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Investigation of Carbon Fiber-Reinforced Composites through Electroless Nickel Plating

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ABSTRACT

The development of carbon fiber–reinforced composites (CFRCs) has significantly advanced material science by integrating high strength, low weight, and long-term durability into a single material system. In this study, electroless nickel (EN) plating was applied to carbon fiber rods to enhance their interfacial compatibility with the Al6061 alloy matrix fabricated through stir casting. Before plating, the fibers were cleaned, cut to size, sensitized, and activated before deposition under EN832 bath conditions. The treated fibers were then incorporated into molten Al6061 and solidified in preheated dies. Material characterization was carried out in accordance with ASTM standards, including density evaluation, Brinell and Vickers hardness testing, and pin-on-disc wear and friction analysis. Microstructural and compositional studies using SEM–EDX confirmed a uniform nickel coating with effective chemical distribution across the fiber surface. The Ni plating substantially improved wettability and interfacial adhesion, resulting in composites with higher hardness, improved strength, reduced density, lower coefficient of friction, and significantly enhanced wear resistance compared to unreinforced Al6061 alloy. An optimized nickel layer thickness provided strong bonding without compromising the integrity of the fibers. The objective of this study is to evaluate the influence of electroless nickel plating on interfacial bonding, mechanical behavior, and tribological performance of carbon fiber–reinforced Al6061 composites, and to establish its suitability for lightweight, high-performance engineering applications. The enhanced mechanical and tribological performance demonstrate that Ni-coated CF/Al6061 composites are promising candidates for aerospace, defense, automotive, and other advanced engineering industries.

INTRODUCTION

The increasing use of carbon fiber reinforced composites (CFRCs) has attracted significant attention in materials science due to their distinctive combination of properties, namely, high strength, low density, and

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excellent specific strength (Kumar et al., 2025). Carbon fibers can serve as reinforcing agents in a variety of matrices, including metals, polymers, and ceramics (Diefendorf, 1985). Among these, carbon fiber–reinforced metal matrix composites (CF-MMCs) are particularly promising as lightweight, high-performance materials for aerospace, automotive, and defense applications. However, one of the key challenges in CF-MMCs lies in the inherently weak bonding between carbon fibers and the metallic matrix, which often limits improvements in strength, toughness, and wear resistance (Zhu et al., 2024). To overcome this issue, several surface modification strategies have been explored. Electroless nickel plating has emerged as one of the most effective approaches, enabling the deposition of a uniform nickel layer onto carbon fiber surfaces through a chemical reduction process without requiring an external current. This modification improves the wettability of carbon fibers, thereby strengthening interfacial bonding with the metal matrix and enhancing the mechanical and tribological performance of the resulting composites (Su et al., 2005). Ali et al. (2019) reported a simple method to metallize fine polyester fabric by copper sensitization followed by silver electroplating, resulting in fabrics with high electrical conductivity, strong EMI shielding (30 MHz – 1.5 GHz), and efficient Joule heating performance. Durability tests under stretching, washing, oxidation, and sulfidation confirmed the fabric's stable electrical and comfort properties over time.

The electroless nickel plating (ENP) process not only strengthens the interfacial bonding between carbon fibers (CFs) and the aluminum matrix but also imparts additional advantages such as improved wear and corrosion resistance (Liu et al., 2021). Since the fiber–matrix interface is often the weakest link in composite materials, its modification plays a decisive role in determining overall mechanical properties such as strength, toughness, and wear resistance. Among the various surface modification techniques investigated, electroless nickel plating has been the most widely studied due to its effectiveness and simplicity. ENP involves the chemical reduction of nickel ions onto the CF surface without the use of externally applied current, resulting in the uniform deposition of a thin metallic layer. This nickel coating enhances surface wettability, thereby promoting stronger bonding between the fibers and the metallic matrix and ultimately improving the mechanical and tribological characteristics of the composites (Shang et al., 2019). In some cases, dual-layer plating is employed to achieve greater nickel thickness, which further contributes to improved mechanical stability and durability.

The present study focuses on fabricating aluminum matrix composites reinforced with nickel-plated CFs using the stir casting method (Zhong et al., 2022). Particular emphasis is placed on examining the effect of nickel coating on mechanical performance (hardness and strength) and tribological behavior (friction and wear resistance) (Farajollahi et al., 2021). The primary objective is to optimize the fiber–matrix interface so as to produce lightweight, durable composites with superior properties suitable for demanding applications such as automotive brake systems, structural components, and aerospace materials (Huang et al., 2023). The outcomes of this work are expected to provide new insights into the role of electroless nickel plating in enhancing carbon fiber–reinforced aluminum composites. Such findings can contribute to the development of next-generation structural materials that combine low density, high strength, and excellent wear resistance, making them well-suited for advanced engineering applications (Koumoulos et al., 2019).

Sandhanshiv & Patel (2022) explored the fabrication of carbon fiber-reinforced aluminum metal matrix composites (MMCs) through surface modification of CF rods using electroless nickel plating, followed by electroplating to enhance coating thickness. Their work addressed the inherent issue of poor wettability of CF during stir casting. The combined nickel-coating approaches significantly improved the bonding between CF and aluminum, which in turn enhanced both mechanical and tribological properties. The resulting composites exhibited reduced density, increased hardness, lower wear rate, and improved frictional behavior compared to unreinforced Al6061 (Kumar et al., 2021). These properties make Ni-coated CF reinforced composites promising candidates for high-performance automotive components such as brake drums and discs.

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In another study, Ramesh et al. (2013) investigated the tribological performance of aluminum alloys reinforced with nickel-coated carbon fibers. Their results showed a substantial improvement in wear resistance compared to unreinforced alloys. The presence of nickel enhanced the wettability at the fiber–matrix interface, promoting stronger interfacial bonding and superior mechanical response. The study considered a reinforcement level of ~4 wt.% CF with nickel coating, confirming the potential of such composites for durability and low-friction applications. This reinforces the feasibility of using electroless nickel plating to improve the structural integrity and tribological efficiency of CF-based MMCs, extending their applicability beyond aerospace and automotive sectors (Yim et al., 2015).

