STRESS-STRAIN BEHAVIOUR OF CONDUCTIVE POLYMER

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STRESS STRAIN BEHAVIOUR OF CONDUCTIVE POLYMER.

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LIST OF ABBREVIATIONS

PU	Polyurethane
FEA	Finite Element Analysis
Ag	Silver
PET	Polyethylene
CIJ	Continuous Inkjet
DOD	Drop On Demand
PDMS	Polydimethylsiloxane
TPU	Thermoplastic Polyurethane
CPNC	Conductive Polymer Nano Composite
PVDF	Poly Vinylidene Fluoride
CNF	Carbon Nano Fiber

ABSTRAK

Disebabkan peningkatan permintaan terhadap penggunaan dakwat konduktif di pasaran, ramai penyelidik telah menghasilkan banyak dakwat konduktif dan menyatukan dengan pelbagai jenis substrat. Matlamat kajian ini adalah untuk menilai prestasi 2 dakwat konduktif yang berbeza iaitu dakwat Ag-PDMS dan dakwat cecair Ag dengan penggunaan Poliuretana sebagai substrat. Untuk mendapatkan sifat bahan bagi kedua-dua dakwat konduktif, ujian lekukan Nano telah dilakukan untuk mendapatkan modulus Elastik dakwat. Manakala bagi substrat poliuretana ujian tegangan uniaksial telah dilakukan untuk mendapatkan graf tekanan melawan ketegangan bagi membina model Neo-Hookean untuk simulasi. Penilaian dilakukan dengan menggunakan perisian ANSYS mendapatkan nilai tekanan dakwat konduktif. Tiga bentuk cetakan digunakan untuk membandingkan bentuk cetakan mana yang lebih baik untuk kedua-dua dakwat konduktif untuk dakwat Ag-PDMS, anjakan ditetapkan kepada 30 mm manakala untuk dakwat cecair Ag ia ditetapkan kepada 10 mm. Daripada keputusan yang kami dapat menunjukkan bahawa untuk dakwat Ag-PDMS kami dapat melihat bahawa bentuk zigzag adalah yang terbaik dengan tegasan maksimum yang lebih rendah diikuti oleh lurus dan ladam. Manakala bagi dakwat cecair Ag kita dapat melihat bahawa zigzag adalah yang terbaik dengan tekanan maksimum yang lebih rendah diikuti dengan ladam kuda dan bentuk lurus.

ABSTRACT

Due to an increasing demand on the use of the conductive ink in the market, many researchers have produced plenty of conductive ink and pairs it with different types of substrates. The goals of this study were to evaluate the performance of 2 different conductive ink which is Ag-PDMS ink and Ag liquid ink with the use of Polyurethane as the substrate. To get the materials properties for both the conductive ink, Nano indentation test was done to get the Elastic modulus of the inks. While for the polyurethane substrate a uniaxial tensile test was done to get the stress strain curve to build the Neo-Hookean model for the simulation. The evaluation was done by using ANSYS software get the stress value of the conductive ink. Three printing shape was used to compare which printing shape was better for both conductive ink for the Ag-PDMS ink the displacement was set to 30 mm while for the Ag liquid ink it was set to 10 mm. From the result that we get it shows that for the Ag-PDMS ink we can see that the zigzag shape is the best with lower maximum stress followed by the straight and horseshoe. While for the Ag liquid ink we can see that the zigzag is the best with lower maximum stress followed by the horseshoe and straight shape.

CHAPTER 1

INTRODUCTION

1.1 Overview Of Stretchable Conductive Polymer.

Nowadays, due to the growing interest in stretchable electronics produced in the field of electrical and electronic systems, numerous studies have been conducted to develop the next generation of high degree flexibility and conductive polymers. From the studies that have been made variety of applications of the stretchable conductive polymer have been introduced such as stretchable heaters, stretchable energy conversion and storage devices, stretchable transistors, sensors, and artificial skin are just some of the stretchable electronic devices that was made using variety of manufacturing processes (Wu, 2019).

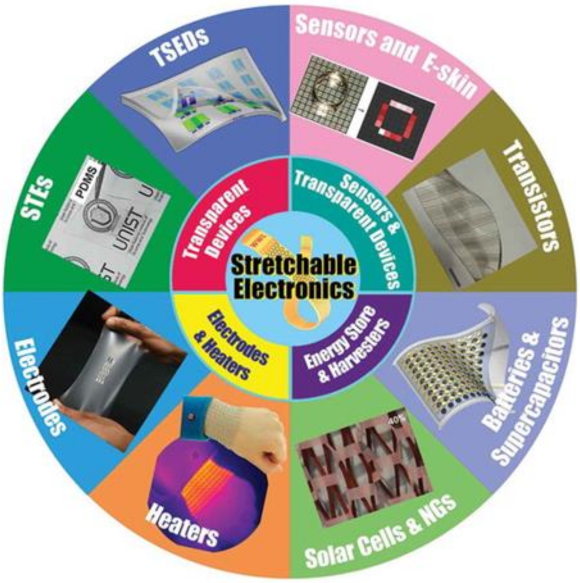


Figure 1.1 Application of stretchable conductive polymer.(Wu, 2019)

The method that was used to make a stretchable conductive polymer is by printing a conductive ink on the substrate. Inkjet printing is seen as a promising method for producing the stretchable conductive electronics because it allows for high volume and diverse manufacturing while having a low environmental impact, inkjet printing is seen as a promising method for flexible electronics. The substrate was made by a stretchable material such as polyurethane (PU). For the conductive inks there is two types of materials are usually used which are noble metal based (copper and silver) and carbon based (carbon nanotube and graphite), and each of these classes of materials has its own set of advantages and limitations (Akindoyo et al., 2021).

New and fascinating biomedical devices are now possible thanks to the development of material science, microelectronics, and microfabrication, as well as the enormous commercial drive provided in recent years by the market for smart portable devices. Research has concentrated on the creation of wearable chemical sensors, microfluids, and smart multiparametric sensing devices, starting with wearable physiological monitoring devices and cardiac monitoring devices. There are variety of applications in the stretchable conductive polymer such as pulse monitoring sensor, motion detector for recovery after orthopaedic surgery and sweat monitoring to monitor the ion such as (H+, Na+, K+, CL-) concentration.

