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THE EFFECT OF SOLVENT RATIO ON THE ELECTRICAL CONDUCTIVITY OF HYBRID GNP/AG CONDUCTIVE INKS UNDER CYCLIC TORSIONAL STRESS

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ABSTRACT

Hybrid conductive inks composed of graphene nanoplatelets (GNP) and silver (Ag) nanoparticles are gaining significant attention for their enhanced electrical conductivity and mechanical properties, particularly in flexible electronics and wearable devices. The solvent ratio is decisive in determining the quality of the ink as it affects nanoparticle dispersion and stability. These factors, in turn, affect the ink's conductivity and overall performance. This study investigates the impact of solvent composition on the electrical performance of GNP/Ag hybrid conductive inks under cyclic torsional stress, specifically comparing the 10T:10B ratio to the 3T:3B ratio of terpinol to butanol. The curing process, a crucial step in ink preparation, was conducted at 250°C for one hour. Following this, electrical resistance and resistivity were measured using a Two-Point probe to assess the ink's performance. After 4000 cycles, the cyclic torsional test results showed that the 10T:10B formulation had significantly lower resistance (0.18 Ω) and resistivity (10.8×10^{-6} Ω.m) compared to the 3T:3B formulation (0.81 Ω and 0.48×10^{-6} Ω.m), indicating superior electrical performance. Prominently, the resistance of the 10T:10B sample was 77.8% lower, indicating more efficient conductivity and a stable and durable conductive network. These findings emphasise the importance of solvent composition and the curing process in optimising the performance and stability of conductive inks for high-stress applications

1. Introduction

Hybrid conductive inks incorporating graphene nanoplatelets (GNP) and silver (Ag) nanoparticles are essential for developing flexible electronics. These include wearable devices and sensors, where maintaining stable electrical properties under mechanical stress is essential.

In such applications, it is important for the inks to withstand deformation while retaining their conductivity. The stability of the conductive network, which is influenced by solvent composition and curing conditions, plays a key role in ensuring the long-term performance of these inks in flexible electronics.

While solvent composition has been widely acknowledged as a significant factor in determining the electrical properties of conductive inks, the specific impact of cyclic mechanical stress on the stability of the conductive network, under torsional forces, has been less explored. Previous research has shown that while solvent ratios can improve the ink's electrical properties, the impact of cyclic mechanical stress remains less understood. For instance, Bakar et al., (2024) demonstrated that a 40:60 ratio of 1-butanol to terpinol resulted in the lowest bulk resistance (0.600 Ω) and resistivity (3.6 x 10-4 Ω.m), suggesting that solvent ratio optimisation can significantly enhance conductivity. However, their study focused on cyclic bending tests, and the effect of cyclic torsional stress was not investigated.

Ismail et al., (2024) examined the impact of the 3T:3B solvent ratio under cyclic torsional testing, finding that resistivity increased by 23.9% after 1000 cycles, 0.12% after 3000 cycles, and 46.0% after 5000 cycles. This demonstrated the significant effect of mechanical stress on ink stability. However, the study tested different cycle counts and did not explore the impact of solvent composition variations, such as 10T:10B, on the stability of the conductive network. Following Ismail et al.'s findings, Jori et al., (2024) used the same solvent ratios, 3T:3B, and added 10T:10B for an additional sample. However, the study did not employ cyclic torsional testing, leaving the effects of mechanical stress on ink stability unexamined. Meanwhile, Noor et al. (2024) investigated the impact of curing conditions and cyclic torsional testing on ink performance at multiple temperatures. This approach limits direct comparison to the specific conditions used in this study.

Previous studies have explored individual factors, such as solvent composition, cyclic stress, and curing conditions, on conductive inks; however, this study uniquely addresses their combined effects on GNP/Ag hybrid inks under cyclic torsional stress. This study aims to fill this gap by evaluating the effects of solvent composition, specifically the 3T:3B and 10T:10B ratios, on the resistance and resistivity of hybrid GNP/Ag conductive inks after 1000, 2000, and 4000 cycles of torsional stress. By integrating these factors, this research will enhance understanding of the stability and performance of conductive inks under continuous mechanical stress conditions.

