Printing and Curing of Conductive Ink Track on Curvature Substrate using Fluid Dispensing System and Oven

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***Abstract*—The present work concerns on the use of sensors to monitor the structural health of wind turbine. Conventionally the inspection was made using non-contact sensing during the turbine's inoperable period hence loss occurred. A real-time monitoring system via embedded wireless sensor is preferred but the sensor could only be implanted using non-contact printing method due to most turbine blades' curved surface. Conductive ink associated with non-contact printing method via fluid dispensing system are proposed since conductive inks are proven stretchable and fluid dispensing system enables printing on various substrates and works well with any materials. Thus, the investigation of printing and curing of conductive ink track is essential to determine the capability of fluid dispensing system to print conductive ink track and oven to cure the ink on curvature substrate. The effect of printing and curing parameters to the characteristics and conductivity of the ink track is investigated. Several mechanical and electrical tests were also administered to determine the cure, hardness, adhesion and resistance level of the ink tracks. The results obtained were as expected which higher printing speed and lower pressure used, a narrower and thinner ink tracks were produced. Sample with 5 mm/s and 70 kPa of printing speed and pressure resulted in dimension closer to the targeted dimension. The longer curing time and higher temperature used, a lower resistance is produced. The lowest resistance achieved is 0.9 Ω which is cured at 160°C at 45 minutes. It is proven that a fluid dispensing system is capable of printing the ink track and oven is suitable to cure the ink track properly on curvature substrate.**

***Index Terms*—Curing, curvature, dispensing, ink, printing**

I. Introduction

The present work concerns on the use of sensors in large wind turbine blades for monitoring its structural health's performance. This is to develop an approach for awareness of damage and determine the severe of damage on the residual life of wind turbine blades using sensor detection. Most of the time, the inspection was made based on schedule method using non-contact type of sensing method [1]. Instead, embedded wireless sensor is preferred since a real-time monitoring system could avoid undetectable damage during turbine's operation which may cause severe damages to consumers. In addition, it could prevent loss as most of the inspections were made during shut down period. However, most of the turbine blades' shape are curved and the conductive ink track that make up the sensor structure could only be printed using a non-contact printing method via fluid dispensing system since this technique enables printing in various substrates and works well with any materials including conductive inks. There were numerous reports regarding the usage of conductive ink in fabricating printed strain gauge on planar substrates such as glass [2], printed circuit board [3], polyethylene terephthalate (PET) [4] and paper [5] via inkjet, flexography, aerosol and gravure printing respectively. There are also reports on other type of sensors fabricated using printing technologies besides strain gauge such as humidity sensors via rotogravure printing [6], RFID tags via inkjet printing [7], electrochemical sensors via rotogravure printing [8], gas sensors via screen printing [9] and organic thin film transistors via inkjet printing [10][11]. But, most of these printing techniques only capable of printing on planar substrates and some of these techniques suffer from clogging as well as limited type of materials to be printed with [12]. In contrast, fluid dispensing system via syringe deposition which equipped with three dimensional coordinate axes is independent of standoff height and not relying to the surface tension between substrates allowing it to be used on various substrates [13]. The system has been widely used in electronic industries especially in solder paste machine and surface mount technology [14]. Currently, there are limited reports on the capability of fluid dispensing system in fabricating functional electronics structure and the potential of the system has not been thoroughly explored especially on printing of electronics structure on non-planar substrates and there are still some concerns especially on the mechanism of the printing process, the characteristic of the ink track printed and the functionality of the pattern printed. Thus, the investigation of printing and curing of conductive ink track is important to determine the capability of fluid dispensing system to print conductive ink track and oven to cure the ink on curvature substrate. The effect of variation of printing and curing parameters to the physical characteristics and conductivity of the ink tracks printed were also investigated.

