RELIABILITY STUDY OF PRINTED ELECTRONICS ON FLEXIBLE SUBSTRATE FOR AUTOMOTIVE LIGHTING APPLICATION

SITI KHUZAIMAH BT MOHD AMIN

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

RELIABILITY STUDY OF PRINTED ELECTRONICS ON FLEXIBLE SUBSTRATE FOR AUTOMOTIVE LIGHTING APPLICATION

SITI KHUZAIMAH BT MOHD AMIN

A report submitted

In fulfilment of the requirements for the degree of

Bachelor of Mechanical Engineering

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

JUNE 2019

DECLARATION

I declare that this project report entitled "Reliability Study of Printed Electronics on Flexible Substrate for Automotive Lighting Application" is the result of my own work except as cited in the references

Signature : ....

Name : ....

Date : ....

APPROVAL

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

Signature : ....

Supervisor's Name : ....

Date : ....

DEDICATION

To my beloved parents;

Hasman bin Mohd, Jumeah bt Awan

ABSTRACT

This research demonstrates the effect of different geometrical parameter on the reliability performance of the printed circuit. The circuit thickness is fixed at 1 mm while the width are varied at 1 mm, 2 mm and 3 mm. The square-shaped circuit pattern is printed on PET substrate by using the screen-printing method. The samples are tested in both functionality and reliability performances. Functionality test result shows that thicker line width contribute to lesser sheet resistivity, which will increase the electrical conductivity. The initial sample's sheet resistance also shows good compliance to the theoretical value provided by the Conductive Ink Technical Data Sheet. The samples are then exposed to twisting test and the overall resistance are recorded. The values are then compared with the preferred resistance value for a standard LED. The resistance comparison before and after application of mechanical load verified that the circuit will experience higher resistance and sheet resistance value. The measured resistance from this research shows exceptionally high reading; exceeding the needed resistance for LED lighting application. Theoretically, the LED, however, will be able to light up but it will contribute to electrical energy wastage since higher current are needed to overcome the high circuit resistance. Thus, it can be concluded that the printed circuit board in this research are only sufficient to act as the benchmark design for further improvement to serve industrial or market purpose.

ABSTRAK

Kajian ini mengenalpasti kesan dari perbezaan parameter pada ketahanan litar bercetak. Ketebalan litar ditetapkan pada 1 mm manakala kelebarannya terbahagi kepada 3 bacaan iaitu 1 mm, 2 mm dan 3 mm. Litar yang berbentuk petak tersebut dicetak diatas substrat PET dengan menggunakan kaedah percetakan skrin. Sampel tersebut diuji dengan dua cara iaitu dari segi fungsi dan juga ketahanan. Keputusan dari ujian fungsi menunjukkan litar yang mempunyai kelebaran yang tinggi menyumbang kepada pengurangan dari nilai rintangan lembaran, dan ini meningkatkan nilai kekonduksian elektrik. Nilai awal bagi rintangan lembaran untuk sampel juga selaras dengan nilai teori seperti yang dinyatakan di Conductive Ink Technical Data Sheet. Sampel kemudiannya didedahkan kepada daya pusingan berulang dan nilai rintangan dicatatkan. Kemudian, nilai tersebut dibandingkan dengan nilai rintangan yang sesuai bagi penggunaan LED. Perbezaan antara kedua bacaan (sebelum dan selepas dikenakan daya) membuktikan bahawa litar akan mengalami nilai rintangan yang lebih setelah dikenakan daya pusingan, melebihi nilai yang dikehendaki oleh LED. Secara teorinya, LED akan dapat dinyalakan tanpa masalah, namun ianya akan mengakibatkan pembaziran tenaga elektrik kerana nilai arus yang tinggi diperlukan bagi mengatasi nilai rintangan litar yang tinggi. Secara konklusinya, litar yang dihasilkan dari kajian ini hanya mampu dijadikan tanda aras bagi pembaharuan rekaan yang akan mempunyai fungsi di pasaran

ACKNOWLEDGEMENT

First of all, I would like to express my gratitude as I was able to participate and take part in this Projek Sarjana Muda (PSM) 1 and to be able to complete both the report writing and also experimental procedure.

Highest gratitude to Dean of Faculty of Mechanical Engineering, Dr Ruztamreen Jenal that allow PSM as one of practical knowledge to expose students towards thesis writing

A special thanks to my lecturer supervisor, Dr Muhd Ridzuan bin Mansur that helped me through his guidance, advices and experience for the completion of this paper.

Also, I would like to thank my lecturers in Universiti Teknikal Malaysia Melaka; specifically, FKM in which, without their knowledge sharing, I wouldn't be able to complete the experimental procedure and also technical report writing.

Support from my parents and guardians are one of my strength to be able to finish this PSM and thus, to my parents are the highest salutation.

Lastly, I would like to thank my fellow friends that always have my back and to support me when needed.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATION

FPCB	- Flexible Printed Circuit Board
FPC	- Flexible Printed Circuit
OLED	- Organic Light Emitting Diode
PET	- Polyethylene terephthalate
PEN	- Polyethylene naphthalate
LCD	- Liquid crystal display
LED	- Light Emitting Diode
PDMS	- Polydimethylsiloxane
RFID	- Radio-frequency identification
CNT	- Carbon Nano Tube
SEM	- Scanning Electron Microscopy

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 BACKGROUND OF RESEARCH

In the uprising demand for downsizing of mobile electronics, flexible electronics have become an important aspect of technology. The evolution of electronic circuitry began with complicated wiring that requires high maintenance and usually end up with bulky design. This has been simplified into a single piece of board which convey the same function but with a minimised and smaller design. The future of electronic board is to have the flexible properties because of the advantageous applications such as in portable or wearable electronics, electric automobiles or even automotive applications. The working principle of a flexible electronic circuit is usually to have a conductive ink, printed onto a flexible substrate, which functions to hold the ink. The usage of ink and the substrate are both to replace the copper layer and circuit board; respectively. The difference being made is the rigid circuit board being substituted with a flexible and bendable material.

The modern automobile has a broad electronic circuit consisting of electric, electromechanical and electronic loads that are vital to either vehicle operation, safety or comfort. In order for a vehicle to function smoothly and safely, it takes more than the engine operation. It also needs other contributing factors such as the air conditioning system for comfort and automotive lighting for safety and illuminating purposes. Example of automotive lighting includes headlights, signal lights and internal lights. The car headlight has a significant influence on traffic safety, the same goes with the signal and internal lights. Nevertheless, it is proven that the main goal of vehicle lighting is to enable the driver to see and for them to be seen. Thus, researchers must progressively develop the lighting systems to make driving safer. (Mou et al., 2018).

This research tested the reliability of flexible, printed electronic circuit for the automotive lighting application. This study will be focused on prototyping of a flexible circuit and to test its function under cyclic twisting and the effect on electricity flow through the measurement of resistivity

1.2 PROBLEM STATEMENT

As said by Lim et al. (2013), the desire of flexibility, compact, lightweight and low cost in current electronic device increases the application of flexible printed circuit board (FPCB). Flexible electronics are not a new thing in industrial applications, but there are always room for improvement and development of the technology. According to Chu et al. (2017), with the popularity of intelligent terminals, flexible electronic products present a huge market prospect. Various experiments are done for the sake of futuristic and sleek application of either devices or machinery. Since the circuit is made up of flexible substrate, it is expected to operate for a supple application with small failure possibilities. Several researches have reported on the reliability performance of FPCB under various mechanical loading by using different type of substrates such as paper, PET, TPU etc and different type of conductive ink such as silver ink, copper etc. However, there is no reported results so far on the reliability performance of FPCB under cyclic twisting load by using PET substrate and carbon-based conductive ink at varying square patterned circuit width. In this research, the performance of the flexible circuit before and after the cyclic twisting test was measured. The performance of the FPCB were assessed in terms of the effect of the cyclic twisting load on the change of sheet resistivity.

1.3 RESEARCH QUESTION

The questions related to this research:

i) What are the effects of cyclic twisting test on the FPCB performance at varying circuit width?
ii) Is this geometrical parameter suits with the LED lighting application?

1.4 OBJECTIVE

The objectives of this research are as listed below:

i) To develop printed electronic sample on flexible substrate using carbon black-based conductive paste
ii) To study the effect of square-patterned connection on sheet resistivity at varying line width
iii) To evaluate the sample reliability when subjected to cyclic twisting load

1.5 RESEARCH SCOPE

1.5.1 Scope of research

The scopes for this research are as follows:

i) Usage of Polyethylene Terephthalate (PET) as the substrate and carbon-black based conductive ink as the circuit
ii) Printing of square-patterned conductive ink on flexible substrate by using screen printing method
iii) Resistance measurement on flexible printed circuit by using a multi-meter
iv) Testing of samples on cyclic twisting load
v) Data collection and analysis

1.5.2 Limitation of study

This limitation of this study are as follows:

Table 1. 1 Limitation of study

Material of substrate	Polyethylene terephthalate
Ink type	Carbon-based
Printing method	Screen printing method
Reliability test	Measurement of the sheet resistivity
Mechanical test	Twisting test

1.6 PLANNING AND EXECUTION

The research activity and PSM progress is being shown as in the Figure 1.1 and 1.2 below.

Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Research title review															
Literature review															
Design of experiment															
Sample fabrication															
Testing/Data collection															
Data analysis															
Report writing															
Report submission															
PSM presentation															

Figure 1. 1 Planning for PSM 1

Activities/Week	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Literature review															
Design of experiment															
Torsion test on samples															
Data collection															
Data analysis															
Report writing															
Report submission															
PSM presentation															

Figure 1. 2 Planning for PSM 2

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter focus on explaining on the materials and testing process for the study. Discussion will include description on polyethylene terephthalate as the substrate, conductive ink, printing method and experimental method such as measurement of bulk resistivity, surface roughness, hardness, optical microscope and adhesion peel test.

2.2 Flexible electronics

Development of the latest technology, gadget and invention has further advanced with the innovation of flexible and durable device; illustration shown in Figure 2.1 below. Electronic printing has been available since the 1950s (Suganuma, 2014) in which some of the requirements are mechanical stability, flexibility and electrical conductivity (Bao et al., 2016; Yang et al., 2018).

Figure 2. 1 Example of flexible display (Royole, 2019)

These devices require smaller and compact circuit that are still functional even though subjected to high deformation and stress (Zhang et al., 2014). Thus, bulky and complicated design are no longer relevant to fulfil this purpose. The timeline of circuit design started with massive wiring components that results in unreliable and impractical design. The main objective of making the design smaller is so that it is able to perform in various fields and aspects such as in latest gadget, home appliances or automotive.

2.2.1 Advantage of flexible circuit

Easiest example for usage of flexible circuits are in smartphones, cordless phones and digital televisions. Advantages for this kind of circuit are obvious, they require less maintenance compared to the old wiring method which requires complex wire harnesses and assemblies, as illustrated in Figure 2.2 below:

Figure 2. 2 Example of flexible printed circuit (Eastwin, 2017)

By removing all those redundant features, flexible circuit make it more cost-effective. Other benefits include a much sleek design that portrays an improved and futuristic invention. Due to its functional advantages, flexible electronics and circuits had received increasing attention from various industries (Sun & Rogers, 2007). The benefits of implementing the flexible circuit are also supported by AirBorn (2018), that lists down the advantages as reduced package size, reliable wiring arrangement, malleable, favourable performances and less costly.

2.2.2 Use of flexible circuit in industry

One of increasing demand for flexible circuit is from the automotive industry and this continue to arise with more various in-vehicle electronics application. As stated in the report of North American Printed Circuit market has shown that the implementation of flexible circuitry in US automotive market has significantly increases at 13% in 2001 and the graph continue to incline for the next few years. The function of a vehicle is not only limited to transporting people or loading from one point to another but also to provide a safe and secure driving experience to avoid any risks regarding the negligence and lack of safety function. In fulfilling both the safety and functionality of a vehicle, the automotive industry has turned their attention toward the application of flexible printed circuit (FPC) for its various benefits such as lesser raw materials being used, easier to recycle, weight reduction and a lower-cost interconnection method (Nur, 2002).

Technological and automotive advancement has recently experiment with production of electrical vehicle and this will increase the demand for the flexible printed circuit (Milmo, 2017). Example for circuit simplification is the usage of flexible Lithium-ion batteries; as in Figure 2.3, that will greatly reduce the overall weight of an electric vehicle.

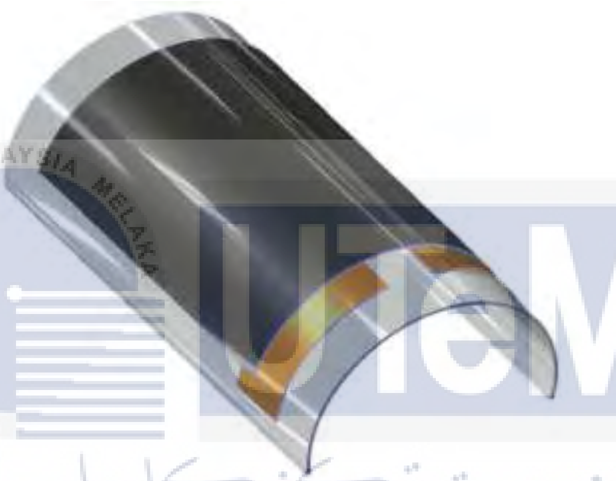


Figure 2. 3 Flexible lithium ion batteries (OperaNewsNow, 2019)

2.2.3 Use of flexible circuit in automotive industry

One of increasing demand for flexible circuit is from the automotive industry and this continue to arise with more various in-vehicle electronics application. As stated in the report of North American Printed Circuit market has shown that the implementation of flexible circuitry in US automotive market has significantly increases at 13% in 2001 and the graph continue to incline for the next few years. The function of a vehicle is not only limited to transporting people or loading from one point to another but also to provide a safe and secure driving experience to avoid any risks regarding the negligence and lack of safety function. In fulfilling both the safety and functionality of a vehicle, the automotive industry has turned their attention toward the application of flexible printed circuit (FPC) for its various benefits such as lesser raw materials being used, easier to recycle, weight reduction and a lower-cost interconnection method (Macleod, 2002).

The FPC, other than help creating a more sleek and compact design, it can also help in improving the vehicle's efficiency; for instance, usage of OLED for automotive lighting and displays. Few challenges faced by the OLED that causing it to take some time to grow in the market are higher initial and production price, difficulty in searching of the material, the mechanism of functional and foldable performance and also the suitable heat and operating temperature range. According to Savastano (2018), most analysts predicted the FPC market to grow in 2020 or 2021, overtaking LCD usage in the process.

FPCB is also greatly used in other application such as flexible electronic textiles (Sun & Rogers, 2007), wearable electronics (Ashebir et al., 2016) and manufacturing automation (Li et al., 2017). In modern technological advancement, flexible electronic devices' status is still under progressive development (Lee & Liu, 2011) in order to ensure the innovation to be applicable in more community-service functional as well as industrial and technological futuristic advancement.

2.3 Conductive ink

Formerly, a traditional method of copper etching is done to form the same conductive pattern on the substrate. This latest technology of printed electronic circuit helps in reducing and minimising of waste product. Conductive ink is a special type of ink that allows electricity to flow through it, and this property makes it differs from the normal graphical ink. It provides functions rather than only displaying colour and pattern. In flexible printed circuit, usage of conductive ink replaces the copper which is formerly used in rigid circuit. The production of conductive ink differs based on their application and thus it is formulated for specific purpose. Commonly, conductive ink is either water-based or solvent-based. Since water-based ink has low viscosity, it causes the ink to evaporate quickly before it can be cured effectively. Thus, it is mostly used for high-speed printing and coating purposes. While the latter type of ink is thicker and has higher viscosity.

2.3.1 Types of ink

To choose the correct ink for the research, a few aspects need to be discussed and studied, for example the cost and conductivity. Comparison had been made between different type of conductive ink and the result shown that silver conductive ink is the best-performing conductor due to its good electrical, optical and chemical properties which are significant for a decent conductive ink (Bose, 2018) and silver also has the lowest resistivity among all materials (Shin et al., 2014)

As said by Rao et al (2015), the properties that make silver suitable are that it is rare, strong, corrosion resistant, and unaffected by moisture. An article from Nano Dimension (2015) agreed that silver has extremely high conductivity which enables user to use less ink and print smaller profiles. In contrast of the benefits, the price for silver conductive ink is higher than other ink. Other types of conductive ink available includes copper (Joo et al., 2014; Joo et al., 2015), gold (Cui et al., 2012; Nur et al., 2002), tin (Jo et al., 2011) and iron (Seefeld et al., 2013).

2.3.2 Carbon ink

Carbon ink is a cheaper alternative e compared to silver (Ito & Mikami, 2011) while providing great electrical conductivity (User, 2018; Mitsubishi Chemical, 2018; Chung et al., 2004), harmless and environmentally friendly (Cho & Ryuh, 2016). According to The Editors of Encyclopaedia Britannica (1998), there are different kind of carbon black that differs in their particle size; depending on their manufacturing processes. For instance, general carbon black particle which are usually spherical in shape and it is less crystalline compared to graphite. The illustration in Figure 2.4 shows the spherical-shaped particle of the carbon black (Liu et al., 2018). Impingement black is produced by the impingement (striking or slamming) the smoky flames on the iron channels, then the deposited black is collected by scraping the iron channels. Next, furnace black is produced by a process of incomplete combustion of either gaseous or liquid hydrocarbon. Thermal black is produced when hydrocarbon is decomposed in contact with a heated refractory (substance that are resistance to heat). Acetylene black is produced in a vacuum chamber by the decomposition process of a preheated acetylene gas, and this black is normally used in application of high electrical conductivity; such as dry cells battery. Lastly is the oldest known black pigment, lampback which is produced by burning oils (normally coal-tar creosote) placed in shallow pans in a furnace which is regulated to give a heavy smoke cloud.

Figure 2. 4 General particle of carbon black (Mitsubishi, 2006)

For this study, a carbon black-based conductive ink has been chosen because naturally, it is chemically inert (Lu & Chung, 2002), electrically conductive (Frysz et al., 1996; Sánchez-González, 2005) and high flexibility (Im et al., 2009). The electrical conductivity of carbon black is also contributed by its very high surface to volume ratio. This means that it has a higher proportion of substance being exposed to stimuli (electricity). Thus, this quality enables the carbon black to react very quickly to the applied stimuli (Imerys Graphite & Carbon, 2018).

Results from an experiment done by Liu et al (2018) also shows that carbon ink has good conductivity since the LED connected together by using the carbon ink shows steady light when given access to power source. Other than its unique capability of conducting electricity through a substrate, it is also useful in various other applications such as tyres, plastics, printing inks (Hauptman et al., 2012).

2.4 Substrate

By definition, substrate is a primary underlying surface for application of other material (ink, paint etc) (BusinessDictionary.com, 2018). While substrate is used in either biological, chemical or electronic area, the function might differ from each field. For example, in biological field, substrate is defined as either animal or plant which act as a surface where other living organisms grow (Wikipedia, 2018). The definition of substrate in chemical field is a medium for the occurrence of chemical reaction (Gerard, 2018). Finally, in electric or electronic field, substrate is a material in which the integrated circuit is embedded (Mason, 2018).