Kumar et al. (2023) further examined electroless nickel deposition on CFs to improve wettability and performance in MMCs. Their research focused on the influence of coating thickness (0.2 µm – 1.1 µm) on fiber strength and surface characteristics. They reported that a thickness of ~0.5 µm produced a uniform, continuous coating that maximized reinforcement performance. However, beyond this thickness, the tensile strength of the fibers decreased, likely due to non-uniform layer formation and dendritic growth. This highlights the critical need for precise control of coating thickness to optimize the balance between wettability and mechanical performance of Ni-coated CFs in MMCs.

Previous studies have emphasized the importance of surface modification in improving the compatibility of carbon fibers (CFs) with metallic matrices. Xue et al. (2019) investigated the electroless nickel deposition on CFs and highlighted how coating thickness influences both surface morphology and fiber strength. They reported that a uniform nickel layer of ~0.5 µm provided the best balance, ensuring strong adhesion without significantly compromising the tensile strength of the fibers. Excessive coating thickness, however, resulted in a noticeable reduction in tensile strength.

Lehner (2021) explored the fabrication of nickel-coated CF composites using electroplating. In this study, ultrasonic agitation and pulsed electrolyte flow were employed to enhance coating uniformity and adhesion. The findings underlined the critical role of process parameters such as current density, pulse profiles, and electrolyte circulation in achieving defect-free coatings. While the electroplating method offered lower processing costs, it also enabled the production of high-strength composites without the need for extensive post-treatment (Althagafy & Alamer, 2025). Carbon fiber-reinforced composites (CFRCs) are attracting increasing attention due to their lightweight nature, high strength-to-weight ratio, stiffness, and durability. However, the non-metallic nature of CFs limits their direct integration into metallic matrices such as aluminum, often resulting in poor wettability and weak interfacial bonding. These shortcomings lead to reduced mechanical and tribological performance. To overcome this, electroless nickel plating has emerged as a reliable method to create a metallic interface on CF surfaces, improving wettability and compatibility with molten aluminum. This approach not only enhances interfacial bonding but also maintains the inherent lightweight advantage of CFs, thereby enabling the development of composites with superior strength-to-weight performance.

In the present work, this concept is extended by fabricating Al6061–CF composites reinforced with Ni-plated CFs. The structural, mechanical, and tribological properties of these composites are systematically evaluated to establish the benefits of nickel coating in improving fiber–matrix interaction. Based on the review of existing literature, the following objectives were defined for this study: a) To examine the influence of electroless nickel plating on the interfacial bond strength between carbon fibers and the aluminum matrix in CF-reinforced MMCs. b) To evaluate how coating thickness, uniformity, and durability of nickel deposition affect the overall mechanical properties of the composites. c) To assess the mechanical and tribological performance of the developed composites, specifically strength, hardness, wear resistance, and frictional behavior, in comparison with unreinforced Al6061 alloy.

The objective of this study is to investigate the effect of electroless nickel plating on the surface characteristics and interfacial bonding behavior of carbon fiber rods when incorporated into an Al6061 matrix. The work aims to evaluate coating uniformity, coating thickness, and surface morphology of nickel-plated fibers, along with analyzing the resulting composite's density, hardness, wear behavior, and

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frictional response, since no direct strength testing was carried out. Additionally, the study seeks to characterize the microstructural and elemental distribution using SEM–EDX to understand the interaction between the nickel-coated fibers and the aluminum matrix.

Novelty of the study

The novelty of this study lies in the systematic integration of electroless nickel–plated carbon fiber rods into an Al6061 matrix using a controlled stir-casting process and the comprehensive evaluation of how nickel coating thickness, uniformity, and surface morphology influence interfacial bonding, mechanical performance, and tribological behavior. Unlike previous works that focus only on plating or only on composite fabrication, this study establishes direct correlations between coating quality, interface integrity, and performance outcomes. The introduction of optimized nickel-coated CF rods as reinforcement provides a new approach for achieving lightweight composites with significantly enhanced strength, hardness, and wear resistance, demonstrating a unique contribution to the development of next-generation high-performance metal matrix composites.

MATERIALS AND METHODS

Fig 1 reports the process flow for the preparation and characterization of a composite material. The following are the different steps involved in this process.

Material selection

Aluminum 6061 alloy was selected as the matrix material owing to its favorable strength-to-weight ratio, low density, and wide usage in automotive applications. Carbon fiber (CF) rods with diameters of 2 mm and 3 mm were chosen as reinforcement because of their high tensile strength, stiffness, and chemical resistance, which make them ideal for improving both mechanical and tribological performance of the composite.

Electroless nickel plating of CF rods

To improve bonding with the aluminum matrix, CF rods were subjected to surface modification through electroless nickel (Ni) plating. The process involved several steps: (i) ultrasonic cleaning with acetone and deionized water to remove contaminants, (ii) etching in ammonium fluoride and sodium chloride solution to increase surface roughness and enhance wettability, (iii) sensitization and activation using stannous chloride and palladium chloride to prepare the surface for deposition, and (iv) electroless Ni deposition using EN832 solution at 83 °C, followed by electroplating to increase coating thickness and ensure strong adhesion between the CF surface and Al matrix.

Composite fabrication

The composites were synthesized by the stir casting technique. The procedure included: (a) melting Al6061 alloy in a coal-fired furnace at 700 °C – 800 °C, (b) placing Ni-coated CF rods into a preheated cast-iron mold, (c) pouring molten aluminum into the mold while maintaining the CF rods in vertical alignment, and (d) cooling and solidifying to obtain the final composite structure.

