

Finite element analysis on deformation of stretchable electronic interconnect substrate using polydimethylsiloxanes (PDMS)

M F Roslan, N M Shaffiar, M K N Khairusshima and I S S Sharifah

Department of Manufacturing and Materials Engineering, International Islamic University Malaysia (IIUM), Jalan Gombak, 53100 Kuala Lumpur, Malaysia

Email: shishaff@iium.edu.my

Abstract. Over the years, the technology of electronic industry has growth tremendously. Open ended research on how to make a better concept of electronic circuit is ongoing especially on the stretchable electronic devices. There are many designs to achieve stretchability in electronic circuits. The problem occurs when deformation applied to the stretchable electronic circuit, it cannot maintain its functionality. Fracture may happen on the conductor. In this research, the study on deformation of stretchable electronic interconnects substrate using Polydimethylsiloxanes is carried out. The purpose of this research are to study the axial deformation occur, to determine the optimum shape of the conductor designs (horseshoe, rectangular and u-shape design) for the stretchable electronic interconnect and to compare the mechanical properties of Polydimethylsiloxanes (PDMS) with Polyurethane (PU) using Finite Element Analysis (FEA). The simulation was done on the FE model of the stretchable circuit with dimension of 2.4 X 2.4 X 0.5 mm. The stretching of the FE model was simulated with the range of elongation at 10, 20 and 30 percent from its original length in order to find the strain value for all three of the conductor designs. The best conductor design is used to simulate with different types of substrate (PDMS and PU). From the simulation result, Horseshoe design record the lowest strain value for each elongation, followed by rectangular and U-shape design. Thus, Horseshoe is considered as the optimum design for the conductor compared to the other two designs. From the result also, it shows that PDMS substrate will offer more maximum allowable stretchability compared to PU substrates. Thus PDMS is considered as a better substrate compare to PU. PDMS is a good material to replace PU since it can perform under tension much better mechanically.

1. Introduction

Recently the research into the design and fabrication of flexible and stretchable circuits and systems has received a lot of attention. Throughout the years, the electronic circuits have driven advanced in technology. Electronic circuit has become smaller, smarter and faster. Due to this advance technology, stretchable interconnecting circuits have been created. With the existent of stretchable interconnecting circuit, it can offer application that is impossible for rigid circuit board of today. Stretchable circuit can experience stress and strain from the deformations that occur and still deliver its function. It has great potential in application of wearable electronics, flexible display, biomedical, healthcare and military [1]. In electronic industry, it is crucial to make sure the stretchable electronic circuit works perfectly



fine when deformation such as stretching and bending occur. At a certain point when elongation happens toward the circuit, it may cause damage toward the circuit and cause failure. The metal line layouts in the circuit can be configured in many different shapes that can accommodate of mechanical stress, while the elastomeric substrate guarantees that the metal line will revert to its original shape [2].

In the recent year, several designs of conductor layout have been created such as U-shape, rectangular shape and horseshoe shape [3]. Each design can vary its performance and functionality of the stretchable electronic circuit. For now, designing the most optimum metal line layout that can deliver its function is still challenging. The stress and strain of the stretchable electronic interconnect substrate PDMS need to be determined when the deformations occur toward it. By doing this, the best shape for the conductor can be determined. The material that is being used in stretchable electronics as the substrates are polymer. Among the characteristics that are needed for any material to be used as the substrate are having a low-modulus with stress/strain responses that can be tailored precisely to match the non-linear properties of biological tissues and it must not be too rigid, too thick or too heavy.

2. Experimental procedures

2.1 Conductor designs

The design of an appropriate shape is crucial to allow stretchability of the conductor [3]. The three design are horseshoe, u-shape and rectangular. All the three designs are chosen because it has the similar shape as serpentine. This is to minimize strains in materials under large deformation, metallic films can be patterned into serpentine-shaped ribbons [4]. Figure 1 illustrates the horseshoe shape, rectangular shape and U-shape formed by copper lines configured in PDMS substrates.

