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Effect of Stretchable Conductive Ink (SCI) on Electrical Conductivity Under Tensile Stress

Nor Azmmi Masripan[1,2*], Lin Soong Jin[1], Mohd Azli Salim[1,2], Nurfaizey Abdul Hamid[1], Muhd Ridzuan Mansor[1], Mohd Zaid Akop[1] , Aminurrashid Noordin[3] and Faizil Wasbari[1]

[1]Fakulti Kejuruteraan Mekanikal, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia
[2]Advanced Manufacturing Centre, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tungggal, Melaka, Malaysia
[3]Faculty of Electrical and Electronic Engineering Technology, Universiti Teknikal Malaysia Melaka, Hang Tuah Jaya, 76100 Durian Tunggal, Melaka, Malaysia

ABSTRACT

Conductive ink is widely used in various fields, especially in the electronic printed industry. Conductive ink is more flexible, smaller, and possesses multi-purpose functions as compared to traditional wire and electronic devices. This research aims to investigate the resistivity of the conductive ink under tensile stress. The carbon conductive ink was printed on the thermoplastic polyurethane (TPU) and cured in the oven at 120 °C for 30 minutes. The conductive ink was clamped on the stretching equipment and stretched at different elongation values. The resistivity was measured by a multi-meter and the sheet resistance was measured by a four-point probe. For the 40 mm length of conductive ink, the initial resistance was 0.562 kΩ and became 1.217 kΩ when it was stretched up to 18 % of its initial length. The sheet resistance of the conductive ink was also increasing due to the defect on the surface of conductive ink under the tensile stress. For the 40 mm length of conductive ink, the sheet resistance was 793.17 R/sq at the initial state and became 3059.37 R/sq when it was stretched until 18 % of its initial length. By comparing the different lengths of the conductive ink, the cracking point for 40 mm length of conductive ink can be observed at the 5.6mm of elongation with the strain level is 0.14. The cracking point of 60mm length of conductive ink was 9.6mm of elongation with 0.16 of the strain levels. The strain level of the cracking point between the different lengths of conductive ink was very closed. In conclusion, under the tensile stress, the sheet resistance and resistivity are increasing, which means the drop in conductivity. The conductive ink started to crack when the strain level reached around 0.15.

Keywords: SCI, electrical conductivity, tensile stress

1. INTRODUCTION

Technology nowadays is utilized to improve the performance of the system and reduce the size of the electronic device so that it becomes more flexible, smaller, and possesses multi-purpose functions. The intention to reduce the size and increase the flexibility of the device requires the traditional solid-state technology such as a copper wire to be replaced with the newly developed technology, which is conductive ink. Several types of conductive have been developed for use in flexible circuit devices such as metal-based inks, conductive polymers, and carbon complex [1]. For metal-based ink, there are a few types of metal are used as the filler for conductive ink such as copper and silver. These types of ink have high conductivity and are commonly used in traditional solid-state electronics. However, metal-based ink is very costly and can oxidize under ambient conditions [2] .

*Corresponding author: norazmmi@utem.edu.my

The carbon complex, which is called graphene consists of a two-dimensional layer of carbon lattice. Graphene has a very good electrical conductivity by using high charge mobility to conduct electricity [3]. Conductive polymers are the creation of the mobility to charge in the polymer's backbone so that it can conduct electricity. An example of conductive polymers is polyacetylene. It compresses pellets that are arranged as a conjugated structure to exhibit electronic conductivity [4].

These types of conductive ink need to be printed on the surface so that they can produce connectivity of the electronic products. Few kinds of printing techniques have been developed to accommodate the fabrication process, which are ink-jet printing, screen printing, and gravure printing [1]. Among these 3 types of printing, screen printing is the most common printing technique used in the industry due to its compatibility. Screen printing is low-cost, scalable, and able to produce both fixed and flexible thin-films as compared to the other printing techniques [5]. Although ink-jet printing is a high cost, it has high registration accuracy with the capability to produce a fine product [6]. During the ink-jet printing, the liquid jets are breaking up and then govern by using the theory of fluid dynamics to form the conductive ink on the surface of the material [7]. For gravure printing, it possesses high scalability, and flexographic printing has high printing resolution, which it can print uniformly. The conductive ink is printed by the rotary-screen printing to form the conductive line on the surface of the paper or plastics film [8].

