Effect of Tensile Load on Electrical Resistivity of Stretchable Conductive Ink (SCI)

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ABSTRACT

To date, research has tended to focus on emerging Electrical Conductive Adhesive (ECA) with stretchable and flexible substrate or known as Stretchable Conductive Ink (SCI). SCI is more flexible, stretchable and multi-purpose compare with the traditional printed circuit. Limitation on the chatacreization of SCI performance especially on it electrical performane under tensile stress has motivate this study. The aim of this research is to investigate the conductivity of the conductive ink under tensile stress at different elongation. The conductive ink carbon black was used to print on the thermoplastic polyurethane (TPU) and cure in the oven at 120°C for 30 minutes. The conductive ink was clamp using in-house stretching equipment with different elongation. The resistivity was measured by four-point probe while surface structure was observed by using Axioscope 2 MAT microscope. The result shows that the resistance increased when the elongation increased. For 40mm length of conductive ink, the initial resistance is 0.562 kΩ and its become 1.217 kΩ when stretch until 18% of its initial length. The sheet resistance of the conductive ink also increased due to the defection (porosity) on the surface of conductive ink after stretching. The strain level for 40mm and 60mm also increase form 0.14 to 0.16 that cause incerase in resistance. However, since there are no crack/defection observes at 80mm after maximum elongaton, the resistance start to decrease that cause increase in SCI conductivity.

KEYWORDS: *Conductive ink, Resistance, Tensile load*

1.0 INTRODUCTION

The revolution of technology has created many opportunities for the discovery of many multi-functional devices that made lives easier, faster and better. New devices are being developed every day, and each of these devices may be able to handle variations in size and functionality. With all of these revolutions, it is always an interest among manufacturer to create a more complex device that have high functionality but smaller in size. In electronic industry, the introduction of modern technology like conductive ink to replace the use of copper wire has able to create a device that is more flexible, smaller and multi-purpose. Example of conductive that has been used in flexible circuit device are metal-based inks, conductive polymers and carbon complex (Tran, Dutta, & Choudhury, 2018). For metal-based ink, there are a few type of metal that has been using as a filler for the conductive ink such as copper and silver. These types of ink

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have high conductivity and they are commonly used in traditional solid-state electronic. However, metal-based ink are high-cost and will be oxidize under ambient condition (Pekarovicova & Husovska, 2016).

The research to date has tended to focus on emerging ECA with stretchable and flexible substrate or known as Stretchable Conductive Ink (SCI) by using conductive filler especially form carbon based like carbon nano tube (CNT), graphene and carbon black. It have very good electrical conductivity by using high charge mobility to conduct electricity (Grandea, et. al., 2012). Conductive polymers are the creation of the mobility to charge on the polymers backbone so that it can conduct electricity. The example of conductive polymers is polyacetylene. It compress pellets to arrange as conjugated structure to exhibit the electronic conductivity (Ramakrishnan, 2011). These several types of conductive ink are needed to be printed on the surface so that it can connect the electronic product together. Few kinds of printing techniques have been developed to achieve the fabrication process which are ink-jet printing, screen printing, and gravure printing (Tran, Dutta, & Choudhury, 2018). Among these types of printing, screen printing is the most common printing technique in the industries process due to its compatibility. Screen printing is also low in cost, scalable and able to produce both fixed and flexible thin-film compare with the others printing technique (Cao, et. al, 2014). Although ink-jet printing is high cost but it has high registration accuracy so that it can produce a fine product (Sirringhaus, et. al, 2000).

Although the development of conductive ink had growth rapidly in the electronic industry, this technology is still not fully replacing the conventional soldering method due to the limitation of low electrical conductivity, low life-cycle, and low stretchability. Therefore, the use of stretchable and flexible polymer like Thermoplastic Polyurethane (TPU) has gain a lot of attention to use as medium to apply conductive ink. TPU is known for its flexibility and stretchability properties that may exhibit strain up to 100%. Thus, combining the mechanical properties of TPU with conductive ink is believed to able to provide a more flexible. Researcher had been continuously researching about conductive ink under stretching condition and improve the stretching ability without affect the electrical conductivity but still the study still limited and not widely explored yet. Besides, the conductivity of the SCI will affect with the elongation of the conductive ink during stretching. This is because, the resistance will increase after many stretching cycles due to the deformation of the stretchable conductive ink (Su, 2017). Hence, the aim of this study is to figure out the conductivity of the stretchable conductive ink under tensile stress and improve the stretchability without changing the resistivity of the conductive ink.