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II. Methodology

A. Deposition of Ink

A non-contact fluid dispensing system (model FISNAR 3-axis, F4200N.1) bench top dispensing machine is used to print the ink tracks as shown in Fig. 1. Integrated software is employed to constitute the printing pattern and the commands could be set using either computer or teach pendant. Preferable printing parameters including printing speed and pressure were set according to the arrangement of the overall printing operation while the deposition height and the nozzle diameter were set to be constant. The printing speed was varied between 4 to 8 mm/s while the pressure was varied from 60 to 100 kPa as tabulated in Table 1.

Fig. 1. FISNAR benchtop dispensing system.

TABLE I
PRINTING AND CURING PARAMETERS

Printing speed (mm/s)	Applied pressure (kPa)	Curing time (minutes)	Curing temperature (°C)
4	60	15	140
5	70	30	150
6	80	45	160
7	90	60	170
8	100	75	180

B. Pattern Design

The design pattern of the electronics structure printed is a strain gauge sensor and its detail dimensions are shown in Fig. 2. The total length is 221.42 mm long with a 2 mm width of track. Fig. 3 shows the strain gauge pattern is successfully printed on curvature substrate

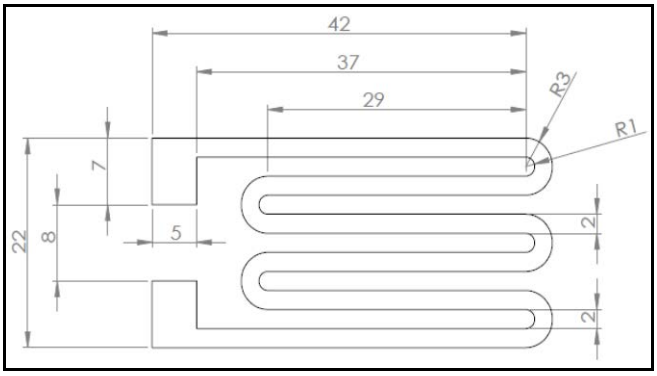


Fig. 2. Dimension of the strain gauge sensor.

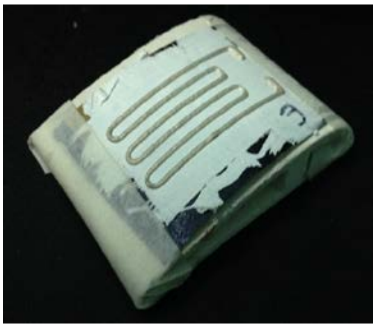


Fig. 3. A strain gauge pattern printed on curvature substrate

C. Conductive Ink

The conductive inks must contain an appropriate highly conductive metal such as copper, gold and silver. Silver ink remains the first choice of end-users although it is more expensive conductive material compared to copper due to its highest characteristic in electrical conductivity, the lowest contact resistance of any metal and its adhesion is better than copper and nickel. Furthermore, silver can also be easily formulated into inks [15] and making it the ideal ink material for this study. Fig. 4 shows the AG806 silver epoxy used but a direct usage of the ink is not possible due to high solid fraction thus a small adjustment of viscosity via dilution with Toluene solvent is necessary without affecting the conductive element in the material.

Fig. 4. AG806 silver epoxy ink

D. Curvature Substrate

Recycled aluminium tin cans are cut into aluminum sheets that are pasted on the surface of aerofoil shape mandrels to mimic the curvature metal substrate as illustrated in Fig. 3. The aerofoil shape mandrel is fabricated using powder-based rapid prototype machine and an additional thin insulator layer via rubber dye ink is needed to avoid short circuit during electrical testing since the substrate is made of aluminum material.

E. Curing Process

The ink drawn on the substrates are usually cured with oven, microwaves and lasers [16]. These processes manipulate heat by radiation in order to evaporate binders and unwanted solvent in conductive inks leaving only metallic content on the substrate that has been hardened and sticks to the intended substrate. The curing parameters investigated are curing temperature and time. The curing temperature was first set to five different temperatures ranging from 140°C to 180°C with an interval of 10°C each.

Curing time as well is set to five different curing times ranging from 15 to 75 minutes with an interval of 15 minutes each as depicted in Table 1 earlier. The oven is heated first and to ensure direct heat is applied to the specimens, the distance of the platform with the filament of the oven is set to the closest possible distance. Generally, to achieve higher conductivity, heating to a higher temperature is the option to burn-out all organic contaminants (solvents).