2. Materials and Methods

2.1 Formulation and Preparation of Hybrid Conductive Ink with Terpinol Ratios

The preparation procedure commenced with the synthesis of a hybrid formulation consisting of Graphene Nanoplatelets (GNP), Silver (Ag), and Silver Acetate (SA) to produce conductive ink. The primary materials utilised in this study comprised 25 µm GNP fillers, with Ag acting as a secondary filler for hybridisation. Organic solvents, such as 1-butanol and terpinol, were employed in the paste formulation, while ethanol was utilised to facilitate the synthesis of the

powdered GNP hybrid. Initially, precise quantities of GNP were mixed with ethanol and subjected to sonication in an ultrasonic bath to ensure uniform dispersion.
The GNP/Ag hybrid formulation adhered to the methodology outlined by Deng et al. (Deng et al., 2021) wherein 0.5g of 25 µm GNP powder was dissolved in 50 ml of ethanol and sonicated for 10 minutes. To this solution, 0.429g of silver flakes (SF) was introduced, along with 0.042g of silver acetate (SA) and the mixture underwent an additional 60 minutes of sonication.

Ethanol, chosen for its solvent properties, aids in reducing viscosity and enhancing the dispersion of particles, which is essential for the ink's printing quality (Yang & Wang, 2016)

Following sonication, the GNP/Ag mixture was stirred at 70°C with a rotational speed of 200 rpm, facilitating the evaporation of the ethanol solvent. Given ethanol's high volatility and relatively low boiling point of 78.37°C, it evaporates easily during heating or stirring processes, especially at temperatures near its boiling point. As a result, the ethanol solvent was effectively removed during the stirring process. The resulting dry solution was then subjected to curing in an oven at 250°C for one hour, after which it was ground into a fine powder to form the GNP hybrid paste. The hybrid powder was subsequently weighed to determine the required terpinol to butanol ratios.

A baseline formulation was prepared using 0.52g of GNP powder, to which three drops of both terpinol and butanol were added. The mixture was then processed in a planetary centrifugal mixer, Thinky Mixer model AR100, set at 2,000 rpm for ten minutes. This specific mixing speed and duration were selected based on their ability to ensure thorough dispersion and homogenisation of the particles. The 2,000 rpm facilitates sufficient shear forces, which effectively break apart any agglomerated particles and promote uniform mixing, ensuring that the GNP and solvents are adequately integrated. The ten-minute duration allows enough time for proper particle dispersion and solvent incorporation without causing excessive heat build-up, which could affect the ink's properties (Wu et al., 2022).

Table 1. Terpinol to Butanol mixing ratio

	Powder			Organic Solvents		
Sample	Graphene	Silver Flakes (g)	Silver Acetates (g)	Ethanol (ml)	Terpinol (drop)	Butanol (drop)
3T:3B	0.5	4.292	0.42	50	3	3
10T:10B	0.5	4.292	0.42	50	10	10

After preparing the GNP/Ag paste, it was stored in a sealed container. Sealing the paste prevents solvent evaporation and preserves formulation homogeneity. It also ensures that the paste remains uncontaminated by environmental factors such as moisture or air, which could alter its viscosity and performance characteristics. Maintaining the paste's stability until further use is crucial. Following the storage of the initial paste, additional pastes were prepared with modified solvent ratios. Specifically, ten drops of both terpinol and butanol were incorporated into the mixture to explore the effects of varying solvent compositions. These pastes were prepared similarly. Table 1 details the composition of the hybrid GNP/Ag conductive ink formulation in the terpinol to butanol ratio.

