Printing and curing of conductive inks on fabric using syringe-based deposition system and oven for wearable antenna application

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Abstract. Wearable antenna is part of clothing for transmitting or receiving wireless signals and due to miniaturization, the antenna required to be compact, light, cheap and almost maintenance-free. Syringe-based deposition system with conductive ink is potential to print the antenna structure on fabric as it provides flexibility and compatible with different viscosity of materials. The study is to investigate the printing and curing of conductive inks on fabric using syringe-based deposition system and oven. The effect of printing and curing parameters to morphology and conductivity of the antenna tracks were investigated. Several mechanical and electrical tests were performed to determine the hardness, adhesion and resistance level. It was observed that the antenna tracks were successfully printed according to its designated shape and printing with higher speed caused narrower antenna ink track while pressure differences influenced the thickness of the antenna tracks. The optimum printing parameters obtained was printing at 23 mm/s speed with a pressure of 1 bar to achieve the required antenna track size. The resistance level achieved was considered low at 1.6Ω curing at 160°C for 45 minutes. It was proven that the syringe-based deposition system and oven is capable of printing and curing antenna tracks on fabric.

1. Introduction
Traditionally, printing industry has been used for production of newspaper and books. Recently, various new printing methods and materials have been established for further applications and technologies. As the printing technologies evolved, the ability of the printing process to make complex patterns has been increased and reaches micrometer and sub-micrometer scales of printing precision. One of the recent advancements is printing of wearable antenna on fabrics substrate using suitable conductive ink. Wearable computing is a fast growing field in application-oriented research. The vision of wearable computing describes future electronic systems as an integral part of our everyday clothing serving as intelligent personal assistants which include tracking, navigation, mobile computing and public safety [1]. This device often made from conductive coating or ink tracks. The conductive ink needs to be printed and cured using proper methods and materials to meet the requirement that fits the application. One of the methods that shows a great potential is syringe-based deposition system in which it deposits inks onto substrate using filamentary concept [2][3] and this conductive ink required to be cured using mainly heating process via oven or laser irradiation process. The heat generated is used to reveal the metallic contents which unwanted solvent in the conductive ink is removed by evaporation process [4]. The objective of the study is to investigate the printing of silver conductive ink track that makes up the
antenna structure on fabric substrate using the syringe-based deposition system. Curing of the conductive ink as well is assessed using a conventional oven. The system associated with conductive ink is potential to print the antenna structure on fabric as it provides flexibility [2] which desirable especially for non-planar substrates and works well with different viscosity of materials. In addition, the study also intends to determine the optimum printing parameters to achieve the desired morphology of the antenna designed with flexible characteristics.

2. Methodology

2.1 Pattern design
Structure of the antenna plays a vital role in order to achieve required performance set by the standard of Specific Absorption Rate (SAR) limits [5]. A type of micro-strip patch antenna was first identified and selected. Upon simulating the performance of the antenna, the dimension of antenna was calculated and modeled using computer-aided design (CAD) software. Figure 1 shows the design of the antenna with its detail dimension respectively. The antenna was designed to be operated at resonance frequency of 1.575 GHz as required by the Multimedia Communication and Malaysian Commission (MCMC) for rescue signal since the intention was to embed antenna on life jacket for rapid response device during emergency. There were four essential parameters to be specified including operating frequency (fₒ), dielectric constant of substrate (Ɛᵣ), height of the dielectric substrate (h) and thickness of the conductor patch (t). Table 1 shows the specification for each of the parameters considered. The total length of the antenna designed is 158 mm long with a 0.80 mm width of track.

