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RELIABILITY PERFORMANCE OF GNP/Ag/SA HYBRIDIZATION STRETCHABLE CONDUCTIVE INK ON CYCLIC BENDING

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ABSTRACT

In this rapidly changing era, new needs and demands for electronic products, particularly flexible electronics, necessitate ever-superior qualities, particularly in terms of flexible and stretchable devices. As a result, the goal of this research is to look into the behaviour of GNP hybrid-based conductive ink when subjected to cyclic bending, which can explain the material's flexibility performance. Sample made with hybrid GNPs and organic solvents. The ink was printed on a single crystal copper (Cu) substrate with two different samples in terms of average graphene size, 5 µm and 25 µm, at three distinct points. The lowest sample with the highest resistance or conductivity was tested using conductive ink characterisation. The electrical performance under cyclic bending conditions shows that the lower the resistivity value, the smaller the average particle size of the hybrid GNP particles. This study's overall findings provide a deeper insight, particularly in terms of selecting acceptable conductive ink qualities that can endure recurrent bending fatigue. Substrate flexibility and bending resistance performance are significant aspects for obtaining optimal electrical and to reduce strain on the ink during bending, resulting in better ink electrical conductivity retention.

1. Introduction

The invention of stretchable conductive ink has enabled the development of flexible and wearable electronic gadgets that can conform to complicated geometries and be worn comfortably on the human body. Stretchable conductive ink is typically made up of conductive nanoparticles placed in an elastic matrix, which allows it to retain its conductivity even after large deformations. Carbon nanotubes were used in one of the first types of stretchable conductive ink (CNTs). Because carbon nanotubes are both extremely conductive and flexible, they are an excellent choice for use in stretchy electrical systems. CNT-based inks, on the other hand, can be difficult to produce and can be poor adherence and dispersity to substrates. (Duan et al., 2022; Islam et al., 2022).

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Because of their outstanding electrical conductivity, mechanical flexibility, and biocompatibility, graphene-based stretchable conductive inks have received a lot of attention in recent years (T. Wang et al., 2021). Graphene is a two-dimensional material made of carbon atoms organised in a hexagonal lattice, and its large surface area and mechanical strength make it an excellent option for use in stretchy electrical devices. Direct printing of graphene ink, inkjet printing of graphene oxide, and combining graphene with other conductive nanoparticles such as silver or copper nanoparticles are all methods for creating graphene-based stretchable conductive inks (Franco et al., 2021). Among these options, it has been demonstrated that combining graphene with other nanoparticles improves the mechanical properties of the ink while lowering its processing costs.

In addition to graphene, additional materials such as silver nanoparticles, gold nanoparticles, and conductive polymers such as polyaniline and PEDOT: PSS have been investigated for use in stretchable conductive inks (Yang et al., 2020). Each of these materials has advantages and disadvantages, and the material used is determined by the application requirements. Overall, the creation of stretchy conductive ink has opened up new avenues for the development of flexible and wearable electronic devices that can be employed in a range of applications ranging from healthcare monitoring to soft robotics. Stretchable conductive ink development is strongly tied to the growth of flexible printed electronics. Stretchable conductive ink is an important component of flexible and wearable electronic devices because it enables the fabrication of circuits and sensors that can survive deformation and bending (Kirubasankar et al., 2021). The utilisation of printed electronic materials on flexible substrates that can be bent, twisted, and stretched is what flexible printed electronics is all about. Lightweight, conformability to varied surfaces, and low-cost production procedures are just a few of the advantages these devices have over traditional rigid electronics (Liu et al., 2021). Stretchable conductive ink is required for the construction of conductive traces and circuits on flexible substrates. The ink must be able to stretch and bend with the substrate without breaking or delaminating while still remaining electrically conductive. Stretchable conductive ink has enabled the development of a variety of flexible and wearable electronic devices, such as flexible screens, electronic skin, and smart textiles (Afroj et al., 2020). Figure 1, shows the flexible screen printing by using stretchable conductive ink.

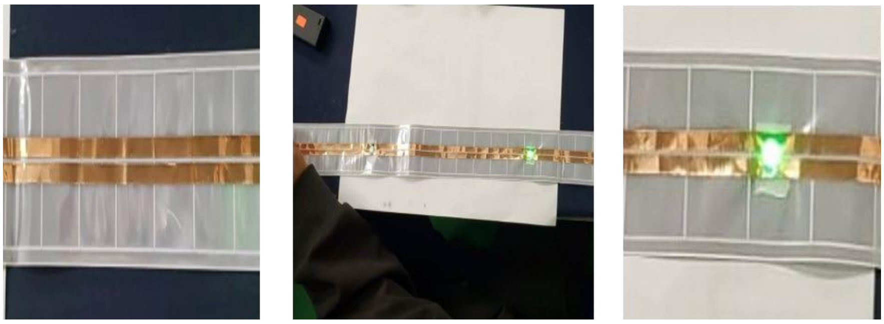

Figure 1 Flexible screen printing

Stretchable conductive ink's mechanical and bending qualities are important to its performance in flexible and wearable electronic systems. Stretchable conductive ink must be able to keep its electrical conductivity even when deformed significantly without breaking or delaminating

