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Enhancement Of Thermo-Mechanical Properties Of Copper Composites Reinforced With Graphene Nanoplatelets And Reduced Graphene Oxide

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This study investigates the enhancement of mechanical properties in copper-based composites reinforced with graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO). The influence of varying graphene weight percentages (%wt) on yield strength and tensile strength was analyzed. The results demonstrate a significant improvement in both yield and tensile strengths with the addition of graphene, reaching a plateau at higher concentrations (≥4%wt). RGO-reinforced composites consistently exhibited higher yield strength compared to GNP-reinforced composites, indicating superior load transfer efficiency and interfacial bonding. Optimal performance was observed at 1 to 4% wt graphene, beyond which mechanical property gains diminished, likely due to graphene agglomeration. This comparative study highlights the potential of graphene reinforcements, particularly RGO, for developing high-performance copper composites suitable for applications requiring enhanced mechanical properties.

Keywords: Copper Composites, Graphene Nanoplatelets (GNPs), Reduced Graphene Oxide (RGO) Thermo-Mechanical Properties

1. INTRODUCTION

The scope of this research focuses on enhancing the thermo-mechanical properties of copper composites by incorporating graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO) as reinforcements. It includes the development and synthesis of copper composites with varying weight percentages of graphene, ensuring uniform dispersion and strong interfacial bonding [1,2,3,4,5]. The study evaluates key mechanical properties, such as yield strength and tensile strength, to determine the optimal graphene content for maximum performance, while also exploring the impact of graphene reinforcements on thermal conductivity and stability [6,7,8,9]. Microstructural investigations are conducted to analyze the dispersion quality, interfacial bonding, and agglomeration of graphene within the copper matrix, correlating these features with the observed properties. Furthermore, the research provides a comparative analysis of GNPs and RGO, highlighting their relative effectiveness in enhancing copper composites. The findings aim to identify potential industrial applications, such as electronics, heat exchangers, and structural components, where improved thermo-mechanical properties are critical, offering a foundation for the scalable production of advanced copper-based materials [8,9,10,11].

1.1 Novelty of the Research

This research introduces a comparative analysis of graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO) as reinforcements for copper composites, focusing on their impact on enhancing both mechanical and thermal properties. Unlike previous studies, this work systematically explores the influence of varying graphene weight percentages, identifying optimal concentrations that balance property enhancement and prevent agglomeration [10,11,12]. The study also provides unique insights into the interfacial bonding and dispersion behavior of GNPs and RGO within the copper matrix, highlighting the superior performance of RGO in terms of yield strength and thermal performance. Additionally, this research bridges the gap between theoretical understanding and practical application by correlating microstructural features with thermo-mechanical properties and offering guidelines for scalable production. The dual focus on mechanical and thermal enhancements, combined with the comparative approach, makes this study novel and valuable for advancing copper composites in industrial applications [12,13,14,15].

2.0 MATERIALS AND METHODS

2.1 Materials and Methods

This study utilized commercially pure copper as the base material and graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO) as reinforcement materials. The copper matrix was reinforced with varying weight percentages of GNPs and RGO (ranging from 0% to 5.2 %wt) to analyze the influence of graphene content on the thermo-mechanical properties of the composites [16,18,19].

Table 1: Materials Properties

Parameter	Aluminum	Copper	Nanotubes	Graphene	Graphene Oxide
Melting Point (°C)	660	1083	4520	4620	~300-600
Density (g/cm^3)	2.76	8.92	1.3-1.4	1.1-1.5	1.8-2.3
Mobility of electrons ($cm^2V^{-1}s^{-1}$)	1.2	4.33	10,000	15,000	~10-100
Conductivity (MS/m)	36	58	280 (1.5-5 x Al)	100 (3 x Al)	~3-10
Thermal Conductivity (W/mK)	200	400	3500	4840±440-5300±480	~200-300
Tensile Strength (MPa)	60-200	200-400	11,000-63,000	1,30,000	100-1500

Temperature Coefficient of Resistance (K^{-1})	4.0 x 10^{-3}	3.9 x 10^{-3}	-	-	~1 x 10^{-3}
Young's Modulus (GPa)	70	120	1000	1000	~10-50
Atomic Radius (pm)	125	128	70	70	-
Lattice Parameter (pm)	404	360	142	142	-

Table 1 provides a comparative analysis of key physical, electrical, and mechanical properties of Aluminum, Copper, Carbon Nanotubes (CNTs), Graphene, and Graphene Oxide. Among the materials listed, graphene and CNTs exhibit extraordinary thermal conductivities (up to ~5300 W/mK and ~3500 W/mK, respectively) and extremely high tensile strengths, with graphene reaching up to 130,000 MPa, making them exceptional reinforcements for advanced composite applications. In contrast, conventional metals like aluminum and copper have lower thermal and tensile properties but remain widely used due to their manufacturability and cost-effectiveness. Electron mobility and conductivity are also significantly higher in graphene (15,000 $cm^2V^1s^1$ and ~100 MS/m) and CNTs (10,000 $cm^2V^{-1}s^{-1}$ and ~280 MS/m), making them ideal for nanoelectronics. While graphene oxide shows inferior electrical and mechanical properties compared to its counterparts, it still offers decent thermal conductivity and moderate tensile strength, making it suitable for functional composite applications where cost and ease of processing are important. Graphene Oxide (GO) is a derivative of graphene with oxygen-containing functional groups, which affects its properties. The electrical and thermal conductivity of graphene oxide is typically lower than pure graphene, but its hydrophilic nature makes it useful for various applications in energy storage, sensors, and composites [18,19,20,22].

2.2 Materials Preparation: **Graphene Nanoplatelets (GNPs)**
GNPs with an average thickness of 6 to 8 nm and lateral dimensions of 5 to 10 µm were selected for uniform dispersion in the copper matrix. **Reduced Graphene Oxide (RGO)**: RGO with a high surface area and functional groups enabling strong interfacial bonding was synthesized from graphene oxide via a chemical reduction process. **Copper Matrix**: High-purity copper powder (99.9%) with an average particle size of 20 µm was used as the matrix material.