1.2 Overview Of Finite Element Analysis Approach.

Finite element analysis (FEA) is a numerical method for solving engineering problems in area such as heat transfer, structural analysis, and fluid flow. The advantage of FEA resides in its capacity to analyses a complicated design and provide information on its efficiency and robustness. Engineers can use FEA to detect issues and failure of the design practices early on. A digital mesh of the design will be created using the finite element approach. This design is made up of numerous smaller components. The name refers to these smaller pieces as "finite elements" which are interconnected at points common to two or more elements (nodal points or nodes) which can be seen as Figure 1.2 below.

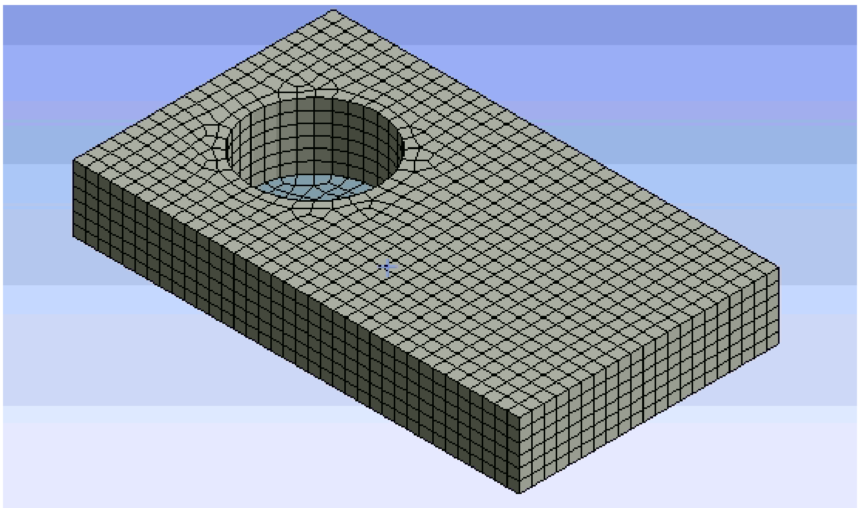


Figure 1.2 Example of meshing.

Instead of solving the problem for the entire structure in one operation, in FEA we develop the equations for each finite element separately and then combine them to produce the solution for the entire structure using the finite element approach. For our case we will be using FEA for a structural analysis. The displacements at each node and the stresses within each element of the structure that is subjected to applied loads are normally determined while solving structural problems (Logan, 2015).

Modern design uses finite element analysis (FEA) to foresee how a component will react to loads and other environmental factors. FEAs identify failure spots using material attributes, geometrical, mechanical, and thermal loads as inputs. The need of FEA method in this study is to see the stress distribution of the different conductive ink printing. To see whether there is a region which are prone to failure.

1.3 Research Objectives.

1. To determine the mechanical properties of 2 different conductive ink.
2. To access and compare the performance of both conductive ink under when the substrate is stretch.
3. To evaluate the Performance of different printing shape of the conductive ink.

1.4 Problem Statement.

Electronic product research has advanced greatly in recent years to provide human comfort in a variety of applications, including medical, fabric, and consumer uses. A stretchable conductive polymer was developed to provide flexibility in product design. It is important to know the mechanical behavior of a material so we can know the stress limit of the material. Compared to the current research, this project was to have better understand the mechanical behavior of the conductive polymer of two different ink which is Ag-PDMS ink and Ag liquid ink with the use of polyurethane polymer as substrate.

1.5 Outline Scope of Projects.

Firstly, Uniaxial tensile test was made to get the stress-strain curve of the polyurethane to use it to get the material properties of the substrate. Then for both the conductive ink which is Ag-PDMS and Ag liquid ink, Nano indentation was used to obtain the mechanical properties of the ink.

For the simulation, three different design of conductive ink was used to determine the performance of the conductive with different printing styles. The 3 different shapes are straight line, zigzag and horseshoes. The specimen was designed using SolidWorks software.

The simulation using ANSYS software was used to see the stress distribution of the 3 printing shapes of the conductive ink when the substrate elongates at a certain displacement. So, this study focusses on comparing two different type of silver ink stress strain behavior. However, the simulation result is a challenge because there is no experimental method that are used to validate the stress and strain of the conductive ink shape after combining it with the substrate.

CHAPTER 2

LITERATURE REVIEW.

2.1 Introduction.

Stretchable conductive circuit was one of the solutions for electronic devices especially in the application in which the circuit need to be stretched. Biomedical field is one of the fields which required a device which are flexible and stretchable to achieve better wearability for human body. Many academics have been interested in the mechanics of stretchable and flexible electronic board materials up until recently. They have conducted a great deal of simulations and laboratory tests in this area.

In this chapter it includes the different types of conductive ink and the printing technology, the difference substrate material that can be used, Nano indentation technique which can be used to get the mechanical properties of the conductive ink and the finite element analysis (FEA) that have been done on the flexible circuit before this.

2.2 Type Of Conducting Ink and The Printing Technology.

Nowadays the demand of the stretchable conductive polymer has increase. So, there are a lot of research that was done on difference type of ink and difference method that can be used to prepare and print the conductive ink. Most of the common conductive ink that was being used was silver conductive ink and graphene conductive ink. For the Silver-based inks are also popular because its nanoparticles have better electrical conductivity than other metallic elements, making them a good candidate for conductive ink composition. Silver nanoparticles make up most of the metallic ink. Silver nanoparticles having a low melting point, a strong resistance to oxidation, and a simple production procedure in addition to their excellent conductivity.

Graphene-based conductive inks are becoming one of the most used conductive because it has desirable combination of electrical and thermal conductivity, mechanical flexibility, chemical and thermal stability, and earth abundance provided by graphene. Graphene ink is not suitable for polymer substrate due to its high annealing temperature and have a high toxic solvent that needs to be used. However, (Htwe et al., 2021) study shows that with the inkjet printing process, less-toxic graphene conductive ink may be used more efficiently to fabricate various conductive patterns with good electrical conductivity and flexibility on polyethylene (PET) substrates.

The conductive ink can be printed to the substrate using a variety of methods. The first are screen-printing processes, which are among the most adaptable for mass printing technologies when compared to other printing techniques. They also go more rapidly and effortlessly. The two different kinds of screen printers utilised in the procedure are rotary and flatbed ones. The setup for this procedure includes the squeegee, substrate, screen, and press bed. A stencil tube, which is often a thin sheet of material, a fine porous fabric mesh, and synthetic fibers or silk, is used to transfer inks to the tool substrate. The screen-printing results can be successfully duplicated by running the cycle on a variety of substrates while using an ideal operating procedure.

