A STUDY ON ELECTRICAL PROPERTIES OF FLEXIBLE PRINTED ELECTRONIC CIRCUIT SUBJECTED TO CYCLIC BENDING LOAD

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UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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A report submitted in fulfillment of the requirements for the degree of Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DECLARATION

I admitted that this project entitled "A Study on Electrical Properties of Flexible Printed Electronic Circuit Subjected to Cyclic Bending Load" is the work of my own except as cited in the references.

Signature :……………………………………………..

Name :……………………………………………..

Date :……………………………………………..

APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering.

Signature :……………………………………………….

Supervisor Name :………………………………………..

Date :…………………………………………………….

ABSTRACT

This study investigates the reliability of printed conductive ink on flexible substrate under cyclic bending. The topic is focused on the resistance effect in conductive ink after being test with cyclic bending on different number of cycles. In this study, the test sample and specimens with various circuit width and thickness were printed on PET substrates. The test samples were printed using screen printing method. The conductive ink used was commercially obtained from Bare Conductive Ink. The ink was water and SWCNT based. The sample prepared were varied in term of circuit line width (1.0mm, 1.5mm, 2.0mm, 2.5mm and 3.0mm) and circuit line thickness (0.05mm, 0.10mm, 0.15mm, 0.20mm and 0.25mm). The readily sample was measured in term of its resistivity prior to bending tests. All of the sample prepared was later subjected to repeated bending cycles of 500, 1000, 1500, 2000 and 2500 times at fixed bending speed of 0.6 second per cycle on 11 volts. The circuit resistance was taken after the bending test. Finally, all of the samples was analyzed by using image analyzer. Results comparison between initial resistance and final data was conducted. The initial resistance without undergo bending cycle shows that the increasing of circuit line width resulting on decreasing of resistivity, while for thickness sample shows the same result where increasing of circuit thickness, resistivity of the circuit decrease except 0.20mm of thickness samples. Additions of ink volume used, means more electron can pass on the circuit and resulting on better conductivity. Meanwhile, for the sample of complete bending cycles, the resistivity tends to decrease when number of cycles increase for the width and thickness samples except for 2.5mm of width and 0.25mm of thickness sample. Up to 2500 cycles, the circuit resistivity is less affected by cyclic bending load.

ABSTRAK

Kajian ini menyiasat kebolehpercayaan dakwat konduktif di cetak pada substrat fleksibel dan dikenakan kitaran lenturan dan memberi tumpuan kepada kesan rintangan dalam dakwat konduktif selepas ujian. Dalam kajian ini, sampel ujian dan spesimen dengan lebar dan ketebalan litar yang berlainan telah dicetak pada substrat PET. Sampel ujian dicetak menggunakan kaedah percetakan skrin. Dakwat konduktif yang digunakan diperoleh secara komersil daripada Bare Conductive Ink. Dakwat itu berasaskan air dan SWCNT. Sampel disediakan bervariasi dari segi lebar litar (1.0mm, 1.5mm, 2.0mm, 2.5mm dan 3.0mm) dan ketebalan litar (0.05mm, 0.10mm, 0.15mm, 0.20mm dan 0.25mm). Sampel yang telah siap diukur rintangannya sebelum ujian lenturan. Kesemua sampel yang disediakan kemudiannya melalui kitaran lenturan berulang 500, 1000, 1500, 2000 dan 2500 kali pada kelajuan lenturan tetap 0.6 saat setiap kitaran pada 11 volt. Rintangan litar telah diambil selepas ujian lenturan. Akhir sekali, semua sampel dianalisis dengan menggunakan penganalisis imej. Perbandingan keputusan antara rintangan awal dan data akhir dijalankan. Rintangan awal tanpa menjalani kitaran lenturan menunjukkan bahawa peningkatan lebar litar menghasilkan penurunan rintangan, sedangkan untuk sampel ketebalan menunjukkan hasil yang sama di mana peningkatan ketebalan litar, rintangan akan menurun kecuali pada 0.20mm sampel tebal. Penambahan jumlah dakwat yang digunakan, bermakna lebih banyak elektron boleh melalui pada litar dan menghasilkan kekonduksian yang lebih baik. Sementara itu, untuk sampel kitaran lenturan yang lengkap, rintangan cenderung untuk menurun apabila bilangan kitaran meningkat untuk sampel lebar dan ketebalan kecuali 2.5mm lebar dan 0.25mm sampel tebal. Sehingga 2500 kitaran, resistensi litar kurang dipengaruhi oleh beban lenturan kitaran.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

The study to complete this project was basically to know the reliability of the commercial bare conductive ink printed on polyethylene terephthalate (PET) substrate or to determine the circuit resistivity toward cyclic bending. It is also being to know the difference in resistivity of the circuit when cyclic bending was given to the sample and without cyclic bending test toward the sample. The study is to know the resistivity of the circuit when some cyclic bending force with set of curvature radius has been applied toward the circuits substrate. The circuit needed are some circuit that can be printed by ink or the specially ink used. The ink used is bare conductive ink where it is ink filled with carbon that can conduct electricity. The ink is basically normal ink that has been mixed with some conductive material and can be used on substrate surface or any applicable surface.

Nowadays, printed electronics are currently developing as it can be used at many item. The. manufacturing industry currently use this kind of method to produce their product. Furthermore, printed electronics will be grow into bigger business in the future as its technologies has a lot of advantage and can be manufactured at low cost (Chrisey, 2000). The material used in this project are bare conductive ink where the ink is carbon based. The ink cure in room temperature and does not need oven to harden it. The substrate used were polyethylene terephthalate or PET. PET are plastic sheet where it can be printed on both side. This printed circuit or printed electronics are created by using a lot of variety techniques in the making of printing process. And for this project, the printing technique use was screen printing where the sample target was to have the even surface. For the resistivity data, it was to plot the graph of resistivity against number of cyclic bending cycle and find the standard deviation of the data collected.

1.2 Problem Statement

Flexible printed electronic (FPE) was growing and adapting very fast into daily application. Among potential type of filler in producing conductive paste for FPE is single-wall carbon nanotube (SWCNT). Carbon nanotubes offers many advantages especially in term of high electrical conductivity and good mechanical properties which was comparable to conventional silver-based nanoparticles. However, based on current literature review, there are still limited reports on studies involving the relationship between conductive layer geometrical parameters to the electrical performance of FPE made from SWCNT paste. In addition, reports on the effect of cyclic bending load for commercial SWCNT / PET substrate resistivity prepared at varying circuit line width and thickness was also scarce in current literature review.

1.3 Objective

The main objectives in completion of this project are

i. To prepare flexible printed circuit using conductive ink at varying circuity width and thickness.

ii. To determine resistivity and performance of printed electrics circuit after being subjected to cyclic bending loads.

1.4 Scope

The scopes of the project are: -

i. To performed literature review
ii. To identified the material needed to prepare the sample
iii. To designed the circuit
iv. To prepare and set up the facility for sample preparation and testing
v. To prepare the sample to undergo the bending test
vi. To test the sample and perform data collection using cyclic bending test apparatus
vii. To analyze the collected data
viii. To prepare the final report based on FKM UTeM thesis writing guidelines

In addition, the project deals with commercial type of conductive ink which is commercial type conductive ink obtained from Bare Conductive Ltd, United Kingdom. The ink then is printed on the surface of polyethylene terephthalate (PET). PET substrate was obtained from Lohmann Technologies UK Ltd, United Kingdom. The ink printing process used is screen printing.

CHAPTER 2

LITERATURE REVIEW

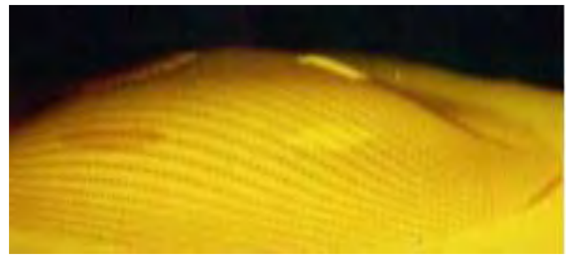
2.1 Introduction

In this chapter, literature reviews conducted encompassed information on polyethylene terephthalate substrate, conductive ink, testing method for flexible printed circuit, and preparation method on the electrical circuit used. The main point included are substrate, ink, bending test, and printing techniques with details description on each point.

2.2 Flexible Electronics

Flexible electronics used majorly in technology for electronic circuits. The production of flexible electronics is through assembly the electronic devices on the any kind of compatible substrate surface. Plus, to print the flex circuits, it can be printed by using conductive ink. Flexible electronics created to replace the hard printed circuit boards, PCB where flexible electronics allow to form in desired shape. Throughout the history of flexible circuit, to raise the power and weight ratio, any kind of item thinned become flexible so silicon solar cells were thinned to ~100µm. Next, the thinned solar cells were then assembling on plastic substrate to obtain flexibility in forty years ago. Through flexible means, it can link with lightweight, bendable, elastic and large area. Today's researchers mostly focus on flexible shaped displays and sensors, electronic textiles and skin (Wong & Salleo, 2009).

In terms of mechanical characteristics for flexibility, it can be classified in three different categories which shown in Figure 2.1: (a)roll able or bendable, (b)elastically shaped and (c)permanently shaped. Flexibility in different means can have many different type of properties in terms of manufactures and users.



(a) (b)

(c)

Figure 2.1: (a)Bendable circuit (b)Silicon island on spherically shaped foil substrate (c)Concept of conformably shaped digital dashboard (Wong & Salleo, 2009)

The electrical connections that used flexible circuits stands as one amongst the most advanced and important technologies as because of their useful and beneficial properties as example is their marginal weight, flexible form factors and thinness. For the application in whole devices, it can help in boost the device functionality by provide portability, freedom of form or flexible, impact resistance, reducing the product weight and thickness (Mitsui et al., 2015).

2.3 Conductive Ink

Conductive ink is an ink that use in a printable surface which they will conducts power. It is commonly made by adding and mix graphite or other materials that can conducts electricity into ink. Conductive inks can be a cheaper approach to set out a modern conductive traces where it can be compared with ordinary industrial standards, for example, drawing copper from copper plated substrates to shape the same conductive follows on relevant substrates, as printing is a simply added substance process creating no waste streams which at that point must be recovered or treated.

There are many types of conductive inks that we can found and use. All of this inks have their own weakness and also advantages that can be applied when they have been printed on substrate or any printable surface. The conductive inks that can be found are formulated based on carbon/graphene, silver flake, silver nanoparticle, carbon nanotube ink, copper flake, copper nanoparticle and conductive polymer.

When the inks contain of highly conductive metal such as copper, gold and silver, it can have classified as conductive inks. For conductive inks, it can separate into two types which is particle and nano-particle where it also can separate into two groups which is organic and non-organic because the solvent used ink the ink was different (Khirotdin et al., 2016).

The electrical properties of different such inks that utilize different sorts of carbon are because of a complex arrangement and interact between the morphology and size of the individual parts, their innate properties and the handling techniques used to scatter them (Phillips et al., 2017).

2.3.1 Carbon Ink

The type of ink that used in this project are carbon based ink or graphene. Nonetheless, graphene, the allotrope of carbon nanotube, is an extremely encouraging material for remote wearable communication applications thanks to its conductivity which mainly high and it properties is one of a kind which unique. Nowadays, researchers and scientist have done some intense investigation towards the usage of graphene or carbon to produce active device like diodes and transistors. Based on that, computerized modulator was achieved by utilizing two graphene transistors (Huang et al., 2016)

Carbon inks have a large group of ideal attributes that enable them to be utilized as a part of these applications, counting synthetic idleness, the capacity to be altered or, then again functionalized on case of electrochemical sensors and capacity to go about as intercalating materials in the instance of vitality stockpiling, and additionally minimal effort and disposability. Carbon inks are applied in established technology where it was used to make sensors for blood glucose (Phillips et al., 2017)

2.4 Substrate

There plenty of substrate which can be used as each of the surface has their own surface resistivity. The substrate that has been commonly used for conductive ink are Polyethylene Terephthalate (PET), Polypropylene (PP), Polyvinyl Chloride (PVC) and some of various types of paper. For this project, polyethylene terephthalate or PET has been choosing to complete the project. The surface of PET is commonly having smooth surface as it will help in printing the circuit. Rough surface will greatly affect the circuit as it will result of uneven contact between the ink and surface. Furthermore, rough surface will be causing missing dots on the circuit (Aijazi, 2014).

Any kind of flexible substrate used in flexible electronics must at least meet the requirements of optical properties, surface roughness, thermal and thermochemical properties, chemical properties, mechanical properties, electrical and magnetic properties (Wong & Salleo, 2009). Table 2.1 summarized the requirements for flexible electronics substrate material.

Table 2.1: Summary of the requirements for flexible electronics substrate material

Material properties	Requirements
Optical properties	Trans missive and bottom emitting displays uses clear substrates
Surface roughness	The sensitivity of electrical function toward surface roughness relies on the how much thinner the device films. Usually, plastic substrate rough only for over long distance
Thermal and thermochemical properties	the temperature for working environment with the substrate must be appropriate and compatible with maximum fabrication process temperature
Chemical properties	The substrate used must not issue contaminants and should be inert against process chemicals
Mechanical properties	The substrate of high elastic modulus resulting in increasing of stiff and the devices layers will be supported by hard surface under impact
Electrical and magnetic properties	Conductive substrate may fill in as common node and as an electrochemical shield. Coupling capacitance minimize when the substrate is electrically insulating

2.5 Manufacturing Method for Flexible Electronics

In the making of flexible electronics, commonly to form the circuit on the surface of the substrate, it involves of printing process. Printed electronics is an innovation that has been constantly improving consistently. This innovation is utilized to produce electrical devices for example making of slim film transistors, capacitors, resistors, batteries and circuits. In printed electronics printing process, there are currently include different kind of method such as screen printing, lithography and rotogravure as shown in Figure 2.2, where it is known as low cost process in industry. Nowadays, an advanced technique has been introduced and it is inkjet printing. The printing can become cheaper, easy for mass production, more convenient, grants flexibility and sustainable (Jiang, 2012).

