Printed Patterns Adhesion dependency on Contact Angle of Ink on Substrate

Adnan Ali¹, Ahsan Rahman¹, Khalid Rahman¹, Nauman Malik Muhammad¹, Arshad Khan¹, J.B. Ko², Saleem Khan², B.S. Yang², H.C. Kim², Y.H. Doh², D.S. Kim³, Prof. K.H. Choi¹
¹School of Mechanical Engineering, Jeju National University, ²School of Electronics Engineering, Jeju National University, 66 Jeju-daehakno, Jeju-si, Jeju, Korea 690-756, ³Korean Institute of Machinery and Materials, Daejeon, Korea

adnanaligohar@gmail.com, khchoi@jejunu.ac.kr

Abstract-- In this paper electro-statically inkjet printed pattern's adhesion is studied with respect to contact angle of ink on substrates. Contact angle of conductive ink on different substrates is measured with Image-Xp software. Ink has made different contact angles on different substrates. Pin to pin setup is used for printing patterns. Patterns are obtained by forcing ink through a small glass capillary orifice by electrostatic forces to adhere with substrate. It is investigated that contact angle has direct relationship with surface roughness of the substrate. Higher the contact angle of ink on a substrate, higher the adhesion on that substrate. After curing, adhesion of patterns with substrate is tested by 3M 610 pressure sensitive tape by following the ASTM D 3359 method B. Life of printed patterns and its stability on different substrates can be evaluated by this study. From this study optimized properties of ink and substrate combination can be obtained.

Index Term-- Adhesion, ASTM D3359 B, Contact angle, Pressure sensitive tape, RMS

I. INTRODUCTION

There has been emerging interest in direct patterning on the surface of the substrate without including complex steps of the micro fabrication like lithography process [1]. Inkjet printing is expected to be a powerful technology for direct fabrication process for both nanotechnology research and applications such as micro electronics [2]. The electrostatic inkjet system has its contributions in reducing cost and time effect on manufacturing of printed electronics like RFID, electronic devices and flexible display, solar cell, sensors etc. Operating principle of inkjet printers is propelling various size (mostly tiny) droplet of liquid (ink) onto the substrate. For commercial printed electronics (PE), the focus has been shifting from piezoelectric and thermal based printing towards the electrostatic approach, because of the mechanical movement constraints, the system for small nozzle size which has strongly affected the drop size and compatibility. Robustness of the electrostatic system increases in respect of reducing mechanical efforts. The electrostatics systems reduce the mechanical efforts and make system more precise even at higher frequencies and also make it is possible to get small and focused droplets with even smaller nozzle sizes [3]. Miniaturization of electronic components are receiving boost in applications outside of conventional printing and marking. Because of this, different necessary techniques and procedures are being used to evaluate its performance and make it more useful and attractive. In printing, different types of materials, mechanisms, arrangements and strategies are needed [4].

II. GOVERNING METHODOLOGY OF ELECTROSTATIC INKJET PRINTING HEAD

In electrostatic inkjet system, the droplet generation process differs from the other inkjet system as this type of system as: firstly, the meniscus is generated, and the drop extraction occurs due to the effect of electrostatic forces. The drops come from the surface of the meniscus and the droplet is much smaller as compared to the diameter of the orifice. The drop size depends on the field applied field on the surface of the meniscus. Therefore, it’s important that the meniscus surface is charged adequately to produce the droplet. When the surface of a meniscus is subjected to an electric field, the field cause a deformation of the meniscus and eventually a stable drop is formed.

In general terms, for the stable meniscus and stable drop-on-demand generation through nozzle head, (inter and intra) molecule forces should be equal to molecule forces of the system values. In this case, it can be divided into two cases, namely stable meniscus and stable drop generation behavior. For obtaining the stable meniscus shape, the main parameters include surface tension of fluid which is counteracting the effect of the pressure applied by the flow of the ink and gravity. Whereas, the stable on-demand behavior need the study of the electrical forces.

