สมบัติการนำไฟฟ้าของหมึกนาโนซิลเวอร์บนสิ่งพิมพ์เฟล็กโซกราฟี

นาย อภิวิชญ์ ลีลาตระกูล

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรมหาบัณฑิต
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ปีการศึกษา 2554

CONDUCTIVE PROPERTY OF NANO SILVER INK ON FLEXOGRAPHIC PRINTS

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A Thesis Submitted in Partial Fulfillment of the Requirements

for the Degree of Master of Master of Science Program in Imaging Technology

Department of Photographic Science and Printing Technology

Faculty of Science

Chulalongkorn University

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Thesis Title	CONDUCTIVE PROPERTY OF NANO SILVER INK ON FLEXOGRAPHIC PRINTS
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อภิวิชญ์ ลีลาตระกูล : สมบัติการนำไฟฟ้าของหมึกนาโนซิลเวอร์บนสิ่งพิมพ์เฟล็กโซกราฟี. (CONDUCTIVE PROPERTY OF NANO SILVER INK ON FLEXOGRAPHIC PRINTS) **อ.ที่ปรึกษาวิทยานิพนธ์หลัก: รศ.ดร.อรัญ หาญสืบสาย, อ.ที่ปรึกษาวิทยานิพนธ์ร่วม** Hiromichi Noguchi, Ph.D.,56**หน้า.**

งานวิจัยนี้มีวัตถุประสงค์เพื่อศึกษาความเป็นไปได้ของการประยุกต์ใช้ระบบพิมพ์เฟล็กโซกราฟีด้วยหมึกนาโนซิลเวอร์ในการผลิตเส้นนำไฟฟ้าบนวัสดุกระดาษ และฟิล์ม การทดลองได้ทำการวิเคราะห์สมบัติการไหลของหมึกและผลของการแปรเปลี่ยนความละเอียดของลูกกลิ้งแอนนิลอกซ์ต่อความเร็วในการพิมพ์และคุณภาพสิ่งพิมพ์ที่ได้ จากนั้นทำการวัดหาความหนาของชั้นหมึกพิมพ์และความต้านทานไฟฟ้าที่เกิดขึ้น พบว่าสมบัติความไม่เป็นลิเนียร์ลิตี้ของหมึกพิมพ์จะส่งผลเล็กน้อยกับความสัมพันธ์ระหว่างพารามิเตอร์ของคุณภาพภาพพิมพ์และภาวะการพิมพ์ เนื่องจากหมึกนาโนซิลเวอร์มีค่าความหนืดต่ำกว่าหมึกพิมพ์ฐานน้ำโดยทั่วไป การตั้งเครื่อง การกำหนดใช้วัสดุรองหนุน และ ลูกกลิ้งรางหมึกมีความสำคัญอย่างยิ่งเพื่อป้องกันการเกิดปัญหาจากการพิมพ์ต่าง ๆ เช่น ภาพผีหลอก และภาพเป็นลายคลื่น เป็นต้น จากผลการพิมพ์พบว่าความละเอียดชองลูกกลิ้งแอนนิลอกซ์ไม่สัมพันธ์กับคุณภาพการพิมพ์ที่ได้ ในขณะที่ความเร็วการพิมพ์ที่สูงขึ้นจะให้คุณภาพการพิมพ์ที่ดีกว่า เช่น ความละเอียดที่ดีขึ้น และการกระจายของหมึกต่ำ แต่ในส่วนของพื้นทึบยังคงไม่สามารถพิมพ์งานให้เรียบสม่ำเสมอได้สำหรับขนาดตัวอักษรที่เล็กที่สุด พบว่าตัวอักษรพอสิทีฟสามารถพิมพ์ได้ที่ 6 พอยต์ และตัวอักษรเนกาทีฟได้ที่ 8 พอยต์ ในการศึกษานี้พบว่าการกำหนดใช้ลูกกลิ้งแอนนิลอกซ์ที่ 600 เส้นต่อนิ้ว และความเร็วในการพิมพ์ที่ 60 เมตรต่อนาทีน่าจะเหมาะสมที่สุด สามารถผลิตขนาดเส้นได้เล็กที่สุดที่ 0.1 มิลลิเมตร ให้การกระจายของหมึกที่ร้อยละ 10 และความหนาชั้นหมึก 5 ไมโครเมตร วัดค่าความต้านทานไฟฟ้าบริเวณพื้นทึบได้ 1.26±0.06 โอห์มซึ่งค่าที่ได้จากการวัดนี้มีค่ามากกว่าค่าความต้านทานไฟฟ้าที่ใช้ในเสาอากาศทั่วไปเล็กน้อย

ภาควิชาวิทยาศาสตร์ทางภาพถ่าย ลายมือชื่อนิสิต..
และเทคโนโลยีทางการพิมพ์

สาขาวิชาเทคโนโลยีทางภาพ ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์หลัก..............................

ปีการศึกษา2554 ลายมือชื่อ อ.ที่ปรึกษาวิทยานิพนธ์ร่วม ....

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APIWIT LEELATRAKUL : CONDUCTIVE PROPERTY OF NANO SILVER INK ON FLEXOGRAPHIC PRINTS.

ADVISOR : ASSOC. PROF.ARAN HANSUEBSAI, Ph.D.,

CO-ADVISOR : HIROMICHI NOGUCHI, Ph.D., 56 pp.

This research is aimed to study the possibility of applying a flexographic printing with nano-silver ink for fabricating conductive lines on paper and film substrates. The rheological behavior of ink and the varying effects of anilox line screen on printing speeds and print quality were investigated. Printed layer thickness and its resistivity were analyzed. It was found that non linearlty of ink gave little effects on relationships between image parameters and printing conditions. It is because the viscosity of nano-silver ink is much lower than that of common water based flexographic ink. Press setting, packing material and rubber ink fountain roller should be in good conditions to protect printing problems such as ghosting and wave patterning. Results showed that anilox line screen did not relate well to print quality, while higher printing speed rather gave preferable printed results such as better resolution and low spreading, but non-homogeneity of solid area was still existed. The smallest text size which could be produced was 6 pt for positive font and 8 pt for negative font. Anilox line screen 600 lpi and printing speed 60 m/min was proposed as best condition in this study. Image of 0.1 mm finest line with about 10% width spreading and 5 μm thickness was achieved. An average sheet resistivity was at 1.26 ± 0.06 Ω/sq. This obtained value is a little larger than that of practical RFID devices.

Department : Imaging and Printing Technology Student's Signature……………………...…

Field of Study : Imaging Technology Advisor's Signature……………………….

Academic Year : 2011 Co-advisor's Signature………………….

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CHAPTER I

INTRODUCTION

Printing becomes an attractive tool to produce conductive lines for manufacturing electronic devices. Prior conductive ink known as electrically conductive adhesive (ECA), has been used as printed conductors in applications such as RFID antenna. Nano-metals usually used to disperse in inks are silver, gold, copper, nickel and platinum [1,2]. The benefit of silver is that it gives low resistivity and a thin oxide layer. Flake-shaped silver particles in inks, compared to those of as spherical shape, are known to cause significant changes in ink rheology. Traditionally, ECA has been screen-printed, but the method is limited due to line resolution, speed and cost.

Flake-shaped particles are good for creating conducting traces, when they are packed in the binder material without melting the silver flakes. Conductivity created in such way is often explained by percolation theory, based on contact of the particles [3]. Note that silver particles in inks should be dispersed well in vehicle to prevent particle agglomeration. One method is that particles are coated by a polymer or by stearic acid. These coatings, however, have an effect on rheology and obtained conductivity [4,5].

Nano-silver inks have been applied for gravure and gravure offset printing to produce conductors [6,7]. Examples of emerging novel applications of conductive inks are intelligent packages and product quality monitoring [8]. Attractive opportunities for printed conductive inks are RFID or UHF-antennas. Two examples of today's RFID systems in Thailand are theft protection systems in shops and systems for remote road toll management. The method of printing antenna with conductive ink is being widely researched. At present, gravure, inkjet and rotary screen printings are well known as these techniques offer a much less expensive solution.A sheet resistance can be less than 0.015 Ω/cm at 25 µm thickness [9].While conductive layers of thickness beneath 10 µm, a commercially available nano-silver ink showed low radiation efficiency at high frequency. On the other hand, a thickness above 30 µm closely resembled radiation characteristics for perfect conductor antennas, i.e. 100 % radiation efficiency.

To achieve good performance of printing, it is desirable to optimize the press setting and to possibly minimize amount of ink used per item, but still maintaining good radiation efficiency, i.e. low resistivity.

Factors affecting the quality of printed conductive lines are:

- viscosity of ink
- particle size of nano-silver, limiting the line resolution
- solvent absorption from the ink into a substrate surface, causing swelling and twisting
- high temperature of ink drying may also vaporize the plasticizers, causing deformation of plastics
- roughness of a substrates
- plate and packing system on press

However, what printers should know about the liquid-conductive ink is its fluidity property as the quantity of the ingredients of ink such as binders and additives should be controlled as less as possible to achieve optimum conductive efficiency. For printing substrates, there are non-coated and coated based. The former needs baking process after printing to break the dispersant around nano silver particles' surface so that the coagulation of these silver particles can be established on the substrates. The temperature is as high as 150°C. Thus, the selection of substrate must be careful for heat resistance. PEN (Polyethylene naphthalate) film is recommended. The coated substrates do not need baking. The mechanism can be explained as there is a chemical sintering process of coating to break dispersant from the silver particles through absorption into coating layer with solvents, by which these flake particles are changed to bulk layer. Water in ink will dissolve coating materials in the substrate by which some of them will be migrated to the top of the coating layer to initiate coagulation of nano silver particles. The conductivity thus can be occurred. In addition, the absorbing layer will be swelled by solvents to improve the adhesion between the substrate and printed ink. These materials are micro-porous such as silica/aluminum pigments.

The aim of this research is to study the rheological property of nano-silver conductive ink applied on flexographic printing and to find out the optimum press setting able to print simple electrical structures, such as conductors, coils and antennas on low-cost flexible substrates.

1.1 The objectives

The objective of this research is to investigate theconductive property of nano silver ink on flexographic prints.

1.2 Scopes of research

In order to investigate the conductive property of nano silver ink on flexographic print, firstly we will analyze the rheological behavior of nano silver ink to find out the optimum rheological of nano particle ink of this study. Then we will investigate the effects of anilox line screen and printing speed on print quality parameters. Finally, we will analyze printed layer thickness and its resistivity of flexographic prints.

1.3 Content of the Thesis

Chapter 2 deals with the overview of the theoretical considerations and literature reviews.

In Chapter 3, the description on materials under the experiment procedures and apparatuses are described.

Chapter 4 contains the results and discussion on this research. Finally, the results are concluded in chapter 5 with some suggestions

CHARPTER II

THEORETICAL CONSIDERATIONS

2.1 Definition of Flexography

Flexography is a method of direct rotary printing that uses resilient relief image plates of rubber or photopolymer material. The plates are mounted to plate cylinders of various repeated lengths, inked by the cell-structured ink-metering roll, with or without a reverse-angle doctor blade, and carrying a fast drying fluid ink to plates that print onto virtually any substrate, absorbent or nonabsorbent.

Flexography is a rotary printing method. For every revolution of the printing plate cylinder, an image is produced. The heart of the flexographic printing process is its simple ink system [10].

A thorough grasp of flexography's definition and the representative diagram are shown in Figure 2-1. The ink-fountain pan supplies ink to the rubber fountain roll, which supplies ink to the anilox roll. Then the anilox roll will transfer uniform levels of ink from its cells in the anilox roll to the surface of the printing plates. The plates mounted to the printing plate cylinder carry the ink to the substrate as it travels through the press. The impression roll supports the substrate.

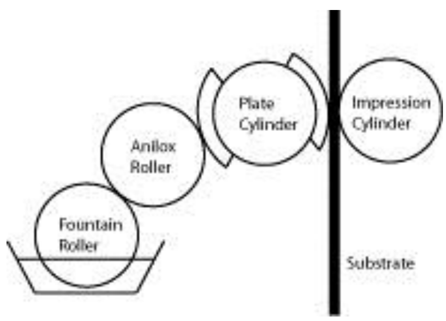


Figure 2-1 Flexographic printing unit

2.2 Photopolymer plate

The direct photopolymer plate is one of the major innovations in modern flexographic printing. It affords the ability to transfer an image from a photographic negative directly onto the surface of the printing plate, thereby giving excellent image fidelity [11].

Photopolymers are ultraviolet light sensitive materials and are used to prepare printing plates for flexography, letterpress and offset, as well as printing resists and proofing films. Flexographic photopolymer printing plates are similar to modeled-rubber plates in that both are flexible, resilient and have excellent ink transfer. There are many systems available for producing photopolymer flexo plates.

Raw materials are available as either viscous liquids, ready to be cast to a desired thickness, or as performed solid sheets of an appropriate thickness. Photopolymer materials, whether liquid or sheet, are converted to flexographic printing plates when exposed to ultraviolet light passed through a photographic negative image of the artwork to be reproduced. The photopolymer is then processed to develop the relief image as shown in Figure 2-2.

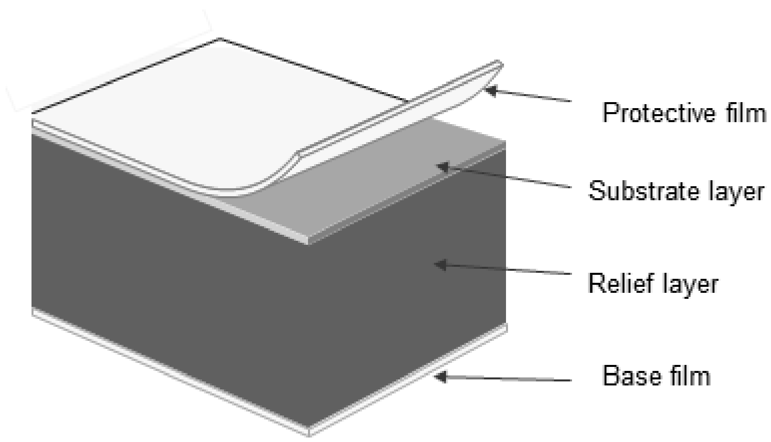


Figure 2-2 Structure of a monolayer flexographic plate

2.3 Plate system

Photopolymer plates are expected to produce good area coverage with low dot gain, fine reverses and light halftones. In corrugated post printing, the system used may often differ in the type of the photopolymer plate employed, the cushion material used and the double-sided tape applied. The choice of the particular elements used have an impact on the plate's performance, tone value increase (TVI) and ink release. The extent of TVI is dependent on the type and caliper of plate, the pressure absorbency characteristics of the cushion and the press settings chosen [12].

2.4 Defining new quality standards in flexo printing

Flexographic plate making can be a complex process which differ with the needs of the end user. Photopolymer plates consist of four main constituents: binders, monomers, photo-initiators and additives. The properties combination and interaction of these components play a crucial part in print performance.