2.0 METHODOLOGY

The thermoplastic polyurethane (TPU) used in this study is commercially available TPU that purchased from Takeda Sangyo that have thickness of 100µm with optically transparent polyester film. The bare conductive ink, carbon black is printed on the TPU with stencil by using screen printing technique. The conductive ink is printed at different length which is 40 mm, 60 mm and 80 mm but with same width (5.0 mm) and thickness (0.2 mm). Later, the substrate undergoes curing process by heating at temperature of 120°C in the oven for 30 minutes. After the curing process, the TPU is stretch until reach 28% from its original length by using in- house stretching test as shown on Figure 1 and the resistivity was measured at every 2% interval by using Four-Point Probe at four different point. Further analysis was done on all the samples in order to qualitatively observe the morphology of the sample surface using Image Analyzer *(Axioscope 2MAT Microscope).*

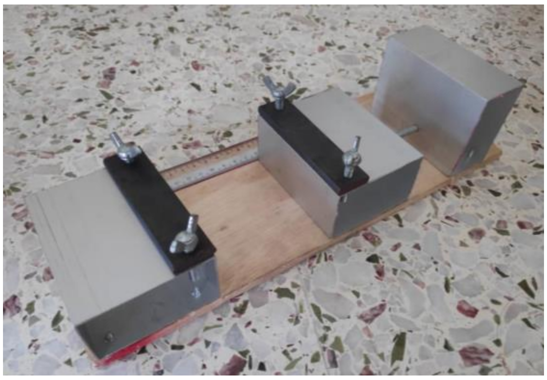


Figure 1. In-house streching test set-up

3.0 RESULT AND DISCUSSION

Figure 2 shows the results for resistivity of conductive ink carbon black printed on TPU at different length (40, 60 and 80)mm. The result reveals that the longer length of printed conductive ink on TPU substrate, the lower the resistivity of the SCI. This is due to the fact that, the rate of cracking and broken is decreased as the length of printed conductive ink increased. This occurance can be observe physically with naked eye in Figure 3. During the experiment, 40 mm length of conductive ink cracked at 14% (5.6 mm) of elongation and broke at 20% (8 mm) of elongation while for 60 mm length, the conductive ink cracked at 16% and does not break until reach 28% of its initial length. For 80 mm of conductive ink, there are no crack occur even after stretch up to 28% of its initial length. This show that the formation of crack on printed conductive ink after strecthing affect the rate of electron flow between the carbon black particles to decrease thus resulting lower conductivity.

