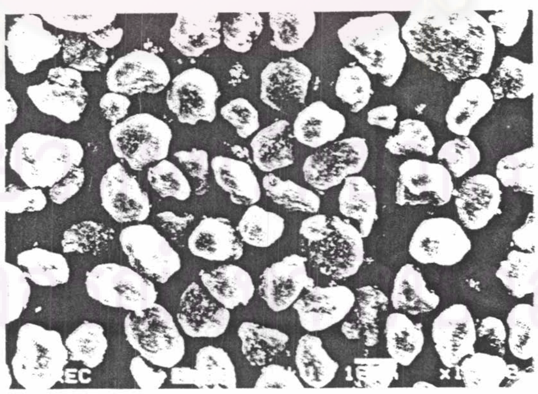
The scanning electron micrographs of all the conductive toners as shown in Figure 4-49, reveal that all toners have irregular shapes. Figure 4-50 displays the SEM photographs of the conductive toner particles, which have the particle shape approaching the spherical-like shape.



a) The toner HMT2059-1

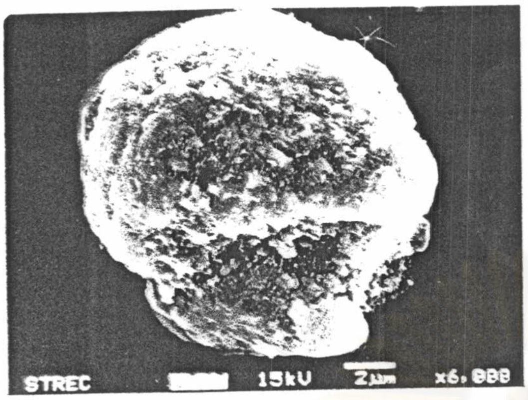


b) The toner HMT2059-2

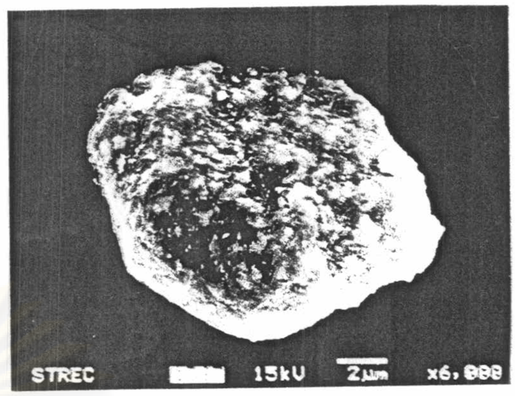


c) The toner HMT2059-3

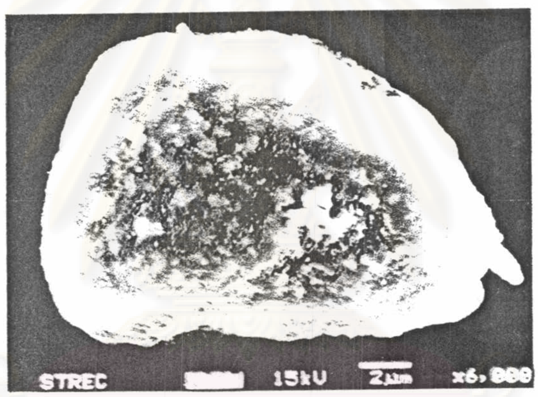
Figure 4-49 Scanning electron micrographs of the conductive toner a) HMT2059-1, b) HMT2059-2, and c) HMT2059-3. (X1000)



a)The toner HMT2059-1



b)The toner HMT2059-2



c) The toner HMT2059-3

Figure 4-50 Scanning electron micrographs of the conductive toner particle a) HMT2059-1, b) HMT2059-2, and c) HMT2059-3. (X6000)

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