In practice printers have used different photopolymer printing plates in combination with different tape, cushion backing and sleeves. This has been done to make maximum advantage of plate characteristics such as elasticity, durometer and ink transfer capabilities in order to suit a specific application or a certain substrates. The most common demand is for plates to produce even and dense ink transfer, with 10 percent dot gain. Other frequent requirements are for accurate and clean print-out of fine reverse and line elements, the elimination of filling-in and smooth printing of difficult tone gradation (60 – 150 lpi with conventional halftone screens). The plate is required to be suitable for all ink system, not only for water-based and solvent-based ink systems, but also for test UV curing inks. In hardness terms it should exceed 60 Shore A so as to reduce dot gain characteristics, but at the same time printers are looking for high elasticity for ease of mounting and to reduce make ready times [13].

As recognized throughout the industry, one of the unfortunately characteristics of flexography is that print pressure is always set higher than theoretically required in order to achieve an even ink transfer. This is done to overcome inconsistencies in plate thickness, mounting press, sleeve and surface structure of the substrate in use. The pressure is partially absorbed in the printing plate, which can lead to differing levels of dot deformation.

A highly uniform print-out is achieved even when using the entire printing which with different pieces of plates of the same thickness.

2.5 Packing system

The photopolymer plate is attached either directly to the steel cylinder by means of foam adhesive tape or to the hard sleeve. Care should be taken to match the tape's adhesive properties to the surface to be glued and it's compressibility to the imprint. For pure halftone printing, a softer undercut should be used to avoid increased dot gain due to deformation of halftone dots, i.e. a softer foam adhesive tape for combination halftone and line work on a plate, on the other hand, a harder foam tape should be used with adhesive the necessary solid density [14].

The structure of a soft, foam-coated sleeve provides the compressible sub-structure desired. Such sleeves are mostly equipped which the upper layer is made of compressible material. The sleeve's compressibility must match that of the print. In this system, the printing plate is fixed to the sleeve using a non-compressible film tape. The tapes adhesive properties should be matched to the surface of the sleeve and the black of the photopolymer plate. Tapes most suitable for this application usually have sizes with widely varying adhesive powers.

2.6 Image quality evaluation

A number of check-procedures were introduced to achieve a stable print quality [15]:

1. checking the press setting condition such as register, balance of anilox roller, doctor blade system, doctor roll system and more.
2. checking the plate quality such as reproduction properties, thickness tolerances, ink transfer properties, TVI characteristics, and more.
3. checking reference values such as process printing, mounting, storage and more.
4. checking material specifications: plate, cushion, ink and substrates

The establishment of standard procedures is recommended for producing a high quality printing result. They are colour sequence, ink quantity transferred, viscosity and temperature. Minimum pressure between plate and impression cylinder is necessary. This includes registering and grey balance.

2.7 Nano silver conductive ink

Conductive ink made of silver nanoparticles was formerly designed for writing and repairing electrical circuit. Nowadays, it could also be applied for fabricating electrical circuit by ink-jet printing [16-20]. Mostly, conductive silver ink was made from silver powder by digestion of silver metal with a physical technique such as milling and spay pyrolysis. Silver powder was then mixed with binder (e.g. hydrocarbon compound and/or polymer) and employing as conductive silver ink. However, silver content of conductive ink should be more than 60-80 % (w/v) because when it dried on a substrate, silver particles could be contacted and became a conductive silver line [21-23].

2.8 Silver nanoparticles

Silver nanoparticles are of great interests in scientific research and industrial application, due to the large surface area to volume ratio and size-dependent properties. Silver nanoparticles have been used in many applications in different area of science such as catalysis [24], surface enhanced vibration [25], optical sensors [26-27], antibacterial agents [28-29], and conductive material [23, 30-31].

Noble metal nanoparticles (especially gold, silver, and copper) exhibit a strong UV-visible absorption band that is not present in the spectrum of the bulk metal. This absorption band results when the incident photon frequency is resonant with the collective oscillation of the conduction electrons and is known as the *localized surface plasmon resonance*(LSPR) [32]. When the environment of metal nanoparticles was changed, LSPR shifts were observed. Electromagnetic field enhancement near the surface of nanoparticles is associated with extinction efficiency of nanoparticles, responsible for the intense signals.

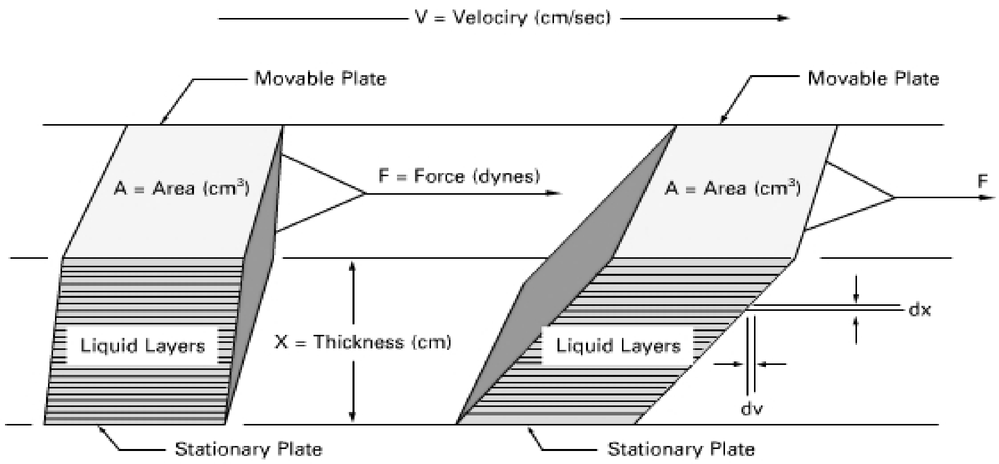
Furthermore, the size of silver nanoparticles affects the melting temperature or sintering temperature. Sintering effects occurs through diffusion of elements across particles, forming interconnection (necking) between particles. This phenomenon always occurs at high temperature. However, sintering can occur at room temperature when particles size is reduced to nano scale. Therefore, silver nanoparticles could be employed as conductive ink or conductive paste for electronic circuit fabrication.

2.9 Size effect in nanochemistry

The size effect in nanochemistry creates a phenomenon that produces the qualitative changing in physical, optical, and thermal properties based on the number of atoms or molecules at the surface of nanoparticles and takes place in the range of1-100 nm. Each new property enables new applications.

2.10 Viscosity and Flow

At the very outset it is important to develop a clear, exact concept of viscosity (the resistance of a liquid to flow). To do this, a model in which a liquid is confined between two parallel plates will be considered. One is movable and another one is stationary. They are separated by a distance x (see Fig. 2-3). Let a force F acts on a top movable plate in tangential direction so that the top plate slides sidewise with velocity v relative to the bottom plate. When it moves, layers of liquid between the two plates are also moved in sidewise direction, as depicted in the right-hand section of Fig. 2-3. The top liquid layer moves with the greatest velocity, whereas the bottom liquid layer moves with the smallest (zero) velocity. Intermediate layers move with intermediate velocities. However, the velocity gradient dv/dx (differential change in thickness dx) for any portion of the liquid is constant. This velocity gradient γ is referred to as the shear rate. In the given situation, the shear rate (velocity gradient) is uniform from top to bottom. Hence dv/dx is also equal to v/x (see Eq. 2.1). Shear velocity v is conventionally expressed in centimeters per second and thickness x in centimeters. Hence shear rate γ (= v/x) has the dimensions of reciprocal seconds (sec^{-1}), because the centimeter unit (present in both the numerator and the denominator) is canceled out leaving only the second unit in the denominator to express the shear rate quantity [33].



τ = shear stress = F/A ($dynes/cm^2$)

γ = share rate = v/x (sec^{-1})

n = velocity = shear stress /shear rate = τ / γ (dyne sec cm^{-2}) or (poise)

Figure2-3 Theoretical parallel plate arrangement illustrating simple (Newtonian) flow [33]

The total force acting tangentially on the top plate (of area A) is F. The force acting on a unit of top plate area is then F/A. This force per unit of area τ is called the shear stress (Eq. 3.2). Shear force F is conventionally expressed in dynes (1 gram weight = 980 dynes) and the area A over which is acts in square centimeters. Hence shear stress τ (= F/A) has the dimensions of dynes per square centimeter.

Now that we have developed the two ideas of shear stress and shear rate, viscosity can be defined. Viscosity n is the ratio of shear stress to shear rate (see Eq. 3.3). It is unfortunate that no consistent set of symbols for shear stress, shear rate, and viscosity has been accepted by rheologists.

Three equations (Eqs. 3.1, 3.2, 3.3) have been developed. They underline the science of flow and should be clearly understood for a proper understanding of all the derived formulas the develop through their use..

γ (shear rate) = dv (differential velocity)/dx(differential thickness) (2.1)

τ (shear stress) = F (force)/A (area) (2.2)

n (viscosity) = τ (shear stress)/γ (shear rate) = (F/A)/(dv/dx) (2.3)

The arrangement of the liquid between the two parallel plates given in Fig. 2-3 is obviously and idealistic situation.

2.11 Flexographic printing problems

Followings are common printing problems encountered [34]:

- poor adhesion
- fill-in of Reverses and Types
- foaming
- ghosting
- pinholes or fisheyes(tiny round voids in printed image)
- tracking (ink appears in non-printed area)

2.12 Resistivity measurement

Resistivity tests are important for analyze conductivity. 'Volume resistivity' is defined as the electrical resistance between opposite faces of unit cube of materials [35] (see Fig. 2-4).

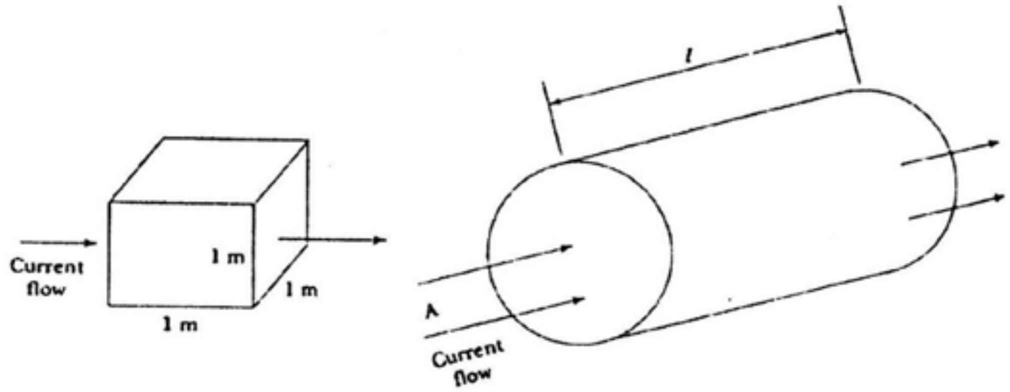


Figure 2-4 Volume resistivity

The volume resistivity is calculated as follows.

$$\text{Resistivity } (\Omega_m) = \frac{average\ resistance\ in\ x\ cross\text{-}sectional\ area\ in\ m^2}{distance\ between\ potentionmetric\ contacts\ in\ meters}$$

CHAPTER III

EXPERIMENT

3.1 Materials

3.1.1 Flexo plate thickness 1.14 mm hard surface 65 Shore A

3.1.2 TESA®Softprint SteelMaster TP* code 52115

3.1.3 Substrates designed by *Mitsubishi Paper* Mills Ltd

- Resin coated (RC) paper
- Transparent PET film
- Opaque white PET film

3.1.4 Silver ink type NCAGF30E-02

Ink property

- Surface tension

The surface tension ofnano-silver ink was much lower than that of common water based flexo ink as shown in Figure 3-1

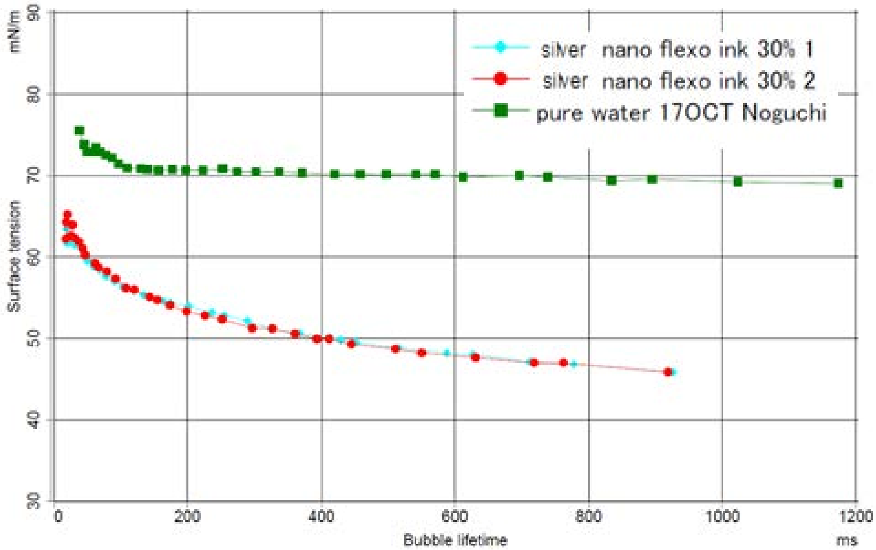


Figure 3-1 Surface tension vs. bubble lifetime of Silver ink type NCAGF30E-02 and pure water.

- Particle Size

Particle size is around 30-55 nm, giving side distribution as shown in Figure 3-2.

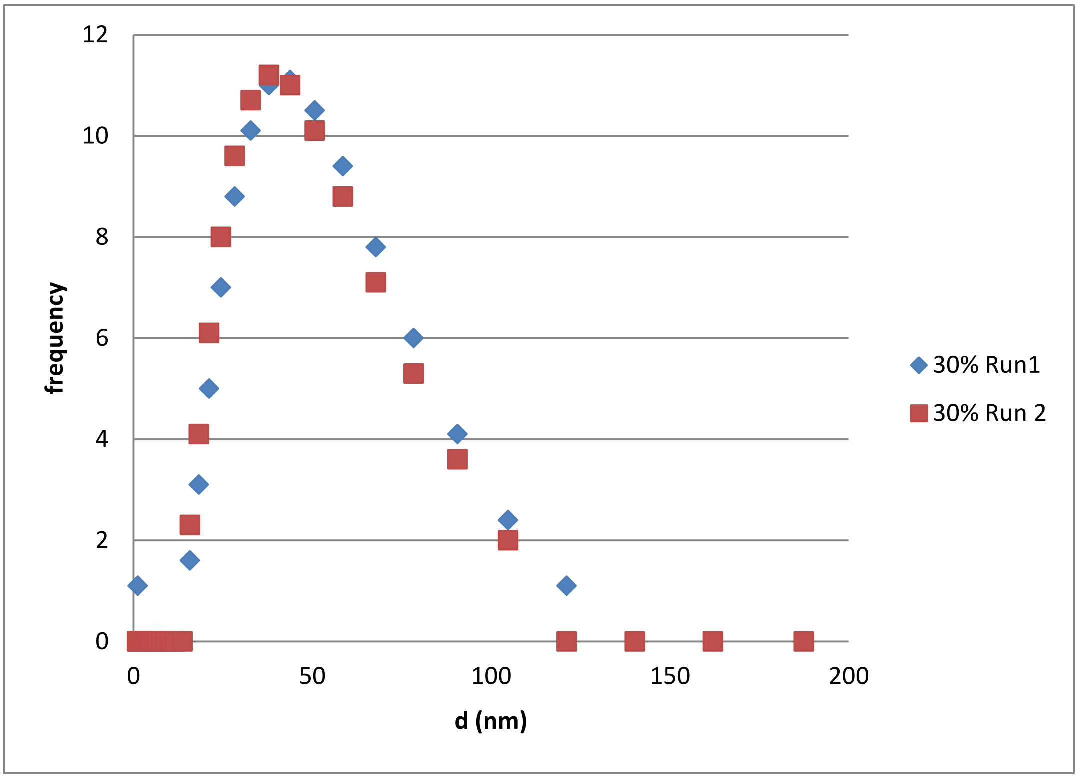


Figure 3-2 Particle size distribution of nano silver ink type NCAGF30E-02.