2.2 Copper Substrate Preparation

The substrate for this hybrid GNP/Ag conductive ink was copper (Cu). Cu was selected for its high thermal conductivity, density, and specific heat capacity, making it ideal for the cyclic torsional tests (Lukacs et al., 2017). The Cu strips were cut to dimensions of 120 mm in length, 7 mm in width, and 0.1 mm in thickness, ensuring a proper fit within the cyclic torsion rig's holders while minimising material wastage.

The GNP/Ag ink was applied to the substrate using a mesh stencil technique. Pressure was applied to the squeegee to ensure the paste spread evenly inside the mould. The squeegee, equipped with a flat, smooth rubber blade, was then used to carefully draw the paste across the stencil mesh, leaving a uniform layer on the Cu substrate. The substrate measuring 3.0 mm in length, 3.0 mm in width, and 60 µm in thickness, ensuring a uniform layer. Consistency in ink thickness is critical to ensuring uniform electrical properties across the substrate. Variations in ink thickness could lead to inconsistent resistance and resistivity measurements, which would affect the reliability of the experimental results. Maintaining consistent ink thickness ensures that any observed changes in resistance and resistivity are from the outcome of the cyclic torsional test itself, rather than variations in the material properties. Furthermore, it is essential for reproducibility, allowing results to be reliably compared across multiple samples and test cycles.

A spacing of 20 mm was maintained between the centres of each conductive ink test point to optimise the copper strip's surface area, allowing accurate resistance measurements and preventing interference between the test points. This strategic positioning of the conductive ink test points enabled effective monitoring of changes in electrical properties arising from the cyclic stress applied during the test. Figure 1 below illustrates the dimension of the hybrid GNP/Ag conductive ink paste, printed on a Cu substrate.

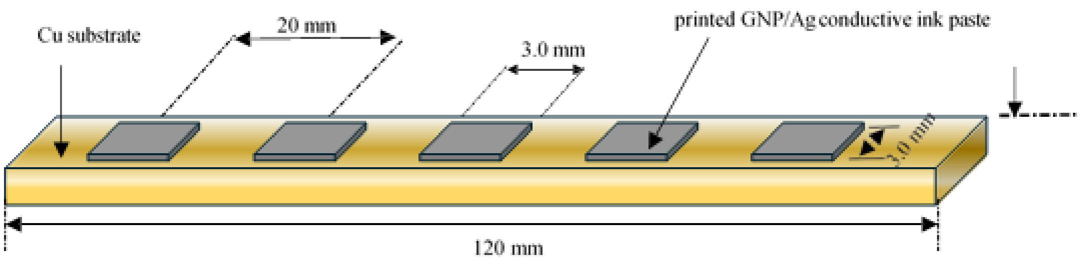

Figure 1. GNP/Ag conductive ink paste on a copper substrate strip

2.3 Cyclic Torsional Test

After preparing the substrates, the printed hybrid GNP/Ag conductive ink substrates were subjected to cyclic torsional testing in accordance with ASTM D7774-17 standards. The substrates were subjected to a ±90° twisting angle, as referenced from Ismail et al. (2024), to simulate mechanical stress. The cyclic rotation was performed for 1000, 2000, and 4000 cycles to evaluate the ink's electrical properties under repeated mechanical stress. Resistance measurements were taken using a Two-Point probe at baseline and after each set of cycles, following the guidelines of IEEE Standard 118-1978 to ensure measurement accuracy.

The conductive ink substrate strip was securely fixed to the test rig, with two grippers controlling its twisting motion. One gripper remained stationary, while the other was responsible for the repeated rotations. This setup allowed the strip to undergo twisting deformations, alternating between clockwise and counterclockwise directions throughout the test. The left end of the strip was attached to the fixed holder, while the right end was secured to the rotating gripper.

2.4 Resistivity Test

Five test points were measured to ensure comprehensive and consistent data collection. For each test point, four separate resistance readings, as in Figure 2, were recorded across the printed test point to ensure accuracy.