The development of conductive ink has grown rapidly in the electronic industry to replace the traditional solid-state wire to produce smaller and flexible electronic components. However, the current technology and design of conductive ink cannot fully replace the conventional soldering method because many unknown variables of the conductive ink require further exploration and understanding. It also has many limitations such as limited electrical conductivity, low life cycle, and low stretchability. The researchers have been continuously researching conductive ink under stretching conditions to improve the stretching ability without affecting the electrical conductivity.

The main parameter that affects the conductivity of the conductive ink under tensile stress is the elongation of the conductive ink during stretching. Based on the previous study using a four-point probe analyser to measure the resistivity of the stretchable conductive ink under stretching conditions, it is discovered that the resistance was increasing when the strain increased due to the cracking on the surface of the conductive ink [9].

Besides that, the stretching cycle also affects the resistance of the stretchable conductive ink. Based on the previous study, the resistance changed for about 3 % of its initial values after 10,000 cycles of stretching with the strain rate of zero to twenty percent. It means the resistance is increasing after many stretching cycles due to the deformation of the stretchable conductive ink. Hence, the study aims to figure out the conductivity of the stretchable conductive ink under tensile stress and improve the stretchability performance without changing the resistivity of the conductive ink.

2. MATERIAL AND METHODS

2.1 Carbon based Conductive Ink

Commercial Bare conductive ink is the type of conductive ink that was chosen to be used in this experiment. The material composition of this ink is water, natural resin, conductive carbon, humectant, and preservatives. Among all the materials, conductive carbon is the most important constituent because it is used to carry the electron to pass through the conductive ink. Carbon is very good at conducting electricity and has a low resistance. The main advantage of using conductive carbon as compared to other metals such as silver and copper is the oxidation resistance when exposed to the surrounding with a significantly lower cost [10]. The curing process for this conductive ink was 15 minutes at room temperature. It was also cured by a thermal curing process so that the unnecessary solvent can be removed thoroughly to ensure that it has good conductivity after the curing process. These conductive inks are self-adhesive, and they can adhere to metal, paper, plastic, and wood surfaces. Thermoplastic polyurethane (TPU) was used as the substrate because of its suitability for the bare conductive ink to be printed on its surface as shown in Figure 1.

Figure 1. Example of bare conductive ink.

2.2 Thermoplastic Polyurethane (TPU)

The reason to choose thermoplastic polyurethane (TPU) as the substrate in this experiment was that thermoplastic polyurethane (TPU) is strong and has high stretchability. Based on a previous study, the maximum elongation of the thermoplastic polyurethane (TPU) was 300 % to 550 % and its melting point was in the range of 190 °C to 220 °C. These parameters are suitable for this experiment and they can be cured in the curing oven with the printed bare conductive ink on its surface.

2.3 Printing Process

The printing technique that was chosen to print the bare conductive ink on the substrate was screen printing. It is because screen printing is a low-cost technique of printing the bare conductive ink on thermoplastic polyurethane (TPU). It does not require any specific machine and instrumentation and only requires the bare conductive ink, scraper, and stencil. Firstly, a piece of thermoplastic polyurethane (TPU) needed to be prepared by drawing the dimension of the conductive ink. Then, the scotch tape was applied on the outside of the dimension as the guide for the bare conductive ink to be printed accurately according to the dimension. After that, the razor blade was used as a scraper to scrape the ink and forcing the ink print on the thermoplastic polyurethane (TPU). Lastly, the scotch tape was removed to expose the conductive ink line on the thermoplastic polyurethane (TPU) surface. Figure 2 shows the printed conductive ink on the TPU surface.

Figure 2. SCI printed on the TPU.