Choosing for the correct substrate for the circuit is important as it affects the performance of PCB (PCBCart, 2018, Lee & Liu, 2011). In the printed electronic field, the flexibility of the circuit board is affected by the substrate used. The advancement of technology has increased the demand of PCB for various field and thus studies had been done to discover different types of substrate that are able to fulfil both current and future electronic needs. Other factors that need to be considered during the substrate selection are cost, weight, easily process and also good mechanical performance. A good substrate will have consistent performance, optimized weight, good ageing and low maintenance cost.

While rigid substrate is a traditional form of PCB, cheaper and mainly used in electronic products (Aqeel, 2018), but the developing manufacturing industry which includes computer and communication leads to a high demand of flexible PCB (Li et al., 2017), since it contributes to higher technological and commercial effect in various applications (Wu et al., 2016).

2.4.1 Polyethylene terephthalate (PET)

Some of existing substrate available in the market includes paper (Merilampi et al., 2009; Bollström, 2013), plastic (Siegel et al., 2010), glass ((Hrehorova et al., 2011), polydimethylsiloxane (PDMS) (Larmagnac al., 2014), polytetrafluoroethylene (Lim et al., 2013), polyethylene (Mandal et al., 2012) and polyethylene naphthalate (Suganuma, 2014).

Some advantages of paper are low cost, foldable, easy disposal and contribute lesser pollution (Zheng et al., 2013; Tao et al., 2011). Properties that make paper unsuitable as substrate for this study are their porosity and roughness (Morais et al., 2018). Plastic is considered as the typical choice for the substrate because it is lightweight, transparent and inexpensive. Thus, for this study, PET is chosen because it is low cost, good thermal stability and inert surface (Faraj et al., 2011).

2.5 Printing method

Various method of ink printing available nowadays, those includes flexography, screen, offset, inkjet, laser induced forward transfer and gravure (Hrehorova et al., 2011; Wood et al., 2005; Inui et al., 2015; Kattumenu et al., 2012; Sico et al., 2016; Suganuma, 2014). While there are various methods of printing the conductive ink onto the substrate, screen printing is chosen as it complements with the ink suitability; as for this research, carbon black is proven to be suitable with screen printing method or inkjet printing method (Liu et al., 2018).

2.5.1 Screen printing

Screen printing method has developed to become one of the reliable printing solutions for the application of conductive ink as it can manufacture and facilitate high volume production with lower overall cost. Screen-printed electronic circuit can be widely applied in electronic field without the need of masking, lithography and etching process (Wu, 2014). Screen printing method has improved the printing quality and control (Chu, 2017) with the application of stencil usage (Galdino et al., 2015; Rojas, 2004; Tudorache & Bala, 2007). According to Chu (2017), the method of screen printing is by firstly placing a substrate under the screen or stencil and ink is then dropped on a blank area on the stencil surface, away from the pattern and a scrapper is then used to spread the ink through the screen openings. Some of parameters that might affect the screen-printed conductive ink are squeegee speed, ink composition and ink viscosity (Goldberg, 1994). A previous research done by Merilampi et al. (2010) tested on screen printing method to fabricate and test the performance of radio-frequency identification (RFID). It tested on different ink thickness and the result shows that the thickest tag emits the strongest signal and the thinnest printed sample emits the weakest signal and this theory can be applied for this research, only that the manipulated variable is the ink line width.

The principle and method of screen-printing method can be illustrated as shown in Figure 2.5 below:

Figure 2. 5 Principle for screen printing method (Santos, 2017)

2.6 Curing process for the ink

Printed ink requires curing process or known as drying process. This is to ensure the ink adhere to the substrate. The ink conductivity and the curing time is closely related. Normally, the ink will be left for two or three days for curing before beginning of experiment. Curing process can be done by leaving the printed ink at room temperature or the process can be accelerated by applying heat on the substrate. While certain ink can only be cured by ultra-violet ray system.

2.7 Sheet resistivity

To evaluate the performance of the conductive ink, the parameter used is the sheet, square or surface resistance (Kazani et al., 2012) and this follow the testing standard of ASTM D-257. Normally, sheet resistivity can be calculated by using an apparatus called four-point probe (Kazani et al., 2012; Mou et al., 2018, Chang et al., 2019), but for this research, this method can't be used because reading can't be measured from the printed ink due to its thickness. An alternative being used is to calculate the resistance value and a formula is being used to calculate the sheet resistivity (Xiao et al., 2018). Theoretically, the value of surface resistivity will decrease with the increment of conductive ink line width. This research will also test the electrical reliability when the sample is subjected to cyclic twisting load; as shown in Figure 2.6. Experimental result as shown in Figure 2.6 shows that the resistivity will increase in time with bending cycle (Mou et al., 2018), and the same trend will be expected for cyclic twisting load, as illustrated in Figure 2.7.

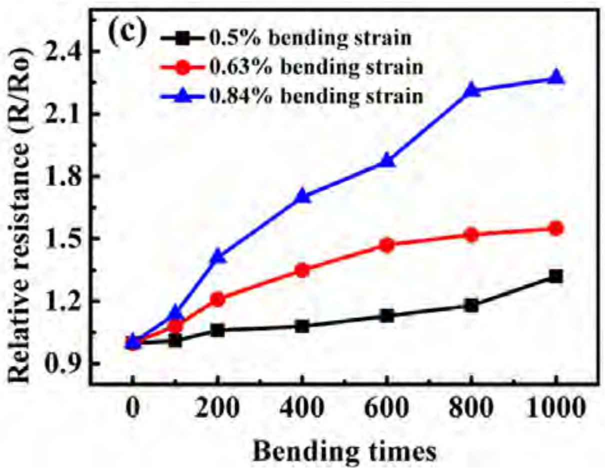


Figure 2. 6 Graph of resistance versus bending time (Mou et al, 2018)

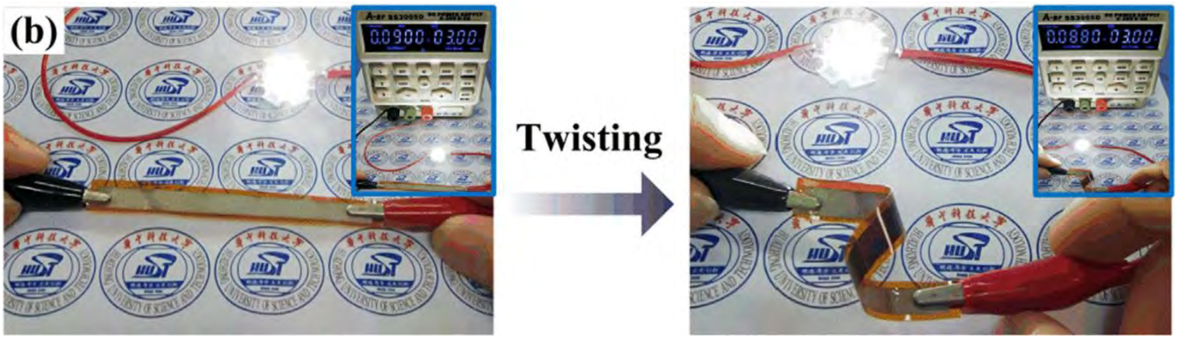


Figure 2. 7 Cyclic twisting load experiment (Mou et al, 2018)

2.8 Mechanical testing method

The most crucial part of determining the performance of a flexible printed circuit board is to test its reliability performance under stress load. Generally, the flexibility of an FPCB is determined by its type of substrate and mainly there are two types of substrate for flexible electronics; stretchable and non-stretchable. In order to test the reliability of the printed thin film or flexible electronics, it is tested under different kind of variables such as bending or twisting motion. Both of the test simulates the usage of the circuit in real life application. Previous research includes an experiment by Bag & Choi (2017) that uses copper thin film and subject it under cyclic bending test in order to study the propagation of the microcrack in the thin film. Next, Chang et. al. (2019) uses a silver-zirconium circuit printed on a glass substrate with manipulated variable of the annealing properties, and to test it under a 10,000 cycle of bending test. Wang et. al. (2019) discover a reliable design of metal film to withstand the bending cycle by adding a nanocomposite of Carbon Nano Tube (CNT) and copper. Guan et. al. (2016) uses silicon nitride (SiN_x) film, printed on polyethylene naphthalate (PEN) substrate and the sample is subjected to a 2-point rotation (2PR) bending test, as shown in Figure 2.8 below. The list for cyclic bending testing done over the years can be further listed, however, there are limited literature on the torsion or twisting test on printed thin films.

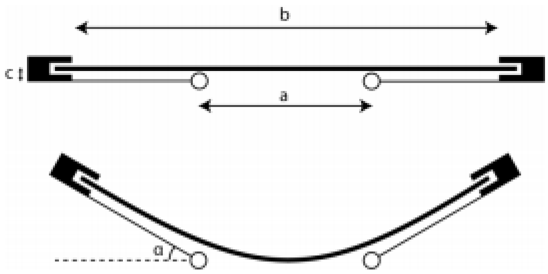


Figure 2. 8 A 2-point rotation test (Guan et al., 2016)

The main objective of the testing is to subject the FPCB with torsion stress loading. In actuality, the load applied on the FPCB is prone to occur with the user's interaction such as bending, twisting or shearing action.

2.8.1 Twisting test

The method used in testing the performance of the printed circuit board follows the test standard of ASTM D1043, which test the stiffness properties of plastics by mean of twisting test. This test is chosen to simulate the real-life situation of the circuit application. Thus, this test is to verify the product quality and to ensure the product's reliability (UniMAP, 2019). The twisting method can have a few manipulated variables. For instance, a twisting experiment done by Lee & Liu (2011) tested the samples according to the twist angle and the effect on the torque reading and the result of the experiment shows that increment in twist angle will increase the torque reading. The sample's deformation is then measured by using laser displacement sensor and it results in higher deformation for samples with higher torque reading as shown in Figure 2.9 below

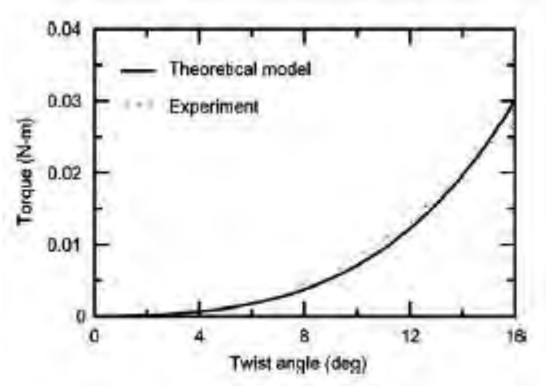


Figure 2. 9 Graph plot of torque vs twist angle (Lee & Liu, 2011)

Next is research done by Chen et al. (2008) that tested the flexible display on both bending and twisting load for a certain reading of cycle number. For twisting load, the twisting jig setup is prepared to have one rotational part and the other is kept fixed. Nine samples are experimented and the number of survived cycles for each sample are tabulated after a twisting test of total 20,000 cycles are done. The results show that 5 samples (55.56%) survived all the cycles, two samples failed before reaching the amount of 15,000 cycles and the other two failed after completing the 15,000 test cycles, as shown in Figure 2.10.

Sample	Number of Cycles
Sample 267	15000 – 15500
Sample 254	S – 20000
Sample 253	S – 20000
Sample 260	19000 – 20000
Sample 263	S – 20000
Sample 262	S – 20000
Sample 281	12000 – 13000
Sample 264	13000 – 14000
Sample 250	S – 20000

Figure 2. 10 Data tabulation for twisting cycle (Chen et al., 2008)

For completion of this project, an amount of 20,000 test cycles exceeding the research capability and scope. Previous research done by Finn et al. (2018) for fabrication and testing process for the roll-to-roll printed organic solar cell that uses both carbon-based ink and also silver nanoparticle ink. The researches chose bending and torsion test as it is a type of deformation that would be highly encountered during either fabrication process or outdoor operation of samples. The highest number of cycles done on the samples were 4,000 as shown in Figure 2.11 below. The results compare the performance between the silver and carbon ink. The carbon ink is observed to be more fragile and this is because the silver-type modules are more flexible and tougher. By referring to this research, an amount of 5,000 test cycles are agreed to be the experimental testing method for this research.

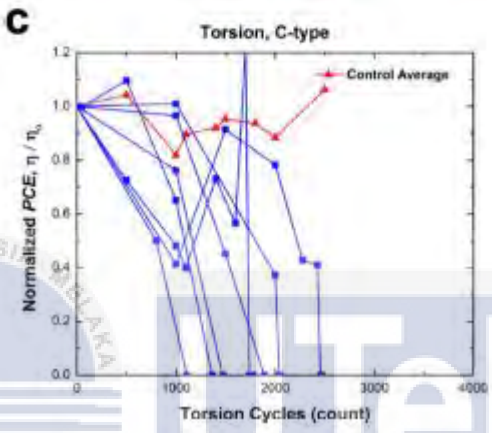
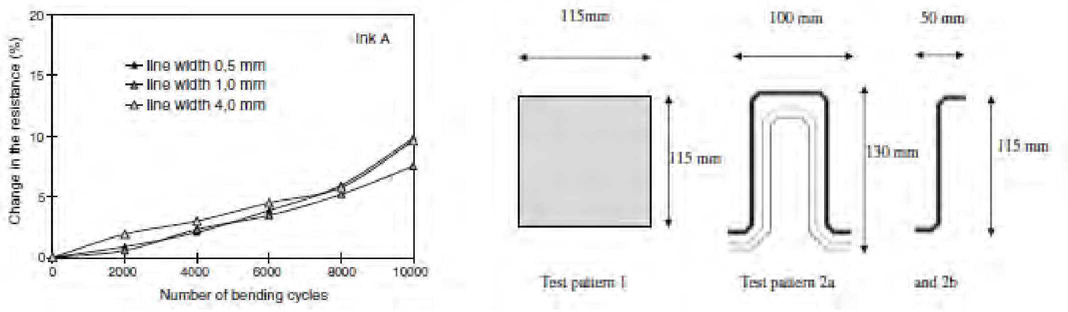


Figure 2. 11 Graph plot for twisting cycle of carbon-based conductive ink (Finn et al., 2018)

Also, a research by Merilampi et al. (2009) tested on different types of substrate (paper, PET, PVC and fabric) and application of silver-based ink with different type of particle content and conductivity. Example of tests done on the samples are adhesion, sheet resistance and the effect of bending and tensile test. For bending test result, the change in the resistance value increases with the increasing amount of bending cycles as shown in Figure 2.12 (a) below. For the printing method, screen printing method is used to model the conductive ink for few patterns or shapes as shown in Figure 2.12 (b) below.



(a) (b)

Figure 2. 12 (a) Graph plot for change in resistance (%) vs number of bending cycles for PET substrate and silver conductive ink (b) Conductive ink pattern variation for Merilampi's research (Merilampi et al., 2009)

A research on cyclic bending is also done by Happonen (2016) which tested the reliability performance by manipulating the line thickness, line width, substrate type and conductive paste. The test results show that the resistance decreases with increment of ink line width and layer addition, as shown in Figure 2.13 below.

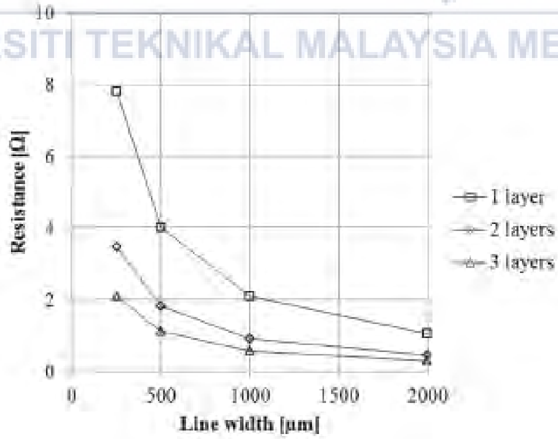


Figure 2. 13 Effect of line width and ink layer on resistance reading (Happonen, 2016)

CHAPTER 3

METHODOLOGY

3.1 INTRODUCTION

In this chapter, the method and procedure of sample preparation, the apparatus and materials used, the test implementation and data collection for the research were discussed. Methodology explained on the processes involved in completing the study; including material preparation, apparatus set up, measurement process and also data collection. Further explanation on the experiment process is attached in Figure 3.1.

This study focused on the effect of circuit pattern on the resistivity and conductivity of ink. The experiment was divided into two parts in which the first part compared the resistivity reading between straight line circuit and also square-patterned circuit. The second part tested the ink resistivity after application of cyclic twisting load.

The materials used in this study includes carbon-based conductive ink and also PET; a flexible and transparent base as the substrate. The resistivity value was calculated by using formula that requires measurement of resistance value; by using a multi-meter. The method to apply the ink onto substrate is known as screen printing. The substrate was first be secured on the stencil with square-patterned circuitry. The ink of suitable amount was placed by the side of stencil and then squeegeed; by using scraper, along the stencil. The samples prepared were of fixed thickness but with varying width. The ink was cured at room temperature and the resistance was then measured by using a multimeter.

For preparation of the first experiment, the sample was divided into two shape; one is square-patterned and the other one is a straight line. The straight-line circuit acted as reference to compare the effect of circuit shape on the resistivity. The second experiment used the same sample, but cyclic twisting load will be applied to the square-shaped circuit sample and the resistivity was measured.

3.2 Project methodology

The project methodology, as shown in Figure 3.1 was explained accordingly in this section

3.2.1 Planning and literature review

Project planning and also literature review is one of important part in completing a study. The project planning is needed to make sure the project and study are able to be completed on time and to make sure the objectives are achieved by the end of the study. Literature review is used to search for relevant and approved information regarding the material and method selection. This study focused on information regarding flexible electronics, carbon-based conductive ink, PET and effect of circuit pattern on sheet resistivity. Main sources for completion of literature review are journals, articles and authorized websites.

