UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Faculty of Mechanical Engineering

Effect of Kirigami Pattern Designs on Ultra-Stretchable Conductive Polymer Mechanical Properties for Thin Film Solar Photovoltaic Application

Muhammad Redzuan Bin Che Noordin

Master of Mechanical Engineering

(Energy Engineering)

2019

EFFECT OF KIRIGAMI PATTERN DESIGNS ON ULTRA-STRETCHABLE CONDUCTIVE POLYMER MECHANICAL PROPERTIES FOR THIN FILM SOLAR PHOTOVOLTAIC APPLICATION

MUHAMMAD REDZUAN BIN CHE NOORDIN

A dissertation submitted
in fulfillment of the requirements for the degree of Master of Engineering
in Mechanical Engineering (Energy Engineering)

Faculty of Mechanical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled "Effect of kirigami pattern designs on ultra-stretchable conductive polymer mechanical properties for thin film solar photovoltaic application" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature : ....

Name : MUHAMMAD REDZUAN BIN CHE NOORDIN

Date : 15.03.2019

APPROVAL

I hereby declare that I have read this dissertation/report and in my opinion this dissertation/report is sufficient in terms of scope and quality as a partial fulfillment of Master of Mechanical Engineering (Energy).

Signature : ....

Supervisor Name : DR. MUHD RIDZUAN BIN MANSOR

Date : 15 - 3 - 2019

DR. MUHD RIDZUAN BIN MANSOR
PENSYARAH KANAN
FAKULTI KEJURUTERAAN MEKANIKAL
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

DEDICATION

To my beloved family

ABSTRACTS

Achieving stretchable conductors with high stretchability and stable conductivity is a great challenge but urgent for multifunctional electronics applications. A kirigami patterned stretchable conductive thin film solar with a highly tunable structure material. Kirigami pattern has high potential in breaking current stretchability limitation of conductive polymers, through the manipulation of the cut-geometrical pattern on the conductive polymer base or substrate material. That kirigami structures combined with thin-film active materials may be used as a simple, low-cost, lightweight and low-profile method to track solar position, thereby maximizing solar power generation. These systems provide benefits over conventional mechanisms, where additional heavy, bulky components and structural supports are often required to synchronize tracking between panels and accommodate forces due to wind loading. Type of design kirigami pattern by using thermoplastic polyurethane (TPU) substrate and analyse the effect for identify the maximum strain ability to produce stretchable conductive circuit. Each kirigami pattern will be evaluated with the changes that take place on variation- X, variation- Y_1 and variation- Y_2. Tension test will be performed on the substrate by mechanical testing method (installation on vernier caliper), the substrate is stretched and assessed the effect until it is break (Full). Effects are seen to be the maximum level of capability that can be produced by the design of the kirigami pattern by obtaining the results of each variation i.e. . Variation-X_1 = 153% - 173% strain, variation-Y_{15}= 267% - 287% strains and variation-Y_{21} = 243% - 263% strain. This means with an increase in the cut length X dan Y_2 would soften the structure with a low effective modulus dan increasing the hinge length Y_1 would make the structure more rigid, leading to a higher strain effective modulus. The kirigami pattern results demonstrate that the effective stress-absorption through structural transformation is able to greatly enhance the stretchability. This research can also assess the appropriate kirigami pattern for use in thin film solar panels according to requirements.