F. Measurement

Printing resolution remains the key method to evaluate the printing quality by measuring the ink track dimensional accuracy. The physical characteristic of the ink track measured including the line width and line thickness. An optical microscope is utilized to measure the dimensions and it is calculated based on the following equation (1).

$$Dimensional\ accuracy\ \% = \frac{sample\ result}{expected\ result}\ x\ 100\% \quad (1)$$

A manual scratch test is applied after each specimen was freshly cured to examine the cure level by scratching the ink track using a needle. If the scratch results in smears, the specimens are considered not fully cured and the next tests were not being performed. Adhesion test is next conducted by cutting one part of the ink track into 100 smaller squares using a knife and a 3M tape is used to adhere the square areas and compressed properly. The tape is then removed and the adhesion level is evaluated based on a scale from 0B to 5B according to ASTM D3359. A hardness test is performed next using HMV micro hardness tester to determine the hardness level of the ink tracks. An electrical test using a digital multimeter is executed to measure the resistance of the ink track. The resistivity and conductivity were then calculated using the following equation (2);

$$\rho = \frac{RA}{l} \quad (2)$$

where ρ is resistivity in Ω·m, R is resistance, A is a cross-sectional area in m^2 and L is the length in meter while conductivity is calculated using the following equation (3);

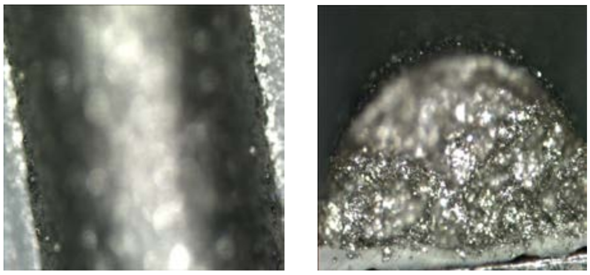
$$\sigma = \frac{1}{\rho} \quad (3)$$

where σ is conductivity in S/m.

III. Results

A. Dimensional Accuracy

Fig. 5 (a) shows the samples' image of the line width obtained while Fig. 5 (b) shows the line thickness of the printed ink track. The experiment is performed using five different variations of printing and curing parameters. Fig. 6 shows the error of dimensional accuracy for all five variations of printing speed with different printing pressures. At printing pressure of 70 kPa with 5 mm/s of printing speed, the line width is at its optimal which is 1.97 mm (the nearest line width to the expected line width of 2 mm). The largest line width printed is 2.59 mm when the printing speed and pressure is set to 4 mm/s and 100kPa. It was observed that the lowest printing speed with the highest printing pressure printed a largest line width of the ink track. There were some failed samples produced due to the presence of air bubbles inside the syringe barrel which resulted in smear. The trend of the line width was decreased as shown in Fig. 7 which the higher printing speed caused a narrower line width. The line width is also narrower when the printing pressure is low.



(a) (b)

Fig. 5. (a) Line width. (b) Line thickness.

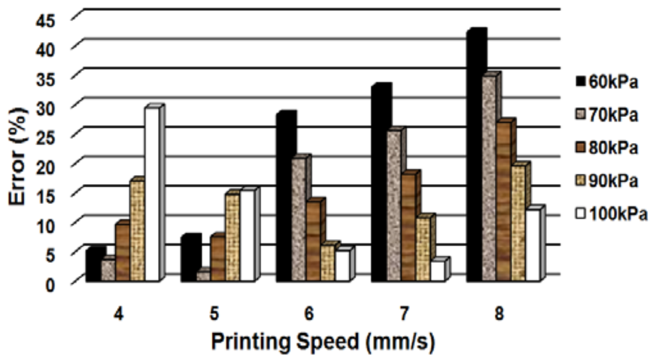


Fig. 6. Error of dimensional accuracy of line width.