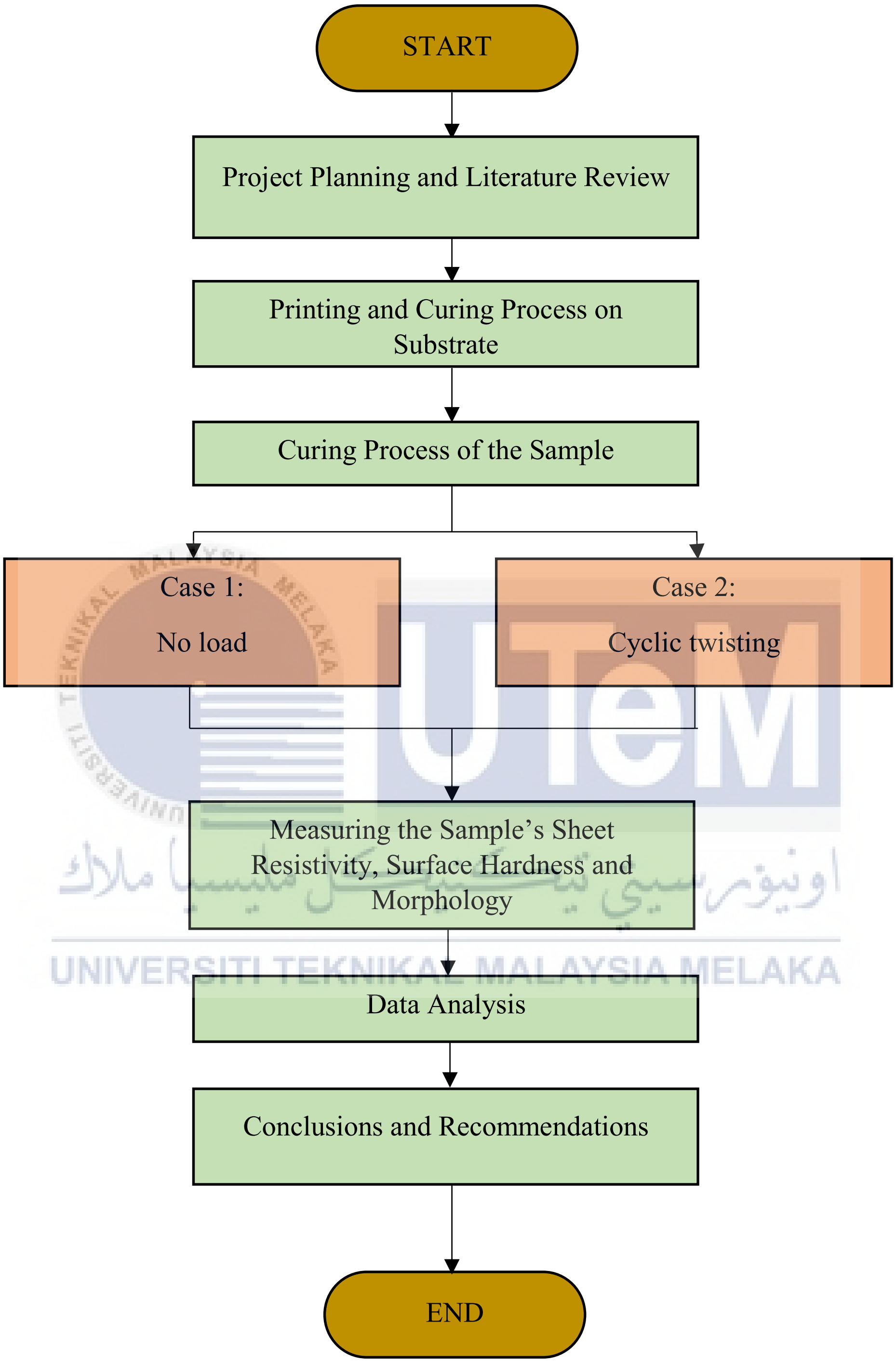


Figure 3.1 Research's flow chart

3.2.2 Material identification

The material used in this experiment is carbon black based conductive ink named Bare Conductive Paint. This type of ink is advantageous as it is non-toxic (Wordpress, 2014), so it won't cause severe harm if exposed to human contact as it can be washed off with plenty of water and soap. The main ingredient of Bare Conductive Paint are water, carbon and natural resin. Although silver, copper and other heavy metal conductive ink will provide greater conductivity, but it will also affect the human health. Compared with carbon, the conductivity is lower and thus the application is not as wide as other ink, but is sufficient for this research. Also, this ink is famous due to its flexibility and wide functional shapes and surfaces. The ink was applied onto the substrate by using screen printing method. This ink also doesn't require heat curing process; it can be cured by exposing it to room temperature for a certain range of time. Another unique properties of this ink is that it adheres well to different type of substrate, for instance wood, paper, plastics, textiles and also metal (Bare Conductive Inc., 2018a). Figure 3.2 (a) and (b) shows the ink and PET roll that are being used in this study.

(a) (b)

Figure 3. 2 (a) Bare Conductive ink (Rapid, 2019) (b) PET roll (IndiaMart, 2019)

The substrate used for this research is PET, a member of polyester family of polymers. This substrate is flexible, but not stretchable, making it favourable for usage of Bare Conducive Paint. It is a heat stabilized material, in which it is commonly used for high heat application which includes circuitry. Since PET is a plastic-type substrate, it is also ideal for flexible electronic display. It is also resistance towards chemical; means it won't react with the ink being applied on it (Masterpiece Graphix, 2017) and it is also tough, durable and flexible, making it highly resistant to deformation (Hosch, 2009). Other unique properties of PET are it is fully recyclable, approved by global safety and sustainable (PETRA, 2015). The properties as stated in the Data Sheet and Application Notes from Bare Conductive Inc. (2018a) are as shown in tables below:

Table 3. 1 Bare Conductive ink information (Bare Conductive Inc., 2018a)

Bare conductive ink	
Properties	**Description**
Colour	Black
pH (value)	5-7
Solubility (Water)	Partially soluble
Solubility (Other)	Partially soluble in organic solvent
Density (g/ml)	1.16
Viscosity	Viscous liquid
Chemical stability	Stable under normal condition
Skin contact	Unlikely to cause skin irritation
Surface resistivity (Ω/sq/50 microns)	55
Typical cure condition	Room temperature (24 deg C) for 15 minutes

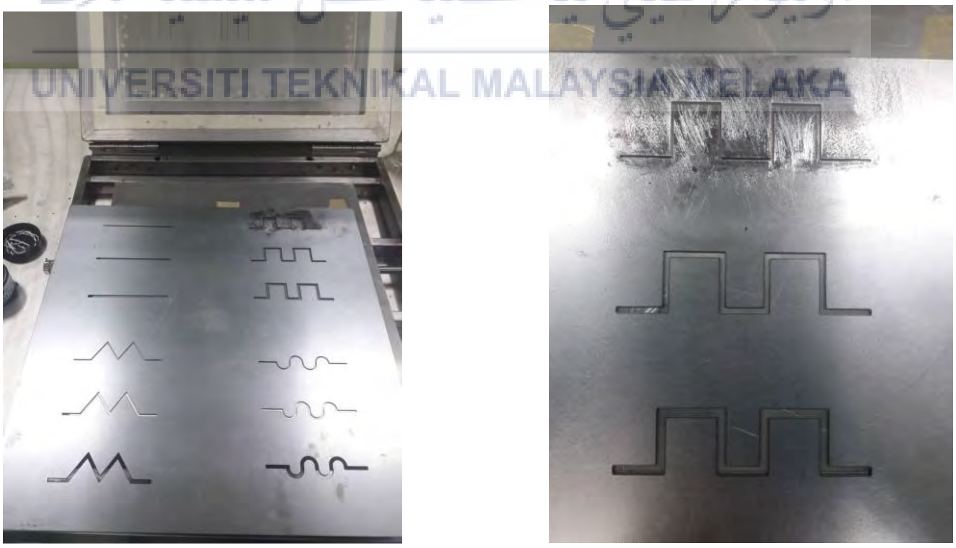
The properties of PET are as shown as in Table 3.2 below:

Table 3. 2 Properties for PET (Azo Material, 2018; Hosch, 2009; PET Resin Association, 2015):

Polyethylene Terephthalate (PET)	
Properties	**Description**
Chemical resistance (Acid)	Good
Surface resistivity (Ω/sq)	10^{13}
Tensile modulus (GPa)	2 – 4
Tensile strength (MPa)	80
Density ($g.cm^{-3}$)	1.3 – 1.4
Thermal conductivity ($W.m^{-1}. K^{-1}$)	0.15 – 0.4

3.2.3 Sample design

Since this study focus on effect of pattern on the electrical resistivity, a square-patterned stencil has been chosen to assist with the screen-printing process



(a) (b)

Figure 3. 3 (a) Available stencil in lab, (b) Square-shaped circuit stencil

As shown in Figure 3.3 (a), there are a variety of stencil pattern available for testing, but for simplification of experiment, this research focuses on square-patterned stencil as shown in Figure 3.3 (b). The thickness of ink is fixed at 1 mm while the line width is varied into three: 1 mm, 2 mm and 3 mm. An additional sample of a straight-line circuit is also prepared in order to compare the result of resistivity measurement between the two and to investigate the effect of circuit shape on the electrical conductivity. Since the data of straight-line circuit will be compared with the square-patterned circuit, thus, the properties (length, width, thickness) should be the same. Since there are no stencil available for the straight-line circuit of desired length, the setup is done manually; as shown in Figure 3.4, by stacking up the masking tape until thickness of 1 mm is achieved.

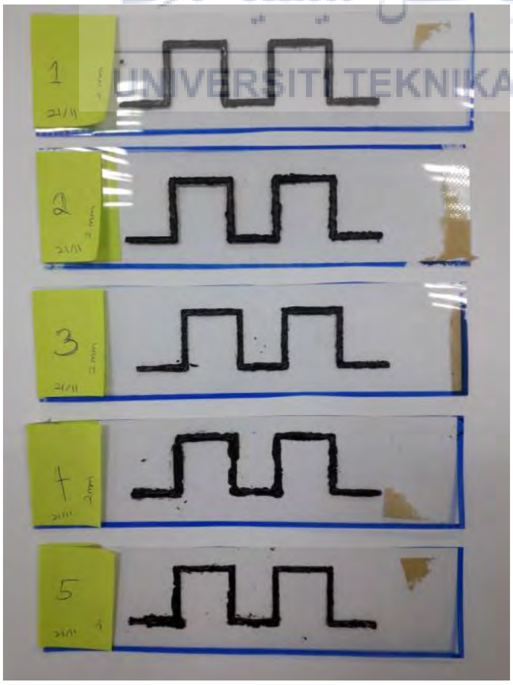
Figure 3. 4 Manual setup for straight line circuit

3.2.4 Sample preparation

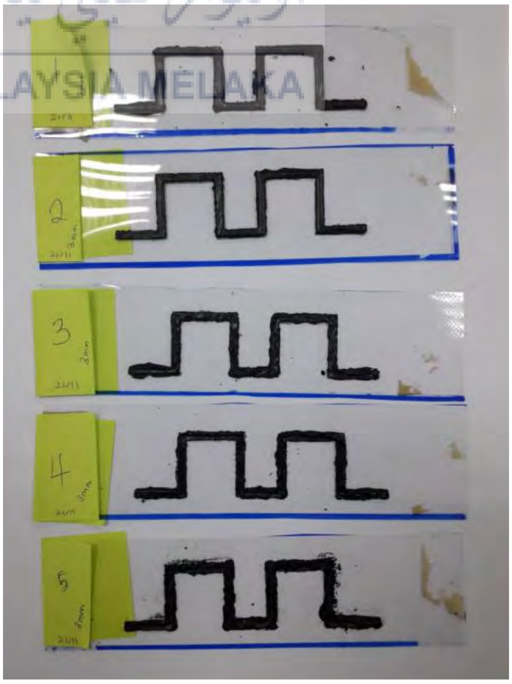
The sample is prepared by using screen printing method; a method which allow application of an even and thin layer of conductive ink. It is low cost with simplified process had high compatibility with various types of ink. This printing method can be done by using either readily-patterned or manually-patterned stencil. The ink is applied onto the stencil and a scraper will be used to even out the ink to fill the patterned area as shown in Figure 3.5

Figure 3. 5 After application of conductive ink

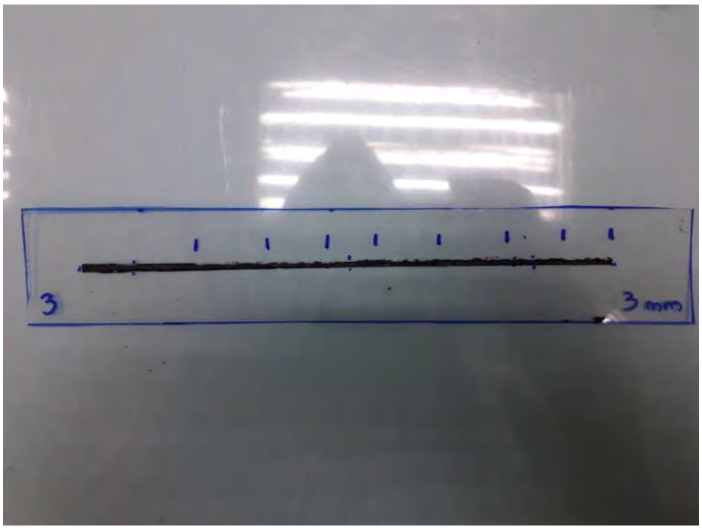
The ink will be left at room temperature for 30 minutes for curing process. The substrate will then be peeled off the stencil after curing. Both Figure 3.6 (a) and Figure 3.6 (b) shows the printed ink of width 2 mm and 3 mm respectively. A straight-line circuit of 3 mm line width is fabricated as shown in Figure 3.6 (c). This circuit function as comparison to the square-patterned circuit.



(a)



(b)



(c)

Figure 3. 6 (a) Line width of 2 mm, (b) Line width of 3 mm, (c) Straight line of width 3 mm

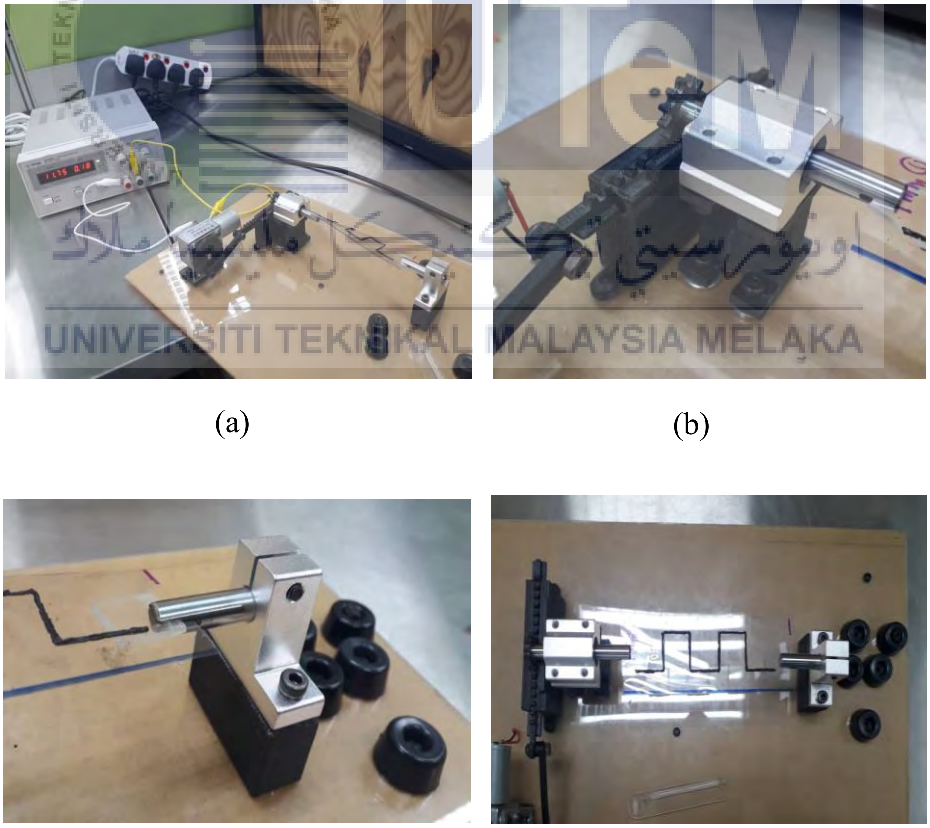
3.2.5 Cyclic twisting

To serve the purpose of testing the samples on twisting or twisting load, a functional design of jig is developed. There are two jigs used in this experimentation; the differences between those two is tabulated in the Table 3.3 below. The illustration of both the jigs are as shown in both Figure 3.7 and Figure 3.8.

Table 3. 3 Differences between jigs used in testing

	Initial jig	**Improved jig**
Motor used	10 rpm	75 rpm
Time required to complete 5000 cycles	10 cycles per minute 5000 cycles / 10 cycles = 500 min (8.3 hrs) Therefore, 1 sample require 8.3 hrs to complete 5000 cycles. There are 9 samples, thus; 9 samples x 8.3 hrs = 75 hrs	75 cycles per minute 5000 cycles / 75 cycles = 66.67 min (1.1 hr) Therefore, 1 sample require 1.1 hr to complete the 5000 cycles. There are 9 samples, thus; 9 samples x 1.1 hr = 9.9 hrs

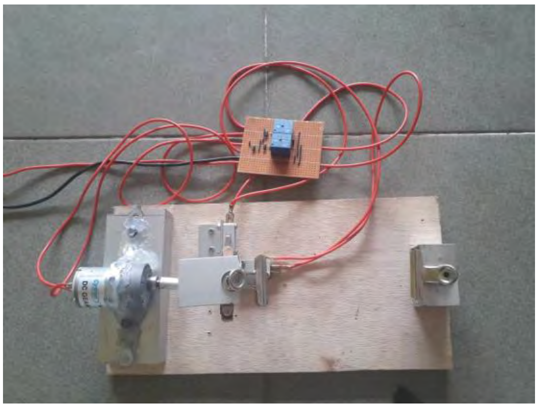
	In a week, experiment can be done for at least 13 hrs. Thus, 75 hrs / 13 hrs = 5.8 weeks The experiment can be completed in 5.8 weeks	The experiment can be done in 1 week
Gearing system	Rack and pinion as shown in Figure 3.7 (b)	No gearing system, instead using limit switch as shown in Figure 3.8 (c)
Angle of twisting	90 degree	90 degree



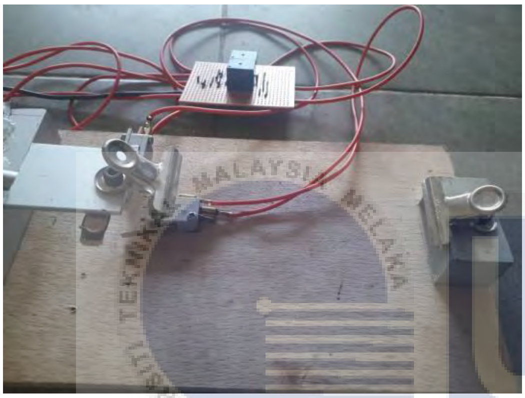
(a) (b)

(c) (d)

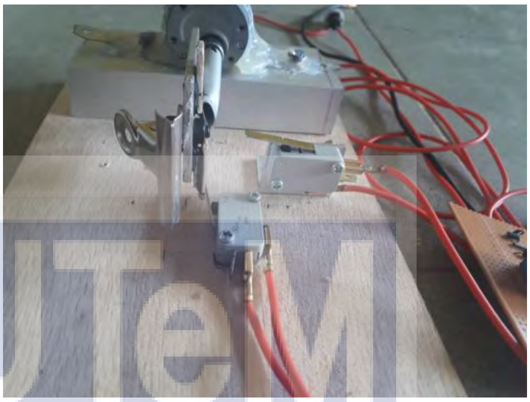
Figure 3. 7 (a) Initial jig used for testing (b) The motor with rack and pinion gearing system (c) Jig fixed end (d) Sample placement



(a)



(b)



(c)

Figure 3. 8 (a) Overall jig illustration (b) Clipping mechanism (c) Usage of limit switch

3.2.6 Testing

A multimeter will be used to measure the resistance of the conductive ink. Then a formula will be used to calculate the square resistivity. Since this study focus on investigation of effect of corner and shape on the value of resistivity, the measurement will be done on each corner, as shown in Figure 3.9.