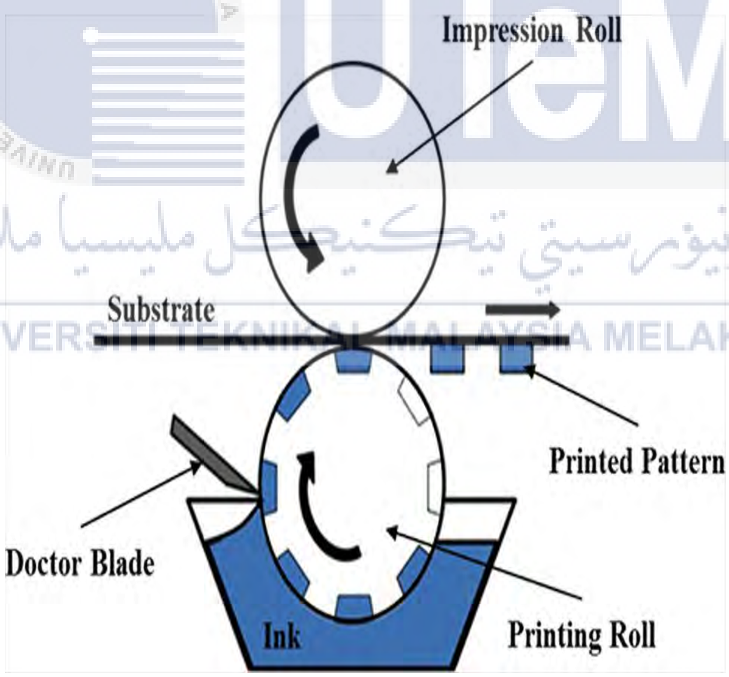


Figure 2.2: Rotogravure printing process (Hoffman et al., 2013)

Fabrication in flexible electronics by using of printing process promise a huge advantages especially in aspect of cost and simplicity compared to PCB manufacturing techniques (Ostfeld et al., 2015). Nowadays, industry more concern about energy consume during manufacturing and fabrication process of conventional electronics. The main attentions focus on finding additive ways to produce flexible electronics components an any substrates (Zheng et al., 2013). For the printing process, there are some plenty printing technologies that can be applied in printing conductive ink on substrate or any other surface. This printing process can be including in two different groups which is impact and non-impact printing technologies. The process type in making of sample of this project are based on screen printing which is under impact printing group.

For this impact printing, there are mainly four types and techniques under of impact printing group which screen printing is one of the techniques. Another three types are flexography, gravure and lithography. For the non-impact printing, the techniques can be form into six different ways. The printing techniques are electrophotography, iconography, magnetography, inkjet, thermography, and photography.

2.5.1 Screen Printing

Screen-printing utilizes a basic procedure in which a screen is conceal on the non-picture territories or area and has openings and graving in the picture regions. Ink is printed by applying the pressure to the screen and the picture is printed on the substrate. One of the greatest advantages of screen printing are the thickness of the printed ink film. The thickness can be varies based on screen thickness. This process is generally utilized as a part of the make of printed circuit boards. Screen printing also were accepted as one of the efficient way to produce and fabricate thermoelectric devices (Varghese et al., 2016).

The screen printing the has been introduces since 1980s offered large scale of manufacturing of highly reproducible but in reasonable price electrode systems. In the process of screen printing, it involving of the patterned deposition of inks onto surface of the substrate by squeezing the ink through screen mask and stencil. For the after printing treatment, it depends on varies of formulation where usually the ink cured at high temperature or let it dried at room temperature on certain period of time (Cai et al., 2010).

For the manufacturing industry, screen printing is one of the popular method to use. It will give form of design or ink which is thick on the substrate or any other surface. Screen printing can be divided into two methods which is flat bed screen printing and also rotary screen printing (Happonen, 2016). The procedure to complete the flat bed screen printing by putting the stencil on the substrate. Next by putting paste or ink on the stencil and pulling it along the stencil surface by using squeegee. Then remove the stencil and wet layer of ink remain on the substrate.

Screen printing methods has two different characteristics compare two other printing method which screen printing are versatile and its ink thickness can be variable. For the versatility of screen printing, it is can be used and apply on any kind of substrate. For the ink thickness, it can changes with different sets of speed, snap-off and pressure apply when pulling the ink by squeegee (Bhore, 2013).

2.6 Cyclic Bending Test

Flexible devices are widely used in flexible electronics, and flexible displays. The real and major test or challenge to produce this was not only it production but these devices stability in forms of mechanical, electrical and electrochemical properties. Despite little knowledge about the impact of mechanical stress either bending or rolling during the devise operation and overall performance, the manufacturing of flexible thick film devices has been developed (Cai et al., 2010).

The bending test conducted to evaluate the functionality and performance of the conductive inks in changing of its behavior when deforms and resistance with variation of bending angles (Khirotdin et al., 2016).

Bending test will be done to the substrate which contain conductive circuit. The bending will be done with varies number of cycle. The resistivity of the circuit will be recorded after some the circuit has been done bending test for number of cycles state. The main process of the bending is to bend the circuit with cyclic bending which is to make the circuit bend at curvature radius.

2.7 Current Research on Flexible Printed Electronics

Based on the research done by (Happonen, 2016), it separate in two different printing process which is screen printing and roll to roll process. For screen printing process, the materials used for the experiment consist of the use of 6 different types of substrate of different types and different thickness. The substrate used is PET Melinex ST506 125µm, Arron transparency 100µm, PET Mylar A 50µm, 4CC 105µm, Staples A4 copy paper 100µm and Lumiart 75µm. all of this substrate had Asahi LS-411AW as a conductive paste. For the printing circuit, it varies on 250µm, 500µm, 1000µm and 2000µm of width and 12µm,24µm and 36µm of circuit thickness. The test was carried out with fixed 6mm bending radius in compression. The final results show the narrower line width resulting in increasing of characteristic lifetime. The substrate used was contribute significantly on the result where the thinner the substrate was resulting in increasing of its lifetime. For another research on roll to roll printing process, the substrate used was PET Melinex ST506 125µm and the ink paste used was Asahi LS-411AW, Asahi SW1400, and DuPont 5064H. the thickness of the printed circuit was fixed at 12µm and its width varies of 125µm, 250µm, 500µm, 1000µm, 2000µm. For the testing part, the bending radius sets at 6mm, 15mm, 20mm, and 30mm. The result taken was Asahi SW1400 was the best paste ink after reliability test where its achieve highest lifetime despite on different bending radius.

Researchers (Khirotdin et al., 2016) studied on the resistance and elastic behavior during deforms of silver conductive inks via silver conductive paint RS186-3600. The ink was studied because the ink was free from oxidation, easily obtain and easily formulated and adhesion onto substrate. The ink was print of three different kind of substrate which is cotton, polyester and nylon. The test done was bending of the substrate started on 10 degrees and end on 160 degrees with 10 degrees' interval on each bending. The result collected shows cotton substrate produce highest resistance and the data increasing when the bending angle was increase. For polyester and nylon, the data collected was fairly same and balanced for both substrates.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This project main study is to find the resistivity of printed circuit when apply with cyclic bending toward the circuit which was printed with bare conductive ink or carbon based ink where it can conduct electricity at low power voltage apply. The conductive ink was printed on the surface of substrate by using polyethylene terephthalate or PET. PET is a flexible substrate where it cannot be stretch.

The circuit printed on the substrate include in total of two sets which for the first set the thickness of the circuit was fixed and the width was varies. For the second set, it was different with first set as the width was fixed and the circuit thickness was varying. The circuit was printed by using screen printing techniques where it is common techniques in printing at manufacturing industries.

The test towards the sample are by using cyclic bending with set radius. The bending cycle can be complete with thousands of cycle bending test towards the sample. After the test has been done, the resistivity of the circuit was collected and record. The analysis of the resistivity by plotting the graph against number of cycle in bending test.

Methodology shows and clarify the whole process of final year project from start until the end of the project. The process of the project started with some study from journal or thesis to guide and help for the whole journey of the project. Next, the process continues with identify the material used in order to do the testing. After that, by referring thesis and journal, the circuit design determines and which variables will be use. Then, the facility to run the testing are prepared and set up. After the facility are ready to use, the testing process will be conducted. Based on the testing, the data gained will be analysis and finally to prepare the final report and will be present to the panel.

3.2 Project Methodology

The overall process of the project flowchart shown in Figure 3.1 below. Detail description for each project process and activities are elaborated in the subsequent section.

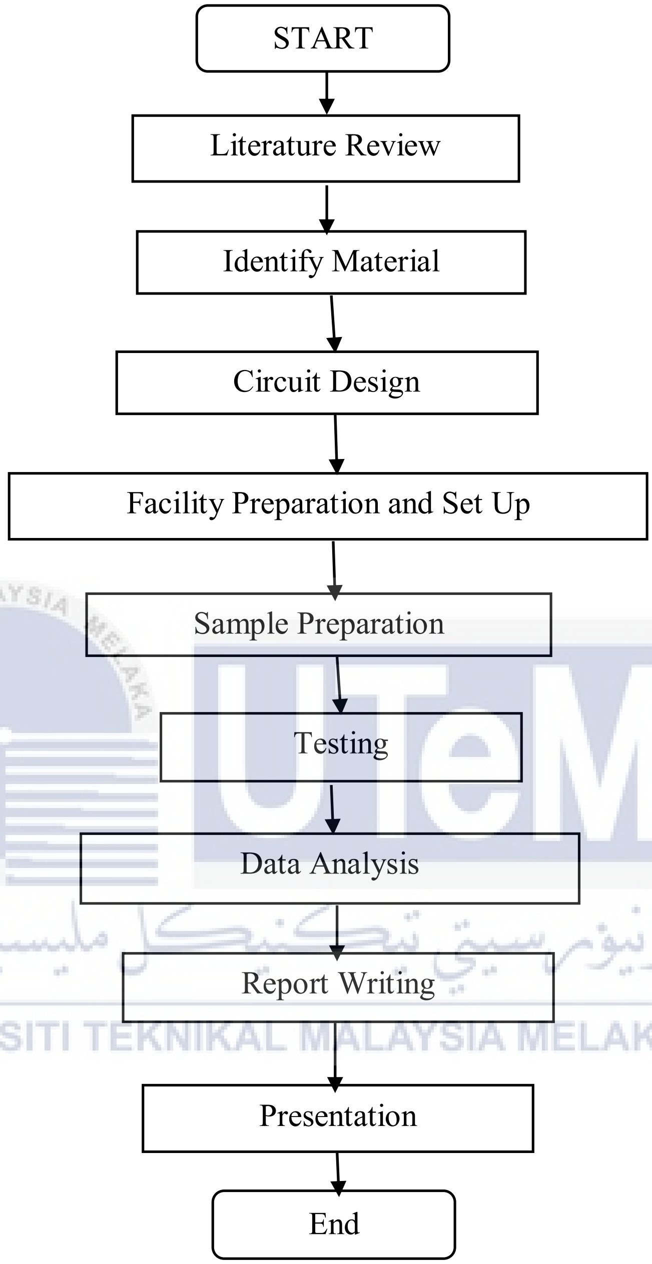


Figure 3.1: Overall Project Flowchart

3.2.1 Literature Review

Literature review are one of the process to complete the project. Basically, literature review is to study the thesis and journal related to the project to gain information and guidance. The study will be focus on flexible electronics, flexible printed electronics and varying circuit thickness and width. The main sources use to review the subject will be on thesis, journal, books and website.

3.2.2 Identify Material

The material used in the project needed to identify where all of the material specifications were studied. The material use for the substrate and ink were determined where the ink used were commercial type of conductive ink which is bare conductive ink. And for the flexible substrate used, the substrate chosen were polyethylene terephthalate (PET). Figure 3.2 shows the type of conductive ink and PET substrate used in this project.

(a) (b)

Figure 3.2 (a) conductive ink, (b) PET sheet roll

Bare conductive ink is water based electrically conductive paint. This kind of ink can be remove easily with water where it is water soluble. The specialty of bare conductive ink is it can be printed and adheres on any kind of compatible substrate. The printing process used was screen printing and bare conductive ink is a unique material where to apply in many different ways. For the curing process of the ink, bare paint can be dry in room temperature. And its drying time can be reduced if placing it near low intensity heat. All of the specification for substrate and conductive ink were studied and identify the ink curing temperature and time. Table 3.1 and Table 3.2 below show technical data sheets and its specification for bare conductive ink and PET, respectively.

Table 3.1: Bare Conductive Ink Properties

Bare conductive ink	
Properties	**Description**
Color	Black
Density	1.16 g/ml^3
Resistivity	46 ohms (20 mm x 15 mm) 76 ohms (50 mm x 20 mm) 431 ohms (70 mm x 3 mm) 455 ohms (110 mm x 3 mm)
Viscosity	Highly viscous
Power Sources	Low voltage DC power not exceeding 12VDC
Drying Temperature	Room temperature or near low intensity heat source to reduce time

Table 3.2: Polyethylene Terephthalate Properties

POLYETHYLENE TEREPTHALATE (PET)	
Properties	**Description**
Ultimate tensile strength	1.6 MPa
Flexural yield strength	60.0 MPa
Flexural modulus	1.9 GPa
Compressive yield strength	0.7 MPa
Compressive modulus	0.03 GPa
Surface resistance	1.0 X 10^{13} ohm

3.2.3 Facility Preparation and Set Up

The facility to do the testing and to prepare the sample will be set up and testing can be conducted. To prepare the sample, the facility that need to be use are circuit design on the stencil, conductive ink and flexible substrate. For the testing facility, the jig for the bending test need to be set up and to read the circuit resistivity, digital multimeter was used. Figure 3.3 and 3.4 shows digital multimeter and measuring equipment used in this project.