ABSTRAK

Mendapatkan konduktor yang boleh diperbaharui dengan ketegangan yang tinggi dan kekonduksian yang stabil adalah satu cabaran besar tetapi untuk aplikasi elektronik pelbagai fungsi. Kirigami yang berbentuk selaras konduktif filem nipis solar yang diperbaharui dengan bahan struktur yang sangat mudah berubah. Corak kirigami mempunyai potensi yang tinggi dalam menambahkan pemanjangan polimer konduktif, melalui manipulasi corak potong geometri pada dasar polimer konduktif atau bahan substrat. Struktur kirigami yang digabungkan dengan bahan aktif filem nipis boleh digunakan sebagai sederhana, rendah kaedah ringan, ringan dan rendah untuk mengesan kedudukan solar, dengan itu memaksimumkan penjanaan kuasa solar. Sistem ini memberi faedah ke atas mekanisme konvensional, di mana tambahan berat, komponen besar dan sokongan struktur sering diperlukan untuk menyegerakkan pengesanan antara panel dan menampung daya akibat beban angin. Rekabentuk jenis corak kirigami dengan menggunakan substrat 'thermoplastic polyurethane' (TPU) dan menganalisis kesan untuk mengenal pasti keupayaan terikan maksimum untuk menghasilkan litar konduktif yang boleh diperbaharui. Setiap corak kirigami akan dinilai dengan perubahan yang berlaku pada variasi - X, variasi - Y_1dan variasi - Y_2. Ujian Ketegangan akan dilakukan terhadap substrat dengan kaedah 'mechanical testing' (pemasangan pada vernier caliper) , substrate diregangkan dan dinilai kesan yang belaku sampai ianya putus. Kesan dilihat sebagai tahap keupayaan maksimum yang boleh dihasilkan oleh reka bentuk pola kirigami dengan memperoleh hasil setiap variasi iaitu:, variasi-X_1 = 153% - 173% ketegangan, variasi -Y_{15}= 267% - 287% ketegangan dan variasi -Y_{21} = 243% - 263% ketegangan. ni bermakna dengan peningkatan panjang potong X dan Y_2 akan melembutkan struktur dengan modulus berkesan yang rendah dan meningkatkan panjang engsel Y_1 akan menjadikan struktur lebih tegar, yang membawa kepada modulus berkesan ketegangan yang lebih tinggi. Hasil corak kirigami menunjukkan bahawa penyerapan tekanan yang berkesan melalui transformasi struktur dapat meningkatkan keanjalan. Kajian ini juga boleh menilai corak kirigami yang sesuai untuk digunakan dalam merekabentuk panel solar filem nipis mengikut keperluan.

ACKNOWLEDGEMENTS

Alhamdulillah, praise to Allah, with his inayah', Finally, I have successfully completed my master project report entitled "Effect of kirigami pattern designs on ultra-stretchable conductive polymer thermal properties for thin film solar photovoltaic application" successfully.

For this golden opportunity, I would like to express my deepest gratitude to my supervisor, Dr. Muhd Ridzuan Bin Mansor his professional ways in giving the guidance and for understanding upon my problem and obstacles, and help to complete this report.

Also thanks to all my friends those always give support and also advices with a good suggestion in completing this project. Not forget to other lecturers that always willing to give me their advices.

This acknowledgement would not be complete without mentioning my lovely family, especially my father and my mother. Thank you all.

Wassalam.

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e	Magnitude of the emf induced inside the coil or the circuit
N	Number of coil turn
Φ	Flux linkages
$\mathbf{L}$	length
B	Magnetic flux density
w	Width
t	Thickness
$\mathbf{\Delta}$	Difference
d_i	Inner dimension
s	Spacing between coil
L_{MT}	Length of the mean turn
A_{Coil}	Coil cross-sectional area
R_c	Coil resistance for a single layer coil
T	Period of oscillation
$\boldsymbol{\varepsilon}$	Strain

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CHAPTER 1

INTRODUCTION

1.1 Background

Sustainable energy sources such as sun or wind energy have the drawback that they are also highly visible elements that are often considered eyesores. Fortunately, new developments in solar, or photovoltaic cell technology, are making solar cell elements more efficient and affordable as well as extremely thin and easy to integrate into architectural applications.

A thin-film solar cell is a second generation solar cell that is made by depositing one or more thin layers or thin films (TF) of photovoltaic material on a substrate, such as glass, plastic or metal. Film thickness varies from a few nanometers (nm) to tens of micrometers (μm), much thinner than thin-film's as shown in Figure 1.1. A conventional, first-generation crystalline silicon solar cell (c-Si) for example uses wafers of up to 200 μm.

The nature of these ultra-thin-film cells allows them to also be flexible, lower in weight and have less drag of friction. They can be used in building integrated photovoltaic and as a semi-transparent, photovoltaic glazing material that can be laminated onto windows.

Fig 1.1 A thin-film solar cell by courtesy of the Material District Rotterdam

In the future as well, a little bend in smartphone might be considered a feature rather than a defect. One of the important components of future electronics include stretchable conductor that can be rolled up, folded or embedded in flexible objects, which would make up components like wires and electrodes. Stretchable conductors are difficult to design and not many are available in market today. Kirigami, the Japanese art of paper cutting can enhance both stretchability properties and also electrical conductivity. The cuts become barriers to electrical conductivity, but when stretched, the conductors are steady performers. Kirigami starts with a folded paper base, which is then cut, unfolded and flattened to make the final art piece. The intricate patterns create beautiful works of art based on math and design principles that can change the mechanical behaviors of the material being cut. For example, a particular pattern can make the paper stronger or more stretchable.