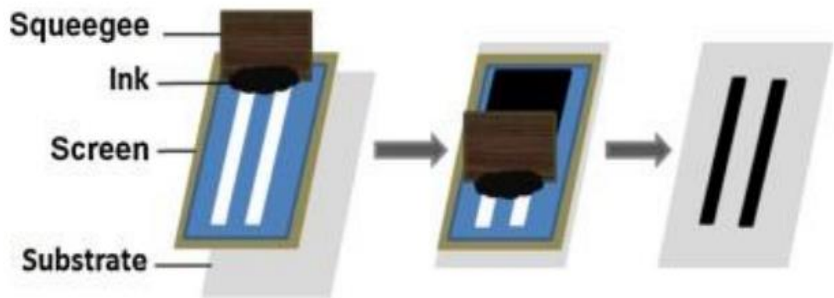


Figure 2.1 Schematic of the working principle for screen-printing technology.(Chu et al., 2017)

Gravure printing techniques make up the second method. The two different kinds of screen printers utilised in the procedure are rotary and flatbed ones. The setup for this procedure includes the squeegee, substrate, screen, and press bed. A stencil tube, consisting of a thin sheet of material, a fine porous fabric mesh, and synthetic or silk fibers, is used to transfer inks to the tool substrate. The cycle can be carried out on different substrates with the best operating procedure, allowing for accurate replication of screen-printing results(Htwe & Mariatti, 2022).

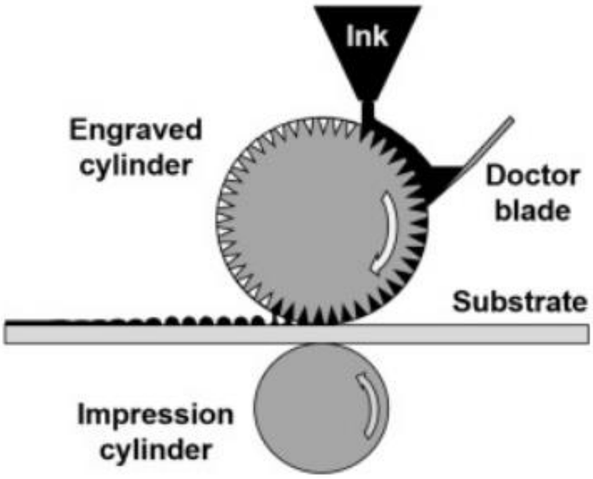


Figure 2.2 Schematic of the working principle for gravure printing techniques.(Sico et al., 2018)

Lastly, the inkjet printing technique is one of the newest fabrication techniques for printing the conductive ink onto the stretchable conductive polymer. Fast printing, decreased material waste, low-temperature fabrication, controlled material deposition, compatibility with a range of substrates, and digital patterning are just a few of the benefits of adopting this printing process. This non-contact printing technique's fundamental idea is to carefully place ink droplets on the necessary spot (pixel), which is being digitally monitored by a pre-programmed computer. Microdroplets are created by heating ink to increase volume and pressure, or by piezoelectric systems that cause mechanical compression through a nozzle. Inkjet printers primarily produce droplets using two different mechanisms: continuous inkjet printing and drop-on-demand printing.

Electronics have made extensive use of both mechanically rigid and flexible polymeric polymers as substrate materials for mounting chips and other electrical components. Depending on the physical properties required by the application, such as operating temperature, frequency, or mechanical strength, a variety of organic materials, including paper impregnated with phenolic resin, woven or nonwoven glass cloth, polyimide, or polyester, can be used as the base material in flexible electronics.

Other factors that must be considered while selecting the substrate materials include low cost and ease of fabrication.

(Hocheng & Chen, 2014a) highlighted three different types of substrates as being frequently utilized in electronic equipment. Solid substrates are the first. Solid substrates are used in most conventional electronic devices because of their excellent robustness against bending and impacts. Solid substrates moreover have the maximum reliability. The flexible substrates are the second of the 15 items. This flexible substrate's poor bendability and low stretchability are two of its disadvantages. The lifespan of the flexible circuit will be significantly reduced if it is folded 1,000 times.

Stretchable substrate usage is beginning to rise in modern times. Stretchable substrates are suitable for use on any nonplanar surface and can withstand significant bending and stretching motions. However, stretchy substrates also have a drawback of their own, which is that they have the shortest lifetime of the three because of the working conditions that require them to be repeatedly bent and stretched. Three categories coplanar, compound, and non-coplanar can be used to categories stretchable substrates.

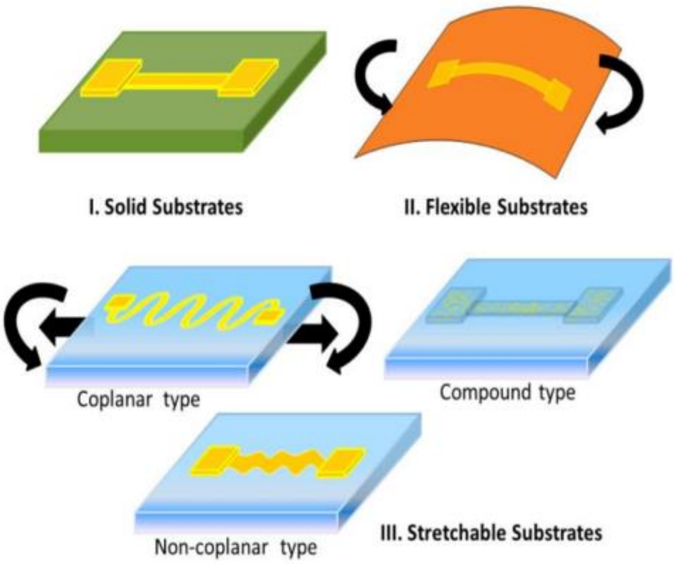


Figure 2.3 Solid substrates, flexible substrates, and stretchable substrates(Hocheng & Chen, 2014b).

Silicones are used in numerous aspects of life. Due to its characteristics, the silicone compound known as polydimethylsiloxane (PDMS) has been widely used in the electronic industry. In contrast to many other rubbery polymers, the (–Si–O–Si–) backbone in the PDMS structure is very flexible. High transparency, flexibility, and biocompatibility are all characteristics of PDMS. The hydrophobic nature of PDMS gives rise to its chemical inertness. It will be possible to create a variety of high-performance devices, including flexible conductors, wearable electronics, and electronic skins, by combining conductive patterns with PDMS (Sun et al., 2016).