2.4 Curing Process

The curing process is an important process to dry the conductive ink so that the bare conductive ink can adhere to the thermoplastic polyurethane (TPU). During the curing process, the thermoplastic polyurethane (TPU) with a conductive line was placed into the oven and the temperature was set at 120 °C for 30 minutes to prevent thermoplastic polyurethane (TPU) from melting or deforming.

2.5 Stretch mechanism

The conductive are printed on the substrate and the substrate was fastened on both clamps so that it can be pull
was moved to stretch the conductive ink.

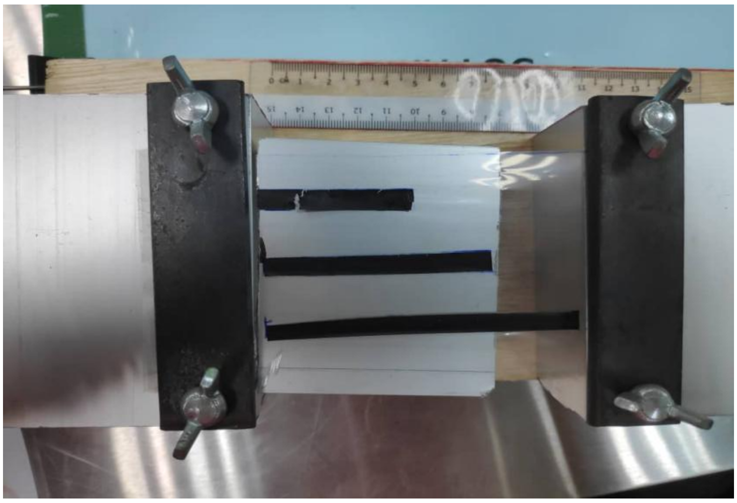

Figure 3. Pulling type of stretching equipment.

Figure 3 shows the design of the pulling mechanism. It consists of 2 clamps mechanism on this equipment, one is stationary, and the other is moveable. The moveable clamp is connected to a turning shaft with a spiral thread. When the shaft is turning, the clamp is moved toward the side of the equipment hence the thermoplastic polyurethane (TPU) is stretched. The elongation can be controlled more accurately due to the spiral thread of the turning shaft [11]. The elongation of the sample was increased every 2 mm until the maximum elongation of 28 mm. The test was executed simultaneously for the samples of 40 mm, 60 mm, and 80 mm.

2.6 Resistivity Measurement

During the stretching with certain elongation values, the resistivity was measured by using a four-point probe as shown in Figure 4.

When using a four-point probe to test the resistivity, it is important to ensure that the sample was positioned flat on the surface with the uniformly printed conductive ink on the thermoplastic polyurethane (TPU). These conditions allow the four-point probe to have contact with each point of the surface and more accurate results can be recorded. Besides, the current used in the four-point probe can affect the reading. Because of that, the current source should be adjusted to the maximum to test the very low resistivity material. The ideal current source is 10nA because of the heating effects and excessive current density at the tips of the four-point probe. On the other hand, it is suitable to use a low current source when testing the high resistivity material to prevent the voltage of greater than 200 mV. Moreover, an uneven or dirty surface can also affect the accuracy of the four-point probe readings.

Figure 4. Four-point probe.

3. RESULTS AND DISCUSSION

3.1 Effect of Elongation on Resistivity Performance

Figure 5 shows the elongation of conductive ink has a significant resistivity, where the increase of percentage elongation causes the higher resistance. At the initial length, the conductive particles inside the conductive ink are having full contact. Hence the resistance is low at 500 Ω /sq for 40 mm, 60 mm, and 80 mm. However, during the stretching process, the distance between the conductive particles is increasing gradually with the percentage of elongation. The increase of the distance between the particles causes an increment in resistance because the contact area is reduced.