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from the substrate. A hybrid ink system made of various materials is one way to enhancing the mechanical characteristics of stretchable conductive ink. For example, (C. Liu et al., 2021) was published a recent work on the creation of a hybrid ink system comprised of graphene oxide, silver nanoparticles, and polydimethylsiloxane (PDMS). Even when exposed to bending radiuses as tiny as 3 mm, the hybrid ink retained remarkable mechanical characteristics and conductivity. A hierarchical structure can also be used to improve the mechanical characteristics of stretchy conductive ink. (Li et al., 2022), for example, reported on the creation of a stretchable conductive ink made of silver nanoparticles and a polyurethane (PU) matrix. Stretchable conductive ink's bending qualities are also critical for its performance in flexible and wearable electronic systems. (Krisnadi et al., 2020) created a stretchable conductive ink from silver nanoparticles and a PDMS matrix. Even with a bending radius of 0.5 mm, the PDMS in the gap crosslinked and seamlessly joined with the surrounding PDMS matrix to generate a mechanically and electrically healed structure.

In addition to hybrid ink systems and hierarchical structures, other factors can also affect the mechanical and bending properties of stretchable conductive ink. These factors include the composition and concentration of the conductive nanoparticles, the type of elastomer used as the matrix, and the processing conditions such as temperature and curing time (Fazli & Rodrigue, 2020). Overall, the mechanical and bending properties of stretchable conductive ink are critical for its performance in flexible and wearable electronic devices. The reliability performance of GNP/Ag/SA hybridization stretchable conductive ink on cyclic bending has been studied extensively in recent years due to its potential applications in wearable electronics. The physical and chemical properties of this conductive ink allow it to withstand repeated mechanical deformations without any significant changes in its electrical conductivity (Silva et al., 2020). The physical properties of GNP/Ag/SA hybridization stretchable conductive ink make it suitable for cyclic bending applications. The electrical properties of GNP/Ag/SA hybridization stretchable conductive ink are also very stable under repeated mechanical deformations. This makes it an ideal material for applications such as wearable electronics, flexible printed circuit boards and other flexible electronic devices. The reliability performance of GNP/Ag/SA hybridization stretchable conductive ink on cyclic bending has been studied using both experimental and theoretical methods.

The interaction of fillers, binders, and solvents is critical for the formulation of conductive inks since it is the first step in understanding the high conductivity inherent in ink loading. Conductive ink characterisation is investigated using a number of techniques, including digital multimeters to gain a thorough knowledge. All of the above stages were repeated with several specimens and samples to identify the lowest resistance or greatest conductivity. In addition to static state analysis, ink effects with some cyclic bending are applied. The primary goal of this investigation is to investigate the influence of cyclic bending on the electrical characteristics of GNP, Ag, and SA. When the effect is subjected to continual cyclic bending, it is thought that the electrical resistance would grow. The findings of this research project have the potential to be highly beneficial for industry, with the potential to be developed into a significant assessment database based on both functionality and dependability in real-world field applications.

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2. Methodology

2.1 Sample formulation process

The first phase of the investigation is to do research on the formulation of graphene nanoplatelets (GNP). The next investigation will focus on the GNP/Ag/SA hybrid formulation with organic solvent or capping agent for application in the production of conductive ink. The research begins with the formation of graphene nanoplatelets (GNP) and concentrates on the precise organic solvent ratio employed in the paste formulation of GNP, silver flake (Ag), and silver acetate (SA).

The formulation of a powder GNP/Ag/SA hybrid is significant because it enables the production of new materials with increased physical and chemical characteristics. Improved electrical and mechanical strength, as well as a larger surface area for catalytic applications, are all part of this. In addition, the formulation enables the creation of GNP hybrids with specialised characteristics for specific applications. For example, a GNP hybrid formulation might be adjusted to optimise compatibility with a certain resin system. Moreover, customised formulations may be developed to enhance the dispersion and orientation of the GNP/Ag/SA hybrid in the composite matrix, resulting in increased composite performance. Figure 2 show the material for preparation and table 1-2, the formulation of the powder and paste graphene nano particle GNP/Ag/SA hybrid as show below.

Figure 2. Material preparation for formulation

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Table 1. Formulation of powder GNP/Ag/SA

No	Item	Amount
1	Graphene Nanoplatelet (GNP)	0.05g
2	Ethanol	50ml
3	Silver Flakes	4.292g
4	Silver Acetate	0.42g

Table 2 Formulation of paste GNP/Ag/SA

No	Item	Amount
1	Graphene Nanoplatelet (GNP)	4.56g
2	Butanol	26 drops
3	Terpineol	26 drops

Before the formulation process began, the entire value was determined. In this investigation, graphene nanoplatelets with diameters of 5 µm and 25 µm were used as the principal filler. A simple procedure including mixing, printing, and curing was used to generate graphene dispersion. The samples with a diameter of 5 µm of graphene were weighed using a digital analytical balance at 0.05g. The same procedure was followed for each scenario, such as graphene with a diameter of 25 µm and a varied weight ratio depending on the mixture composition.