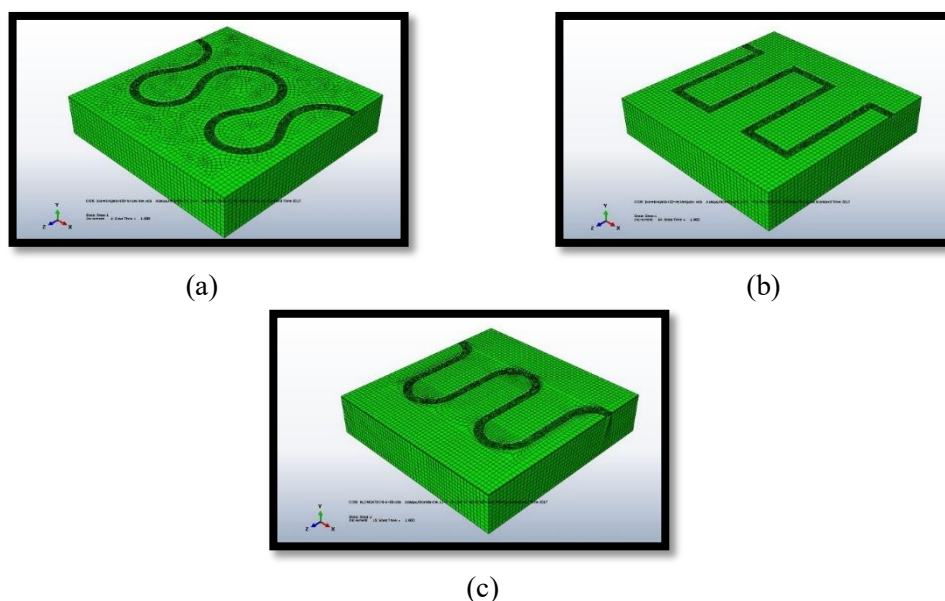


Figure 1: FE modeling of stretchable electronics. (a) Horseshoe, (b) Rectangular, (c) U-shape.

2.2 Finite element modelling

In this simulation, Abaqus software was used for the modeling and analyzing of the stretchable electronic model. The simulation was done on the FE model of the stretchable circuit with dimension of 2.4x2.4x0.5mm. Three shapes of conductors are designed and embedded into the substrate as shown in figure 1. The thickness of the conductor thin films is 0.018mm with a width of 0.1mm. The stretching of the FE model was simulated with the range of elongation at 10, 20 and 30 percent of its original length for each design.

Two parts involved in the simulation are conductor metal thin films and substrate. The parts are modelled first using solidwork software and imported to Abaqus software for Finite Element Modelling. In Abaqus software, it consist numbers of module that is parts, property, assembly, step, interaction, load, mesh, optimization, job, visual and sketch. Few steps must be done before the simulation can be run. In this research, all finite element models interface between the conductor and substrate are considered as perfectly bonded.

The material properties assign for conductor is copper (Cu) while for the substrates is polydimethylsiloxanes (PDMS) and polyurethane (PU) respectively as shown in table 1. Copper is used as metal thin films because it is a good conductor of electricity and it is widely used in stretchable interconnect circuit.

Table 1. Material Properties of conductor and substrates use.

| Material | Properties |
|-----------------------|--|
| Copper | Density = 8.96 g/cm ³ Yielding Point = 200 Mpa Poisson's Ratio = 0.3 Young Modulus, E = 85 Gpa |
| Polydimethylsiloxanes | Density = 0.965 g/cm ³ Yielding Point = 2.24 Mpa Poisson's Ratio = 0.47 Young Modulus, E = 1.2 Mpa |
| Polyurethanes | Density = 1.2 g/cm ³ Yielding Point = 138 Mpa Poisson's Ratio = 0.5 Young Modulus, E = 69 Mpa |

Meshing is used to manage material deformation during crushes on simulation. A finer mesh will result in more accurate result. In Abaqus software, there are several types of mesh generation techniques. In certain condition, mesh cannot be done because of the complex geometry of the model. Meshing technique needs to be change or smaller partition of the model need to be created. The Element shape that can be use is Hex, Hex-dominate, Tet and wedge. The Hex element shape is chosen. For the substrate part, partitioning need to be done because meshing it without partitioning will cause a poor element being created and will affect the accuracy of the result.

