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RESEARCH ARTICLE

INFLUENCE IN SOLVENT COMPOSITION ON MICROSTRUCTURAL INTEGRITY AND FATIGUE RESISTANCE OF PRINTED GNP/Ag CONDUCTIVE INKS

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Abstract. Conductive inks are essential for flexible and wearable electronics, however their mechanical durability under torsional fatigue remains poorly understood. This study investigated the formulation and mechanical behaviour of hybrid graphene nanoplatelet and silver conductive inks to address this gap. Three ink formulations were developed using fixed ratios of graphene nanoplatelets at 0.5 g, silver flakes at 4.292 g, and silver acetate at 0.42 g, with varying butanol-to-terpineol solvent ratios of 5:10, 10:10 and 15:10 corresponding to samples labelled as 5-B, 10-B and 15-B respectively to influence viscosity and filler dispersion. The inks were screen-printed onto copper substrates and thermally cured at 250 °C for five hours. Cyclic torsional fatigue testing, conducted up to 16,000 cycles at an angle of 90 degrees and speed of 211 cycles per minute to assess resistance stability under repeated mechanical stress. The results revealed that solvent composition played an important role in determining the mechanical and electrical performance of the printed inks. The 10-B sample with a 10:10 butanol-to-terpineol drops improved filler network formation, leading to enhanced conductivity and structural cohesion. Scanning electron microscopy (SEM) at ×800 and ×2000 magnifications identified microstructural failure modes such as cracking, filler agglomeration, and void formation, with more severe degradation observed in formulations in the 5-B sample. Among the tested samples formulations of 5-B, 10-B and 15-B, the optimised 10-B formulation exhibited an excellent resistance stability with initial resistance of 0.325 ohms and after 16,000 cycles, which increased to 0.520 ohms with minimal physical deterioration, confirming its superior fatigue endurance. This work highlights the importance of solvent-engineered rheology and filler interaction in achieving mechanically robust and electrically stable conductive inks.

Keywords: GNP/Ag, hybrid conductive ink, torsional, microstructural degradation, printed electronics.

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1. INTRODUCTION

Conductive inks have become foundational materials in the evolution of flexible electronics, supporting innovations in wearable health monitors, foldable displays, and interconnected Internet of Things (IoT) devices. Unlike conventional rigid circuitry, these inks allow the realisation of lightweight, stretchable, and conformable systems by enabling the direct printing of conductive traces onto diverse substrates including polymers, textiles, and metals. Among emerging materials, hybrid conductive inks that combine graphene nanoplatelets (GNPs) with silver (Ag) nanoparticles are of particular interest based on their synergistic properties. The GNPs offer excellent mechanical flexibility, high fracture toughness, and high carrier mobility, whereas Ag provides exceptional electrical conductivity. These materials enable the development of multifunctional composites that respond favourably to mechanical stress while maintaining superior electrical performance [1]. Despite these advantages, a critical limitation remains: their mechanical durability under repeated or dynamic loading, particularly in environments subject to complex deformation modes.

Recent advancements in hybrid GNP/Ag inks have focused on improving dispersion, interfacial bonding, and the mechanical reinforcement of printed films. Several studies demonstrate that GNPs mitigate crack propagation and enhance durability under uniaxial stress conditions such as bending or stretching [2]. However, these findings do not translate directly to torsional fatigue scenarios, which involve more complex and multidirectional stress fields. Existing studies on pure Ag inks under torsional stress have reported failure at grain boundaries in the interest of cyclic shear [3].

There is an insufficiency of data on how GNP/Ag hybrids perform under similar conditions. This constitutes a significant knowledge gap, especially given the growing demand for materials capable of withstanding repeated torsion in emerging flexible electronics. Furthermore, the mechanical performance of conductive inks under torsion is influenced not only by filler composition but also by solvent system, adhesion to substrate, and microstructural integrity during cycling. Despite the critical nature of these parameters, there remains a lack of systematic investigation into how solvent ratios and filler morphology influence mechanical resilience under torsional fatigue.

This study aims to address these gaps by investigating the torsional fatigue behaviour of hybrid GNP/Ag conductive inks printed on copper substrates. Copper substrates were selected for their excellent electrical conductivity, low cost, and good adhesion properties with hybrid conductive inks. In addition, copper is widely used as a substrate material in flexible electronic applications for its high ductility and mechanical compatibility with printed conductive layers [4].

Cyclic torsional testing is employed to simulate real-mechanical loading, while scanning electron microscopy (SEM) is used to analyze failure modes such as micro-cracking, delamination, and nanoparticle redistribution. The scanning electron microscopy has been widely used to identify microstructural failure modes such as cracking, delamination, and particle agglomeration in hybrid conductive inks under mechanical fatigue [5]. The findings are benchmarked against literature on uniaxial deformation to elucidate the unique mechanical challenges posed by torsion. Ultimately, this research seeks to provide mechanistic insights into the development of robust hybrid inks for future applications in mechanically dynamic flexible electronics.