Figure 3.3: Digital Multimeter

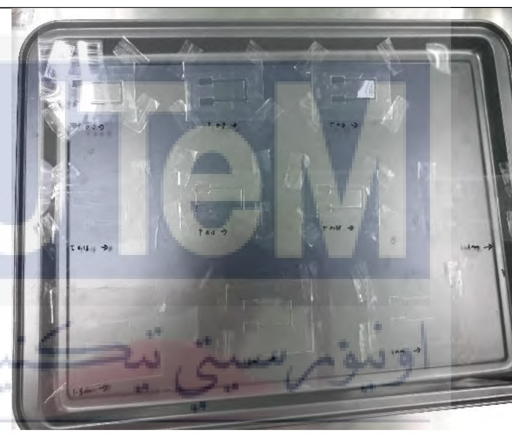
Figure 3.4: Measuring equipment using digital caliper

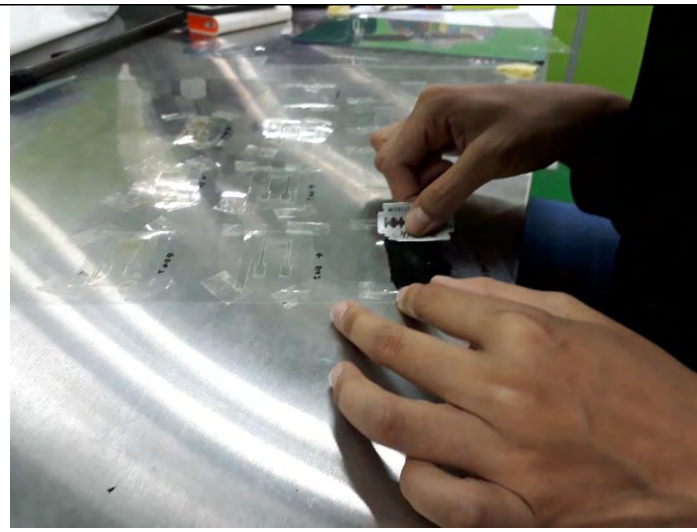
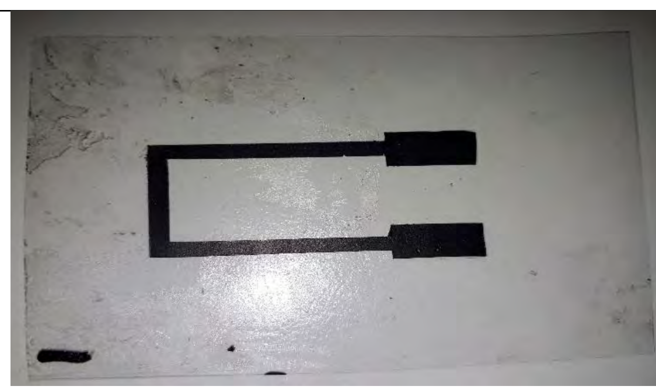
In order to use digital multimeter to measure the circuit resistance, connect black test lead to COM terminal and red test lead to the V/OHM input terminal. The function range must be set to OHM range and finally just connects the test leads across resistance under measurement and read the display value.

3.2.4 Sample Preparation

For the sample preparation to run the testing, the circuit design that has been decided will be engraved on the stencil. The overall project test plan is shown in Table 3.4. To print the circuit, substrate will be lay below the stencil and ink will be pour on the stencil to create the circuit. The circuit design will have two sets which set A will be set of varies thickness but same width. For Set B, the width will be varying and thickness of the circuit will be fix. The sample preparation procedure applied in this project are described on Table 3.3 below: -

Table 3.3: Sample preparation procedure

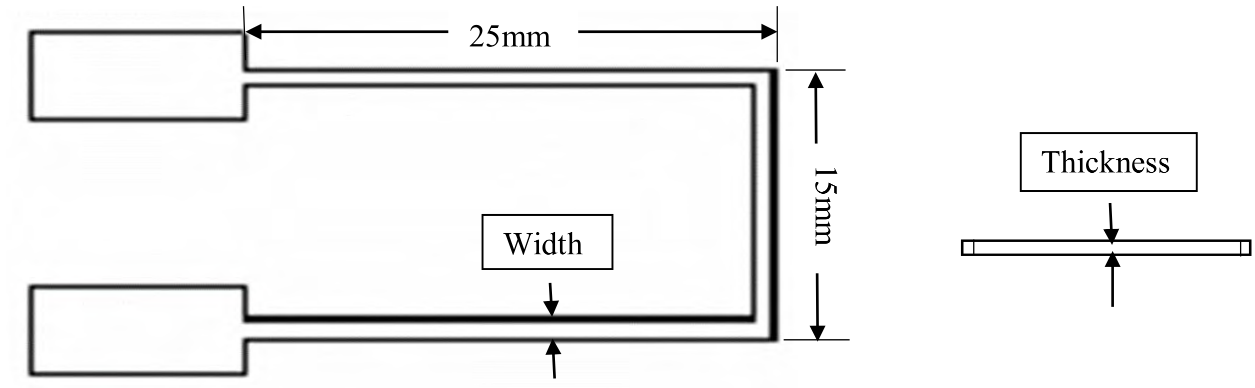
STEP	PROCEDURE	OVERVIEW
1	Around the circuit design set, the adhesive tape had been pasted on the substrate surface.	
2	Step 1 was repeated for different thickness and width on different substrate surfaces	
3	The conductive ink was pour onto the surface of the substrate which does not pasted with adhesive tape	

4	The ink was align according to the thickness of adhesive tape	
5	The ink was harden at room temperature for 25 minutes	
6	The adhesive tape was carefully removed without damaging the circuit.	

The ink that has been printed on the substrate will undergo curing process in the oven, the temperature and time in the oven will be set and same for all of the sample. Figure 3.5 and 3.7 shows schematic circuit design and actual circuit design printed on substrate. Table 3.5 shows the two sets of circuit dimension.

Table 3.4: Sample test plan

REQUIREMENT	DESCRIPTIONS
SAMPLE PREPARATION	Set A sample preparation • Fixed thickness, varies width
	Set B sample preparation • Fixed width, varies thickness
TESTING	Set A testing (Bending test) • No of cycle (500, 1000, 1500, 2000, 2500)
	Set B testing (Bending test) • No of cycle (500, 1000, 1500, 2000, 2500)
ANALYSIS	Data analysis for set A and B • Resistivity measure with digital multimeter
	Plot the graph of resistance against number of cycle



(a) (b)

Figure 3.5: (a)Top view of schematic circuit design (b) Front view of schematic circuit design

Table 3.5: List of circuit dimension

DIMENSIONS (Width × Thick)	
SET A	**SET B**
1.0mm x 0.05mm	2.0mm x 0.05mm
1.5mm x 0.05mm	2.0mm x 0.10mm
2.0mm x 0.05mm	2.0mm x 0.15mm
2.5mm x 0.05mm	2.0mm x 0.20mm
3.0 mm x 0.05mm	2.0mm x 0.25mm

(a) (b)

Figure 3.6: (a) Setting up the sample before printing process (b)Samples after printing completed

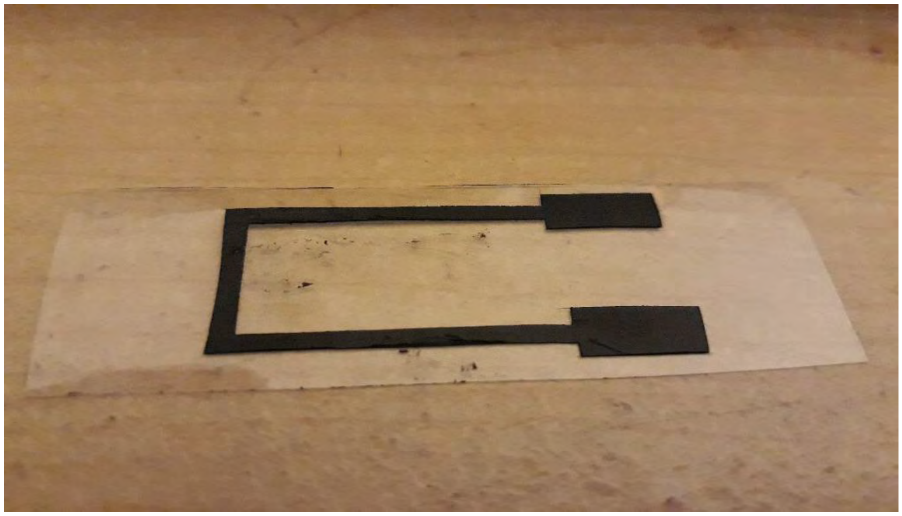


Figure 3.7: Actual circuit design printed on substrate

To control the prescribed circuit thickness for each sample, the substrate ready for printing process will be first measured in thickness by using digital caliper to determine and conformation to any desired thickness as shown in Figure 3.7. The process of measuring this thickness is done to each sample that is ready for process printing and if the sample meets the desired thickness the next process will be executed.

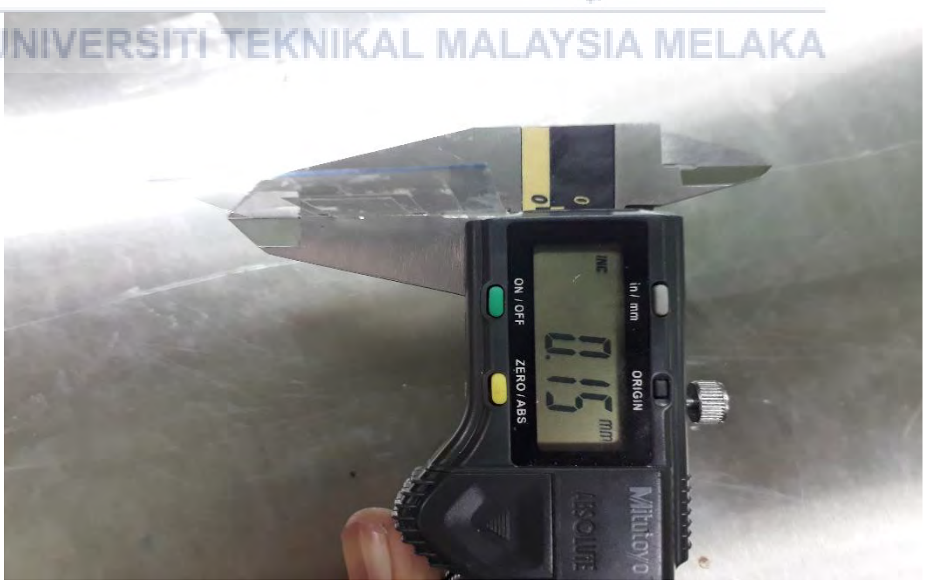


Figure 3.8: Thickness measuring process

3.2.5 Testing

Testing will be focus on reliability test at the ink. The test is to do bending test on the substrate which the bending cycle will be varies. The sample was given cyclic bending repeatedly. The set-up of the system consists of two holders to hold the sample where one of the holder were fixed and another holder was moved to bend the sample. Figure 3.9 below illustrated the movement of the test rig. The parameters for the test was set on 500, 1000, 1500, 2000 and 2500 bending cycle. After the bending test are done, the resistivity on the circuit will be read by using digital multimeter. Figure 3.10 shows the bending cycle rig used to complete the test with different number of cycle. The motor input power was set on 11 volts which the speed for the bending was 100 cycle per minute. To complete a round of bending, it takes 0.6 seconds.

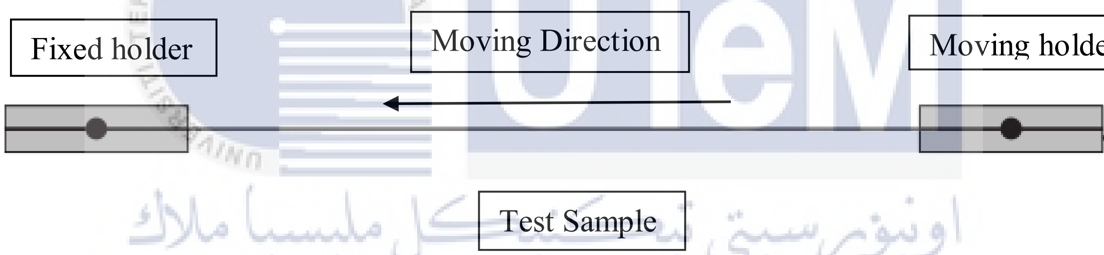


Figure 3.9: Schematic illustration of testing

Figure 3.10: Cyclic Bending Rig

3.2.6 Data Analysis

All of the data gained from testing will be analyze and different set and sample data will be put in the graph. From the graph line, the standard deviation and average value will be determined. Standard deviation is the measure of data collected spread away from its mean and average. In example are does the standard deviation close to average or scores better than average or below the average. The standard derivation can be get with its formula as stated in Equation 3.1 (Math Centre, 2003). Figure 3.11 shows the resistance data taken by using digital multimeter.

$$S = \sqrt{\frac{\sum f(x-\bar{x})^2}{n}} \quad \text{(Equation 3.1)}$$

Where, S = Standard Deviation

X = each value in the set of data

$\bar{x}$ = mean of all values in data set

f = frequency with which value of data

n = number of values in data set

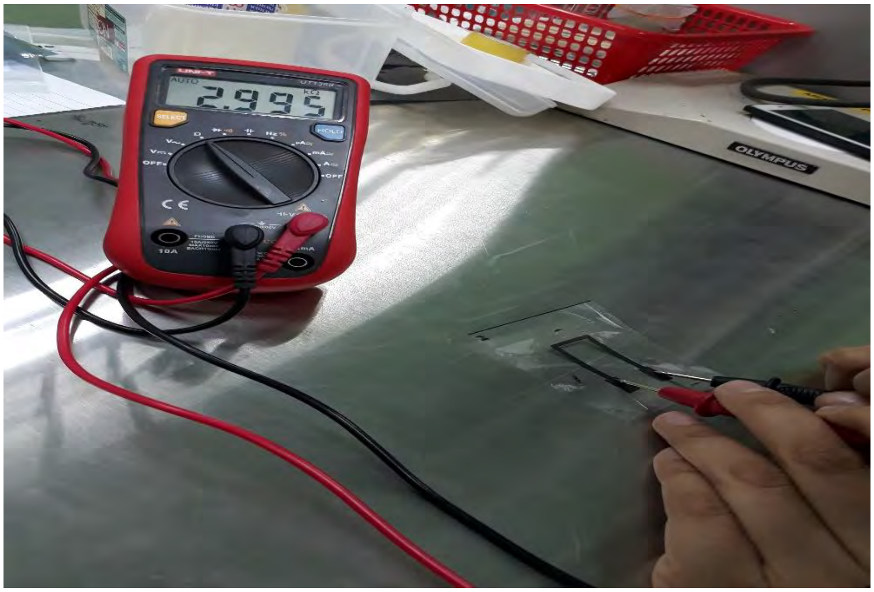


Figure 3.11: Circuit resistance data collection

3.2.7 Report Writing and Presentation

Report writing will be based on the testing and data analysis which has been done previously. The report writing will be follow on final year report format. For the presentation, all of the objective, testing, data and conclusion will be presented to the panel.