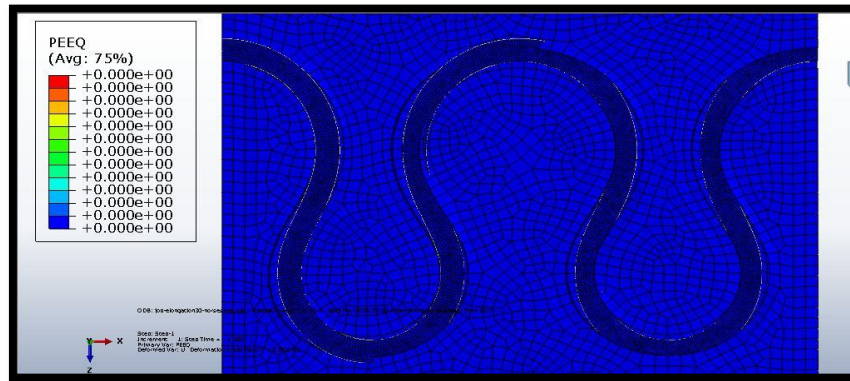
For the loading, set one side of the FE model at fixed position using the boundary condition while the other end of the model is set as a region to be pull or elongated on the positive X-axis direction. For the fixed side, ENCASTRE ($U_1=U_2=U_3=UR_1=UR_2=UR_3=0$). It means that the region is restrained to move along all axes. Next boundary condition is to insert the value of elongation at U_1 for the movement in X-axis direction.

3. Results and Discussion

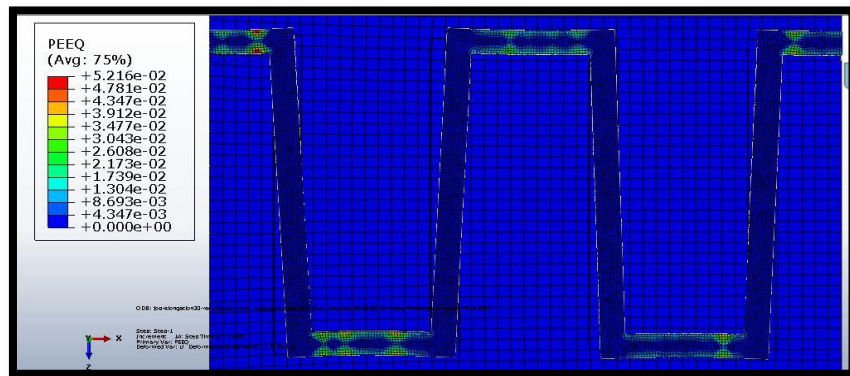
3.1 Result of three different conductor designs

During axial stretching, the copper conductor is under tension when the line is parallel to the stretching direction and is under compression when the copper conductor is perpendicular to the stretching direction [3]. Locally, the outer part of the copper line is in compression and the inner part in tension. In order to make a comparison of results, several simulations were done for each design of copper conductor with an elongation of 10, 20 and 30 percent from original length being applied. Figure 2

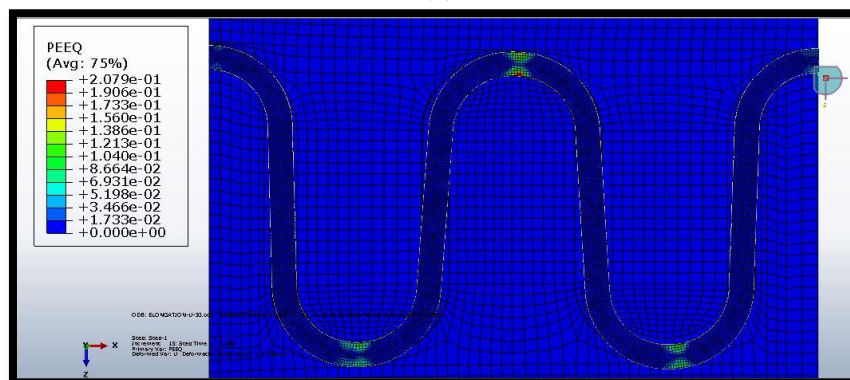
shows the strain distribution for each design being applied with 30% elongation from its original length and in the table 2 shows the maximum strain value for each elongation being applied.