![Image](https://via.placeholder.com/150)

**Table 1.** Specification of antenna designed

| Specification               | Width (mm) | Length (mm) | Thickness (mm) |
|-----------------------------|------------|-------------|----------------|
| Dimension of ink track      | 0.80       | 158.00      | 0.22           |
| Substrate (polyester fabric)| 30.00      | 30.00       | 0.15           |
| Ground plane layer          | 30.00      | 30.00       | 0.11           |

**Figure 1.** Micro-strip patch antenna design with detail dimension (units in mm)

2.2 Printing and curing
The dispenser used to dispense the conductive ink is an automatic syringe-based deposition machine (Model: FISNAR F4200N.1) as shown in Figure 2. The system is a compact and economically priced bench top robot consist of continuous path motion for accurate three-dimensional movement (x, y, z). The system has 200 x 200 mm of work area with a step and repeat function which can program one object for multiple identical objects. It is also equipped with portable air compressor to deposit the conductive ink via syringe and nozzle onto substrate with different parameters. There were several printing parameters identified which are the nozzle diameter, height deposition, printing speed, pressure, ink’s viscosity and the substrate itself. In this study, printing speed was varied from 21 to 25 mm/s with increment of 1 mm/s and the pressure was varied from 0.75 to 1.75 bar with the increment of 0.25 bar while the other parameters were set to constant at certain value as illustrated in Table 2. Some of the parameters were set to constant because of limited nozzle tips and variation of height deposition did not affect too much on the characteristic of the ink track [6]. The range of parameters selected were determined after conducting several series of pilot test previously.
Figure 2. Automatic syringe-based deposition system (Model: FISNAR F4200N.1)

In the meantime, the curing process was employed using an oven (Memmert model 100-800) at an optimum curing time and temperature set to reduce the percentage of unwanted material in conductive ink since conductive ink; either oil-based, water or solvents-based is mundanely comes in liquid. Oven is used as a curing process since it provides a consistent and stable temperature and the samples could be cured at a higher temperature if needed. In addition, oven is easy to set up by simply adjust the timer and the temperature gauge. Several pilot tests were previously performed to determine the optimum curing parameters that result in the lowest resistance. Table 2 shows the optimum curing parameter used and Figure 3 shows the successfully printed micro-strip patch antenna and cured using oven on fabric.

Table 2. Printing and curing parameters selected

| Parameters            | Specification (unit) |
|-----------------------|----------------------|
| Nozzle Diameter       | 0.51 mm              |
| Height Deposition     | 1.00 mm              |
| Ink’s viscosity       | 2400 mPa.s           |
| Substrate             | Polyester            |
| Printing speed        | 21.00 – 25.00 mm/s   |
| Printing pressure     | 0.75 – 1.75 bar      |
| Curing time           | 45 minutes           |
| Curing temperature    | 160°C                |

Figure 3. Printed micro-strip patch antenna

Figure 4. Silver-epoxy based conductive ink (Model: AG806)

2.3 Material and substrate

Most studies have focused on conductive metal nano-particles like silver (Ag), copper (Cu) and nano composites. Among them, Ag nano-particles has been considered as the most appropriate conductive ink for printed electronic circuit for its low resistivity, stable property, anti-oxidation, low acid and alkali resistivity [7]. The metal particles that act as conductive ink such as gold, copper and silver played an important role as different printing techniques require suitable conductive ink to print. The differences of them are their viscosity, conductivity and curing process [8]. The conductive ink used throughout the whole study is silver epoxy-based ink (Model : AG806) as shown in Figure 4 and direct usage of the ink is not possible due to high solid fraction thus an adjustment of viscosity via dilution with Toluene solvent is necessary. Viscosity of the ink is one of the important properties to be determined in order to ensure the ink could be deposited in a required manner. High viscosity may leads to clogging problem hence
the mixture ratio of silver ink and toluene is crucial to obtain suitable viscosity for printing process. The viscosity required was 2,400 mPa.s and to certify the desired silver ink viscosity is obtained, each mixture is measured every time the toluene is added. 0.50 ml of Toluene was consistently added for each mixture until the preferred viscosity is achieved. The ink’s viscosity was measured using vibro-viscometer.