2. MATERIALS AND METHODS

2.1 Materials

All chemicals and materials were used as received without further purification. Graphene nanoplatelets (GNP) with 25 µm particle size were obtained from Sigma-Aldrich, St. Louis, MO, USA. Silver flakes (SF) and silver acetate (SA) were supplied by Sigma-Aldrich, St. Louis, MO, USA. Ethanol (99 % purity) was purchased from Madasai Laboratory, Shah Alam, Malaysia. Butanol (99.9

% purity) was obtained from Sigma-Aldrich, St. Louis, MO, USA. Terpineol (High Purity Grade) was obtained from Gouden Reagents, Selangor, Malaysia. Copper substrates with thickness of 0.1 mm were used. These materials were used to prepare the hybrid GNP/Ag conductive ink, where GNP and Ag served as the primary conductive fillers. Ethanol served as the main chemical solvent, while butanol and terpineol functioned as organic solvents, acting both as binders and viscosity modifiers. An overview of the materials used in the formulation is presented in Table 1.

The electrical conductivity of the ink was derived from a coactive combination of GNP powder (25 µm particle size) and silver flakes (SF), with the conductivity further enhanced by the addition of silver acetate (SA). The SA is believed to contribute during the sintering process by promoting the formation of a continuous and robust conductive network [6]. The conductive fillers were uniformly dispersed in a solvent matrix consisting primarily of ethanol, with varying proportions of butanol and terpineol added to modify ink rheology. The key parameters for ink rheology include viscosity, surface tension, drying rate, thixotropic behavior, and shear thinning properties. The viscosity affects printability, surface tension influences adhesion, and thixotropic behavior ensures smooth flow during printing and quick recovery after deposition [7].

Table 1: Materials used hybrid graphene nanoplatelets silver conductive ink

Category	Material	Role
Filler	Graphene nanoplatelets powder (25 µm nanoparticle size)	Provide mechanical strength and conductivity
	Silver flakes	Enhances electrical conductivity
	Silver acetate	Precursor for improved particle dispersion
Solvent	Ethanol (99.99 % purity)	Primary solvent for initial dispersion
	Butanol	Controls viscosity and drying rate
	Terpineol	Improves ink stability and printability

Table 2 details the specific composition of the hybrid GNP/Ag conductive ink formulations used in this study. The table outlines the weight ratios of each component in the ink mixture. Three different ink samples were developed, each characterized by varying proportions of butanol while maintaining a constant amount of terpineol. These variations were intended to examine the influence of solvent composition on the rheological and electrical properties of the ink.

The butanol-to-terpineol ratios of 5:10, 10:10, and 15:10 were selected to investigate the effect of solvent polarity and evaporation rate on ink performance. The butanol is a low boiling point solvent that promotes rapid drying, while terpineol has a high boiling point that slows evaporation and improves film uniformity. Preparation of hybrid GNP/Ag conductive ink with different ratios of 1-butanol to terpineol and found that the solvent ratio directly influences ink properties such as viscosity and printability. The balanced 10:10 ratio was expected to provide optimal viscosity for screen printing, whereas the 5:10 and 15:10 ratios represented lower and higher butanol extremes to evaluate the sensitivity of ink properties to solvent composition [8].

Table 2: Formulation of hybrid graphene nanoplatelets silver conductive ink

Sample	Graphene (g)	Silver Flake (g)	Silver Acetate (g)	Ethanol (ml)	Butanol (drops)	Terpineol (drops)
5-B	0.5	4.292	0.42	50	5	10
10-B	0.5	4.292	0.42	50	10	10
15-B	0.5	4.292	0.42	50	15	10

The research methodology followed a stepwise process begin with preparation of the conductive powder, formulation of the ink paste, copper substrate preparation, ink application through printing, curing, and subsequent mechanical testing. The printed samples underwent a cyclic torsional fatigue test, where they were subjected to controlled rotational deformation across a range of cycles. Electrical resistance was measured both before and after torsional loading to evaluate the ink ability to maintain conductivity under repeated mechanical stress. This evaluation provides critical insight into the mechanical reliability and electrical durability of hybrid GNP/Ag inks for flexible and wearable electronics applications.

2.2 Ink Preparation

2.2.1 Formulation of Hybrid Graphene Nanoplatelets Silver Conductive Ink Paste

The formulation of the conductive ink paste began with the grinding of the prepared hybrid powder using a mortar to achieve uniform particle size. The ground powder was then carefully weighed to determine the appropriate ratios of butanol and terpineol. After transferring the powder into a mixing container, the solvents were added dropwise using a dropper to control the volume and ensure consistency. Finally, the Thinky mixer ARE-310, THINKY Corporation, Tokyo, Japan was operated using mixing and deforming parameters to ensure a homogeneous and bubble free conductive ink paste, suitable for application on copper substrates. This formulation strategy is supported by studies that have optimized solvent ratios to enhance the electrical performance of hybrid conductive inks [9].