(a)



(b)



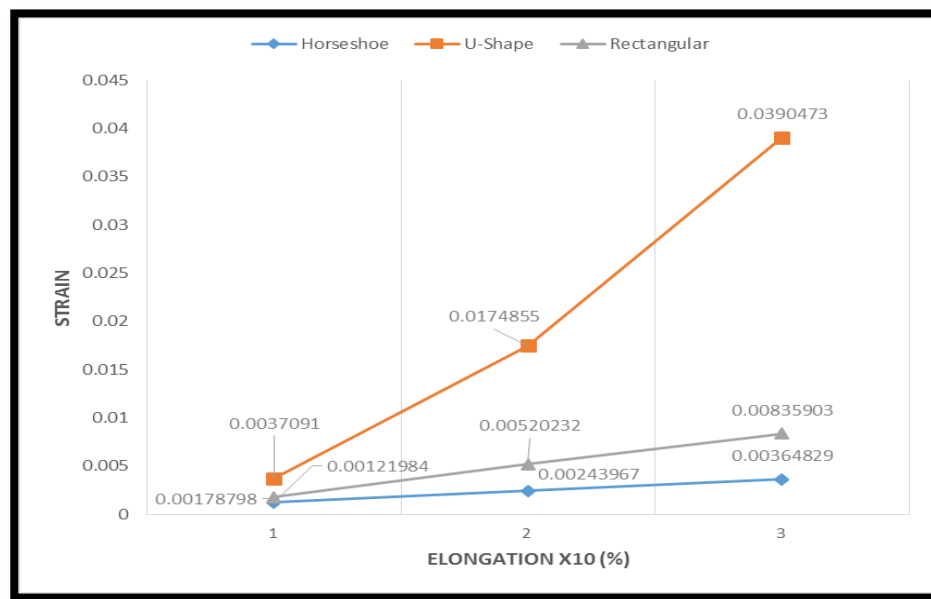
(c)

Figure 2: Strain distribution in copper conductor line for three different conductor shapes at 30% elongation (a) Horseshoe, (b) Rectangular, (c) U-shape.

Table 2. Maximum strain value for Horseshoe ,U-shape and Rectangular design.

| Elongation % | Strain | | |
|--------------|------------|-----------|-------------|
| | Horseshoe | U-Shape | Rectangular |
| 10 | 0.00121984 | 0.0037091 | 0.00178798 |
| 20 | 0.00243967 | 0.0174855 | 0.00520232 |
| 30 | 0.00364829 | 0.0390473 | 0.00835903 |

Based from the strain values in table 2, a graph was plotted and shown in figure 3.

**Figure 3.** Strain versus Elongation for each designs.

From the graph, it can be seen that as the elongation being applied toward the stretchable circuit increase, the strain value also will be increased. It shows an agreement on the increasing trend for the graph of total deformation Vs plastic strain made by other researcher [3]. Strain comparison is enough for choosing the optimum conductor design, predominant failures are expected in regions where the highest plastic strain concentration located [3]. Thus the region where the copper experiences the highest strain is most likely to fail. This is because as the elongation increase, the amount of deformation and strain will increase thus increasing the stress that copper conductor experience. As the stress increase, it will eventually reach the ultimate stress point where it is the point corresponding to the maximum stress that a material can handle before it failure. The failure of the conductor will cause the circuit to stop conducting the electricity or signal. Thus the lowest strain value will give a better stretchable electronic circuit. From the graph in figure 3, it shows that Horseshoe design record the lowest strain value for each elongation, followed by rectangular and U-shape design. Thus, Horseshoe is considered as the optimum design for the conductor compared to the other two designs.