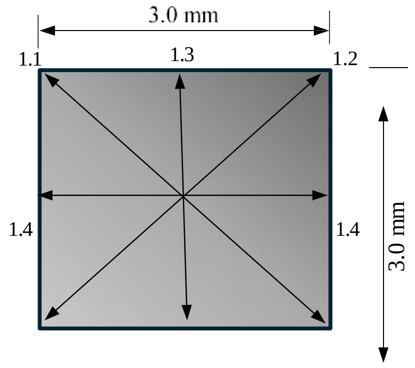

Figure 2. Four points of printed GNP/Ag hybrid on Cu substrates with observation positions for resistance measurement data collection using a Two-Point probe multimeter

These readings were then averaged to represent the resistance for that test point. The same method was applied to the other four test points. Their resistance values were averaged to obtain the total average resistance of the strip. This resistance is referred to as the bulk resistance of the strip. Bulk resistance refers to the resistance to the flow of electric current within the material itself, rather than just its surface. It is a key characteristic in understanding electrical conduction and is affected by factors such as the material's composition, temperature, and structural properties (de Oliveira et al., 2024). Resistance was directly measured using the Two-Point probe, meanwhile, resistivity measured in ohmmeters (Ω.m), was calculated using Ohm's Law formula. Equation 1 for resistivity was as follows.

$$Resistivity,\ \rho = \frac{R}{L} \times A \quad (1)$$

where R is the resistance, L is the length of the current path, A is the area of the conductive path, printed on the Cu substrate. The given formula to calculate the area of the test cross-section was as shown in Equation 2 below.

$$Cross\ Section\ Area,\ A = \omega \times L \quad (2)$$

where multiply the length, L of the conductive strip or patch by the applied ink's uniform thickness, ω. For these experiments, the thickness of the ink utilised was 60 microns.The averaged resistance values from each test point were then used to provide an accurate representation of the material's electrical behaviour. Cracks formed at the edges of the conductive ink as a result of the mechanical stress were noted, corroborating the findings of Bilisik & Akter, (2022) and Fu et al., (2022). This method enabled the detection of changes in the ink's resistance, providing valuable inss into its long-term durability under cyclic torsional stress and revealing the material failure mechanisms resulting from continuous mechanical stress.

3. Results

This study investigates the effects of two different terpinol (T) to butanol (B) solvent ratios on the electrical and thermal conductivity of hybrid graphene nanoplatelets (GNP) and silver (Ag) conductive inks after undergoing a cyclic torsional test. The resistance and resistivity data collected at various cycle counts, zero, 1000, 2000, and 4000, provide critical insights into the durability and performance of these inks under mechanical stress. The solvent ratios were chosen to assess their influence on ink performance, with 3T:3B and 10T:10B designated as the test samples. The key findings highlight significant differences in the electrical performance of these samples, which are further discussed below. Table 2 presents the resistance and resistivity obtained from the cyclic torsional test.

Table 2 Total average resistance and total average resistivity after cyclic torsional test.

Samples	Cycles	Total Average Resistance (Ω)	Total Average Resistance Error Bar 5%	Total Average Resistivity (Ω.m)	Total Average Resistivity Error Bar 5%
3T:3B	0	0.60	0.03	**0.36 x 10^{-6}**	1.80 x 10^{-6}
	1000	0.54	0.03	0.32 x 10^{-6}	1.62 x 10^{-6}
	2000	0.75	0.04	0.45 x 10^{-6}	2.25 x10^{-6}
	4000	0.81	0.04	0.48 x 10^{-6}	2.43 x10^{-6}
	0	0.12	0.01	7.20 x 10^{-6}	36.0 x 10^{-6}

	1000	0.14	0.01	8.40×10^{-6}	42.0×10^{-6}
	2000	0.13	0.01	7.8×10^{-6}	39.0×10^{-6}
	4000	0.18	0.01	10.8×10^{-6}	54.0×10^{-6}

The small error bars, representing 5% of the measured values, indicated reliable and precise data, ensuring confidence in the observed trends. All samples were verified for their credibility with a low percentage of error values. Figure 3 represents the plotted values for resistance and resistivity of every cycle conducted and measured.