2.3 Sample Preparation

In this research, thin copper films were selected as substrates owed to their high electrical conductivity, low cost, good mechanical flexibility and strong adhesion with hybrid conductive inks. The copper substrates were used in their original condition and cut to the required size, with dimensions of 120 mm in length, 7 mm in width, and 0.1 mm in thickness. The copper surfaces were gently abraded using sandpaper to prevent oxidation which can hinder conductivity. This process created a textured surface that enhanced the adhesion of the conductive ink. Three pieces of copper substrate were prepared for this study, with each substrate marked with five points printed for subsequent testing at intervals of 20 mm for the printing process.

2.3.1 Formulation of Hybrid Graphene Nanoplatelets Silver Conductive Ink Paste

After preparing the material, the following stage was the printing technique. This experiment involved printing utilising various sample widths and patterns. The mesh stencil 120-34T, Khai Lien Sdn Bhd, Selangor, Malaysia with a 60 µm thickness was utilised as a guide to achieve precise dimensions and grid positions. The paste of nano-scale hybrid GNP/Ag typically placed on the mesh stencil at 3 mm by 3 mm grid point to the copper substrates. Each grid point was chosen to verify a consistent size for testing and assessment. The pressure was applied to a squeegee with 3 inchs width made of polyurethane (PU) material from IMI Silk Screen, Batu Pahat, Johor Bahru, Malaysia to get the paste spread inside the mould in the preferred form. 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 onto the copper substrate. This printing method needs to repeat at five designated sites along the length of each copper substrate like as shown in Figure 1.

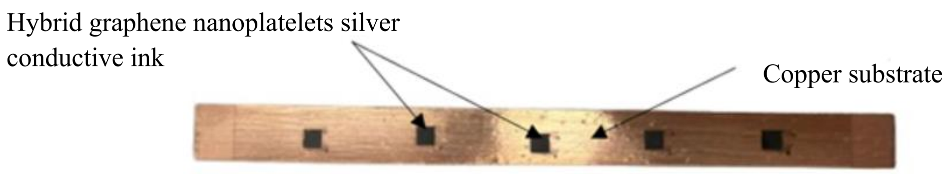

Figure 1: Ink printed on copper substrate

The curing process is an essential post-treatment step conducted after the printing stage to enhance the electrical and mechanical properties of the printed ink. In this study, the printed samples were carefully placed on trays and cured in a convection oven model UF55, Memmert GmbH + Co. KG, Schwabach, Germany set at 250 °C for five hours. This elevated curing temperature facilitates both the evaporation of residual solvents and the sintering of the conductive particles within the ink matrix. After the curing period, the samples were gradually cooled to room temperature under ambient conditions. This slow cooling step is essential to preserve the microstructural integrity of the conductive network and to prevent thermal stresses or cracking that might otherwise occur because of rapid temperature changes [10].

2.4 Cyclic Torsional Test

The cyclic torsional test is a severe mechanical evaluation method used to assess the fatigue resistance of materials under repetitive torsional strain and an essential characteristic for conductive inks intended for use in flexible and wearable electronics [11]. In this study, printed hybrid GNP/Ag conductive ink samples were subjected to control an alternating torsional deformation to simulate the mechanical stress conditions experienced in an actual flexible electronic application. The test was conducted following ASTM A938-18 and ASTM E2207-15 standards to observe the condition of conductive ink when the thin copper in torsion.

As illustrated in Figure 2, an experimental setup includes a torsional testing machine developed by a PhD student at Universiti Teknikal Malaysia Melaka (UTeM) was equipped with a secure sample holder and calibrated angular displacement controls. The torsional angle was set +90°, which has been shown to effectively replicate the shear stress conditions in flexible circuitry.

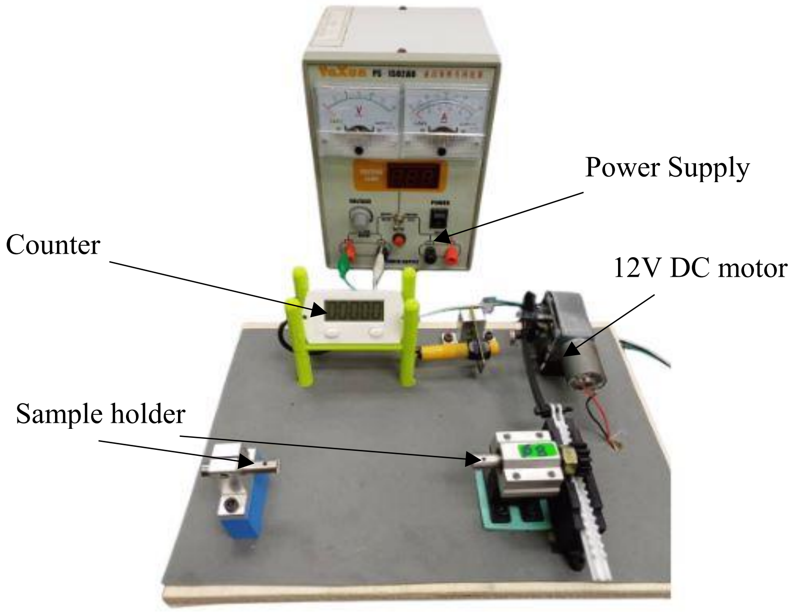

Figure 2: Torsional testing machine

The system operated at a constant voltage of 6 V and a rotational speed of 211 cycles per minute, equivalent to 12,660 cycles per hour. Resistance measurements were recorded at six specific intervals at 0, 1000, 2000, 4000, 8000, and 16,000 cycles to monitor changes in conductivity and evaluate the durability of the ink under progressive mechanical stress.