3.3 Project Gantt Chart

Task \ Week	PSM I														Semester Break	PSM II													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14		1	2	3	4	5	6	7	8	9	10	11	12	13	14
Consultation with supervisor	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	X
Literature Review	x	x	x	x	x	x	x	x	x	x	x	x	x	x		x	x	x	x	x	x	x	x	x	x	x	x	x	x
Project Planning	x																												
Identify Material		x																											
Facility Set Up			x	x																									
Set A Sample Preparation					x	x	x	x																					
Set B Sample Preparation									x	x	x	x																	
PSM I Report Writing													x																
PSM I Presentation														x															
Testing Set Up																x	x												
Set A Testing																		x	x	x	x								
Set B Testing																						x	x	x	x				
Data Analysis																										x			
PSM II Report Writing																											x	x	
PSM II Presentation																													x

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Overview

After completion of preparing different sample of circuit widths and thickness, all samples were taken initial resistivity and all of the resistance after completing each steps of the cycle were recorded and were shown in Table 4.1 to Table 4.10. With the data obtained, resistance-no of cycle curve for each of the sample with different width and thickness were shown on Figure 4.1 to Figure 4.10. Additionally, each of the table and line curve includes some summaries about the data obtained. Standard deviation on each tables was used to determine the consistency for each samples data.

4.2 Sample Data

All of the resistance data obtained before and after bending test was recorded and by using the resistivity data, resistance-no of cycle curve was formed.

4.2.1 Sample Width

(a) 1.0mm

Table 4.1: Resistance data of 1.0mm circuit width

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	7.340	5.002	7.817	6.720	1.230
500	7.118	4.664	7.443	6.408	1.240
1000	7.067	4.027	7.403	6.166	1.518
1500	6.947	4.015	7.327	6.096	1.480
2000	6.820	3.888	9.527	6.745	2.303
2500	7.883	3.834	8.203	6.640	1.988

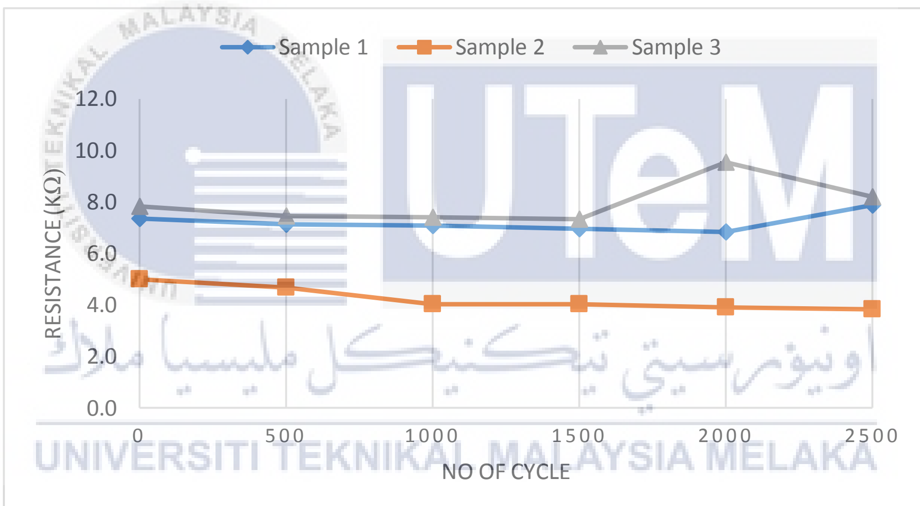


Figure 4.1: Average resistance of 1.0mm width sample

Table 4.1 shows the average resistance data for 1.0mm of width sample. The pattern of the resistance line shows on graph on Figure 4.1. From the data presents for 1.0mm, the highest average resistance occurs when the cyclic bending reach on 2000 cycles. Also shown the lowest average resistivity occurs when the cycle reach on 1500. The pattern line of the graph shows that when the 1.0mm off width sample bears with bending cycle, the resistance decrease on first 1500 cycles and increasing afterwards.

(b) 1.5mm

Table 4.2: Resistance data of 1.5mm circuit width

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	4.472	6.327	6.830	5.876	1.014
500	4.579	5.374	5.57	5.174	0.429
1000	4.614	5.553	5.937	5.368	0.556
1500	4.717	5.322	5.823	5.287	0.452
2000	4.770	5.370	5.603	5.248	0.351
2500	4.849	5.340	5.483	5.224	0.272

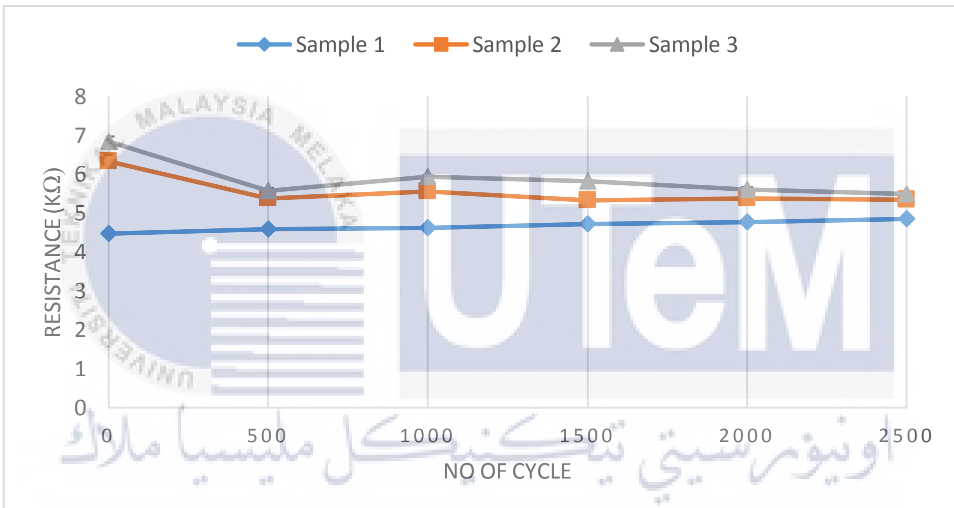


Figure 4.2: Average resistance of 1.5mm width sample

For the average resistance data for 1.5mm, the result was shown on Table 4.2. the line pattern for each of the sample shown in Figure 4.2. From the data obtain, as the bending cycle increase, the average resistance decrease. For the three sample tested, sample 1 of 1.5mm width show increment of average resistance, while for sample 2 and 3, the average resistance decrease.

(c) 2.0mm

Table 4.3: Resistance data of 2.0mm circuit width

No of Cycle	**Resistance (kΩ)**			**Average Resistance (kΩ)**	**Standard Deviation**
	S1	**S2**	**S3**		
0	3.595	3.349	3.317	3.420	0.124
500	3.042	3.096	3.081	3.073	0.023
1000	2.930	3.539	3.053	3.174	0.263
1500	2.948	3.326	3.000	3.091	0.167
2000	2.877	3.207	3.077	3.054	0.136
2500	2.833	2.989	2.989	2.937	0.074

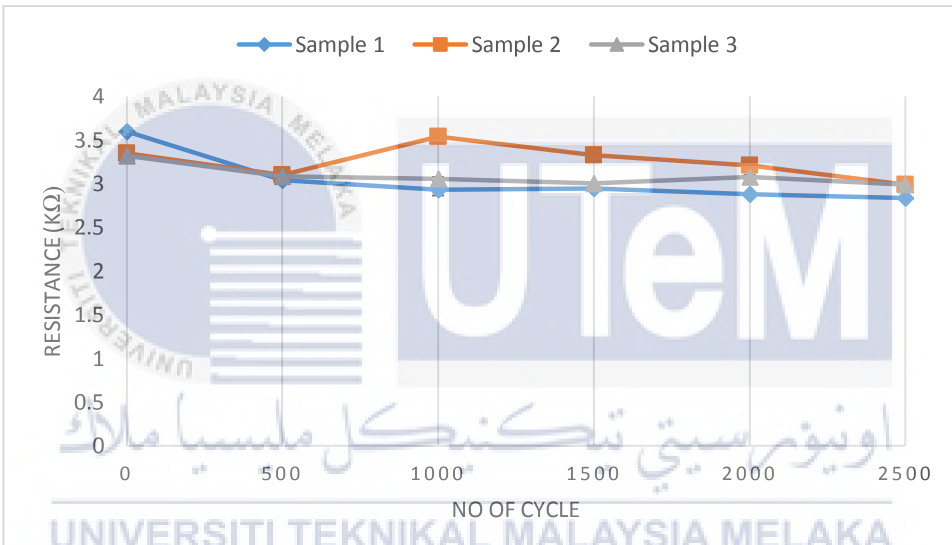


Figure 4.3: Average resistance of 2.0mm width sample

The average resistance for sample of 2.0mm width shown in Table 4.3. From Figure 4.3, the line graph pattern of 2.0mm width sample was shown. As shown in Figure 4.3, increasing of number of cycle resulting in decreasing of average resistance. The lowest resistance gets when the cycle reach 2500 where it was the last data reading after bending test. When bending cycle complete on all three samples, each of the samples resistance stays on average 2.9kΩ. meanwhile, the highest resistance recorded on initial resistance where no bending take place.

(d) 2.5mm

Table 4.4: Resistance data of 2.5mm circuit width

No of Cycle	**Resistance (kΩ)**			**Average Resistance (kΩ)**	**Standard Deviation**
	S1	**S2**	**S3**		
0	1.836	1.999	1.377	1.737	0.263
500	1.879	1.981	1.316	1.725	0.292
1000	1.908	2.001	1.392	1.767	0.268
1500	1.916	1.983	1.321	1.740	0.298
2000	1.949	1.917	1.37	1.745	0.266
2500	1.936	1.914	1.388	1.746	0.253

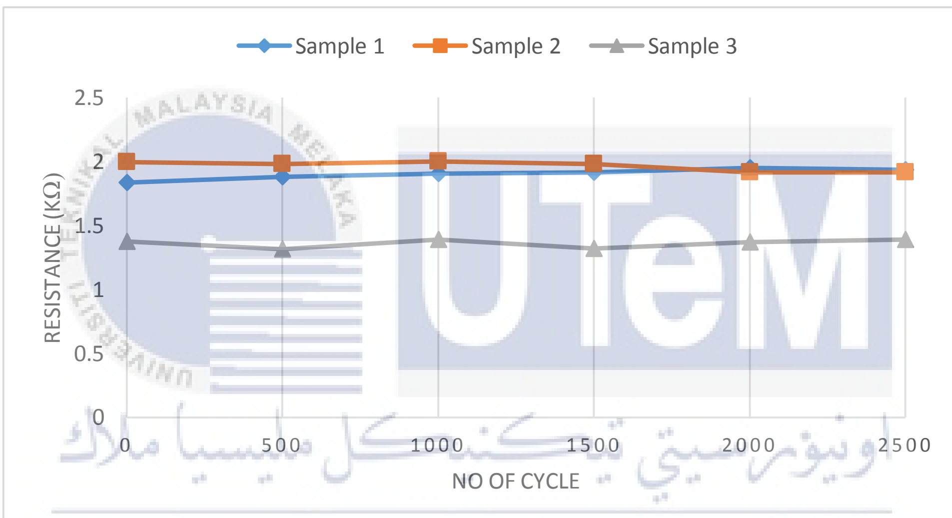


Figure 4.4: Average resistance of 2.5mm width sample

Table 4.4 presents the resistance data for 2.5mm width sample. The data then use to form line graph as shown on Figure 4.4. From the pattern of the line graph, 2.5mm of width sample tends to stay average constant where only slightly difference on each of the bending cycle done. The highest average resistance recorded on 1000 cycles mark where it reaches on 1.767kΩ of average with difference of 0.03kΩ from initial resistance. For average, the final data reading when complete 2500 bending cycles, each of the samples record 1.9kΩ while sample 3 on 1.3kΩ.

