Investigation of Micro-cracks in Inkjet-Printed Silver Traces on Polyethylene Terephthalate Substrates for Flex Sensors

W.A.C. Perera, S. W. D. K. R. M. Manamendra, W. L. P. K. Wijesinghe, G. C. Wickramasinghe, D. L. Weerawarne*

Department of Physics, Faculty of Science, University of Colombo, Sri Lanka

dweerawa@phys.cmb.ac.lk

1. ABSTRACT

Flexible electronics represent a transformative advancement in modern technology, enabling the integration of functional electronic components into pliable substrates that can bend, stretch, and conform to complex surfaces. This study explores the differences between disordered and ordered micro-crack arrangements in flex sensors for soft robotics, manufactured via an easy, affordable process. Conversely, creating ordered cracks generally requires more intricate, expensive techniques. Using inkjet-printed silver nanoparticle films on polyethylene terephthalate (PET) substrates, we systematically evaluate the effect of dimensional, mechanical, and thermal parameters, such as conductive path width, applied load, and sintering conditions affect sensor performance. Our findings reveal that wider conductive paths and moderate applied loads optimize sensor sensitivity and reliability, while controlled sintering at 100°C for two hours ensures consistent electrical behavior. Although disordered cracks demonstrate strong potential, their inherent variability currently limits their ability to fully replace ordered configurations, underscoring the need for further refinement in fabrication techniques to achieve scalable, reproducible sensor solutions for real-world applications.

Keywords: Silver Inkjet Printed, Polyethylene Terephthalate, Disordered Crack, Flex sensors

2. INTRODUCTION

Soft robotics is a rapidly developing field that focuses on the designs of robotic systems composed of soft and compliant materials, enabling safe interaction with humans and adaptability to complex and unstructured environments. Unlike conventional rigid robots, soft robots can undergo large deformations such as stretching, bending, and twisting, making them suitable for wearable devices, human–robot interaction, and adaptive manipulation tasks [1][2]

To enable effective control and perception, soft robotic systems rely on strain (flex) sensors capable of real-time monitoring of deformation, motion, and force. These sensors are essential for shape sensing, proprioception, and tactile feedback. Flexible strain sensors often operate based on the piezoresistive effec**t**, where applied strain alters the conductive network within the sensing material, producing measurable changes in electrical resistance. Common sensing mechanisms include resistance change due to material piezo resistivity, disconnection of conductive pathways, tunnelling effects, and crack propagation in thin films [3] .Micro-crack-based sensing mechanisms have been widely investigated to enhance strain sensor performance. As strain increases, cracks open and propagate, sharply reducing conductive paths and resulting in large relative changes in resistance. This mechanism can produce ultrahigh sensitivity, wide working ranges, and excellent motion detection capabilities. [4][5]

Microcrack structures can be broadly categorized as ordered or disordered. Ordered microcracks exhibit controlled orientation, spacing, and geometry, which produce uniform and predictable sensor responses, and can be fabricated via advanced patterning techniques or lithographically defined gaps; however, these processes are often complex, expensive, and difficult to scale for large-area flexible electronics.

In contrast, disordered microcracks form randomly within the conductive layer through simpler fabrication approaches such as pre-stretching, microgroove templates, solvent evaporation, or mechanical deformation. The generation of microcracks significantly improves sensitivity by amplifying strain effects through the disconnection and reconnection of conductive networks, demonstrating their effectiveness for flexible strain sensing in soft robotics and wearable platforms. [6]. This study explored the electrical properties and fabrication potential of disordered micro-cracks using inkjet-printed silver nanoparticles on PET substrates for flexible electronics.

3. METHODOLOGY

i. Selecting the materials and fabrication

The first step involves selecting materials and fabrication. Polyethylene terephthalate (PET) was chosen for its flexibility and stability. Silver (Ag) nanoparticle ink (Novacentrix Metalon JS-B25P) was selected for its electrical conductivity and applied via inkjet printing on an EPSON L-130 printer.

ii. Designing Silver traces

The second step involves designing the conductive traces in Figure 1 with a length of 6 cm and widths of 3 mm, 5 mm, 7 mm, and 10 mm to fit human fingers.