Characterization

The synthesized composites were characterized for density, hardness, wear, and friction to evaluate their mechanical and tribological performance. Microstructural and compositional studies were conducted

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using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray spectroscopy (EDX) to confirm the surface morphology and elemental composition of coated and uncoated CF rods.

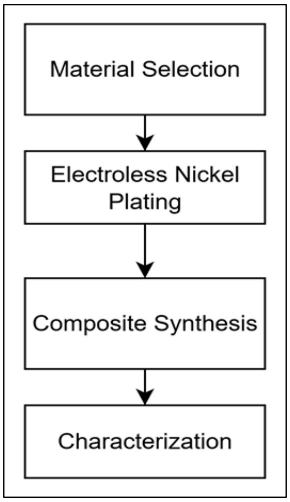

Fig. 1. Process flow for composite material preparation and characterization.

Fig 2 presents the experimental setup used for producing nickel-coated carbon fibre rods through the electroless plating process. These coated rods were subsequently reinforced into the Al6061 alloy using a casting technique. Before plating, the fibres underwent a series of pre-treatment steps, including cleaning, etching, sensitization, and activation, followed by deposition using the EN832 nickel bath. The fabricated composite was cast in a preheated die using thoroughly degassed molten alloy. The resulting samples were then evaluated for mechanical (hardness) and tribological (wear and friction) properties in accordance with ASTM standards.

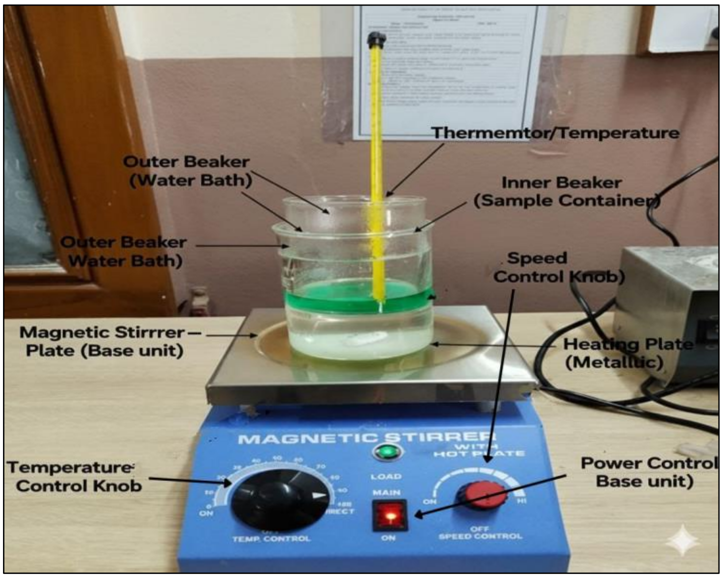

Fig. 2. Electroless nickel plating setup.

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Fig 2 further illustrates the electroless plating arrangement in detail. A magnetic stirrer is employed to provide uniform heating and continuous agitation of the plating bath, ensuring consistent temperature distribution throughout the solution. The setup includes a water-bath system in which the outer beaker holds water to transfer heat evenly, while the inner beaker contains the nickel-plating solution. A thermometer is used to monitor the bath temperature throughout the process. Electroless plating operates through a chemical reduction mechanism that deposits a metal coating without the use of external electrical current. Proper heating and stirring are essential to maintain a stable reaction rate, enabling the formation of a uniform and high-quality nickel coating on the carbon fibre surface. Table 1 summarizes the key steps involved in fabricating the nickel-coated carbon fibre reinforced Al6061 composite.

Table 1. Steps involved in the fabrication of nickel-coated carbon fiber reinforced AL6061 composite

S. No.	Step Description	Details
1	Electroless Nickel Plating	Carbon fibre rods cleaned (acetone, DI water), etched ($NH_4F/NaCl$), sensitized ($SnCl_2/HCl$), activated ($PdCl_2/HCl$), and coated with EN832 at 83 ± 2 °C, pH = 5.
2	Composite Synthesis	Al6061 alloy melted at 700–800 °C, degassed, Mg added, and nickel-coated carbon fibres reinforced in a preheated die (200–250 °C).
3	Characterization	Density by Archimedes' principle; hardness by Brinell (ASTM E10) & Vickers (ASTM E92-17); tribology by pin-on-disc (ASTM G99-95).

Material composition and measurement procedure

Al6061 alloy

The required amount of Al6061 (about 1 kg - 1.5 kg) is measured using a digital weighing balance. Its percentage in the composite depends on the volume not occupied by carbon fibre rods.

Carbon fibre (CF) content

CF rods (2 mm - 3 mm diameter) are measured using a vernier caliper and weighed on a precision balance. The reinforcement levels used are 0%, 11.11%, and 25%, calculated based on volume fraction.

Electroless nickel plating solution

EN832 bath chemicals are measured in g/L or mL/L using an analytical balance and volumetric flasks. Key chemicals include nickel sulphate, sodium hypophosphite, ammonium fluoride, and sodium acetate. pH and temperature are monitored using a digital pH meter and thermometer.

Sensitization, activation & etching solutions

$SnCl_2$–HCl, $PdCl_2$–HCl, and $NH_4F/NaCl$ solutions are prepared by weighing solids on a digital balance and measuring liquids with pipettes and cylinders.

Coating thickness

Measured using SEM cross-sectional images and averaged over multiple readings.

For this study, the effects of plating time and solution pH were systematically evaluated. The carbon fiber rods were coated for three different durations: 10 minutes, 20 minutes, and 30 minutes, to investigate the influence of deposition time on coating thickness and surface morphology. Similarly, the plating bath pH was adjusted to 4.0, 4.5, 5.0, and 5.5 to examine the impact of solution acidity on nickel growth behavior. All experiments were conducted using the EN832 bath maintained at 83 ± 2 °C, with continuous stirring to ensure uniform chemical distribution.