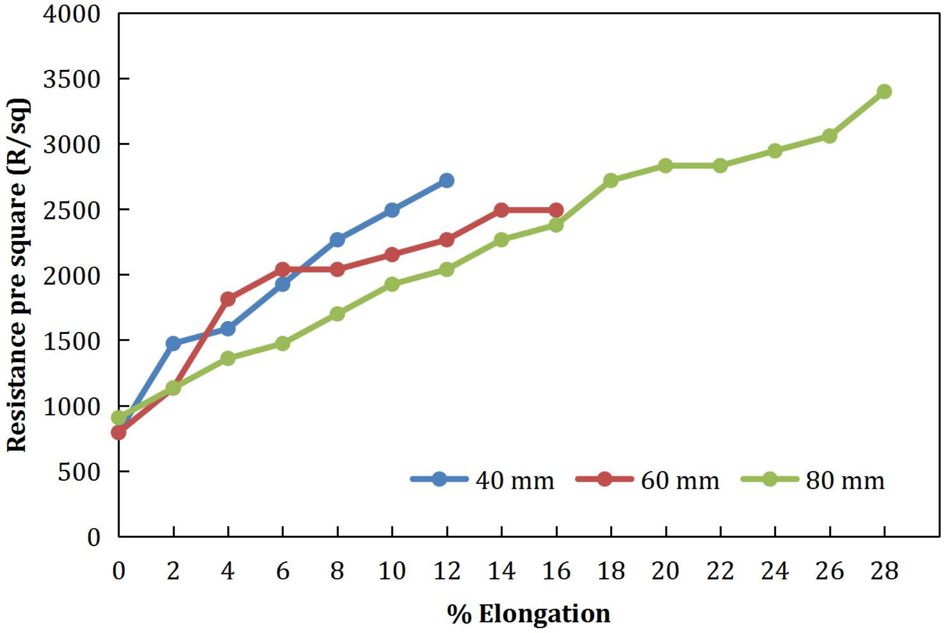

Figure 5. Resistance of 40mm, 60mm, and 80mm length that measure by four-point probe.

Figure 6 shows that the elongation of the different initial lengths of conductive ink can affect the strength of conductive ink. The longer length of conductive ink shows better performance than the shorter conductive ink. When the length of the conductive ink is increased, the rate of cracking and breaking is decreased. During the experiment, 40 mm length of conductive ink cracked at 14 % of elongation and broke at 20% of elongation. While for 60 mm length of conductive cracked at 16 % and it did not break when stretching until it reached 28 % of its initial length. Then, 80 mm length of the conductive ink did not have any deflection when it is stretched until 28 % of its initial length. This shows that the longer length of conductive ink had better stretchability performance.

Moreover, the sheet resistance of the conductive ink did not increase significantly when it was stretched for the longer length of conductive ink. This is because no defect occurred on the surface of the conductive ink for the longer length of conductive ink. When the surface of conductive ink is smooth and flat, the electricity can travel smoothly, and it has better conductivity and smaller resistance.

The effect of tensile strain on the conductivity of the ink film on PVC can be explained by microstructural changes in the ink film with microcracking inside the stretchable conductive ink. It leads to partial connection breaking between the conductive materials [12].