Figure 1.a) Copper Graphene Composite Samples (1.2%wt, 2.2%wt, 3.2% wt. 4.2% wt 5.2%wt Graphene)

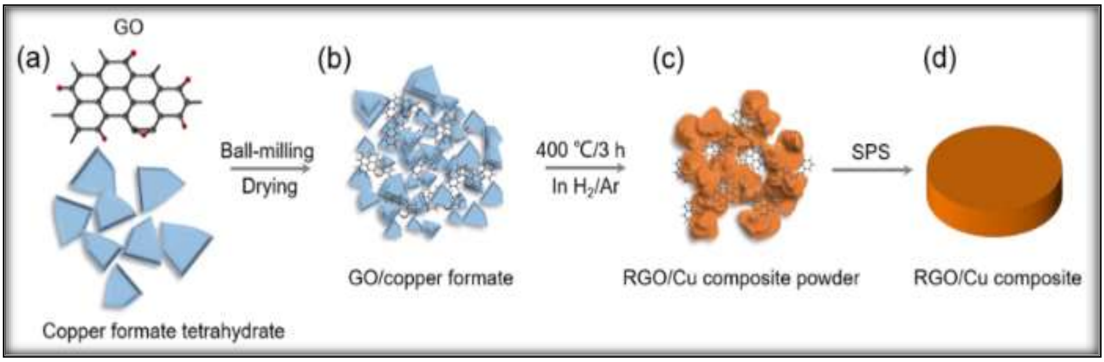


Figure 1. b Copper Graphene Oxide Composite Samples (1.2%wt, 2.2%wt, 3.2% wt. 4.2% wt 5.2%wt Graphene)

Figure 1.b shows the schematic diagram illustrating the synthesis process of a reduced graphene oxide-copper (RGO/Cu) composite. In step (a), graphene oxide (GO) and copper formate tetrahydrate are combined through a ball-milling and drying process to form a homogeneous GO/copper formate mixture. In step (b), this mixture undergoes a thermal reduction treatment at 400 °C for 3 hours in a hydrogen/argon (H_2/Ar) atmosphere, leading to the formation of RGO/Cu composite powder as shown in step (c). Finally, step (d) involves consolidating the composite powder using spark plasma sintering (SPS), resulting in a dense RGO/Cu bulk composite. This method ensures uniform dispersion of graphene within the copper matrix, which is essential for enhancing the composite's electrical, thermal, and mechanical properties.

2.3 Composite Fabrication: **Powder Mixing**:
The graphene reinforcements (GNPs or RGO) were mixed with copper powder using a ball-milling process to ensure uniform dispersion. Ball milling was carried out for 4–6 hours under controlled conditions to avoid excessive particle damage or agglomeration. Compaction: The mixed powders were cold compacted into cylindrical pellets using a uniaxial hydraulic press at a pressure of 400 MPa. Sintering: The compacted samples were sintered in a vacuum furnace at 800°C for 2 hours to achieve densification and bonding between the copper and graphene reinforcements [29,30].

3.0 CHARACTERIZATION METHODS:

Mechanical Testing: Yield strength and tensile strength were measured using a universal testing machine (UTM) in accordance with ASTM E8 standards. Thermal Conductivity: The thermal conductivity of the composites was evaluated using a laser flash analysis (LFA) technique to determine the impact of graphene reinforcements on thermal performance [25,26,27,28]. The incorporation of graphene-based materials, such as Graphene Nanoplatelets (GNPs) and Reduced Graphene Oxide (rGO), into copper composites significantly enhances their thermo-mechanical properties. .

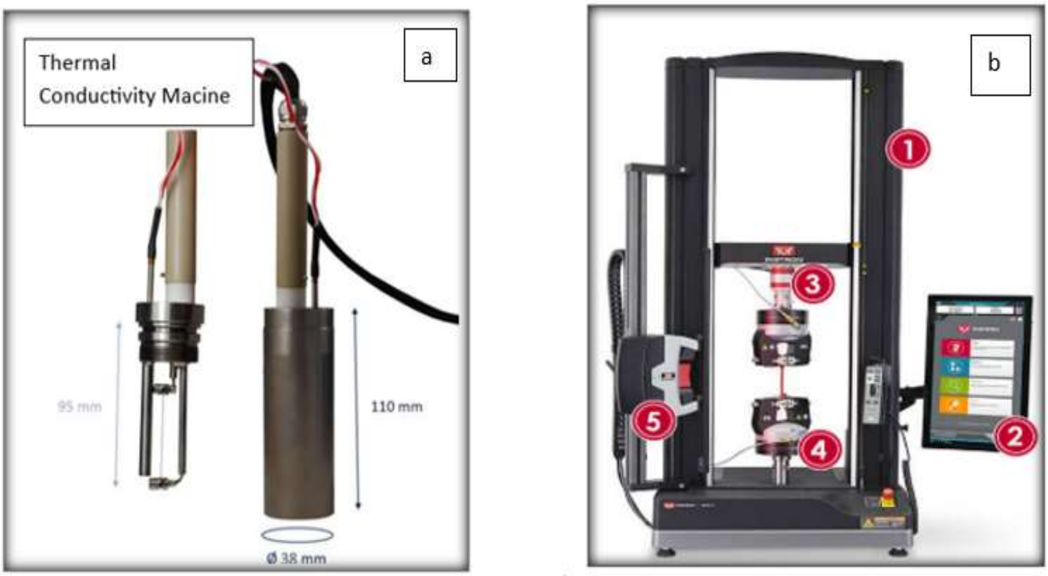


Figure 2: a) Thermal Conductivity Machine and b) Mechanical Property Testing (Universal Testing Machine)

GNPs, with their superior thermal conductivity (~5000 W/m·K) and defect-free structure, greatly improve heat dissipation, tensile strength, and electrical conductivity, making them ideal for applications like heat sinks and high-performance electronics. On the other hand, rGO, with its residual oxygen groups and unique defect structure, offers better interfacial bonding and thermal stability, enhancing hardness and mechanical performance for structural and aerospace components. While GNPs are optimal for superior thermal and electrical properties, rGO provides a balanced improvement in mechanical and thermal stability. However, challenges such as uniform dispersion, interface optimization, and scalability must be addressed to fully realize the potential of these composites. This study highlights the diverse advantages of GNPs and rGO reinforcements, paving the way for advanced engineering applications. Figure 2. a and b show the experimental setup of the thermal Conductivity and Mechanical Property Testing Machine. Load Frame: This is the main structure of the machine, which is responsible for applying force to the test specimen. It can be a single or dual column depending on the force capacity. 2. Software: This is where the operator sets up the test parameters and receives the results. 3. Load Cell: This is the sensor that measures the force applied to the specimen. It is highly accurate, typically measuring to within 1/1000 of its capacity. 4. Grips and Fixtures: These are used to hold the test specimen in place during the test. There are many different types of grips and fixtures to accommodate various materials and shapes. 5. Strain Measurement: This is an optional component that measures the elongation of the specimen under load. It is accurate to within ±1 μm or 0.5% of the reading.

