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ELECTRICAL PROPERTY CHANGES OF GNP HYBRID CONDUCTIVE INKS UNDER TORSIONAL LOADING ON FLEXIBLE COPPER SUBSTRATES

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ABSTRACT

This study investigated the effect of torsion cycles on the electrical properties of conductive materials at two different displacement levels (5 µm and 25 µm) to understand the changes in the material microstructure. The samples were studied using a controlled torsion method for 500 cycles, measuring resistance and resistivity, and the results were obtained before and after the test using the two-point probe technique. The results showed a significant increase in both parameters: at 5 µm, the average resistance increased by 7.6% (0.844 Ω to 0.908 Ω) with the resistivity increasing from 2.533×10^{-5} Ω·m to 2.725×10^{-5} Ω·m, while at 25 µm, the resistance increased from 0.867 Ω to 0.997 Ω and the resistivity increased from 2.600×10^{-5} Ω·m to 2.992×10^{-5} Ω·m (corresponding to a 15.4% increase). The statistical analysis performed showed an increase in the standard deviation after torsion, indicating variation in response between samples due to the non-uniformity of the microstructure. These findings demonstrate that torsional deformation not only significantly alters the electrical properties of materials, but also exhibits a magnitude-dependent effect, with larger effects observed at higher displacement levels. The implications of the study suggest the need for special consideration in applications of conductive materials that are subjected to torsional stress, especially in environments with cyclic loading. The data obtained provide a solid basis for modeling material durability in electromechanical engineering design and for future use in studies on flexible electronics.

1. Introduction

Flexible screen printing is an effective method for producing large-scale printed electronics. To support its continued advancement, long-term and continuous modifications are necessary to maintain performance. One area of interest is the mechanical performance of Graphene Nano Platelet (GNP) hybrids in stretchable conductive inks. The development of flexible and stretchable electronics has enabled new applications across various fields, including wearable devices, soft robotics, and biological sensors (Li et al., 2019). Stretchable conductive inks particularly those based on hybrid conductive substrates have become a key focus for enhancing the performance and durability of electronic components (Huang et al., 2019).

The mechanical and torsional loading of stretchable conductive ink are critical to its performance in flexible and wearable electrical devices (Nie et al., 2022). Stretchable conductive inks must maintain electrical conductivity under various conditions, including severe deformation, without breaking or delaminating from the flexible copper substrate. To address this challenge, hybrid ink systems incorporating multiple components can be employed to enhance the mechanical properties of stretchable conductive inks (Gao et al., 2023).

Stretchable conductive inks have the potential to serve a wide range of applications and are highly sought after in fields such as automotive, healthcare, sports equipment, and flexible electronics. The ability of these inks to maintain electrical conductivity and structural integrity under mechanical stress, such as torsion, is crucial to ensuring the long-term performance of the device (Ziaei et al., 2023). In real-world applications, flexible devices often undergo repeated stretching, bending, and twisting, which can lead to mechanical failures such as cracking or delamination from the substrate. Therefore, the development of hybrid conductive ink systems incorporating fillers such as Graphene Nanoplatelets plays a key role in enhancing the mechanical performance of conductive inks, particularly under torsional loading conditions.

This study focuses on the mechanical performance of GNP-based hybrid conductive inks under torsional loading when printed on flexible copper substrates. By evaluating the mechanical behavior and structural stability of the ink under torsional conditions, this research aims to support the development of more durable conductive inks suitable for a wide range of future flexible electronic applications.

2. Methodology

GNP hybrids produce unique material mixtures with improved chemical and physical properties. For example, it is highly desirable to create GNP hybrid formulations with specific characteristics for specific purposes, such as enhancing the resin system of a particular product. The performance of the composite is enhanced by adding GNP hybrids to the sample (Aliyeva et al., 2023).

The preparation of GNP hybrids involves preparing a sample with specific formulation parameters including the mixture ratio of ingredients, temperature, and time allocated for each process. Subsequently, the sample undergoes a printing process on a flexible copper substrate. Mechanical tests were conducted according to standard protocols to measure specific properties such as torsion, tensile strength, flexural modulus, and others.

2.1 Sample Formulation Process

Following the creation of the GNP hybrid, the conductive ink paste is applied to the copper substrate using the mesh stencil process. During the printing process, a scraper is used to guarantee that a significant amount of the merged patch is on the specified grid. After the paste is visible on the substrate, the sample is cured in an oven set to 300°C for 60 minutes. Table 1 shows the formulation used for the GNP hybrid.