3.2 Apparatus

1.2.1 BROOKFIELD - DV-E Viscometer

1.2.2 Voltmeter Sanwa YX 361 TR

1.2.3 Nilpeter-FB 3300 S press

1.2.4 Anilox resolution 360,400,500,600and700lpi

1.2.5 Scanning Probe Microscope (SPM) Controller type Nano Scope IV

1.2.6 JSM-6400 Scanning electron microscope

1.2.7 Optical stereo microscope Olympus typeSZH10

1.2.8 IHARA® Densitometer

3.3 Procedure

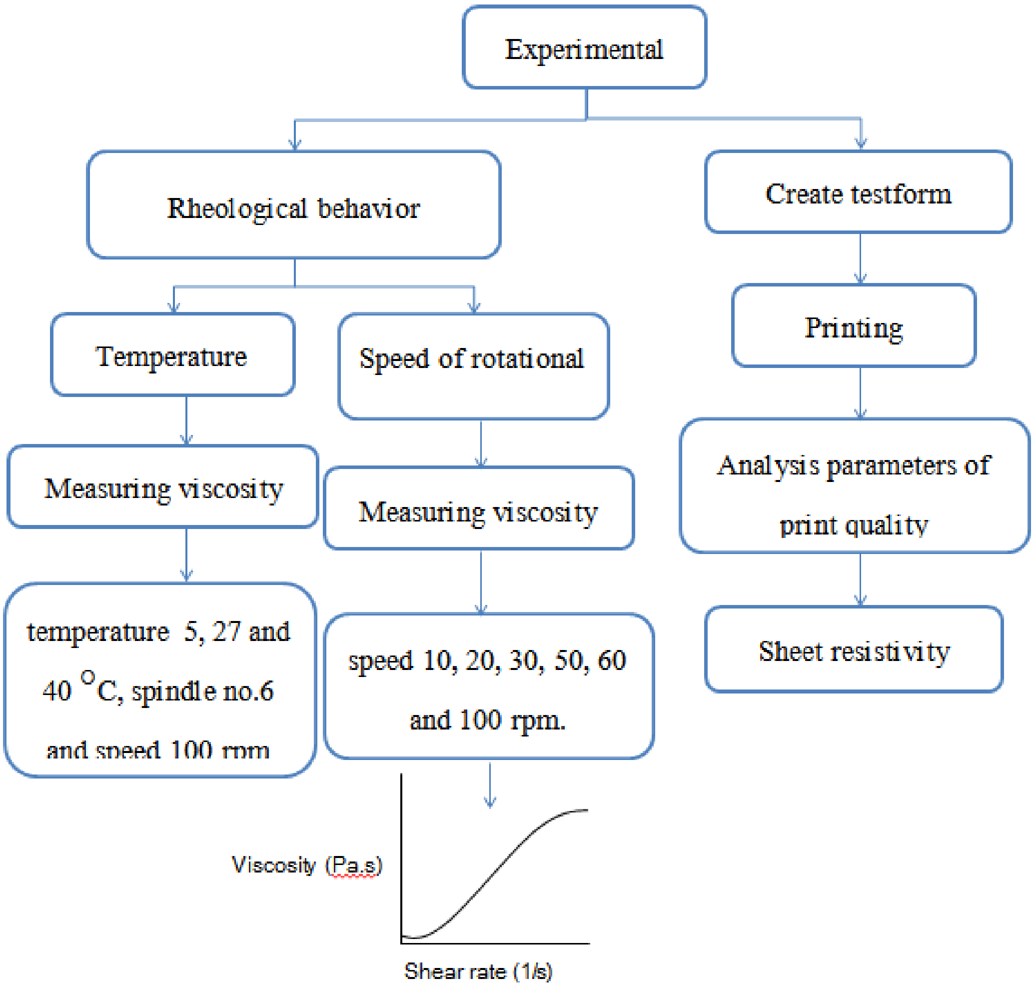


Figure 3-3 Procedure of experiment

3.3.1 Evaluation rheological property of ink

Rheological property is reported in the form of flow behavior by Brookfield.

3.3.1.1 Effect of temperature on rheology

1) contain silver nanoparticle ink in three 500 ml. plastic bottles.

2) bring first bottle of ink into oven at temperature 40 ° C for 3 hours.

3) take second bottle of ink into refrigerator at temperature of 5 ° C for 3 hours.

4) measure viscosity of 3 bottles of ink by BROOKFIELD - DV-E Viscometer using screw spindleno.6 with speed setting at 100 rpm. Each bottle will have temperature 5, 27 and 40 ° C, respectively.

3.3.1.2 Shear Response

Viscosity was measured using screw spindle no.2, 3, 4, 5 and 6 with speed setting at 10, 20, 30, 50, 60 and 100 rpm.

3.3.2 Test form design

Test form was designed in a digital form by the Adobe Illustrator program. It consisted of following elements.

- line resolution target
- font size target
- Solid Area 2x11 cm^2
- continuous tone patch
- RFID / antenna image

3.3.3 Press operation

Printing was done on Nilpeter-FB 3300 S press with 3 substrates. The plate 1.14 mm thickness was mounted on the printing cylinder with TESA®Softprint SteelMaster TP* code 52115. Anilox line screen was varied using 360, 400, 500, 600 and 700 lpi (lines per inch) and printing speed from 15 to 60 m/min(meter per minute).

3.3.4 Resistivity measurement

Sheet resistivity on solid area and RFID part was measured by two-point probe measurement using Voltmeter Sanwa YX 361 TR.

3.3.5Relationships among rheological property, resistivity and print quality parameters

3.3.5.1Analysis of rheological property

Viscosity and shear stress was determined. Result of nano-silver ink and common water based flexo ink was compared.

$$\eta = \tau / \gamma$$

γ = shear rate (sec^{-1})

τ = shear stress($dynes/cm^2$)

η = viscosity(Pa.s)

3.3.5.2 Analysis of resistivity

Average resistivity value and standard deviation was defined on solid area and RFID antenna.

3.3.5.3 Analysis of print quality parameters

(a) Thickness of ink layer, shape and surface topography of three substrates were determined by SEM with 1,000 and 20,000 magnification. Scanning Probe Microscope (SPM) Controller type Nano Scope IV was used to measure roughness of printed surfaces.

(b) Tone Reproduction

- Density of tone scale from 2 to 100% was measured using IHARA® Densitometer.
- The relationship of input tone values and density was obtained by plotting graph.

(c) Analysis of line and text

- Optical stereo microscope Olympus typeSZH10was used to take picture and analyze line width and text size.

CHAPTER IV

RESULTS AND DISCUSSION

4.1 Rheological Properties

4.1.1 Effect of Temperature on viscosity

The result of ink viscosities measured at temperatures 5, 27 and 40 °C was given in Table 4-1 .There was relationship between Temperature (°C) and measured viscosity (mPa.s) as shown in Figure 4-1. The ink tended to lower its viscosity when the temperature was raised. Note that the change of viscosity was not so strong after 27 °C.

Table 4-1Viscosity of nano silver ink at different temperatures

Temperature (°C)	Viscosity (mPa.s)
5	225
27	196
40	195

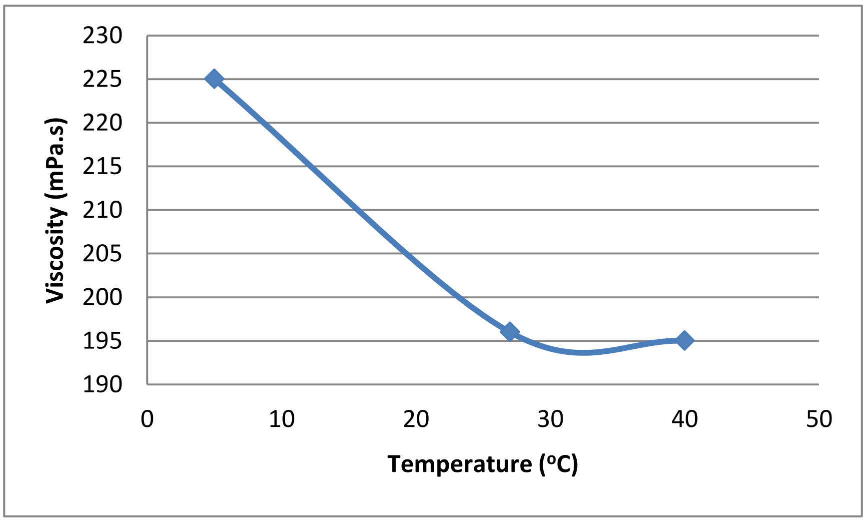


Figure 4-1 Viscosity of nano-silver ink on temperature dependence

It is because its behavior upon evaporation gave continuous change from liquid state to pseudo-liquid state, However, the limitation of evaporation was about 27°C. The measurement suggested that the ink had visco-elastic property.

4.1.2 Shear Response

Table 4-2, 4-3 were the data of measured viscosities and shear stress by BROOKFIELD - DV-E Viscometer with screw spindle no.2, 3, 4, 5 and 6 at speed 10, 20, 30, 50, 60 and 100 rpm. Shear rate (sec^{-1}) was obtained as equal to rpm/60.

Table 4-2 Viscosity and Shear Rate of nano silver ink

		Viscosity (Pa.s)				
		Spindle Number				
Shear Rate (1 / s)	Brookfield Speed (rpm)	2	3	4	5	6
0.167	10	0.602	0.695	0.770	0.960	1.500
0.333	20	0.388	0.413	0.440	0.500	0.800
0.5	30	0.310	0.342	0.367	0.425	0.750
0.833	50	0.221	0.244	0.244	0.280	0.390
1	60	0.192	0.212	0.210	0.227	0.335
1.667	100	0.151	0.158	0.163	0.148	0.245

Table 4-3 Shear Stress and Shear Rate of nano silver ink

		Shear Stress($Dynes/cm^2$)				
		Spindle Number				
Shear Rate (1 / s)	Brookfield Speed (rpm)	2	3	4	5	6
0.167	10	0.100	0.116	0.128	0.160	0.250
0.333	20	0.129	0.138	0.147	0.167	0.267
0.5	30	0.155	0.171	0.183	0.213	0.375
0.833	50	0.184	0.203	0.203	0.233	0.325
1	60	0.192	0.212	0.210	0.227	0.335
1.667	100	0.252	0.263	0.272	0.247	0.408

Relationships between shear rate (sec $^{-1}$) vs viscosity (Pa.s); and shear rate (sec $^{-1}$) vs shear stress (dynes/cm^{2}) were plotted as shown in Figure 4-2, 4-3 respectively.

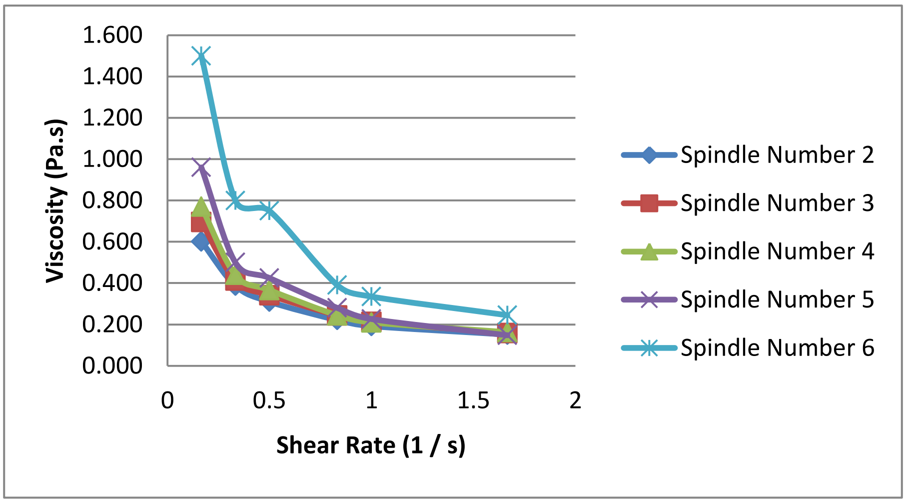


Figure 4-2 Viscosity of nano-silver ink on shear rate dependence

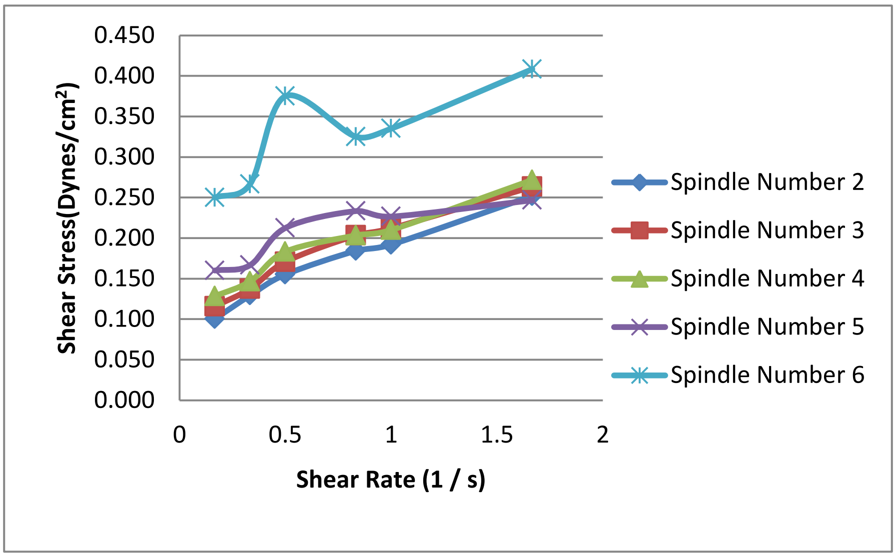


Figure 4-3 Shear response of nano silver ink (shear rate – shear stress curve)

Results showed that the decrease in viscosity as shear rate increased indicated shear thinning behavior. This is typical of ink with high solid content system. The higher solid content is, the stronger the change of viscosity becomes. The ink thus represents non-linearity of viscosity on shear rate dependence. For the shear rate-shear stress curves, nano silver ink showed the same effect that higher shear rate caused lowering viscosity.