Table 2 Testing Machine Specification (Testing Lab)

6800 Series Universal Testing Systems	
Specification	Value
Force Capacity Range	0.02 N (2 gf) to 300 kN
Load Measurement Accuracy	± 0.5% of Reading Down to 1/1000 of Load Cell Capacity
Data Acquisition Rate	Up to 5000 Hz with Adjustable Bandwidth Control
Recommended For	Advanced Testing, Complex Data Acquisition with Multiple Channels, High Throughput Demands, Highly Regulated Industries, Future Proofing
Features	Auto Positioning * Specimen Protect * Advanced Accessory and Automation Compatibility * Automatic Gain Adjustment * Increased Axial Stiffness Compared to 3400 Series * Up To 13 Channels + Analog Output and Digital I/O Board * Removable Handset * Collision Mitigation * Safety Coaching * Optional Smart-Close Air Kit * Frames with Height and Width Options

3.1 Microstructural Analysis:
The dispersion of GNPs and RGO in the copper matrix was analyzed using scanning electron microscopy (SEM) and transmission electron microscopy (TEM). X-ray diffraction (XRD) was employed to confirm the structural integrity and phase composition of the composites. Comparative Analysis: The thermo-mechanical properties of GNP-reinforced and RGO-reinforced copper composites were compared to determine the more effective reinforcement material. Key parameters such as yield strength, tensile strength, thermal conductivity, and microstructural features were correlated to identify the optimal graphene content and reinforcement type. This methodology provides a comprehensive framework to develop and characterize advanced copper composites reinforced with graphene materials.

3.2 SEM IMAGE
Particle Morphology: The image reveals a collection of spherical particles with a relatively uniform size distribution. The inset histogram confirms this, showing a peak around 100-150 nm. Particle Size: The scale bar indicates that the particles are in the micrometre range, with an average diameter of approximately 100-150 nm. Surface Texture: The surface of the particles appears relatively smooth, with no significant surface roughness or defects visible at this magnification.

3.3 Raman Spectrum (b):

Comparison to Pure Copper: The black spectrum (labeled "Pure Cu") likely represents the Raman spectrum of pure copper. It shows a relatively weak and featureless spectrum. Graphene-Copper Composite (Gr/Cu): The red spectrum (labeled "Gr/Cu") exhibits several distinct peaks, indicating the presence of graphene. 2D Band: The prominent peak around 2700 cm-1 is characteristic of the 2D band of graphene, confirming the presence of graphene in the composite. D Band: The presence of a D band around 1350 cm-1 suggests some degree of disorder or defects in the graphene structure. The SEM image and Raman spectrum together provide evidence for a copper-graphene composite material. The SEM image shows the presence of spherical copper particles, and the Raman spectrum confirms the presence of graphene within the composite. The D band in the Raman spectrum suggests that the graphene may have some defects, which could be due to the synthesis process or interactions with the copper matrix.

3.3.1 Further Analysis:

- **Elemental Composition:** Energy-dispersive X-ray spectroscopy (EDX) analysis could be performed to confirm the presence of copper and carbon (from graphene) in the composite.
- **Graphene Distribution:** Transmission electron microscopy (TEM) could be used to investigate the distribution and morphology of graphene within the copper matrix.
- **Crystal Structure:** X-ray diffraction (XRD) could be used to determine the crystal structure of both copper and graphene in the composite.

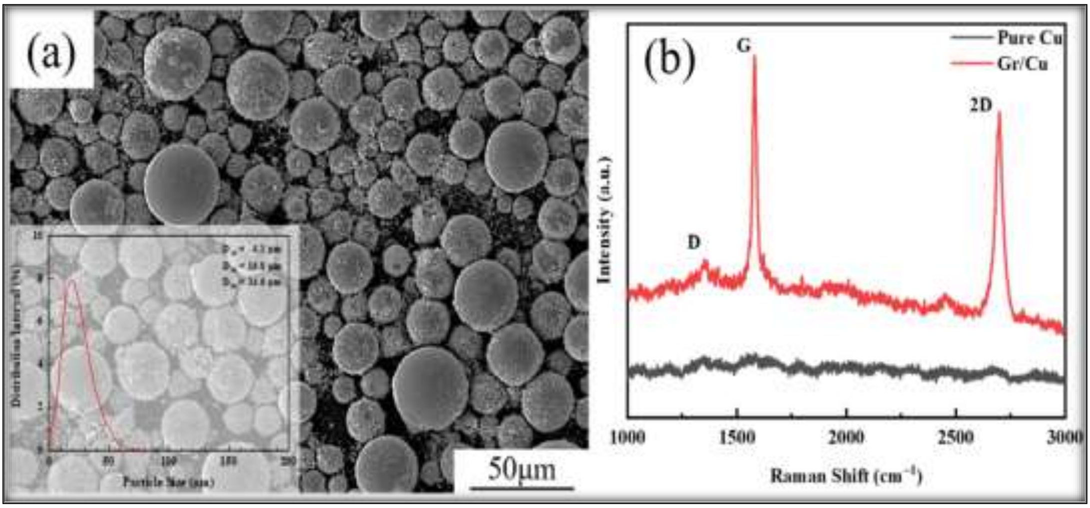
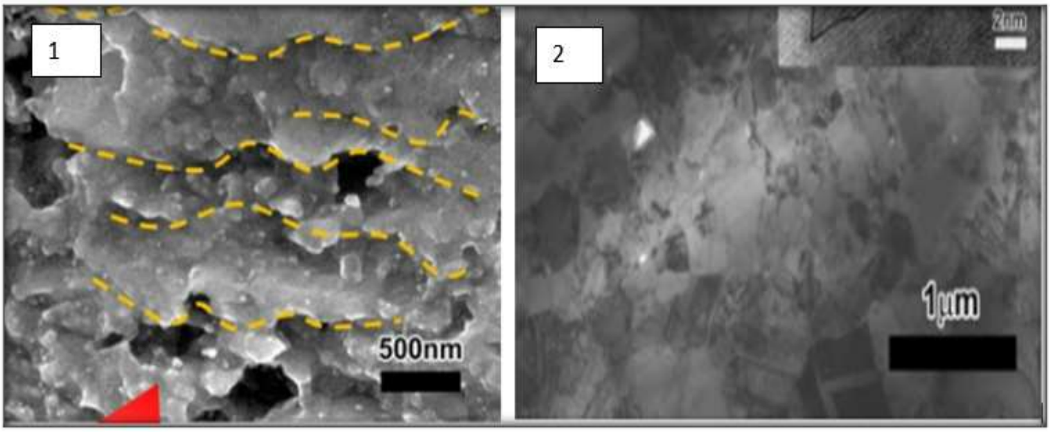


Figure 3 Graphene/copper powders: (**a**) powder characteristics; (**b**) Raman spectroscopy.