Stabilise the unit, the beaker is placed in the centre of the weighing pan and left for a few seconds. Ensure accurate results when weighing the material, the weight of the beaker is set aside by pushing the tar button until the display panel reads 0.0000 g. The organic solvent, 50 ml of ethanol, is added next. To use an ultrasonic bath, the sample is wrapped in aluminium foil. This procedure will only take around ten minutes. The GNPs are then dispersed in an ethanol solution and sonicated to break up any agglomerates. After 10 minutes, combine the silver pieces and sonicate them in an ultrasonic bath for one hour. The process is then repeated for about an hour, combining with silver acetate until done.

The stirring process is the last step in the powder preparation process. Continue magnetic stirring until the mixture is dry at 70°C and 200 rpm. After the entire mixture has dried, place it in a 250°C oven for one hour to cure. The powder is then dried at room temperature and allowed to cool. The final step in making this ink paste is to pound it with a mortar until it is smooth. Before the printing process begins, the ink paste should be prepared so that the entire experiment in terms of preparing the GNP/AgNP/SA manufacturing formulation can be successfully accomplished. The powder is properly weighed after it has been ground to a fine powder to confirm that it is compatible with the formulation for mixing the butanol and terpineol solvents. Add butanol and terpineol to the required formulation, which is 26 drops, with a dropper. This method is continued with the thought thinky mixer until the predetermined alignment is complete.

After all of the formulation stages for the creation of GNP/AgNP/SA powder and ink paste have been accomplished, the printing process is completed by depositing the Conductive Ink Paste on the copper sheet using the mesh stencil method. When the printing technique was about to begin, a scraper was used to apply a portion of the combined paste to the specified

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grid. Once the paste was visible on the substrate, the samples were cured in an oven for 30 minutes at a temperature of 250°C.

The graphene ink used in this work contains 4.56g of GNPs with average particle sizes of 5 µm and 25 µm. The sample was manufactured and bent 500 times using a 5.1V speed control voltage. The purpose of this bending technique was to see how the resistance of conductive ink changed once the bending process was finished. The resistance of the GNP hybrid conductive ink was measured before and after the cyclic bending test with a digital multimeter. The cyclic bending test is a reliability and performance test for GNP hybrid conductive ink that determines the ink's durability and capacity to sustain repetitive mechanical strain. This test was designed to evaluate the dependability of GNP hybrid conductive ink for various applications, such as microelectronics, printed electronics, and flexible displays (Zhuldybina et al., 2021). The cyclic bending test is an important method to evaluate the dependability and performance of GNP hybrid conductive inks in flexible and stretchable electronic devices. This is due to the fact that such devices are frequently bent and deformed during usage, and it is critical that the conductive ink can endure this mechanical stress without impairing its electrical performance.

2.2 Printing process

Printed electronics encompasses a wide range of printing techniques for the deposition of electrical components and structures. Such processes include inkjet, flexographic, screen, and gravure printing (Lorenz et al., 2022). This research also focuses on the production of printed conductors using screen printing technologies on flexible substrates. This method is widely utilised, particularly by researchers, because to its simple technique, low cost, and printing process parameters. Screen printing is a manufacturing technique that allows for the production of dense layers on a substrate. There are two types of screen-printing techniques: flatbed screen printing and rotary screen printing (Ney et al., 2022; Tepner et al., 2020).

Figure 3 shows the printing process before screen printing operation. Creating the desired

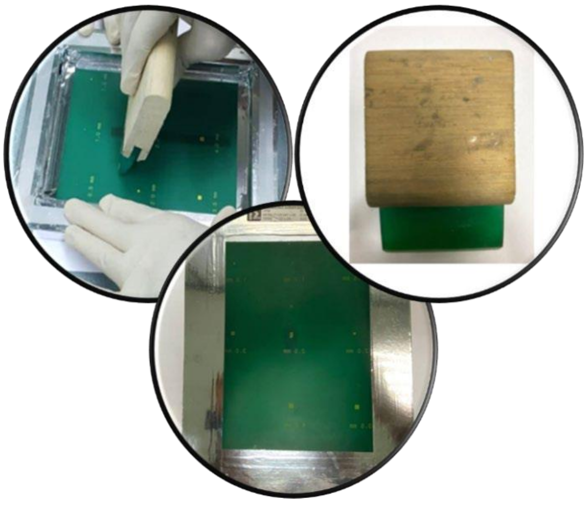

Figure 3. Printing Process

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design on the substrate, a stencil with the mesh and emulsion exposed to the desired pattern is connected to the substrate Figure 4. Using a squeegee at a 45° angle, the material is forced into the stencil aperture Figure 5. The printed design stays on the substrate as a wet layer after removing the stencil and squeegee Figure 6. Lastly, the print pattern is dried for 30 minutes at a temperature of 250°C to remove the moisture in the wet ink and some binders, allowing the filler particles to connect each other and establish conductive channels.