Figure 4-4 shows viscosity, as a function of shear rate, for nano-silver ink and water based flexo ink. It was found that viscosity of nano-silver ink was much lower than that of common water based flexo ink. Its condition thus was more fluidity.

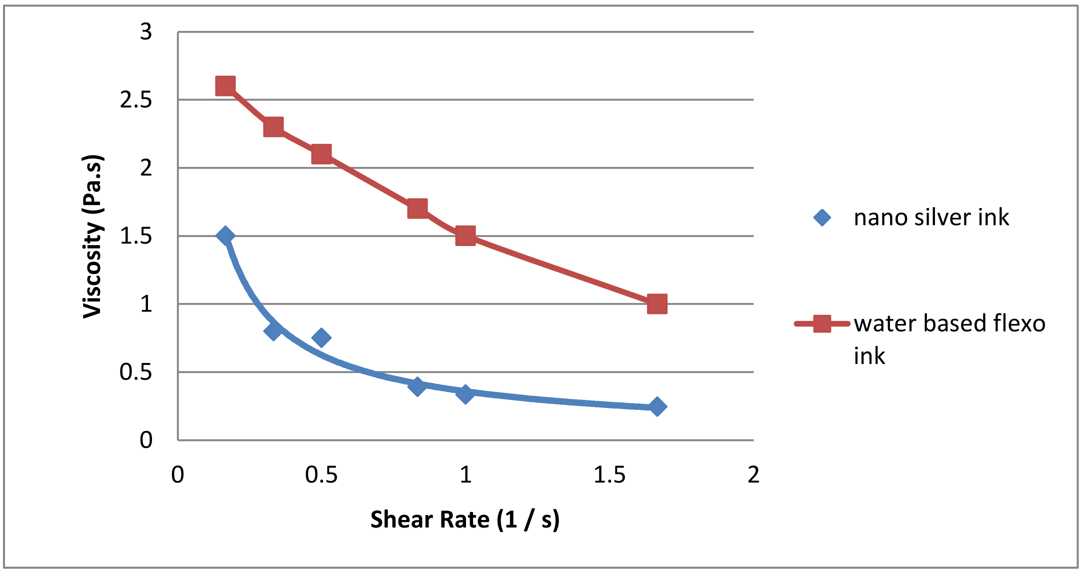


Figure 4-4 Viscosity of nano-silver ink and water based ink on shear rate dependence

4.2 Test-form design

The test-form for print evaluation was designed as shown in Figure 4-5 and Figure 4-6. It included necessary standard targets for specifying the printing parameter and resistivity property.

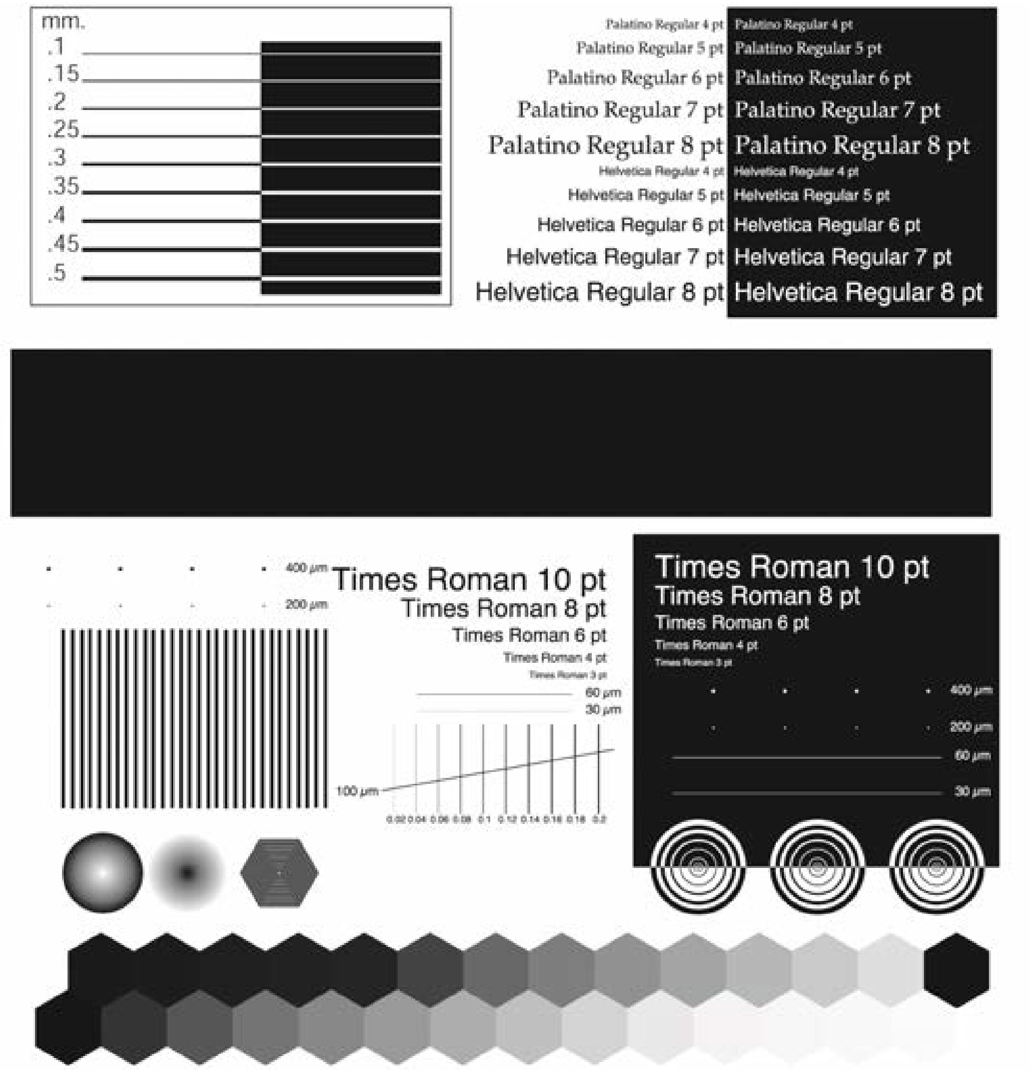


Figure 4-5 Print testform

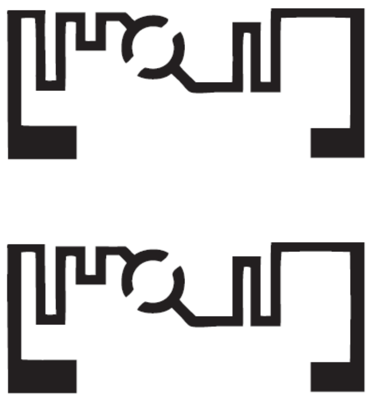


Figure 4-6 RFID pattern (1.7x4 cm^2)

4.3 Resistivity vs printing condition

The printing experiment was done on a Nilpeter-FB 3300 S press with the plate thickness 1.14 mm and TESA® Softprint SteelMaster TP* code 52115. The anilox line screen was varied from 400 to 700 lpi at printing speed 15 - 60 meter per minute.

4.3.1 Resistivity measurement

4.3.1.1 Printing speed dependence

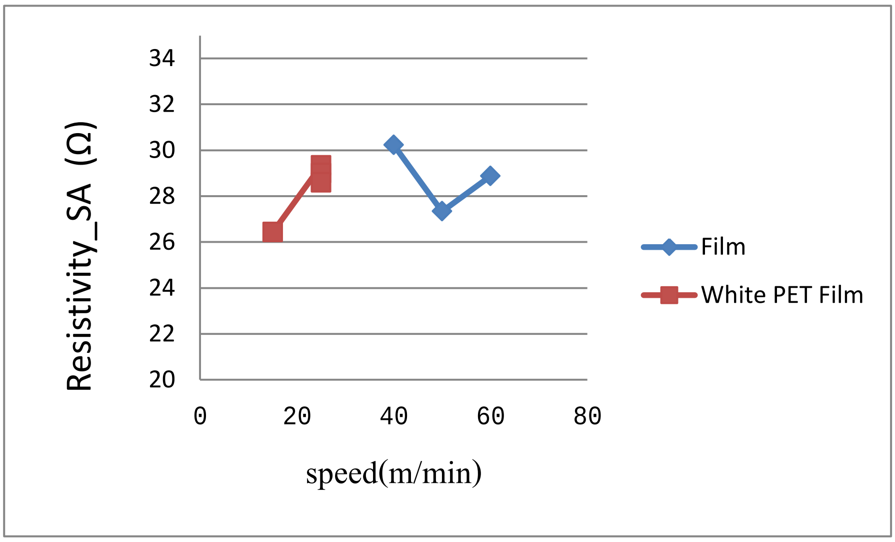


Figure 4-7 Sheet resistivity vs printing speeds (m/min)

The relationship between printing speed and sheet resistivity on film and white PET substrates was shown in figure 4-7. The obtained values among two substrates were not varied much. The sheet resistivity of transparent PET film at 40 - 60 m/min was about 27.3 - 30.2 Ω or 1.24 – 1.37 Ω/sq. and opaque white PET film at 15 - 25 m/min was 26.4 – 29.3 Ω or 1.2 – 1.33 Ω/sq.

4.3.1.2 Anilox line screen dependence

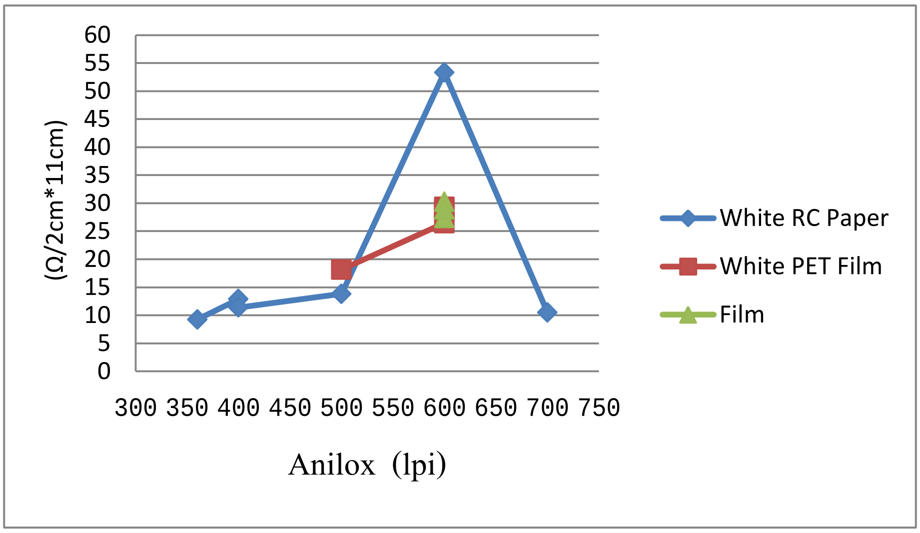


Figure 4-8 Sheet resistivity vs anilox line screen (lpi)

The results of sheet resistivity were measured on resin coated (RC) paper based, transparent PET film and opaque white PET film as shown in Figure 4-8. The resistivity of nano silver on RC paper fell in the range of 9.25 to 12.88 Ω or 0.42 - 0.63Ω/sq., except the condition using anilox line screen at 600 lpi that the obtained value was cut off. While those on transparent PET film and opaque white PET film showed similar behavior. Higher anilox line screen tends to give lower resistivity. It is due to lesser amount of ink transferred.

4.3.1.3 Antenna resistivity vs printing speed (m/min)

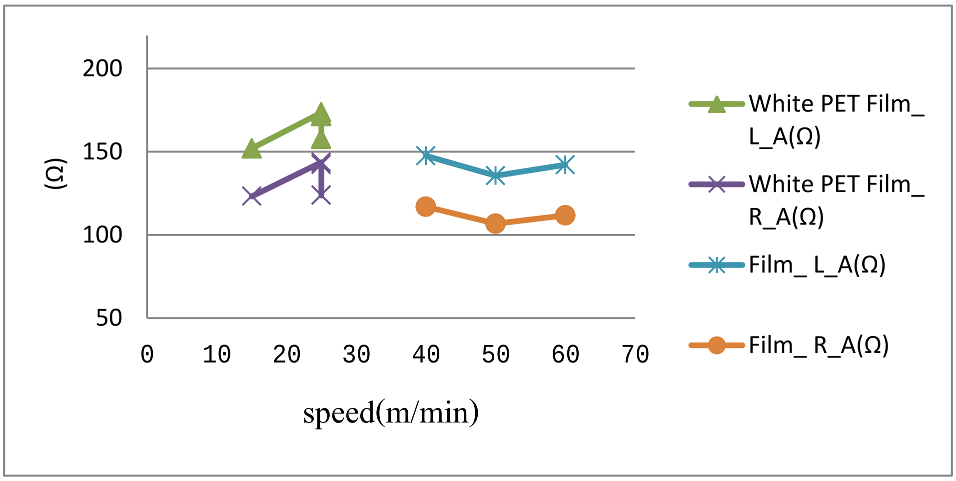


Figure 4-9 Antenna resistivity vs printing speed

Figure 4-9 showed the relationship between the resistivity of nano silver ink on the left and right side of antenna and printing speed. It was found that the measured resistivity values on two substrates were not much different. The resistivity of opaque white PET film gave the resistivity on the left side at 135.56 – 147.44Ωand the right side at106.67 – 116.92Ω during printing speed 15-25 m/min. For transparent PET film, the resistivity on the left side was 151.9 – 173.61 Ω and the right side was 123.09 – 143.61 Ω during printing speed 40-60 m/min.