2.4 Measurement
The printed conductive ink track underwent an electrical test using inductance, capacitance and resistance (LCR) meter to determine its resistance level. The resistivity is next calculated using the equation (1) shown;

\[ \rho = \frac{RA}{l} \]  

where \( \rho \) is the volume resistivity in \( \Omega \cdot \text{m} \), \( R \) is resistance, \( A \) is area of the ink track in \( \text{mm}^2 \) and \( l \) is length in meter while conductivity is calculated using equation (2) shown below;

\[ \sigma = \frac{1}{\rho} \]  

where \( \sigma \) is conductivity in \( \Omega^{-1} \text{m}^{-1} \).

Several mechanical tests were also conducted including hardness and adhesion measurement to determine the hardness and adhesion level of the track. The hardness test was performed using a micro-hardness tester and the hardness level was determined by measuring the size of an impression left by an indenter. To establish the suitable load applied, samples with lowest and highest resistance were used according to ASTM E-384. A variation of load ranged from 98.07 \( \mu \text{N} \) to 19.61 N was applied and a minimum of diagonal width was observed on both samples when the load used is 490.3 \( \mu \text{N} \). Thus, a minimum load of 490.3 \( \mu \text{N} \) (HV0.05) was selected. In addition, the adhesion test was conducted to measure the adhesion level of the ink track on substrate. The ink track was cut into several small squares according to ASTM D3359 and 3M tape was used to peel off the small squares. The adhesion level were classified based on 1B to 5B range depended on the strength of adhesion between the ink track and the substrate.

3. Result and discussion

3.1 Morphology analysis
Morphological analysis was performed to identify the relationship between variations of printing parameter with the physical properties of printed ink track. Each width and thickness as illustrated in Figure 5 (a) and (b) of the antenna tracks was measured and all results were averaged for accuracy purposes as shown in Table 3. The cross-sectional area and total length of the ink track were also tabulated to calculate resistivity. It is important to ensure the barrel is packed with ink without air pocket left thus a continuous and straight ink track is produced.

Figure 6 (a) shows the change of width of the ink track with respect to variations of printing speed. The widest ink track observed was almost twice the value of the desired width which is 1.58 mm. It was due to the high amount of ink is dispensed onto the substrate at a pressure of 1.75 bar with lower printing speed of 21 mm/s. The higher the pressure used, the wider the ink track printed. At printing speed of 23 mm/s with a pressure of 1 and 0.75 bar, the desired width of 0.80 mm was achieved. Meanwhile, Figure 6 (b) shows the change of thickness of the ink track with respect to variations of speed. It was found that the change of speed only slightly influence the thickness of the ink track at different pressure used.
Figure 5. (a) Thickness and (b) width of the ink track