However, the modulus, durability, and rip strength of silicone elastomers are low. To improve the mechanical qualities, polymers can be blended. Additionally, the addition of particle fillers is necessary to create silicones with adequate mechanical characteristics. The application of reinforcing fillers can provide a several-fold improvement in tensile strength, tear strength, and abrasion resistance. Colloidal silica is one of the most popular fillers that is frequently used to improve the mechanical properties of silicone elastomers. The surface area of the particles and the van der Waals and hydrogen bonding between the filler and the polymer have a significant impact on the capacity of silica fillers to reinforce materials (Agar, 2011).

For this project we have chosen polyurethane as the substrate for the conductive ink. Polyurethanes are a group of linear segmented copolymers with exceptional mechanical qualities Polyurethanes (PUs) can be utilised on their own or as part of composite materials. Along with coatings, adhesives, and varnishes, PUs can be used to create foams. PUs can be either thermoplastics or thermosets, in contrast to epoxies. These elastomers typically have strong tear strength, high tensile strength and elongation, and good abrasion resistance. Due to their chemical makeup, there are several chances to modify the structure to satisfy particular property needs.

(Sharma et al., 2021) designed and developed thermoplastic polyurethane (TPU) for its potential application as a urological implant. Several thermoplastic polyurethanes (TPU) modified with polydimethyl siloxane (PDMS) were developed. High tensile and tear strength, elongation, and versatility in terms of chemistry and processing possibilities make TPU a very useful class of segmental copolymers. Table Sows the mechanical properties of the combination of TPU and PDMS gained.

Table 2.1 Mechanical properties of different polyurethane. (Sharma et al., 2021)

Sample	Composition (wt%)		% Elongation at failure	UTS (MPa)	Elastic Modulus, E (MPa)	Storage Modulus, E' (MPa)	Loss Modulus, E'' (MPa)
	TPU	PDMS					
TPU	100	0	1315 ± 72	29.0 ± 3.5	9.2 ± 0.3	29.0 ± 0.5	1.62 ± 0.03
DT9P1	90	10	1020 ± 37	24.1 ± 1.8	9.0 ± 0.2	28.0 ± 0.3	1.50 ± 0.01
T9P1			1252 ± 58	19.5 ± 2.1	8.5 ± 0.1	24.8 ± 0.8	1.43 ± 0.01
DT8P2	80	20	939 ± 46	15.7 ± 0.5	8.4 ± 0.1	21.5 ± 1.1	1.41 ± 0.01
T8P2			1006 ± 44	10.9 ± 2.0	8.0 ± 0.2	18.6 ± 0.8	1.29 ± 0.02
DT7P3	70	30	915 ± 35	11.2 ± 1.2	7.9 ± 0.5	16.4 ± 0.2	1.22 ± 0.03
T7P3			945 ± 50	8.4 ± 0.6	7.1 ± 0.9	14.7 ± 0.5	1.17 ± 0.02
T6P4	60	40	637 ± 26	3.8 ± 0.3	5.8 ± 0.6	12.1 ± 0.7	0.97± 0.05

2.3 Nano Indentation.

One test that can be used to determine a material's hardness and elastic modulus is nano indentation. In a nanoindentation experiment, the indenter tip is subjected to an external load. The material can be forced into the tip with the help of this force, leaving a microscopic imprint on the surface known as a nanoindentation. Contrary to conventional indentation or micro indentation experiments, which rely on optical imaging of the indentation imprint for analysis, nanoindentation methods continually record the load, displacement, time, and contact stiffness throughout the indentation process. This data is evaluated to ascertain the mechanical characteristics of the material without using optical imaging. (Mann, 2005).

Nanoindentation employs a variety of nominal tip forms, including pyramidal, conical, and spherical. It's important to distinguish between sharpness and acuteness when dealing with pointed (pyramidal, conical) indenters. Up to the point, a sharp tip retains its nominal shape. More acute is a point with a smaller included angle between its surfaces. Indentation experiments often use blunt ends to prevent problems caused by sample 'cutting.' In many cases, a sharp indenter is desired. The most used tip in the nanoindentation is the Berkovich pyramid. The Berkovich pyramid is commonly employed in small-scale indentation investigations because the edges of the pyramid can be built to meet at a single point instead of the inevitable line that arises in the four-sided Vickers pyramid (“Nanoindentation Testing,” 2000).

Figure 2.4 show the visualization of the nano indentation process. Figure 2.4(a) shows the visualization at a maximum loading P_{max}. When, in relation to the original surface, the indenter is pressed into the material by an amount h_t which is the total depth. Along the indenter's axis, the indenter is in touch with the material for a distance h_c which is the contact depth. Near the tip, there is a zone of plastic deformation that is thought to be roughly hemispherical which are the shaded region. The indentation elastically recovers when the indenter is released. At the instant of final unloading as in figure b the indenter rests in the recovered indentation at a depth of h_f which is the final depth. Reloading to P_{max} would result in the load displacement data just retracing the unloading data if the unloading process were indeed elastic.

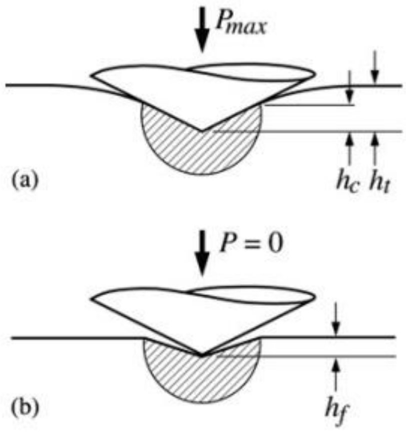


Figure 2.4 Visualization of the nano indentation process. (a) at maximum load and (b) after the unloading. (Baker & Liu, 2016)

With the help of instrumented indentation equipment, Oliver and Pharr created a technique that is now frequently used to determine the elastic modulus of small volume materials. With this technique, the derivative of the initial unloading curve can be used to determine the elastic modulus of the material under investigation. Oliver-Pharr methods is frequently used due to its simplicity of usage to determine elastic modulus and hardness. On the other hand, the literature also favors the work of indentation approach and the displacement approach to indentation to minimize errors brought on by the materials' tendency to build up or sink in(Uzun et al., 2008).