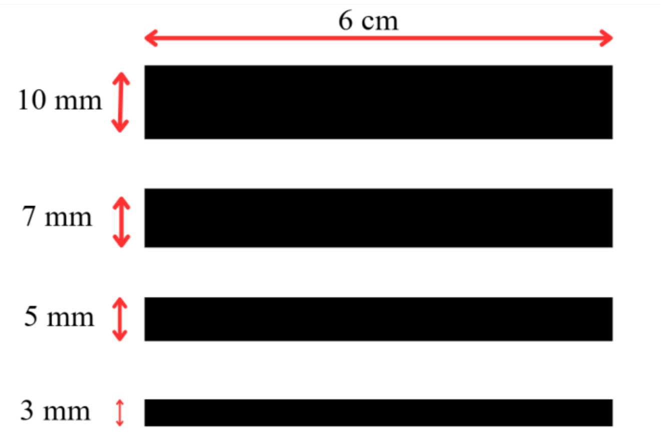

Figure 1: Designs for silver traces for Inkjet printing

iii. Inkjet Printing and Sintering

An EPSON L130 desktop document printer was used to print the silver traces. After printing, the traces were oven-sintered at 100°C and 50°C for four different time periods: one hour, two hours, three hours, and four hours.

iv. Micro Crack Fabrication

Microcracks were generated using a scientific method known as the crease test [7]. Weights of 20 g, 100 g, 500 g, 1 kg, and 2 kg were applied to induce cracks in the silver trace. The process involved placing the printed trace on a flat surface, bending it halfway with the printed side inward, and then rolling the selected weight over the trace without applying any additional hand pressure.

v. Characterizations

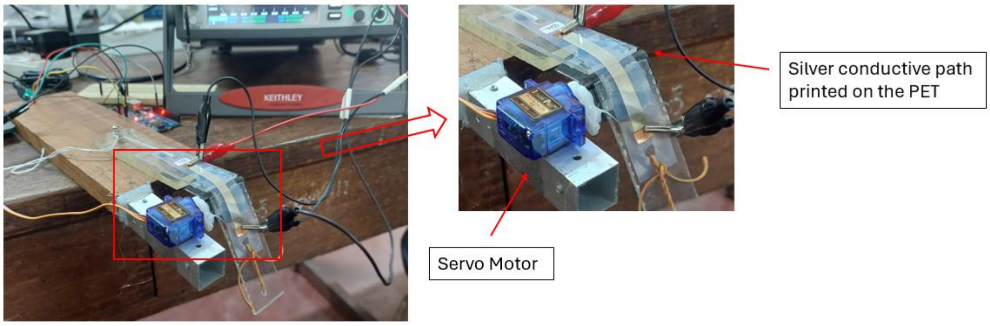

Figure 1: An automated angle-bending machine for the printed silver traces on a substrate.

The process indicated in Figure 2 was controlled using a Servo Motor and an Arduino, ensuring precise and repeatable movements. The moving slide advances the printed path from 0° to 140° at 5 s intervals. To monitor resistance variations over time, a Keithley 2450 source meter was connected to the end of the conductive path. Hence, resistance measurements were made using a Keithley meter employing the 4-probe method before and after crack formation. The automated angle-bending machine performed cycling tests at 5 s intervals to assess changes in resistance over time. Crack morphology was analyzed using a digital microscope. Data analysis focused on calculating percentage changes in resistance and plotting variations across bending cycles to explore the relationship between micro-crack formation and electrical behavior in flexible conductive systems.

4. RESULTS AND DISCUSSION

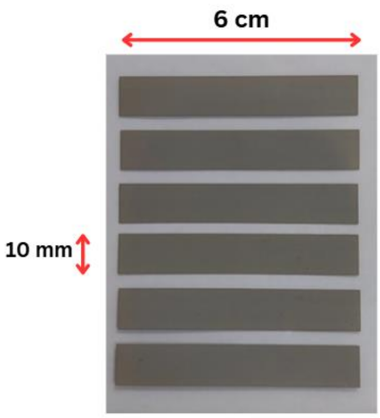

Figure 3: Printed samples using silver on PET with a 10 mm width and 6 cm length.

Figure 3 shows the printed silver traces on a PET substrate used in this study. Each sample has a length of 6 cm and a width of 10 mm, and the images depict the traces before the integration of micro-cracks. These samples were fabricated using inkjet printing with a conductive silver ink, resulting in uniform and well-defined rectangular traces. The smooth surface and consistent dimensions confirm successful deposition on the flexible PET film, which serves as the base for subsequent mechanical or electrical testing. Analysis of Applied Load Variation.