Table 3. Results of physical and electrical properties of the printed ink track

| No. of samples | Speed (mm/s) | Pressure (bar) | Width (mm) | Thickness (mm) | Resistance (Ω) | Area (mm²) | Resistivity (Ωm) | Conductivity (Ω⁻¹m⁻¹) |
|----------------|--------------|----------------|------------|----------------|----------------|------------|-----------------|------------------------|
| 1              | 21           | 0.75           | 0.710      | 0.246          | 6.60           | 0.137      | 5.73            | 174.50                 |
| 2              | 21           | 1.00           | 1.041      | 0.402          | 3.90           | 0.315      | 7.79            | 128.37                 |
| 3              | 21           | 1.25           | 1.133      | 0.536          | 3.10           | 0.477      | 9.37            | 106.72                 |
| 4              | 21           | 1.50           | 1.379      | 0.598          | 2.40           | 0.648      | 9.84            | 101.63                 |
| 5              | 21           | 1.75           | 1.409      | 0.608          | 1.90           | 0.673      | 8.09            | 123.61                 |
| 6              | 22           | 0.75           | 0.897      | 0.347          | 3.50           | 0.244      | 5.42            | 184.50                 |
| 7              | 22           | 1.00           | 1.106      | 0.513          | 2.90           | 0.446      | 8.19            | 122.10                 |
| 8              | 22           | 1.25           | 1.189      | 0.547          | 2.50           | 0.511      | 8.08            | 123.76                 |
| 9              | 22           | 1.50           | 1.358      | 0.582          | 2.20           | 0.621      | 8.64            | 115.74                 |
| 10             | 22           | 1.75           | 1.479      | 0.607          | 2.00           | 0.705      | 8.90            | 112.36                 |
| 11             | 23           | 0.75           | 0.790      | 0.259          | 8.30           | 0.161      | 8.46            | 118.20                 |
| 12             | 23           | 1.00           | 0.800      | 0.406          | 3.80           | 0.255      | 6.14            | 162.87                 |
| 13             | 23           | 1.25           | 1.074      | 0.508          | 3.10           | 0.429      | 8.42            | 118.76                 |
| 14             | 23           | 1.50           | 1.198      | 0.516          | 2.80           | 0.485      | 8.60            | 116.28                 |
| 15             | 23           | 1.75           | 1.379      | 0.578          | 2.20           | 0.626      | 8.72            | 114.68                 |
| 16             | 24           | 0.75           | 0.615      | 0.289          | 7.20           | 0.139      | 6.37            | 156.99                 |
| 17             | 24           | 1.00           | 1.138      | 0.412          | 2.60           | 0.368      | 6.07            | 164.74                 |
| 18             | 24           | 1.25           | 1.283      | 0.544          | 2.20           | 0.548      | 7.64            | 130.89                 |
| 19             | 24           | 1.50           | 1.518      | 0.552          | 2.00           | 0.658      | 8.33            | 120.05                 |
| 20             | 24           | 1.75           | 1.587      | 0.669          | 1.90           | 0.834      | 10.03           | 99.70                  |
| 21             | 25           | 0.75           | 0.639      | 0.249          | 6.30           | 0.125      | 4.99            | 200.32                 |
| 22             | 25           | 1.00           | 1.068      | 0.409          | 2.90           | 0.343      | 6.31            | 158.52                 |
| 23             | 25           | 1.25           | 1.230      | 0.538          | 2.40           | 0.519      | 7.89            | 126.68                 |
| 24             | 25           | 1.50           | 1.417      | 0.576          | 2.20           | 0.641      | 8.92            | 112.04                 |
| 25             | 25           | 1.75           | 1.582      | 0.671          | 1.60           | 0.833      | 8.44            | 118.44                 |
Figure 6. Change of (a) width and (b) thickness of the ink track with respect to variation of speed at different pressures

Figure 7 (a) shows the effect of pressure towards the width of ink track. It was observed that as pressure increase, the width of the ink track increased. It is because of more inks are deposited on the substrate result in wider ink track. In the meantime, Figure 7 (b) shows the effect of pressure to the thickness of the ink track. The trend line shows an increasing value of thickness when the pressure increased. The lowest thickness observed is 0.24 mm at pressure of 0.75 bar with printing speed of 21 mm/s. In some occasion, the nozzle tip swept some of the ink during printing thus causing the ink track thickness to be very low.

Figure 7. Change of (a) width and (b) thickness of the track with respect to variations of pressure at different printing speeds

The printing speed plays a vital role in depositing the conductive ink on polyester fabric. The higher the printing speed, less conductive ink is deposited onto the substrate. Printing speed also is very important to ensure the continuity of the deposited ink track. The width and thickness underwent a significant change when the variations of printing speed were applied. Theoretically, increase in printing pressure causes the width and thickness to increase. Pressure also is necessary since small droplets can only be generated using small diameter of nozzle tip. The force to dispense the conductive ink out from a small nozzle has to be high enough to overcome the friction from the internal surface of the nozzle tip so that a perfect ink track could be printed. Moreover, low printing pressure caused inconsistency of the ink deposited which may leads to clogging of the nozzle tips.
Conductive ink’s viscosity is also one of the important parameter that has to be determined in careful manner. Viscosity of the ink ensures the possibility for the ink to be dispensed on the substrate consistently. The dynamic viscosity of the ink has to be measured first and dilution process is necessary to obtain the desired kinematic viscosity for deposition purposes. An appropriate level of viscosity is very crucial to ensure the deposition of the ink is done properly. This will reflect to the conductivity level thus judgement on the suitability of the viscosity to the conductivity level desired has to be well considered accordingly.