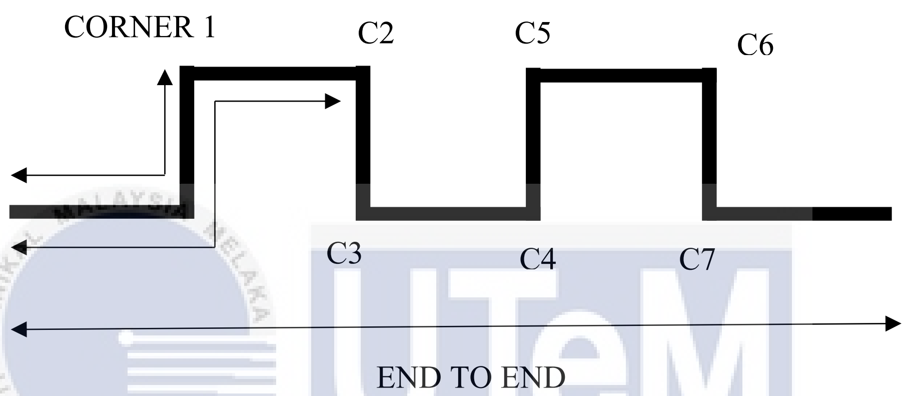


Figure 3. 9 Distance for resistance measurement for square-shaped circuit

The resistance measurement for the straight-line circuit sample will have the same distance as the square-shaped circuit, as shown in Figure 3.10 below:

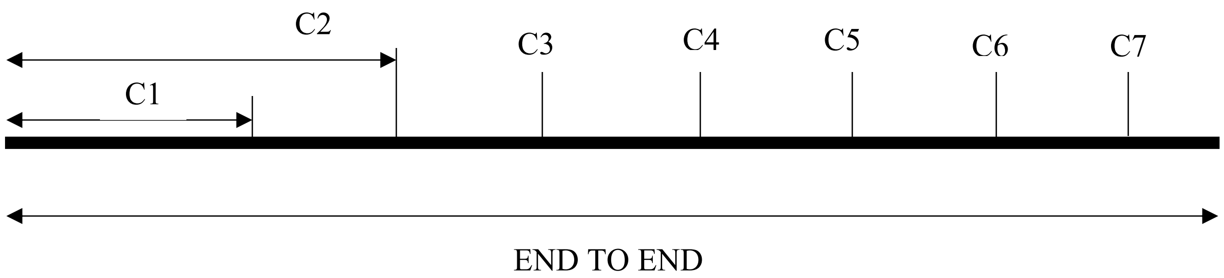


Figure 3. 10 Distance for resistance measurement for straight line circuit

After the resistance has been measured by using a multimeter, the square resistivity will be calculated by using the following formula (Chase, 2008 & Xiao et al., 2018):

$$R_S = R \cdot \frac{W}{L}$$

, where R_S = Sheet resistance (kΩ/sq)

R= Resistance (kΩ)

W= Width (mm)

L= Length (mm)

3.2.7 Data collection and analysis

Table 3.3 shows the total number of samples prepared for this research. The resistance for each sample will be measured and the resistivity will be tabulated. An average value for the samples will be calculated and a total of two graphs for each sample will be plotted; a resistance against L/W ratio and also sheet resistivity against number of corners. The sheet resistivity between the circuit pattern and line width will be compared and analysed.

Table 3. 4 Total number of samples

TOTAL SAMPLES	
Square-shaped circuit **Thickness: 1 mm (Fixed)**	
Line width	**No of samples**
1 mm	4
2 mm	5
3 mm	5
Straight line circuit **Thickness: 1 mm (Fixed)**	
Line width	**No of samples**
3 mm	3
Total number of samples	**17**

Table 3. 5 Total number of samples available for testing

TOTAL SAMPLES FOR TESTING	
Square-shaped circuit **Thickness: 1 mm (Fixed)**	
Line width	**No of samples**
1 mm	3
2 mm	3
3 mm	3

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

This chapter will display the data and value of resistance measured from the experiment and also sheet resistivity calculated from the formula. Table 4.1 and Table 4.2 shows the data tabulation of resistance and sheet resistivity for square-shaped pattern with line width of 1 mm, 2 mm and 3 mm respectively. Two graphs; resistance versus L/W ratio and sheet resistance VS number of corners. Table 4.3 shows comparison between the square-shaped and straight-line circuit of line width 3 mm. Both the resistance and sheet resistivity of both circuit shape is compared and graphs were plotted to show the relationship between the manipulated variables.

4.2 Sheet resistance measurement before twisting load

All the resistance and sheet resistance of the square-shaped and straight-line circuit are tabulated and the graphs plotted are as shown:

4.2.1 Total resistance reading

The experimental result in Table 4.1 shows that sample with 1 mm line width has the highest resistance value ranging from 1.33 Ω to 5.74 Ω. Line width of 2 mm and 3 mm sample has the range of 0.48 Ω to 2.09 Ω and 0.32 Ω to 1.42 Ω respectively. A huge gap between the 1 mm and 2 mm data is observed as shown in graph of Figure 4.1. Theoretically, the sample with line width of 1 mm should have the highest resistance among the three sample. A noticeably high resistance for 1 mm observed in data tabulation is due to few problems in sample fabrication. Main problem is caused by the usage of stencil with thickness of 1 mm; which makes the conductive ink to stick to the blank spaces in the stencil pattern and causing the printing outcome to be distorted. Distortion in printing process will disturb the electricity flow in the circuit; as a result of increasing resistance.

Table 4. 1 Total resistance and number of corners

RESISTANCE (kΩ)			
Corner	1 mm	2 mm	3 mm
C1	1.327	0.476	0.319
C2	2.140	0.762	0.496
C3	2.435	0.977	0.660
C4	3.119	1.212	0.817
C5	3.954	1.368	0.925
C6	4.711	1.593	1.077
C7	5.419	1.828	1.267
END TO END	5.724	2.094	1.421

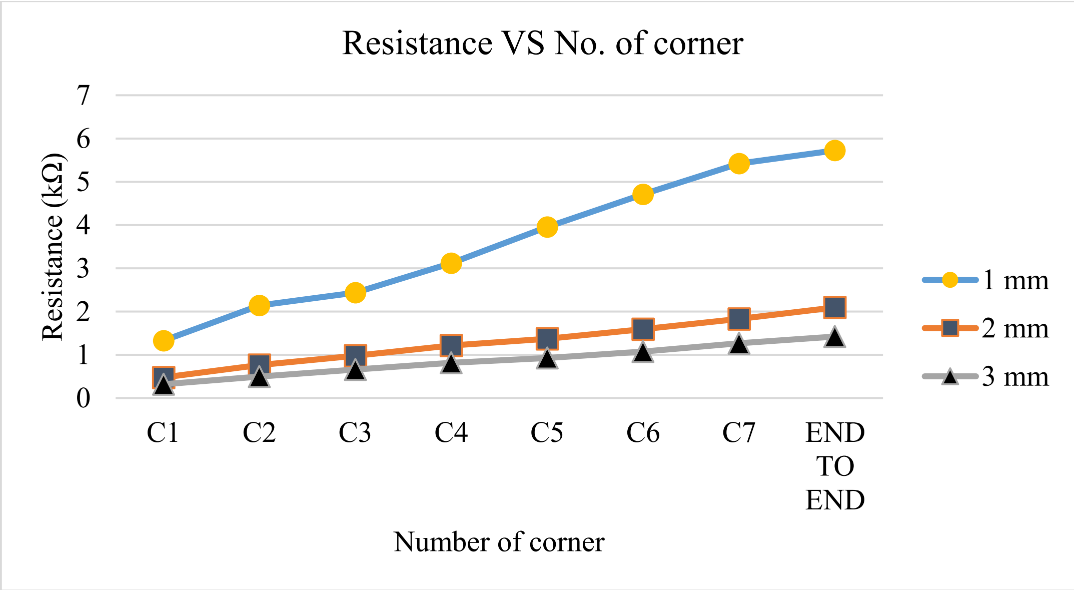


Figure 4. 1 Total resistance and number of corners

4.2.2 Total sheet resistivity

Data tabulation as shown in Table 4.2 shows the average sheet resistivity for square-shaped circuit. The trend of the result tabulation shows that the sheet resistivity value will decrease with the increment in sample's line width. The data for sheet resistivity is calculated by using the formula as stated in Chapter Three. Normally, a four-point probe apparatus will be used to directly measure the sheet resistivity but the sample's line thickness causes the ink to stick to the end-point of the apparatus and thus, the apparatus isn't able to measure any data. The graph in Figure 4.2 shows that there's only a slight decrease between the line width of 2 mm and 3 mm, accompanied with a huge gap between those data and 1 mm line width data.

Table 4. 2 Average sheet resistivity for square-shaped circuit

SHEET RESISTIVITY (kΩ/sq)			
Corner	1 mm	2 mm	3 mm
AVERAGE	**0.033**	**0.0232**	**0.0223**

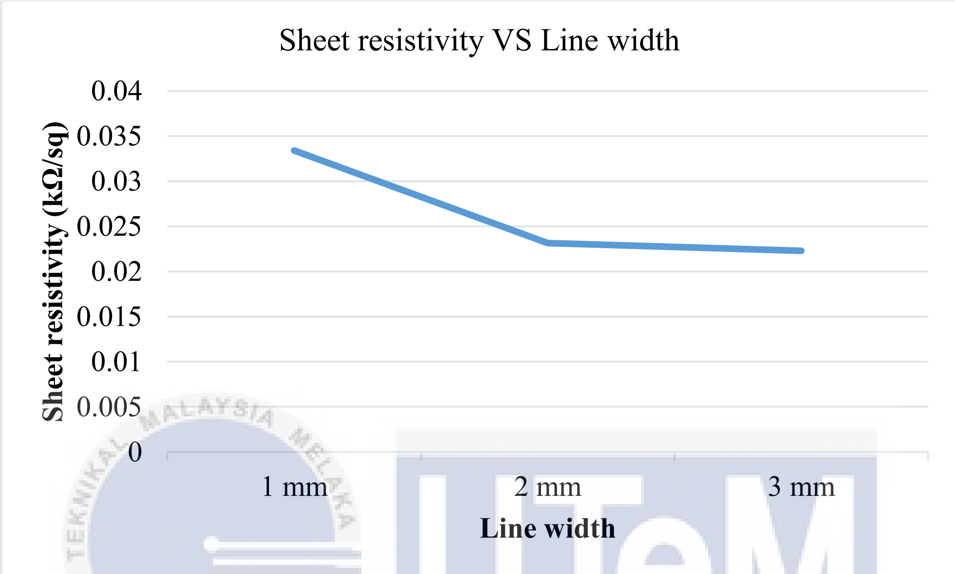


Figure 4. 2 Sheet resistivity versus Line width

4.2.3 Comparison between square-patterned circuit and straight-line circuit

Data tabulation in Table 4.3 shows the comparison of resistance and sheet resistivity between the square-shaped circuit and also straight-line circuit. The line width used is 3 mm with thickness of 1 mm. The graph plotted in Figure 4.3 and Figure 4.4 shows that both the resistance and sheet resistance of straight-line circuit is higher than the square-shaped pattern. This may be affected by the manual stencil used for straight-line circuit fabrication and technical error during the sample printing process.

Table 4. 3 Comparison between square-shaped and straight-line circuit

DATA COMPARISON			
WIDTH: 3 mm			
PATTERN			
Corner	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	0.0250	0.3187	0.0332
C2	0.0172	0.4963	0.0369
C3	0.0128	0.6599	0.0311
C4	0.0102	0.8165	0.0318
C5	0.0084	0.9249	0.0332
C6	0.0073	1.0775	0.0344
C7	0.0063	1.2667	0.0343
END TO END	0.0057	1.4211	0.0323
STRAIGHT LINE			
Corner	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	0.0250	0.4590	0.0336
C2	0.0172	0.7233	0.0334
C3	0.0128	0.9402	0.0323
C4	0.0102	1.1492	0.0327
C5	0.0084	1.3863	0.0322
C6	0.0073	1.6743	0.0328
C7	0.0063	1.8533	0.0316
END TO END	0.0057	2.0573	0.0318

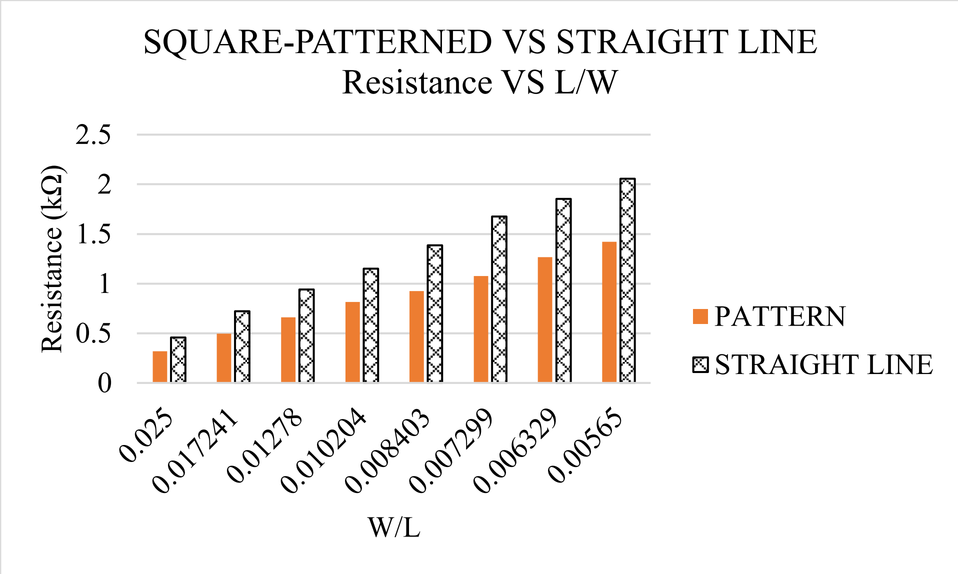


Figure 4. 3 Comparison circuit: Resistance versus W/L

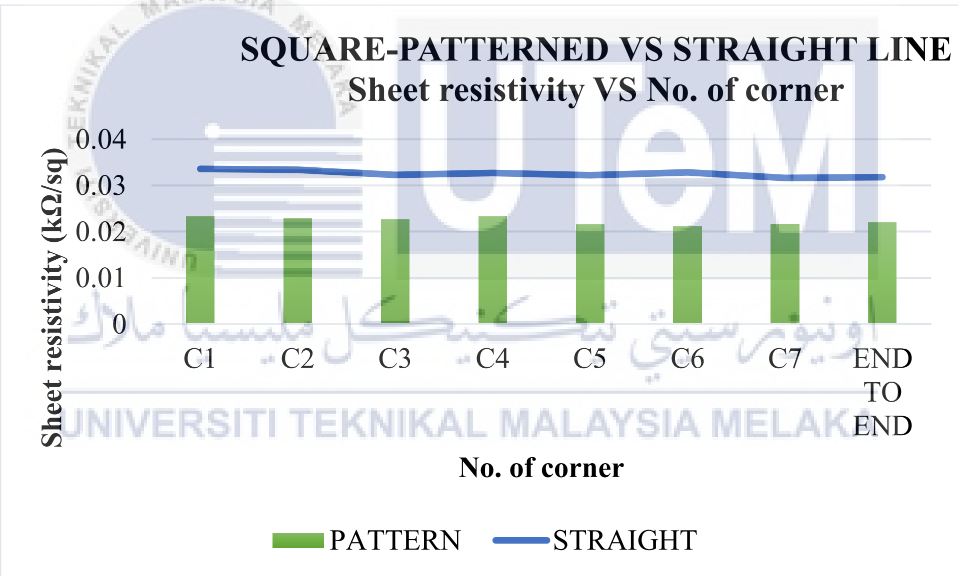


Figure 4. 4 Comparison circuit: Sheet resistance versus Number of corners

4.3 Sheet resistance measurement after twisting load

4.3.1 Twisting test: Line width 1 mm

The average data tabulation for 1 mm line width is as shown in Table 4.4, while Figure 4.5 and Figure 4.6 shows the trend in both resistance and sheet resistance reading. Averagely, it can be seen that the first corner of the circuit experienced most damage, and this is indicated with the abnormally high reading of resistance. The rest of the circuit also experienced increment in both resistance and sheet resistance. From the total of three samples, two of the samples undergone failure. Both the samples experienced failure at 790 and 2700 cycles respectively.

Table 4. 4 Data tabulation for thickness of 1 mm

Corner	L (mm)	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	40.00	0.025000	162.0329	4.0508
C2	58.00	0.017241	1.8888	0.0326
C3	78.25	0.012780	2.7568	0.0352
C4	98.00	0.010204	22.8107	0.2328
C5	119.00	0.008403	23.8200	0.2002
C6	137.00	0.007299	25.4722	0.1859
C7	158.00	0.006329	6.4378	0.0407
END TO END	177.00	0.005650	6.6211	0.0374

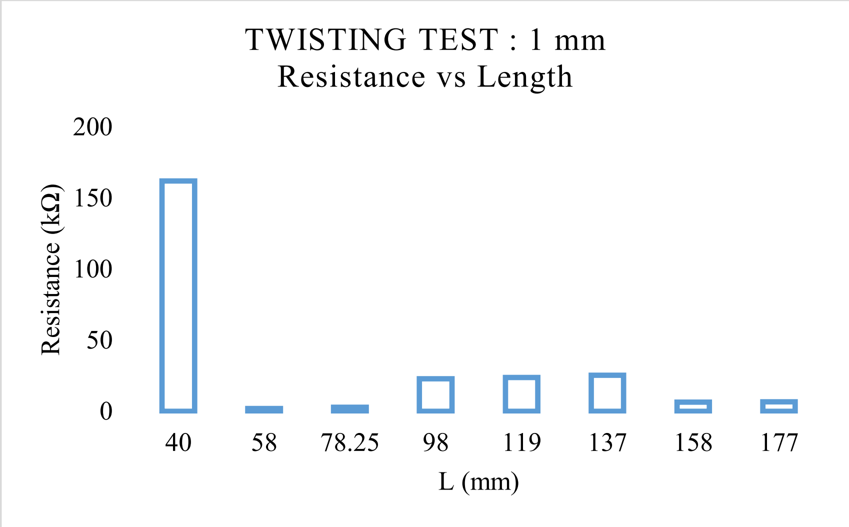


Figure 4. 5 Graph of resistance versus length for thickness of 1 mm

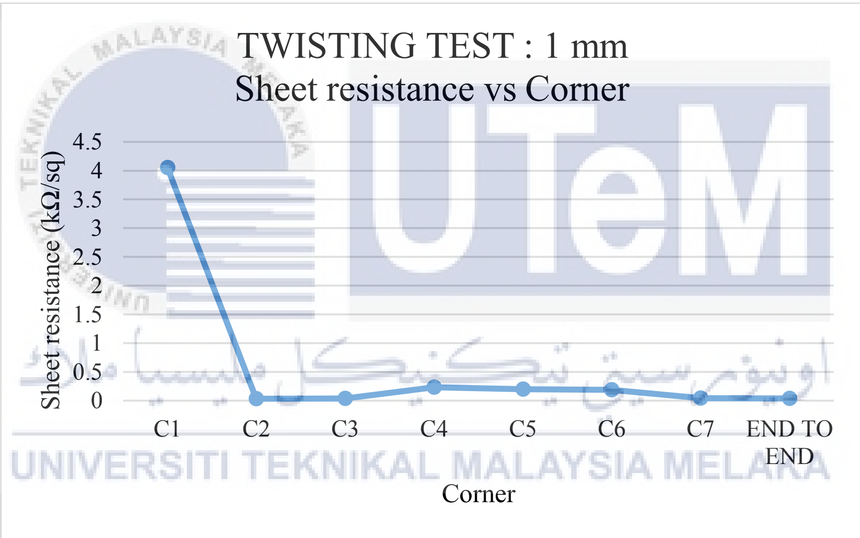


Figure 4. 6 Graph of sheet resistance versus Corner for thickness of 1 mm

4.3.2 Twisting test: Line width 2 mm

The graph plotted in Figure 4.7 shows that the resistance reading increases in quite a consistent linear trend and Figure 4.8 shows the sheet resistance value, as tabulated in Table 4.5. The resistance reading increases with the length and the highest reading is at the end of the circuit (11.58 kΩ). While for the sheet resistance, the reading decreases steadily from the first corner to the fourth corner and gradually increases again to the end of the circuit. The lowest sheet resistance value is at the fourth corner (0.0897 kΩ/sq) while the highest reading is at the end of the circuit (0.1259 kΩ/sq). Out of three samples, only one failed (at 2520 cycles) due to crooked ink in one of the corners.