In contrast, the trend of the line thickness was increased as shown in Fig. 8. A higher printing pressure caused the line thickness to be thicker. Besides, the line thickness becomes thinner when the printing speed is higher. At printing pressure of 60 kPa with 8 mm/s of printing speed, the line thickness is at its optimal which is 0.32 mm. The largest thickness of ink track printed is 1.44 mm when the printing speed and pressure were set at 4 mm/s and 100 kPa. It was observed that the lowest printing speed with the highest printing pressure printed a largest line thickness of the ink track.

B. Effect of Printing Speed

Printing speed plays an important role in determining the amount of ink deposited. A discontinued ink track will occur if the printing speed is set to too high because less volume of silver ink is dispensed. However, a low printing speed results in unnecessary delivery of excess ink as illustrated in Fig. 9 which shows two printed line track using a same pattern and printing parameters, with the exception of relative printing speed.

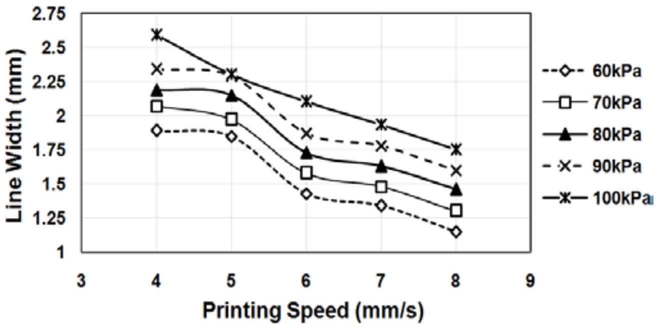


Fig. 7. Changes of line width of printed ink track.

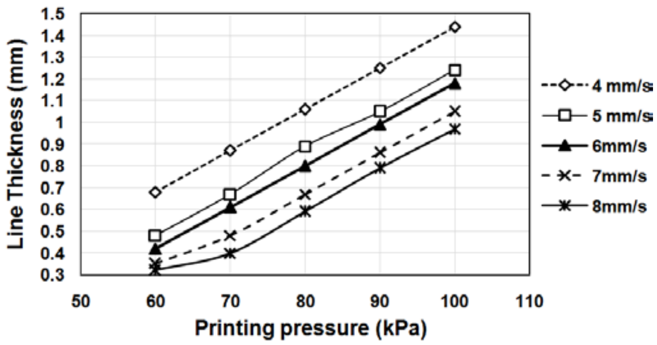


Fig. 8. Changes of line thickness of printed ink track.

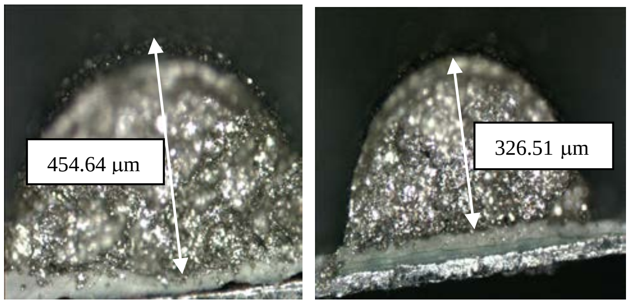
C. *Effect of Printing Pressure*

A printing pressure as well plays an important part in determining the amount of conductive ink deposited. A low printing pressure can result in inconsistent volume ink deposited, which might cause the ink to clog the nozzle. The optimum printing pressure must be set to obtain the acceptable print until an acceptable print quality is obtained. The appropriate pressure is needed to help the ink pass through the nozzle and dispense on the substrate. If the ink viscosity is too high, higher pressure is required to deliver the ink.

(a) (b)

Fig. 9. (a) Pattern printed with a printing speed of 4 mm/s (b) The same pattern printed with a speed of 8 mm/s

Fig. 10 (a) and (b) show two printed line track thickness using the same pattern and printing parameters, with the exception of relative printing pressure. A higher printing pressure, a thicker the resultant tracks thickness, but the spacing between the parallel tracks is preserved. On the other hand, if the nozzle dispenses with a low pressure, the thickness of the line track is much better due to the resistance is higher when the line thickness is smaller according to the formula of resistivity as shown earlier in equation (2). Thus, the conductivity could be improved with the ink track with larger cross sectional area since it is easily to control the size of the line track using the fluid dispensing system. From the equation, a future researcher should use selected printing parameters which only thin ink track is printed but make sure the width of the ink track is close enough to the targeted line width. Besides that, it has to be subjected to the curing parameters selected in order to realize higher conductivity of the ink track.