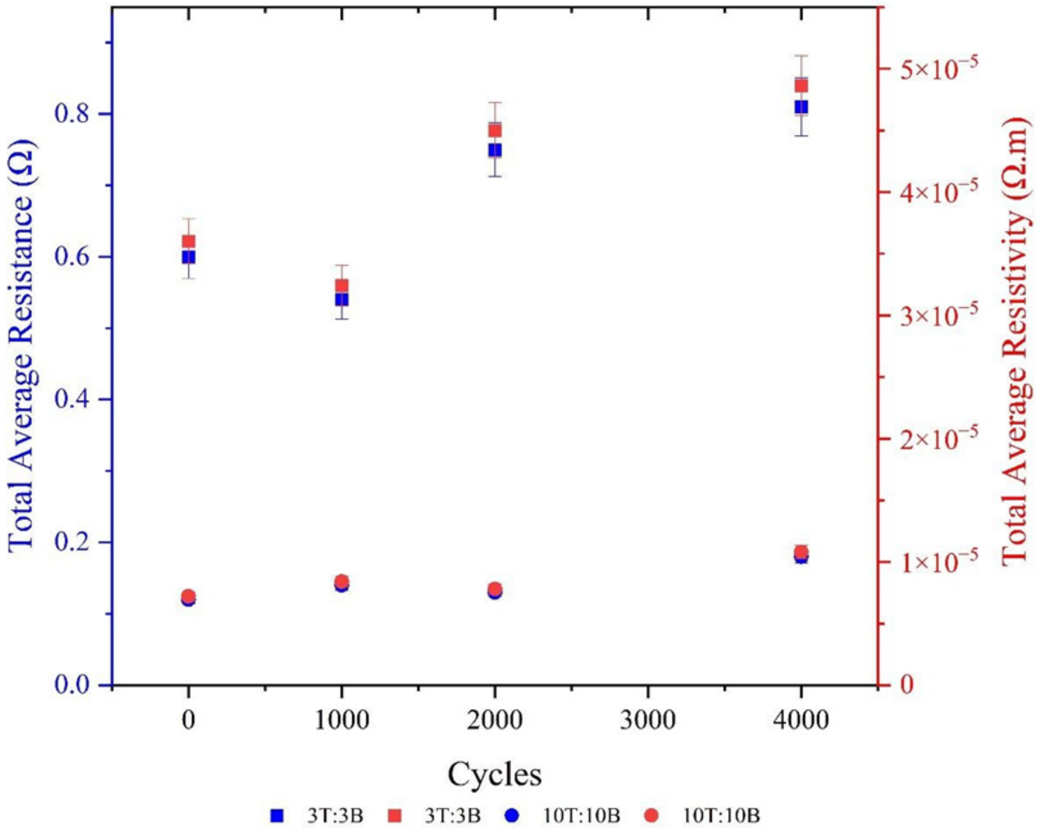

Figure 3. Total average resistance and resistivity graph after cyclic torsional test

4. Discussion

In this section, the results of the cyclic torsional testing on the 3T:3B and 10T:10B formulations are discussed. The focus was on the changes in resistance and resistivity after 1000, 2000 and 4000 cycles. The analysis examines how mechanical stress impacts the conductive network, specifically the alignment and redistribution of nanoparticles, which in turn influence the overall conductivity of the ink. Additionally, the impact of solvent characteristics, such as the polarity and volatility of terpinol and butanol, on dispersion and the stability of the conductive network is evaluated. The effect of curing the formulations at 250°C for 1 hour is also explored, specifically examining how this curing process alters the resistance and resistivity of the conductive network after cyclic torsional testing. Comparisons of the resistance and resistivity outcomes between these two formulations in responses to cyclic loading and their stability under repeated mechanical strain are made.