Table 4. 5 Data tabulation for thickness of 2 mm

Corner	**L (mm)**	**W/L**	**Resistance (kΩ)**	**Sheet resistance (kΩ/sq)**
C1	40.2	0.049751	2.3569	0.1173
C2	61.0	0.032787	3.3721	0.1106
C3	83.0	0.024096	4.1137	0.0991
C4	101.2	0.019763	4.5390	0.0897
C5	122.6	0.016313	5.6037	0.0914
C6	144.4	0.013850	6.7143	0.0930
C7	166.4	0.012019	9.8067	0.1179
END TO END	184.0	0.010870	11.5800	0.1259

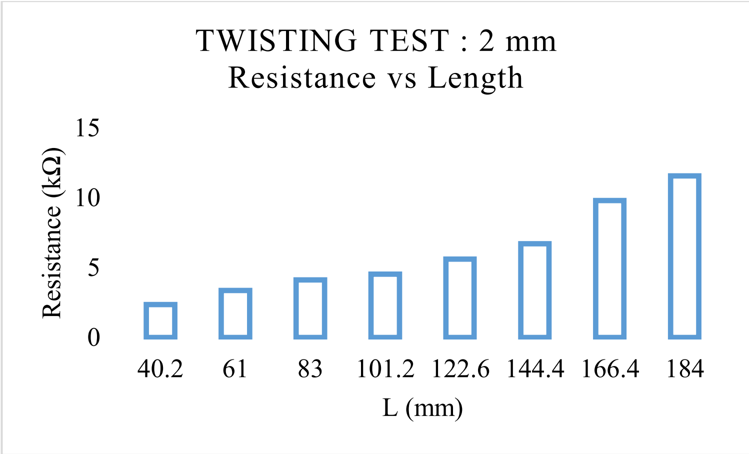


Figure 4. 7 Graph of resistance versus length for thickness of 2 mm

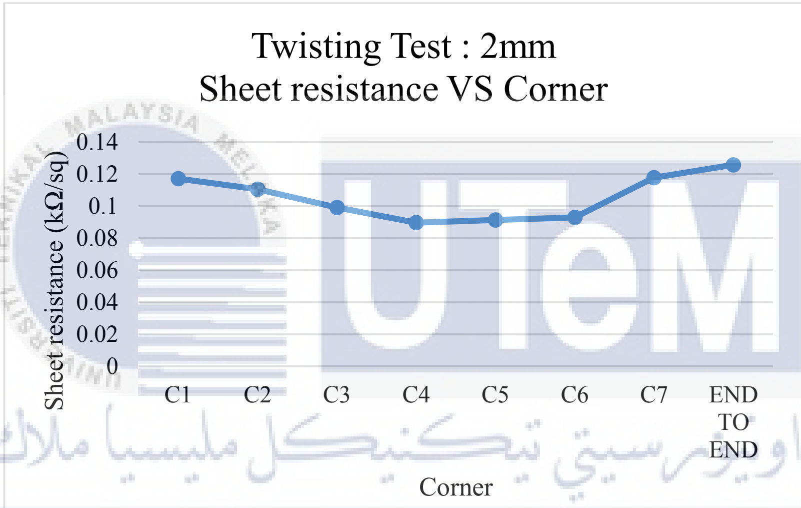


Figure 4. 8 Graph of sheet resistance versus Corner for thickness of 2 mm

4.3.3 Twisting test: Line width 3 mm

The data tabulated in Table 4.6 shows the data tabulation for circuit width of 3 mm. The graph plotted in Figure 4.9 shows that the resistance reading increases as the circuit length increases, while the sheet resistance reading fluctuates as shown in Figure 4.10. The highest resistance recorded is 4.6722 kΩ. As for the sheet resistance value, it ranges from 0.0659 kΩ/sq to 0.0722 kΩ/sq.

Table 4. 6 Data tabulation for thickness of 3 mm

Corner	L (mm)	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	41.0	0.073171	0.9000	0.0659
C2	65.0	0.046154	1.5111	0.0697
C3	87.4	0.034325	2.0222	0.0694
C4	105.4	0.028463	2.500	0.0712
C5	129.0	0.023256	2.8778	0.0669
C6	153.0	0.019608	3.4556	0.0678
C7	175.8	0.017065	4.1222	0.0703
END TO END	194.2	0.015448	4.6722	0.0722

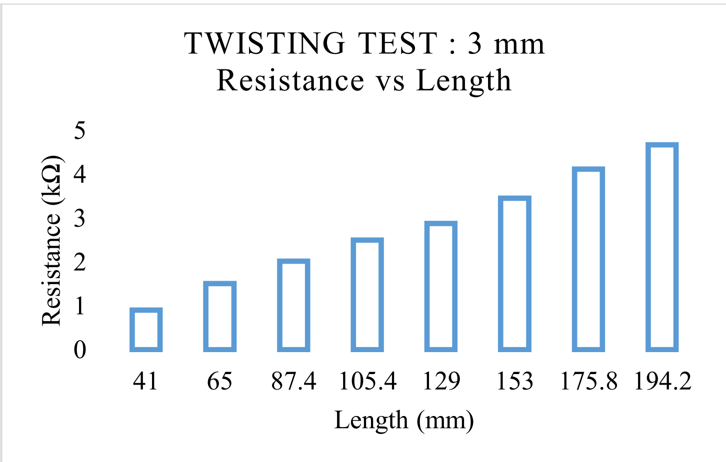


Figure 4. 9 Graph of resistance versus length for thickness of 3 mm

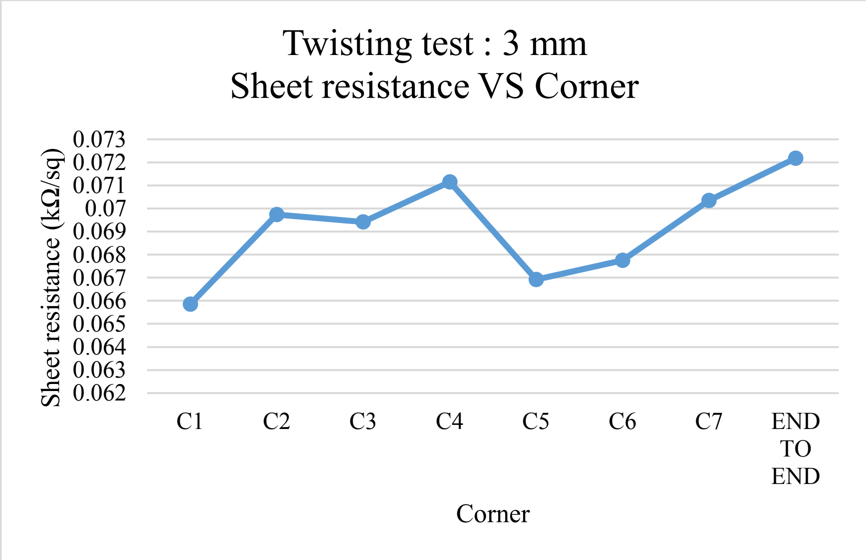


Figure 4. 10 Graph of sheet resistance versus Corner for thickness of 3 mm

4.4 Data comparison

Data in Table 4.7 shows the resistance and sheet resistivity reading before and after implementation of twisting test. The resistance reading before twisting test is nearly stable with sheet resistance ranging from approximately 0.01 to 0.06 kΩ/sq. Contrary with the trend, the after-test result shows uneven reading of sheet resistivity due to random and unpredictable sample failure during experimentation. However, it can be concluded that the sheet resistance value increases after the twisting test. The only outlier for the graph in Figure 4.11 is for sample named as 1mm-3 (third sample of thickness 1 mm sample). The sheet resistance after the experiment is lower than initial value. This is because, the sample experienced failure during the experiment which causes the ink to peel off from the substrate and causing the inability of current flow. Thus, the resistance reading declined to zero.

Table 4. 7 Data comparison

		Sheet resistance (kΩ/sq)	
Thickness	**Sample**	**Before test**	**After test**
1 mm	1	0.0414	0.0530
	2	0.0545	0.0592
	3	0.0166	0
2 mm	1	0.0252	0.1254
	3	0.0237	0.1409
	4	0.0192	0.1112
3 mm	1	0.0254	0.1182
	2	0.0251	0.0556
	5	0.0146	0.0427

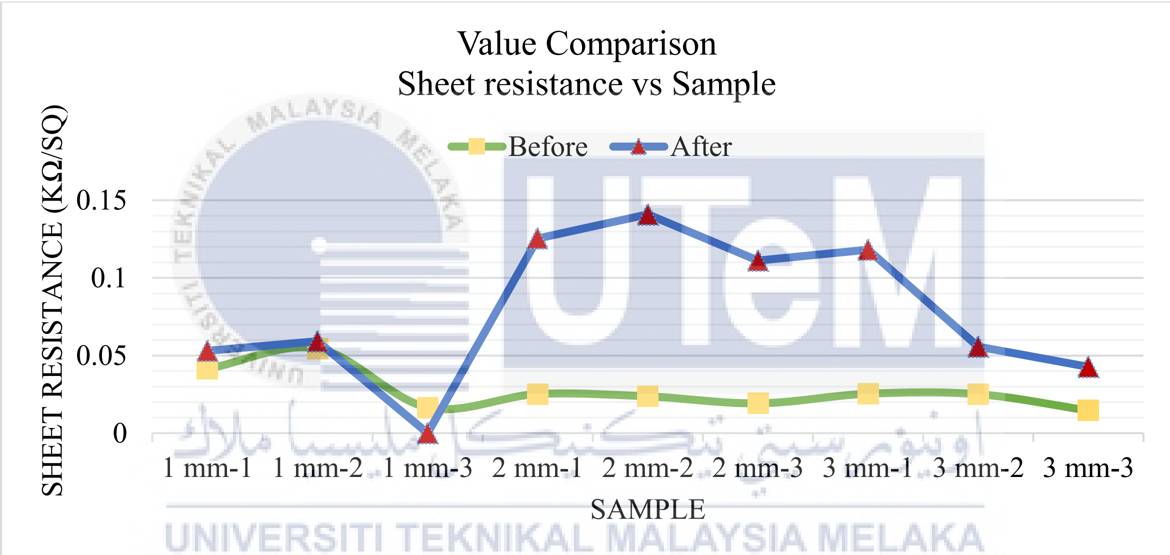


Figure 4. 11 Graph of data comparison

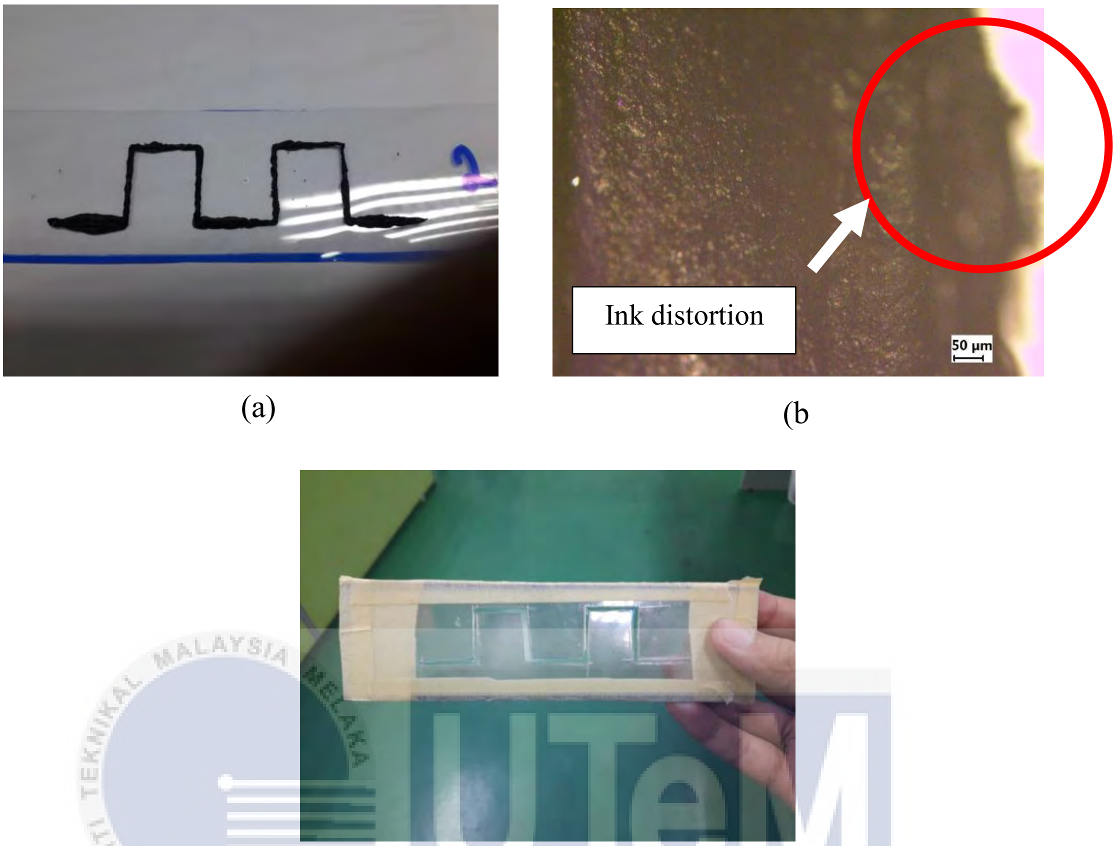
4.5 Discussion

4.5.1 Initial resistance

The sample fabrication is started off by using the screen-printing method as it is one of most suitable method to be used with the black carbon-based ink (Liu et al., 2018). As shown in Figure 3.3 (b), the square-patterned stencil shape is designed to have three different line width: 1 mm, 2 mm and 3 mm. As stated in the Bare Conductive Ink Data Sheet, the optimum curing temperature for the ink is at room temperature. Thus, the ink is left for 30-45 minutes before peeling it off the stencil.

The resistance measurement for each line width is recorded and the data is as tabulated in Table 4.1 and the graph is plotted in Figure 4.1. Then, the value of sheet resistivity is calculated and the average value is as shown in Table 4.2 and Figure 4.2 shows the plotted graph. From Figure 4.1, the resistance reading for 1 mm line width is observed to be the highest, while 3 mm line width has the lowest resistance value. This result agrees with the suggested design choices to enable higher conductivity (Happonen, 2016).

However, it can be observed in graphs in Figure 4.1 and Figure 4.2 that the resistance and sheet resistivity of 1 mm line width is comparatively higher than both 2 mm and 3 mm line width. This is due to the stencil error during the fabrication and printing process. The stencil used for this experiment is thicker than the average thickness used in previous researches. Thus, problems occurred during the final process of sample printing (substrate peeling off). The ink printed are distorted, as shown in Figure 4.12 (a) and Figure 4.12 (b) below and causes disturbance in electric flow. To mend the result, a manual square-patterned stencil has been made as shown in Figure 4.12 (c) but it failed to show better result.



(a) (b

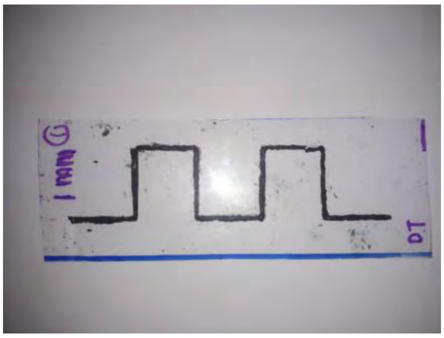
(c)

Figure 4. 12 (a) Distorted printed ink (b) Ink distortion under microscope observation (c) Manual stencil for square-shaped circuit

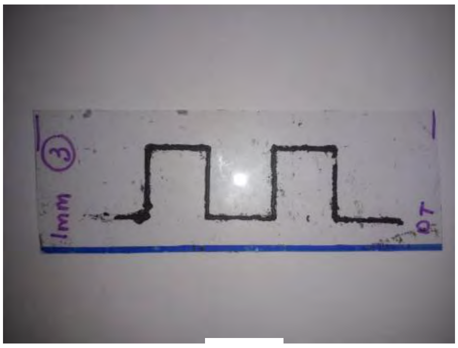
For better performance comparison, a straight-line circuit of the same length, width and thickness are fabricated manually by using layered PET as shown in Figure 3.4. Similarly, the ink is left to be cured at room temperature for 30-45 minutes. Then, the resistance reading for both circuit shapes are measured and compared. From the graph plotted in Figure 4.3, the resistance reading shows an outlier trend since the straight-line circuit shows higher value. The result opposes with the initial hypothesis even after few samples repetitions. The straight-line circuit is printed manually as shown in Figure 3.6 (c) and the resistance measurement is taken at points shown in Figure 3.11.

4.5.2 Resistance changes after twisting test

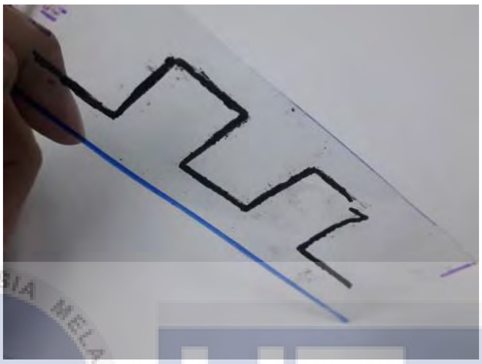
The resistance of the circuit undergoes significant changes during the 5000-cycle twisting test. Data tabulation in Table 4.4 shows the effect of the twisting test on sample with thickness 1 mm. Compared to the resistance reading from the other sample's thickness, the readings are quite irregular as plotted in Figure 4.5. The reason for this is the uneven damage due to the twisting test, and this causes no observable and significant linear inclination or declination for this sample thickness. Also, it can be observed that the average resistance reading for the first corner is above average and shows the highest reading which is 162.0329 kΩ. This is due to the failure experienced by the samples at the end of the experiment and this can be shown in Figure 4.13 which shows the photograph of the samples condition after completion of 5000 twisting cycles. The sample failure is due to the ink peeled-off from the substrate and causes it to become disconnected from the rest of the circuit. For better visualisation, the samples are observed under the microscope and the images are as shown in Figure 4.14. Figure 4.14 (a) shows the initial ink surface of the sample before the experiment and the damaged ink can be noticed in both Figure 4.14 (b) and Figure 4.14 (c). Figure 4.14 (b) shows the damage at the first corner of the sample which causes the resistance reading to increases significantly while Figure 4.14 (c) shows the impairment of one of the other corners.