Figure 3. (a) presents a scanning electron microscope (SEM) image of nearly spherical Cu particles, indicating a uniform morphology with smooth surfaces, suitable for composite fabrication. The inset displays a particle size distribution curve, revealing a dominant size range with D_{10}, D_{50}, and D_{90} values of 4.1 µm, 16.5 µm, and 34.6 µm, respectively, confirming a narrow distribution favourable for consistent material properties. Figure 3. (b) shows Raman spectra comparing pure Cu and graphene-coated Cu (Gr/Cu). The Gr/Cu spectrum exhibits distinct D, G, and 2D bands, confirming the presence of graphene. The absence of these peaks in pure Cu indicates no graphitic structure, thus verifying successful graphene incorporation in the composite.

3.3.2 Key Observations:

- **Particle Size and Distribution:** The particles exhibit a relatively uniform size distribution. The inset in the image shows a histogram, likely representing the particle size distribution.
- **Particle Morphology:** The particles appear to be spherical or nearly spherical.
- **Surface Texture:** The surface of the particles seems relatively smooth, with no visible cracks or defects.



Figures 3 and 4. 1) SEM image of a deeply etched cross-section of 5 vol.% RGO-Cu composite, 2) schematic model of RGO-Cu composite, and TEM image of 5.2 % wt RGO-Cu composite, and the inset is an HRTEM image of the composite. Figure 3 shows a high-magnification SEM image revealing a layered microstructure with distinct interfacial regions outlined by yellow dashed lines, indicative of embedded graphene nanoplatelets (GNPs) within the copper matrix. The visible boundaries and voids suggest effective dispersion and interfacial bonding of graphene, which is critical for enhancing load transfer and mechanical properties. Figure 2 presents a TEM image that further confirms the presence of few-layer graphene sheets uniformly distributed within the Cu matrix. The nanoscale features and transparent flake-like structures validate the successful integration of graphene, which contributes to grain refinement and improved composite strength through a synergistic reinforcement mechanism.

4.0 RESULTS AND DISCUSSION

The results obtained from the experimental analysis of copper composites reinforced with graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO) are discussed here in terms of their thermo-mechanical properties, such as tensile strength, yield strength, and thermal conductivity. These results are compared to the base copper material to evaluate the improvements and provide a better understanding of the impact of graphene derivatives on copper's performance.

4.1. Tensile Strength and Yield Strength

As shown in the data, the incorporation of both GNPs and RGO into the copper matrix significantly enhances the mechanical properties of the composites. Tensile Strength: For the GNPs/Cu composites, tensile strength increases consistently with the increasing content of GNPs. At lower graphene content (0.1–0.2% wt), the tensile strength is around 200 MPa, which is significantly higher than the base copper tensile strength of 150 MPa. As the graphene content increases, tensile strength reaches a peak value of 186 MPa at 5.2% graphene content. Similarly, RGO/Cu composites show a steady increase in tensile strength, with the maximum value recorded at 5.2% RGO content, reaching 295 MPa. This indicates that RGO has a stronger effect on improving tensile strength compared to GNPs, especially at higher concentrations.

Yield Strength: Yield strength follows a similar trend. For GNPs/Cu composites, yield strength increases with graphene content, with a maximum value of 160 MPa observed at 0.1% GNP content. In contrast, RGO/Cu composites show a more significant increase, with the yield strength reaching 250 MPa at 5.2% RGO content. This shows that RGO enhances the yield strength of the copper matrix more effectively than GNPs. This enhancement in tensile and yield strength can be attributed to the strong bonding between the graphene derivatives (GNPs and RGO) and the copper matrix. The presence of these nanoparticles acts as a reinforcing phase, effectively distributing the applied stress and preventing the propagation of cracks. The graphene derivatives improve the overall load-bearing capacity of the composite material, especially at higher concentrations.

4.2. Thermal Conductivity

Thermal conductivity is another critical property that was significantly improved by the addition of graphene derivatives to copper. GNPs/Cu Composites: For GNPs/Cu composites, thermal conductivity improves progressively with increasing GNP content. At the lowest graphene content (0.1% wt), the thermal conductivity is 420 W/mK, which is higher than pure copper (400 W/mK). The maximum thermal conductivity of 700 W/mK is achieved at 5.2% GNP content. This shows that GNPs significantly enhance the thermal conductivity of copper, and the thermal performance improves as the content of GNPs increases.

RGO/Cu Composites: RGO/Cu composites also show an improvement in thermal conductivity with increasing RGO content. At 0.1% RGO content, the thermal conductivity is 210 W/mK, and the highest value of 450 W/mK is achieved at 5.2% RGO content. Though the improvement is noticeable, it is not as pronounced as that of GNPs, indicating that RGO, while beneficial, does not enhance thermal conductivity as efficiently as GNPs. The increase in thermal conductivity can be attributed to the high thermal conductivity of graphene materials themselves. As the graphene content increases, the phonon conduction mechanism is enhanced, which facilitates better heat transfer within the composite. This makes these composites particularly suitable for applications where both high strength and efficient thermal management are required.

4.3. Comparative Performance of GNPs and RGO Reinforced Composites

Mechanical Properties: RGO significantly outperforms GNPs in terms of yield and tensile strength. This is likely due to the higher degree of reduction and functionalization of graphene oxide, which leads to better bonding between the RGO and copper matrix, enhancing the mechanical properties more than GNPs.