4.1 Resistance and resistivity analysis at 1000 cycles

The 3T:3B formulation exhibited a 10% reduction in both resistance (from 0.60 Ω to 0.54 Ω) and resistivity (from 0.36 x10^{-6} Ω.m to 0.32 x10^{-6} Ω.m) after 1000 cycles. The initial alignment and redistribution of particles under the mechanical stress induced by the cyclic torsional test resulted in this decrease. As the ink undergoes the applied strain, particle rearrangement and

alignment occur, which enhances the connectivity between the GNP and Ag particles, facilitating improved electron flow. This realignment of the fillers results in a more efficient conductive network, temporarily improving conductivity and lowering both resistance and resistivity (Wright & Celik, 2023). The improvement in conductivity aligns with Dong et al., (2021) previous studies, which found that aligned fillers reduce the percolation threshold and enhance conductivity, even under mechanical stress.

In contrast, the 10T:10B formulation displayed a slight increase in resistance from 0.12 Ω to 0.14 Ω, and for resistivity, from 7.20 x 10^{-6} Ω.m to 8.40 x 10^{-6} Ω.m. Unlike the 3T:3B formulation, which showed a clear improvement in conductivity, the 10T:10B formulation exhibited an anticipated, although slightly different, response under similar cyclic stress. The increase in resistance and resistivity observed in this formulation was an expected behaviour for materials subjected to cyclic loading, as minor alterations in the conductive network are commonly observed because of nanoparticle interactions under such conditions. These alterations typically manifest as slight agglomeration or minor shifts in particle contact, which can slightly disrupt the conductive pathways (Li et al., 2024). Gradual increases in resistance and resistivity, resulting from these reconfigurations of the nanoparticle network, are well-documented (Cahn et al., 2021), further supporting the observed trend in the 10T:10B formulation.

However, despite these changes, the 10T:10B formulation demonstrates a degree of stability in its conductive network. The slight increase in resistance and resistivity suggests that the formulation can maintain its conductive properties under mechanical stress, resisting significant degradation during the early stages of the cyclic test. This stability reflects the formulation's ability to endure minor reconfigurations of the nanoparticle network while retaining its structural integrity. Such stability is a favourable characteristic for applications where materials must endure repetitive mechanical stresses without compromising their performance.

The observed increase in resistance and resistivity for the 10T:10B formulation aligns with the expected material behaviour under mechanical strain. In this context, the resistance and resistivity changes typically observed during cyclic loading provide a deeper understanding of the material's ability to maintain functionality under stress. These parameters are significant because they reflect the structural integrity of the conductive network and the material's ability to withstand mechanical deformation. Small increases in resistance and resistivity are common in the initial stages of cyclic loading, indicating the early phase of material degradation or realignment within the nanoparticle network as cracks form in conductive ink (Li et al., 2024). The observed changes in the 10T:10B formulation are consistent with these typical material behaviours, confirming that the formulation retains its structural stability while undergoing minor adjustments in its conductive network under cyclic loading.

4.2 Resistance and resistivity analysis at 2000 cycles

The observed changes in resistance and resistivity at 2000 cycles for the 3T:3B and 10T:10B formulations highlight the impact of solvent composition on the performance of GNP/Ag conductive inks under mechanical stress, as evidenced by the 3T:3B formulation showed a significant 38.89% increase in both resistance (from 0.54 Ω to 0.75 Ω) and resistivity (from0.32 x $10^{-}6$ Ω.m to 0.45 x $10^{-}6$ Ω.m). This increase is attributed to the specific solvent composition, which affects conductivity. On the other hand, the 10T:10B formulation, which contains a higher proportion of terpinol, demonstrated a 7.14% decrease in both resistance (from 0.14 Ω to 0.13 Ω) and resistivity (from 8.40 x10^{-6} Ω.m to 7.80 x10^{-6} Ω.m). This improvement in conductivity indicates that a higher ratio of terpinol and butanol results in better performance stability under mechanical stress.