Due to electrical forces the Maxwell effect will be applied on the nozzle orifice. Due to effect of the Maxwell forces on the nozzle orifice, the effect of the gravity is negligible, as the other forces on the meniscus (like surface tension, electrical stress, viscosity, pressure and electric field) will overcome it as shown in the fig. 1.
But to predict the meniscus shapes both theoretically and experimentally under the influence of given electric pressure and hydrostatic pressure, the electrostatic and hydrostatic equations should be solved simultaneously [1]. The maximum meniscus extension is presented as a function of voltage, surface tension, hydrostatic pressure, orifice diameter, material and electrode spacing for tube-plane geometry, surface of nozzle and its relation to fluid properties. Among all these parameters the two most effective parameters are the electrostatic force and flow rate pressure, which counteract the surface tension. Generally it can be given as:

\[ F_{st} = F_e + F_q \]  

where \( F_{st} \) is surface tension, \( F_q \) is the flow rate and \( F_e \) is electrostatic force applied to the meniscus.

When the surface of a meniscus is subjected to an electric field, the field causes a deformation of the meniscus and eventually a stable liquid meniscus is formed again. The surface of the liquid meniscus is subjected to surface tension \( \sigma_s \), hydrostatic pressure \( \sigma_h \) and electrostatic pressure \( \sigma_e \) is valid at each point on the liquid surface [1], given as:

\[ \sigma_h + \sigma_e + \sigma_s = 0 \]  
\[ \sigma_h = \rho g \Delta h \]  
\[ \sigma_e = \frac{1}{2} \varepsilon_0 E_n^2 \]  

where \( \rho \) is the density of liquid, \( g \) the acceleration due to gravity, \( \Delta h \) the liquid level difference between the container and the free end of the nozzle, \( \varepsilon_0 \) is the relative permittivity of the liquid to vacuum permittivity, and \( E_n \) the electric field strength normal to the liquid surface. Li et al has explained this behavior, that in the Electro-hydro dynamics spraying process, the normal electric stress is likely to produce a dripping mode while the tangential electric stress will move liquid from the meniscus surface to the apex of the meniscus to form a jet [1]. When the tangential stress is intensive enough, a cone-jet is formed. For this reason, both the normal electrical stress and tangential electrical stress are important in the drop generation mechanism and this behavior has been analyzed using two different nozzle heads. If the tangential electric stress is great enough to move the surface layer of the meniscus to form a jet, a portion of the liquid in the meniscus has to backflow into the meniscus because of the electric stress [5].

In this research, the idea is to relate the contact angle of ink making on the substrate and surface roughness of substrate for evaluation of adhesion of patterns. Also interface of the pattern and substrate is studied. The term interface is used to explain the region at which the attachment between pattern and substrate takes place. Adhesion between two different materials is a complicated phenomenon and is comprised of physical, mechanical, electrostatic, diffusional, and chemical mechanisms [6]. To evaluate durability of printed patterns of electronic circuitry, interface study is very important as only this region can give enough information about its life and durability.

III. EXPERIMENTAL SETUP

In experiment first contact angle on each substrate is measured by using Contact Angle Analyzer (Phoenix 300). The experimental setup for contact angle measurement is given in fig.2. First of all, ink is loaded in syringe and then after putting the syringe in contact angle analyzer a drop is generated which impacted on substrate. The image of contact angle made by drop on substrate is captured and the contact angle is measured by Image- Xp Software.

The experimental setup for print head driven by on demand electrostatic forces designed is shown in the fig.3.
holder with Z-axis control. Actuating and ground electrodes are the electrodes used for the ejection of droplets. Pin to pin setup is used for experiment [4-7]. The ground electrode is connected to the negative potential of the high voltage source and the other potential to electrode in the nozzle head for activating the ink and providing the necessary potential to ink in the nozzle head for drop extraction. To control droplet ejection, the square wave form is applied between the nozzle head and the ground electrode to develop extraction potential. The duty cycle maintained 50% at all frequencies.