3.2 Electrical properties
Table 3 shows the tabulated results for the resistance level measured with LCR meter. Overall the lowest resistance achieved was at 1.6Ω curing at 160°C for 45 minutes. Based on this it proved that oven capable of removing unwanted material in conductive ink by curing process properly. In addition, Figure 8 shows the relationship of different cross-sectional area of the ink track to resistance. It was observed that bigger cross-sectional area result in lower resistance. The results also validated the theoretical formula shown earlier in equation (1) which bigger cross-sectional area of the ink track result in lower resistance value. Wider ink track has greater cross-sectional area and the greater cross-sectional areas, the less resistance the electric charge to flow. The total length of the ink track also affected the amount of resistance where the longer the ink track caused the resistance to be higher because of the electron travels in a longer path and more collisions occurred. The resistance is also affected by the conductive material used. Not all materials are created equal in terms of their conductive ability and some materials are better conductors than others and offer less resistance to the flow of charge. The conducting ability of a material is often indicated by its resistivity.

![Figure 8. Relationship of different cross-sectional areas to resistance](image)

3.3 Mechanical properties
Based on the graph shown in Figure 9, the trend shows an inversely proportional trend between the hardness level and resistance. It is as expected since the curing level increased when more of the unwanted solvent in the conductive ink track evaporated during curing process. The process leaves the metallic particles stronger bond between one another hence increase the hardness level. It is validated by the highest value of hardness level obtained which is 29.21 HV at the lowest resistance of 1.6 Ω respectively. In addition, the sample cross-sectional area was 0.833 mm² and considered to be among the biggest cross-sectional area of the ink track printed.

According to Figure 10, it was concluded that the higher the value of resistance, the lower adhesion level of the ink track on the substrate. This is due to there were still left unwanted solvent that is not evaporated result in lack of bond between the metallic particles and the substrate. All samples were cured in the oven for 45 minutes at 160 °C to remove the unwanted solvent via evaporation process but since variation of printing parameters used caused a different amount of volume of the ink dispensed. The resistances level obtained are varies thus several adhesion level were achieved. Hence, the area of
the conductive ink track influence the value of the resistance but subjected to the selected curing parameters used and it is also validated by the equation (1) where the value of resistance are inversely proportional to the cross sectional area of the ink track.

Figure 9. Change in hardness with respect to different resistance level

Figure 10. Adhesion level with respect to different resistance level

4. Conclusion
Printing and curing parameters play a vital role to ensure the silver ink tracks are properly printed on fabric substrate. The parameters used consisted of printing speed, pressure, curing time and temperature have influenced the morphology, mechanical and electrical characteristics of the ink track printed. The objective of the study was successfully achieved which syringe-based deposition system associated with oven curing process had been proven capable of printing and curing conductive ink track on fabric substrate. The optimum printing parameters for silver conductive ink on fabric substrate had also been determined accordingly. The system’s printing parameters was easily controlled since the printing speed and pressure had shown critical influence on the morphology of the silver ink track. This could be used to provide a greater cross-sectional area of the ink track thus higher conductivity required could be achieved subjected to the suitable optimum curing parameters used. The variation of printing parameters also able to reduce the error of the dimensional accuracy of the printed ink track and gave different effect to the width and thickness. The targeted dimension of the antenna pattern was achieved by controlling the printing speed and pressure and the optimum printing parameters obtained was at printing speed of 23 mm/s with a pressure of 1 bar. The used of oven also proved cured the conductive ink properly as the lowest resistance achieved was at 1.6Ω cured at 160°C for 45 minutes.

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