Table 1 Formulation of GNP Hybrid

No	Item	Amount
1	Graphene Nanoplatelet (GNP)	4.56g
2	Ethanol	50ml
3	Silver Flakes	4.292g
4	Silver Acetate	0.42g
5	Butanol	26 drops
6	Terpineol	26 drops

2.2 GNP Hybrid Printing Process

In order to achieve the best screen printing and dense layer on the substrate, various techniques can be used. Two of the more effective methods are rotary screen printing and flat screen printing (Tepper et al., 2020). The substrate used in this screen-printing process is flexible copper. It is a suitable choice due to its easy nature to bend, twist, and shape as it is a torsional flexible material. This substrate can also conduct electricity well. According to Yu et al. (2023), the main requirement for a flexible stretchable conductor is to offer a highly conductive path with excellent resistance to deformation, bending, and torsion. The length and width of the substrate are measured to ensure reliability during torsion testing. This substrate can be seen before and after printing in Figure 1.

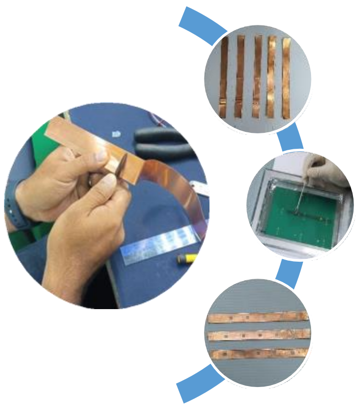

Figure 1. Flexible copper substrate before and after printing process

2.3 GNP Hybrid Torsion Test

A substrate or sample was subjected to a twisting or rotating force as part of a mechanical test called a torsion test to see how it responded to torsional stress. In this test, a GNP hybrid substrate which was a stretchable conductive ink, applied under a controlled twisting force and its mechanical and electrical properties were evaluated. A special experimental apparatus with a torsion method was required to test the resistivity of GNP hybrid materials under such torsional stress. Sample preparation, torsion test setup, electrical contact, resistance measurement, and resistivity measurement comprised the standard procedure for evaluating the resistivity of GNP hybrid materials during torsion testing.

As a result, one part of evaluating electrical performance under mechanical stress is the measurement of resistance, namely during torsion testing. The evaluation of mechanical stress depends on the various tests performed (Azlan et al., 2022). This evaluation considered both mechanical and electrical characterization methodologies to provide a comprehensive torsional reliability assessment of the GNP hybrid materials. Figure 2 shows the torsion testing process performed on each sample and Figure 3 shows the schematic of the test component in cyclic torsion test.

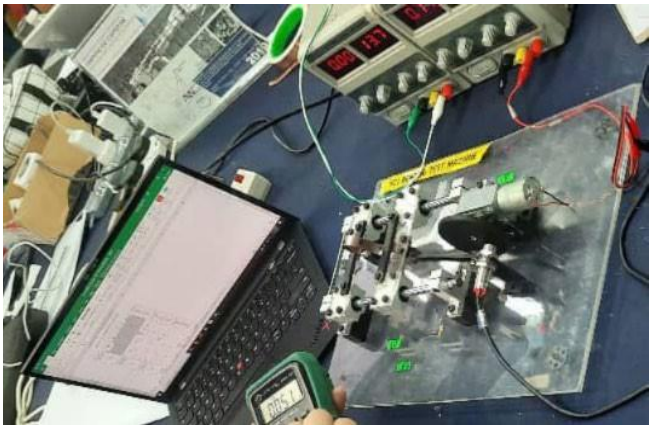

Figure 2. Torsion test process

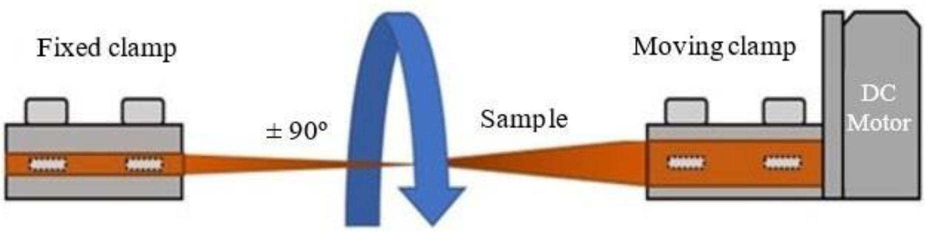

Figure 3. Schematic of the test component in a cyclic torsion test rig

3. Results

The experimental data demonstrates a consistent increase in both resistance and resistivity values across all samples following 500 cycles of torsion testing. This phenomenon indicates that the materials underwent structural modifications or degradation as a direct consequence of the repeated mechanical stress. The resistivity measurements reveal a notable pattern where both 5µm and 25µm samples exhibit elevated resistivity after undergoing torsion testing, with the 25µm samples consistently showing higher resistivity values both prior to and subsequent to testing.