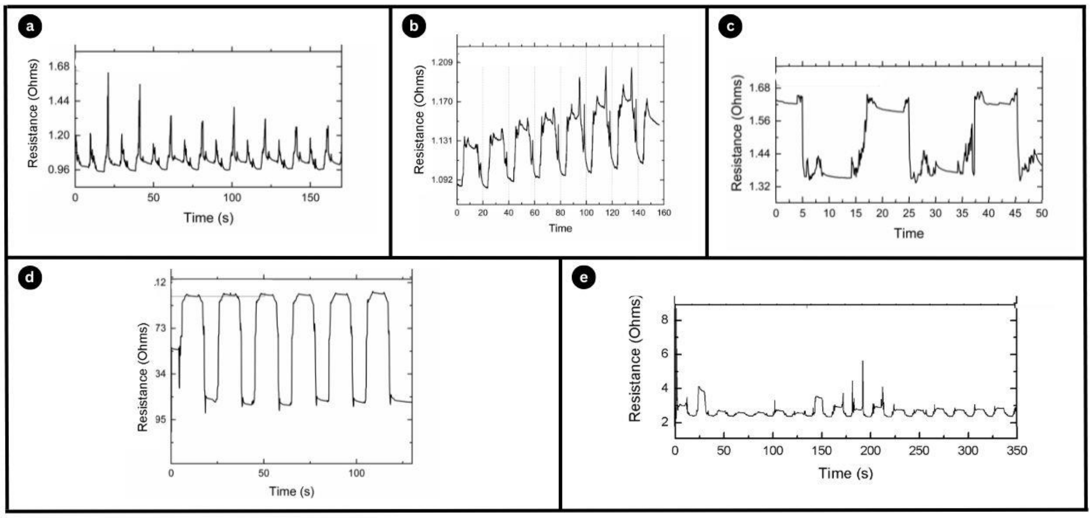

Figure 4: Variation of the resistance with time, for the sample (6 cm x 10 mm) creased using different weights. Sintered for 4 hours and 100 ^{o}C a.) sample creased using 20 g, b.). sample creased using 100 g, c.) sample creased using 500 g, d.) sample creased using 1 kg, and e.) sample creased using 2 kg.

Figure 4 shows the results obtained for the sample creased using different weights. Load-optimization studies identified 1 kg as the optimal creasing weight, effectively balancing crack density with structural integrity. Both lower loads (100 g, 500 g) and higher loads (2 kg) resulted in diminished performance due to insufficient or excessive cracking. The reason for choosing the 10 mm for the initial investigation was to match the width of the human finger.

i. Analysis of Dimensional variation.

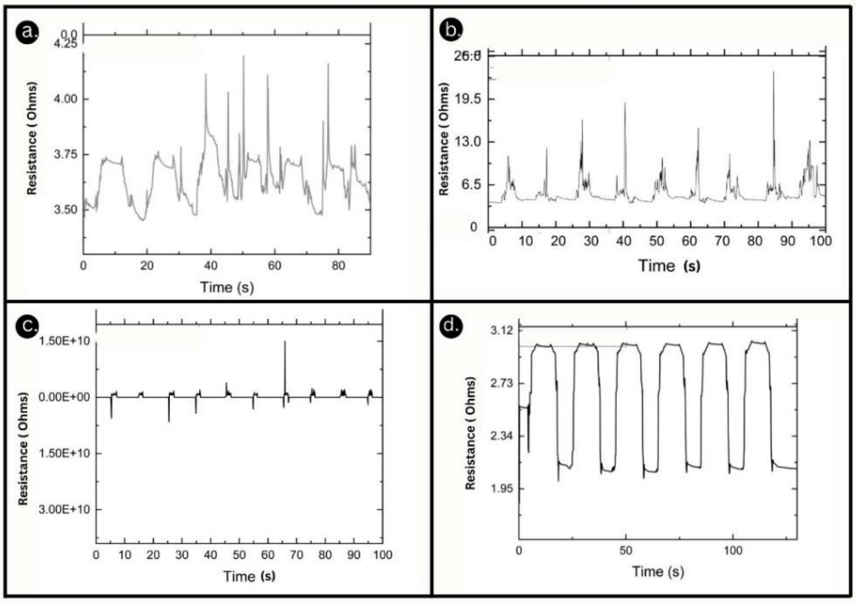

Figure 5: Variation of the resistance with time for the sample creased using 1 kg for different lengths: a.) 6 cm x 3 mm, b.) 6cm x 5mm, c.) 6 cm x 7 mm, and d.) 6 cm x 10 m.

Investigations in Figure 5 revealed the significant relationships between sensor design parameters and performance in disordered micro-crack configurations. Dimensional analysis demonstrated that wider conductive paths (10 mm) substantially outperformed narrower variants (3 mm, 5 mm, 7 mm, 10 mm) by facilitating multiple stable conductive routes, thereby enhancing sensitivity and reliability.

ii. Analysis of sintering temperature dependency.