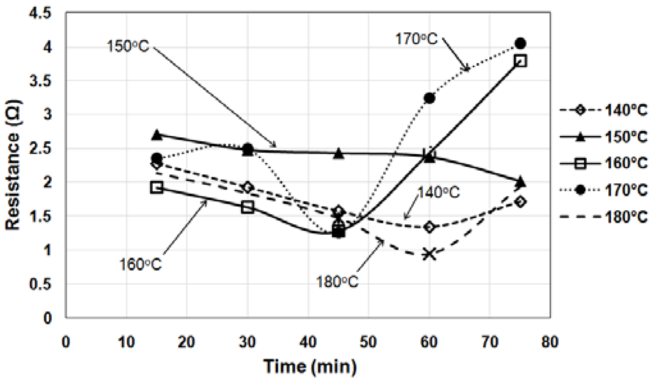
(b) (b)

Fig. 10. (a) Pattern printed with a printing pressure of 100kPa (b) The same pattern printed with a pressure of 60kPa

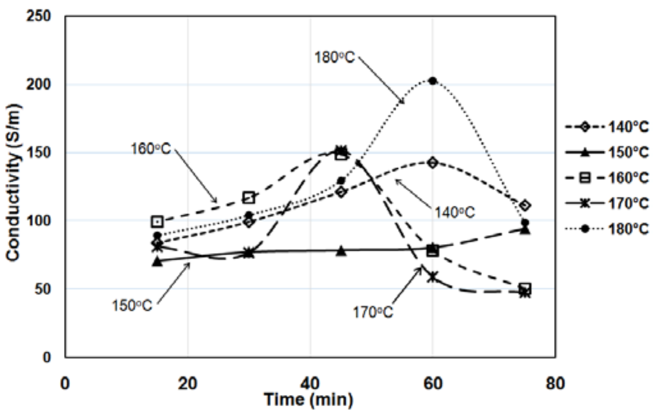
D. *Resistance*

Fig. 11 (a) and (b) show the resistance and conductivity results of the samples with variation of curing temperature and times, ranging from 140 °C to 180°C with 10°C incremental and from 15 minutes to 75 minutes with 15 minutes' intervals. In Fig. 11 (a), the graph shows the resistances for most of the samples were decreased as the curing time increased as expected. At a variation of curing temperature ranging from 140°C to 180°C also showing a constant decreased in resistance starting from 15 minutes to 45 minutes but a sudden spike in value occurred after reaching certain times. This is due to over cure phenomenon where some silver metals were burnt out and this increases the resistance. It is also shows that the sample with lowest resistance achieved is 0.9 Ω which is cured at 160°C at 45 minutes. The trend shown the resistance slowly drops but at one point it rise suddenly due to the ink track is over cured, resulting in the spike of resistance. Thus, as the temperature is higher the resistance are reduced to a lower rate but the ink over cures at a much faster rate resulting in a much steeper spike of resistance value.