After 500 test cycles, it is clear that the resistance and resistivity of each sample increased. This indicates that the torsion tests caused some deformation or degradation in the samples. After 500 cycles, the resistivity level consistently increased for all samples. This pattern suggests that the mechanical load applied during torsion changed the electrical characteristics of the material. In addition, the standard deviation of the average resistivity increased, indicating a degree of irregularity in the resistivity readings. The repeated torsion is the cause of these effects on the material characteristics.

3.1 Resistivity and Resistance Changes Caused by Torsion

The effect of torsion on the electrical properties of the samples was investigated by comparing the resistivity and resistance before and after 500 torsion cycles at different displacement values of 5 µm and 25 µm. It was shown that the resistivity and resistance generally increased after 500 torsion cycles. The average resistance increased from an initial value of 0.844 Ω to a post-torsion value of 0.908 Ω. As a result, the average resistivity increased from 2.533×10^{-5} Ω·m to 2.725×10^{-5} Ω·m. This torsion caused variations in the resistivity and resistance of the material, which changed its electrical and physical properties. Furthermore, the standard deviations of the resistivity and resistance showed a largely consistent pattern across all samples. When the torsional displacement is increased to 25 µm, the resistance and resistivity changes show the same pattern. The analysis shows that the average resistance increases from 0.867 Ω to 0.997 Ω. In parallel, the average resistivity also increases from 2.600×10^{-5} Ω·m to 2.992×10^{-5} Ω·m, which is consistent with the observed microstructural changes. The standard deviation further confirms the changes observed in the 5 µm displacement scenario.

The widening of standard deviation ranges in measurements taken after torsion suggests emerging heterogeneity in the electrical properties throughout the material structure. This variability likely stems from non-uniform structural alterations induced by the cyclic torsional forces. As illustrated in Figures 4 and 5, the comparative analysis between initial state and torsion-affected state clearly visualizes these electrical property transformations, with the 25µm samples displaying more pronounced changes than their 5µm counterparts, indicating a possible correlation between sample thickness and susceptibility to torsion-induced modifications.

The observed increase in resistance and resistivity following torsion cycles clearly demonstrates how mechanical deformation of sample shape affects the material's electrical characteristics. This behavior stems from subtle structural modifications induced by torsional stress. Various factors including material composition, microstructure, and mechanical properties can influence how torsion impacts electrical properties. Resistance and resistivity changes exhibit relatively consistent patterns across both 5 µm and 25 µm displacement levels. This consistency indicates that the magnitude of applied torsion does not substantially alter the resulting changes in electrical characteristics. These findings have implications for materials with electrical components sensitive to torsional deformation, suggesting their properties change in response to mechanical stress regardless of the deformation degree.