(a)



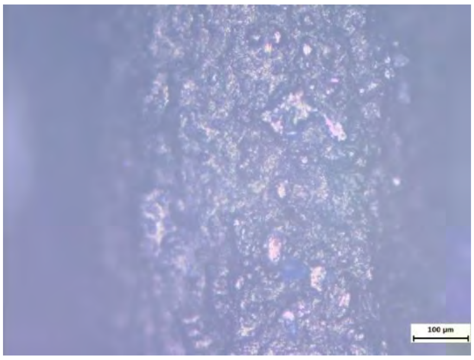
(b)



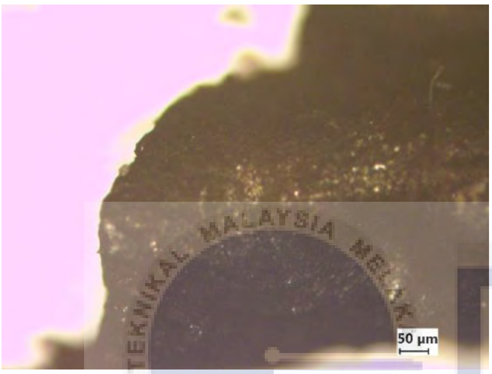
(c)

Figure 4. 13 (a) First sample of 1 mm after test (b) Third sample of 1 mm after test

(c) Close up of circuit failure



(a)



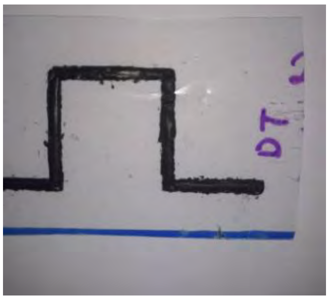
(b)

(c)

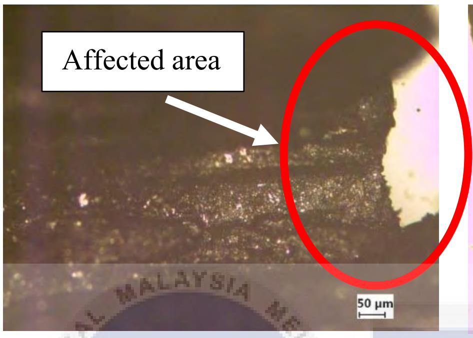
Figure 4. 14 (a) 1 mm sample before test (b) Damage at first corner

(c) Damage at sixth corner

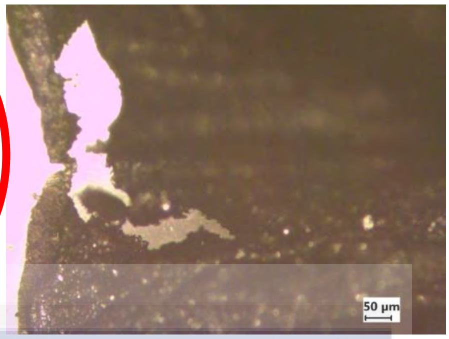
The data tabulation from the Table 4.5 tabulates the result of twisting test for sample of thickness 2 mm. The circuit failure is not obvious in the photograph as shown in Figure 4.15 (a), but the crooked ink can be seen during the microscope observation as shown in Figure 4.15 (b)and Figure 4.15 (b). The damaged area is slightly thin compared to the rest of ink surface area and this affects the resistance reading.



(a)



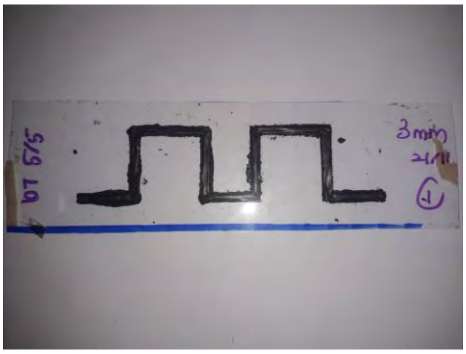
(b)



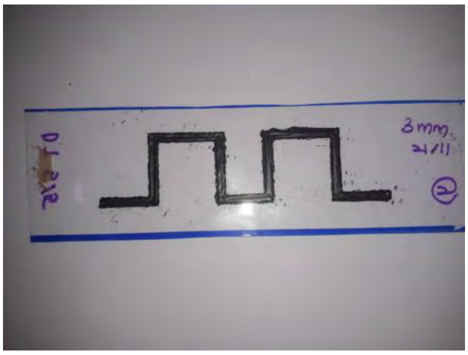
(c)

Figure 4. 15 (a) Failure in sixth corner (b) & (c) Microscopic image of circuit damage

Images shown in Figure 4.16 displays the end result of the twisting test for sample with 3 mm line width. Naked eye observation shows no physical and apparent damage to the ink condition, but the resistance reading and sheet resistance calculation proves that there is tiny and miniscule damage which can't be observed with mere observation or under microscope observation. The overall test result as tabulated in Table 4.8 shows irregular sheet resistance value due to unpredictable and random trend of damage which occurred during the twisting test.



(a)



(b)

(c)

Figure 4. 16 The end result of 3 mm line width sample (a) First sample (b) Second sample (c) Third sample

The data tabulation shown in Table 4.7 compares the result of sheet resistance taken from end to end of the circuit before and after the application of twisting load for all the nine samples. In average, the reading after the twisting load is significantly higher than before the experiment. The overall result complies with the previous researches which stated that the sample's reliability will be affected in presence of performance testing (Lee & Liu, 2011 & Merilampi et al., 2009).

Data tabulation in Table 4.7 also shows that the range of initial sheet resistance is from 0.0146 kΩ/sq to 0.0545 kΩ/sq. The range changes to 0 – 0.1409 kΩ/sq at the end of the twisting test. From the Technical Data Sheet as attached in Appendix J, the expected value of sheet resistance from a manually screen-printed circuit is 0.032 kΩ/sq. This value proved that the initially printed sample satisfied the theoretical value as provided by the Data Sheet.

Table 4. 8 Experimental data summary

Ink width	Sample	Point to failure (cycle)	Overall resistance (kΩ)	Sheet resistance (kΩ/sq)
1 mm	1	790	9.38	0.05
	2	-	10.48	0.06
	3	2700	0	0
2 mm	1	2520	11.54	0.13
	2	-	12.97	0.14
	3	-	10.23	0.11
3 mm	1	-	7.65	0.12
	2	-	3.60	0.06
	3	-	2.77	0.04

Table 4.8 shows the summary of the research's overall result. It shows that the circuit with lower line with are prone to circuit damage before the completion of 5000 cycles. Out of nine samples, only three samples experienced failure at cycle range of 790 to 2520. The rest of the samples does not experience circuit breakage before the end of the test. However, all the samples had larger value of sheet resistivity after the test completion. This shows that even though there are no visible damage seen on the circuit, the miniscule damage done as an effect of the cyclic twisting load were the cause of the resistance increment.

One of this research's objective is to investigate the circuit reliability for automotive LED application. Thus, the following calculation is done based on Standard LED Red 3 mm specification:

LED forward voltage	:	2.1 V
Max LED current	:	25 mA
Typical LED current	:	20 mA
Battery voltage	:	12 V
Calculated resistance	:	495 Ω

From the experimental value, the resistance reading range for circuit length ranging from 177 mm to 194 mm are as shown below:

Square shaped circuit (before testing)	: 1.42 kΩ - 5.72 kΩ
Square shaped circuit (after testing)	: 4.67 kΩ - 11.58 kΩ
Straight-line circuit	: 2.06 kΩ

The resistance obtained for this experiment is much higher than the required resistance for LED lighting. However, the LED will still be able to be light up, but prolong usage of the circuit will contribute to electrical energy wastage since higher current are needed to overcome the circuit resistance and also the LED resistance.

CHAPTER 5

CONCLUSION

5.1 Conclusion

The main objective of this research is to develop printed electronic sample on flexible substrate using carbon black-based conductive paste. A total of nine samples printed by using the screen-printing method for this research. The thickness of the samples is fixed at 1 mm and the manipulated variable was the line width which are varied at 3 readings: 1 mm, 2 mm and 3 mm. The substrate used was PET which is commonly known as plastic and the carbon-based conductive ink was used.

Next, the effect of the square-printed connection circuit on the sheet resistivity were studied. The results show that the 3 mm line width has the least sheet resistivity and the 1 mm line width has the highest reading. This is because the line width affects the current flow in circuit

Lastly, the sample's reliability is also tested by the application of cyclic twisting load of 5000 cycles. The result shows that the sample's sheet resistivity increases greatly after the load application. Observation was done with both naked eye and also microscope shows that there are damages on the circuit that causes the sheet resistivity to increase. However, there are also damages that are too miniscule to be observed.

5.2 Recommendation for future work

For future work, the geometrical parameters of the circuit can be changed in order to successfully provide an adequate resistance value for LED lighting application. For instance, manipulating the ink thickness and width and also change the circuit shape and to compare the effect of different geometrical effect on their circuit resistance reading.

Also, the reliability of printed circuit can be further improved and developed through a more diverse testing method. For instance, the shearing effect on a coated (laminated) printed substrate or the performance of printed circuit under different environmental temperature and humidity. The substrate used can also varies from paper to fabric in order to maximise the range of application of usage of circuit in order to serve futuristic and technological innovation and advancement.

The surface hardness, adhesion strength and also surface morphology can also be measured. The surface hardness test is to test the sample by using Nano-indenter to measure the hardness of the sample when subjected to different operating temperature. This test is significant to investigate the behaviour of the printed circuit under thermal loading. Theoretically, increment of temperature with prolong duration will produce an oxidation layer on the ink surface. This will increase the possibility of material to have cracks and to be malfunction. In order to prove the performance malfunction and to observe the crack, Scanning Electron Microscopy (SEM) is to be done at the end of the experiment.

REFERENCES

AirBorn. (2018). *Why Flexible Printed Circuit Board (PCB).* Retrieved from https://www.airborn.com/products/flexible-circuits/why-flex-

Aqeel, A. (2018). *Rigid PCB - The Engineering Projects*. Retrieved from https://www.theengineeringprojects.com/2018/04/rigid-pcb.html

Ashebir, G., Zambou, S., Männl, U., Setshedi, R., Härting, M., & Britton, D. T. (2016). *Fully screen printed LRC resonant circuit*. Microelectronic Engineering, 162, 6-11. doi:10.1016/j.mee.2016.04.021

Association Connecting Electronics Industries. (2018). *IPC Releases PCB Industry Results for October 2018* | IPC. Retrieved from http://www.ipc.org/ContentPage.aspx?pageid=IPC-Releases-PCB-Industry-Results-for-October-2018

AzoMaterial. (2018). *Polyethylene Terephthalate Polyester (PET, PETP) - Properties and Applications*. Retrieved from https://www.azom.com/article.aspx?ArticleID=2047

Bag, A., & Choi, S. (2017). *Initiation and propagation of microcracks in Cu thin films on flexible substrates through the thickness direction during a cyclic bending test*. Materials Science and Engineering: A, 708, 60-67. doi: 10.1016/j.msea.2017.09.079

Bao, Z., & Chen, X. (2016). *Flexible and Stretchable Devices*. *Advanced Materials,28*(22), 4177-4179. Doi:10.1002/adma.201601422

Bare Conductive Inc. (2018a). *Electric Paint Application Notes*. Retrieved from https://docs-apac.rs-online.com/webdocs/137d/0900766b8137d81c.pdf

Bare Conductive Inc. (2018b). *Technical Data Sheet*. Retrieved from https://docs-apac.rs-online.com/webdocs/133a/0900766b8133a784.pdf

Bollström, Roger & Toivakka, Martti. (2013). *Paper substrate for printed functionality*. 945-966.

Bose, S., Chakraborty, S., & Sanyal, D. (2018). *Water-Ethylene Glycol Mediated Synthesis of Silver Nanoparticles for Conductive Ink*. Materials Today: Proceedings,5(3), 9941-9947. doi:10.1016/j.matpr.2017.10.191

BusinessDictionary. (2018). *What is a substrate? Definition and meaning.* Retrieved from http://www.businessdictionary.com/definition/substrate.html

Chang, C., Lin, H., Huang, U., Hong, H., & Huang, J. (2019). *Effects of different annealing processes on optoelectronic and bending fatigue properties of AgZr and ITO/AgZr thin film metallic glass.* Optics and Lasers in Engineering, 115, 100-106. doi:10.1016/j.optlaseng.2018.11.009

Chase, G. (2008). *ESD Journal - Ohms per square*. Retrieved from http://www.four-point-probes.com/ohms-per-square-what.pdf

Chen, Q., Xu, L., Salo, A., Neto, G., & Freitas, G. (2008). *Reliability study of flexible display module by experiments*. 2008 International Conference on Electronic Packaging Technology & High Density Packaging. doi:10.1109/icept.2008.4607161

Cho, C., & Ryuh, Y. (2016). *Fabrication of flexible tactile force sensor using conductive ink and silicon elastomer.* Sensors and Actuators A: Physical, 237, 72–80. doi:10.1016/j.sna.2015.10.051

Chu, Z., Peng, J., & Jin, W. (2017). *Advanced nanomaterial inks for screen-printed chemical sensors*. Sensors and Actuators B: Chemical, 243, 919-926. doi:10.1016/j.snb.2016.12.022

Chu, Z., Peng, J., & Jin, W. (2017). *Advanced nanomaterial inks for screen-printed chemical sensors*. Sensors and Actuators B: Chemical, 243, 919-926. doi:10.1016/j.snb.2016.12.022

Chung, D. D. L. (2004). *Electrical applications of carbon materials*. Journal of Materials Science, 39(8), 2645–2661. doi:10.1023/b:jmsc.0000021439.18202.e

Cui, W., Li, J., Zhang, Y., Rong, H., Lu, W., & Jiang, L. (2012). *Effects of aggregation and the surface properties of gold nanoparticles on cytotoxicity and cell growth*. Nanomedicine: Nanotechnology, Biology and Medicine, 8(1), 46–53. doi:10.1016/j.nano.2011.05.005 Dordrecht London.

Eastwin. (2017). *Flexible Printed Circuit Board (FPC) Manufacturer* | EastwinPCBA. Retrieved from https://www.eastwinpcba.com/flexible-printed-circuit-board/

Faraj, M., Ibrahim, K. and Ali, M. (2011). *PET as a plastic substrate for the flexible optoelectronic applications. Optoelectronics and Advanced Materials* – Rapid Communications, 5(8), pp.879-882.

Finn, M., Martens, C. J., Zaretski, A. V., Roth, B., Søndergaard, R. R., Krebs, F. C., & Lipomi, D. J. (2018). *Mechanical stability of roll-to-roll printed solar cells under cyclic bending and torsion*. Solar Energy Materials and Solar Cells, 174, 7-15. doi:10.1016/j.solmat.2017.08.015

Frysz, C. A., Shui, X., & Chung, D. D. L. (1996). *Carbon filaments and carbon black as a conductive additive to the manganese dioxide cathode of a lithium electrolytic cell.* Journal of Power Sources, 58(1), 41–54. Doi: 10.1016/0378-7753(95)02291-0

Galdino, F. E., Foster, C. W., Bonacin, J. A., & Banks, C. E. (2015). *Exploring the electrical wiring of screen-printed configurations utilised in electroanalysis.* Analytical Methods, 7(3), 1208-1214. Doi: 10.1039/c4ay02704c

Gerard, J. (2018). *What Is a Substrate in Chemistry?* [Online] Sciencing. Available at: https://sciencing.com/what-substrate-chemistry-4673739.html

Goldberg, H. D., Brown, R. B., Liu, D. P., & Meyerhoff, M. E. (1994). *Screen printing: a technology for the batch fabrication of integrated chemical-sensor arrays.* Sensors and Actuators B: Chemical, 21(3), 171–183. Doi: 10.1016/0925-4005(94)01249-0

Happonen, T. (2016). *Reliability studies on printed conductors on flexible substrates under cyclic bending.*

Hauptman, N., Vesel, A., Ivanovski, V., & Gunde, M. K. (2012*). Electrical conductivity of carbon black pigments.* Dyes and Pigments, 95(1), 1-7. doi:10.1016/j.dyepig.2012.03.012

Hosch, W. L. (2009). *Polyethylene terephthalate | Structure, Properties, & Uses*. Retrieved from https://www.britannica.com/science/polyethylene-terephthalate

Hrehorova, E., Rebros, M., Pekarovicova, A., Bazuin, B., Ranganathan, A., Garner, S., Merz, G., Tosch, J., & Boudreau, R. (2011). *Gravure Printing of Conductive Inks on Glass Substrates for Applications in Printed Electronics*. Journal of Display Technology, 7(6), 318-324.

Hrehorova, E., Rebros, M., Pekarovicova, A., Bazuin, B., Ranganathan, A., Garner, S., … Boudreau, R. (2011). *Gravure Printing of Conductive Inks on Glass Substrates for Applications in Printed Electronics.* Journal of Display Technology, 7(6), 318–324.

Im, J. S., Kim, J. G., & Lee, Y.-S. (2009). *Fluorination effects of carbon black additives for electrical properties and EMI shielding efficiency by improved dispersion and adhesion*. Carbon, 47(11), 2640–2647. doi:10.1016/j.carbon.2009.05.017

Imerys Graphite & Carbon. (2018). *Carbon Black Electrical Conductivity*. Retrieved from http://www.imerys-graphite-and-carbon.com/1-carbon-black-electrical-conductivity/index.html

IndiaMart. (2019). *Transparent Pet Film Roll*. Retrieved from https://www.indiamart.com/proddetail/transparent-pet-film-roll-13332610148.html

Inui, T., Mandamparambil, R., Araki, T., Abbel, R., Koga, H., Nogi, M., & Suganuma, K. (2015). *Laser-induced forward transfer of high-viscosity silver precursor ink for non-contact printed electronics.* RSC Advances, 5(95), 77942–77947.