However, when using the Oliver-Pharr method to analyse nanoindentation data, several mistakes could happen because of pile-up and sink effects, thermal and electrical drifts, and creep effects. Based on elastic contact mechanics calculations, the Oliver-Pharr method only allows for "sink-in" forms of indents. However, pile-up can also form around a depression, as shown in Figure below. If a specimen has a low work-hardening rate, it is easier for the material beneath the indenter to flow sideways to make room for the indenter than it is for it to flow downward to cause the underlying material to deform. In this case, the indenter will attract material. In this case, the indenter will attract material. Further penetrating the point requires deforming the underlying material because the material above the indent will immediately solidify. If the pile-up scenario occurs, the Oliver-Pharr approach could yield incorrect results.

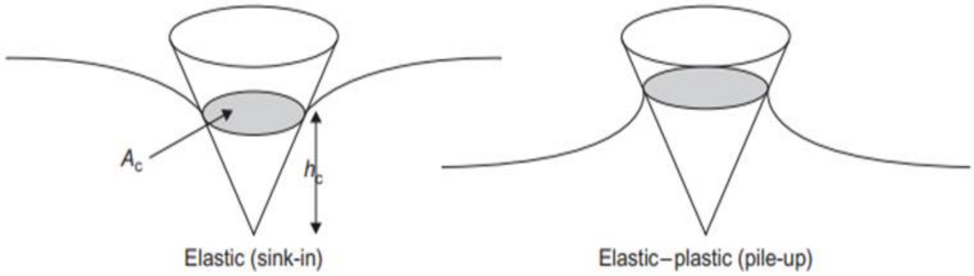


Figure 2.5 sink in and pile up morphologies of indentation. (Smallman & Ngan, 2014)

Secondly is thermal and electronic drift, in a nanoindentation experiment, thermal expansion or contraction of machine parts is the main contributor to drift in addition to electrical drifts. Nanoindentation analyses suffer from drifts. As a typical illustration, a test lasting, approximately five minutes can have a drift rate of 0.1 nm s-1. A total of 0.1x300= 30 nm would have been the lost in displacement. When compared to h_{max}, which for hard materials under light loads could be as little as 100 nm, this might not be insignificant. Drift rates on the order of approximately 0.1 nm s-1 are more frequently found, however drift rates of the order of approximately 0.01 nm s-1 are possible in extremely steady conditions.

Lastly was creep, The Oliver-Pharr technique presupposes that the sample will recover entirely elastically during unloading. Nevertheless, even high-melting solids might experience some viscoelastic creep during the first unloading phase of nanoindentation settings. There may be 3 reason that can make the sample creep severely which is the peak load is high, there is insufficient or no holding of the load before unloading, and the unloading speed is slow. Additionally, compared to hard materials like metals and ceramics, soft materials like polymers and biological tissues creep far more quickly (Smallman & Ngan, 2014).

2.4 Finite Element Analysis for Stretchable Polymer.

(Norhidayah et al., 2017) study on the stress behaviour of a stretchy electronic circuit by using numerical and experimental analysis. The result for each analysis was compared and evaluated. For the experimental analysis they used a plastic substrate and a formed polymer with Ag fillers as conductive ink is presented in this research. Material constant for neo-Hookean model was determine by tensile test. After that, the simulations of stress analysis were conducted with three different printing shapes which are straight, zigzag and horseshoe shapes.

The simulation results are in good agreement with the experimental data in most cases. Straight ink printing has a nominal stress value of 184 % with 92 mm elongation, whereas zigzag has a stress value of 123 % with 61.5 mm and horseshoe has a stress value of 133 % with 66.5 mm elongation. For the three various ink printing shapes, the three models provide elongation of greater than 100%. The mechanical behaviour of the stretchable circuit reveals that the horseshoe form has the least stress concentration followed by zigzag and lastly straight shape The horseshoe design, on the other hand, provides the highest stress value at the crest. For the neo-Hookean model, the finding is valid for up to 200 % strain.

(Prasad et al., 2021) The proposed flexible polymer's performance was anticipated using finite element analysis in both compression and tension mode. When building different sensing devices like strain sensors, pressure sensors, and other types of sensors, the results obtained in tension and compression modes will help in forecasting and identifying the sensor's failure behaviour. Specific conditions cannot be considered in the modelling portion due to several issues. As a result, assumptions that the membrane model would be uniform, the membranes would only possess the specific flaw, and the membrane would be devoid of any other defects, must be considered while analysing the results of this study. The model of conductive polymer nano composite (CPNC) membranes were modelled in Solid Works 19 having (60 × 30 × 0.065) mm structure.

Poly vinylidene fluoride (PVDF) has subpar elastomeric and mechanical properties as a polymer material. Pure PVDF membrane had the maximum deformation of 10.249 mm due to its plastic behaviour. When carbon nano fibre (CNF) was added to PVDF, the deformation was controlled and decreased to 5.7076 when compared to pure PVDF. This means that the CNF serves as a reinforcing material, giving the membrane strength in a similar way as reinforced cement combined with iron bars gives the membrane strength. According to the examination of the CPNC membrane, CNF increased strength whereas IL increased flexibility. A combined effect was observed in the PVDF/CNF/IL sample, with the lowest deformation being 0.18673 mm.

(Aziz et al., 2020) experimented with using conductive ink made of Ag-PDMS and polydimethylsiloxane (PDMS). For the modelling of the Finite Element model, they used 3 types of printing shapes which are rectangular, zigzag and horseshoe shape. For the substrate it has an area of 100 mm × 3 16.75 mm × and 0.5 mm thickness. While for the conductive ink it was modelled as 1.5 mm wide and 0.018 mm thick. For the boundary condition the model is fixed at one end or y=0 mm and applied with displacement (L) at the other end or y=L mm. The x-axis and z-axis displacements are both set to zero. The displacement at the moving end is set to 10% of the length the model due to the application of SEC which resulted in a 10% strain.

According to the analysis, the Equivalent stresses play a significant role in the horizontal displacement at the horizontal line for rectangular shapes, the inner sharp edge for zigzag shapes, and the inner curve for horseshoe shapes. In a rectangular design, the circuit printing parallel to the loading along a horizontal circuit has less significance than the lines perpendicular to the loading at a vertical circuit for the crucial equivalent stress region for vertical displacement. While the inner curve of vertical lines parallel to the loading in a horseshoe shape exhibits critical equivalent stress, the inner area of all slanted lines in a zigzag form exhibits significant stress.