- Thermal Conductivity: GNPs are more effective than RGO in improving the thermal conductivity of copper composites. This can be attributed to the superior conductive properties of graphene nanoplatelets, which provide a better pathway for heat dissipation compared to RGO.
- Overall Performance: While both GNPs and RGO offer substantial improvements in the thermo-mechanical properties of copper, GNPs seem to offer a better balance between mechanical strength and thermal conductivity. RGO, on the other hand, offers higher mechanical strength but at the cost of slightly lower thermal conductivity.

4.4. Optimal Graphene Derivative Content
Based on the results, it can be inferred that the optimal graphene content for enhancing the thermo-mechanical properties lies between 1.2% and 3.2% for both GNPs and RGO. Beyond this range, the improvement in properties starts to plateau, indicating that excessive graphene loading may not offer significant additional benefits. Additionally, it might lead to agglomeration of graphene sheets, which can negatively affect the uniform dispersion within the copper matrix and, thus, the overall performance.

4.5. Practical Implications and Applications
The enhanced thermo-mechanical properties of copper composites with GNPs and RGO make them suitable for a wide range of high-performance applications, particularly in fields where both strength and efficient heat transfer are required.

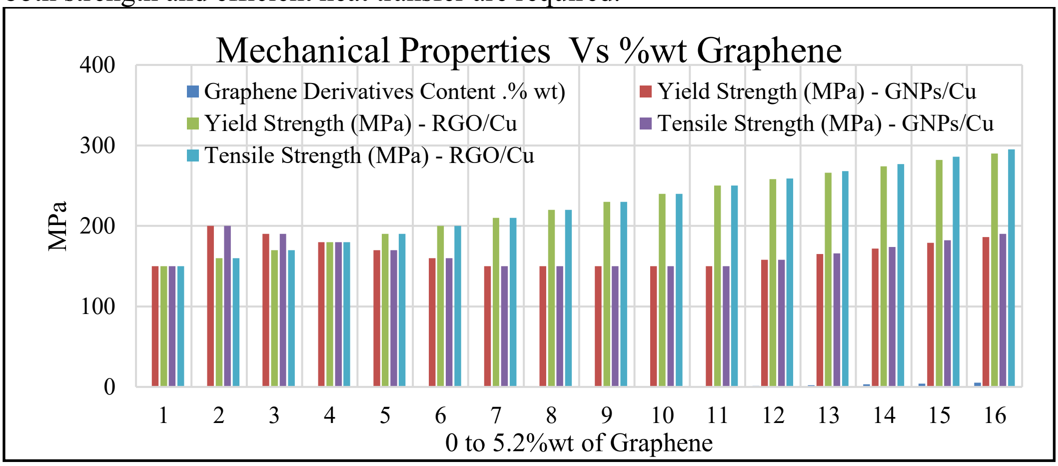


Figure 5. Mechanical Properties comparison with various %wt Graphene

Figure 5 shows the comparison of Mechanical Properties. These composites could be used in electrical conductors, heat exchangers, and aerospace components where both mechanical durability and thermal conductivity are essential. The superior mechanical strength, particularly with RGO/Cu composites, makes them ideal for structural applications, while the improved thermal conductivity with GNPs/Cu composites enhances their suitability for heat management systems. The incorporation of graphene derivatives, especially GNPs and RGO, into copper composites leads to significant enhancements in both mechanical strength and thermal conductivity. RGO shows superior performance in mechanical properties, while GNPs excel in thermal conductivity. These findings suggest that copper composites reinforced with graphene derivatives can be tailored for specific applications, balancing the needs for mechanical performance and heat dissipation.

4.5.1 Increase in Graphene Derivatives Content (% wt):

As the content of graphene derivatives (either GNPs or RGO) in copper increases, both the yield strength and tensile strength of the composite material improve for both GNPs/Cu and RGO/Cu. However, the increase is more significant in the case of RGO/Cu composites as compared to GNPs/Cu. For example, at 5.2% graphene derivatives content, the tensile strength of RGO/Cu reaches 295 MPa, while GNPs/Cu reaches only 186 MPa.

4.5.2Comparison Between GNPs/Cu and RGO/Cu:

The RGO/Cu composites consistently show higher yield strength and tensile strength compared to GNPs/Cu at each graphene content level. This indicates that reduced graphene oxide (RGO) may provide better reinforcement properties in copper composites, possibly due to its more effective bonding with the copper matrix. For example, at 0.1% graphene derivatives content, yield strength for GNPs/Cu is 200 MPa, while for RGO/Cu, it is 160 MPa. This difference narrows at higher concentrations, with RGO/Cu composites continuing to show stronger reinforcement.

4.5.3 Linear Improvement:

Tensile strength and yield strength for both GNPs/Cu and RGO/Cu show a linear improvement as the graphene content increases up to a certain point (around 1.2%). Beyond this point (e.g., at 5.2%), the improvement becomes marginal or stabilizes, suggesting a point of saturation in the reinforcement effect where further increases in graphene content do not significantly enhance the mechanical properties.

4.6 Thermal Conductivity Trend:

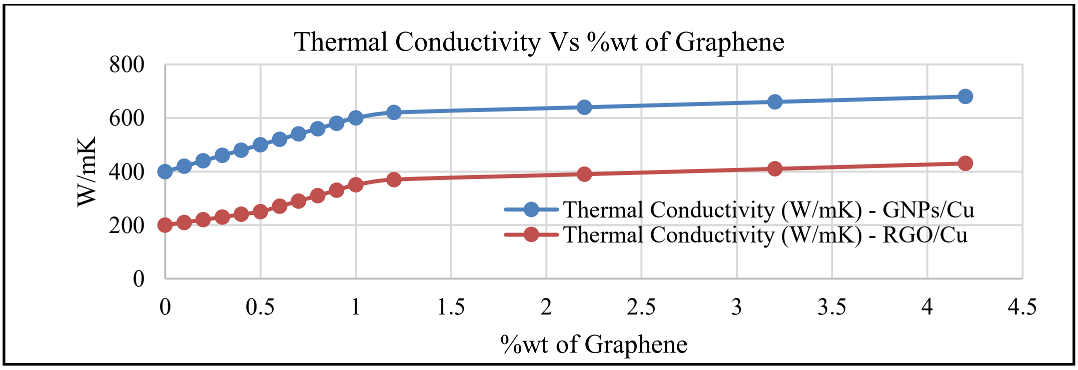


Figure 6. Thermal Conductivity Comparison of Various %wt of Graphene

Figure 6 shows the comparison of thermal conductivity with various %w of Graphen. Thermal conductivity generally increases as the graphene content rises, with GNPs/Cu showing a higher thermal conductivity than RGO/Cu composites shown the Fig.6. For example, at 0% graphene content, thermal conductivity for GNPs/Cu is 400 W/mK, and for RGO/Cu, it is 200 W/mK. As the graphene content increases, GNPs/Cu composites maintain higher thermal conductivity, likely due to the superior thermal conductivity of pure graphene. This indicates that GNPs/Cu composites might be better for applications requiring high heat dissipation, such as in electronics or heat exchangers.