2.5 Resistivity

The electrical conductivity of the printed conductive ink was evaluated on the copper substrate surface using a Two-Point probe resistance measurement setup Model 1009, Kyoritsu Electrical Instruments Works, Ltd., manufactured in Thailand. The Two-Point probe, designed specifically for assessing electrical resistance, was configured to operate in it is standard two-point mode for this measurement. The selector switch was adjusting to the resistance (ohm, Ω) setting. This configuration checks the device solely monitors electrical resistance, eliminating the influence of other electrical variables. Measuring resistance at multiple locations ensures that the calculated resistivity value for each sample is accurate and representative of the entire printed region, reducing the impact of local inconsistencies.

2.6 Scanning Electron Microscopy

The Scanning Electron Microscope (SEM) Model JSM-6010PLUS/LV, JEOL Ltd., Tokyo, Japan as illustrated in Figure 3 is a dynamic characterization technique used to investigate the surface morphology, microstructural features, and failure mechanisms of conductive materials at high resolution. In this study, SEM was employed to observe the physical integrity of hybrid GNP/Ag conductive ink coatings on copper substrates after cyclic torsional loading. The analysis focused on identifying crack propagation, particle dispersion, interfacial delamination, and other surface defects that may have developed under mechanical stress. High magnification imaging at x800 and x2000 was used to evaluate the microstructural evolution of the conductive pathways over time. The SEM is particularly suited for such analysis as its ability to resolve nanoscale features and distinguish between conductive fillers and the surrounding matrix. This morphological insight is critical for linking observed electrical degradation with physical damage mechanisms.

Figure 3: Scanning electron microscopy machine

2.6.1 Sample Preparation for SEM

Accurate and reliable SEM imaging can be ensured by samples that were carefully prepared following standard procedures. After the cyclic torsional test, printed copper substrates were cut into smaller segments around the torsion zone to isolate the area of interest as shown in Figure 4(a). The specimen with conductive ink then was placed in a mounting mould and there is a tube holder to support and hold the specimen position as illustrated in Figure 4(b). The sample undergoes a cold mounting technique for safety and convenience during the grinding and polishing stages. The cold mounting process required two important ingredients: epoxy resin and hardener. Figure 5(a) shows the epoxy resin and hardener using in this study. The ingredients were mixed in ratio 3:1 which is 3 for epoxy resin and 1 for hardener by referring to manufacturer mixing ratio as illustrated in Figure 5(b). The specification of epoxy resin and hardener for the cold mounting can be seen in Table 3.

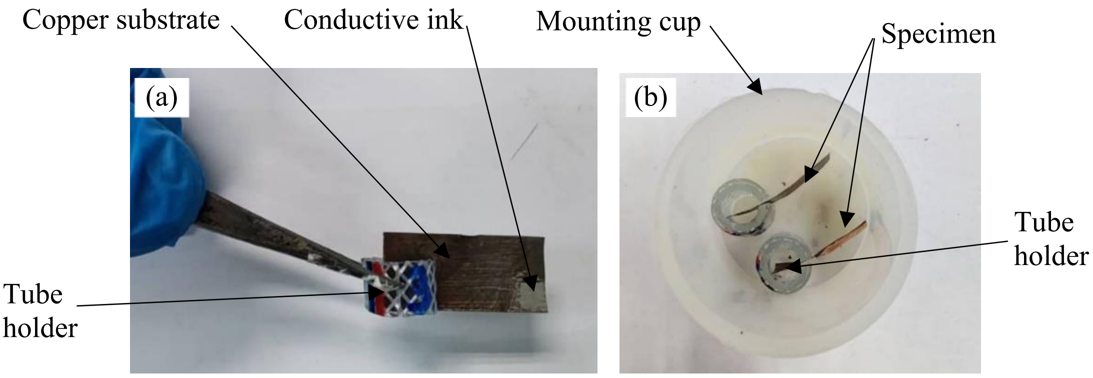

Figure 4: (a) Specimen of printed copper substrate and (b) Specimen in mounting mould

Table 3: The specification of epoxy resin and hardener for the cold mounting

Properties	Color	Physical	Curing time (10 ^{0}C)	Curing time (25 ^{0}C)	Ratio by weight	Hardness (g/cm^3)
Epoxy resin	Clear	Liquid	40 hours	20 hours	3	1.14
Hardener	Clear	Liquid	40 hours	20 hours	1	1.03