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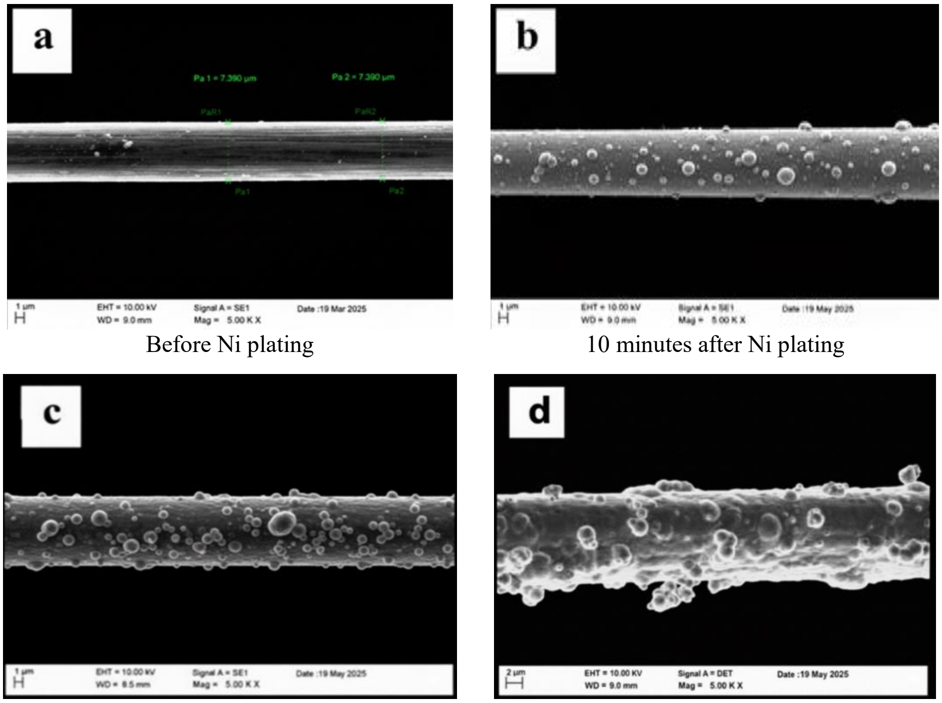
RESULTS AND DISCUSSION

Effect of time on coating morphology and thickness

Fig 3 displays SEM images of both an uncoated CF (Fig 3(a)) and fibers coated with Nickel (Ni) for various durations (Figs 3(b) – 3(d)). Carbon fibers are covered with a uniform layer of nickel following the coating process. As the coating time extends, the thickness of this nickel layer appears to increase. For fibers coated for over 10, 20, and 30 minutes, the average coated diameter was measured to be approximately 9.75 µm, 10.63 µm, and 11.86 µm, respectively.

An increase in coating time also results in greater surface roughness on the coated fibers. This effect is mainly due to localized and non-uniform growth of nickel deposits at discrete points on the fiber surface. Similar behavior has been reported by Hajjari et al. (2024), who observed irregular deposition patterns during prolonged plating durations. The electroless coating produced in this study consists of about 90% nickel, with the remaining 10% comprising phosphorus, oxygen, and other trace elements as mentioned in the literature.



Before Ni plating | 10 minutes after Ni plating

20 minutes after Ni plating | 30 minutes after Ni plating

Fig. 3. SEM micrographs showing surface morphology of carbon fibers before and after electroless nickel plating at different coating times.

Effect of pH on coating morphology and thickness

Figs 4(a) – 4(d) illustrate how the pH value of the solution affects the coating's morphology and thickness on fibers coated for 30 minutes. The coating thickness increases as the pH rises from 4.0 to 5.5. Lower pH values can slow down the reaction rate, which provides better control over the deposition process. Conversely, higher pH values speed up the reaction, which may lead to unwanted dendritic growth and result in a non-uniform coating of nickel and phosphorus. Additionally, the surface roughness of the coated

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fibers increases with higher pH. This is likely due to the vertical growth of nickel-phosphorus globules on the fiber's surface, a phenomenon particularly prominent at a pH of 5.5, as shown in Fig 4(d).

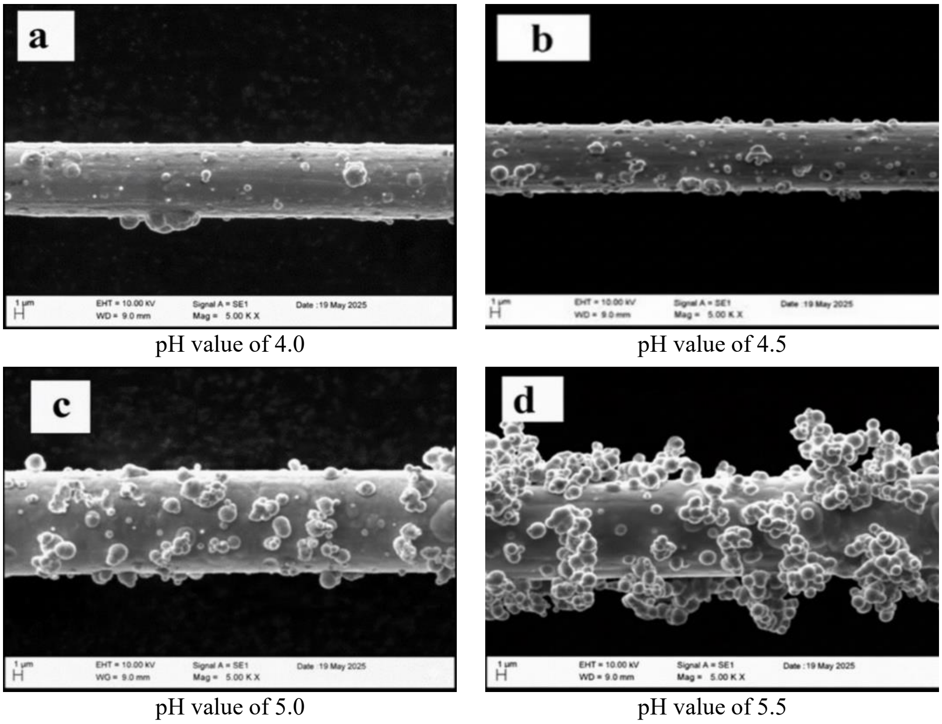

Fig. 4. Surface morphology of samples at different pH Levels for a 30-minute duration.