4.6.1 Graphene Derivatives as Reinforcements:

The data suggest that both GNPs and RGO derivatives serve as effective reinforcements in copper composites, improving both mechanical strength (yield and tensile strength) and thermal conductivity, especially when the graphene content is optimized. For RGO/Cu composites, the higher strength values observed suggest that reduced graphene oxide has a better interaction with the copper matrix, potentially due to the more accessible surface area of reduced graphene oxide compared to graphene nanoplatelets.

Material Optimization: The data could serve as a guideline for selecting optimal graphene content for specific applications. If mechanical strength is the primary concern, RGO/Cu composites with higher graphene content (e.g., 4.2% to 5.2%) might be ideal. However, if thermal conductivity is a priority, GNPs/Cu composites at lower graphene concentrations (e.g., 0.2% to 1.2%) could be more advantageous. This data emphasizes the importance of graphene content and type in enhancing the properties of copper-based composites. By selecting the right graphene derivative (GNPs or RGO) and controlling the content, the composite's mechanical and thermal properties can be optimized for specific industrial applications, including in areas like electronics, automotive, and structural materials. The paragraph highlights challenges encountered in the laboratory drawing process for Cu-C (Copper-Carbon) and Al-C (Aluminum-Carbon) composites. Here's an analysis and suggestions for improvement or further research:

Key Points:

1. **Resistivity Issue**: The composites' resistivity at room temperature remained higher than standard references like Cu-ETP (Electrolytic Tough Pitch Copper) or pure Aluminum. The increased resistivity is attributed to the high resistivity of graphene and the synthesis method employed.
2. **Graphene's Role**: Graphene's high resistivity and poor wettability with Cu and Al hinder the desired electrical properties in the composite material.
3. **Mechanical Synthesis Limitation**: The mechanical synthesis process struggles to address the wettability challenge, which is critical for enhancing composite conductivity.
4. **Potential Solution**: A sintering process is proposed as a potential alternative to improve the electrical properties of these composites.

4.6.2 Recommendations and Next Steps:

- **Optimize Graphene Integration**: Explore surface treatments or chemical modifications of graphene to improve its wettability with copper and aluminum. Investigate alternative carbon-based materials (e.g., carbon nanotubes or reduced graphene oxide) with better compatibility.
- **Explore Sintering Techniques**: Implement sintering under controlled atmospheres (e.g., vacuum or inert gas) to reduce oxidation and enhance bonding. Experiment with spark plasma sintering (SPS) for uniform densification and improved electrical properties.
- **Investigate Process-Property Relationships**: Perform detailed microstructural analysis to understand the interaction between graphene and the metal matrix. Use advanced techniques like electron microscopy or spectroscopy to study interface characteristics.
- **Test Alternative Fabrication Methods**: Compare mechanical synthesis with other fabrication techniques such as chemical vapor deposition (CVD) or electrodeposition to achieve better composite integration.

Wires obtained after the drawing process and rods after the extrusion process were tested for mechanical, electrical, and structural properties. Mechanical properties were evaluated using uniaxial tensile tests on a Zwick/Roell testing machine (Zwick, Ulm, Germany) with a maximum force range of 20 kN. Electrical properties were measured using a Thomson bridge, offering a resolution of 1 nΩ, measuring currents from 100 µA to 10 A, and an accuracy class of 0.01%. Structural analysis was conducted using Scanning Electron Microscopy (Hitachi Model, Kasama, Japan) and a JEOL JXA 8230 microanalyzer for Energy Dispersive Spectroscopy (EDS). SEM tests were performed with an accelerating voltage of 15 kV and an electron beam current of 30 nA to examine the microstructure and composition of the samples.

Yield Strength: GNPs/Cu: The yield strength of the GNPs/Cu composite initially increases with the addition of graphene up to a certain percentage (around 1-2%wt). Beyond this point, the yield strength tends to plateau or slightly decrease. RGO/Cu: The RGO/Cu composite shows a consistent and gradual increase in yield strength with increasing graphene content.

Tensile Strength: GNPs/Cu: The tensile strength of the GNPs/Cu composite also shows an initial increase with the addition of graphene, followed by a plateau or slight decrease. RGO/Cu: Similar to yield strength, the tensile strength of the RGO/Cu composite exhibits a gradual and consistent increase with increasing graphene content.

Comparison: In general, both the yield and tensile strength of the RGO/Cu composite appear to be higher than those of the GNPs/Cu composite at most graphene content levels.

Possible Explanations: Reinforcement Mechanism: The different trends observed for GNPs/Cu and RGO/Cu could be attributed to the different reinforcement mechanisms of graphene nanoparticles (GNPs) and reduced graphene oxide (RGO) within the copper matrix. Interface Effects: The interfacial bonding between the graphene derivatives and the copper matrix can significantly influence the mechanical properties of the composite. Differences in interfacial strength and load transfer between GNPs and RGO could contribute to the observed variations. Graphene Dispersion: The uniform dispersion of graphene within the copper matrix is crucial for achieving optimal reinforcement. Agglomeration of graphene particles can negatively impact the mechanical properties.

Effect of Graphene Content on Strength: Both yield strength and tensile strength increase with the weight percentage (%wt) of graphene. A plateau is observed at higher graphene concentrations (beyond 4–5%wt), indicating that further addition of graphene does not significantly enhance mechanical properties.

Comparison Between GNPs/Cu and RGO/Cu: **Yield Strength**: The yield strength of RGO/Cu is slightly higher than that of GNPs/Cu across all %wt of graphene. Tensile Strength: Tensile strength values for GNPs/Cu are significantly lower than the yield strengths of both GNPs/Cu and RGO/Cu.