Ito, S., & Mikami, Y. (2011). *Porous carbon layers for counter electrodes in dye-sensitized solar cells: Recent advances and a new screen-printing method*. Pure and Applied Chemistry, 83(11), 2089–2106. Doi: 10.1351/pac-con-11-04-03

Jo, Y. H., Jung, I., Choi, C. S., Kim, I., & Lee, H. M. (2011). *Synthesis and characterization of low temperature Sn nanoparticles for the fabrication of highly conductive ink*. Nanotechnology, 22(22), 225701. doi:10.1088/0957-4484/22/22/225701

Joo, S.-J., Hwang, H.-J., & Kim, H.-S. (2014). *Highly conductive copper nano/microparticles ink via flash light sintering for printed electronics*. Nanotechnology, 25(26), 265601. doi:10.1088/0957-4484/25/26/265601

Joo, S.-J., Park, S.-H., Moon, C.-J., & Kim, H.-S. (2015). *A Highly Reliable Copper Nanowire/Nanoparticle Ink Pattern with High Conductivity on Flexible Substrate Prepared via a Flash Light-Sintering Technique*. ACS Applied Materials & Interfaces, 7(10), 5674–5684. Doi: 10.1021/am506765p

Kattumenu, R., Rebros, M., Joyce, M., Hrehorova, E., & Fleming, P. D. (2012). *Evaluation of Flexographically Printed Conductive Traces on Paper Substrates for RFID Applications*. Laser-induced forward transfer of high-viscosity silver precursor ink for non-contact printed electronics. RSC Advance. 5(95), 77942-77947

Kazani, I., Hertleer, C., Mey, G. D., Schwarz, A., Guxho, G., & Langenhove, L. V. (2015). *Electrical Conductive Textiles Obtained by Screen Printing*. Doi: 10.3403/30293513

Larmagnac, A., Eggenberger, S., Janossy, H., & Vörös, J. (2014). *Stretchable electronics based on Ag-PDMS composites*. Scientific Reports, 4(1). Doi: 10.1038/srep07254

Lee, Y., & Liu, T. (2011). *Deformation of Multilayer Flexible Electronics Subjected to Torque*. Experimental Techniques, 38(1), 13-20. doi:10.1111/j.1747-1567.2011.00780.x

Li, X., Su, X., & Liu, Y. (2017). *Adaptive region control for robotic soldering of flexible PCBs*. 2017 18th International Conference on Advanced Robotics (ICAR). doi:10.1109/icar.2017.8023521

Lim, Y. Y., Goh, Y. M., & Liu, C. (2013). *Surface Treatments for Inkjet Printing onto a PTFE-Based Substrate for High Frequency Applications. Industrial & Engineering Chemistry Research*, 52(33), 11564-11574

Liu, Y., Zheng, H., & Liu, M. (2018). *High performance strain sensors based on chitosan/carbon black composite sponges*. Materials & Design, 141, 276-285. doi:10.1016/j.matdes.2017.12.046

Lu, W. and Chung, D. (2002). *A comparative study of carbons for use as an electrically conducting additive in the manganese dioxide cathode of an electrochemical cell*. Carbon, 40(3), pp.447-449.

Mandal, S., Purohit, G., & Katiyar, M. (2012). *Inkjet Printed Organic Thin Film Transistors: Achievements and Challenges*. Materials Science Forum, 736, 250-274.

Mason, T. O. (2018). *Electronic substrate and package ceramics*. In Encyclopedia Britannica. Retrieved from https://www.britannica.com/technology/electronic-substrate-ceramics

Masterpiece Graphix. (2017, December 4). *The Advantages and Disadvantages of Printing on Plastics - Masterpiece Graphix.* Retrieved from https://mgxdigital.com/the-advantages-and-disadvantages-of-printing-on-plastics/

Merilampi, S. L., Bjorninen, T., Vuorimaki, A., Ukkonen, L., Ruuskanen, P., & Sydanheimo, L. (2010). *The Effect of Conductive Ink Layer Thickness on the Functioning of Printed UHF RFID Antennas*. Proceedings of the IEEE, 98(9), 1610-1619. doi:10.1109/jproc.2010.2050570

Merilampi, S., Laine-Ma, T., & Ruuskanen, P. (2009). *The characterization of electrically conductive silver ink patterns on flexible substrates*. Microelectronics Reliability, 49(7), 782-790. doi:10.1016/j.microrel.2009.04.004

Milmo, S. (2017). *Flexible and Printed Electronics Make Gains in European Automotive Market*. Retrieved from https://www.printedelectronicsnow.com/issues/2017-11-01/view_features/flexible-and-printed-electronics-make-gains-in-eur

Mitsubishi. (2006). *Three Main Properties of Carbon Black*. Retrieved from http://www.carbonblack.jp/en/cb/tokusei.html

Mitsubishi Chemical. (2018). *Application Examples of Carbon Black*. Retrieved from http://www.carbonblack.jp/en/cb/youto.html

Morais, R. M., Klem, M. S., Ozório, M. S., Gomes, T. C., & Alves, N. (2018*). Roughness influence on the sheet resistance of the PEDOT:PSS printed on paper*. Current Applied Physics, 18(2), 254–260. doi:10.1016/j.cap.2017.11.008

Mou, Y., Zhang, Y., Cheng, H., Peng, Y., & Chen, M. (2018). *Fabrication of highly conductive and flexible printed electronics by low temperature sintering reactive silver ink. Applied Surface Science, 459, 249-256. doi:10.1016/j.apsusc.2018.07.187*

Nano Dimension (2015). *Printed Electronics: Choosing the Right Ink for Your Application*. Retrieved from https://www.nano-di.com/blog/printed-electronics-choosing-the-right-ink-for-your-application

Nur, H. M., Song, J. H., G. Evans, J. R., & Ediringsihe, M. J. (2002). *Ink-jet printing of gold conductive tracks*. London, UK: Kluwer Academic Publisher.

OperaNewsNow. (2019). *Global Solid Thin Film Battery Market Research Report 2018 Forecast Till 2023*. Retrieved from https://operanewsnow.com/global-solid-thin-film-battery-market-research-report-2018-forecast-till-2023/125400/

PCBCart. (2018). *What Type of PCB Substrate Material Is Right for Your PCB?*. [Online] Available at: https://www.pcbcart.com/article/content/the-right-PCB-substrate-material-1.html

PET Resin Association. (2015). *Fact Sheet - An Introduction to PET (polyethylene terephthalate) | PETRA: Information on the Use, Benefits & Safety of PET Plastic*. Retrieved from http://www.petresin.org/news_introtopet.asp

Rao, V. K., Korada, V. A., & Singh, S. P. (2015). *Conductive silver inks and their applications in printed and flexible electronics*. RSC Advances, 5(95), 77760-77790. Doi:10.1039/c5ra12013f

Rapid. (2019). *Bare Conductive Electric Paint Jar 50ml*. Retrieved from https://www.rapidonline.com/bare-conductive-electric-paint-jar-50ml-70-0874

Rojas, J., Fontana Tachon, A., Chevalier, D., Noguer, T., Marty, J., & Ghommidh, C. (2004). *Chemometric analysis of screen-printed biosensor chronoamperometric responses*. Sensors and Actuators B: Chemical, 102(2), 284-290. doi:10.1016/j.snb.2004.04.034

Royole. (2019). *Flexible Display Corporation*. Retrieved from https://www.royole.com/en/flexible-display

Sánchez-González, J., Macías-García, A., Alexandre-Franco, M. F., & Gómez-Serrano, V. (2005). *Electrical conductivity of carbon blacks under compression*. Carbon, 43(4), 741–747. doi:10.1016/j.carbon.2004.10.045

Santos, K. (2017, June 30). *Screen Printing or DTG Printing - Which Print Method Is Better?* Retrieved from https://feltmagnet.com/textiles-sewing/Screen-Printing-or-DTG-Printing-Which-Method-is-Better

Savastano, D. (2018). *Opportunities Ahead for Flexible, Foldable Displays*. Retrieved from https://www.printedelectronicsnow.com/contents/view_online-exclusives/2018-07-25/opportunities-ahead-for-flexible-foldable-displays/

Seefeld, S., Limpinsel, M., Liu, Y., Farhi, N., Weber, A., Zhang, Y., Law, M. (2013*). Iron Pyrite Thin Films Synthesized from a Fe (acac) 3 Ink*. Journal of the American Chemical Society, 135(11), 4412-4424. Doi: 10.1021/ja311974n

Shin, D.-H., Woo, S., Yem, H., Cha, M., Cho, S., Kang, M., Piao, Y. (2014). *A Self-Reducible and Alcohol-Soluble Copper-Based Metal–Organic Decomposition Ink for Printed Electronics.* ACS Applied Materials & Interfaces, 6(5), 3312–3319. Doi: 10.1021/am4036306

Sico, G., Montanino, M., De Girolamo Del Mauro, A., Imparato, A., Nobile, G., & Minarini, C. (2016). *Effects of the ink concentration on multi-layer gravure-printed PEDOT: PSS*. Organic Electronics, 28, 257-262.

Siegel, A. C., Phillips, S. T., Dickey, M. D., Lu, N., Suo, Z., & Whitesides, G. M. (2010). *Foldable Printed Circuit Boards on Paper Substrates*. Advanced Functional Materials, 20(1), 28–35. doi:10.1002/adfm.200901363

Suganuma, K. (2014). *Introduction to Printed Electronics* (1st ed.). New York: Springer-Verlag New York.

Sun, Y., & Rogers, J. A. (2007). *Inorganic Semiconductors for Flexible Electronics*. doi:10.1002/chin.200739224

Tao, H., Chieffo, L. R., Brenckle, M. A., Siebert, S. M., Liu, M., Strikwerda, A. C., Omenetto, F. G. (2011). *Metamaterials on Paper as a Sensing Platform*. Advanced Materials, 23(28), 3197–3201. doi:10.1002/adma.201100163

The Editors of Encyclopaedia Britannica. (1998, July 20). *Carbon black : Chemistry*. Retrieved from https://www.britannica.com/science/carbon-black

Tudorache, M., & Bala, C. (2007). *Biosensors based on screen-printing technology, and their applications in environmental and food analysis*. Analytical and Bioanalytical Chemistry, 388(3), 565-578. Doi: 10.1007/s00216-007-1293-0

UniMAP. (2019). *TORSION TEST* (ENT 251/4 – Solid Mechanics). Retrieved from UniMAP website:http://portal.unimap.edu.my/portal/page/portal30/Lecture%20Notes/KEJURUTERAAN_MEKATRONIK/SEM1_08_09/ENT251SOLIDMECHANICS/LABMODULES/E4-TORSION%20TEST.PDF

User, S. (2018). *Carbon Black Uses - International Carbon Black Association - ICBA.* [Online] Carbon-black.org. Available at: http://carbon-black.org/index.php/carbon-black-uses

Wang, G., Cai, Y., Ma, Y., Cao, Z., & Meng, X. (2019). *Ultrastable cyclic bending response of carbon nanotube/copper laminate composite film*. Composites Part A: Applied Science and Manufacturing, 121, 189-195. doi:10.1016/j.compositesa.2019.03.032

Wikipedia. (2018, November 9). *Substrate (biology)*. Retrieved from https://en.wikipedia.org/wiki/Substrate_(biology)

Wood, L. K., Hrehorova, E., Joyce, T. W., & Fleming, P. D. (2005). *Paper Substrates and Inks for Printed Electronic*s. Doi: 10.3403/30304004u

WordPress. (2014, February 4). *Bare Conductive's Electric Paint: First Impressions*. Retrieved from https://alisuchan.wordpress.com/2013/11/24/bareelectricpaint/

Wu, W., Yang, S., Zhang, S., Zhang, H., & Jiang, C. (2014). Fabrication, characterization and screen printing of conductive ink based on carbon@Ag core–shell nanoparticles. *Journal of Colloid and Interface Science, 427*, 15-19. doi:10.1016/j.jcis.2013.10.064

Wu, X., Han, Y., Zhang, X., Zhou, Z., & Lu, C. (2016). *Large-Area Compliant, Low-Cost, and Versatile Pressure-Sensing Platform Based on Microcrack-Designed Carbon Black@Polyurethane Sponge for Human-Machine Interfacing*. Advanced Functional Materials, 26(34), 6246–6256. doi:10.1002/adfm.201601995

Xiao, L., Yu, G., Zou, J., & Xu, Y. (2018). Experimental investigation into the coupling effects of magnetic field, temperature and pressure on electrical resistivity of non-oriented silicon steel sheet. *Journal of Magnetism and Magnetic Materials*, *454*, 314-319. doi:10.1016/j.jmmm.2018.01.099

Yang, J., Ye, Y., Li, X., Lü, X., & Chen, R. (2018). Flexible, conductive, and highly pressure-sensitive graphene-polyimide foam for pressure sensor application. *Composites Science and Technology, 164*, 187-194. Doi:10.1016/j.compscitech.2018.05.044

Zhang, T., Wang, X., Li, T., Guo, Q., & Yang, J. (2014). Fabrication of flexible copper-based electronics with high-resolution and high-conductivity on paper via inkjet printing. *Journal of Materials Chemistry C*, (2).

Zheng, Y., He, Z., Gao, Y., & Liu, J. (2013). *Direct Desktop Printed-Circuits-on-Paper Flexible Electronics*. Scientific Reports, 3(1). Doi: 10.1038/srep01786

LIST OF APPENDICES

APPENDIX A

RAW DATA OF SQUARE-SHAPED CIRCUIT

LINE WIDTH: 1 mm

Sample no/Resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	2.200	3.406	3.369	4.156	5.253	6.180	7.030	7.380
	2.140	3.370	3.328	4.129	5.440	6.130	7.060	7.260
	2.146	3.334	3.523	4.030	5.336	6.140	6.890	7.340
2	2.270	3.660	3.546	5.450	6.750	8.150	9.410	9.710
	2.169	3.552	3.640	5.195	6.530	8.380	9.640	9.690
	2.180	3.469	3.536	5.103	6.410	7.980	9.380	9.530
3	0.428	0.764	1.095	1.46	1.81	2.155	2.499	2.934
	0.429	0.772	1.081	1.44	1.844	2.152	2.514	2.917
	0.437	0.796	1.104	1.464	1.806	2.153	2.472	2.940

Sample no/Average resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	2.162	3.370	3.406	4.105	5.343	6.150	6.993	7.326
2	2.206	3.560	3.574	5.249	6.563	8.170	9.476	9.643
3	0.431	0.777	1.093	1.455	1.820	2.153	2.495	2.930

NO OF CORNER	C1	C2	C3	C4	C5	C6	C7	End to end
L (mm)	40	58	78.25	98	119	137	158	177
W/L	0.025	0.017	0.012	0.010	0.008	0.007	0.006	0.005
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.054	0.058	0.043	0.041	0.044	0.044	0.044	0.041
2	0.055	0.061	0.045	0.053	0.055	0.059	0.059	0.054
3	0.011	0.013	0.014	0.015	0.015	0.016	0.016	0.017

APPENDIX B

RAW DATA OF SQUARE-SHAPED CIRCUIT

LINE WIDTH: 2 mm

Sample no/Resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	0.620	0.830	1.070	1.402	1.448	1.755	1.978	2.417
	0.524	0.871	0.960	1.208	1.427	1.773	1.953	2.276
	0.484	1.005	1.057	1.182	1.427	1.735	1.980	2.261
2	0.461	0.729	0.963	1.092	1.313	1.499	1.909	2.190
	0.499	0.747	0.936	1.144	1.383	1.517	1.780	2.120
	0.555	0.689	0.964	1.182	1.320	1.767	1.905	2.212
3	0.470	0.730	0.955	1.171	1.430	1.670	1.873	2.222
	0.464	0.753	1.035	1.222	1.414	1.598	1.932	2.151
	0.471	0.781	0.991	1.161	1.441	1.652	1.940	2.180
	0.395	0.656	0.909	1.008	1.175	1.352	1.509	1.741
4	0.420	0.678	0.914	1.021	1.178	1.344	1.555	1.751
	0.421	0.633	0.936	1.013	1.192	1.344	1.543	1.806
	0.460	0.724	0.980	1.137	1.453	1.603	1.856	2.020
5	0.446	0.737	1.002	1.203	1.372	1.656	1.844	2.042
	0.453	0.871	0.978	1.228	1.542	1.634	1.863	2.026

Sample no/Average resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	0.542	0.902	1.029	1.264	1.434	1.754	1.970	2.318
2	0.505	0.721	0.954	1.139	1.338	1.594	1.865	2.174
3	0.468	0.754	0.993	1.184	1.428	1.640	1.915	2.184
4	0.412	0.655	0.919	1.014	1.182	1.347	1.536	1.766
5	0.453	0.777	0.986	1.455	1.456	1.631	1.854	2.029

NO OF CORNER	C1	C2	C3	C4	C5	C6	C7	End to end
L (mm)	40.2	61	83	101.2	122.6	144.4	166.4	184
W/L	0.049	0.033	0.024	0.019	0.016	0.013	0.012	0.010
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.027	0.029	0.024	0.024	0.023	0.024	0.023	0.025
2	0.025	0.023	0.022	0.022	0.021	0.022	0.022	0.023
3	0.023	0.024	0.023	0.023	0.023	0.022	0.023	0.023
4	0.020	0.021	0.022	0.020	0.019	0.018	0.018	0.019
5	0.022	0.025	0.023	0.028	0.023	0.022	0.022	0.022

APPENDIX C

RAW DATA OF SQUARE-SHAPED CIRCUIT

LINE WIDTH: 3 mm

Sample no/Resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	0.375	0.582	0.698	0.877	1.04	1.21	1.409	1.63
	0.347	0.582	0.704	0.89	1.049	1.206	1.417	1.64
	0.358	0.555	0.714	0.912	1.045	1.217	1.407	1.657
2	0.361	0.512	0.689	0.855	1.003	1.186	1.394	1.616
	0.363	0.534	0.726	0.9	1.045	1.19	1.418	1.622
	0.371	0.534	0.734	0.879	1.036	1.252	1.507	1.645
3	0.401	0.699	0.936	1.008	1.203	1.356	1.686	1.711
	0.443	0.654	0.967	1.033	1.243	1.463	1.605	1.746
	0.414	0.646	0.916	1.094	1.236	1.375	1.565	1.675
4	0.239	0.354	0.491	0.565	0.698	0.841	1.016	1.157
	0.254	0.401	0.503	0.57	0.708	0.845	1.067	1.166
	0.234	0.408	0.507	0.618	0.724	0.879	1.061	1.215
5	0.216	0.324	0.43	0.495	0.587	0.71	0.805	0.958
	0.204	0.33	0.435	0.499	0.626	0.708	0.818	0.959
	0.201	0.33	0.448	0.506	0.63	0.724	0.826	0.92

Sample no/Average resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	0.360	0.573	0.705	0.893	1.044	1.211	1.411	1.642
2	0.365	0.526	0.716	0.878	1.028	1.209	1.439	1.627
3	0.419	0.666	0.939	1.227	1.227	1.398	1.618	1.710
4	0.242	0.387	0.500	0.584	0.71	0.855	1.048	1.179
5	0.207	0.328	0.437	0.500	0.614	0.714	0.816	0.945

SAMPLE / SHEET RESISTANCE (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
L (mm)	41	65	87.4	105.4	129	153	175.8	194.2
W/L	0.073	0.046	0.034	0.028	0.023	0.019	0.017	0.015
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.026	0.026	0.024	0.025	0.024	0.023	0.024	0.025
2	0.026	0.024	0.024	0.024	0.023	0.023	0.024	0.025
3	0.030	0.030	0.032	0.034	0.028	0.027	0.027	0.026
4	0.017	0.017	0.017	0.016	0.016	0.016	0.017	0.018
5	0.015	0.015	0.015	0.014	0.014	0.014	0.013	0.014

APPENDIX D

RAW DATA OF STRAIGHT-LINE CIRCUIT

LINE WIDTH: 3 mm

Sample no/Resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	0.434	0.634	0.83	1.023	1.251	1.554	1.701	1.94
	0.419	0.614	0.821	1.045	1.276	1.502	1.717	1.928
	0.407	0.643	0.842	1.033	1.219	1.513	1.711	1.925
2	0.483	0.819	1.064	1.308	1.536	1.882	1.985	2.164
	0.522	0.809	1.042	1.242	1.526	1.817	1.984	2.166
	0.489	0.821	1.042	1.244	1.51	1.778	2.022	2.221