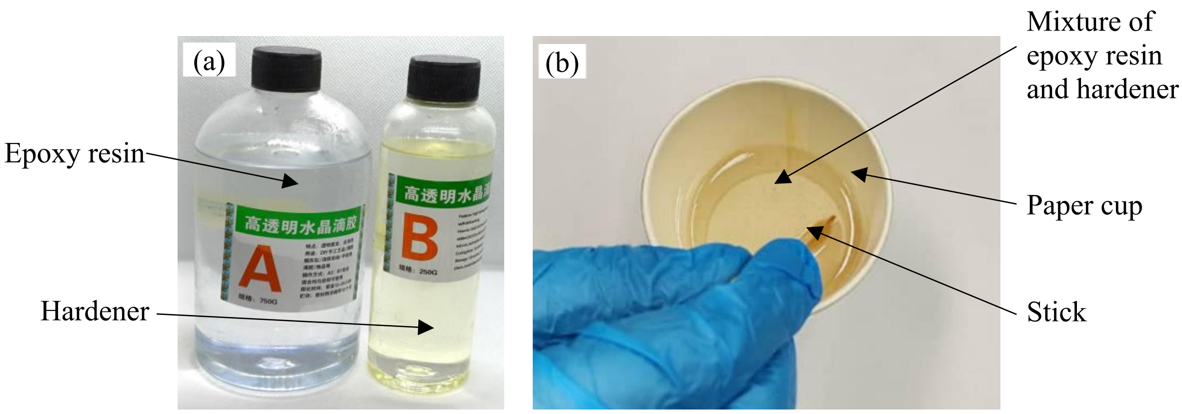

Figure 5: (a) Epoxy resin and hardener and (b) Mixture of epoxy resin and hardener

The next process is to pour the mixture into the mounting cup. The sample was left for a day to ensure proper curing and stabilization. After the mounting was stable, the mounting cup was removed to get the sample. There were three samples prepared with different formulations of the conductive ink. Figure 6 shows the samples that was hardened to go through mechanically cross-section using a Grinder and Polisher Machine Model NANO 2000T, Pace Technologies, Tucson, AZ, USA with sandpaper grid sizes of 350, 600, 800 and 1000, respectively. Tap water was used as a coolant during the grinding process to reduce temperature increase during friction between the sandpaper and the cold mounting sample. Lastly, the samples were then polished with a polishing cloth, 0.05 µm Nano polish Alumina and DIAMAT Polycrystalline Diamond suspension with particle sizes of six, three and one microns at 400 rpm for well-balanced speed for polishing.

All samples then were sputter with metal coating, platinum (Pt) layer using sputter coating machine Model JFC-1600, JEOL Ltd., Tokyo, Japan to increase secondary electron release and minimizes charging problems in the SEM image. The secondary electrons were used in this study because they are highly sensitive to surface topography and provide high resolution images of microstructural features such as cracks, voids and particle distribution on the ink surface. The image of the scan object became severed because of obscured, fragmented and strong bright areas in the SEM image. The specimens were exposed to typical electron accelerating voltages above 10 kV where non-conductive materials tend to accumulate negative charge. This charge build-up results from an excess of electrons landing on and subsequently leaving the specimen as secondary electrons.

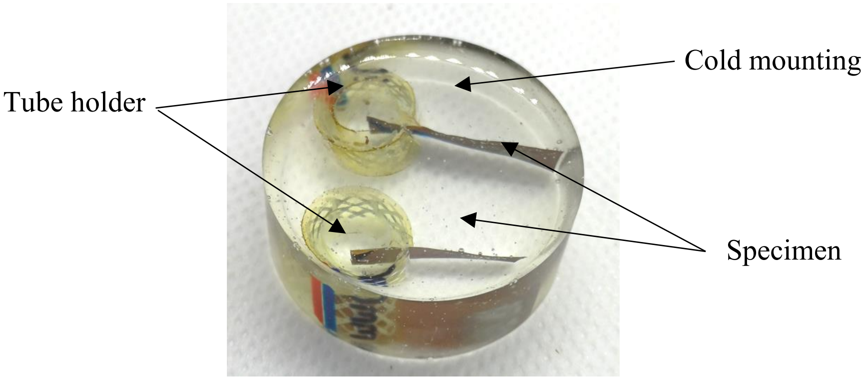

Figure 6: The specimen holds by the tube in the mounting cup

The sample coated with Pt was then placed on the jig before being placed on the specimen chamber at SEM. The sample must follow the tolerance of the jig to avoid destruction during the scanning process. The SEM are often for larger and work in a vacuum and might increase the times to images' capture to the sample. Proper sample preparation is essential for capturing representative micrographs and establishing a clear correlation between mechanical fatigue and morphological degradation.