(e) 3.0mm

Table 4.5: Resistance data of 3.0mm circuit width

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	1.002	0.974	1.243	1.073	0.121
500	0.946	0.971	1.155	1.024	0.093
1000	0.921	1.033	1.173	1.042	0.103
1500	0.886	1.005	1.166	1.019	0.115
2000	0.869	1.081	1.155	1.035	0.121
2500	0.922	0.993	1.144	1.020	0.093

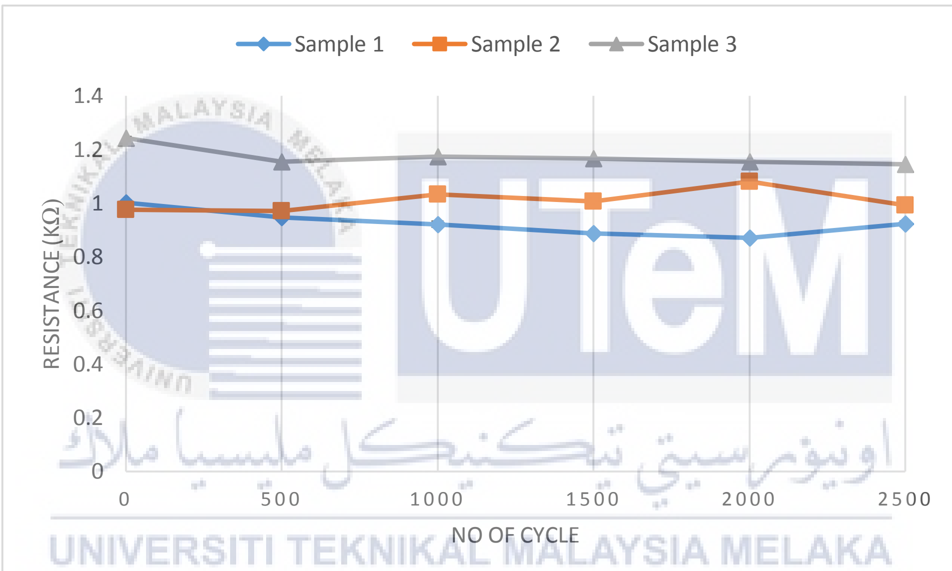


Figure 4.5: Average resistance of 3.0mm width sample

The resistance data of 3.0mm width sample was shown in Table 4.5. Figure 4.5 shows the line pattern of average resistance of 3.0mm width sample. Based on the data recorded, the resistance data for sample 1 and 3 shows decreasing of resistance meanwhile sample 2 recorded of increment. For the average resistance on each cycle, the final data taken on 2500 cycled recorded lower resistance compare with initial resistance reading as the line pattern of the graph averagely shows decreasing of resistance through cycles.

(f) Width sample average resistance

Table 4.6: Average data of width sample

No of Cycle	**Average Resistance (kΩ)**				
	1.0mm	**1.5mm**	**2.0mm**	**2.5mm**	**3.0mm**
0	6.720	5.876	3.420	1.737	1.073
500	6.408	5.174	3.073	1.725	1.024
1000	6.166	5.368	3.174	1.767	1.042
1500	6.096	5.287	3.091	1.740	1.019
2000	6.745	5.248	3.054	1.745	1.035
2500	6.640	5.224	2.937	1.747	1.020

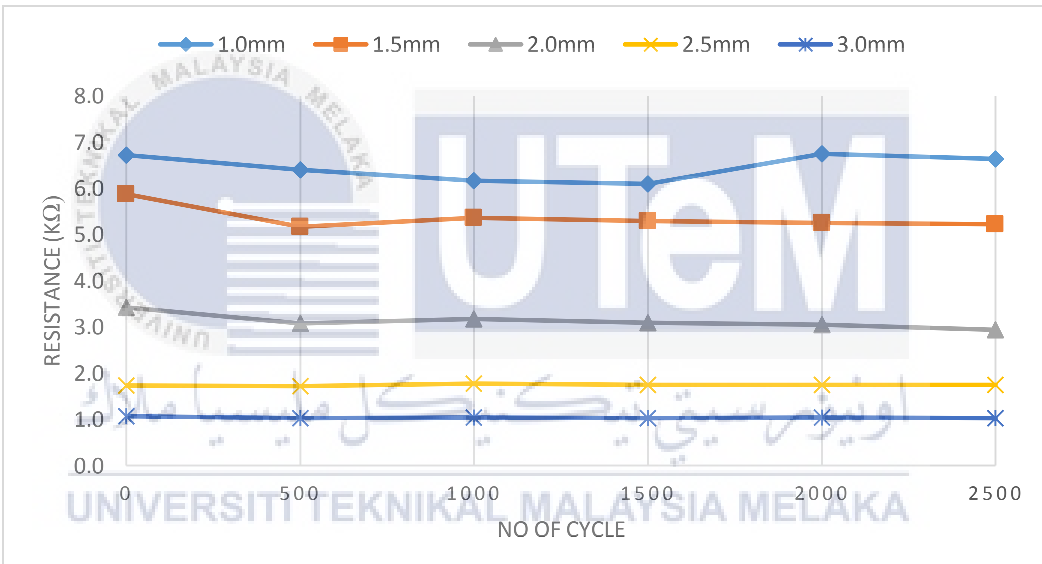


Figure 4.6: Line graph of width sample average resistance

The average resistance for width sample were shown in Table 4.6. Meanwhile, Figure 4.6 show the line pattern graph for width sample average resistance. From Table 4.6, the resistivity of the circuit tends to decrease when the circuit line width was increase. 1.0mm width data has shown highest resistivity on 6.720kΩ and the lowest was 3.0mm width on 1.073kΩ. After undergo cyclic bending load, the resistivity on each width shows reduction except on 2.5mm of width samples.

4.2.2 Sample Thickness

(a) 0.05mm

Table 4.7: Resistance data of 0.05mm circuit thick

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	3.027	2.977	2.921	2.975	0.053
500	3.001	3.139	2.519	2.886	0.326
1000	2.516	3.096	2.674	2.762	0.300
1500	2.425	3.076	2.448	2.650	0.369
2000	2.373	3.066	2.487	2.642	0.372
2500	2.315	3.075	2.589	2.660	0.385

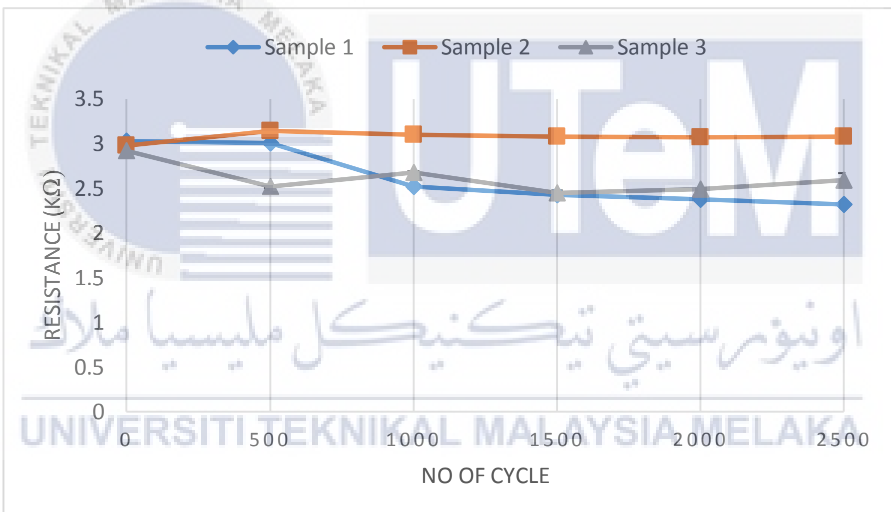


Figure 4.7: Average resistance of 0.05mm thick sample

Table 4.7 represents resistance data of 0.05mm thick sample. From the data obtained, the line pattern graph as shown in Figure 4.7 shows that increasing of number of cycle resulting in decreasing of the circuit resistance. Each of the sample completing the bending cycle shows lower resistance reading compare with initial resistance where the difference with both data were on 0.315kΩ.

(b) 0.1mm

Table 4.8: Resistance data of 0.1mm circuit thick

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	2.504	1.779	1.051	1.778	0.593
500	2.055	1.808	1.103	1.655	0.403
1000	1.96	1.741	1.082	1.594	0.373
1500	1.885	1.704	1.105	1.565	0.333
2000	1.886	1.665	1.138	1.563	0.314
2500	1.817	1.657	1.176	1.550	0.272

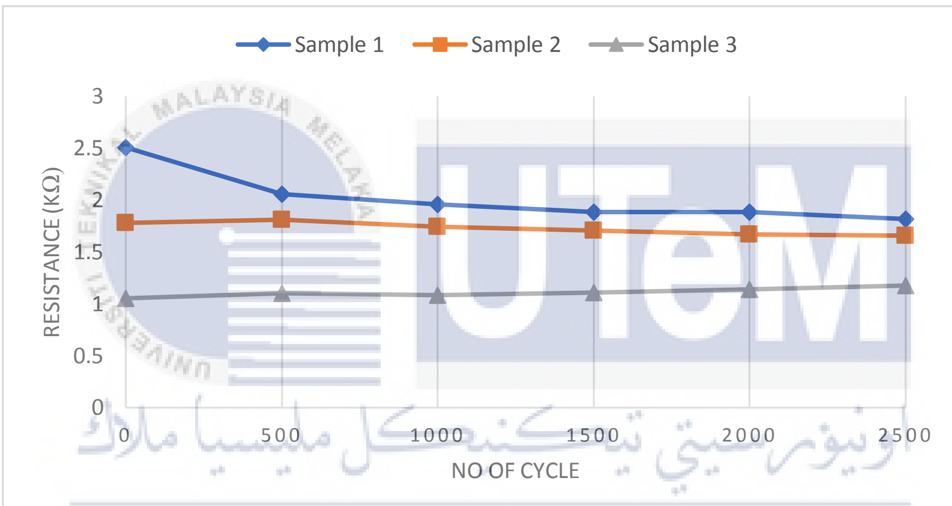


Figure 4.8: Average resistance of 0.1mm thick sample

For sample with 0.1mm of ink thickness, Table 4.8 shows the resistance recorded on each sample differ with number of cycles. Recorded data has been translated into line pattern graph as shown on Figure 4.8. For the data recorded, it was average same with 1-layer thickness data where it shows decreasing of average resistance until the end of the 2500 cycles. Sample 1 and 2 produce lower resistance compare with its initial reading before bending test while sample 3 recorded of increment of its resistivity.

(c) 0.15mm

Table 4.9: Resistance data of 0.15mm circuit thick

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	1.112	1.474	0.943	1.176	0.222
500	1.066	1.283	0.972	1.107	0.130
1000	1.012	1.262	1.074	1.116	0.106
1500	0.968	1.264	1.031	1.088	0.127
2000	0.944	1.283	1.016	1.081	0.146
2500	0.909	1.264	1.107	1.093	0.145

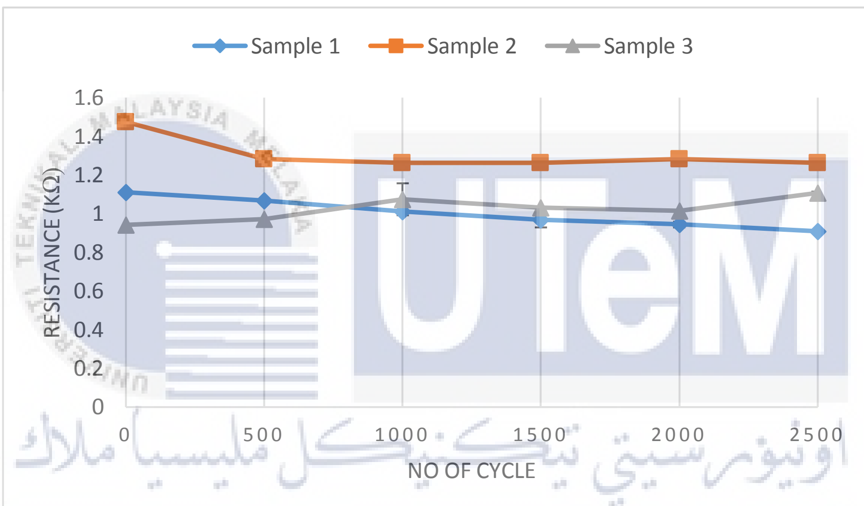


Figure 4.9: Average resistance of 0.15mm thick sample

Table 4.9 represents set of resistance data for 0.15mm thick sample and Figure 4.9 shows line pattern for the data recorded. Average resistance on each of the cycle until 2500 cycles recorded of decreasing resistance. The lower resistance from the initial resistance was shown on sample 1 and 2 while only sample 3 record of increasing of the circuit resistivity. At the end of the cycles, the resistance difference was recorded on about 0.083kΩ lower from initial resistance reading.