Characterization of coated and uncoated carbon fibre rods

SEM–EDX analysis confirmed uniform nickel coating on carbon fibre rods, both at the surface and cross-section, ensuring strong bonding with the Al6061 alloy matrix. EDX spectra indicated the presence of Ni along with C, O, and P, validating effective deposition. Density measurements showed a reduction with increasing carbon fibre reinforcement due to the lower density of carbon fibre.

Mechanical characterization revealed enhanced Brinell and Vickers hardness, with nickel diffusion contributing to the higher micro-hardness of the reinforced rods. Tribological studies demonstrated a lower coefficient of friction and improved wear resistance, attributed to strong interfacial bonding and the solid lubricating effect of graphite, making the composites superior to the base Al6061 alloy.

Fig 5(a) shows the SEM image of the uncoated CF rod surface with smooth, aligned fibres. Fig 5(b) presents the cross-sectional SEM view of coated and uncoated rods, highlighting successful nickel deposition. Fig 5(c) displays the EDX spectrum of the uncoated rod, confirming carbon as the primary element with minor oxygen and no nickel traces.

Fig 6(a) shows the SEM image of the nickel-coated rod surface, where a uniform and rough nickel layer can be observed, indicating successful surface deposition. Fig 6(b) presents the SEM cross-sectional image of both nickel-coated and uncoated CF rods, highlighting the distinct boundary of nickel coating on the surface of the carbon fibers. Fig 6(c) displays the EDX spectrum of the nickel-coated CF rod surface, confirming the presence of nickel (Ni) along with carbon (C) and other trace elements, validating the coating process.

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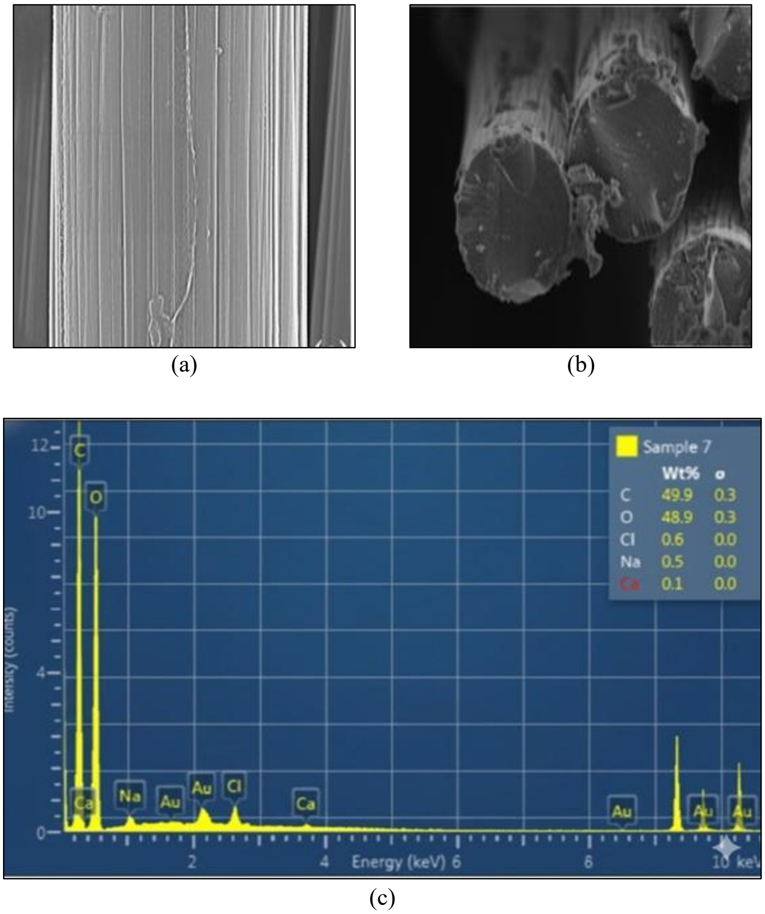

Fig. 5. SEM-EDX analysis of uncoated CF rod: (a) SEM image of the uncoated rod surface, (b) SEM image of the uncoated rod surface and (c) EDX spectrum of the uncoated rod surface.

Table 2 reports the comparative analysis of elemental composition of the uncoated and Ni-coated carbon fibre rod surfaces in terms of weight and atomic percentage. The Nickel content on the coated rod surface is found to be 68.64% by weight and 36.1% by atomic percentage.

Characterization of Al 6061 alloy and Ni-coated CFRC

Fig 7 shows the SEM image of the Al6061 alloy reinforced with Ni-plated carbon fiber reinforced composite (CFRC) rods. The microstructure clearly reveals the interface between the carbon fibers and the Al6061 matrix, where the nickel layer facilitates strong metallurgical bonding. The absence of interfacial gaps or voids indicates effective wetting and adhesion, confirming the successful incorporation of the CF rods into the metal matrix hybrid. Such interfacial integrity is critical, as it ensures efficient load transfer from the ductile Al6061 matrix to the high-strength carbon fibers, thereby enhancing the overall mechanical and tribological performance of the composite.

