STRESS ANALYSIS OF STRETCHABLE ELECTRONIC CIRCUIT

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by

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LIST OF ABBREVIATION

SEC	Stretchable Electronic Circuit
PCB	Printed Circuit Board
TPU	Thermoplastic Polyurethane
LED	Light Emitting Diode
PDMS	Polydimethylsiloxane
Ag	Silver
Cu	Copper
FEA	Finite Element Analysis
LSP	Laser Selective Plating
2D	Two Dimensional
3D	Three Dimensional
ASTM	American Society for Testing and Materials
BS	British Standard European Norm
ISO	International Standards Organization
UTM	Universal Testing Machine
CNT	Carbon Nanotube
AgNWs	Silver Nanowires
NPs	Nanoparticles
ANSYS	Analysis System
SW	Solidwork
.sat	Standard ACIS file format
EMN	Element Midside Nodes
DIC	Digital Image Correlation

LIST OF SYMBOLS

C_1	Neo-Hookean Constant
E_t	Tangential modulus
σ_{eng}	Engineering stress
σ_{true}	True stress
σ_y	Stress at yield (yield stress)
ε_y	Strain at yield
ε_{eng}	Engineering strain
ε_{true}	True strain
$\varepsilon_{plastic}$	Plastic strain
ε_{total}	Total strain
E	Young's Modulus
λ	Stretch ratio
G	Shear modulus
v	Poisson's ratio

ANALISIS TEGASAN LITAR ELEKTRONIK BOLEH REGANG

ABSTRAK

Litar elektronik boleh regang (SEC) adalah produk elektronik yang telah dibangunkan baru-baru ini untuk memberi keselesaan kepada manusia dalam pelbagai aplikasi seperti sensor. Ia telah dimulakan dengan memperkenalkan litar dengan konsep saling hubungan menggunakan bahan logam dengan mengawal saiz dan reka bentuk saling hubungan yang dimasukkan ke dalam substrat yang fleksibel. Sambungan telah dikembangkan secara berterusan dengan mengawal jenis bahan yang digunakan dan reka bentuk litar untuk meningkatkan ketegasannya. Kajian ini membentangkan tingkah laku tegasan SEC menggunakan bahan polidimetilsiloksana (PDMS) sebagai substrat dan campuran rumusan baru serpihan Ag dan PDMS sebagai bahan litar dalam bentuk cecair yang dikenali sebagai dakwat konduktif Ag-PDMS. Tingkah laku mekanik substrat dan dakwat konduktif dicirikan menggunakan ujian tegangan. Data ujian tegangan digunakan untuk mencirikan sifat-sifat bahan menggunakan model Neo-Hookean dan plastik multilinear untuk dakwat substrat dan konduktif masing-masing mewakili tingkah laku litar dalam perisian Analisis Unsur Terhingga (FEA). Beberapa reka bentuk asas SEC seperti bentuk segi empat tepat, siku-sika dan ladam telah dimodelkan menggunakan Solidwork dan dieksport ke ANSYS Workbench untuk analisis struktur awal. Analisis telah dijalankan untuk menentukan tingkah laku tegasan terikan litar di bawah geometri dan arah beban yang berbeza. Selain itu, analisis struktur juga dijalankan pada prototaip sebenar sebagai aplikasi litar sensor haba. Tingkah laku ubah bentuk litar diselidik untuk menilai struktur integriti litar di bawah geometri, pemuatan dan bahan yang berbeza.

Dapat dilihat bahawa kawasan kritikal untuk tumpuan tegasan bergantung pada arah pemuatan sama ada selari atau tegak lurus dengan percetakan litar. Selain itu, ia menunjukkan tegasan yang tinggi tertumpu di bahagian dalaman kawasan puncak untuk kedua-dua rekaan kekuda dan siku-sika. Tegasan alah bagi dakwat konduktif adalah 0.20 MPa. Manakala, keputusan tegasan terikan untuk keseluruhan litar mudah menunjukkan nilai tertinggi tegasan setara masih di bawah tegasan alah had hingga 10 % terikan yang digunakan iaitu pada 0.19 MPa. Walaubagaimanapun, keputusan tegasan setara tertinggi untuk litar sensor haba telah melebihi tegasan alah untuk pemuatan menegak dan dwipaksi masing-masing pada 66.66 % dan kurang daripada 10 % ubah bentuk plastik. Pemuatan mendatar tidak menghasilkan terikan ubah bentuk plastik pada 0.16 MPa tegasan setara tertinggi.