(d) 0.2mm

Table 4.10: Resistance data of 0.2mm circuit thick

No of Cycle	**Resistance (kΩ)**			**Average Resistance (kΩ)**	**Standard Deviation**
	S1	**S2**	**S3**		
0	1.250	1.641	1.015	1.302	0.258
500	1.245	1.536	0.991	1.257	0.223
1000	1.227	1.322	0.972	1.174	0.148
1500	1.256	1.285	0.935	1.159	0.159
2000	1.351	1.231	0.919	1.167	0.182
2500	1.304	1.117	0.912	1.111	0.160

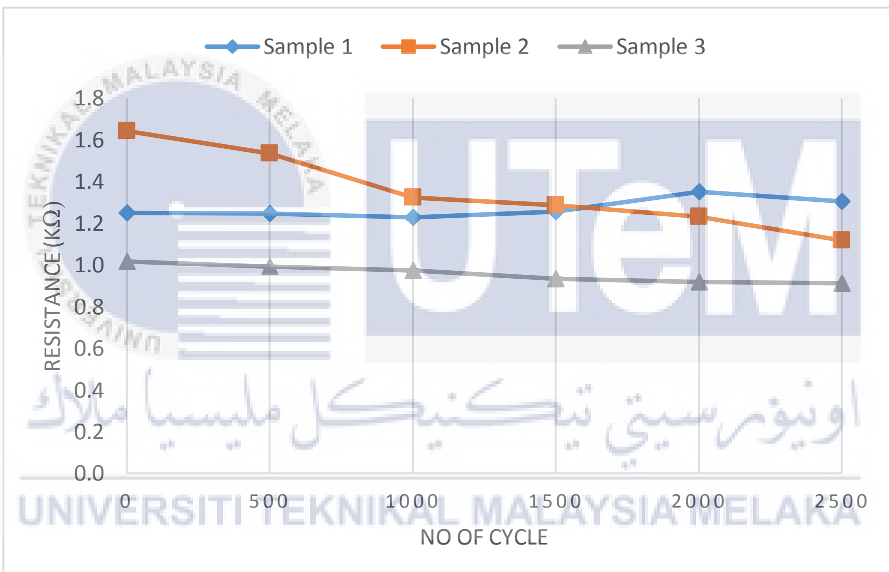


Figure 4.10: Average resistance of 0.2mm thick sample

The complete sets of average resistance on three sample of 0.2mm was record on Table 4.10. Next, Figure 4.10 shows the line pattern graph for average resistance of 0.2mm thick sample. From the data obtained, huge difference was recorded on sample 2 where the final reading after complete 2500 cyclic bending was about 0.524kΩ lower from its initial reading. Based on average resistance for each cycle for all of the sample, the pattern of the resistance was lower on complete 2500 bending cycle test.

(e) 0.25mm

Table 4.11: Resistance data of 0.25mm circuit thick

No of Cycle	Resistance (kΩ)			Average Resistance (kΩ)	Standard Deviation
	S1	S2	S3		
0	0.976	0.596	0.729	0.767	0.157
500	1.069	0.788	0.782	0.880	0.134
1000	1.156	0.816	0.861	0.944	0.151
1500	1.183	0.838	0.875	0.965	0.155
2000	1.311	0.848	0.874	1.011	0.212
2500	1.436	0.861	0.950	1.082	0.253

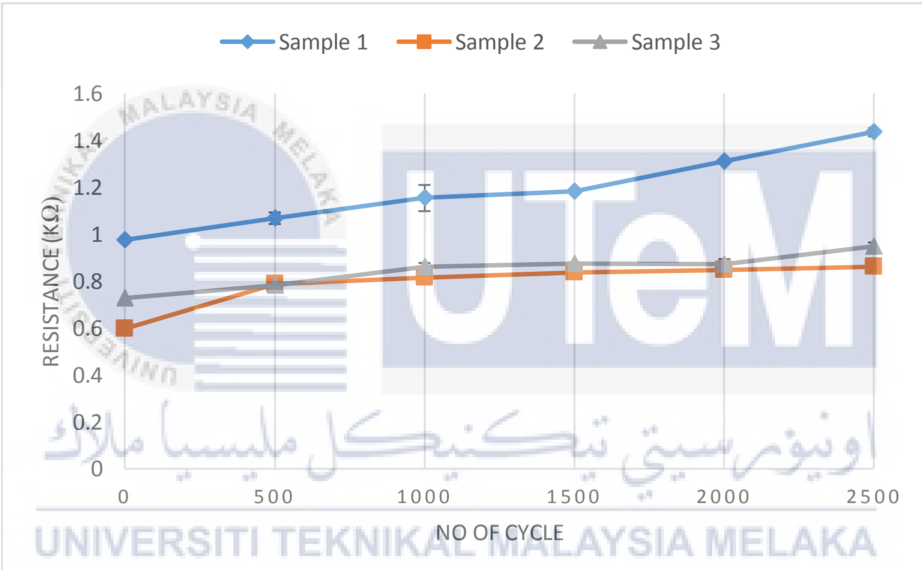


Figure 4.11: Average resistance of 0.25mm thick sample

All of the sample data for 0.25mm thick was recorded on Table 4.11. Based on the data obtained, the line graph was plot as shown on Figure 4.11. From the line graph plotted, 0.25mm thick sample was the only sample with increment of its circuit resistance alongside number of cycle. All three sample shows increment with increasing of bending cycle number. The average resistance on final cycle was about 0.315kΩ higher than its initial resistance.

(f) Thickness sample average resistance

Table 4.12: Average data of thickness sample

No of Cycle	Average Resistance (kΩ)				
	0.05mm	0.10mm	0.15mm	0.20mm	0.25mm
0	2.975	1.778	1.176	1.302	0.767
500	2.886	1.655	1.107	1.257	0.880
1000	2.762	1.594	1.116	1.174	0.944
1500	2.650	1.565	1.088	1.159	0.965
2000	2.642	1.563	1.081	1.167	1.011
2500	2.660	1.559	1.093	1.111	1.082

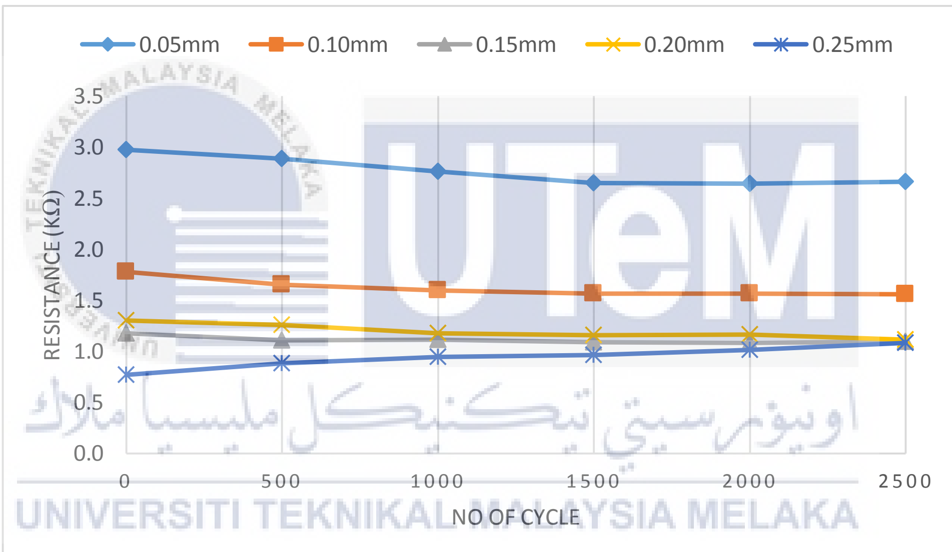


Figure 4.12: Line graph of thickness sample average resistance

The sets of average resistance on thickness was record on Table 4.11. Figure 4.12 shows the line graph of thickness sample average resistance. Based on the line graph on Figure 4.12, the initial resistance recorded on decreasing of resistivity when the circuit thickness increase where 0.05mm recorded on 2.975kΩ and 0.25mm recorded on 0.767kΩ. After completing cyclic bending load, the resistivity on each thickness samples tends to decreased except on the thickest samples which was 0.25mm recorded on increasing of resistivity.

4.3 Discussion

4.3.1 Initial Resistance

The process on fabrication of conductive ink print on surface of PET was illustrated in Table 3.3 where the process was done by using manual technique. The pattern design of the circuit was design by using Catia program which the width and the length of the circuit was properly measured.

Based on the recorded data, on an early resistance without bending cycle, we see a significant standard deviation gap at width 1.0mm and 1.5mm. Based on the observation using the image analyzer as shown in Figure 4.13 and 4.15, there is a defect on the circuit line and that may be due to inaccuracy and human error when the process makes the sample and printing process take place. The sample preparation procedure by using adhesive tape can be another factor whereby the early resistance does not constant. The proper way to complete screen printing by using correct tools such as solid stencil where usually by using thin sheet metal where the design of the circuit will be engraving on it. Such factors may be the reason why there is a relatively large gap in the data resistance at even on the same width.

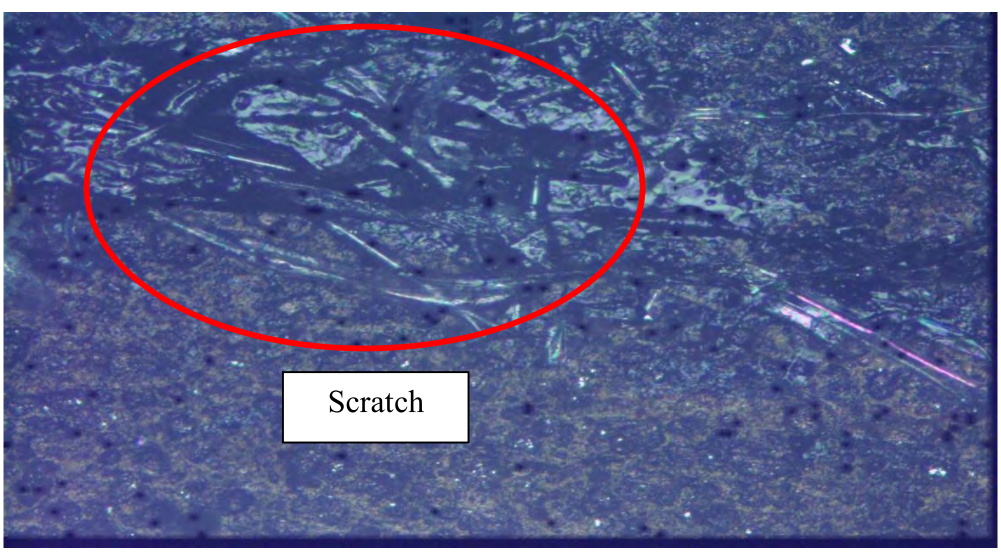


Figure 4.13: Sample 3 of 1 mm width with scratch circuit

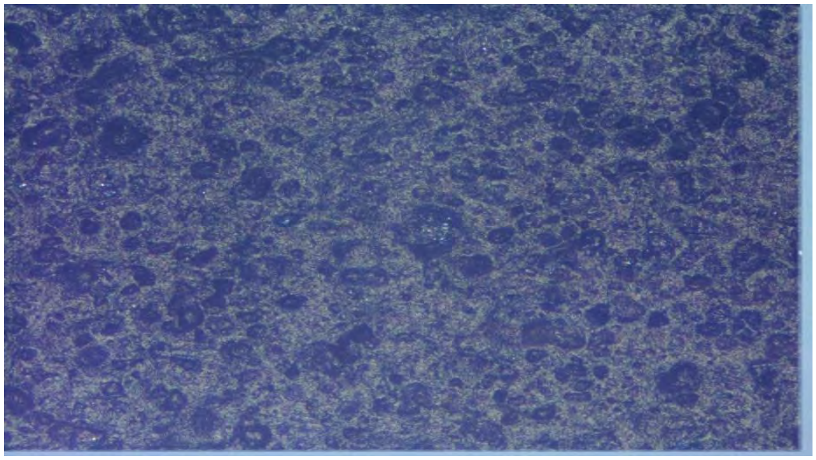


Figure 4.14: Sample 1 of 0.25mm thickness with normal surface

In addition to cracking, on samples with relatively high resistance, there is also a porosity on the circuit that may be due to uneven surface of the substrate. The problems with uneven surface occur usually because of the scratch on the surface of the PET because of the mark of peeling adhesive tape from the PET following the line of the pattern. The result of porosity could be occur based on the thickness off the ink layer. This means on the sample of 1 layer, the ink use was particularly less compare with 4 or 5 layers of sample. When the ink use was less, the ink could go into PET cavity if have. Different amount of ink on different material use for the substrate resulting in differences of resistance of the ink. When the thickness of the ink on the samples was bigger, the resistance produce is lower and it was greatly because of the amount of the ink used was much more. If there are large thickness variation, there was partially less ink amount use in the circuit and can increase the resistance (Merilampi et al., 2009). Figure 4.15 show the sample of circuit with porosity.

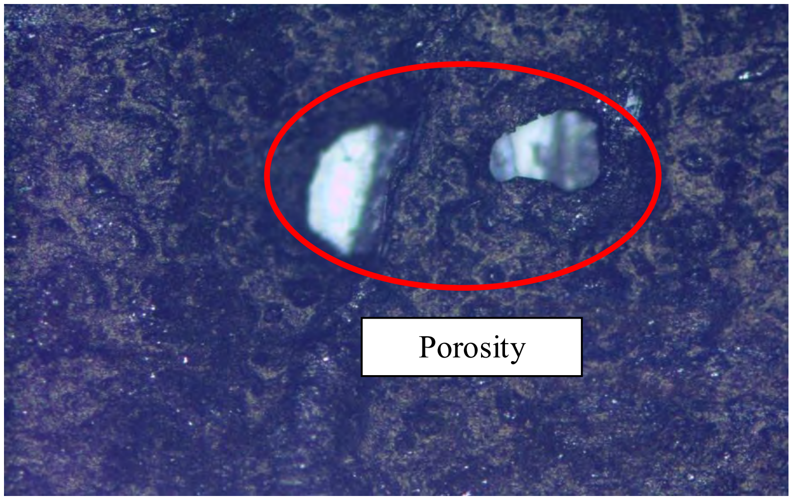


Figure 4.15: Sample 1 of 2.5mm width with porosity

The conductive ink manufacturer which was Bare conductive states that to their electric conductive ink was fast drying at room temperature. But on completing the sample, it was placed in air conditioning room which may negatively or greatly affect the performance of the ink and also the physical condition which resulting of different group of early resistance data. The ink curing time can be reduced by placing the ink near low intensity heat such as incandescent lamp and gives off no fumes when drying process occur. The cured ink composition may greatly affect the resistance of the ink resistance followed by its shape, orientation, amount of particles in the ink, particle size distribution, and resistance other effect (Merilampi et al., 2009)

4.3.2 Resistance Changes After Bending Tests

All of the sample tested was dispersed with bare carbon conductive ink. The ink used was to completely fabricate the flexible sample on flexible substrate which was PET by using screen printing technique. The conductive ink was cured at approximately room temperature for about one day before taking the initial resistance reading. All of the data after bending test was taken rightly after completing each number of cycles. This study goal was to determine the ink printed on PET substrate resistance after it goes each number of bending cycles. The bending test were performed using circular to linear motion mechanism testing rig as shown in Figure 3.10. The changes of resistance after bending test was shown in Figure 4.1 to Figure 4.10.