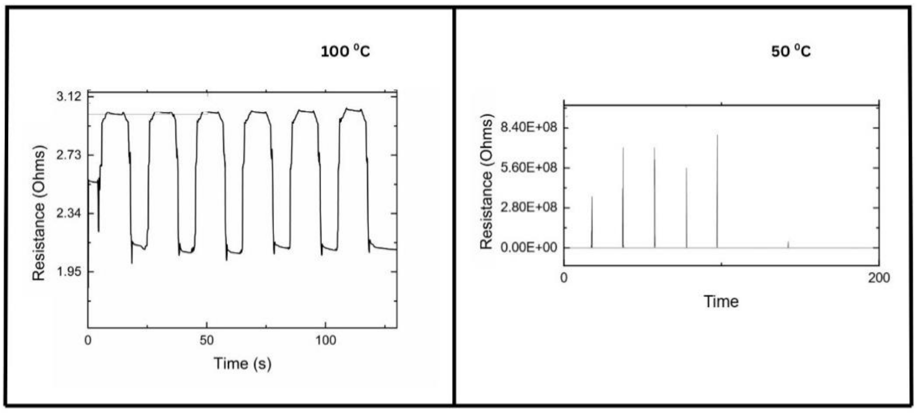

Figure 6: 6 cm x 10 mm samples sintered at 50 ^{0}C and 100 ^{0}C for four hours and creased using 1 kg.

The resistance–time response of the silver traces sintered at 100 °C and 50 °C is shown in the figure. The 100 °C sample exhibits a stable and repeatable resistance variation of around 2–3 Ω, while the 50 °C sample shows very high resistance with significant noise and poor repeatability, indicating inferior electrical performance at the lower sintering temperature.

iii. Analysis of Sintering Time Dependency

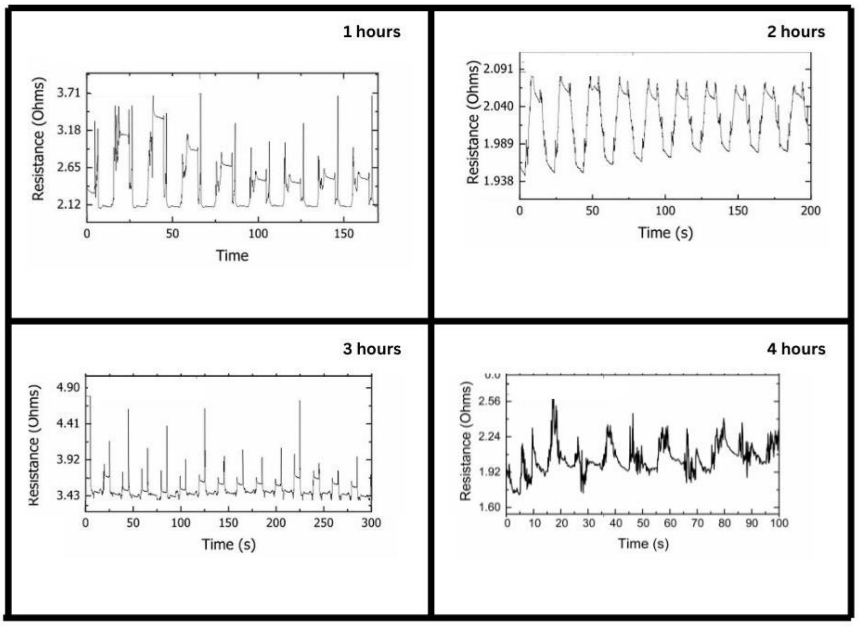

Figure 7: Variation of the resistance with time for the different sintering times for three samples 6 cm x 10 mm sample, and a creased sample using 1 kg, respectively.

In addition, the current study identified the optimal sintering time to propagate microcracks. The results were observed four different times: one hour, two hours, three hours, and four hours. Figure 7 shows the effects of sintering temperature for Ag inkjet printer trace on PET for the formation of the micro-crack pattern during angle bending and the conductivity of the silver trace with micro-cracks. According to these Figures, samples sintered for 2 hours were able to produce a more repetitive pattern compared to other time periods. Longer sintering times lead to greater evaporation, which can increase crack formation. This can be controlled by choosing the correct sintering time to achieve the optimal crack density for better results.

iv. Digital microscopic analysis of the Results.