2.5 Summary.

From the literature review we can see that there were several methods of producing and making the conductive starting from the printing method and different kind of conductive ink and substrate. Finite element analysis can be a good platform to see the stress-strain concentration of different printing shape of the conductive ink. Although there is variety of research on this field, there has been no research on comparing two several ink usages on a same substrate to see how the stress strain behavior of both inks was.

CHAPTER 3

METHODOLOGY

3.1 Introduction.

A conductive ink was being produced and was being tested by using a Nano indentation machine to obtain the materials properties. There were 2 different silver-based ink that was produced for the nano indentation test. 3 different printing shape of conductive ink were created in SolidWorks for the finite element analysis. For the finite element analysis ANSYS software was used. To get a most efficient meshing size a mesh sensitivity test for 1 of the printing shape of the conductive ink. The simulation for the stress analysis for the conductive ink at 50% strain of the substrate was done for conductive ink for 3 different printing.

3.2 Ink Preparation.

There were 2 types of ink that were used for this paper the first ink was the Ag-PDMS ink. The ink was prepared by combining silver particles with PDMS-OH epoxy resin for 24 hours at 280 rpm using a magnetic stirrer to fully dissolve all of the particles in PDMS, a conductive dispersion was created. D4 and ETMS were then added, and the mixture was again agitated for five to ten minutes. Finally, the silver-based solution was given 1–2 minutes to combine with acetic acid and DBDTL. The mixture was then applied to an ASTM D412 Type C rectangular mold and left to cure for 24 hours at room temperature.(Zulfiqar et al., 2021a). Figure 3.1 shows the finished Ag-PDMS ink.

Figure 3.1 The Ag-PDMS ink sample.

Secondly were the liquid Ag inks which was directly printed to the polyurethane substrate for the nano indentation test. Figure 3.2 shows the printing process of the inks. The ink printing was printed with 14 layers to make it thicker to undergo the Nano Indentation test. After the printing the conductive ink were sintered to heat-induced solidification of a solid coherent mass made of loose, small particles without melting the particles completely.

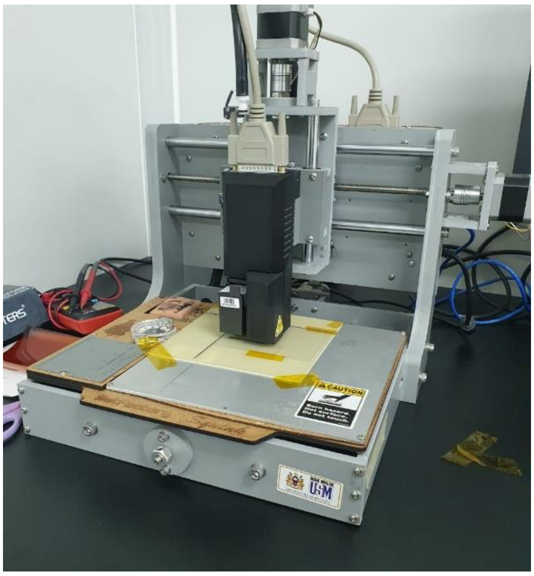


Figure 3.2 Inkjet printing of the Ag ink using Bot Factory printer.

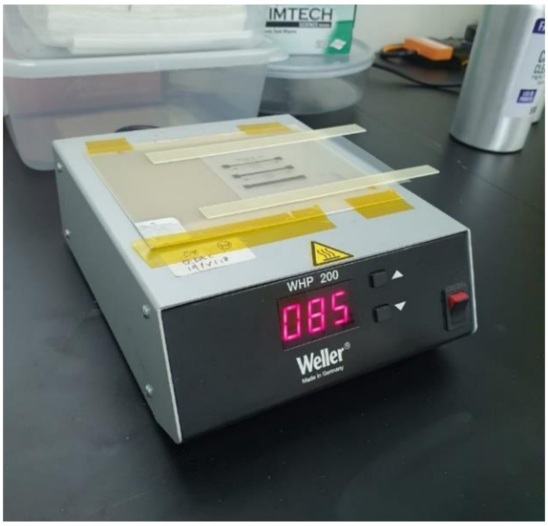
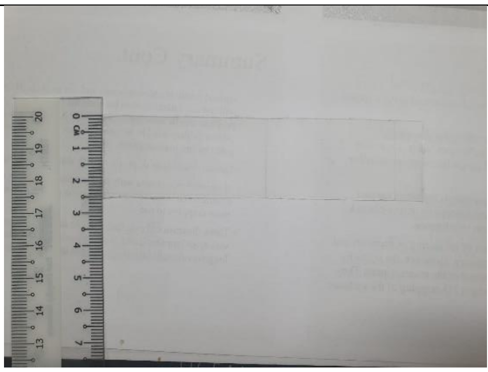


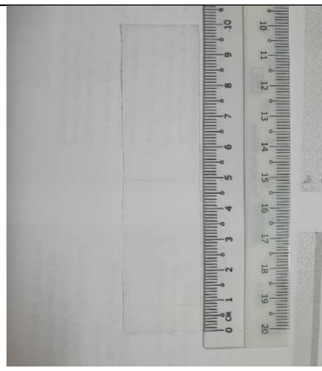
Figure 3.3 sintering process after printing the conductive ink.

3.3 Uniaxial tensile test.

The uniaxial tensile test was done to get the stress-strain curve for the substrate of the polyurethane substrate. The Universal testing machine that was used are UTM-INSTRON 3366. The specimen that was prepared as figure 3.4 below with a length of 10cm and a width of 2.5 cm. However, during the setup, the length of the specimen was then decreased to 3 cm because it needs to be clip to the Universal Testing Machine (UTM). The loading rate of the experiment are 50 mm/min with 10kN load cell at room temperature.



(a)



(b)

Figure 3.4 The dimension of specimen (a) width of specimen (b) length of specimen.

3.4 Nano indentation Test.

Nano indentation test was done to get the mechanical properties of the conductive ink. The mechanical properties that can be gain are hardness, shear modulus and young modulus. For the experiment the size of the specimen that were prepared was 8mm x 20mm. The parameters for the test have been shown in table 3.1 below for the Ag-PDMS ink. A Berkovich triangular pyramid indenter was used in this test.