STRESS ANALYSIS OF STRETCHABLE ELECTRONIC CIRCUIT

ABSTRACT

Stretchable electronic circuit (SEC) is an electronic product that has been developed recently in serving human comfort in various applications such as sensor. It was started by introducing a circuit with interconnection concept using metallic material by controlling the size and the design of the interconnection embedded into a flexible substrate. The interconnection has been developed continuously by controlling types of material used and the design of the circuit to enhance its stretchability. This study presents the stress behaviour of the SEC using a polymer material of polydimethylsiloxane (PDMS) as the substrate and a new formulated mixed Silver flakes and PDMS as the circuit material in the form of liquid known as Ag-PDMS conductive ink. The mechanical behaviour of the substrate and conductive ink was characterized using tensile testing. Tensile test data were used in characterizing the material properties using a Neo-Hookean model and a multilinear plastic model for substrate and conductive ink respectively to represents the circuit's behaviour in Finite Element Analysis (FEA) software. Several basic designs of SEC such as rectangular, zigzag and horseshoe shape were modelled using Solidwork and was exported to ANSYS Workbench for preliminary structural analysis. The analysis was conducted to determine the stress-strain behaviour of the circuit under different geometry and loading condition. Besides, the structural analyses were also conducted on a real prototype of thermal sensor circuit application. The deformation behaviour of the circuit was investigated to assess the structural integrity of the circuit under different geometry, loading and material. It can be seen that the critical area for the

stress concentration depended on the loading direction either parallel or perpendicular to the circuit printing. Besides, it showed high stress concentrated at the inner side of crest area for both horseshoe and zigzag design. The yield stress for the conductive ink was 0.20 MPa. Meanwhile, the stress-strain results of the entire model showed that the maximum equivalent stress was below the yield stress for simple circuit limited to 10 % strain applied at 0.19 MPa. However, the maximum equivalent stresses for thermal sensor circuit is exceeding the yield stress for uniaxial vertical and biaxial loading at 66.66 % and below than 10 % plastic deformation respectively. The horizontal loading give no plastic deformation for thermal sensor circuit at maximum equivalent stress is 0.16 MPa.

CHAPTER ONE

INTRODUCTION

1.1 Research Background

Stretchable electronic circuit (SEC) is a technology which has been improved from rigid printed circuit board (PCB's) to be bendable, twistable and stretchable (Bossuyt et al., 2013; Rogers et al., 2010). The SEC mainly consists of flexible or stretchable substrates (i.e. PDMS and Walopur TPU), flexible or stretchable conductive ink as a circuit (i.e. Ag, Cu, Ag-PDMS) and electronic components (i.e. LED, transistor, resistor, capacitor and integrated circuit). The advantages of SEC are flexible for human body application and improves reliability of the devices subjected to strain (Adrega and Lacour, 2010; Gonzalez et al., 2009; Kim and Rogers, 2008). The applications are mostly for sensor like strain sensor, robotic skins and wearable displays (Hu et al., 2016; Sekitani and Someya, 2010; Wang et al., 2011).

1.2 Problem Statement

Recently, researchers have shown interests in the development of the stretchable circuit and substrate since both elements are the key aspect to control the stretchability of the SEC. The stretchability is controlled by changing two parameter which are the stretchable material and stretchable design used for both the substrate and conductor (Rogers et al., 2010; Wang et al., 2011). Previous study shows lack of information regarding the stretchability control by design for the material which related to our study which is silver nanoparticles and nanocomposites. Besides, these materials are widely used to print the integrated circuit and previous research show interest on its conductivity only which said still can be improved (Ding et al., 2016).

The stretchability controlled by design shows the stretchable conductor were studied in terms of (1) geometry by controlling the width and thickness and (2) different printing shape of the circuit by introducing horseshoe shape as the best design to reduce the plastic strain. Besides, the substrate design was studied by (Amjadi et al., 2014) which has introduced (3) sandwich structure of substrate material that covers the whole part of the conductor to extend the failure limits of the conductor. Thus, fundamental studies were done in this project to know the limitation of the SEC in application as a basic circuit geometry and thermal sensor circuit using both experimental and finite element analysis.