3. RESULTS AND DISCUSSION

3.1 Electrical Performance under Cyclic Torsional Loading

The electrical resistance of each ink formulation which are 5-B, 10-B, and 15-B was recorded at six key torsional cycle intervals 0, 1,000, 2,000, 4,000, 8,000, and 16,000 cycles. Bulk resistance measurements were taken at four defined points on each cured sample using a two-point probe configuration. The selected cycle intervals were chosen to capture the evolution of electrical resistance from the initial state through progressive fatigue stages. The selected cycle intervals were chosen to capture the evolution of electrical resistance from the initial state through progressive fatigue stages, as recommended in studies on cyclic testing of conductive inks [12].

Table 4 summarizes the corresponding bulk resistance and resistivity values following thermal curing at 250 °C. Among the three formulations, the 10-B sample (with a 10:10 butanol to terpineol ratio) demonstrated the lowest electrical resistance of 0.325 Ω and resistivity of 6.82×10^{-9} Ω·m. In contrast, the 15-B formulation (15:10 ratio) exhibited the highest resistance at 0.460 Ω and a resistivity of 9.93×10^{-9} Ω·m. The differences in electrical performance are attributed to the influence of solvent composition on ink rheology and microstructure formation during curing. Butanol acts as a volatile solvent, aiding initial dispersion but evaporating rapidly during thermal treatment. An excessive proportion of butanol (as seen in 15-B) disrupts uniform film formation and impedes the formation of percolated conductive networks between GNPs and Ag particles. The balanced ratio in 10-B promotes a more cohesive microstructure with improved particle connectivity and interfacial contact, thereby enhancing electron transport pathways.

These findings underscore the critical interplay between ink formulation and functional performance, especially in applications where mechanical flexibility and electrical stability are essential. Optimising the solvent ratio is not merely a matter of processing convenience. It directly governs the ink's electrical durability and structural coherence under mechanical strain. Besides, it observed resistivity trends highlight the importance of controlling solvent evaporation rates and filler dispersion to achieve low-resistance conductive pathways.

Table 4: Resistance and resistivity of hybrid graphene silver conductive ink

Hybrid Ink	Sample	Ratio (butanol:terpineol)	Resistance (Ω)	Resistivity (Ω.m)
Curing Temperature of 250 ^{0}C	5-B	5:10	0.425	1.62×10^{-8}
	10-B	10:10	0.325	6.82×10^{-9}
	15-B	15:10	0.460	9.93×10^{-9}

3.2 The SEM Analysis of Microstructural Degradation

The microstructural integrity of the printed hybrid GNP/Ag conductive ink was examined using the SEM at magnifications of ×800 and ×2000 for all samples following 16,000 torsional cycles, to elucidate the physical origins of degradation and structural defects. Figure 7(a), at ×800 magnification for the 5-B sample, presents a cross-sectional view revealing a thick, layered morphology comprising bright regions of Ag particles embedded within a darker matrix, presumed to be GNPs. The Ag particles are well-dispersed, forming a semi-continuous conductive network through the ink layer's thickness. This network is critical for preserving electrical conductivity, as it facilitates multiple percolation pathways for electron flow, enabling partial compensation for localised defects.

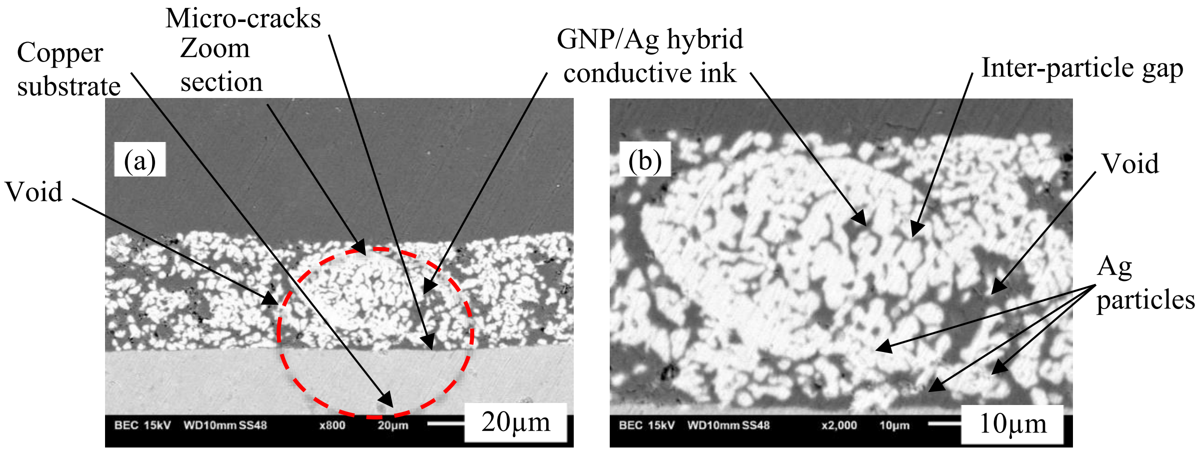

Figure 7: (a) Hybrid GNP/Ag conductive ink at x800 magnification and (b) The particles distribution of 5-Butanol to 10-Terpineol