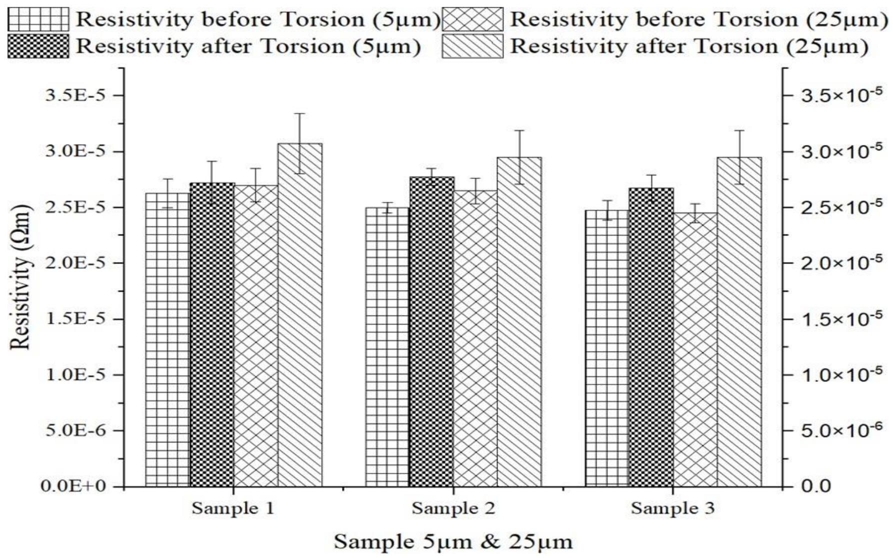

Figure 4. Resistivity before and after torsion test

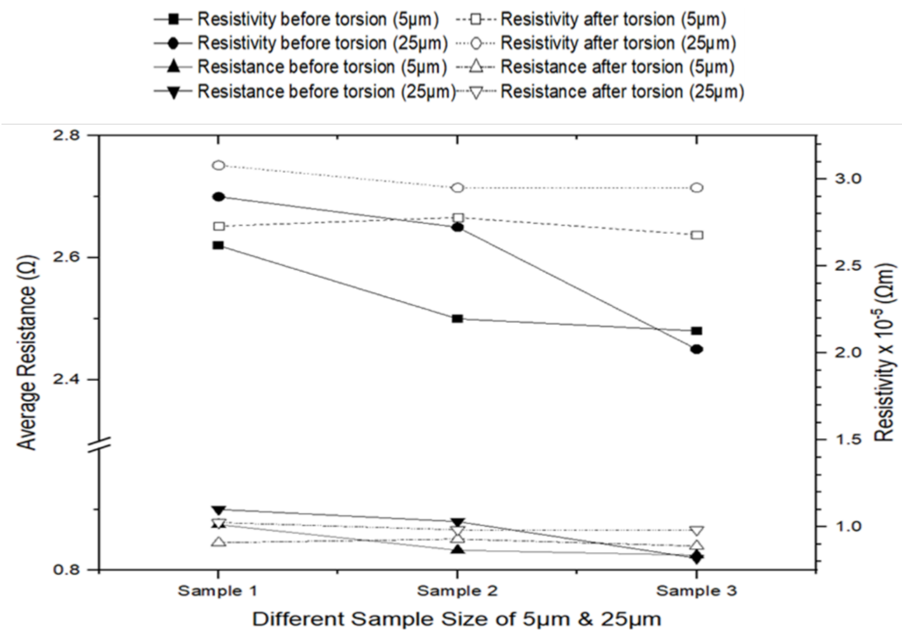

Figure 5 Average resistance and resistivity during the torsion test

3.2 Torsion at 5 µm and 25 µm Displacement

Exposing the sample to 500 cycles of torsion at 5 µm causes a significant increase in average resistance, from an initial value of 0.844 Ω to 0.908 Ω. Accordingly, the average resistivity increases from 2.533×10^{-5} Ω·m to 2.725×10^{-5} Ω·m after torsion. This represents an approximate 7.6% increase in resistivity, indicating a subtle change in electrical characteristics as a result of torsion. Additionally, the standard deviation for both resistance and resistivity increase with torsion, which indicates that each sample is reacting differently.

In contrast to the measurements at 5 µm, the average resistance increases after 500 torsion cycles at 25 µm. Before torsion, the average resistance is 0.867 Ω, and it increases to 0.997 Ω throughout the torsion process. For resistivity as well, similar trends are noted. Prior to torsion, the average resistivity was 2.600×10^{-5} Ω·m, and it increased to 2.992×10^{-5} Ω·m after torsion. It should be noted that the increase in average resistivity is 15.4% at 500 cycles of torsion, indicating a more significant change in the electrical properties compared to the 5 µm condition. Additionally, similar to the 5 µm condition, the standard deviation for both resistance and resistivity increases after torsion, reflecting differences in response across individual samples.

3.3 Analysis and Consequences

The observed increase in resistance and resistivity after these torsion cycles clearly illustrates how the electrical properties of a material are affected by the mechanically altered shape or condition of the sample. Torsional stress causes small structural changes that lead to this behavior. Many elements, including material composition, microstructure, and mechanical properties, can affect how torsion influences these electrical properties. Across different displacement levels of 5 µm and 25 µm, the resistivity and resistance changes show a fairly uniform trend. This indicates that the change in electrical properties is influenced by the torsion performed, regardless of the degree of distortion and the behavior of materials whose electrical components are subjected to torsional deformation.

4. Discussion

4.1 Overview of Key Findings

This study demonstrates consistent increases in the resistance and resistivity of GNP hybrid inks after applied torsional loading, especially at 25 µm displacement. These results highlight the electrical behavior and its strain-dependent changes that are critical for flexible electronics. Torsion tests conducted on conductive ink samples before and after loading provide valuable insights into the reliability and performance of these samples in real-world applications. Torsion tests involve subjecting materials to alternating semi-rotational forces, which simulate the mechanical stresses that the material may experience during it intended use.