Figure 3.5 The specimen of conductive ink that are glued to the holder for nano indentation test.

Table 3.1 The variable for the Nano indentation test for the Ag-PDMS ink.

Loading rate (mN/s)	0.3				
Unloading rate (mN/s)	0.3				
holding time (s)	2				
Loads (mN)	1	3	5	8	10

For the second conductive ink which is the Ag-liquid ink only one loads was used for the test because we do not compare the result with any other test. For this test the so the variable for the test can be seen as table 3.2.

Table 3.2 The variable for the Nano indentation test for the Ag liquid ink.

Loading rate (mN/s)	0.1
Unloading rate (mN/s)	0.1
Holding time (s)	0
Loads (mN)	1

3.5 Finite element analysis.

The stress analysis using ANSYS was to analyses the stress level of the conductive ink with 3 different printing shape at 50% strain for the Ag-PDMS ink and 17% strain for the Ag liquid ink.

3.5.1 CAD modelling

The CAD model was developed using Solidworks software. The dimensions of the substrate can be seen as figure 1 which has the width of 25mm and 60mm of length. Then 3 different shape of conductive ink printing was designed with diameter of 5 mm.

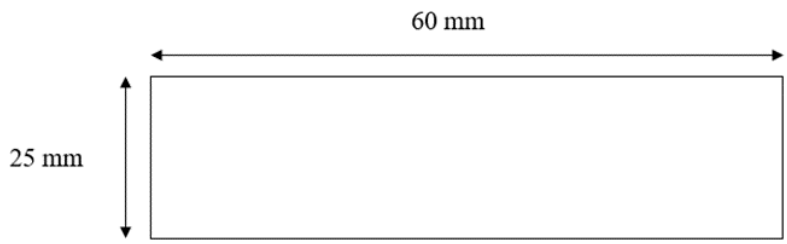


Figure 3.6 Substrate dimension.

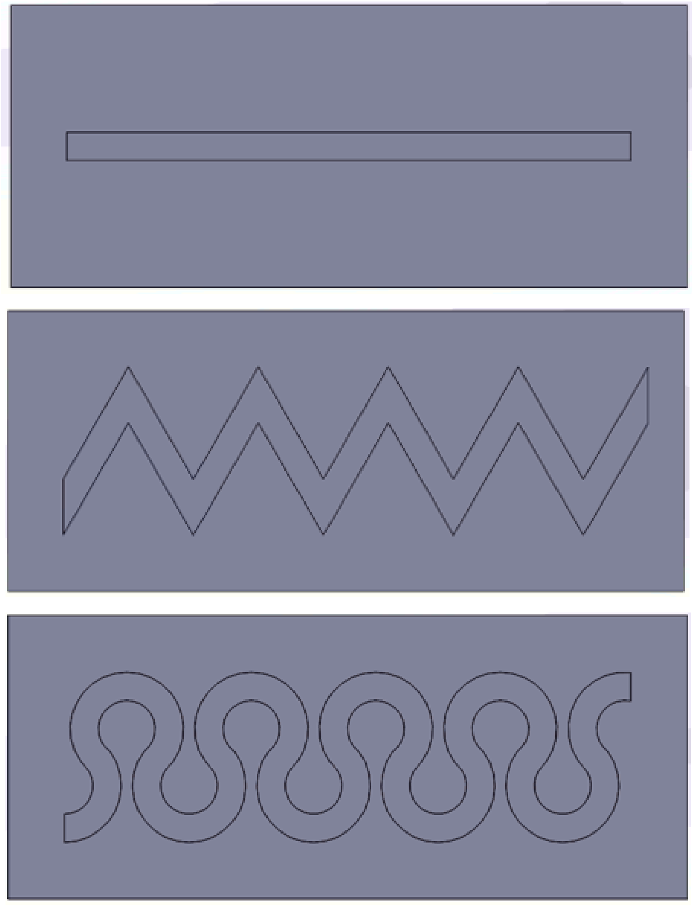


Figure 3.7 modelling of conductive ink with straight, zigzag and horseshoe shapes.

After designing all 3 of the models, meshing was done in the ANSYS software. For the meshing of this specimen the element size of the substrate is larger compared to the size of element for the conductive ink. This is because the targeted area for this study is the stress on the conductive ink. The number of elements for the straight printing shape model was 42540 elements, while for the zigzag shape was 58719 elements and lastly the horseshoe shape contains 66244 elements.