The observed differences in resistance and resistivity are influenced by solvent polarity, a key factor that affects nanoparticle dispersion and overall ink stability, as previously discussed. Terpinol, with its higher polarity, stands out as a more effective agent in facilitating the dispersion of nanoparticles, thereby ensuring a more uniform distribution within the solvent (Bakar et al., 2024). This unique property of terpinol reduces nanoparticle agglomeration and enhances the conductivity of the network. The interactions between the solvent and nanoparticles, such as hydrogen, dipole-dipole forces, and van der Waals attractions, stabilise the ink, which is essential for maintaining conductivity (Madeira et al., 2024). These interactions are fundamental in solubility and stability, as solvent polarity determines how well it can interact with the solute (Zakaria et al., 2014; Wang et al., 2010). However, terpinol has a higher boiling point at 219 °C and evaporates at a slower rate during drying. A smaller quantity of terpinol in the formulation is unable to fully assist in optimal particle dispersion, which can lead to uneven dispersion in the 3T:3B formulation, causing particle clumping and weakening the conductive pathways. This increased resistance and resistivity.

Butanol, at its boiling point of 117.7°C, on the other hand, is a moderately polar solvent with a higher evaporation rate, supports rapid drying and helps form a smooth, continuous film (Jori et al., 2024). This rapid evaporation prevents premature particle aggregation during the curing process, contributing to the formation of a closer contact between particles in the conductive network. An optimal evaporation rate can lead to better control over the ink's formability and stability under deformation, which is essential for high-quality printed electronics (Guo et al., 2022). Particularly in the 3T:3B formulation, a lesser composition of butanol with a faster evaporation rate can make the material more susceptible to structural changes under mechanical stress and also lead to uneven particle distribution and higher resistance, a consequence of poor connectivity (Suzuki et al., 2015), which poses challenges for maintaining network stability.

Solvents that enhance the ink's homogeneity and reduce viscosity are preferred for achieving lower electrical resistance and better print quality (Cândido et al., 2023; Hatala et al., 2019). The higher proportion of terpinol in the 10T:10B formulation promotes better nanoparticle dispersion, resulting in a more stable conductive network. The increased terpinol content prevents agglomeration and maintains a more homogeneous distribution of nanoparticles, which is key to improving the conductive network's efficiency. The rapid evaporation of butanol further aids in forming a smooth film, while the increased ratio of terpinol reduces clumping and enhances the network's resistance to mechanical degradation.

4.3 Resistance and resistivity analysis at 4000 cycles

Both the 3T:3B and 10T:10B formulations were subjected to 4000 cycles of cyclic torsional testing, with their resistance and resistivity measured after being cured at 250°C for 1 hour, marking the final cycles of the testing. The results revealed a significant difference in the increases of both resistance and resistivity. Specifically, the 3T:3B formulation exhibited an 8% increase in resistance, from 0.75 Ω to 0.81 Ω and a rise in resistivity from 0.45 $\times 10^{-6}$ Ω.m to 0.48 $\times 10^{-6}$ Ω.m. In contrast, the 10T:10B formulation showed a more substantial increase, with resistance rising by 38.46%, from 0.13 Ω to 0.18 Ω, and resistivity increasing by 38.46%, from 7.80 $\times 10^{-6}$ Ω.m to 10.8 $\times 10^{-6}$ Ω.m. Despite the larger percentage increase in the 10T:10B formulation, its resistance and resistivity remained significantly lower than those of the 3T:3B formulation, indicating better overall electrical performance under cyclic stress.