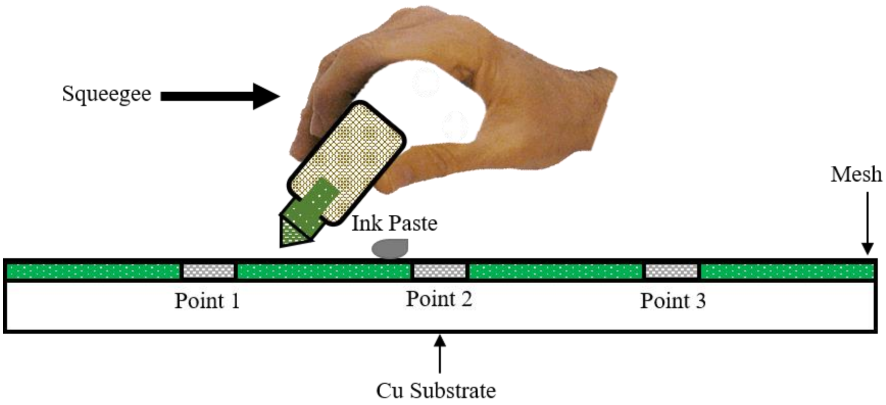

Figure 4. Stencil screen-printing for conductive ink

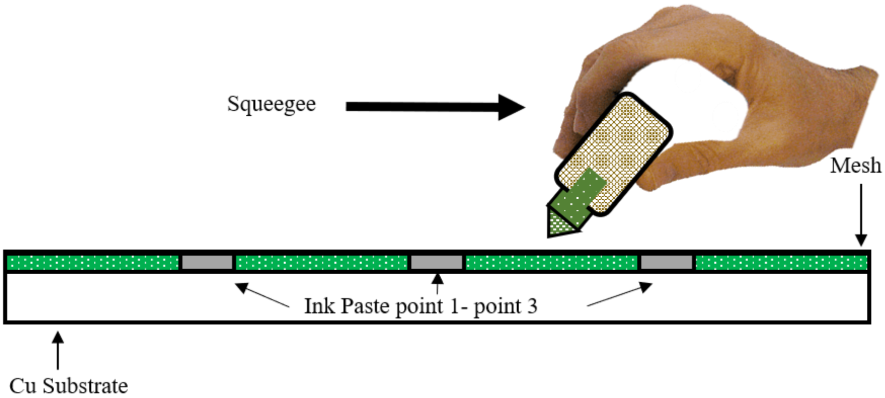

Figure 5. Printed design on the substrate

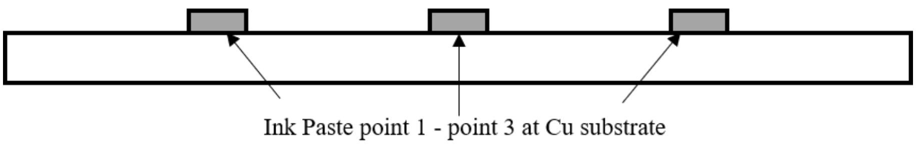

Figure 6. Printed pattern ready for cured process

The reason copper (Cu) used as a substrate is because copper is a highly flexible material that can be easily bent, twisted, and shaped without breaking. Apart from that, copper is an excellent conductor of electricity, and in terms of durability, copper is a highly durable material that can withstand harsh environmental conditions, such as high temperatures and humidity. Copper is relatively inexpensive compared to other conductive materials such as gold and silver. This makes it an attractive option for

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large-scale production of flexible electronic devices. All substrates have been measured in terms of length and width in order to provide reliability during cyclic bending tests. Figure 7 shows the test specimen, which was composed of 110 mm in length with a thickness of 1 mm and three points for the substrate. The same figure also depicts a sample's top view by drawing the top view of the test specimen on a scale of a different magnitude in comparison to the top view with 1 mm of thickness.