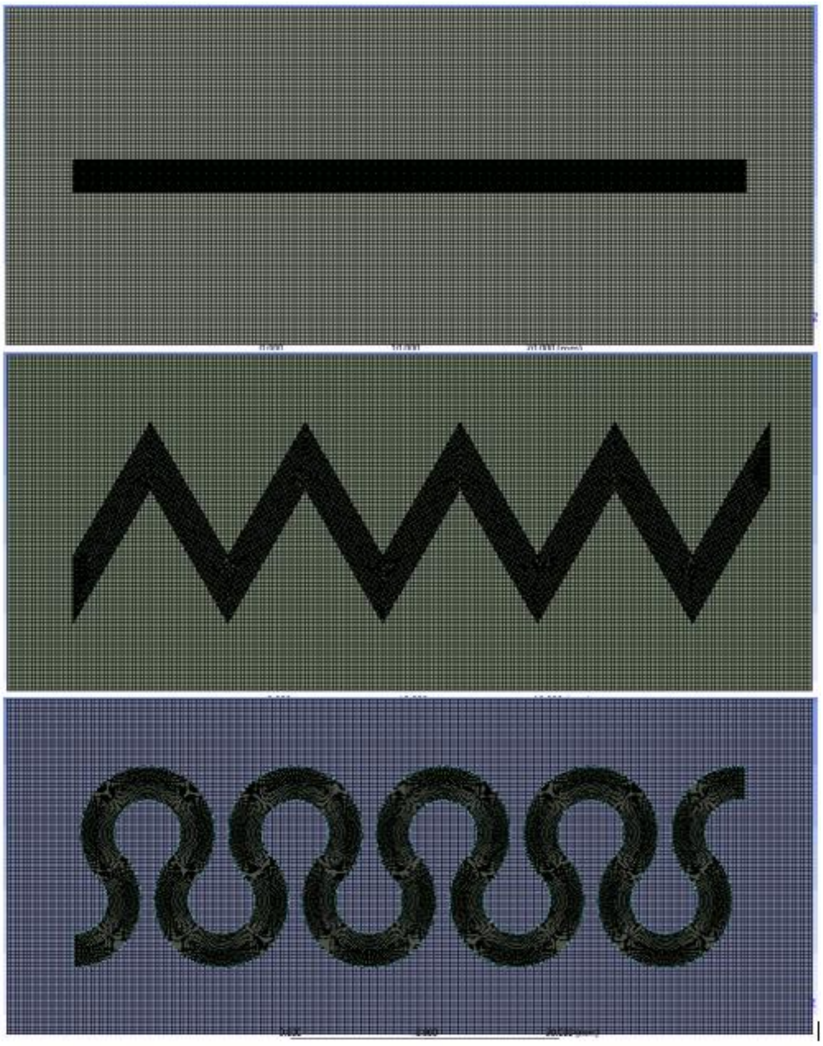


Figure 3.8 The meshing of the straight, zigzag and horseshoe printing shape.

For both the analysis we will use 2 different inks with same substrate which is polyurethane. For the conductive ink isotropic elasticity was used for the material properties. While for the polyurethane the Neo-Hookean model was used because the polyurethane was a hyperplastic material. For the Neo Hookean shear modulus, the tensile test data was inserted into the ANSYS software to generate a Neo-Hookean model by using a curve fit. While the ink materials properties are acquired from the Nano Indentation test.

Table 3.3 Material model and properties of the stretchable conductive polymer.

Component	Model	Materials properties required
Polyurethane	Neo-Hookean hyperplastic	G= 0.8281 Mpa
Ag-PDMS conductive ink	Linear plastic	E=5.16 Mpa v= 0.37
Ag liquid ink		E=209 Mpa v=0.35

3.5.2 Mesh sensitivity analysis.

Mesh sensitivity analysis is done running same simulation with several grid resolutions, and the converged solution is examined to see how much it varies with each mesh. The mesh sensitivity analysis was done to determine the lowest number of elements that can be used for the simulation such that after we refine the mesh it will have little to no effect on the solution. This is important step to be done so that we can save our time to do the simulation while getting an accurate result.

The mesh sensitivity was done on one of the models which is the zigzag model. A range of elements from 339 to 102254 was being run get the value of the Equivalent stress for the model. Figure 3.9 shows the result for the mesh sensitivity analysis. We can say that the result is independent of number of element when the mesh reach 44050 number of elements and above.

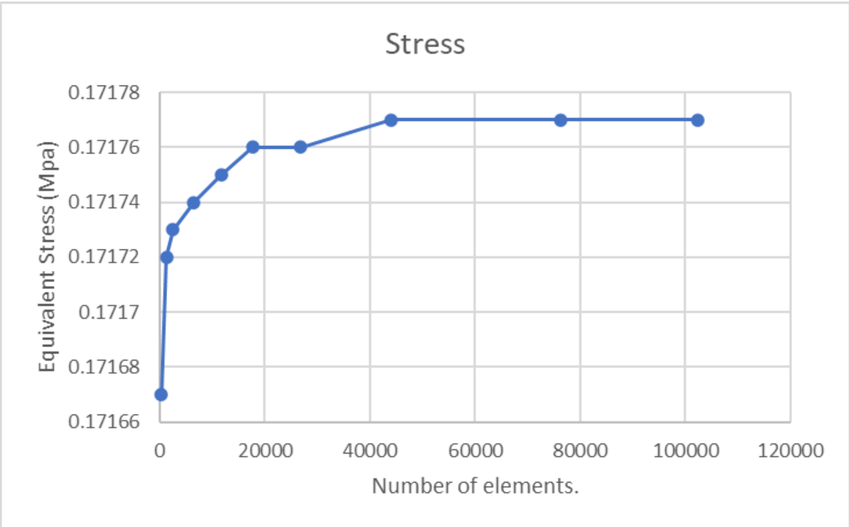


Figure 3.9 The graph of Equivalent Stress (Mpa) against the number of elements in the model.

3.5.3 Stress Analysis

The boundary condition for this analysis for all three different conductive ink printing was schematically shown in Figure. A horizontal force is applied in the positive y direction. Then the model was fixed at one end. The displacement on the x and z axis was set to free while the y direction was set to 30mm which is half of the specimen length. For the Ag- PDMS ink however for the Ag- liquid ink the displacement can only be set until 10 mm in the y direction.

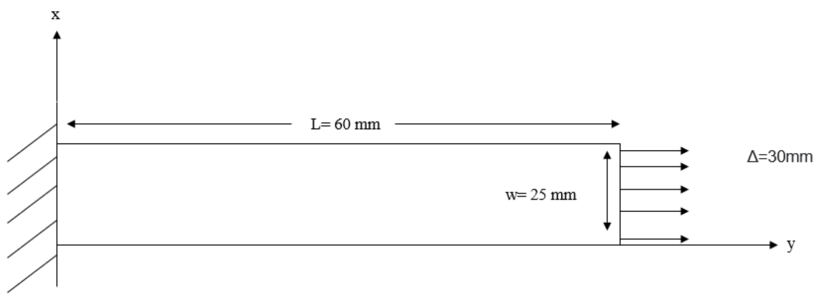


Figure 3.10 Schematic diagram for boundary condition for Ag-PDMS ink.

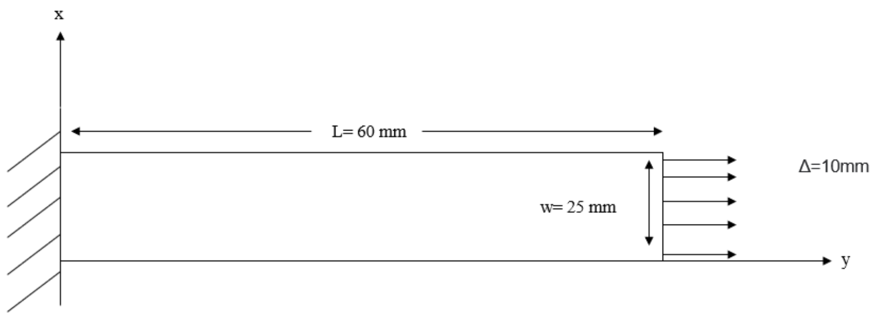


Figure 3.11 Schematic diagram for boundary condition for Ag liquid ink.