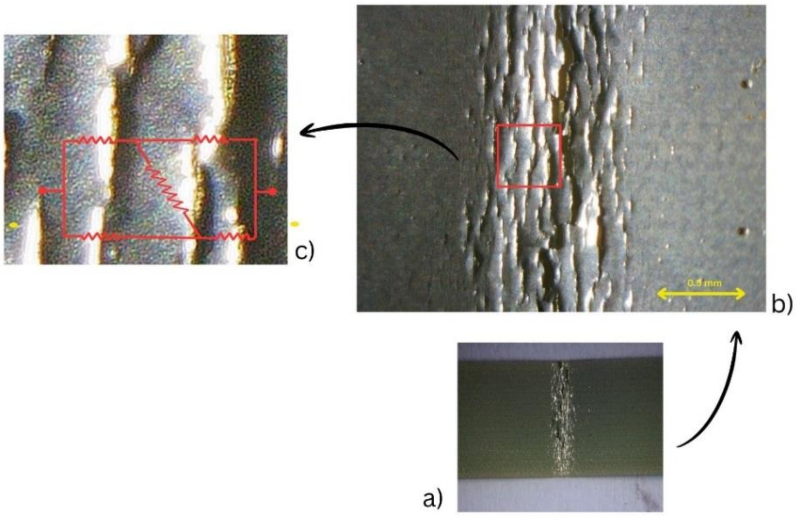

Figure 8: a.) Photograph of creased Inkjet printed silver trace on PET, b) Digital microscopic image of cracks c) Circuit for resistance variation for formation of micro cracks on a sample creased using 1 kg, sintered at 100 °C for four hours.

Digital microscopic analysis confirmed the random nature of crack formation, explaining performance variability. The crack pattern observed here resembles the "network pattern" on inkjet-printed Ag on PET in Figure 8 (b) reported by [8]. Such network cracks enable a wider operational range by preserving conductive pathways through bridges or by distributing stress via out-of-plane deflection. Figure 8 (c) illustrates the resistance variations according to the pattern of formation of microcracks on Ag silver traces. However, their slower resistance increase results in lower sensitivity.

v. Repeatability of the Results

To check whether the result can be reproducible, we compared three samples that produced microcracks under the same conditions. However, despite maintaining identical fabrication parameters, the microcrack patterns obtained from the three samples exhibited significant variability, indicating a lack of repeatability under the tested conditions.

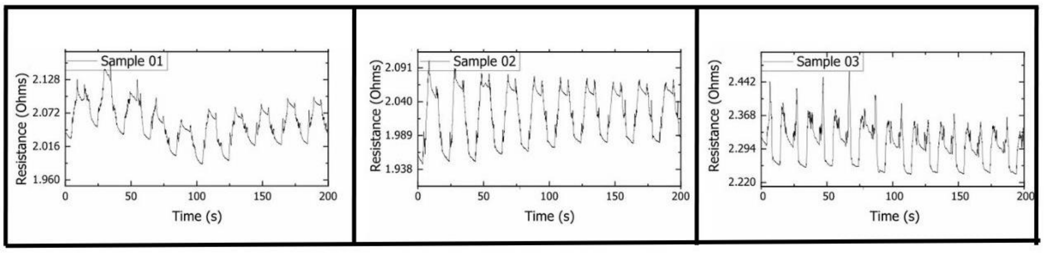

Figure 11: Variation of the resistance with time for three samples (6cm x 10 mm) sintered at 100 °C for 2 hours and creased using 1kg.

5. CONCLUSION

Wider conductive paths enhanced sensor performance by providing stable conduction routes, while narrower paths limited effectiveness. Optimal results were achieved at moderate loads (approximately 1 kg), whereas extreme loads negatively affected sensor responsiveness. Although higher crack density generally improves performance, irregular crack geometry can sometimes allow smaller or lightly loaded samples to outperform larger ones, demonstrating the influence of unpredictable crack patterns. Larger samples (10 mm × 6 cm) yielded more accurate results due to their greater capacity for conducting current. However, the randomness of crack formation hinders reproducibility, as similar conditions may yield different results based on crack connectivity. Sintering for 2 hours at 100 °C provided the best balance between bonding and crack formation, whereas lower temperatures or longer sintering times resulted in poorer sensor characteristics. In conclusion, while disordered cracks from creasing and stretching show promise under certain conditions, their unpredictability limits their ability to replace ordered cracks in strain sensors inkjet printed with silver on a PET substrate. Future research should aim to enhance the control and reproducibility of crack formation to enable reliable, cost-effective flex sensor manufacturing.

6. REFERENCES

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