For the width samples, the samples with width 1.5mm achieved the highest difference between its initial resistance (5.876kΩ) and resistance after completing 2500 bending cycles (5.224kΩ). Meanwhile, for the thickness sample, the most difference resistance achieved by 0.25mm thickness of ink samples where the initial resistance was 0.767kΩ and complete 2500 bending cycles resistance was 1.082kΩ. After completing 2500 bending cycles, the adhesion of the ink with the substrate was good as no samples with peel off ink from the substrate. In average, the resistance difference on each samples were highest for the first 500 cycles where the difference varies on 0.012kΩ until the highest was 0.702kΩ recorded on 1.5mm width samples. However, on the end of complete bending cycles, the samples with different width of conductive ink shows slightly effect changes on its resistance from initial until complete cycles as shown in Table 4.1-4.5.

Breaking of the inter particles contact and breaking of the networks were the basic mechanism in producing the increment of resistance when goes under cyclic bending test (Merilampi et al., 2009). When the structure of the ink was affected such as crack or breaking from particles contact, the resistance of the ink may increase. This was different from the data obtained in this study whereby no data was linearly increased. From the ink structure seen by using image analyzer**,** the ink structure that goes cyclic bending test does not crack nor breaks apart on each other which means the ink structure has a good bonding between each other. This can be concluded that the adhesion of the Bare conductive ink and the surface of PET was good that it still intact with each other. The image of the ink structure was shown on Appendix K and L**.**

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Based on the objectives, flexible printed circuit using SWCNT conductive ink on PET substrate at varying circuity width and thickness was fabricated. Each sample set 3 repetitions was conducted and the initial resistivity for all samples were taken. Results showed that higher circuit width and thickness produced lower circuit resistivity.

The samples were later subjected to varying cyclic bending load and changes in resistivity were recorded. From all of the resistivity data obtained, almost all set of samples varying width and thickness achieved decreased in resistivity after being subjected with higher bending cycles. Up to 2500 bending cycle, as the width increase, resistivity reduced except for 2.5mm width. Similarly, up to 2500 bending cycles, incremental of thickness resulting in decreasing of resistivity except for 0.25mm thickness. It can also be observed that at higher thickness, the ink that went into bending cycles were producing additional resistivity.

5.2 Recommendation

For the recommendation for future improvement and study, to improve the resistance result, from the first step of sample preparation must be done with proper way, technique, tools and equipment. This has to be done to reduce error on initial resistivity and to achieve almost similar resistance on same sample width or thickness. The curing time for the ink must followed the guide given from ink manufacturer. Plus, a detailed experimental observation data must be obtained to know the conductive ink characteristics. To minimize testing error during conducting test, proper test rig must be used in order to reduce time of test and error. To reduce the time during testing, higher speed motor is required. Besides that, different pattern of circuit print on PET substrate can be studied to determine the effect of circuit pattern toward resistivity.

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APPENDIX A

Raw Data of 1.0mm Width Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	7.360	7.360	7.300	7.340	0.035
	500	7.200	7.220	7.110	7.177	0.059
	1000	7.080	7.070	7.050	7.067	0.015
	1500	6.900	6.910	7.030	6.947	0.072
	2000	6.820	6.840	6.800	6.820	0.020
	2500	7.830	7.930	7.890	7.883	0.050

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	5.008	5.001	4.996	5.002	0.006
	500	4.662	4.661	4.668	4.664	0.004
	1000	4.024	4.040	4.018	4.027	0.011
	1500	4.032	4.023	3.989	4.015	0.023
	2000	3.901	3.903	3.859	3.888	0.025
	2500	3.830	3.852	3.820	3.834	0.016

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	7.750	7.800	7.900	7.817	0.076
	500	7.450	7.410	7.470	7.443	0.031
	1000	7.420	7.390	7.400	7.403	0.015
	1500	7.300	7.320	7.360	7.327	0.031
	2000	9.020	9.920	9.640	9.527	0.461
	2500	8.270	8.200	8.140	8.203	0.065

APPENDIX B

Raw Data of 1.5mm Width Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	4.451	4.482	4.484	4.472	0.019
	500	4.587	4.565	4.585	4.579	0.012
	1000	4.613	4.618	4.612	4.614	0.003
	1500	4.720	4.724	4.708	4.717	0.008
	2000	4.761	4.780	4.768	4.770	0.010
	2500	4.868	4.848	4.832	4.849	0.018

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	6.300	6.380	6.300	6.327	0.046
	500	5.400	5.350	5.372	5.374	0.025
	1000	5.460	5.630	5.570	5.553	0.086
	1500	5.430	5.327	5.210	5.322	0.110
	2000	5.480	5.414	5.217	5.370	0.137
	2500	5.403	5.349	5.268	5.340	0.068

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	6.980	6.730	6.780	6.830	0.132
	500	5.500	5.620	5.590	5.570	0.062
	1000	5.940	5.970	5.900	5.937	0.035
	1500	5.820	5.850	5.800	5.823	0.025
	2000	5.530	5.670	5.610	5.603	0.070
	2500	5.430	5.460	5.560	5.483	0.068

APPENDIX C

Raw Data of 2.0mm Width Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	3.628	3.600	3.558	3.595	0.035
	500	3.060	3.055	3.011	3.042	0.027
	1000	2.976	2.961	2.853	2.930	0.067
	1500	2.966	2.960	2.917	2.948	0.027
	2000	2.864	2.894	2.874	2.877	0.015
	2500	2.825	2.807	2.867	2.833	0.031

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	3.38	3.341	3.326	3.349	0.028
	500	3.108	3.071	3.109	3.096	0.022
	1000	3.559	3.528	3.531	3.539	0.017
	1500	3.349	3.303	3.325	3.326	0.023
	2000	3.194	3.201	3.227	3.207	0.017
	2500	2.982	2.989	2.996	2.989	0.007

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	3.329	3.327	3.294	3.317	0.020
	500	3.095	3.085	3.064	3.081	0.016
	1000	3.076	3.052	3.032	3.053	0.022
	1500	3.005	3.003	2.993	3.000	0.006
	2000	3.076	3.056	3.098	3.077	0.021
	2500	2.982	2.989	2.996	2.989	0.007

APPENDIX D

Raw Data of 2.5mm Width Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	1.823	1.852	1.833	1.836	0.015
	500	1.883	1.879	1.875	1.879	0.004
	1000	1.905	1.911	1.908	1.908	0.003
	1500	1.913	1.915	1.921	1.916	0.004
	2000	1.945	1.949	1.953	1.949	0.004
	2500	1.937	1.933	1.938	1.936	0.003

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	1.998	1.980	2.020	1.999	0.020
	500	1.979	1.990	1.973	1.981	0.009
	1000	2.008	1.992	2.003	2.001	0.008
	1500	1.984	1.969	1.996	1.983	0.014
	2000	1.934	1.896	1.920	1.917	0.019
	2500	1.916	1.900	1.925	1.914	0.013

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	1.383	1.372	1.377	1.377	0.006
	500	1.311	1.319	1.318	1.316	0.004
	1000	1.396	1.394	1.386	1.392	0.005
	1500	1.314	1.326	1.322	1.321	0.006
	2000	1.369	1.375	1.366	1.370	0.005
	2500	1.389	1.386	1.390	1.388	0.002

APPENDIX E

Raw Data of 3.0mm Width Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	1.010	1.001	0.994	1.002	0.008
	500	0.947	0.948	0.942	0.946	0.003
	1000	0.933	0.920	0.911	0.921	0.011
	1500	0.884	0.885	0.890	0.886	0.003
	2000	0.869	0.873	0.865	0.869	0.004
	2500	0.920	0.932	0.914	0.922	0.009

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	0.98	0.953	0.989	0.974	0.019
	500	0.972	0.968	0.974	0.971	0.003
	1000	1.027	1.033	1.038	1.033	0.006
	1500	1.002	1.001	1.011	1.005	0.006
	2000	1.083	1.087	1.074	1.081	0.007
	2500	0.998	0.989	0.993	0.993	0.005

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	1.238	1.245	1.246	1.243	0.004
	500	1.155	1.158	1.151	1.155	0.004
	1000	1.172	1.176	1.17	1.173	0.003
	1500	1.166	1.17	1.163	1.166	0.004
	2000	1.159	1.154	1.151	1.155	0.004
	2500	1.142	1.14	1.149	1.144	0.005

APPENDIX F

Raw Data of 0.05mm Thick Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	3.050	3.010	3.021	3.027	0.021
	500	2.675	2.679	2.649	2.668	0.016
	1000	2.515	2.494	2.539	2.516	0.023
	1500	2.445	2.416	2.413	2.425	0.018
	2000	2.369	2.377	2.374	2.373	0.004
	2500	2.326	2.314	2.304	2.315	0.011

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	2.978	2.973	2.979	2.977	0.003
	500	3.105	3.158	3.153	3.139	0.029
	1000	3.097	3.096	3.096	3.096	0.001
	1500	3.079	3.096	3.052	3.076	0.022
	2000	3.072	3.057	3.069	3.066	0.008
	2500	3.076	3.072	3.078	3.075	0.003

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	2.913	2.922	2.927	2.921	0.007
	500	2.525	2.53	2.503	2.519	0.014
	1000	2.692	2.675	2.655	2.674	0.019
	1500	2.454	2.472	2.418	2.448	0.027
	2000	2.486	2.489	2.486	2.487	0.002
	2500	2.561	2.532	2.675	2.589	0.076

APPENDIX G

Raw Data of 0.1mm Thick Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	2.503	2.516	2.493	2.504	0.012
	500	2.066	2.045	2.054	2.055	0.011
	1000	1.946	1.998	1.935	1.960	0.034
	1500	1.887	1.889	1.879	1.885	0.005
	2000	1.885	1.880	1.893	1.886	0.007
	2500	1.818	1.811	1.822	1.817	0.006

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	1.808	1.774	1.755	1.779	0.027
	500	1.800	1.808	1.801	1.803	0.004
	1000	1.749	1.736	1.738	1.741	0.007
	1500	1.703	1.702	1.706	1.704	0.002
	2000	1.674	1.654	1.668	1.665	0.010
	2500	1.661	1.659	1.650	1.657	0.006

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	1.048	1.050	1.055	1.051	0.004
	500	1.103	1.105	1.101	1.103	0.002
	1000	1.071	1.087	1.089	1.082	0.010
	1500	1.099	1.114	1.101	1.105	0.008
	2000	1.153	1.130	1.130	1.138	0.013
	2500	1.171	1.179	1.178	1.176	0.004

APPENDIX H

Raw Data of 0.15mm Thick Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	1.115	1.116	1.104	1.112	0.007
	500	1.060	1.072	1.065	1.066	0.006
	1000	1.015	1.012	1.010	1.012	0.003
	1500	0.982	0.999	0.922	0.968	0.040
	2000	0.941	0.959	0.932	0.944	0.014
	2500	0.912	0.910	0.906	0.909	0.003

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	1.484	1.475	1.462	1.474	0.011
	500	1.290	1.275	1.283	1.283	0.008
	1000	1.274	1.266	1.247	1.262	0.014
	1500	1.259	1.265	1.268	1.264	0.005
	2000	1.283	1.286	1.279	1.283	0.004
	2500	1.255	1.257	1.280	1.264	0.014

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	0.940	0.945	0.945	0.943	0.003
	500	0.970	0.974	0.972	0.972	0.002
	1000	1.171	1.023	1.029	1.074	0.084
	1500	1.029	1.027	1.036	1.031	0.005
	2000	1.016	1.017	1.015	1.016	0.001
	2500	1.112	1.11	1.099	1.107	0.007

APPENDIX I

Raw Data of 0.2mm Thick Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard deviation
		1	2	3		
1	0	1.252	1.251	1.246	1.250	0.003
	500	1.234	1.246	1.254	1.245	0.010
	1000	1.234	1.215	1.231	1.227	0.010
	1500	1.255	1.254	1.259	1.256	0.003
	2000	1.342	1.356	1.355	1.351	0.008
	2500	1.303	1.309	1.301	1.304	0.004

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	1.653	1.628	1.641	1.641	0.013
	500	1.548	1.524	1.537	1.536	0.012
	1000	1.324	1.322	1.319	1.322	0.003
	1500	1.291	1.281	1.284	1.285	0.005
	2000	1.236	1.234	1.222	1.231	0.008
	2500	1.168	1.186	1.179	1.178	0.009

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	1.018	1.017	1.010	1.015	0.004
	500	0.993	0.989	0.991	0.991	0.002
	1000	0.982	0.966	0.969	0.972	0.009
	1500	0.940	0.934	0.930	0.935	0.005
	2000	0.918	0.920	0.918	0.919	0.001
	2500	0.913	0.911	0.912	0.912	0.001

APPENDIX J

Raw Data of 0.25mm Thick Sample

Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
1	0	0.976	0.983	0.97	0.976	0.007
	500	1.041	1.091	1.075	1.069	0.026
	1000	1.127	1.221	1.121	1.156	0.056
	1500	1.186	1.184	1.179	1.183	0.004
	2000	1.307	1.311	1.316	1.311	0.005
	2500	1.425	1.427	1.457	1.436	0.018