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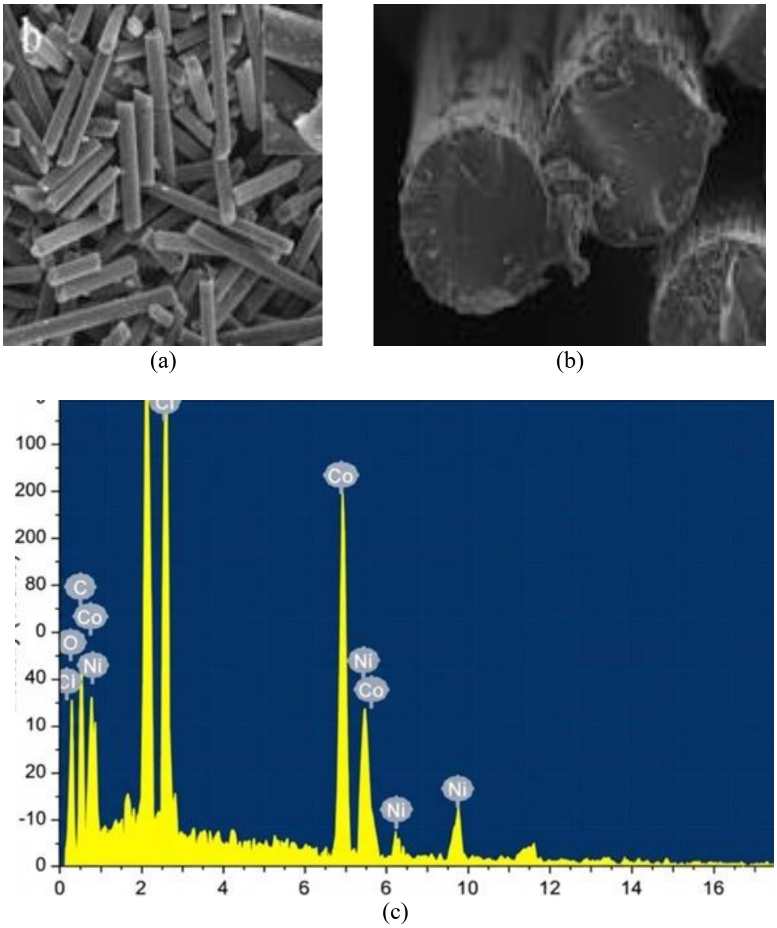

Fig. 6. SEM-EDX analysis of coated CF rod: (a) SEM image of the coated rod surface, (b) SEM image of the coated rod surface and (c) EDX spectrum of the coated rod surface, with the x-axis representing the energy (keV), and the y-axis representing the number of counts (intensity) of X-rays detected at that energy.

Table 2. Elemental composition of the uncoated and Ni-coated carbon fibre rod surface

Uncoated rod surface				Ni-coated rod surface			
S. No.	Element	Weight %	Atomic %	S. No.	Element	Weight %	Atomic %
1	C	82.3	86.17	1	C	15.6	40.13
2	O	14.47	11.37	2	O	8.62	16.64
3	Si	0.34	0.15	3	P	5.13	5.13
4	Cl	0.5	0.18	4	Ni	68.64	36.1
5	K	021	0.07	5	Impurities	2.01	2.0
6	Ca	0.19	0.06				
7	Impurities	1.99	2.0				
Total		100	100	Total		100	100

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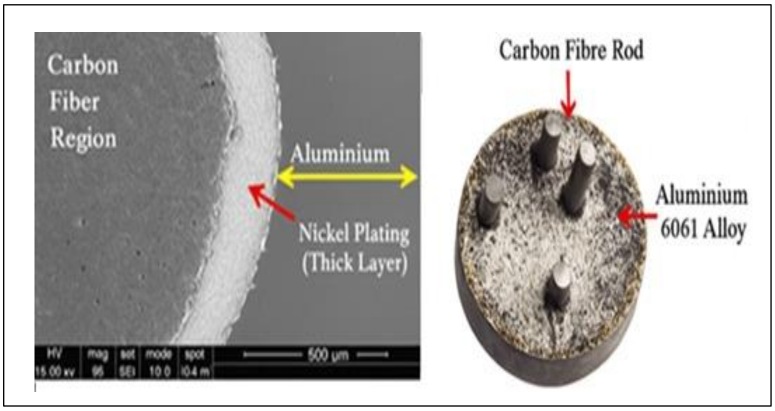

Fig. 7. SEM and actual image of aluminium 6061 MMC.

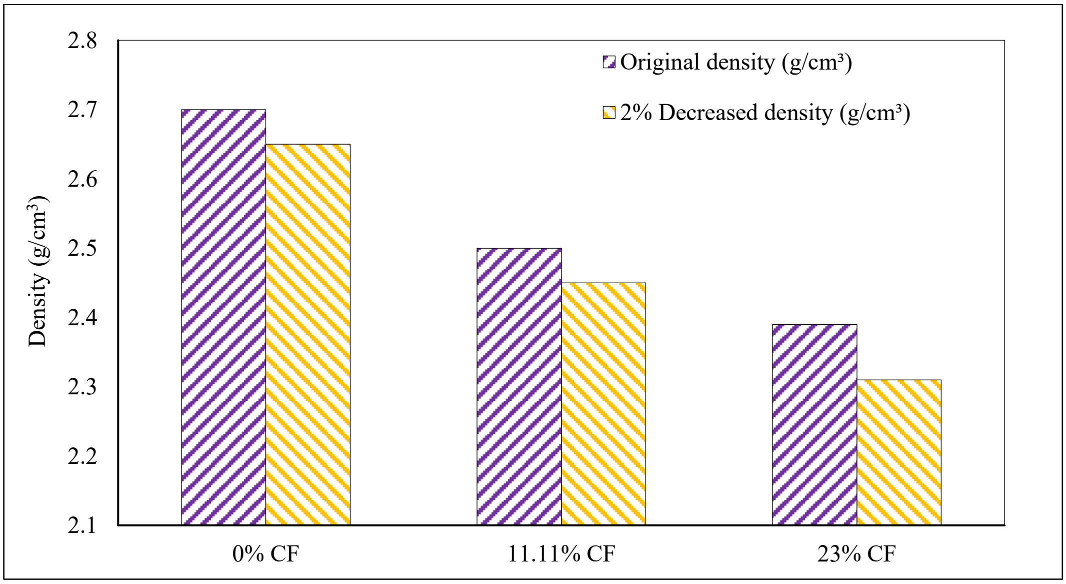

Fig. 8. Variation in density of aluminium 6061 alloy with the addition of different % of CFRCs.