IV. EXPERIMENT

For experiment purpose, a commercially available, solvent based ink containing 20 % silver pigments is used. Other properties of the ink such as density, viscosity, surface tension and metallic pigments were found to be: 1.07 g/cm\(^3\), 10cps, 30–32 dynes /cm with silver (Ag) nano particles, respectively. The liquid pressure is controlled by using pressure injection pump. Vertically inserted single electrode head is used, which is given in fig.4.

![Fig. 4. Schematic description of discrete pin to pin set up for Electrostatic Inkjet Printing](image)

After developing the meniscus, result is analyzed to find the optimal values for the given nozzle. This is done by changing potential to get jetting volatge. For observation purpose, high speed camera is used. The zooming magnification of lens is 11X with frame rate of 600 frames per second.

Printed Patterns on different substrates are achieved through electrostatic inkjet printer by using conductive ink. Different substrates are being used for comparison of adhesiveness and interface analysis e.g. PET, Photo Inkjet Paper, transparency, OHP and Glass (ITO Coated).

V. RESULTS OBTAINED

Surface roughness of each substrate and respective contact angle, made by ink on substrate is given in table I. Contact angle is obtained by contact angle analyzer given below in fig.5.

![Fig. 5. Contact Angle on different Substrates made by conductive ink](image)

### Table 1: Printing Parameters for each substrate are given

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Voltage (kV)</th>
<th>Stand-off (µm)</th>
<th>Flow rate (µl/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Substrate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OHP</td>
<td>8.8</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>PET</td>
<td>7.5</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>Transparency</td>
<td>8.5</td>
<td>100</td>
<td>150</td>
</tr>
<tr>
<td>Glass (ITO Coated)</td>
<td>4.8</td>
<td>50</td>
<td>150</td>
</tr>
<tr>
<td>Photo Inkjet Paper</td>
<td>3.5</td>
<td>100</td>
<td>150</td>
</tr>
</tbody>
</table>

Patterns obtained by electrostatic inkjet printing on each substrate are given in fig.6.

![Fig. 6. Printed Pattern on Different substrates are given along with width of each one](image)

3M 610 pressure sensitive tape is used for qualitative evaluation of conductive ink adhesion on different substrates. ASTM D3359-B method is used and the results obtained are given in table II for each substrate.
Table II

<table>
<thead>
<tr>
<th>Substrate</th>
<th>5B</th>
<th>4B</th>
<th>3B</th>
<th>2B</th>
<th>1B</th>
<th>0B</th>
</tr>
</thead>
<tbody>
<tr>
<td>OHP</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>PET</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Transparency</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Photo Inkjet Paper</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Glass (ITO Coated)</td>
<td>+</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

VI. ANALYSIS

By comparing ASTM D 3359-B adhesion results of table II, with the contact angle and surface roughness values, given in fig.5, it is concluded that higher the surface roughness of substrate means higher the contact angle and in turn higher the value of adhesion of ink with the substrate. From fig.5, it’s clear that glass (ITO Coated) has high RMS value of surface roughness, so conductive ink has made high contact angle on it. In relation to this information from table II of adhesion test it is clear that ink has strong adhesion on glass (ITO Coated) as compared to other substrates. Similarly surface roughness values of PET and OHP are almost same and thus ink has made almost same contact angle on it. In reflection ink has given the same degree of adhesion on both substrates i.e. PET and OHP.

VII. CONCLUSION

From this study, it is concluded that ink has better adhesion with those substrates which has high RMS value and with which it makes high contact angle as compared to surfaces which have lower RMS values. Also, life and stability of printed pattern on different substrates can be predicted by having a prior knowledge of contact angle of ink o a substrate. Also this study will help to improve and to get optimized properties of ink and substrate combination.

ACKNOWLEDGMENT

This study is supported by Ministry of Knowledge Economy of Korea through project “Strategic Technology Development Project”

REFERENCES