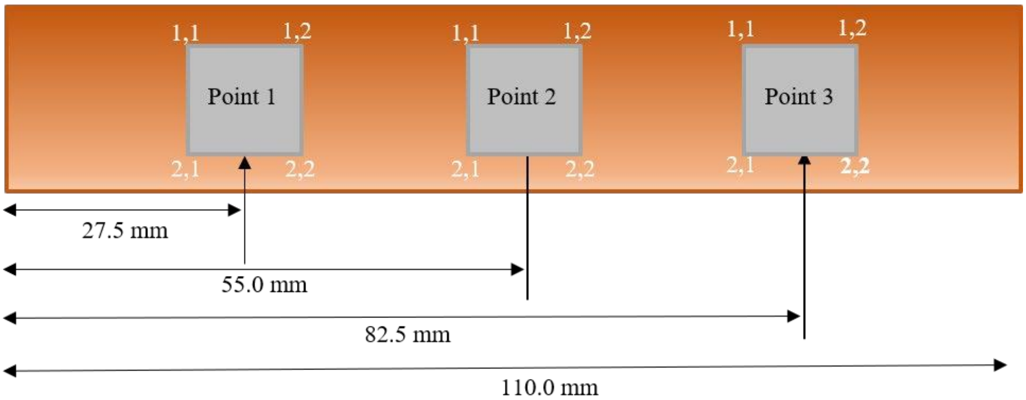

Figure 7. The Specimens

2.3 Measurement and equations

Resistance, R, is an important feature of electrical properties that indicates how much flowing current has been resisted in the circuit trace and influences the conductivity of the circuit. IEEE Std 118-1978 is used to measure it (IEEE Standards Board, 1978). The standard serves as a guideline for selecting the suitable method, which is determined by the degree of precision required and the design of the circuit to be measured. The ohm resistance unit is designed to be the closest functional approximation to the International System resistance unit (SI). SI units are discussed in greater depth in ANSI/IEEE Std. 268-1976, Regular Metric Practice.

The resistance of the sample was measured with a digital multimeter. The equation below was used to calculate the current flow resistance between two planes of the trace's cross-sectional area, and the equation can also be used to calculate volume resistivity (ρ).

$$R = (\rho \times L) / A \quad (1)$$

$$\rho = R \times A / l \quad (2)$$

where A represents the printed line's cross-sectional area and l indicates the length.

Bulk resistivity is a quantity that describes the resistance of a material and is measured in ohm metres (Ω.m). Based on the dimensions of the printed patterns and the observed resistance, the resistivity of the printed traces was determined.

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2.4 Cyclic bending test and practice

Bending test systems were created to subject printed test samples to repetitive cyclic bending. The testing system included custom-built mechanics, fixed and moving clamps, an arm, a wheel, a DC motor, and a proximity sensor. The tester's mechanics were based on a direct current motor that rotated the arms of the apparatus, resulting in a horizontally moving holder. After the other holder was fixed, a flexible test component was fastened between these holders and made to bend, as indicated schematically in Figure 8 to Figure 9 and in practise of the test component in cyclic bending in Figure 10. The mechanics' repeated movement, the fixed size of the test sample (l = 110 mm). For the cyclic bending test, test samples were bent repeatedly, and electrical properties in the unbent state (straight) were measured after every 500 cycles to determine the effect on the degrading behaviour of the test sample. The stepping motor was programmed to run continuously in one direction with a speed of 4 seconds per cycle in this dynamic bending test configuration.

Figure 8. Schematic of the test component in a cyclic bending test rig in a flat position

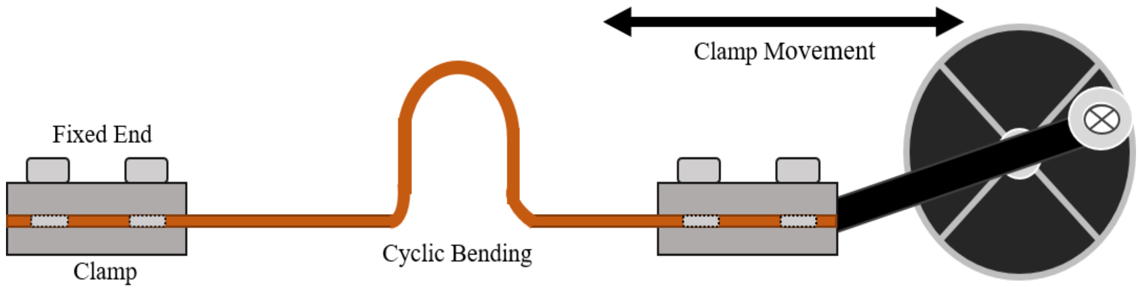

Figure 9. Schematic of the test component in a cyclic bending test rig in a bent position

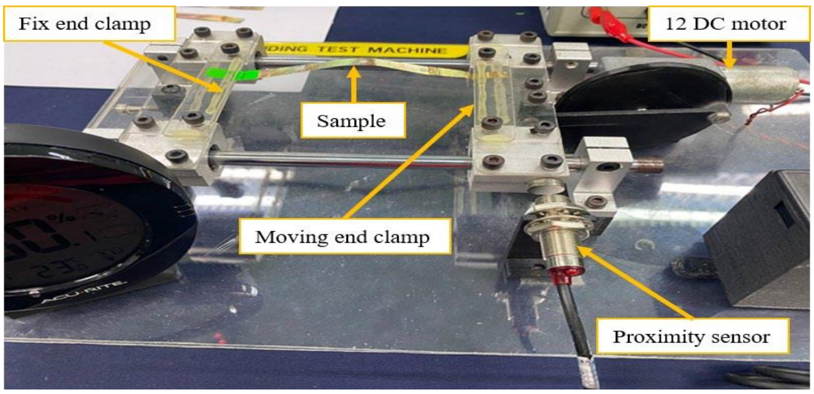

Figure 10. Condition in practical of the test component in cyclic bending test rig with a constant bending radius