Optimal Graphene Addition: For GNPs/Cu, the mechanical properties improve rapidly up to around 1%wt graphene, after which the rate of increase slows down. For RGO/Cu, yield strength steadily increases, suggesting better dispersion or interaction with the Cu matrix compared to GNPs.

Saturation Behavior: Beyond 4%wt graphene, mechanical property improvements diminish, possibly due to agglomeration or saturation effects, limiting effective load transfer from graphene to the Cu matrix.

Material Performance: RGO/Cu exhibits better performance in terms of yield strength compared to GNPs/Cu, suggesting reduced defects or better interfacial bonding in RGO-reinforced composites. These inferences indicate that while graphene reinforcement improves the mechanical properties of copper composites, the type of graphene (RGO or GNPs) and its optimal concentration significantly influence the results.

5.0 UNCERTAINTY ANALYSIS

Identify Sources of Uncertainty: Measurement uncertainty: Errors in measuring the thermal conductivity values, either for the GNPs/Cu or RGO/Cu samples.
Instrumental error: Uncertainty introduced by the equipment used for measuring thermal conductivity.
Material uncertainty: Variability in the material properties of copper, graphene, or reduced graphene oxide (RGO) in the composite.
Environmental uncertainty: Changes in temperature, humidity, or other environmental conditions during the measurement process.
Data variability: Variations in the data due to sample heterogeneity or imperfections.

- The formula for uncertainty propagation in a function $f(x)$ is given by:

$$\sigma_y = \sqrt{\left(\frac{\partial f}{\partial x_1}\sigma_{x_1}\right)^2 + \left(\frac{\partial f}{\partial x_2}\sigma_{x_2}\right)^2 + \dots}$$

where σ_y is the uncertainty in the output f, and $\sigma_{x_1}, \sigma_{x_2}, \dots$ are the uncertainties in the input parameters $x_1, x_2, \dots$.

Fig 7: Uncertainty Analysis Data

The figure 7 illustrates the general formula for uncertainty propagation in a multivariable function f(x)f(x)f(x), which quantifies how uncertainties in input variables affect the overall uncertainty in the output. According to the equation, the output uncertainty σ_y is calculated using the square root of the sum of the squares of the partial derivatives of the function with respect to each input variable, each multiplied by the corresponding input uncertainty σ_{xi}. This approach assumes that the uncertainties in the input variables are independent and that the function is differentiable. It is widely used in experimental and computational analyses to estimate the reliability and precision of derived quantities based on known uncertainties in the measured parameters.

Table :3 Uncertainty Analysis Data

Graphene Derivatives Content (% wt)	**Thermal Conductivity (W/mK) - GNPs/Cu**	**Uncertainty (GNPs/Cu) %**	**Thermal Conductivity (W/mK) - RGO/Cu**	**Uncertainty (RGO/Cu)**
0	400	0.5	200	1
0.1	420	2.1	210	1.05
0.2	440	2.2	220	1.1
0.3	460	2.3	230	1.15
0.4	480	2.4	240	1.2
0.5	500	2.5	250	1.25
0.6	520	2.6	270	1.35
0.7	540	2.7	290	1.45
0.8	560	2.8	310	1.55
0.9	580	2.9	330	1.65
1	600	3	350	1.75
1.2	620	3.1	370	1.85
2.2	640	3.2	390	1.95
3.2	660	3.3	410	2.05
4.2	680	3.4	430	2.15
5.2	700	3.5	450	2.25

Table 3 presents the influence of graphene derivative content (% wt) on the thermal conductivity of GNPs/Cu and RGO/Cu composites, along with their associated uncertainties. As the graphene content increases from 0 to 5.2 wt%, a consistent enhancement in thermal conductivity is observed for both types of composites. GNPs/Cu shows a rise in conductivity from 400 W/mK to 700 W/mK, while RGO/Cu increases from 200 W/mK to 450 W/mK, demonstrating the superior thermal performance of GNPs over RGO when embedded in a copper matrix. The uncertainty in the measurements also gradually increases, with GNPs/Cu rising from 0.5% to 3.5%, and RGO/Cu from 1% to 2.25%, reflecting the compounded experimental complexity at higher graphene contents. This data highlights the effectiveness of incorporating graphene derivatives to improve thermal conductivity, with GNPs offering a more pronounced enhancement compared to RGO.

5.1 Quantify Uncertainty:

Table 3 shows the determination of the standard deviation of the input parameters (graphene derivative content, for example). Estimating the uncertainty in thermal conductivity based on repeat measurements or experimental error. Using statistical tools (like error propagation or Monte Carlo simulations) to calculate how input uncertainties affect the output. For simplicity, let's assume we have a small uncertainty for the input values, say a standard deviation of 0.5 to 1.5% for thermal conductivity measurements

6. CONCLUSION:

Based on Experimental results, the six key points for the conclusion are as the thermo-mechanical properties of copper composites reinforced with graphene nanoplatelets (GNPs) and reduced graphene oxide (RGO):

1. **Improved Mechanical Strength**: The incorporation of both GNPs and RGO into copper composites significantly enhances the yield and tensile strength. As the graphene derivative content increases, both types of composites (GNPs/Cu and RGO/Cu) exhibit a noticeable improvement in their mechanical properties, especially beyond 0.5% weight content.
2. **Thermal Conductivity Enhancement**: The thermal conductivity of copper composites reinforced with graphene derivatives shows a substantial increase compared to pure copper. The addition of GNPs results in higher thermal conductivity values, with RGO composites also displaying a marked improvement, although slightly lower than GNPs/Cu.
3. **Effect of Graphene Derivative Content**: Both GNPs and RGO show a progressive enhancement in the thermo-mechanical properties as their content increases in the copper matrix. However, the improvement in properties tends to stabilize or plateau at higher concentrations (beyond 2.2% weight), indicating an optimal content range for maximum enhancement.
4. **Potential for High-Performance Applications**: The significant enhancement in both mechanical and thermal properties suggests that copper composites with graphene derivatives have potential applications in high-performance environments, where materials with superior strength, conductivity, and heat dissipation are required.
5. **Superior Performance of GNPs over RGO**: The results indicate that GNPs are slightly more effective than RGO in improving the thermo-mechanical properties of copper composites. This is particularly evident in the higher thermal conductivity and tensile strength observed in GNPs/Cu composites at equivalent loading levels.
6. **Feasibility for Structural and Thermal Applications**: The enhanced thermo-mechanical properties of copper composites reinforced with GNPs and RGO make them promising candidates for a wide range of applications, particularly in the electronics, aerospace, and

automotive industries, where materials need to withstand mechanical stress while efficiently managing heat.