4.3.1.4 Antenna resistivity vs anilox line screen

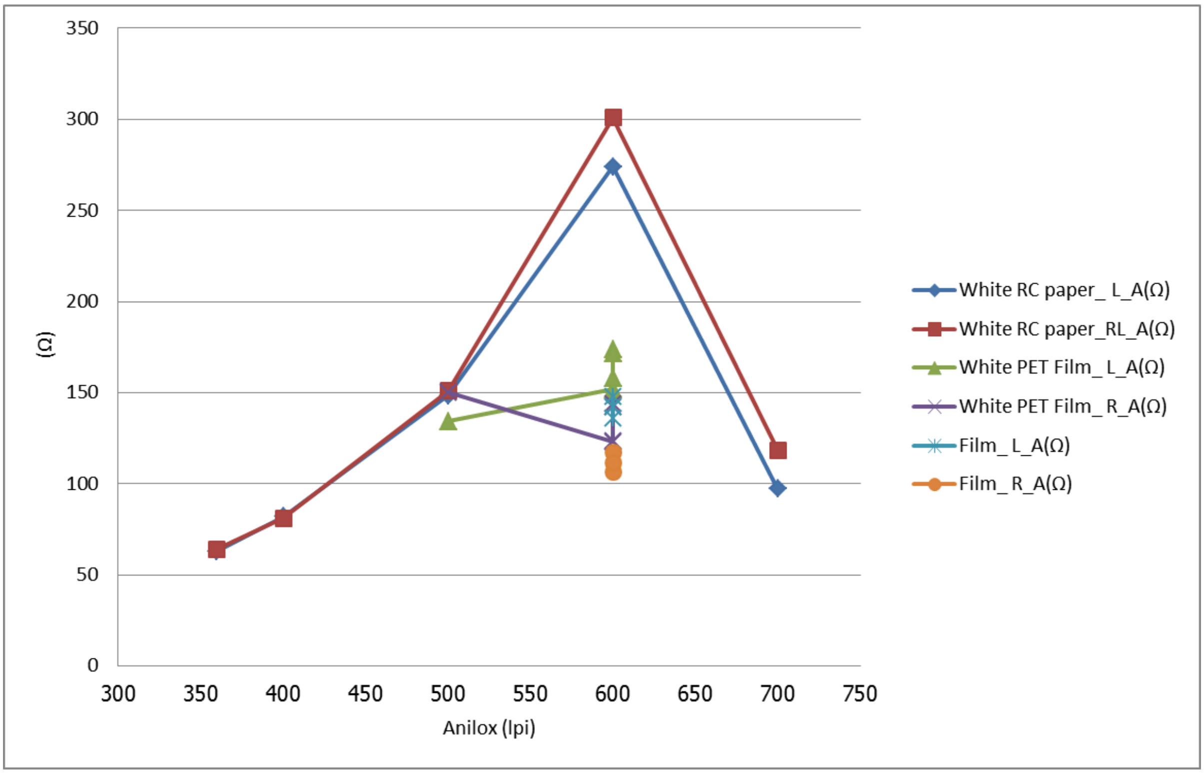


Figure 4-10 Antenna resistivity vs anilox line screen (lpi)

The results of resistivity of the left and right sides of antenna printed on resin coated (RC) paper based, transparent PET film and opaque white PET film at different anilox line screen were shown in Figure 4-10. The resistivity of printed nano silver ink on three substrated fell in the range of 63.05 - 97.08 Ω for the left sideand 64.16 to 118.3 Ω for the right side, except the condition of using anilox line screen at 600 lpi that the measured value was cut off. For transparent PET film and opaque white PET film, the measured resistivity values showed similar behavior. Higher anilox line screen tends to give lower resistivity. It is due to lesser amount of ink transferred.

4.3.2 Printed ink film thickness on solid area

Fig. 4-11 - Fig 4-16 showed SEM photomicrograph of printed nano silver layer on solid area. It was found that ink penetrated and laid down only on the surface of these substrates. It was estimated that there was immediate reaction between nano silver ink and coating materials. This help ink dry quickly whereby its conductivity was occurred.

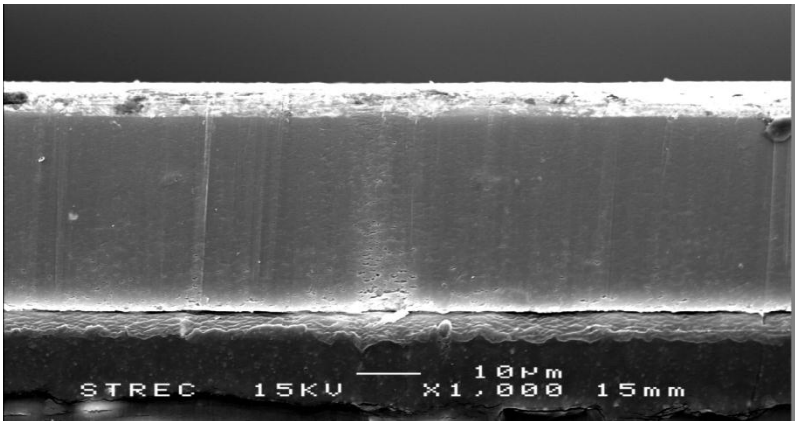


Figure 4-11 Cross section of printed nano silver ink on RC paper

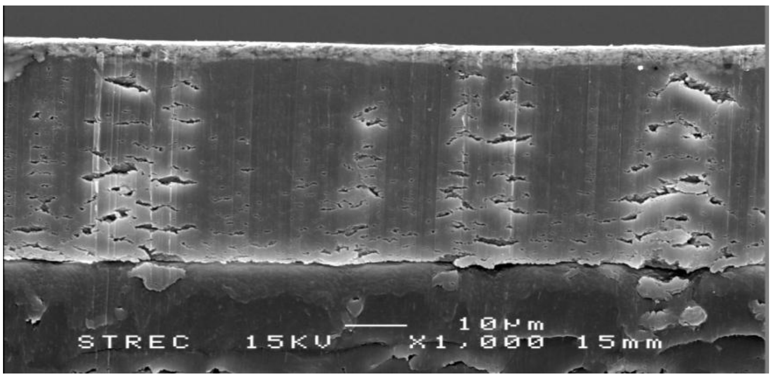


Figure 4-12 Cross section of printed nano silver ink on RC paper

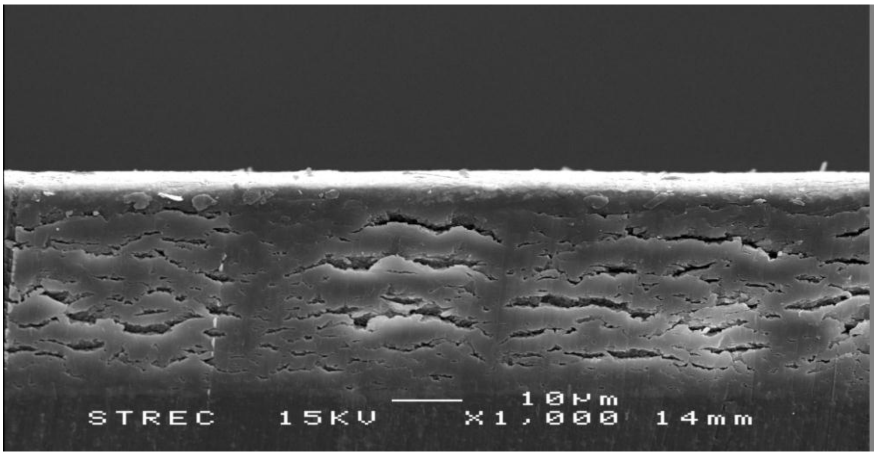


Figure 4-13 Cross section of printed nano silver ink on TransparentPET film

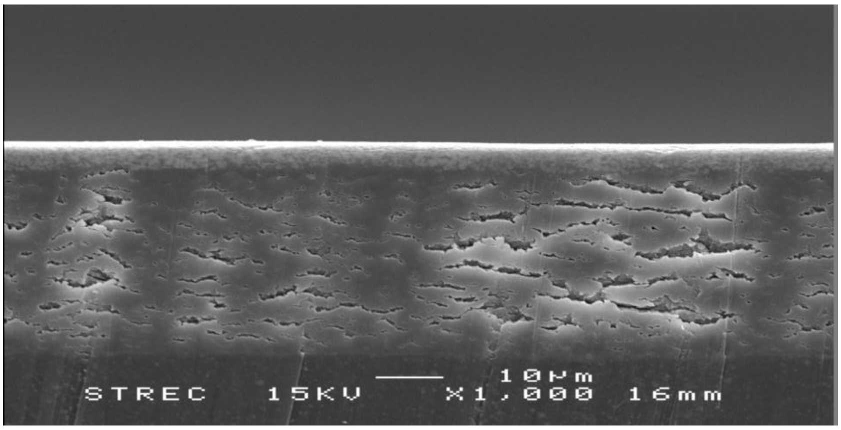


Figure 4-14 Cross section of printed nano silver ink on TransparentPET film

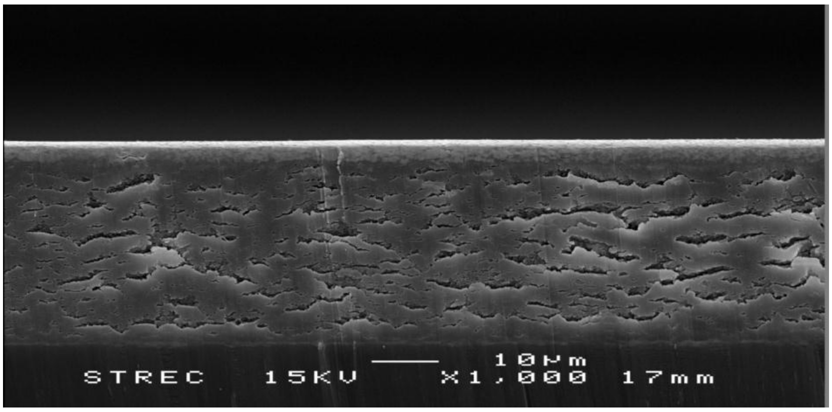


Figure 4-15 Cross section of printed nano silver ink on Opaque white PET film

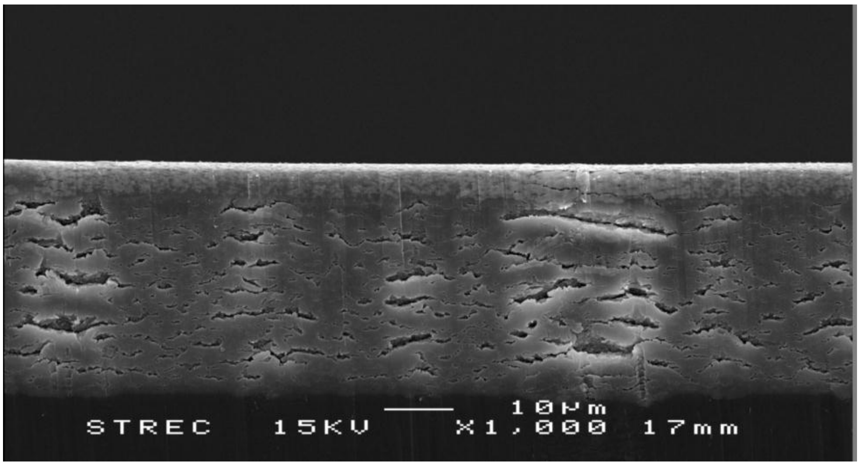


Figure 4-16 Cross section of printed nano silver ink on Opaque white PET film

The measured ink film thickness on these substrates related to varied conditions was given in Table 4-4. Most of printed samples was based on anilox line screen 600 lpi with printing from 15-50 m/min. The thickness fell in the range of 4.95 to 7.67µm.

Table 4-4Thickness of silver layer of RC paper, opaque white PET film and transparent PET film

	anilox (lpi)	speed(m/min)	Ag layer (µm)
RC paper	360	15	5.1
RC paper	600	15	7.67
Opaque white PET	600	25	5.81
Opaque white PET	600	25	6.38
Transparent PET film	600	40	7.14
Transparent PET film	600	50	4.95

4.4 Print quality evaluation

Print quality parameters will be evaluated as follows:

4.4.1 Tone reproduction

Figure 4-17 represents tone reproduction curves of printed nano silver ink on 3 substrates, plotted between input tone values and corresponding optical densities. It was found that all substrates gave the tone curves in similar manner. As it was metallic surface, the obtained tone reproduction curves were not as good as those of conventional inks. Their flattened tone range was existed whereby halftone image is not recommended.

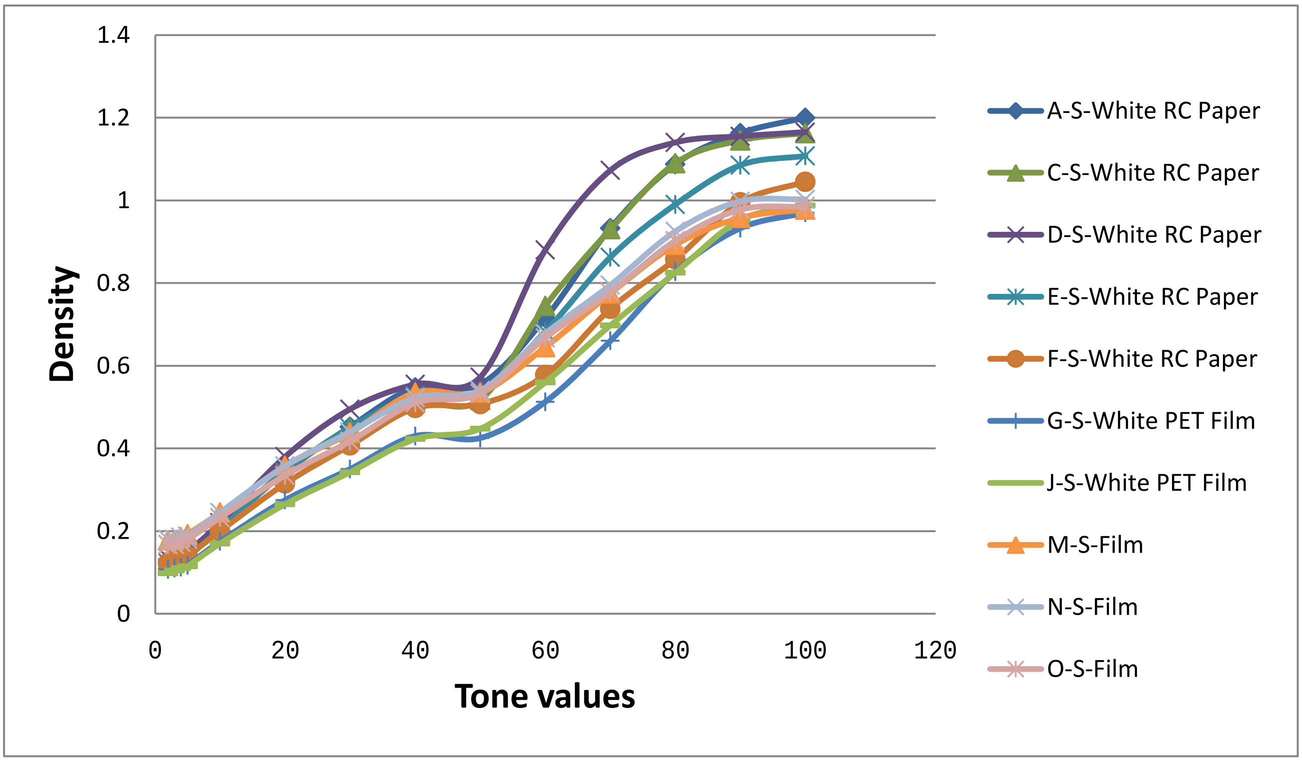


Figure 4-17 Tone reproduction curves of printed silver nano ink on all substrates

Figure 4-18, 4-19, 4-20 show the tone curves of printed nano silver ink on RC paper, white PET film and transparent PET film with varying anilox line screen. These curves gave the same tendency with different amount of ink transferred. As mentioned before that halftone image is not recommended. In addition, there was fill-in effect in the shadow area.