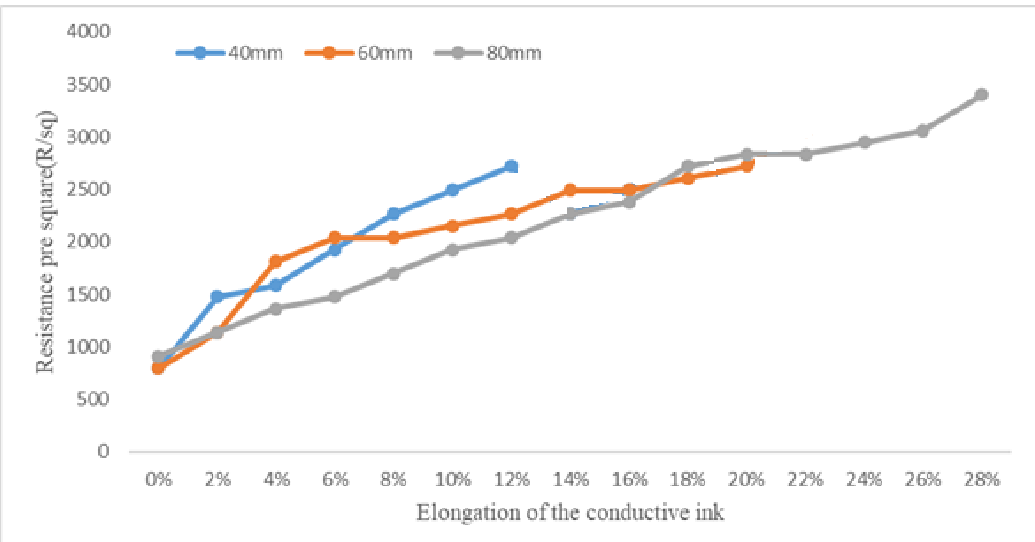


Figure 2. Resistivity of 40 mm, 60 mm and 80 mm length at different elongation

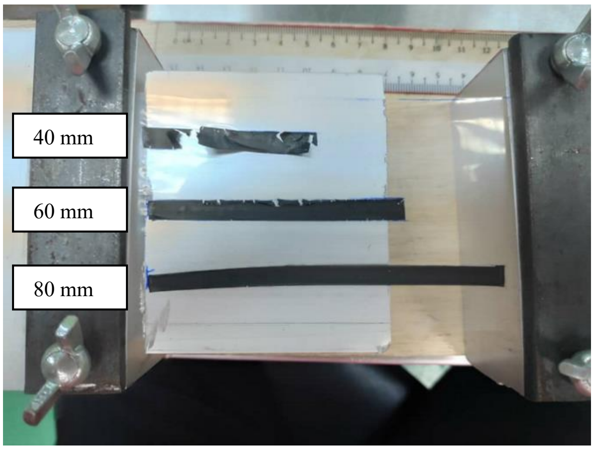
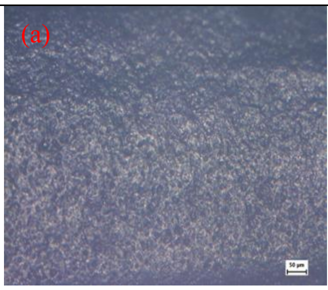
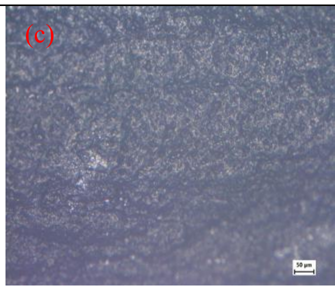
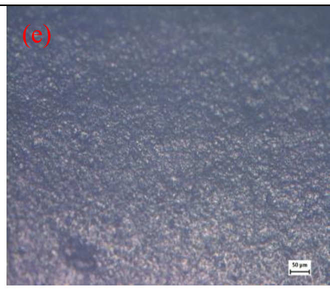


Figure 3. Physical appearance of printed conductive ink on TPU after strecthing

Further analysis to study the structural behaviour of the SCI when stretching up to 28% of elongation was done by using image analyser (*Axioscope 2MAT microscope*). The microstructure of the conductive ink at length of 40 mm shows a smooth surface without any imperfection at initial state as shown in Table 1(a) . After stretching, there are lot of porosity that clearly found on the surface of the conductive ink due to the deformation of conductive ink when stretching as shown in Table 1(b). Moreover, there are a crack in the middle of the conductive ink which represent the broken part of the conductive ink. All of the imperfections are affecting the conductivity of conductive ink. At 60 mm length of conductive ink, some porosity also could be found after stretching up to 28% of its intial length as shown in Table 1(d). However, the porosity are not as distinct as founded in 40 mm length. While for length of 80 mm, there are no defection occur at the surface of the conductive ink when comparing the result of microtrusture before (Table 1(e)) and after (Table 1(f)) stretching. This phenomenon shows that a surface with no defect will give small gap between the particles that create conductive paths allowing the ease of electron movements as explained by Merilampi (Merilampi, Laine-Ma, & Ruuskanen, 2009). Therefore, the longer the length of printed conductive ink, the higher the conductivity of the conductive ink.