The curing process, involving both temperature and duration, is essential in determining the electrical properties of conductive inks. Proper curing ensures the complete evaporation of solvents and solidification of conductive pathways, which in turn enhances the ink's conductivity (Zou et al., 2023). Higher curing temperatures typically reduce the required curing time, improving process efficiency and ensuring more uniform nanoparticle dispersion (Fernandes et al., 2020). However, while higher temperatures can shorten curing times, prolonged curing is often recommended to enhance conductivity. Extended curing allows for more complete cross-linking and sintering of the conductive materials, ultimately improving electrical properties (Shu et al., 2021). In this study, a 1-hour curing period was chosen to specifically evaluate the effects of different solvent ratios on resistance and resistivity under these conditions.

The observed increases in resistance and resistivity in both formulations can be analytically attributed to the mechanical stress applied during the 4000 cycles, which induced particle reorganisation, compaction, and displacement within the ink matrix. This disruption of the conductive network compromised the efficiency of the percolation pathway, resulting in increased resistance and resistivity. It is worth considering that such reorganisation may not only stem from direct mechanical stress but could also involve nanoparticle interactions that further intensify the loss of continuity within the conductive paths. Moreover, the curing temperature of 250°C for one hour played an important role in determining the dispersion and alignment of the nanoparticles, which directly impacted the stability of the conductive network under mechanical stress. In particular, the alignment and uniform distribution of nanoparticles influenced the continuity and integrity of the percolation network, which is essential for maintaining low resistance.

The 3T:3B formulation, characterised by a lower proportion of terpinol, exhibited less effective dispersion of nanoparticles compared to the 10T:10B formulation. The less optimal dispersion in the 3T:3B formulation led to particle aggregation, compromising the integrity of the conductive network and resulting in higher resistance and resistivity under cyclic stress. Thermal conductivity is a critical factor in determining a material's ability to manage heat generated during mechanical stress (Noor et al., 2024). Additionally, the lower thermal conductivity of the 3T:3B formulation highlighted a potential area for improvement in heat dissipation during cyclic loading. High thermal conductivity materials are vital for thermal management in electronics and photonics, as efficient heat dissipation is necessary to prevent overheating and ensure reliable performance (Broido et al., 2017). The 3T:3B formulation's lower thermal conductivity hindered heat distribution, resulting in localised heating that degraded the conductive pathways. This excess heat further weakened the percolation paths, ultimately increasing resistance. In simpler terms, the material's inability to efficiently distribute heat is a key factor in the breakdown of the conductive network, contributing to the observed rise in resistance.

5. Conclusion

This study examines the effect of solvent composition, specifically the optimal terpinol-to-butanol ratios, on the performance of GNP/Ag hybrid conductive inks under cyclic torsional stress. The comparative analysis of resistance and resistivity outcomes between the two samples, 3T:3B and 10T:10B, reveals significant differences in their electrical performance. Sample 3T:3B exhibited a resistance of 0.81 Ω and a resistivity of 0.48 x10-6 Ω.m. In contrast, sample 10T:10B demonstrated better electrical performance with a resistance of 0.18 Ω and a resistivity of 10.8 x10-6 Ω.m. The resistance of sample 10T:10B was approximately 77.8% lower than that of sample 3T:3B, highlighting its more efficient conductivity. This improved performance can be attributed to the enhanced dispersion of nanoparticles in the 10T:10B formulation, which facilitated the formation of a more efficient conductive network by ensuring uniform distribution and connectivity. This ideal dispersion prevented localised heating and reduced the risk of increased resistance, contributing to the improved stability and functionality of the sample under cyclic torsional stress.

These findings highlight the pivotal role of solvent composition in optimising the conductivity and thermal stability of conductive inks. The results accentuate the importance of solvent composition in high-stress applications that require long-term functionality. Future research should further investigate a broader range of solvent compositions to optimise the dispersion and stability of these inks. A more detailed analysis using techniques such as scanning electron microscopy (SEM) and thermal conductivity measurements could offer deeper insights into the mechanisms driving the enhanced performance of these inks.

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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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