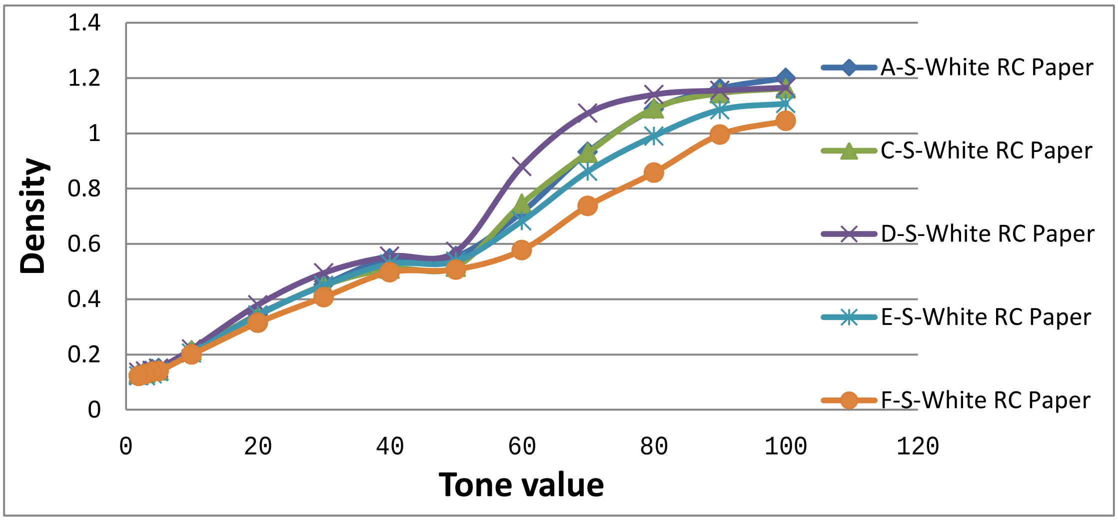


Figure 4-18 Tone reproduction curves of nano silver ink on resin coated (RC) paper

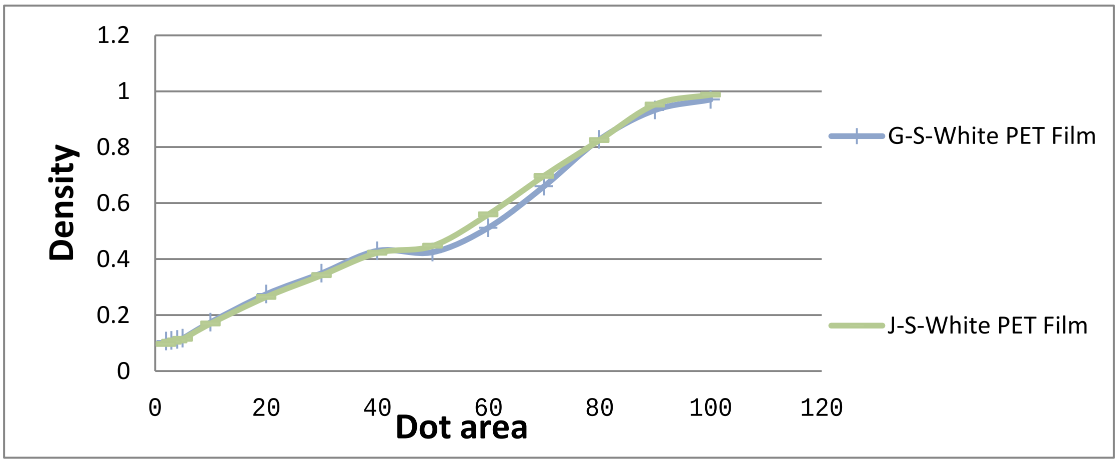


Figure 4-19 Tone reproduction curves of silver nano ink on white PET film

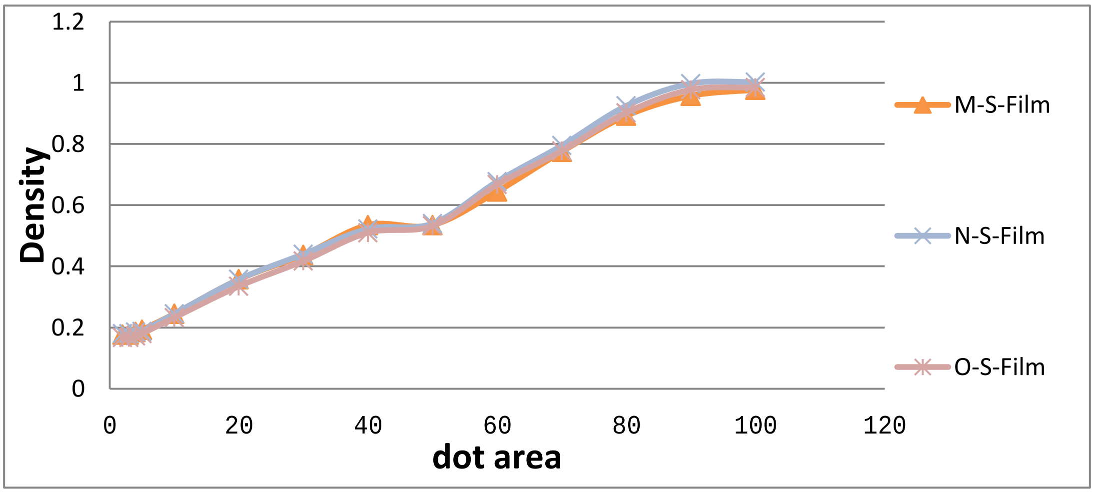


Figure 4-20 Tone reproduction curves of printed nano silver ink on transparent PET film

4.4.2 Line width and font size

The printed conductive lines were examined under an optical microscope to find out the smallest line width and font size that can be reproduced.

4.4.2.1 Line width target

Results of the measurement of printed positive line width at different anilox line screen on RC coated paper are given in Table 4-5 and Figure 4-21. It was found that the obtained data was close to the target values ± 0.03 mm, with the exception of the data from anilox line screen at 360 lpi. Finest line was 0.1 mm width. Ink spreading fell in the range of 10%.

Table 4-5 Printed positive line width at different anilox line screen on RC coated paper

			Positive-line									
			0.1 mm.		0.2 mm.		0.3 mm.		0.4 mm.		0.5 mm.	
White RC Paper	Anilox (lpi)	speed (m/min)	$\bar{x}$	SD	$\bar{x}$	std0.2	$\bar{x}$	std0.3	$\bar{x}$	std0.4	$\bar{x}$	std0.5
D	360	15	0.12	0.01	0.23	0.01	0.34	0.01	0.45	0.01	0.54	0.00
C	400	15	0.12	0.01	0.21	0.01	0.32	0.00	0.41	0.01	0.51	0.00
E	500	15	0.11	0.01	0.22	0.01	0.30	0.00	0.41	0.00	0.50	0.00
F	600	15	0.11	0.01	0.20	0.00	0.29	0.00	0.39	0.00	0.51	0.00
A	700	15	0.12	0.01	0.22	0.00	0.33	0.01	0.42	0.01	0.52	0.01

For printed negative lines, the results are given in table 4-6. It was found that the obtained data also was close to the target value ± 0.04 mm. The finest line was 0.1 mm width. Ink spreading fell in the range of 10%.

Table 4-6 Printed negative line width with different anilox line screen on RC coated paper

White RC Paper	Anilox (lpi)	speed (m/min)	Negative-line 0.1 mm. $\bar{x}$	SD	0.2 mm. $\bar{x}$	std0.2	0.3 mm. $\bar{x}$	std0.3	0.4 mm. $\bar{x}$	std0.4	0.5 mm. $\bar{x}$	std0.5
D	360	15	0.09	0.01	0.18	0.01	0.26	0.01	0.34	0.01	0.47	0.00
C	400	15	0.11	0.01	0.16	0.01	0.27	0.00	0.37	0.01	0.50	0.01
E	500	15	0.09	0.36	0.18	0.01	0.28	0.00	0.38	0.00	0.49	0.01
F	600	15	0.08	0.32	0.20	0.00	0.29	0.01	0.39	0.00	0.50	0.00
A	700	15	0.11	0.01	0.16	0.03	0.26	0.01	0.34	0.00	0.46	0.02

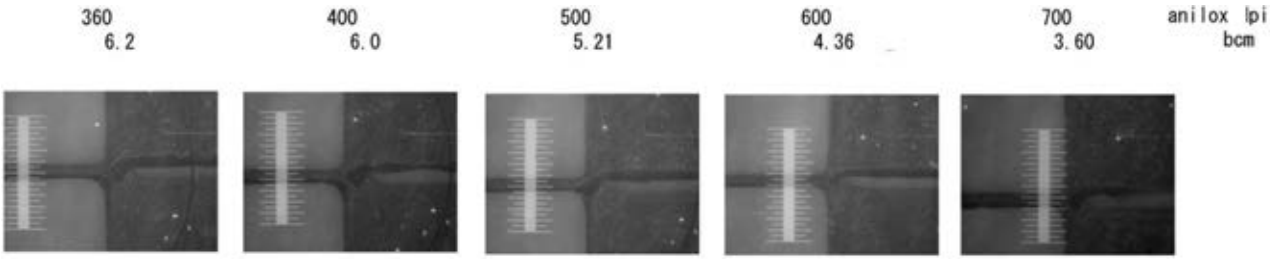


Figure 4-21 Image of pos. and neg. line width 0.1 mm of printed silver nano ink on RC paper at different anilox line screen 360, 400, 500, 600 and 700 lpi.

Results of the measurement of printed positive line width at anilox line screen 600 lpi with different printing speed (from 40 to 60 m/min) on transparent PET film are given in Table 4-7. It was found that the obtained data was close to the target values ± 0.01 mm. The finest line was 0.1 mm width. Ink spreading fell in the range of 10%. For printed negative lines, the results are given in Table 4-8. It was found that the obtained data also was close to the target value± 0.01 mm. The finest line was 0.1 mm width. Ink spreading fell in the range of 10%.

Table 4-7 Printed positive line width with different printing speed on Transparent PET film

			Positive-line									
			0.1 mm.		0.2 mm.		0.3 mm.		0.4 mm.		0.5 mm.	
Film	Anilox (lpi)	speed (m/min)	$\bar{x}$	SD	$\bar{x}$	std0.2	$\bar{x}$	std0.3	$\bar{x}$	std0.4	$\bar{x}$	std0.5
M	600	40	0.11	0.01	0.20	0.01	0.30	0.00	0.40	0.01	0.50	0.00
N	600	50	0.11	0.01	0.21	0.00	0.30	0.01	0.40	0.00	0.51	0.00
O	600	60	0.11	0.01	0.21	0.00	0.30	0.00	0.40	0.00	0.49	0.00

Table 4-8 Printed negative line width with different printing speed on Transparent PET film

			Negative-line									
			0.1 mm.		0.2 mm.		0.3 mm.		0.4 mm.		0.5 mm.	
Film	Anilox (lpi)	speed (m/min)	$\bar{x}$	SD	$\bar{x}$	std0.2	$\bar{x}$	std0.3	$\bar{x}$	std0.4	$\bar{x}$	std0.5
M	600	40	0.09	0.00	0.19	0.00	0.30	0.00	0.41	0.01	0.50	0.01
N	600	50	0.09	0.00	0.20	0.00	0.31	0.01	0.40	0.01	0.51	0.01
O	600	60	0.10	0.00	0.21	0.00	0.31	0.01	0.40	0.00	0.50	0.01

Results of the measurement of printed positive line width at anilox line screen 600 lpi with printing speed at 15 and 25 m/min) on opaque PET film are given in Table 4-9. It was found that the obtained data was close to the target values ± 0.01 mm. The finest line was 0.1 mm width. Ink spreading fell in the range of 10%. For printed negative lines, the results are given in table 4-10. It was found that the obtained data also was close to the target value ± 0.01 mm. The finest line was 0.1 mm width. Ink spreading fell in the range of 10%.

Table 4-9 Printed positive line width using anilox line screen 600 lpi and printing speed at 15 and 25 m/min on opaque white PET film

			Positive-line									
			0.1 mm.		0.2 mm.		0.3 mm.		0.4 mm.		0.5 mm.	
White PET Film	Anilox (lpi)	speed (m/min)	$\bar{x}$	SD	$\bar{x}$	std0.2	$\bar{x}$	std0.3	$\bar{x}$	std0.4	$\bar{x}$	std0.5
G	600	15	0.11	0.00	0.19	0.00	0.30	0.00	0.40	0.00	0.51	0.00
J	600	25	0.11	0.01	0.19	0.01	0.31	0.00	0.39	0.01	0.51	0.00

Table 4-10 Printed negative line width using anilox line screen 600 lpi and printing speed at 15 and 25 m/min on opaque white PET film

			Positive-line									
			0.1 mm.		0.2 mm.		0.3 mm.		0.4 mm.		0.5 mm.	
White PET Film	Anilox (lpi)	speed (m/min)	$\bar{x}$	SD	$\bar{x}$	std0.2	$\bar{x}$	std0.3	$\bar{x}$	std0.4	$\bar{x}$	std0.5
G	600	15	0.09	0.00	0.19	0.00	0.30	0.00	0.40	0.00	0.48	0.00
J	600	25	0.09	0.00	0.19	0.01	0.28	0.00	0.40	0.01	0.51	0.00

Figure 4-22 shows the images of printed positive and negative lines on 3 substrates from Table 4-5 to 4-10. This reconfirmed that different printing speed between 15 and 60 m/min did not affect the reproduction of the finest line width. 0.1 line width with 10% spreading could be achieved. While the preference of anilox line screen was probably 600 lpi.