1.3.1 Objective

Objectives of the research are:

i. To characterize the material properties of the stretchable circuit material.
ii. To evaluate the stress-strain behavior of the three different geometries of stretchable circuit under different loading condition.
iii. To assess the stress-strain behaviour of stretchable circuits in application as thermal sensor circuit under different loading and material.

1.3.2 Scope of work

The research is limit to the analysis for PDMS substrate as the substrate material and Ag-PDMS conductive ink as the conductor material. The preliminary study is on controlling the stretchability by design using Ag-PDMS conductive ink as the circuit material and PDMS substrate for the substrate material using FEA. Several material models in combination with universal tensile test have been selected to define the material properties of the Ag-PDMS conductive ink and PDMS substrate material. FEA was conducted to study the stress-strain performance of stretchable circuit in thermal sensor circuit application to assess suitable circuit design for future application. All the works in the thesis were conducted at room temperature and the material was characterized using constant tensile load. In addition, the simulation is conducted using static structural analysis.

1.5 Thesis Organization

The thesis is presented in five chapters. In chapter one, a brief presentation of background study, problem statement, objectives and scope of research are introduced. Chapter two consist of three major sections which are on previous testing used to characterize the stress-strain curve of thin film polymer, material model used in finite element analysis which relate to the material properties used for substrate and conductor and the last section shows several analyses involved for SEC experimentally and theoretically. Methodology shows the specimen preparation and tensile testing for experimental part and also modelling and analysis for simulation part. In chapter four, effects of geometry, loading direction and material were presented for simple model and customized SEC model. Finally, conclusion and recommendations for future work is pointed out in chapter five.

CHAPTER TWO

LITERATURE REVIEW

This chapter will review three key topics related to the stress analysis of substrate and conductive ink for SEC application. The topics are the mechanical testing for thin film specimen, suitable material models for rubber and structural analysis of SEC. The first part of this chapter will cover the characterization of mechanical properties of substrate and conductive ink which require a review on the suitable mechanical testing for thin film specimen. Secondly, the review will focus on the general material models which have been used by the previous researcher for the substrate and conductive ink material. The third part of this chapter will review on the general stress-strain analysis of the substrate and conductive ink in terms of the materials and structural analysis parameter which has been studied before.

2.1 Mechanical testing for thin film specimen of SEC

The aim of the mechanical testing is to characterize the stress-strain curve of the material. Several testing has been introduced for the mechanical properties characterization of stretchable electronic circuit as a thin film material such as uniaxial tensile, biaxial tensile, bulge test and nanoindentation test (Eric A Roe B . S . 2010; Merle 2013; Lee et al. 2015). Several researchers have introduced two ways in classifying the testing technique for thin film specimen called testing of free-standing films and supported films (Figure 2.1). Both specimens configuration for thin film testing have theirs advantage and disadvantage where the freestanding films can directly measure the stress-strain result but challenging in sample preparation at microscale and nanoscale. In contrast, the supported films have simpler sample preparation where the coating can be directly printed onto the substrates but the result evaluation is very crucial due to the effect of substrates (Eric A Roe B . S ., 2010; Gibson, 2014; Merle, 2013; Midturi, 2010; Whiteside et al., 2016).