Fig. 11 (b) depicted the conductivity value of the ink track. The graph for all temperatures rises significantly. For both temperatures at 170°C and 180°C, the conductivity value drops greatly past the 45-minute mark. Nevertheless, for ink track cured at lower temperature, namely 150°C and 160°C, shows a sudden rise in conductivity especially for 160°C at the 60-minute mark and sees a sudden drop at 75-minute mark. As for 140°C, the graph increased steadily at a smaller rate. It was proven that the thickness of the conductive ink track has some effects on resistance and it is validated by the equation (2) previously. The thicker the conductive ink track, the lower the resistance obtained. The reduction in resistivity is due to the densification of the double layer conductive ink track and it is increased the contact area between the individual particles which enhanced the conduction through the conductive ink track. This phenomenon could be explained as more layer or thicker the cross-sectional area, the more electric current could be delivered through the conductor since the amount of the contact between particles is increased. This is similar to the concept of electric wire in which the thicker wire allows bigger electric current to flow through and the thin wire could only provide small amount of the electric current. It is also observed that the sample with highest conductivity is sample 12 (211.9477 S/m) which is cured at 160°C at 45 minutes. The graph shows that the trend for each line is at one point which is the highest point of the line, the conductivity suddenly drops. As the temperature is higher, the drop is steeper. This is because the ink is over cured and higher temperature gives a faster rate of curing thus the point of threshold is earlier. For both temperatures at 170°C and 180°C, the point of threshold is at the 45 minutes' mark whereas for samples cured at 150°C and 160°C, their point of threshold is at 60 minutes' mark. The 140°C line did not actually follow the trend due to at lower temperature, the point of threshold where the samples are over cured takes longer than 75 minutes' in total. The time is not extended to find the point of threshold for 140°C because the conductivity at 75 minutes is not even higher than sample 12, thus finding the point is not relevant.



(a)



(b)

Fig. 11. (a) Changes of resistance at variation of temperature and time (b) Changes in conductivity at variation of temperature and time

E. Mechanical Testing

The results from the crosshatch pattern (adhesion test) are compared to the adhesion level based on a scale of 0B to 5B and the results are shown in Fig. 12. Based on the result, the adhesion level increased fairly rapidly due to increasing of the curing time and temperature result in better adhesion properties. A hardness test is also conducted to measure the hardness level of the ink track using micro-hardness tester. A load was subjected on the indenter to penetrate the cured ink track. The indentation produced a square based mark on the ink track surface called diagonal. The diagonal length of the indentation indicates the cured level. The depths of the penetration represent the hardness condition of the inks track. It was found that the suitable test load was HV0.1 which is about 0.9807N. The results of hardness level are depicted in Fig. 13 which the hardness level of the ink tracks showed inclination trend similar to the previous adhesion test which when the cured temperature and time increased, the hardness level of the ink tracks was also increased accordingly.

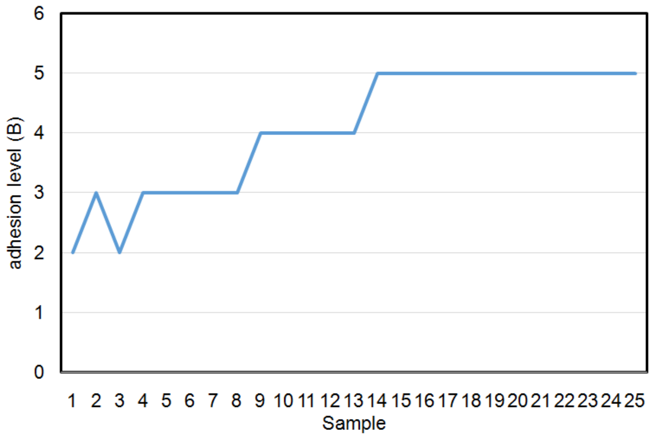


Fig. 12. Adhesion level for the ink track

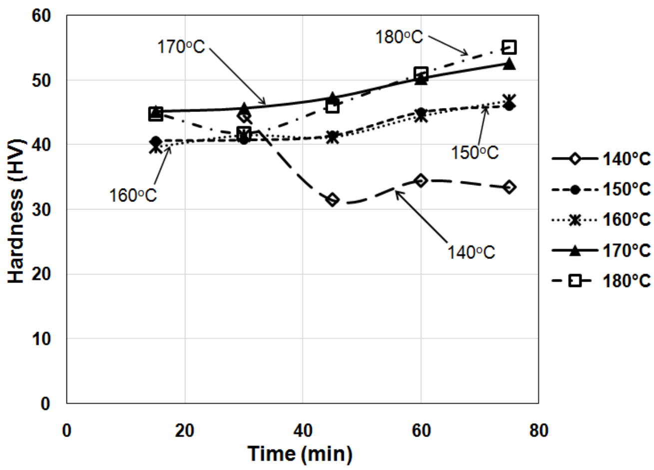
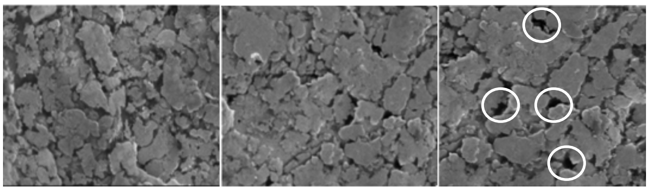