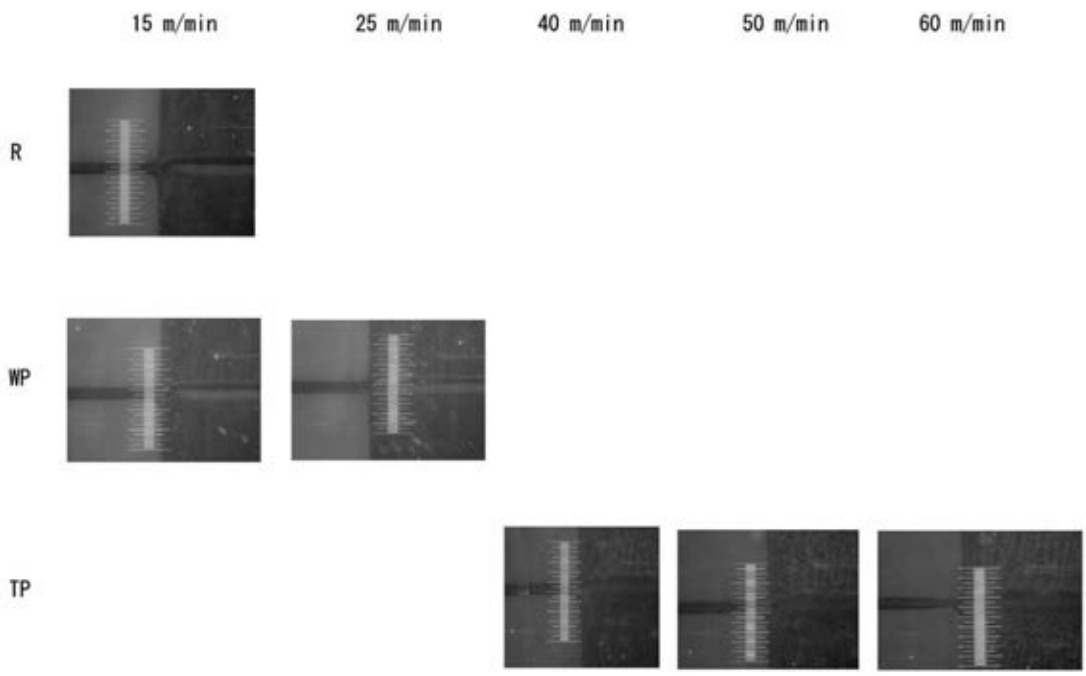


Figure 4-22 Printed line width 0.1 mm on 3 substrates at printing speed 15, 25, 40, 50 and 60 m/min.

4.4.2.2 Font size target

The printed fonts of nano silver ink as shown in Figure 4-23 on all substrates was examined under an optical microscope.

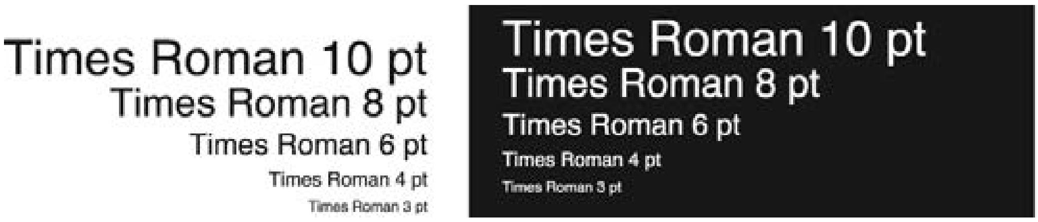


Figure 4-23 Font size target

Results of the measurement of printed positive and negative font size at different anilox line screen, with fixed printing speed at 15 m/min, on RC coated paper are given in Table 4-11. It was shown that the smallest positive font size as 6 points could be reproduced at higher anilox line screen. It was suggested at 600 and 700 lpi. While the smallest negative font size as 6 points could be reproduced only at anilox line screen 600 lpi. Interestingly the positive font size larger than 6 points could be reproduce at any printing conditions. For negative font size, such 8 or 10 points, anilox line screen 600 lpi was recommended.

Table 4-11 Printed positive and negative fonts at different anilox line screen on RC coated paper

White RC Paper	Anilox (lpi)	Speed (m/min)	Positive font(pt)			Negative font (pt)				
D-S2	360	15	-	8	10	-	-	-	-	-
C-S1	400	15	-	8	10	-	-	-	-	-
E-S1	500	15	-	8	10	-	-	-	-	10
F-S3	600	15	6	8	10	-	-	6	8	10
A-S3	700	15	6	8	10	-	-	-	-	-

Table 4-12 shows the results of printed positive and negative fonts on Transparent PET film, using fixed anilox line screen 600 lpi with varying printing speeds of 40, 50 and 60 m/min. It was found that any printing from 40 – 60 m/min could reproduce the font size from 6 points. Reproduction of less than 6 points was not perfect.. While smallest negative font size could be achieved at 3 points, but high printing speed was necessary. It was suggested that printing speed be from 50 m/min. This printing condition also could reproduce other font sizes as well.

Table 4-12 Printed positive and negative font at anilox line screen 600 lpi with printing speed 40-60 m/min on Transparent PET film

Film	Anilox (lpi)	Speed (m/min)	Positive font(pt)			Negative font (pt)				
M-S6	600	40	6	8	10	-	-	-	8	-
N-S3	600	50	6	8	10	3	4	6	8	10
O-S3	600	60	6	8	10	3	4	6	8	10

In case of using low printing speed, 15 – 25 m/min, the results of printed font size were given in Table 4-13. It was found that at anilox line screen 600 lpi, the smallest positive and negative font sizes that could be reproduced were 8 and 10 points respectively.

Table 4-13 Printed positive and negative font size using anilox line screen 600 lpi and printing speed 15-25 m/min on opaque white PET film

White PET Film	Anilox (lpi)	Speed (m/min)	Positive font(pt)			Negative font (pt)				
G-S6	600	15	-	8	10	-	-	-	-	10
J-S4	600	25	-	8	10	-	-	-	-	10

4.4.3 Print homogeneity

Figure 4-24 shows the images of printed positive and negative fonts of nano silver ink on Resin coated (RC) paper with different anilox line screen from 360 to 700 lpi, at printing speed 15 m/min. It was found that all cases gave the printed images with non-homogeneity, even at higher anilox line screen. This included poor shape and sharpness. It is due to the fluidity of ink phenomenon by which ink retention on the surface of substrates during printing has problem.

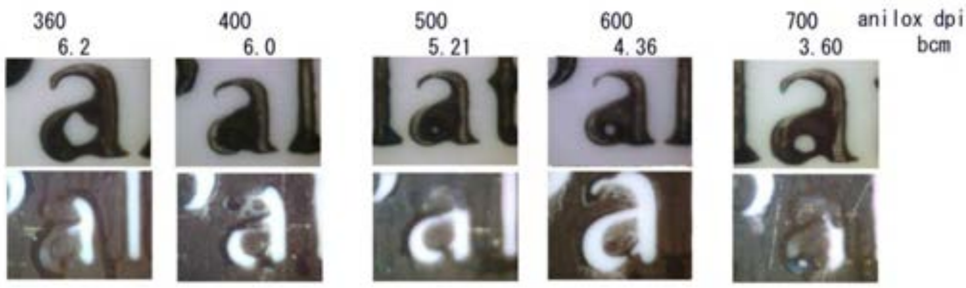


Figure 4-24 Images of printed positive and negative fonts on RC paper at anilox line screen 360, 400, 500, 600 and 700 lpi.

To examine image homogeneity at varying speed, the results of printed positive and negative fonts on RC coated paper and other substrates are shown in Figure 4-25. It was found that high printing speed at 50-60 m/min gave better image shape and sharpness for both positive and negative fonts, but print non-homogeneity was still existed.

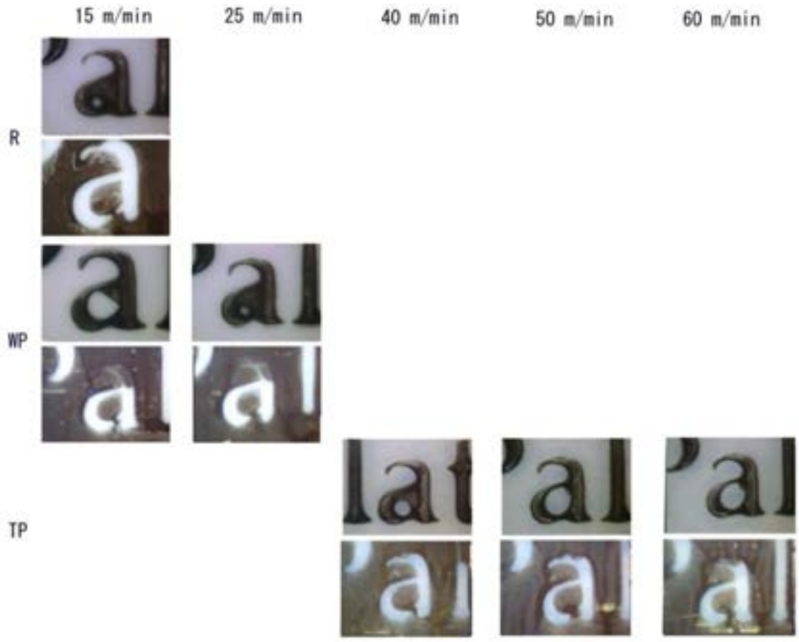


Figure 4-25 Printed positive and negative fonts of nano silver ink on 3 substrates using printing speed at 15, 25, 40, 50 and 60 m/min.

4.4.4 Print surface roughness

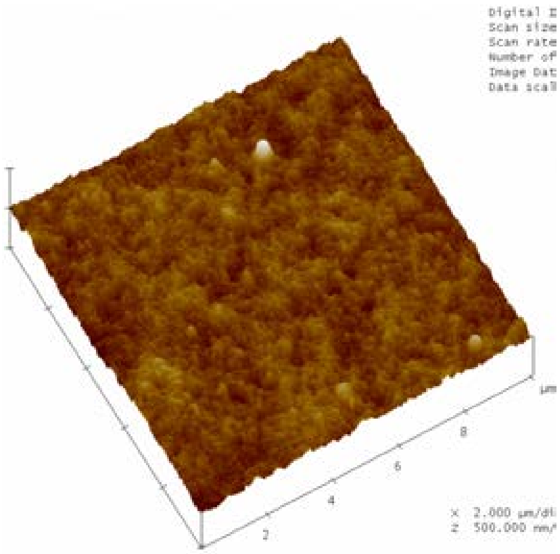
Results of rms surface roughness of printed nano silver ink layer on 3 substrates are given in Table 4-14. It was found that there was a little bit increase of roughness on printed ink. This may be the effect of the coagulation of nano silver particles forming a layer of ink film on the surface of substrate. Note that we measured with the small number of samples. This is why the obtained data of roughness on Resin coated (RC) paper was smaller than that of before printing, Figure 4-26, 4-27 and 4-28 show SPM Images of surface roughness of printed ink on 3 substrates.

Table 4-14 rms surface roughness* values of printed nano-silver samples

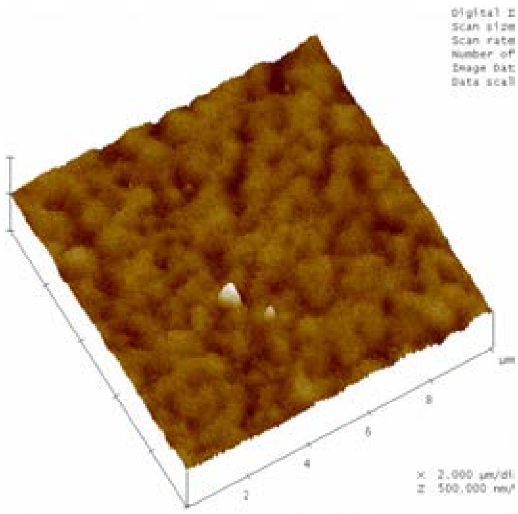
(anilox 600 lpi, printing speed 40 m/min)

Substrate	rms roughness (nm)	
	before printing	after printing
RC paper	21.45	20.99
Opaque white PET	22.05	23.41
Transparent PET film	19	23.68

*scan size 10 μm, scan rate 1.00 Hz, no. of sample 512, data scale 200 nm

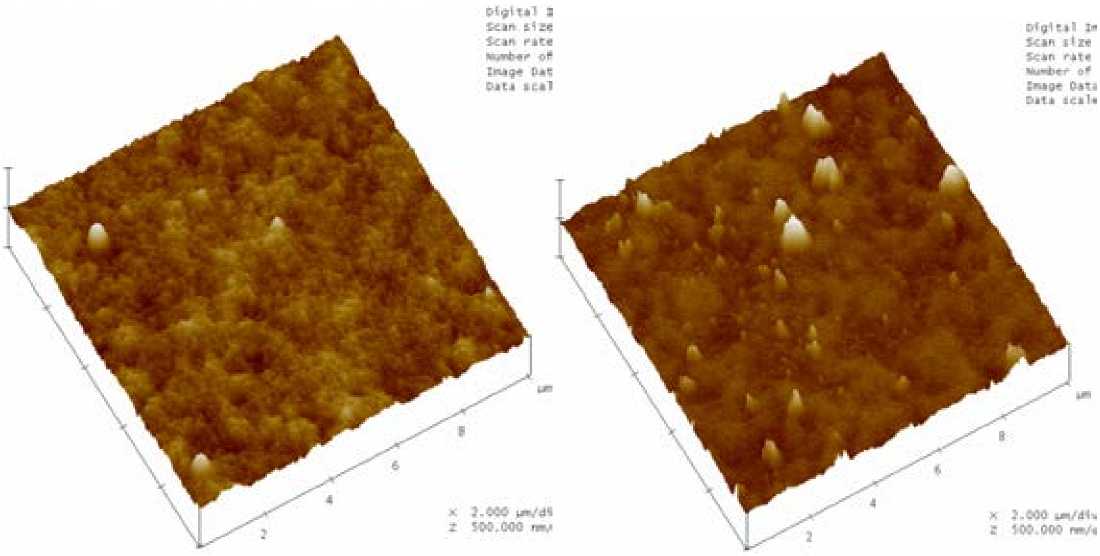


(a) 21.45 nm



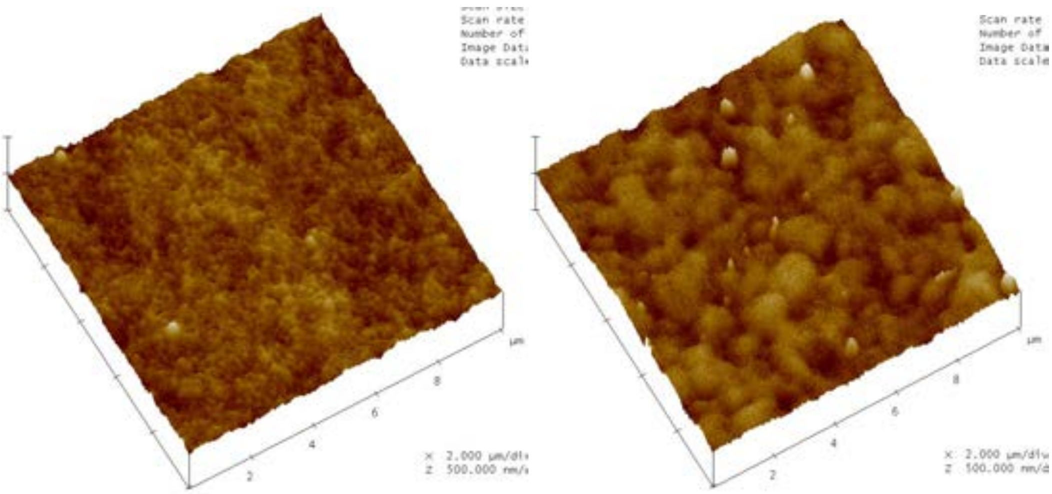
(b) 20.99 nm

Figure 4-26 Surface roughness of RC paper (a) before and (b) after printing with nano-silver ink (scan size 10 μm, scan rate 1.00 Hz, no. of sample 512, data scale 200 nm)



(a) 22.05 nm (b) 23.41 nm

Figure 4-27 Surface roughness of Opaque white PET film (a) before and (b) after printing with nano-silver ink (scan size 10 µm, scan rate 1.00 Hz, no. of sample 512, data scale 200 nm)



(a) 19.00 nm (b) 23.68 nm

Figure 4-28 Surface roughness of Transparent PET film (a) before and (b) after printing with nano-silver ink (scan size 10 µm, scan rate 1.00 Hz, no. of sample 512, data scale 200 nm)

CHAPTER V

CONCLUSIONS AND SUGGESTIONS

Conclusions

It was found that non linearly of ink gave little effects on relationship between image parameters and printing conditions. It was because the viscosity of nano-silver ink was much lower than that of common water based flexo ink. To adjust ink viscosity is not recommended. However, higher printing speed rather gave better print quality such as better resolution and low spreading, but non-uniformity of solid surface was still existed. The smallest text size which could be produced was 6 pt for positive font and 8 pt for negative font. Anilox line screen 600 lpi and printing speed 60 m/min was best condition in this study. Result showed that image of 0.1 mm finest line with about 10% width spreading and 5 μm thickness was achieved.