Table 1. Microstructure image of printed conductive ink before and after stretching

SCI length	40	60	80
Before			

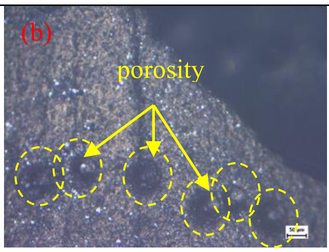
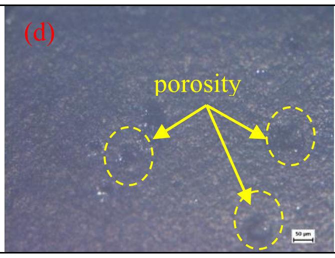
After			

Figure 4 is the comparison study of strain level between 40 mm, 60 mm and 80 mm length of printed conductive ink. Strain was measured to evaluate the amount an object deforms as a result of a force. It was measured when the change in a dimension (length) is divided by the original value of that length. The cracking point of 40 mm length of printed conductive ink is at 5.6 mm of elongation with the strain level of 0.14. Meanwhile, the cracking point of 60 mm length of printed conductive ink is at 9.6mm of elongation with the strain level of 0.16. Based on the previous study using four-point probe analyser to measure the resistivity of the stretchable conductive ink under stretching condition, as the strain level increase, the sheet resistance incresae as well due to the cracking on the surface of the conductive ink (Park, Lee, Kwon, Nam, & Choa, 2018). However, as for 80 mm length, no cracking occur after elongation up to 28% and the resistance was decrease eventhough the strain was predicted to occur at more higher of strain level which is 0.2 and above.

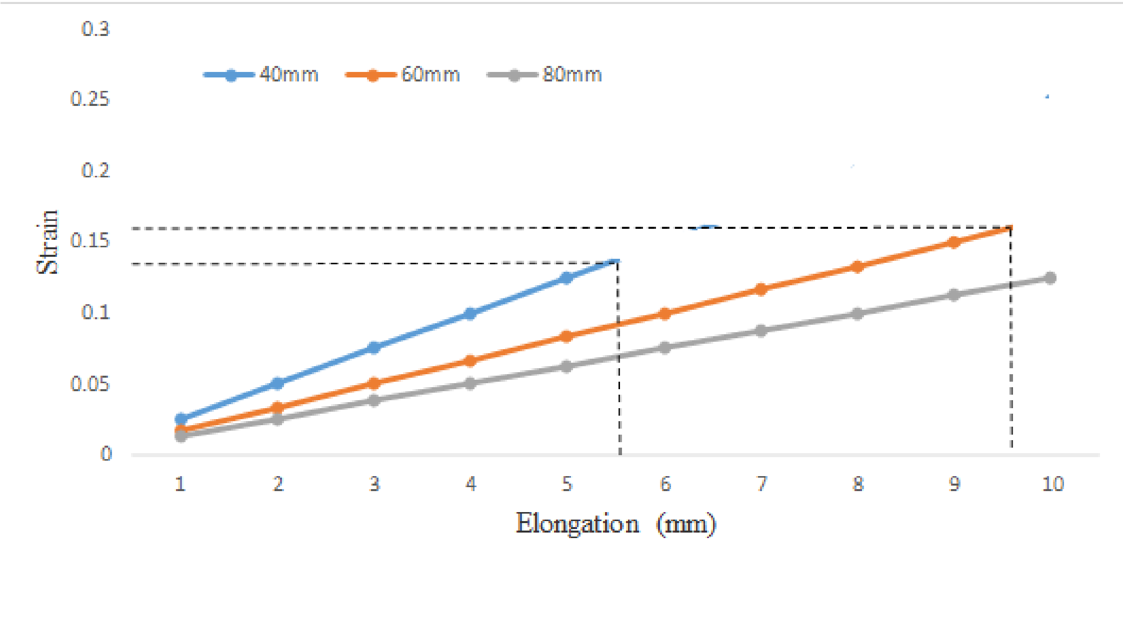


Figure 4. Graph of strain against elongation between different length of conductive ink

4.0 CONCLUSION

In summary, this paper succesfully investigate the effect of tensile stress on the different length of conductive ink printed on the TPU. The sheet resistance increase as the the length of printed conductive ink decrese due to the effect of porosity formation at the conductive ink surfaces. The formation of porosity cause the printed conductive ink to crack and reduce the conductive path. However, when the length of SCI is increase, the resistivity was decrease that cause the conductiviti of SCI increase since there are no crack observed.

5.0 ACKNOWLEDGEMENT

The authors gratefully acknowledge to Universiti Teknikal Malaysia Melaka (UTeM) for providing laboratory facilities.

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