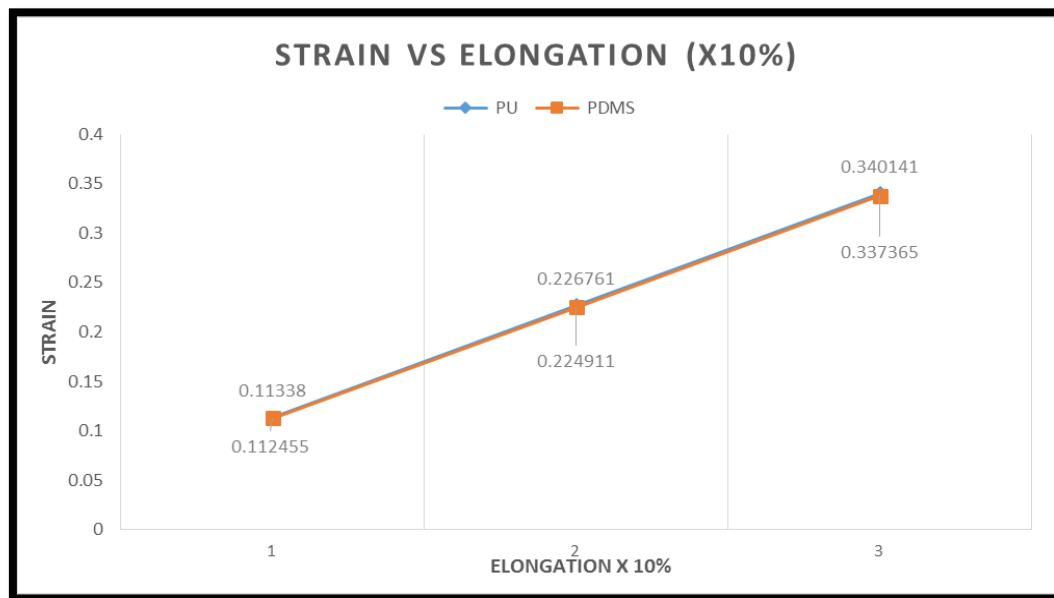
3.2 Result of different substrates

Simulation being done for two types of substrate materials that is Polyurethanes and Polydimethylsiloxanes to show the comparison between these two materials as a substrate. Horseshoe design conductor was used for the copper conductor. Each model undergoes elongation at 10%, 20% and 30%. Table 3 shows the maximum strain and stress value for each elongation being applied.

Table 3. Maximum strain & stress for PDMS and PU substrates at different elongation.

| Elongation % | Strain | | Stress | |
|--------------|----------|----------|----------|----------|
| | PU | PDMS | PU | PDMS |
| 10 | 0.11338 | 0.112455 | 7.82E+06 | 1.35E+05 |
| 20 | 0.226761 | 0.224911 | 1.56E+07 | 2.70E+05 |
| 30 | 0.340141 | 0.337365 | 2.35E+07 | 4.05E+05 |

Based from the strain values in table 3, a graph was plotted and shown in figure 4.

**Figure 4.** Strain for PU and PDMS versus Elongation.

From the graph, PDMS substrate record a lower strain compare to PU substrate. Thus PDMS is considered as a better substrate to be used for the stretchable electronic circuit. This is because PDMS has a lower Young Modulus compared to PU. Increasing the stiffness of the substrate will decrease the maximum allowable stretchability of the structure [3]. As the Young Modulus increase, the stiffness of the structure or materials will also increase. From the result, it shows that PDMS substrate will offer more maximum allowable stretchability compared to PU substrates. Based from the stress values in table 3, a graph was plotted and shown in figure 5.