To consider printed Ink layer, it became bulky composing of small aggregates of Ag particles around 1 micrometer, which are larger than those of original nano-silver ink. Result showed slightly increase of surface roughness compared with those of the substrates. This inevitably affects the resistivity property of print. It was found that the average sheet resistivity was at 1.26 ± 0.06 Ω/cm^2. This sheet resistant value is a little larger than that of practical RFID devices.

Suggestions

Future research, we need to find out how the performance of conductive lines such as antenna will be improved with lower thickness. The antenna characteristics such as total area, structure and shape should be discussed.

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APPENDIX

APPENDIX A

Density of printed halftone scale of nano silver ink

Table A-1 Density of printed halftone scale of nano silver ink on RC paper (sample A)

White RC Paper	Density						
Tone	A-S1	A-S2	A-S3	A-S4	avg	mean	std
100	1.12	1.24	1.23	1.21	1.20	1.22	0.05
90	1.11	1.18	1.18	1.18	1.16	1.18	0.03
80	1.01	1.11	1.12	1.11	1.09	1.11	0.05
70	0.90	0.90	0.97	0.96	0.93	0.93	0.04
60	0.68	0.71	0.75	0.72	0.72	0.72	0.03
50	0.54	0.57	0.55	0.56	0.56	0.56	0.01
40	0.55	0.55	0.55	0.54	0.55	0.55	0.01
30	0.44	0.46	0.45	0.46	0.45	0.46	0.01
20	0.34	0.35	0.35	0.34	0.35	0.35	0.01
10	0.21	0.20	0.22	0.22	0.21	0.22	0.01
5	0.14	0.14	0.16	0.16	0.15	0.15	0.01
4	0.14	0.14	0.15	0.16	0.15	0.15	0.01
3	0.14	0.14	0.14	0.14	0.14	0.14	0.00
2	0.14	0.10	0.14	0.14	0.13	0.14	0.02
substrate	0.07	0.07	0.07	0.08	0.07	0.07	0.01

Table A-2 Density of printed halftone scale of nano silver ink on RC paper (sample C)

White RC Paper	Density						
Tone	C-S1	C-S2	C-S3	C-S4	avg	mean	std
100	1.10	1.19	1.19	1.17	1.16	1.18	0.04
90	1.10	1.17	1.15	1.16	1.15	1.16	0.03
80	1.04	1.09	1.12	1.11	1.09	1.10	0.04
70	0.84	0.94	0.96	0.98	0.93	0.95	0.06
60	0.72	0.79	0.79	0.68	0.75	0.76	0.05
50	0.50	0.52	0.52	0.53	0.52	0.52	0.01
40	0.50	0.51	0.52	0.51	0.51	0.51	0.01
30	0.43	0.46	0.46	0.45	0.45	0.46	0.01
20	0.34	0.34	0.35	0.34	0.34	0.34	0.00
10	0.21	0.23	0.22	0.20	0.22	0.22	0.01
5	0.14	0.15	0.14	0.14	0.14	0.14	0.00
4	0.14	0.15	0.14	0.14	0.14	0.14	0.00
3	0.14	0.13	0.13	0.13	0.13	0.13	0.01
2	0.14	0.12	0.13	0.13	0.13	0.13	0.01
substrate	0.07	0.07	0.08	0.08	0.08	0.08	0.01

Table A-3 Density of printed halftone scale of nano silver ink on RC paper (sample D)

White RC Paper	Density						
Tone	D-S2	D-S3	D-S4	D-S5	avg	mean	std
100	1.17	1.17	1.16	1.16	1.17	1.17	0.01
90	1.17	1.14	1.16	1.15	1.16	1.16	0.01
80	1.17	1.14	1.12	1.13	1.14	1.14	0.02
70	1.04	1.05	1.11	1.09	1.07	1.07	0.03
60	0.77	0.91	0.95	0.89	0.88	0.90	0.08
50	0.63	0.55	0.56	0.55	0.57	0.56	0.04
40	0.56	0.55	0.56	0.55	0.56	0.56	0.01
30	0.51	0.49	0.49	0.49	0.50	0.49	0.01
20	0.37	0.38	0.38	0.39	0.38	0.38	0.01
10	0.21	0.23	0.22	0.22	0.22	0.22	0.01
5	0.14	0.16	0.14	0.16	0.15	0.15	0.01
4	0.14	0.14	0.14	0.15	0.14	0.14	0.00
3	0.14	0.14	0.14	0.14	0.14	0.14	0.00
2	0.14	0.13	0.13	0.14	0.14	0.14	0.01
substrate	0.08	0.07	0.08	0.07	0.08	0.08	0.01

Table A-4 Density of printed halftone scale of nano silver ink on RC paper (sample E)

White RC Paper	Density						
Tone	E-S1	E-S2	E-S3	E-S4	avg	mean	std
100	1.10	1.14	1.03	1.16	1.11	1.12	0.06
90	1.10	1.15	0.97	1.12	1.09	1.11	0.08
80	0.94	1.02	1.01	0.99	0.99	1.00	0.04
70	0.85	0.78	0.96	0.86	0.86	0.86	0.07
60	0.62	0.69	0.76	0.66	0.68	0.68	0.06
50	0.53	0.55	0.55	0.52	0.54	0.54	0.02
40	0.52	0.53	0.52	0.54	0.53	0.53	0.01
30	0.43	0.42	0.51	0.44	0.45	0.44	0.04
20	0.33	0.33	0.38	0.33	0.34	0.33	0.03
10	0.22	0.20	0.20	0.20	0.21	0.20	0.01
5	0.14	0.15	0.13	0.13	0.14	0.14	0.01
4	0.13	0.13	0.13	0.13	0.13	0.13	0.00
3	0.12	0.12	0.12	0.13	0.12	0.12	0.01
2	0.12	0.12	0.12	0.13	0.12	0.12	0.01
substrate	0.08	0.08	0.09	0.08	0.08	0.08	0.01

Table A-5 Density of printed halftone scale of nano silver ink on RC paper (sample F)

White RC Paper	Density						
Tone	F-S1	F-S2	F-S3	F-S4	avg	mean	std
100	1.02	1.05	1.05	1.06	1.045	1.05	0.017321
90	0.98	0.98	1	1.02	0.995	0.99	0.019149
80	0.83	0.87	0.87	0.86	0.8575	0.865	0.01893
70	0.73	0.74	0.76	0.72	0.7375	0.735	0.017078
60	0.56	0.59	0.58	0.58	0.5775	0.58	0.012583
50	0.5	0.52	0.5	0.51	0.5075	0.505	0.009574
40	0.5	0.49	0.51	0.49	0.4975	0.495	0.009574
30	0.4	0.4	0.42	0.41	0.4075	0.405	0.009574
20	0.32	0.31	0.33	0.3	0.315	0.315	0.01291
10	0.19	0.21	0.21	0.19	0.2	0.2	0.011547
5	0.14	0.14	0.15	0.13	0.14	0.14	0.008165
4	0.14	0.14	0.14	0.13	0.1375	0.14	0.005
3	0.13	0.13	0.14	0.12	0.13	0.13	0.008165
2	0.13	0.11	0.13	0.12	0.1225	0.125	0.009574
substrate	0.09	0.07	0.09	0.09	0.085	0.09	0.01

Table A-6 Density of printed halftone scale of nano silver ink on Opaque white PET film (sample G)

White PET Film	Density						
Tone	G-S1	G-S2	G-S3	G-S4	avg	mean	Std
100	0.98	0.96	0.96	0.98	0.97	0.97	0.01
90	0.95	0.92	0.92	0.94	0.93	0.93	0.02
80	0.84	0.81	0.82	0.84	0.83	0.83	0.02
70	0.68	0.65	0.63	0.68	0.66	0.67	0.02
60	0.51	0.51	0.51	0.52	0.51	0.51	0.01
50	0.41	0.41	0.44	0.44	0.43	0.43	0.02
40	0.44	0.41	0.43	0.44	0.43	0.44	0.01
30	0.35	0.34	0.36	0.35	0.35	0.35	0.01
20	0.29	0.27	0.27	0.27	0.28	0.27	0.01
10	0.17	0.17	0.18	0.18	0.18	0.18	0.01
5	0.11	0.13	0.11	0.12	0.12	0.12	0.01
4	0.11	0.11	0.11	0.12	0.11	0.11	0.01
3	0.11	0.11	0.11	0.11	0.11	0.11	0.00
2	0.11	0.11	0.11	0.10	0.11	0.11	0.01
substrate	0.07	0.08	0.08	0.06	0.07	0.08	0.01

Table A-7 Density of printed halftone scale of nano silver ink on Opaque white PET film (sample J)

White PET Film	**Density**						
Tone	**J-S1**	**J-S2**	**J-S3**	**J-S4**	**avg**	**mean**	**std**
100	1.02	0.97	0.99	0.97	0.99	0.98	0.02
90	0.98	0.95	0.95	0.93	0.95	0.95	0.02
80	0.83	0.83	0.82	0.82	0.83	0.83	0.01
70	0.72	0.68	0.71	0.68	0.70	0.70	0.02
60	0.54	0.57	0.55	0.58	0.56	0.56	0.02
50	0.44	0.44	0.46	0.45	0.45	0.45	0.01
40	0.42	0.44	0.42	0.41	0.42	0.42	0.01
30	0.34	0.35	0.34	0.34	0.34	0.34	0.00
20	0.26	0.26	0.27	0.27	0.27	0.27	0.01
10	0.16	0.17	0.17	0.18	0.17	0.17	0.01
5	0.11	0.12	0.11	0.12	0.12	0.12	0.01
4	0.11	0.11	0.11	0.11	0.11	0.11	0.00
3	0.10	0.11	0.10	0.11	0.11	0.11	0.01
2	0.09	0.10	0.10	0.10	0.10	0.10	0.01
substrate	0.07	0.08	0.08	0.08	0.08	0.08	0.01

Table A-8 Density of printed halftone scale of nano silver ink on Transparent PET film (sample M)

Film	Density						
Tone	M-S2	M-S3	M-S4	M-S6	avg	mean	std
100	0.97	0.97	0.99	0.98	0.98	0.98	0.01
90	0.95	0.94	0.97	0.97	0.96	0.96	0.02
80	0.89	0.89	0.88	0.91	0.89	0.89	0.01
70	0.77	0.77	0.76	0.80	0.78	0.77	0.02
60	0.63	0.64	0.65	0.66	0.65	0.65	0.01
50	0.51	0.54	0.55	0.54	0.54	0.54	0.02
40	0.52	0.53	0.54	0.55	0.54	0.54	0.01
30	0.44	0.43	0.44	0.44	0.44	0.44	0.01
20	0.36	0.35	0.36	0.36	0.36	0.36	0.01
10	0.24	0.24	0.25	0.25	0.25	0.25	0.01
5	0.19	0.19	0.19	0.20	0.19	0.19	0.01
4	0.18	0.19	0.18	0.19	0.19	0.19	0.01
3	0.18	0.18	0.17	0.18	0.18	0.18	0.00
2	0.18	0.18	0.17	0.18	0.18	0.18	0.00
substrate	0.13	0.13	0.14	0.14	0.14	0.14	0.01

Table A-9 Density of printed halftone scale of nano silver ink on Transparent PET film (sample N)

Film	Density						
Tone	**N-S2**	**N-S3**	**N-S4**	**N-S5**	**avg**	**mean**	**std**
100	1.03	0.99	1.00	0.99	1.00	1.00	0.02
90	1.03	0.99	0.99	0.98	1.00	0.99	0.02
80	0.94	0.92	0.93	0.91	0.93	0.93	0.01
70	0.79	0.80	0.80	0.79	0.80	0.80	0.01
60	0.68	0.67	0.69	0.67	0.68	0.68	0.01
50	0.53	0.54	0.55	0.54	0.54	0.54	0.01
40	0.53	0.52	0.53	0.51	0.52	0.53	0.01
30	0.45	0.44	0.45	0.42	0.44	0.45	0.01
20	0.36	0.36	0.36	0.35	0.36	0.36	0.01
10	0.23	0.25	0.26	0.24	0.25	0.25	0.01
5	0.17	0.19	0.20	0.19	0.19	0.19	0.01
4	0.17	0.19	0.19	0.19	0.19	0.19	0.01
3	0.17	0.17	0.19	0.19	0.18	0.18	0.01
2	0.17	0.17	0.19	0.19	0.18	0.18	0.01
substrate	0.15	0.14	0.15	0.15	0.15	0.15	0.00

Table A-10 Density of printed halftone scale of nano silver ink on Transparent PET film (sample O)

Film	Density						
Tone	O-S1	O-S2	O-S3	O-S4	avg	mean	std
100	1.00	0.98	0.98	0.98	0.99	0.98	0.01
90	0.99	0.97	0.98	0.97	0.98	0.98	0.01
80	0.93	0.88	0.90	0.90	0.90	0.90	0.02
70	0.79	0.77	0.77	0.78	0.78	0.78	0.01
60	0.66	0.66	0.67	0.68	0.67	0.67	0.01
50	0.55	0.53	0.54	0.51	0.53	0.54	0.02
40	0.52	0.49	0.52	0.51	0.51	0.52	0.01
30	0.43	0.41	0.41	0.42	0.42	0.42	0.01
20	0.35	0.33	0.32	0.34	0.34	0.34	0.01
10	0.25	0.22	0.22	0.24	0.23	0.23	0.02
5	0.19	0.17	0.17	0.19	0.18	0.18	0.01
4	0.18	0.17	0.16	0.18	0.17	0.18	0.01
3	0.18	0.16	0.15	0.18	0.17	0.17	0.02
2	0.18	0.16	0.15	0.18	0.17	0.17	0.02
substrate	0.13	0.13	0.14	0.13	0.13	0.13	0.01

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