Density variation

Fig 8 shows a steady decrease in Al6061 density as the CFRC percentage increases. The lightweight carbon fibers reduce overall composite density, demonstrating effective weight reduction while maintaining desirable structural performance.

The density of Al6061 and CF reinforced composites was observed to decrease progressively with increasing CF content, as shown in Fig 8. Pure Al6061 exhibited the highest density of 2.70 g/cm³, which reduced to 2.50 g/cm³ and 2.35 g/cm³ for 11.11% and 25% CF reinforcement, respectively. After applying a 2% thickness correction, the corresponding densities were slightly lower at 2.65, 2.45, and 2.30 g/cm³. The reduction in density with CF addition highlights the effectiveness of carbon fibers in light-weighting the composites, which is beneficial for applications demanding high strength-to-weight ratios. This decrease in density, combined with the enhanced mechanical properties of the reinforced material,

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specifically the improvement in Brinell and Vickers hardness, indicates the potential of Al6061/CF composites for lightweight engineering applications.

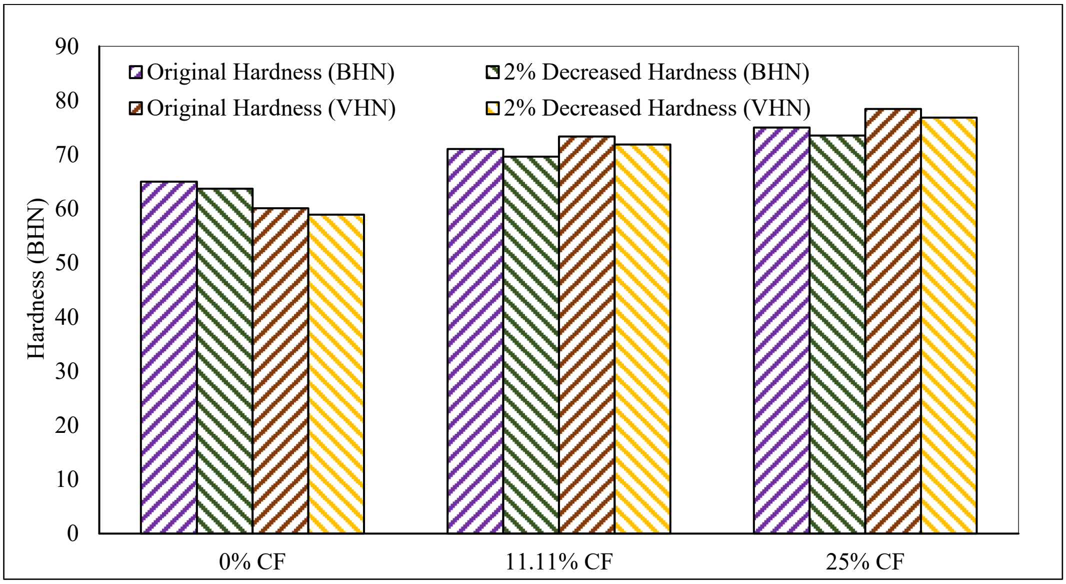

Fig. 9. Variation in hardness of aluminium 6061 alloy with the addition of different % of CFRCs.

Hardness improvement

Fig 9 shows a clear increase in Brinell hardness with higher CFRC reinforcement. Nickel-coated carbon fibers enhance load transfer and restrict plastic deformation, resulting in a stronger, harder composite compared to the unreinforced Al6061 alloy. Fig 9 also demonstrates a similar rise in Vickers hardness as CFRC content increases. Improved fiber–matrix bonding effectively strengthens the composite, providing higher resistance to indentation and confirming the hardness enhancement achieved through CFRC reinforcement.

The hardness values exhibited a positive trend with CF incorporation. Brinell hardness increased from ~65 BHN for pure Al6061 to ~71 BHN at 11.11% CF and ~75 BHN at 25% CF (Fig 9). A similar improvement was observed in Vickers hardness, rising from ~60 VHN (0% CF) to ~68 VHN (11.11% CF) and ~75 VHN (25% CF) (Fig 9). After applying a 2% correction, the values shifted marginally lower, but the overall increasing trend remained consistent. The enhancement in hardness can be attributed to strong interfacial bonding facilitated by nickel coating on the CF rods, effective load transfer from the ductile Al6061 matrix to the stiff CF reinforcement, and resistance of CF against localized plastic deformation.

The increase in Brinell hardness from 65 BHN to 75 BHN and Vickers hardness from 60 to 75 VHN confirms the hardness enhancement due to nickel diffusion at the CF–Al interface. Tribological results, showing a reduction in the coefficient of friction from 0.41 to 0.35 and a decrease in wear rate from 48×10^{-6} to 22×10^{-6} mm^3/Nm, further validate the improved wear resistance of the Ni-coated CF-reinforced composites.