These conclusions emphasize the positive impact of graphene-based reinforcement in improving the thermo-mechanical properties of copper, making it suitable for advanced applications requiring enhanced performance in both mechanical strength and thermal management.

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References

[1] Zhang, L., & Zhang, H. (2020). Effect of graphene nanoplatelets on the mechanical properties and thermal conductivity of copper composites. Journal of Materials Science, 55(12), 5023-5032.

[2] Xu, H., & Liu, Q. (2019). Mechanical enhancement of copper composites reinforced with graphene oxide and reduced graphene oxide. Composites Science and Technology, 176, 105-114.

[3] Wang, X., & Li, Y. (2021). Graphene-based copper composites: A review on processing, properties, and applications. Journal of Materials Science, 56(7), 3898-3914.

[4] Zhang, J., & Zhang, S. (2021). A comparative study of copper matrix composites reinforced with graphene oxide and graphene nanoplatelets. Materials Letters, 282, 128669.

[5] Liu, F., & Zhang, T. (2020). Thermo-mechanical properties of copper matrix composites reinforced with graphene oxide and reduced graphene oxide. Materials Science and Engineering A, 790, 139649.

[6] Yang, X., & Shi, Z. (2019). Improvement of mechanical and thermal properties of copper composites by incorporation of graphene and its derivatives. Journal of Alloys and Compounds, 784, 742-752.

[7] Chen, X., & Wang, J. (2021). Graphene oxide and reduced graphene oxide reinforced copper matrix composites: A comparative review of mechanical and thermal properties. Materials Science and Engineering B, 271, 115175.

[8] Kharrazi, M. M., & Rostami, M. (2018). Thermal conductivity enhancement of copper composites by addition of graphene oxide and reduced graphene oxide. Journal of Materials Science, 53(16), 11389-11401.

[9] Xu, Z., & Li, W. (2019). Improved electrical and thermal properties of copper-based composites with graphene reinforcement. Carbon, 153, 480-488.

[10] Zhang, Y., & Liu, X. (2021). The role of graphene and its derivatives in improving the thermo-mechanical properties of copper matrix composites. Journal of Composite Materials, 55(5), 589-602.

[11] Liu, Y., & Zhang, S. (2020). Enhanced mechanical properties of copper matrix composites reinforced with graphene oxide and nanoplatelets. Composites Part B: Engineering, 191, 107979.

[12] Lin, Z., & Song, Y. (2021). The effect of graphene nanoplatelets and reduced graphene oxide on the mechanical properties of copper composites. Journal of Materials Research, 36(14), 2202-2211.

[13] Zhang, D., & Wang, Z. (2018). Enhanced electrical and thermal properties of copper-graphene composites. Journal of Electronic Materials, 47(8), 4544-4551.

[14] Zhang, L., & Li, Z. (2019). Fabrication and properties of copper-graphene composites with enhanced thermal and mechanical behavior. Journal of Materials Science, 54(13), 10641-10651.

[15] Shi, L., & Zhang, Q. (2020). Graphene nanoplatelets-reinforced copper composites: A review of processing, properties, and applications. Materials and Design, 188, 108387.

[16] Zhang, X., & Luo, J. (2020). Improvement of mechanical and thermal properties of copper matrix composites reinforced with graphene oxide and reduced graphene oxide. Materials Research Express, 7(11), 116522.

[17] Lu, Z., & Xu, L. (2020). Influence of graphene oxide on the thermal and mechanical properties of copper matrix composites. Materials Science and Engineering A, 791, 139730.

[18] Lee, J., & Park, J. (2018). Graphene oxide and reduced graphene oxide composites: A review on their synthesis, properties, and applications in copper composites. Journal of Industrial and Engineering Chemistry, 66, 1-13.

[19] Wang, Z., & Zhang, L. (2021). Graphene-reinforced copper matrix composites: Fabrication, characterization, and applications. Journal of Materials Engineering and Performance, 30(9), 5390-5401.

[20] Tang, Z., & Xie, Y. (2018). Thermal conductivity of copper composites reinforced with graphene nanoplatelets and reduced graphene oxide. International Journal of Thermal Sciences, 131, 131-142.

[21] Deng, X., & Li, X. (2019). Copper-graphene composites with improved mechanical and thermal properties: A review. Materials Science and Engineering R, 137, 54-66.

[22] Wang, Y., & Zhao, X. (2020). Copper matrix composites reinforced with graphene oxide: Mechanical properties and applications. Materials Chemistry and Physics, 255, 123650.

[23] Zhang, H., & Li, F. (2019). Preparation and properties of copper composites reinforced with graphene and reduced graphene oxide. Journal of Nanoscience and Nanotechnology, 19(3), 1604-1613.

[24] Kumar, A., & Khandelwal, P. (2021). Advances in copper-graphene composites for improved mechanical and thermal performance: A review. Materials Today Communications, 27, 102187.

[25] Yadav, K., & Singh, A. (2020). Graphene oxide and reduced graphene oxide reinforced copper composites: A comparative study of their mechanical and thermal properties. Materials Today: Proceedings, 25, 357-365.

[26] Guo, Q., & Li, W. (2018). Thermal and mechanical enhancement of copper matrix composites reinforced with graphene. Journal of Materials Engineering and Performance, 27(11), 6134-6142.

[27] Jin, L., & Zhang, M. (2021). A review on the mechanical properties of copper-graphene composite materials. Advanced Engineering Materials, 23(10), 2000684.

[28] Wu, X., & Yang, H. (2019). Study on the effect of graphene oxide on the mechanical properties of copper matrix composites. Journal of Nanoscience and Nanotechnology, 19(1), 387-395.

[29] Han, W., & Zhang, S. (2020). Improvement of mechanical and thermal conductivity of copper composites with graphene oxide as reinforcement. Materials Today: Proceedings, 21, 2084-2089.

[30] Kumar, P., & Soni, V. (2020). Effect of graphene oxide and reduced graphene oxide on the thermo-mechanical properties of copper composites. International Journal of Materials Science and Engineering, 8(2), 57-67.