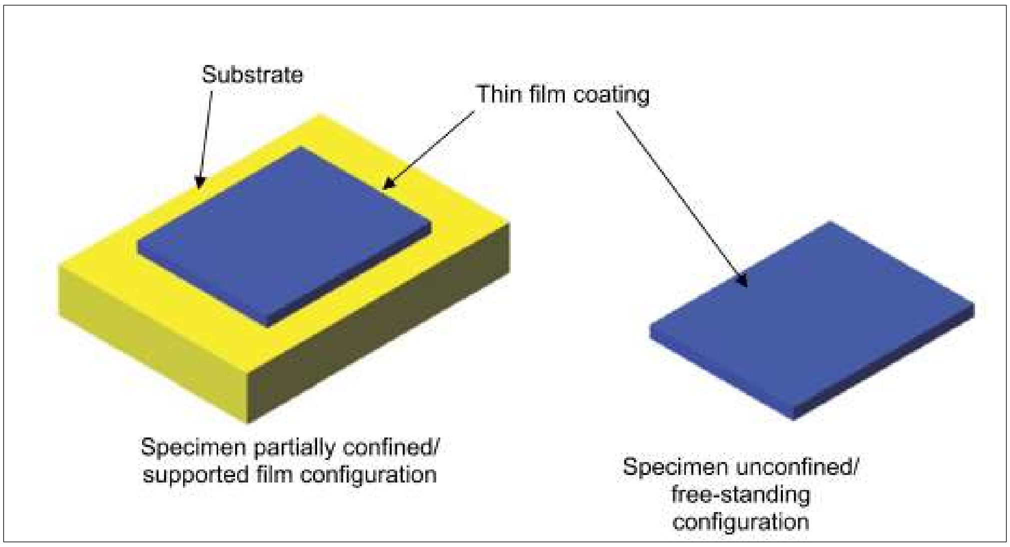

Figure 2.1 Two different specimen configuration for thin film testing
(Eric 2010)

The advantage and disadvantage of each of the listing method is reviewed in term of the specimen preparation, experimental setup and data evaluation. Biaxial test is multiaxial tests that consist of two techniques which are wafer curvature measurement and point deflection technique. Wafer curvature measurement is useful for calculating the stress present in the film using mathematical equation. The stress-strain diagram of wafer curvature technique is obtained by heating up the specimen to have a set of strain value with respect to the elongation after heating. This method is suitable to study the thermo-mechanical fatigue life of thin films but the stress-strain curve is highly affected by the temperature. Point deflection technique is a technique which combines the advantage of bulge and nano-indentation test in order to have the material properties of the thin film. However much of the testing using this technique was conducted using finite element analysis and little experimental work has been carried out (Merle, 2013). On the other hand, the biaxial test is challenging on the experimental setup (Melzer et al., 2011).

Nanoindenter test is useful to have the hardness and modulus of specimen at microscale and nanoscale. It does not require specific specimen size and thickness unless the specimen can be locate on its 2.5 mm diameter test section. However, this technique is extremely sensitive to the surface finish of specimen that can contribute to inaccurate result. In addition, the result involves complex conversion process from load-depth curve to stress-strain curve. The load-depth conversion technique of nanoindentation test is different for different specimen configuration such as freestanding and coating specimen where coating specimen need to consider the effect of substrate (Martínez et al., 2003; Miguel et al., 2015; Sun et al., 2007; Wu et al., 2009).

Bulge test is an indirect method that requires complex equation. The specimen can be prepared in three shapes (circular, square and rectangular) that relates to the stress-strain formula used for data evaluation. The result is measure in terms of residual stress-strain where it classified as indirect testing which conversion is needed to obtain the engineering stress-strain curve. The review on the strengths and weaknesses on several testing used for thin film material is summarized in Table 2.1 (Eric A Roe B . S . 2010; Merle 2013).

Table 2.1 Testing technique to characterize mechanical properties for thin film polymer

Testing	Specimen preparation	Experimental setup	Data evaluation
Uniaxial Tensile	Challenging for micro size sample preparation	-	Give data directly and need simple calculation to have the stress-strain curve
Biaxial Tensile	-	Challenging for experimental setup	-
Nanoindenter	Require no specific specimen size preparation	-	Need complex calculation in converting the load-depth curve to stress-strain curve
Bulge	Challenging sample preparation	Challenging experimental setup	Challenging result interpretation

Uniaxial testing is widely used and most developed by people as a direct testing. The major attraction is on the ease of data interpretation. The stress-strain curve is directly measured involving simple equation and curve fitting. Larmagnac et al, (2014) has reported their research in characterization of conductive ink use for the application of SEC based on Ag-PDMS composites using bulk specimen of large dumbbell specimen with no specific gauge length and width.

Several studies have been reported as a guideline in selecting the commonly used specimen testing geometry for rubber material. There were two type of specimen used either large dumbbell or small strip. The ASTM standard used for the rubber test is mostly not stated. In 2008, British standard was used to test soft polymer specimen with 5 mm specimen width at 100N load cell. In 2012, ASTM D412 was modified to test natural rubber at very small gauge length 10 mm and loading rate 10 mm/min with 500 N load cell. In 2014, large dumbbell specimen was used to test rubber with Ag fillers at lower loading rate 6 mm/min. In 2015, the