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3. Results

3.1 Average resistance and resistivity

Why this experiment is being conducted because the aim is to see the state of the sample can be evaluated for changes in electrical conductivity or other properties. Through this test, we can determine the electrical properties of the conductive ink under cyclic bending, including bending strength, flexibility, and resistance to cracking and penetration. This information can then be used to optimize the formulation and manufacturing process of the ink to improve its performance and reliability for its intended use. Figure 11 shows the average sample resistance and the resistivity for different samples of 5 µm and 25 µm. Figure 11 shows that the 5 µm and 25 µm sample resistances give very close resistance readings. This means that before the bending process is done, the resistance value for both samples are at the current reference value. This is determined because the state of the sample is still in a constant state without interruption from any process (Cataldi et al., 2020). As for the resistance reading, it shows that before the bending process is done, the resistance value for the 5 µm and 25 µm samples is low. Figures 11 shows the significant difference involves a 25 µm sample where the average resistance value is higher than the 5 µm. This result also shows that there is a difference with the statement (L. Wang et al., 2020) which says wearable and flexible electronic devices that can be bent, twisted, and stretched without losing their function are different because there is a difference according to the average particle size at each value of resistance and also resistivity in each sample.

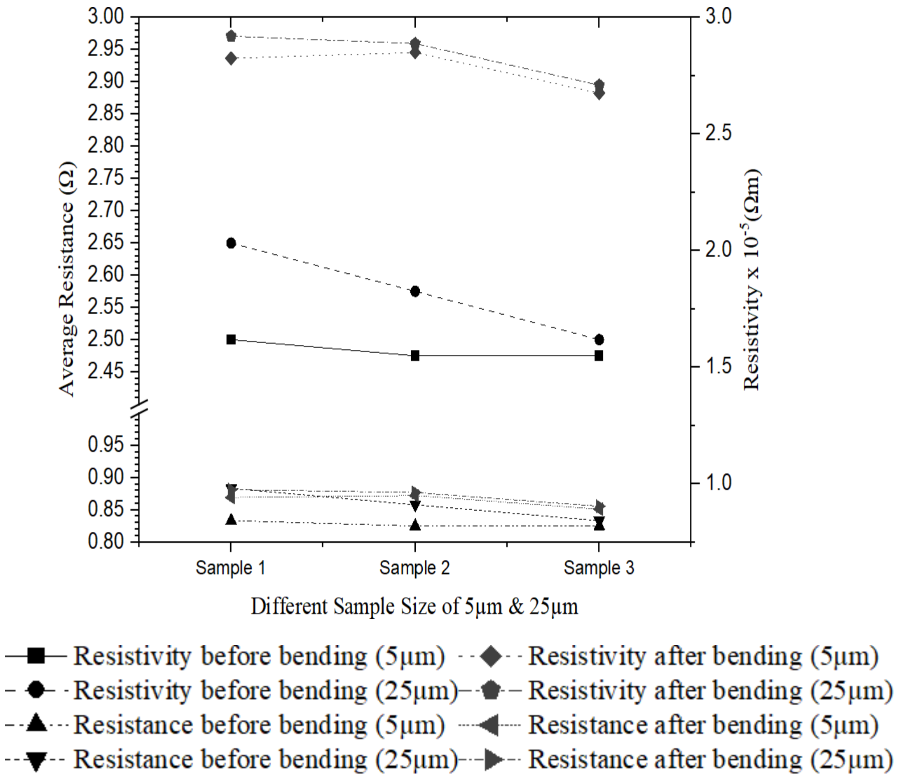

Figure 11. Average resistance and the resistivity

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3.2 Resistivity before and after cyclic bending

How this cyclic bending test before and after can benefit the reliability and performance of conductive ink samples. The reliability and performance of this conductive ink are critical to evaluating durability, maintaining conductivity, and improving adhesion that is sampled to repeated bending, any areas of poor adhesion can also be identified and addressed. By varying the composition of the ink and subjecting it to cyclic bending, the optimal formulation for maximum durability and conductivity can be determined. In Figure 12, for the 5 µm and 25 µm samples after the bending process, the resistivity value increases according to the number of cyclic bending times carried out. Therefore, the performance of this reliability has a significant effect on the experiment conducted. For resistivity, there are clear differences between before and after the bending process of the 500 cycles. These differences also involve the sample value before the bending process of the cycle and involves the sample value before the cyclic bending process. This means there is a significant difference from the literature (He et al., 2019).