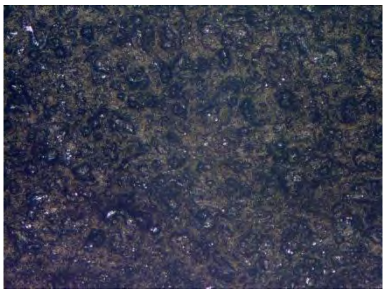
Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
2	0	0.578	0.612	0.599	0.596	0.017
	500	0.778	0.796	0.789	0.788	0.009
	1000	0.822	0.815	0.812	0.816	0.005
	1500	0.84	0.839	0.835	0.838	0.003
	2000	0.849	0.845	0.851	0.848	0.003
	2500	0.859	0.863	0.861	0.861	0.002

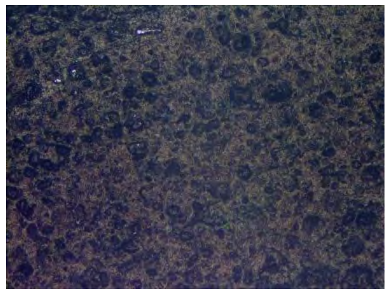
Sample	Cycle	Resistance (k Ω)			Average resistance (k Ω)	Standard Deviation
		1	2	3		
3	0	0.726	0.730	0.731	0.729	0.003
	500	0.782	0.786	0.779	0.782	0.004
	1000	0.879	0.860	0.843	0.861	0.018
	1500	0.880	0.875	0.869	0.875	0.006
	2000	0.897	0.86	0.864	0.874	0.020
	2500	0.968	0.947	0.935	0.950	0.017

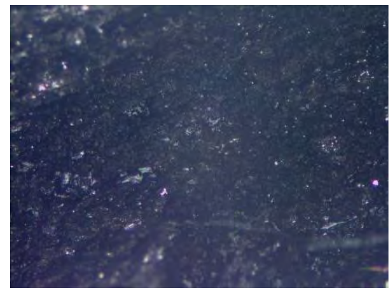
APPENDIX K

Image Analyzer of Width Sample

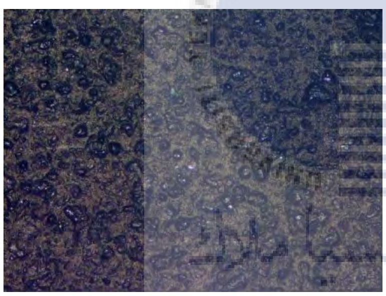
<u>1.0mm</u>

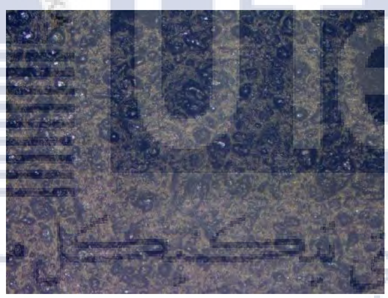


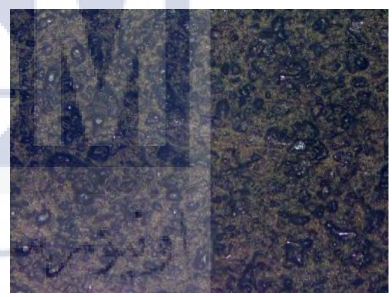




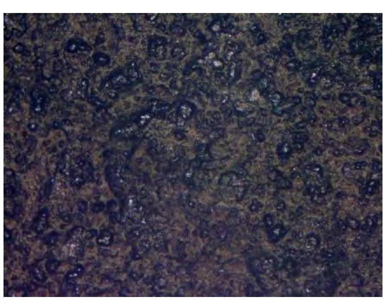
<u>1.5mm</u>

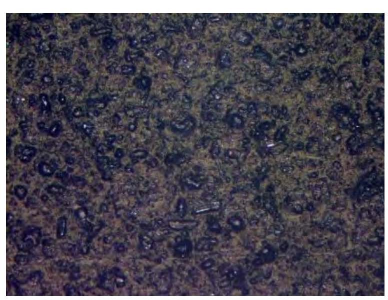


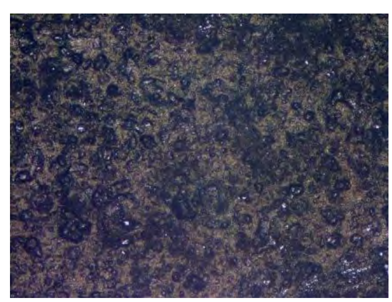




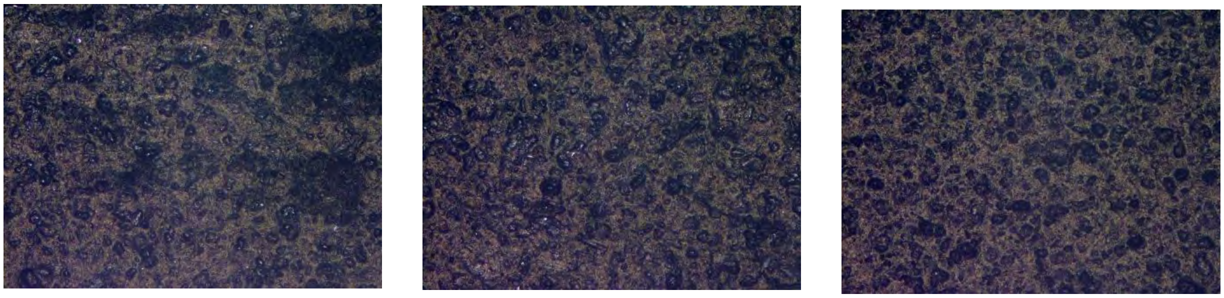
<u>2.0mm</u>







2.5mm

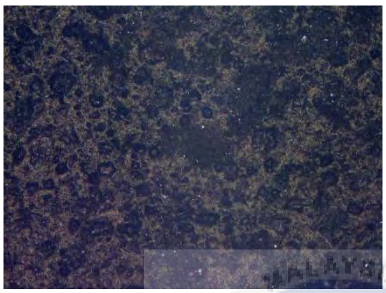
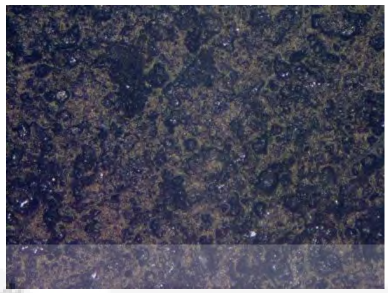
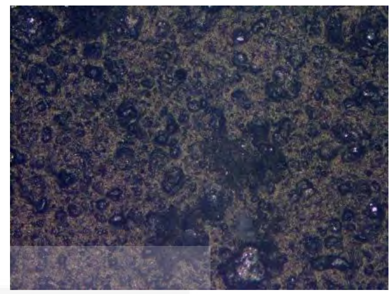


3.0mm

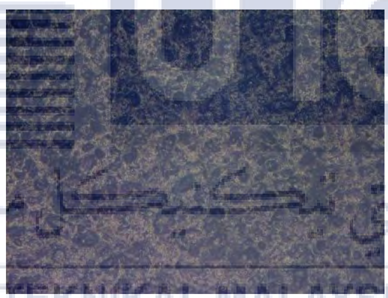
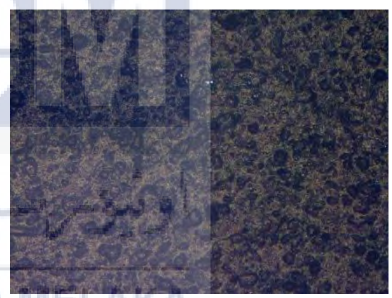
APPENDIX L

Image Analyzer of Thickness Sample

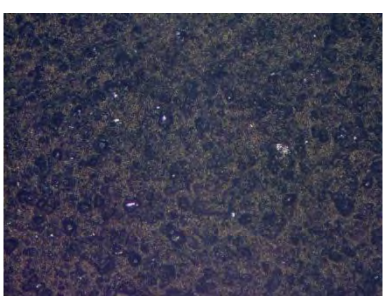
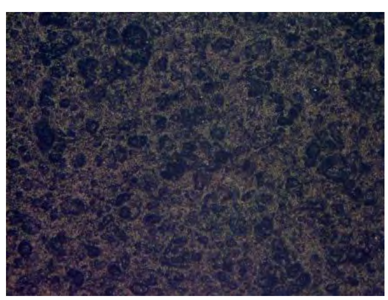
<u>0.05mm</u>

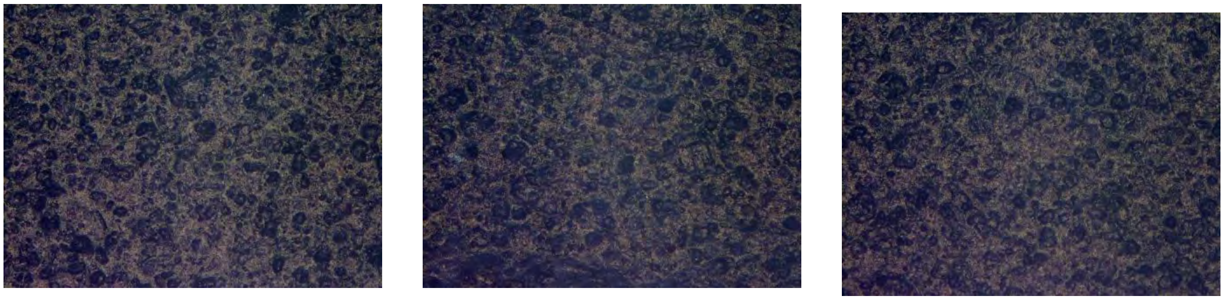
<u>0.10mm</u>

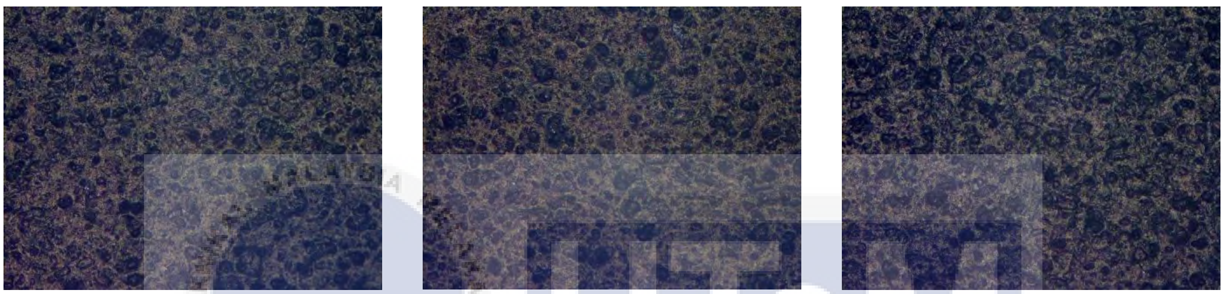
<u>0.15mm</u>


0.20mm



0.25mm



APPENDIX M

Bare Conductive Ink Technical Data Sheet

BARE CONDUCTIVE

ELECTRIC PAINT

Technical Data Sheet

PRODUCT DESCRIPTION

Electric Paint is a nontoxic, water based, water soluble, electrically conductive paint. It can be used in circuits as a painted resistor element, a capacitive electrode or can function as a conductor in designs that can tolerate high resistivity. It is intended for applications with circuits using low DC voltages at low currents. **Electric Paint** adheres to a wide variety of substrates and can be applied using screen printing equipment. Its major benefits include low cost, solubility in water and good screen life. It is black in colour and can be over-painted with any material compatible with a water-based paint.

ADVANTAGES / PRODUCT BENEFITS

- High resistivity
- Nontoxic
- Water-soluble
- Can be used to create capacitive touch and proximity sensors
- Can be used as a potentiometer or resistive circuit element
- Compatible with many standard printing processes
- Low cost

TYPICAL PROPERTIES

Colour /	Black
Viscosity /	Highly viscous and shear sensitive (thixotropic)
Density /	1.16 g/ml
Surface Resistivity /	55 Ω/Sq/50 microns
Vehicle /	Water-based
Drying Temperature /	**Electric Paint** should be allowed to dry at room temperature for 5 – 15 minutes. Drying time can be reduced by placing Electric Paint under a warm lamp or other low intensity heat source.

See below summary table of typical properties.

PROCESSING AND HANDLING

Screen Printing Equipment /	Manual
Screen Types /	Polyester, stainless steel (43T – 90T gauge mesh)
Typical Cure Conditions /	Room temperature (24'C) for 15 minutes
Typical Circuit Line Width /	0.5 – 10mm (43T-mesh stainless steel screen)
Clean-up Solvent /	Warm water and soap
Surface Resistivity /	32Ω/Sq when using a brush or manual screen printing
Shelf Life /	6 months after opening
Storage /	**Electric Paint** should be stored, tightly sealed in a clean, stable environment at room temperature. Composition should be thoroughly mixed prior to use.

See below graph to predict resistance using manual screen printing.

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TYPICAL PROPERTIES TABLE

TEST	PROPERTIES
TABLE 1 TYPICAL PHYSICAL PROPERTIES	
Sheet Resistivity (ohms/sq/50 microns)	55
Density (g/ml)	1.16
TABLE 2 COMPOSITION PROPERTIES	
Viscosity	Thixotropic
Thinner	Water

Table 1 and 2 show anticipated physical properties for **Electric Paint** based on specific controlled experiments in our labs when applied highly accurately. For more realistic values for application of the paint with brushes and screen printing see the below graph and equation. Further notes on working with **Electric Paint** can be found in **Application Notes.**

PROCESSING GRAPH AND EQUATION

When processed using manual screen printing one can expect a surface resistivity of 32 Ω/Sq. The below graph illustrates how resistance changes with line shape and a simple equation can be applied to roughly predict surface resistance:

Resistance = 19.77(length/width) + 12