Kirigami are potentially useful for developing optoelectronic and optical devices, such as stretchable lithium-ion batteries, solar cell tracking systems, beam steering devices and triboelectric nanogenerators (Chen et al., 2018). The kirigami approach can be used to obtain predictable strain-property relationships in mechanical metamaterials, which are beneficial for developing stretchable optoelectronic and mechanical devices (Shyu et al., 2015). For example, Lamoureux et al., (2015) have stated that kirigami-based stretchable solar cell trackers not only have increasing energy generation efficiency, without significantly increasing the installation costs, but also expand the application of solar tracking systems. The advancement of kirigami have many potential applications, including electronic skin (thin electronic material that mimics human skin, often used in robotic and health applications), bendable display screens, and electronic paper. But its most useful application could be in smart clothing, a market that analysts say could reach $4 billion by 2024.

Motorized trackers that keep flat photovoltaic panels pointed toward the sun are, in their conventional form, heavy, bulky, and expensive-not suited for use on a typical home rooftop. But researchers at the University of Michigan have come up with a way to tilt solar cells in a simple, compact way such that the whole apparatus can fit within a flat solar panel.The only requirement is that the solar cells be of the thin-film variety and on a flexible substrate.

The technique is based on Japanese kirigami paper art, and is easily understandable upon seeing the apparatus (see Figure 1.2). A cut pattern consisting of rows of alternating slits in an otherwise continuous sheet allows the array of solar cells, when pulled, to buckle in a predetermined way so that it expands and at the same time tilts at an angle that is virtually the same across the entire sheet. The tilt of the cells can be controlled to within $\pm 1^{\circ}$ of the predicted pointing vector. In a finished unit, the apparatus would be contained within a thin double-pane structure to protect it from the weather and keep it from sagging, shown in Figure. 1.2.

Fig 1.2 Concept cut kirigami in for thin-film photovoltaic cells Lamoureux et al., (2015).

The working principle of kirigami printed conductive polymer composite is the combine of conductive ink as a capacitive electrode or can function as a conductor in designs that can tolerate high resistivity with the materials with elastic and conductive characteristics, such as polymers and carbon nanotubes. This research will test the reliability of stretchable, printed electronic circuit on the thermoplastic poly-urethane (TPU) with applying the kirigami method on it. This research will focus on prototyping of a stretchable printed circuit with applying kirigami method and to test it function under cyclic stretching and the effect of the resistivity.

1.2 Problem Statement

For centuries, cutting and folding paper with special patterns has been used to build beautiful, complex and immersive three-dimensional structures. Inspired by the old idea of kirigami (paper cutting), and kirigami pattern has high potential in breaking current stretchablity limitation of conductive polymers, through the manipulation of the cut-geometrical pattern on the conductive polymer base or substrate material.

That kirigami structures combined with thin-film active materials may be used as a simple, low-cost, lightweight and low-profile method to track solar position, thereby maximizing solar power generation. These systems provide benefits over conventional mechanisms, where additional heavy, bulky components and structural supports are often required to synchronize tracking between panels and accommodate forces due to wind loading. By eliminating the need for such components, kirigami serves to decrease installation costs and expose new markets for solar tracking, including widespread rooftop, mobile and spaceborne installations. Kirigami-enabled systems are also cost-effective and scalable in both fabrication and materials, and similar design rules may be extended for use in a wide range of optical and mechanical applications, including phased array radar and optical beam steering.

However, up to date, there are limited reports on how different kirigami patterns are able to increase the stretchability properties of such conductive material and in the same maintaining low voltage drop across the conductor and minimizing local strain fields created due to the given deformation. Furthermore, the information on the correlation between the specific geometrical properties such as length, width and angle of cut to the stretchability property, which is crucial as guideline for tailoring the conductive polymer performance, is also limited. Hence, this research is initiated to understand the fundamental principles behind the kirigami pattern designs effect on ultra-stretchable conductive polymer thermal properties for thin film solar photovoltaic application, and to what extend the stretchability property is affected and observing the failure mechanics which arise due to the geometrical modifications.

1.3 Research Hypothesis

This research is kirigami-based strategy is being investigated for evaluate the effects of strains that occur when using the kirigami pattern, this is to assess the degree of suitability of kirigami patterns used in the solar panel of thin-film solar cells. This study is also to investigate the maximum level of tension obtained when using the kirigami pattern method. Research on the kirigami pattern cuts will help prolong the damage to the thin-film circuit to produce a renewable conductive circuit. The kirigami pattern is studied in three different variants of the three variants that is variation- X, variation- Y_1, and variation- Y_2. Each variant will have the maximum possible length of elongation that can be done by kirigami pattern cuts. Another working hypothesis brought up in this research is that the identify when strain occurs on the pieces of the kirigami pattern by assessing the effects on the kirigami pattern cuts, in terms of damage to the form or damage to the sample of the study. This will be able to identify the appropriate kirigami pattern for use without the damage to solar panels of the solar cell thin-film in the event of elongation.