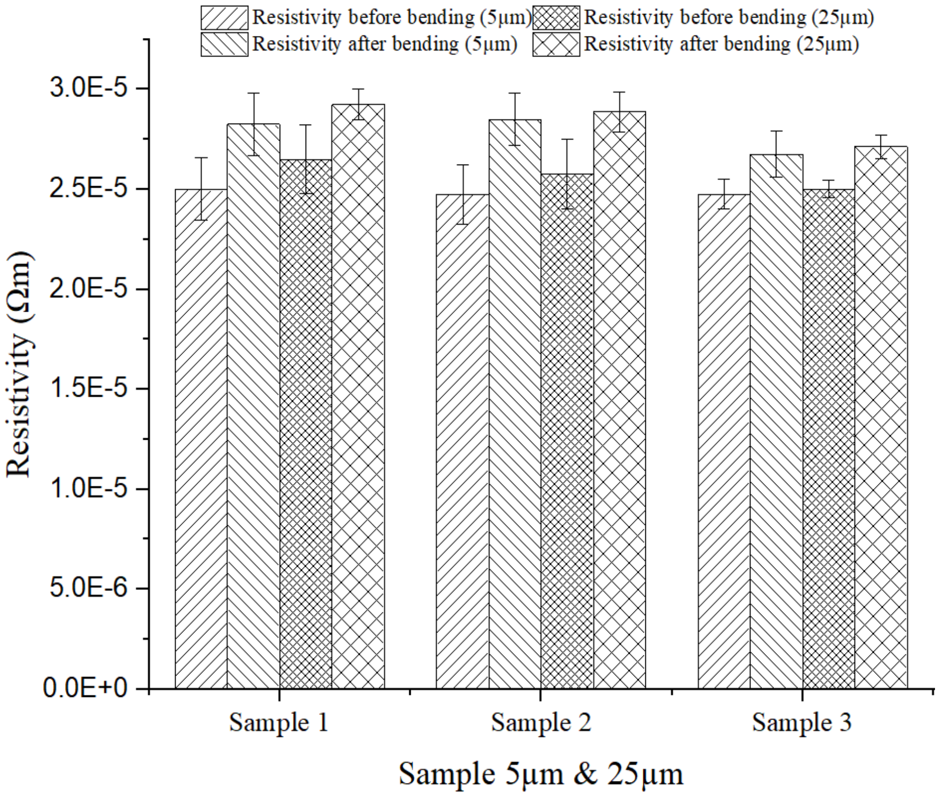

Figure 12. Resistivity before and after bending

As a result of continuous bending, the bent film surface has been subjected to maximum tensile stress, and the film width and microstructure have changed. The distance between the filler particles increased as the film's breadth increased. In this case, the constriction resistivity increases because the contact asperities between particle surfaces have reduced (Ismail et al., 2020) Cyclic bending tests to evaluate the reliability performance of GNP/Ag/SA hybrid conductive inks typically involve repeatedly bending the sample back and forth to simulate the mechanical stress it might experience during normal use, causing a difference in values on this

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sample to occur. In this study, it was also found that the GNP/Ag/SA hybrid conductive ink exhibited good mechanical reliability, with change in resistivity even after 500 bending cycles. Test parameters, such as bending cycles of 500 times, substrate thickness, and sample points when bending is involved can have a significant effect on the results for resistivity.

However, no catastrophic failure occurred during the experiment, such as crack formation, erosion, or other defects (Gonzalez-Julian, 2021; Kubik et al., 2022). This cyclic bending test, on the other hand, is used to evaluate the mechanical properties and durability of the manufactured samples. The number of cycles and the magnitude of stress applied to the sample can have an impact on the sample's performance and material properties. Cyclic bending can cause fatigue failure, microstructural changes, and other material properties effects depending on the test conditions and specific material properties (Jen and Ni, 2022; Tang et al., 2021).

This cyclic bending test process will also result in cracking or cracking which depends on the level of stress applied during the cyclic bending test. The GNP/Ag/SA hybrid has the potential to break or crack. This sample can cause a reduction in mechanical strength and conductivity. Microstructural changes during cyclic bending can also cause changes in the microstructure of GNP/Ag/SA hybrids. For example, repeated bending can cause the GNP/Ag/SA hybrid to become denser, leading to changes in its mechanical and electrical properties. Changes in electrical conductivity for GNP/Ag/SA hybrid samples are known for their high electrical conductivity, but cyclic bending can cause changes in their conductivity. This is due to changes in the alignment and orientation of the graphene layers in the nanoplatelets (Kamal et al., 2020; Luo and Schubert, 2021). According to (Kujala et al., 2020), confirmed the reliability of the print with the correct curing process. A good curing process has been significantly demonstrated in this experiment.

Tables 3 and 4 show the bending test resistivity of the GNP/Ag/SA hybrid. The resistivity percentage change (%) for conductive ink can vary depending on several factors, including ink type, substrate, and printing process. Conductive inks, in general, have a lower resistivity than traditional inks, allowing them to conduct electricity. The resistivity percentage change (%) for conductive ink is typically calculated by measuring the ink's resistivity before and after printing on a substrate. Table 3 and 4 shows that samples 2 have a high resistivity percentage change for both average particle sizes of 5 µm and 25 µm. To calculate the percentage change, divide the difference between the two resistivity values by the original resistivity value and multiply by 100. The resistivity percentage change (%) for conductive ink can range from a few percent to several hundred percent depending on the ink formulation and printing process used. (Saad et al., 2020) was mentioned a printed circuit's resistivity can be affected by factors such as ink thickness, curing temperature, and substrate properties. To achieve the desired resistivity properties for a specific application, the appropriate conductive ink and printing process must be carefully selected. This tends to happen because the sample provides the most critical area during the bending test, which is the tip of the bending notch (Branco et al., 2022; Zeng et al., 2021).