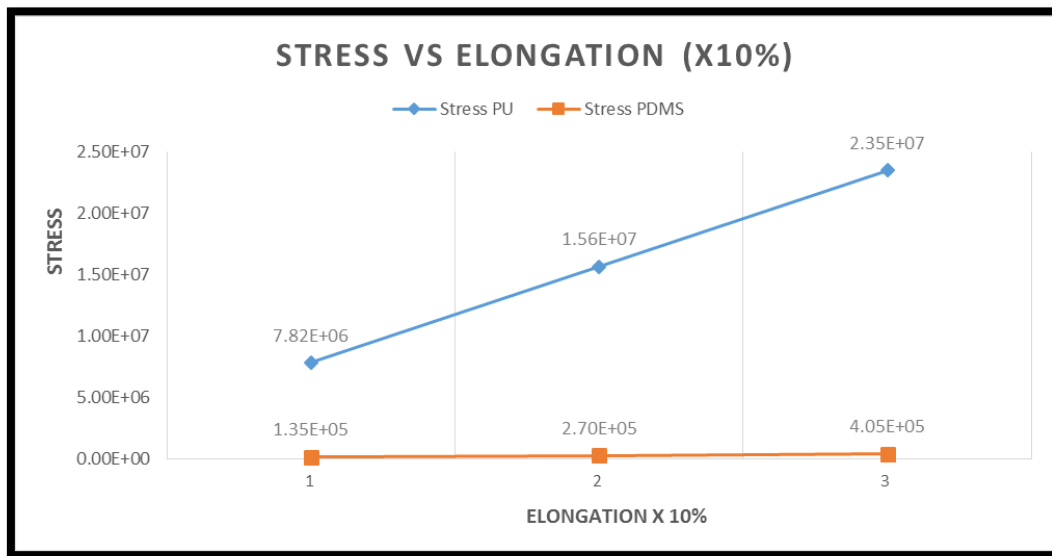


Figure 5. Stress for PU and PDMS vs Elongation.

From the graph, PDMS substrate record a lower stress (Pa) compare to PU substrate at each elongation. This indicates that in order for the stretchable circuit to stretch to a certain elongation or length, PU substrate will give higher stress compare to PDMS substrate. It shows that PDMS is more stretchable than PU substrate. Thus PDMS is considered as a better substrate to be used for the stretchable electronic circuit. This is also because PDMS has a lower Young Modulus compared to PU. According to Verstraete.H et al [5], by increasing the Young's modulus, the entire device has become stiffer and the maximum stress has increased. As the Young Modulus increase, the stiffness of the structure or materials will also increase. From the result, it shows that PDMS substrate will offer more maximum allowable stretchability compared to PU substrates. Thus PDMS is considered as a better substrate compared to PU.

PDMS is a good material to replace PU since it can perform under tension much better mechanically. By using PDMS also it will offer a much softer substrate material compared to PU. The PDMS have a hardness unit of 40-80 Shore A[6]. The PU has a hardness unit of 90 Shore A[7]. Shore A unit was used to measure the hardness of flexible rubbers that range in hardness from very soft and flexible, to medium and somewhat flexible to hard with almost no flexibility at all. Extremely soft and viscous materials were suggested as a good candidate for the encapsulation layer of stretchable electronics [8]. Thus, PDMS is a better material to be used as substrate because it is softer compared to PU.

4. Conclusion

To summarize, in this research, the study on deformation of stretchable electronic circuit was done. In order to get a deeper knowledge on how the deformation affects the stretchable electronic circuit, Abaqus Explicit software is used. Axial deformation was applied for the simulation of the FE model. Based on the several runs of simulation from the three different designs of conductor that are Rectangular, Horseshoe and U-shape at different elongations, the strain value can be observed. As the elongation increase, the strain value will also increase. As strain rate increase it will leads to failure of the copper conductor. In conclusions:

- Among the three designs, Horseshoe recorded the lowest strain value. Thus, it is considered as the optimum design for the copper conductor.
- PDMS recorded a lower strain and stress compare to PU at elongation 10%, 20%, and 30%. It offered more maximum allowable stretchability compared to PU substrates.

- PDMS is a good material to replace PU since it can perform under tension much better mechanically.

Acknowledgement

This work was supported by the International Islamic University Malaysia (IIUM).

References

- [1] Harrop D P 2013 *Stretchable electronics comes to market* IDTechEx
- [2] Hua Lin 2015 *Analysis of stress concentration phenomenon in stretchable interconnects* University of Electronic Technology Guilin, China
- [3] Gonzalez M, Axisa F, Bulcke M V, Brosteaux D, Vandeveld B and Vanfleteren J 2008 *Reliability* **48** 825–832
- [4] ThomasWidlund, ShixuanYang, Yung-Yu Hsu and Nanshu Lu 2014 *International Journal of Solid and Structures* **51** 23-24
- [5] Verstraete H, Pakazad S and Dekker 2016 *Design of stress-deflecting objects and shapes for metal interconnects in stretchable electronic circuits using finite element analysis* (Eindhoven, Netherlands)
- [6] Cidra Precision 2017 Polydimethylsiloxane (PDMS)
<http://www.cidraprecisionservices.com/life-sciences-materials-pdms.html>
- [7] Pleiger 2016 Polyurethane Material Properties <http://pleiger.com/polyurethane-materialproperties>
- [8] Yuan J H, Pharr M, Feng X, Rogers JA and Huang Y 2016 *Design of Stretchable Electronic Against Impact*