1.4 Objectives

The objectives of this project are:-

i. To design type of kirigami pattern by using thermoplastic polyurethane (TPU) substrate to produce stretchable conductive circuit.

ii. To analyse the effect of kirigami geometry against (TPU) substrate and identify the maximum strain ability for each kirigami pattern design.

1.5 Scopes and Limitation

The overarching aim of the research project was to examine effects kirigami pattern on ultra-stretchable conductive polymer thermal properties for thin film solar photovoltaic and the scopes of this project are:-

i. To conduct literature review on kirigami pattern design on TPU stretchable thin film material.
ii. To design and fabricate three kirigami pattern designs using manual cutting method.
iii. To test the stretchability performance using uniaxial tensile test method.
iv. To measure stretchability performance in term of maximum elongation to failure.
v. To measure failure mode and location for the samples using visual inspection method.
vi. To perform data analysis and report writing.

The study focused on the stretchabiluty on the substrate without applying any conductive film on in.

1.6 Thesis Outline

This thesis has five main chapters. Chapter 1 briefly describe about kirigami pattern design on thin - film solar PV (TPU) material and their problem statement about the previous kirigami pattern design. It also presents the research objective, scope and hypothesis.

Chapter 2 is about literature review from others researcher related to the derivation of the kirigami pattern design. Achieving stretchable conductors with high stretchability and stable conductivity is a great challenge but urgent for multifunctional electronics applications. A kirigami-patterned stretchable conductive film with a highly tunable structure is prepared by manual cutting at thermoplastic polyurethane (TPU). The kirigami film with an optimal structure exhibits both superior ultimate elongation as high and stable conductivity under high strain levels. The as-prepared highly kirigami pattern designs ultra-stretchable conductive polymer thermal properties for thin film present huge potential for emerging applications in stretchable electronics, especially those operating at high strain levels. Then, the literature related to the stretchable conductive film. Additionally, the chapter elaborates about the mechanical properties of a kirigami structure can be tuned and programmed based on a tailored pattern of cuts. Finally, the critical discussion is experimental method on the stretchability and connectivity of the electrical conductors during cyclic-mechanical loading has been performed in chapter 2.

The chapter 3 acquires the most appropriate kirigami design for use in thin film solar. With this solar designer acquire the right idea to use the kirigami share on thin film sola. Experiment was performed on thermaplastic Poly-Urethane (TPU) with three different variations. This is done in order to identify the effects that occur in the kirigami design.

The kirigami design is done with mechanical regulation with three different variations, i.e. variation-X, variation- Y_1 and variation- Y_2. In this experiment, it can evaluate the effects that occur on each variation according to their respective designs. The highlights and major conclusions drawn from this research together with recommendations for future work are finally presented in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The method of Kirigami (the art of cutting-paper) to generate highly extendable geometry has been aggresively investigated for development of higly stretchable electronic components. There are three basic Kirigami pattern configurations to enable higher deformation performance, which are the zigzag cut pattern, cut-N-twist pattern and cut-N-shear pattern. The zigzag cut pattern enable high stretchability but also caused out-of-plane deformation, while the cut-N-twist and cut-N-shear patterns is able to produce high stretchability without out-of-plane deformation. In addition, the cut-N-shear pattern also able to double the packing density of the material as opposed to cut-N-twist pattern (Song et al., 2015). Apart from type of cut, the pattern motif also plays a role in tailoring the stretchability and electrical conductivity performance of conductive polymer, such as Y-shape motif with varying with, length and spacing distance between them (Vachicouras et al., 2017). Within the available literature, many researchers have reported significant improvement on the stretchability properties of the conductive polymer. Morikawa et al. (2018) reported stretchability improvement up to µm 470% and 840% using 11 thin parylene-platinum conductive polymer at pattern configuration of 5x91 slits and 3x91 slits, respectively. Elsewhere, Han et al. (2017) reported tensile strain enhancement up to 3 to 5 times for kirigami modified hexagonal boron nitride (h-Bn) nanosheet compared to pristine h-Bn nanosheet. Kirigami pattern introduced to conductive film made from carbon