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Table 3. Bending test resistance and resistivity of the GNP/Ag/SA hybrid 5 µm

Sample 5um	Average resistance before bending (Ω)	Average resistivity before bending (Ω.m)	Average resistance after bending (Ω)	Average resistivity after bending (Ω.m)	Standard deviation (Ω.m)	Resistivity percentage change (%)
S1	0.833	2.500E-05	0.942	2.825E-05	1.56E-06	10.38%
S2	0.825	2.475E-05	0.950	2.850E-05	1.30E-06	10.68%
S3	0.825	2.475E-05	0.892	2.675E-05	1.15E-06	3%

Table 4. Bending test resistance and resistivity of the GNP/Ag/SA hybrid 25 µm

Sample 25um	Average resistance before bending (Ω)	Average resistivity before bending (Ω.m)	Average resistance after bending (Ω)	Average resistivity after bending (Ω.m)	Standard deviation (Ω.m)	Resistivity percentage change (%)
S1	0.883	2.650E-05	0.975	2.925E-05	7.50E-07	10.38%
S2	0.858	2.575E-05	0.9625	2.888E-05	9.92E-07	12.14%
S3	0.833	2.500E-05	0.90	2.713E-05	5.73E-07	8.05%

4. Discussion

Experimental results show that GNP/Ag/SA hybridization significantly influences the reliability performance of stretchable conductive ink under cyclic bending conditions. Sample 3 demonstrated the most superior performance with the lowest percentage change in resistivity at 3% for the 5 µm substrate and 8.05% for the 25 µm substrate, suggesting that the composition ratio in this sample creates an optimal balance that enhances mechanical stability. This superiority can be attributed to the synergistic effect between GNP which provides mechanical strength and electrical conductivity, silver particles which enhance overall conductivity, and sodium alginate which functions as a binder that improves adhesion to the substrate while maintaining flexibility. Thinner substrates (5 µm) showed better reliability compared to 25 µm substrates due to more uniform distribution of bending stress, reducing localized strain that could lead to microcrack formation or delamination. These resistivity changes are directly related to microstructural modifications in the conductive ink layer, where increased resistivity is often caused by high dislocation density and dispersion as stated by Sadeghi and Cavaliere (2021), while decreased resistivity is associated with structural restoration that produces new dislocation-free grains according to Kunčická et al. (2022).

These findings have important implications for the development of reliable stretchable electronics. The performance of GNP/Ag/SA hybrid ink, especially with the composition of sample 3, offers promising potential for applications requiring repeated mechanical deformation. For future research, several areas requiring further investigation include long-term reliability assessment, the influence of environmental factors humidity, temperature,

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exploration of additional substrate materials, optimization of printing parameters, and microscopic analysis of failure mechanisms to better understand the relationship between microstructural changes and electrical performance.

5. Conclusion

In conclusion, the results of cyclic bending tests can be used to determine the suitability of GNP/Ag/SA conductive inks for flexible or stretchable electronic devices. The primary goal of this study is to investigate the effect of cyclic bending on the reliability performance of GNP/Ag/SA hybridised stretchable conductive ink. When an impact is subjected to continuous cyclic bending, electrical resistance is thought to increase. The results show that the particle size of the 5 µm and 25 µm samples differs significantly before and after the cyclic bending test, with different values before and after. Resistance and resistivity increase with cyclic bending test time. When samples begin to fatigue, the microstructure between the filler and binder weakens, resulting in an increase in the gap or distance between the filler particles. This situation increases the tunnelling distance, making electron hopping to another filler particle much more difficult and increasing the resistance and resistivity within the ink samples. The cyclic bending behaviour of these inks is critical for their applications in flexible electronics. Several mechanisms or factors, such as aspect ratio, dispersion quality, and substrate properties, can influence the electrical properties of the GNP/Ag/SA conductive ink during cyclic bending. The aspect ratio of GNP/Ag/SA refers to the length-to-width ratio of the nanoplatelets. It is highly significant when assessing the electrical properties of GNP/Ag/SA conductive inks. High-aspect-ratio GNPs are more likely to form conductive networks in ink. These networks can withstand bending without affecting their electrical conductivity significantly. GNPs with lower aspect ratios, on the other hand, tend to agglomerate, resulting in decreased electrical conductivity during bending. Another important factor that can affect the electrical properties of GNP/Ag/SA conductive inks during cyclic bending is the dispersion quality of GNPs in the ink. A well-dispersed ink contains GNPs that are evenly distributed throughout the ink matrix, resulting in the formation of a highly conductive network. Poorly dispersed inks, on the other hand, contain agglomerates of GNPs that can break apart during bending, resulting in a decrease in conductivity. Flexible substrates can help to reduce strain on the ink during bending, resulting in better ink electrical conductivity retention.

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Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this manuscript, the author(s) used OpenAI's ChatGPT to assist in improving the readability and language of the text. All content generated by ChatGPT was subject to thorough review, editing, and revision by the authors to ensure its accuracy, completeness and alignment with the research objectives. The author(s) take full responsibility for the integrity and content of the published work. This declaration complies with ICGESD 2025 guidelines on the use of generative AI in scientific writing.

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