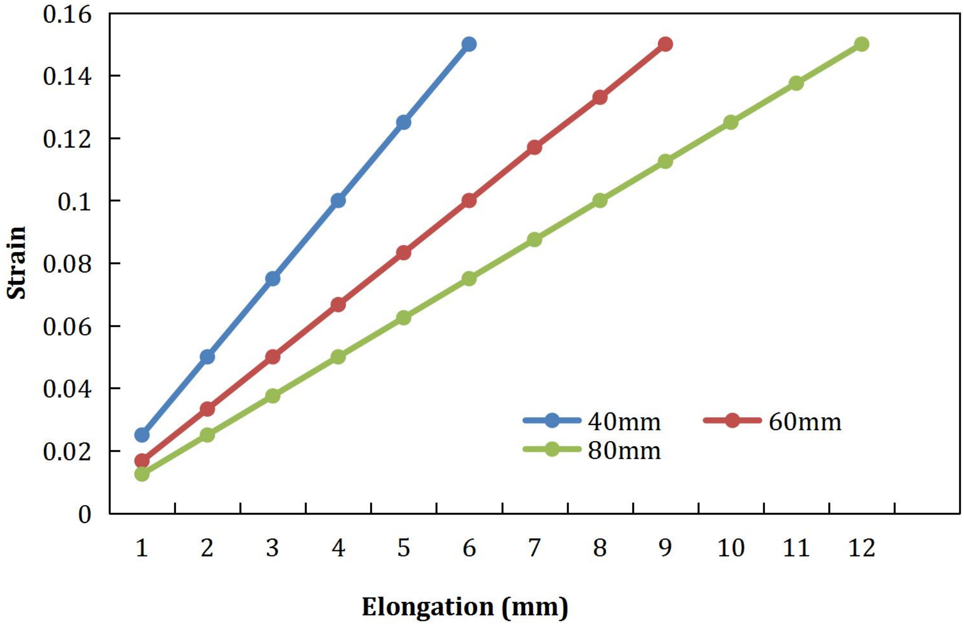

Figure 6. Graph of strain against elongation between the different lengths of conductive ink.

Figure 7 shows the condition of conductive ink at 12 mm of elongation. The conductive ink with an initial length of 40 mm started to crack under the strain of 0.15 with the 6 mm of elongation. At the elongation of 12 mm, the 40 mm conductive was breaking off with total failure and cannot function as a conductive ink anymore. For the 60 mm, the conductive ink started to crack at around 0.15 strain with an elongation of 9 mm. At the maximum elongation of 12 mm, the crack became more severe. However, the 60mm conductive could still function as conductive ink but the resistance was higher as compared to unimpaired conductive ink. The 80 mm conductive ink showed a totally different outcome. No crack can be observed on the surface at the maximum elongation of 12 mm with 0.15 of strain. Hence, the longer the length of conductive ink, the better the conductivity of the conductive ink.

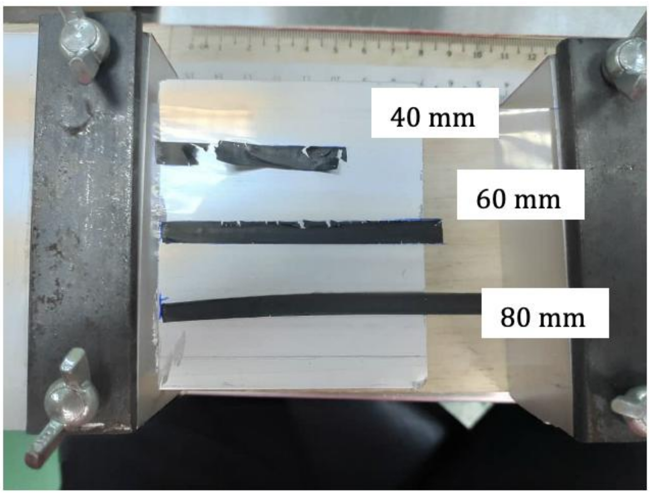

Figure 7. Defect of conductive in during stretch condition.

4. CONCLUSION

The result showed that the resistance was increasing when the elongation was increased. For the 40 mm length of conductive ink, the initial resistance was 0.562 kΩ, and it became 1.217 kΩ when it was stretched until 18 % of its initial length. The sheet resistance of the conductive ink also increased due to the defect on the surface of conductive ink under tensile stress. For the 40 mm length of conductive ink, the sheet resistance was 793.17 R/sq at the initial state and it became 3059.37 R/sq when it was stretched until 18 % of its initial length. By comparing the different lengths of the conductive ink, the cracking point can be observed for the 40 mm length of conductive ink when it was stretched at 5.6 mm of elongation with the strain level of 0.14. The cracking point of 60 mm length of conductive ink can be observed at 9.6 mm of elongation with 0.16 of the strain level. The strain level of the cracking point between different lengths is very closed. In a conclusion, under tensile stress, the sheet resistance and resistivity are increasing which means the drop in conductivity. The conductive ink started to crack when the strain level reached around 0.15.

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