Fig. 13. Hardness level for the ink track

F. Micro-structure Analysis

The observation from scanning electron microscopy (SEM) made for silver particle arrangements of the conductive ink were shown in Fig. 14 (a), (b) and (c). The comparison made is based on the lowest, medium and highest value of electrical resistance properties between the samples. The gaps existed in the arrangement of silver particle for sample 21 is greater than sample 4 and sample 12 respectively. It shows that the frequency of gaps between silver particle affecting the electrical resistance properties of the conductive ink track. As the gap number increased, the resistance increased due to higher voltage needed in order to allow the current to flow through the silver particles. From the EDX analysis performed, two elements consisted of silver and carbons were observed. The EDX result for sample 12 is shown in Fig. 15. The silver particles are referred to the element of conductive ink used while carbon particles are referred to the leftover of binder in the conductive ink from the curing process. Sample 21 has the atomic weight percentage of 85.28% silver while sample 4 and 12 were 87.26% and 88.63% consecutively. The higher the atomic weight of silver, the lower the resistance of conductive ink track because lesser amount of carbon particle that obstruct the movement of electron between silver particles.



(a) (b) (c)

Fig. 14. Surface topography under SEM (a) Sample 12 (b) Sample 4 (c) Sample 21.

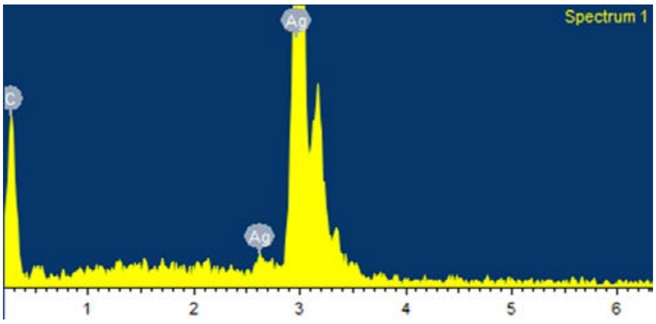


Fig. 15. EDX analysis of Sample 12 showing the contents of silver (88.63%) and carbon (11.37%) in weight percentage.

IV. Conclusion

This study presents an alternative of printing technique via fluid dispensing system for printing silver conductive ink and curing the ink using oven on curvature substrate. The objectives of the investigation were achieved as fluid dispensing system is capable of printing silver conductive ink track on curvature substrate. In addition, the printing and curing parameters including printing speed, pressure applied, curing time and temperature influenced the physical characteristics and conductivity of the pattern printed. The line width of ink track becomes smaller when the printing speed is fast. Besides, a thinner ink track is printed when the printing pressure is low. On the other hand, silver conductive ink used is proven to be appropriate for the study. Silver conductive ink is the most stretchable type of conductive ink than others to be used for printing purpose on curved substrate. To realize a good conductive ink track, a proper control of the curing process is significant especially in determining the right temperature and curing time. An oven is proven capable of curing the ink on curvature substrate. Variations of curing time and temperature have been seen produced different effects on the conductivity produced. There are still some improvements that could be made in future including a miniature electronics structure with different geometric patterns could be investigated as most electronics structure nowadays are miniature-based structure. A suitable printing technique to obtain a smoother surface of the insulation layer could also be employed which potentially resulted in smoother surface for the inks to be printed on the curvature substrate. Furthermore, the nozzle head is needed to be cleaned up after printing to achieve a good quality of the ink track and maintained the stability of ink's dispersion.

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