Furthermore, the distinct and intact ink-substrate interface with no signs of delamination indicates strong interfacial adhesion, which is vital in resisting mechanical failure under cyclic torsional loading [13]. At higher magnification (×2000), as shown in Figure 7(b), microstructural voids and inter-particle gaps become evident. These voids likely arise from incomplete sintering during the curing process, where insufficient thermal energy inhibits full coalescence of Ag particles. The voids observed in SEM can be confirmed as incomplete sintering artifacts by comparing samples cured at different temperatures or using Energy Dispersive X-ray Spectroscopy (EDS) mapping to detect residual organics in void regions. The sintering profile for this research is 250°C for 5 hours as detailed in Section 2.3.1. Such defects act as electron scattering centres, elevating resistivity, and serve as stress concentrators that can evolve into micro-cracks under repeated mechanical loading [14].

The presence of dark zones adjacent to Ag particles suggests localised strain accumulation, which can propagate with continued cyclic torsion, thereby disrupting the conductive pathways and accelerating electrical degradation. This microstructural analysis highlights the crucial role of particle dispersion, sintering quality, and interface stability in determining the durability of conductive inks.

The SEM imagery of the 10-B sample uncovers a distinctive stratified microstructure formed after 16,000 torsional cycles, as depicted in Figures 8(a-b). It reveals a tri-layer configuration comprising, a relatively homogeneous topmost layer exposed to the environment, an intermediate conductive stratum rich in Ag particles exhibiting strong electron contrast and a basal layer directly interfacing with the copper substrate. This laminar structure likely results from differential phase segregation during drying and curing, influenced by the rheological properties of the ink and solvent evaporation kinetics [15]. Within the middle conductive layer, a semi-continuous Ag network is evident, the presence of pervasive porosity and micro-cracks signals incomplete sintering and weak particle bonding. Such microstructural flaws act as stress concentrators, becoming nucleation sites for crack initiation under cyclic torsion.

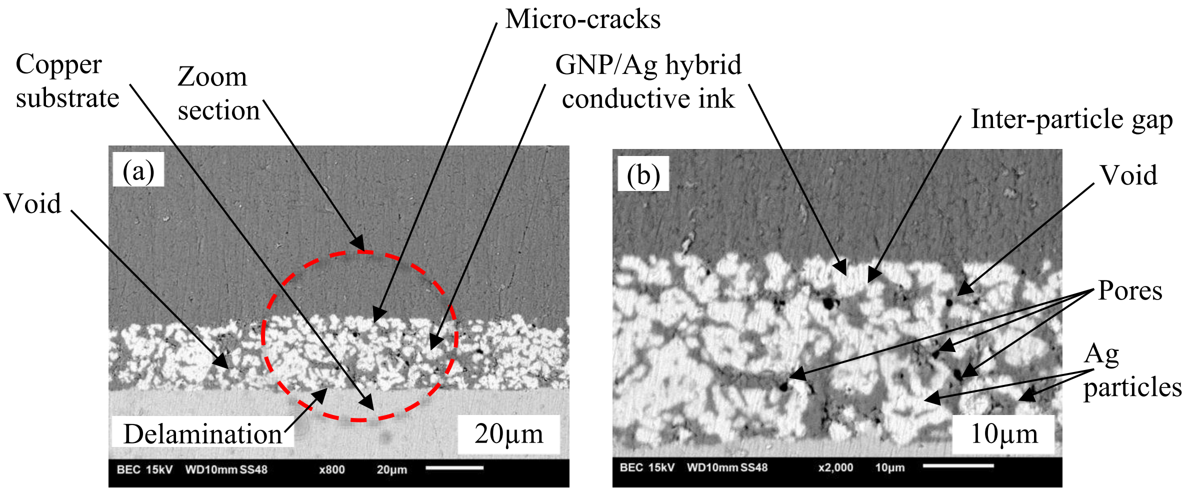

Figure 8: (a) Hybrid GNP/Ag conductive ink at x800 magnification and (b)The particles distribution of 10-Butanol to 10-Terpineol

The SEM micrographs of the 15-B sample, presented in Figures 9(a-b) reveal a stratified microstructure comprising three distinct zones.