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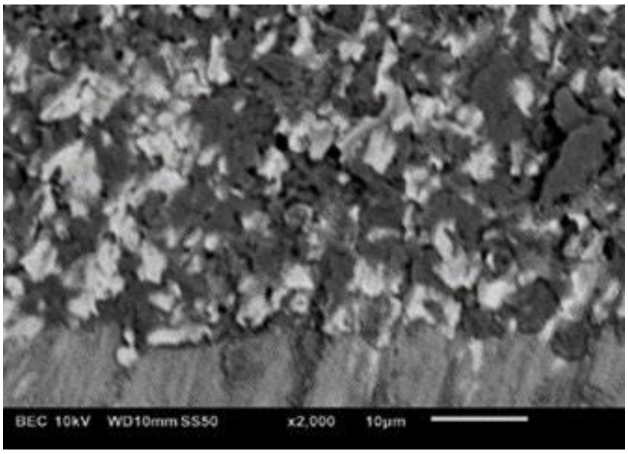

Figure 6. The SEM images interfacial slippage and orientation

The increase in resistance is shown to be a result of torsional stress disrupting the percolation pathway or inversion of GNP orientation and interfacial slippage. Figure 6 shows the SEM image the interfacial slippage. Despite the microstructural changes, the sample still maintains its basic conductivity and proves its durability. The strain amplification effect occurs at a more pronounced change at 25 µm indicating the accumulation of nonlinearities, where large displacements exceed the elastic recovery limit of the conductive network. This is consistent with real-world scenarios such as repetitive motion in wearable devices.

4.2 Mechanical Strength Evaluation

Torsion testing allows for the evaluation of mechanical strength, durability, and flexibility of the GNP hybrid conductive ink. The results show that the study samples:

i. Still maintain good electrical conductivity after torsion loading.
ii. Show good structural integrity even with increasing applied resistance.
iii. Are suitable for dynamic applications such as wearable electronics, biomedical sensors, and other printed electronics. This proves that the samples and materials used are able to withstand mechanical stress without critical degradation.

4.3 Comparison with Previous Studies

This trend aligns with the study on the reliability of GNP/Ag/SA composites based on polymer composites by Ismail et al. (2024). In this GNP Hybrid ink, higher strain sensitivity is demonstrated due to the geometry of the platelets. Unlike the carbon or filler composites used by Wahid et al. (2022), this composite ink does not show a relatively slow recovery of conductivity or change after torsion. This indicates a permanent change in the filler network in the sample.

The GNP hybrid conductive ink consists of proportioned materials dispersed in a polymer matrix, which provides enhanced conductivity and better electrical network formation. This conductive ink formulation shows promising potential for flexible electronic applications including strain sensors for human movement detection, printed circuit boards on formable substrates, and monitoring devices requiring mechanical durability. The GNP hybrid ink maintains its initial conductivity after 500 torsion cycles at twist angles of 0-90°, with minimal resistance changes under constant mechanical stress, outperforming conventional carbon-based inks. These finding complements research by Zhang et al. (2023) that demonstrated similar stability in graphene-based inks and electromechanical performance in flexible electronics.

4.4 Limitations and Future Directions

In principle, several limitations should be acknowledged in the present study. The test was limited to 500 torsional cycles, while real-world applications may require a number of cycles exceeding this limit. In addition, environmental factors such as temperature and humidity variations may intensity the observed effects. Future research should focus on:

i. Improving strain tolerance through targeted material modification, especially at the particle-matrix interface.
ii. Developing protective techniques that maintain electrical performance under mechanical stress.
iii. Exploring hybrid formulations with various ratios of conductive components to optimize the balance between mechanical durability and electrical performance.
iv. Investigating the combined effects of various mechanical and torsional stresses to better simulate real-world conditions.
v. Improving the substrate adhesion mechanism to minimize penetration under repeated torsional loading.

5. Conclusion

In conclusion the GNP hybrid substrate, when used as a flexible conductive ink, exhibits predictable changes in electrical properties after undergoing torsional loading. Its strong, effective, and flexible conductive structure allows it to withstand torsional stress without significant loss of conductivity, even after multiple cycles of mechanical deformation. This resilience emerges from the synergistic interaction when these materials are combined at the nanoscale level. The experimental results demonstrate that while resistance and resistivity increase under torsional strain, the changes remain within acceptable parameters for functional applications.

This result has significant implications for the development of wearable electronics, flexible displays, and biomedical sensors where mechanical flexibility is paramount. The construction of robust and flexible electronic devices with diverse applications, enabled by these properties, provides not only insightful information on the changes in electrical properties and torsional reliability performance but also establishes design guidelines to optimize the balance between mechanical durability and electrical performance in next-generation flexible electronics. Future work could focus on improving the durability of substrates after torsion testing so that changes in electrical properties and strain tolerance through targeted material modification can provide added value to materials used in the future.

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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 author(s) 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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