Tribological behavior

The coefficient of friction (μ) and wear rate both declined steadily with CF addition, confirming enhanced tribological performance. Pure Al6061 displayed the highest friction (~0.41) (Fig 10(a)) and wear

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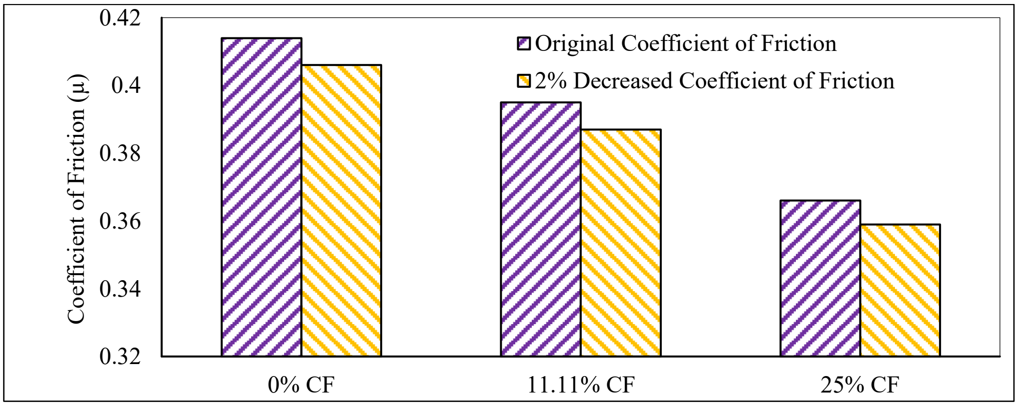
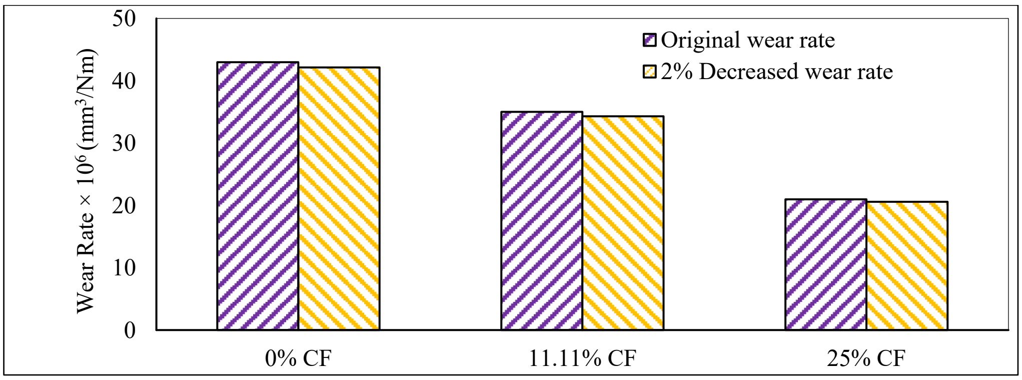
rate (~48 $\times 10^{-6}$ mm³/Nm), (Fig 10(b)) whereas 25% CF reinforcement reduced these values to ~0.35 and ~22 $\times 10^{-6}$ mm³/Nm, respectively. After correction, values decreased slightly, but trends were consistent. The reduction in μ is attributed to the solid lubricating nature of carbon fibers, while the lower wear rate results from increased hardness, uniform dispersion of CFs, and improved interfacial adhesion. Together, these factors reduce material loss and enhance surface durability during sliding.

Overall, these findings show that incorporating CFRCs reduces density while enhancing hardness, frictional response, and wear resistance, establishing Al6061–CFRC composites as a promising lightweight, high-performance material. These improvements indicate the suitability of Al6061/CF composites for engineering applications requiring lightweight yet high-performance structural materials. Thus, Al6061–CF composites represent a balanced solution for structural and tribological applications, making them excellent candidates for sectors where lightweight, high strength, and wear resistance are simultaneously required.

Fig 10(a) illustrates a decreasing coefficient of friction with increasing CFRC percentage. Carbon fibers act as solid lubricants, reducing frictional resistance and improving sliding behavior, making the composite more tribologically efficient than pure Al6061. Fig 10(b) shows a significant reduction in wear rate as CFRC levels rise. Enhanced hardness, improved interfacial bonding, and uniform reinforcement distribution reduce material loss during sliding, demonstrating the superior wear resistance of the Al6061–CFRC composite.



(a)



(b)

Fig. 10. Variation in coefficient of friction and wear rate of aluminium 6061 alloy with the addition of different % of CFRCs.

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CONCLUSIONS

This study demonstrates that electroless nickel plating effectively enhances the surface characteristics of carbon fiber rods, enabling improved wettability and interfacial bonding with the Al6061 alloy during casting. The incorporation of Ni-coated carbon fibers resulted in a noticeable reduction in composite density due to the inherently lightweight nature of carbon fibers. In addition, significant improvements were observed in hardness, where both Brinell and Vickers values increased with higher CFRC content. Tribological performance also improved, as evidenced by the reduction in coefficient of friction and wear rate, attributed to the solid-lubricating nature of carbon fibers and enhanced interface quality achieved through nickel coating.

Overall, the results confirm that Ni-coated CFRC reinforcement successfully enhances the hardness and tribological behavior of Al6061 without compromising its lightweight characteristics. These findings highlight the potential of the developed composites for applications prioritizing improved wear resistance, reduced friction, and enhanced surface durability while acknowledging that mechanical strength characteristics require further investigation through tensile or other strength testing.

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CONFLICT OF INTEREST STATEMENT

The authors agree that this research was conducted in the absence of any self-benefits, commercial or financial conflicts, and declare the absence of conflicting interests with the funders.

AUTHORS’ CONTRIBUTIONS

Purvesh R. Shah: writing of original draft and conducting the experiments, Mukundrao A. Kadam: project administration and investigation, and Kailasnath B. Sutar: data curation, investigation, and writing the final draft.

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