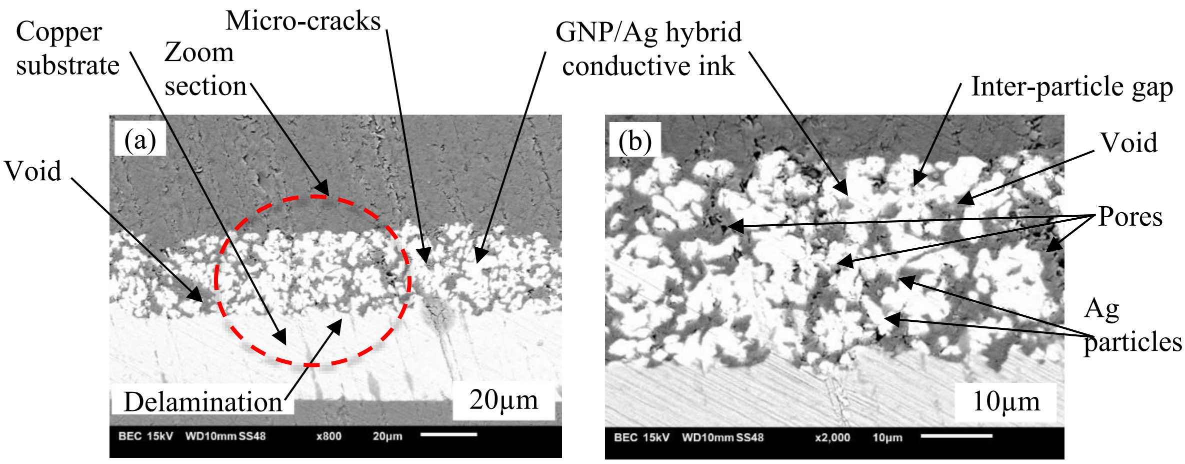

Figure 9: (a) Hybrid GNP/Ag conductive ink at x800 magnification and (b) The particles distribution of 15-Butanol to 10-Terpineol

The uppermost surface exhibits extensive micro-cracking, while the middle layer is characterised by a bright, highly textured region densely populated with silver particles. The lower region forms a relatively smooth interface with the substrate, marked by mechanical polishing traces. Despite this apparent layering, the microstructure demonstrates pronounced degradation. Within the conductive middle layer, the distribution of Ag particles and GNP clusters is markedly heterogeneous, with evident particle agglomeration.

These clustered regions act as loci for stress concentration, creating preferential sites for crack nucleation under cyclic torsional loading. The resulting cracks tend to propagate along particle boundaries, facilitating partial delamination at the ink-substrate interface. This phenomenon reflects the weakening of inter-particle cohesion and filler-substrate adhesion caused by repeated mechanical deformation, critically undermining both structural integrity and electrical continuity [16].

Comparative SEM analysis of samples 5-B, 10-B, and 15-B after 16,000 torsional cycles offers valuable insights into the interplay between microstructure and mechanical-electrical behaviour. While all samples exhibited layered morphologies with Ag-rich conductive domains interspersed with micro-voids and micro-cracks, the 5-B formulation demonstrated a more cohesive conductive network and minimal interfacial delamination, indicative of superior fatigue resistance. In contrast, the 10-B and 15-B samples revealed more pronounced void formation, incomplete particle sintering, and filler agglomeration. These defects acted as stress concentrators, accelerating crack growth and interfacial separation, which collectively impede electron transport and contribute to rising electrical resistance under cyclic strain. The presence of such stress concentration zones and filler detachment highlights the paramount importance of optimising particle dispersion and strengthening filler-substrate adhesion to mitigate fatigue-induced failure. The 5-B sample, which exhibited fewer voids and better particle connectivity in SEM micrographs, showed the most stable resistance after 16,000 cycles. In contrast, the 10-B and 15-B samples, which displayed more pronounced void formation and particle agglomeration, experienced larger increases in resistance after 16,000 cycles [17].

4. CONCLUSIONS

In conclusion, the present investigation underscores the critical influence of solvent composition on the performance of hybrid GNP/Ag conductive inks under mechanical strain. The key values achieved in this research are an initial resistance of 0.325 Ω and resistivity of 6.82×10^{-9} Ω·m for the 10-B formulation, representing the best conductivity, while the 5-B formulation demonstrated the best fatigue resistance with resistance decreasing from 0.425 Ω to 0.235 Ω after 16,000 cycles. The balanced 10:10 butanol to terpineol ratio emerged as the optimal formulation, delivering enhanced electrical conductivity and mechanical robustness by fostering uniform filler dispersion and resilient conductive networks. Microstructural analysis using SEM, elucidated the mechanisms underpinning ink degradation, revealing that defects such as incomplete sintering, particle agglomeration, and void formation exacerbate electrical resistance and mechanical failure during cyclic torsion. Conversely, inks with well-dispersed particles and continuous conductive pathways exhibited superior endurance against fatigue-induced damage. It is not only offering a foundation for designing ink formulations with enhanced durability but also contribute to the advancement of reliable flexible electronic components capable of enduring dynamic mechanical stresses. Future research should focus on further optimisation of sintering parameters and the inclusion of additives to improve interfacial adhesion and mechanical flexibility, thereby prolonging the operational lifespan of printed electronics in real-world applications.

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Author Contributions

All authors contributed toward data analysis, drafting and critically revising the paper and agree to be accountable for all aspects of the work.

Disclosure of Conflict of Interest

The authors have no disclosures to declare.

Compliance with Ethical Standards

The work is compliant with ethical standards.

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