Sample no/Average resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	0.420	0.630	0.831	1.033	1.248	1.523	1.709	1.931
2	0.498	0.816	1.049	1.264	1.524	1.825	1.997	2.183

SAMPLE / SHEET RESISTANCE (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
L (mm)	41	65	87.4	105.4	129	153	175.8	194.2
W/L	0.073	0.046	0.034	0.028	0.023	0.019	0.017	0.015
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.030	0.029	0.028	0.029	0.029	0.029	0.029	0.029
2	0.036	0.037	0.036	0.035	0.035	0.036	0.034	0.033

APPENDIX E

RAW DATA OF TWISTING TEST

LINE WIDTH: 1 mm

Sample no/Resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	1.73	2.68	3.88	4.61	5.68	8.32	9.25	9.43
	1.82	2.71	3.87	4.73	5.64	8.20	9.04	9.31
	1.79	2.67	3.91	4.64	5.63	8.00	9.07	9.41
2	1.34	2.18	3.33	4.49	5.80	7.31	10.24	10.54
	1.32	2.19	3.35	5.53	5.72	7.29	10.2	10.49
	1.23	2.17	3.50	4.48	5.75	7.24	10.14	10.41
3	445	0.80	0.92	62.19	58.99	61.42	0	0
	482	0.79	1.12	58.29	60.62	60.94	0	0
	522	0.82	0.92	56.33	60.55	60.53	0	0

Sample no/Average resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	1.78	2.68	3.89	4.66	5.65	8.17	9.12	9.38
2	1.32	2.18	3.40	4.84	5.76	7.28	10.19	10.48
3	483	0.80	0.99	58.94	60.05	60.96	0	0

NO OF CORNER	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
L (mm)	40	58	78.25	98	119	137	158	177
W/L	0.025	0.017	0.013	0.010	0.008	0.007	0.006	0.005
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.04	0.05	0.05	0.05	0.05	0.06	0.06	0.05
2	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.06
3	12.08	0.01	0.01	0.60	0.50	0.44	0	0

Corner	L (mm)	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	40	0.025	162.03	4.05
C2	58	0.017	1.89	0.03
C3	78.25	0.013	2.76	0.04
C4	98	0.010	22.81	0.23
C5	119	0.008	23.82	0.20
C6	137	0.008	25.47	0.19
C7	158	0.006	6.44	0.04
END TO END	177	0.005	6.62	0.04
AVERAGE SHEET RESISTANCE				0.60

APPENDIX F

RAW DATA OF TWISTING TEST

LINE WIDTH: 2 mm

Sample no/Resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	0.56	0.83	1.22	1.36	1.84	2.69	9.78	12.43
	0.57	0.81	1.31	1.33	1.84	2.96	9.30	11.46
	0.59	0.81	1.19	1.36	1.85	2.67	8.18	10.73
2	1.90	4.20	5.60	6.10	7.90	10.00	11.30	12.90
	2.30	4.40	5.20	6.20	8.00	9.30	11.00	12.90
	2.10	4.30	5.30	6.40	8.30	9.00	11.20	13.10
3	4.50	5.00	5.90	6.20	6.90	8.00	9.10	10.30
	4.80	5.20	5.70	6.00	6.90	7.90	9.20	10.00
	3.90	4.80	5.60	5.90	6.90	7.90	9.20	10.40

Sample no/Average resistance (kΩ)	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
1	0.57	0.82	1.24	1.35	1.84	2.78	9.09	11.54
2	2.10	4.30	5.37	6.23	8.07	9.43	11.17	12.97
3	4.40	5.00	5.73	6.03	6.90	7.93	9.17	10.23

NO OF CORNER	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**End to end**
L (mm)	40.2	61	83	101.2	122.6	144.4	166.4	184
W/L	0.049	0.033	0.024	0.019	0.016	0.014	0.012	0.011
SAMPLE/**SHEET** RESISTANCE (kΩ/sq)								
1	0.03	0.03	0.03	0.03	0.03	0.04	0.11	0.13
2	0.10	0.14	0.13	0.12	0.13	0.13	0.13	0.14
3	0.22	0.16	0.14	0.12	0.11	0.11	0.11	0.11

Corner	L (mm)	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	40.2	0.049	2.36	0.12
C2	61	0.032	3.37	0.11
C3	83	0.024	4.11	0.10
C4	101.2	0.019	4.54	0.09
C5	122.6	0.016	5.60	0.09
C6	144.4	0.014	6.71	0.09
C7	166.4	0.012	9.81	0.12
END TO END	184	0.011	11.58	0.13
AVERAGE SHEET RESISTANCE				0.11

APPENDIX G

RAW DATA OF TWISTING TEST

LINE WIDTH: 3 mm

Sample no/Resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	1.30	2.50	3.40	4.40	4.90	5.80	7.00	7.70
	1.40	2.50	3.20	4.40	4.80	5.90	6.90	7.60
	1.30	2.60	3.40	4.40	4.80	5.80	6.80	7.60
2	0.80	1.10	1.60	1.80	2.20	2.70	3.30	3.60
	0.80	1.10	1.50	1.80	2.20	2.70	3.20	3.60
	0.80	1.10	1.50	1.80	2.20	2.70	3.30	3.60
3	0.60	0.90	1.20	1.30	1.60	1.90	2.20	2.50
	0.50	0.90	1.20	1.30	1.60	1.80	2.20	2.60
	0.60	0.90	1.20	1.30	1.60	1.80	2.20	3.20

Sample no/Average resistance (kΩ)	C1	C2	C3	C4	C5	C6	C7	End to end
1	1.33	2.53	3.33	4.40	4.83	5.83	6.90	7.65
2	0.80	1.10	1.53	1.80	2.20	2.70	3.27	3.60
3	0.57	0.90	1.20	1.30	1.60	1.83	2.20	2.77

NO OF CORNER	C1	C2	C3	C4	C5	C6	C7	End to end
L (mm)	41	65	87.4	105.4	129	153	175.8	194.2
W/L	0.073	0.046	0.034	0.028	0.023	0.019	0.017	0.015
SAMPLE/SHEET RESISTANCE (kΩ/sq)								
1	0.10	0.12	0.11	0.13	0.11	0.11	0.12	0.12
2	0.06	0.05	0.05	0.05	0.05	0.05	0.06	0.06
3	0.04	0.04	0.04	0.04	0.04	0.04	0.04	0.04

Corner	L (mm)	W/L	Resistance (kΩ)	Sheet resistance (kΩ/sq)
C1	41	0.073	0.90	0.07
C2	65	0.046	1.51	0.07
C3	87.4	0.034	2.02	0.07
C4	105.4	0.028	2.50	0.07
C5	129	0.023	2.88	0.07
C6	153	0.019	3.46	0.07
C7	175.8	0.017	4.12	0.07
END TO END	194.2	0.015	4.67	0.07
AVERAGE SHEET RESISTANCE				0.07

APPENDIX H

TWISTING TEST

DATA SUMMARY

RESISTANCE (kΩ)			
Corner	1 mm	2 mm	3 mm
C1	162.033	2.357	0.900
C2	1.889	3.372	1.511
C3	2.757	4.114	2.022
C4	22.811	4.539	2.500
C5	23.820	5.604	2.878
C6	25.472	6.714	3.456
C7	6.438	9.807	4.122
END TO END	6.621	11.580	4.672
STD DEV	53.665	3.211	1.290
SHEET RESISTIVITY (kΩ/sq)			
Corner	1 mm	2 mm	3 mm
C1	4.0508	0.1173	0.0659
C2	0.0326	0.1106	0.0697
C3	0.0352	0.0991	0.0694
C4	0.2328	0.0897	0.0712
C5	0.2002	0.0914	0.0669
C6	0.1859	0.0930	0.0678
C7	0.0407	0.1179	0.0703
END TO END	0.0374	0.1259	0.0722
STD DEV	1.396145	0.014024	0.002164

APPENDIX I
BARE CONDUCTIVE INK DATA SHEET

BARE CONDUCTIVE®

ELECTRIC PAINT®

Safety Data Sheet

ACCORDING TO EC-REGULATIONS
1907/2006 (REACH) & 1272/2008 (CLP)

1. IDENTIFICATION OF THE SUBSTANCE / MIXTURE AND OF THE COMPANY / UNDERTAKING

1.1	**Product identifier**	
	GHS Product Identifier	**Bare Conductive Paint**
	Chemical Name	*Water-based dispersion of carbon pigment in Natural resin*
	Other names	
	CAS No.	Mixture — Notapplicable
	EINECS No.	Mixture — Notapplicable
1.2	**Relevant identified uses of the substance or mixture and uses advised against**	
	Identified use(s)	Electrically conductive paint
	Uses advised against	None
1.3	**Details of the supplier of the safety data sheet**	
	Company Identification	Bare Conductive Limited First Floor 98 Commercial Street London E1 6LZ
	Telephone	+44 (0)20 3432 5385
	E-Mail (competent person)	**info@bareconductive.com**
1.4	**Emergency telephone number**	
	Emergency Phone No.	**+44 (0)20 3432 5385 / Technical manager**

2. HAZARDS IDENTIFICATION

2.1	**Classification of the substance or mixture**	
2.1.1	**Regulation (EC) No. 1272/2008 (CLP)**	
2.1.2	**Directives 1999/45/EC**	Preparation is not classified as hazardous according to Directives 1999/45/EC.
2.2	**Label elements**	
2.2.1	**Label elements**	According to Regulation (EC) No. 1272/2008 (CLP)
2.2.2	**Label elements**	According to Directive 1999/45/EC
	Hazard Symbol	Not applicable
	Risk Phrases	Not applicable
	Safety Phrases	Not applicable
2.3	**Other hazards**	

3. COMPOSITION / INFORMATION ONINGREDIENTS

3.1 Substances

EC Classification No. 1272/2008

Ingredients	%W/W	CAS No.	EC No.	Hazard statement(s)
Water		7732-18-5	231-791-2	Not classified.
Natural Resin		Trade secret	Trade secret	Not classified.
Conductive carbon		Trade secret	Trade secret	Not classified.
Humectant		Trade secret	Trade secret	Not classified.
Processing aids and preservatives		Trade secret	Trade secret	Individual levels below 1% do not give rise to classification

EC Classification No. 67/548/EEC

Hazard statement(s)	%W/W	CAS No.	EC No.	Classification and Risk Phrases
None				

3.2 Substances

For full text of R/H/P phrases see section 16.

4. FIRST AID MEASURES

4.1	**Description of first aid measures**	
	Inhalation	Remove patient from exposure. Give oxygen if breathing difficult. Apply artificial respiration if necessary. Obtain medical attention if ill effects occur.
	Skin Contact	Wash affected skin with plenty of soap and water. Remove contaminated clothing and wash before reuse. Obtain medical attention if ill effects occur.
	Eye Contact	If substance has got into the eyes, immediately wash out with plenty of water for at least 15 minutes. Obtain medical attention.
	Ingestion	If swallowed, rinse mouth with water (only if the person is conscious). Do not induce vomiting. Obtain medical attention.
4.2	**Most important symptoms and effects, both acute and delayed**	Unlikely to cause harmful effects under normal conditions of handling and use.
4.3	**Indication of the immediate medical attention and special treatment needed**	None

5. FIRE-FIGHTING MEASURES

5.1	**Extinguishing media**	
	Suitable Extinguishing Media	As appropriate for surrounding fire.
	Unsuitable Extinguishing Media	As appropriate for surrounding fire.
5.2	**Special hazards arising from the substance or mixture**	Combustion or thermal decomposition will evolve toxic and irritant vapours. (Nitrogen oxides)
5.3	**Advice for fire-fighters**	Self-contained breathing apparatus to be worn if involved in fire. Water spray should be used to cool containers.

6. ACCIDENTAL RELEASE MEASURES

6.1	**Personal precautions, protective equipment and emergency procedures**	Put on protective clothing.
6.2	**Environmental precautions**	Do not allow to enter drains, sewers or watercourses. If substance has entered a watercourse or sewer advise police and water authority.
6.3	**Methods and material for containment and cleaning up**	Adsorb spillages onto sand, earth or any suitable adsorbent material. Transfer to a lidded container for disposal. Clean area afterward with water and detergent
6.4	**Reference to other sections**	See Section: 8 (Exposure controls / PPE) & 13 (Disposal)

7. HANDLING AND STORAGE

7.1	**Precautions for safe handling**	Avoid contact with skin and eyes. Natural ventilation is adequate.
7.2	**Conditions for safe storage, including any incompatibilities**	Keep in the original container in a cool, dry place.
	Storage Temperature	Maximum temperature 25 degC. Product may be refrigerated but do not freeze
	Storage Life	Six months at 25 degC. After opening, use within two months
	Incompatible materials	Strong oxidising agents.
	Other information	Product may settle on storage Stir thoroughly before use

8. EXPOSURE CONTROLS / PERSONAL PROTECTION

8.1	**Control parameters**	
8.1.1	**Occupational Exposure Limits**	**WEL: Workplace Exposure Limit (UK HSE EH40)**
	LTEL (8 hr TWA mg/m³)	Not listed
	LTEL (8 hr TWA mg/m³)	Not listed
8.2	**Exposure controls**	
8.2.1	**Appropriate engineering controls**	Ventilation recommended. Follow the principles of good occupational hygiene to control personal exposures.
8.2.2	**Personal protection equipment**	
	Eye/face protection	Safety spectacles recommended.
	Skin protection (Hand protection/ Other).	Plastic or rubber gloves recommended
	Respiratory protection	No personal respiratory protective equipment normally required.
	Other	General hygiene measures for the handling of chemicals are applicable. Wash hands before breaks and after work. Wash contaminated clothing before reuse.
8.2.3	**Environmental Exposure Controls**	Do not allow to enter drains, sewers or watercourses.

9. PHYSICAL AND CHEMICAL PROPERTIES.

9.1	**Information on basic physical and chemical properties (Solution)**	
	Appearance	Liquid
	Colour	Black
	Odour	Slight
	Odour Threshold (ppm)	Not applicable
	pH (Value)	5-7
	Melting Point (°C) / Freezing Point (°C)	Approx -10 degC
	Boiling point/boiling range (°C)	Approx 102 – 105 degC
	Flash Point (°C) [Closed cup]	Not applicable. (Not combustible)
	Evaporation rate (Water = 1)	1
	Explosive limit ranges	Not applicable
	Vapour Pressure (mmHg)	17 mmHg at 20 degC (Water)
	Vapour Density (Air=1)	Not applicable
	Density (g/ml)	1.2 – 1.25 at 25 degC
	Solubility (Water)	Partially soluble
	Solubility (Other)	Partially soluble in organic solvents
	Partition Coefficient (n-Octanol/water)	Not applicable
	Auto Ignition Temperature (°C)	Not applicable
	Decomposition Temperature (°C)	> 100 degC (Partly Evaporates)
	Viscosity	Viscous liquid
	Explosive properties	Not explosive
	Oxidising properties	Not oxidising
9.2	**Other information**	

10. STABILITY AND REACTIVITY

10.1	**Reactivity**	Oxidises
10.2	**Chemical stability**	Stable under normal conditions
10.3	**Possibility of hazardous reactions**	Possibility of highly exothermic reaction with strong oxidizing agents
10.4	**Conditions to avoid**	High temperatures
10.5	**Incompatible materials**	Strong oxidising agents
10.6	**Hazardous Decomposition Product(s) Nitrogen oxides**	

11. TOXICOLOGICAL INFORMATION

11.1	**Information on toxicological effects**	
11.1.1	**Substances**	
	Acute toxicity	
	Ingestion	LD50 :>10 000 mg/kg (rat) (Calculated as product)
	Inhalation (4 hrs)	Not applicable
	Skin Contact	LD50 :> 10 000 mg/kg (rabbit) (Calculated as product)
	Skin corrosion / irritation	Unlikely to cause skin irritation
	Serious eye damage / irritation	Product is slightly irritant to eyes. Contains low concentrations (< 0.5%) of corrosive ingredients
	Respiratory or skin sensitization	Product is not sensitizing
	Mutagenicity	There is no evidence of mutagenic potential
	Carcinogenicity	No evidence of carcinogenicity
	Reproductive toxicity	No evidence of reproductive toxicity
	STOT-single exposure	**Inhalation:** Irritation of the respiratory tract. Coughing. Unlikely route of exposure.
		Ingestion: Nausea, vomiting
	STOT-repeated exposure (91 days)	NOAEL > 10 000 mg/kg/day(rat)(Calculated as product)
11.2	**Other information**	

12. ECOLOGICAL INFORMATION

12.1	**Toxicity**	
	(Fish) (96hrs)	LC50 > 1000 mg/l (Calculated as product)
	(Daphnia magna) (48hrs)	EC50 > 1 000 mg/l (Calculated as product)
	(Algae) (72hrs)	EC50 > 1 000 mg/l (Calculated as product)
12.2	**Persistence and degradability**	The organic ingredients are Biodegradable
12.3	**Bioaccumulative potential** (96 hrs)	The product has no potential for bioaccumulation.
12.4	**Mobility in soil**	The substance is predicted to have high mobility in soil.
12.5	**Results of PBT and vPvB assessment**	Not classified as PBT or vPvB.

13. DISPOSAL CONSIDERATIONS

13.1	**Waste treatment methods**	Do not empty into drains. Dispose of this material and its container at waste collection centre. Dried paint may be disposed of by landfill in accordance with local regulations.
13.2	**Additional Information**	The waste is considered to be non hazardous.
12.6	**Other adverse effects**	

14. TRANSPORT INFORMATION

14.1	**Land transport (ADR/RID)** UN number	Not classified as dangerous for transport.
14.2	**Sea transport (IMDG)** UN number	Not classified as dangerous for transport.
14.3	**Air transport (ICAO/IATA)** UN number	Not classified as dangerous for transport.

15. REGULATORY INFORMATION

15.1	**Safety, health and environmental regulations/legislation specific for the substance or mixture**	
15.1.1	**EU regulations** Authorisations and / or restrictions on use.	Not applicable
15.1.2	**National regulations**	Not applicable
15.2	**Chemical Safety Assessment**	No Chemical Safety Assessment (CSA) has been carried out

16. OTHER INFORMATION

References	European Chemicals Agency
	European Chemicals Bureau
	European Regulations and Directives
	Published chemical directories
	Suppliers' safety data sheets
	UK Health and Safety Executive
Risk Phrases	
Safety Phrases	
Hazard statement(s)	

Additional Information

Information contained in this publication or as otherwise supplied to Users is believed to be accurate and is given in good faith, but it is for the Users to satisfy themselves of the suitability of the product for their own particular purpose. Bare Conductive Limited gives no warranty as to the fitness of the product for any particular purpose and any implied warranty or condition (statutory or otherwise) is excluded except to the extent that exclusion is prevented by law. Bare Conductive Limited accepts no liability for loss or damage (other than that arising from death or personal injury caused by defective product, if proved), resulting from reliance on this information. Freedom under Patents, Copyright and Designs cannot be assumed.

Prepared by:
Edmund Fowles
EF Chemical Consulting Ltd
17 Kings Crescent East
Chester CH3 5TH
UK

T: +44 (0)1244 351644
E: edmund@efchemicalconsulting.co.uk