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Enhancing Delamination Resistance in CFRP Composites through surface Functionalization of Woven carbon Fiber by CuO Nanostructures

Ravi Shankar Rai[1,*], Vikas Kumar[2], Rajeev Kumar[3]

Abstract

In order to produce a nanostructured interphase that improves the interfacial interaction with an epoxy resin matrix, copper oxide (CuO) nanostructures were hydrothermally formed onto woven carbon fibers (WCF). Hexagonal CuO nanorods were created using a two-step, seed-assisted solvothermal technique on plain woven carbon fiber. This study investigates the effects of surface modification of carbon fibers by the formation of CuO nanostructures using a hydrothermal technique on the mechanical properties of carbon fiber-reinforced polymer composites. To make hybrid composites, carbon fiber fabric that had been CuO-treated was used as reinforcement in a bisphenol-A epoxy resin matrix. In a regulated reaction mixture, the CuO nanostructures were created on the carbon fibers by first seeding them and then growing them. At a fixed growth temperature of 90 °C and a 4-hour hydrothermal period, various CuO nanostructure forms, such as nanowires, hexagonal rods, and nanoflower morphologies, were produced by adjusting the molar concentrations in the solution. The resulting morphologies were characterized using energy-dispersive X-ray spectroscopy and field emission scanning electron microscopy. The final nanostructure development was significantly influenced by the timing of the seeding and growing phases. After that, the CuO-coated woven carbon fiber was vacuum-bagged and added to a laminated composite with an epoxy resin matrix. CuO-treated WCF was vacuum-bagged into a matrix composed of a bisphenol-A epoxy resin and dimethyl aniline hardener combination to create laminated hybrid composites. By reducing the void content, this procedure raised the volume fraction of CuO nanostructure, which improved the mechanical characteristics. Drop-down impact testing and a universal testing machine were used to assess the tensile and impact strengths of the epoxy composite samples reinforced with CuO-coated WCF. The results demonstrate significant gains for the CuO-coated WCF reinforced composites in impact energy absorption (increased by 74.8%), elastic modulus (52% increase), tensile strength (42% increase), and in-plane shear strength (32% increase). This study shows that by increasing the interfacial surface area between the fiber and matrix, CuO nanostructures can significantly prevent delamination and improve composite performance, boosting the materials' potential uses in structural contexts. Because of their excellent mechanical qualities at a very cheap cost and little experimental setup, the produced hybrid composites samples are a good substitute for standard carbon fiber reinforced polymer composites for a variety of applications.

Keywords: CFRP, Nanostructures Delamination, Hydrothermal Technique, CuO, Composites.

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INTRODUCTION

The Carbon fiber-reinforced polymer (CFRP) composites are widely used in high-performance industries including automotive, aerospace, and others because of their exceptional stiffness, corrosion resistance, and strength-to-weight ratio [1, 2]. Despite these advantages, CFRP composites are prone to a critical issue: delamination. This phenomenon, involving the separation of layers within the composite structure, undermines both structural integrity and durability [3]. Delamination can result from factors such as mechanical stress, impact loading, or environmental conditions, making it vital to address this challenge to improve the material's reliability [4]. Recent developments in materials science suggest that modifying the surface of CFRP components can enhance interlayer bonding, thereby increasing resistance to delamination. One promising approach is surface functionalization using nanostructured materials, which strengthens the fiber-matrix interface—a common point of failure in CFRP composites [5,6]. Because of their distinct mechanical and chemical characteristics, copper oxide (CuO) nanoparticles stand out among the nanostructures examined and can improve the performance of the composite [7]. CuO nanostructures enhance the mechanical interlocking and possible chemical reactions that strengthen the link between carbon fibers and the polymer matrix [8,9]. The integration of metal-oxide nanostructures, such as CuO, into the surface treatment of CFRP components also benefits the textile industry. These nanostructures enable the production of advanced textiles with added functionalities suitable for applications across various sectors, including aerospace, electronics, construction, and defense [10–12]. The high surface-area-to-weight ratio of textiles, which enables creative material modifications, is the source of the synergy between nanotechnology and textiles [13,14]. Because of their adaptability, carbon fiber composites are being used more and more in both military and civilian applications [15]. They can be combined with various matrix materials, such as metals, polymers, ceramics, and cements, to produce a wide range of functional products. Among these, polymeric composites dominate most applications. To ensure effective bonding between carbon fibers and polymer matrices, specific surface treatments and finishes are applied. Hybrid composites containing metal-oxide nanostructures exhibit exceptional load-bearing capabilities, making them ideal for demanding applications [16,17]. By strengthening interlocking and bonding with polymeric structures, metal-oxide nanostructures' strong interfacial interactions with carbon fibers and their reactivity to polar functional groups like carboxyl, hydroxyl, and carbonyl improve the composite's mechanical performance [18,19]. The mechanical characteristics of CuO nanostructures are not as thoroughly studied as their chemical characteristics. Nanoparticles, nanowires, nanoribbons, nanoplates, microspheres, and even dandelion-like formations are some of the different shapes that these nanostructures can take. Sol-gel synthesis, vapor-liquid-solid growth, laser ablation, arc discharge, and electron beam evaporation are some of the methods used to create CuO nanostructures [20–23]. Because it can produce CuO nanostructures with a variety of shapes at very low temperatures, the hydrothermal technique is particularly versatile [22,24–26].

The effects of adding CuO nanowires to polyester resin composites reinforced with woven carbon fibers (WCF) were investigated by Deka et al. [13]. Their results revealed significant improvements in modulus, impact resistance and tensile strength. Similarly, by carefully controlling chemical precursors on WCFs and adjusting heat conditions throughout a 12-hour hydrothermal growth phase, Kong et al. [9] showed the potential for creating CuO nanostructures with a variety of morphologies, from petal-like to cuboid-like shapes. A seed-assisted hydrothermal growing technique was used by Ravi Shankar Rai [8] to functionalize carbon fiber textiles with monoclinic CuO nanostructures. The modified WCF samples showed decreased void content and enhanced interfacial surface area and bonding capability by varying the hydrothermal treatment parameters. This was accomplished during composite production by allowing the nanostructures to cross-link with the polymer matrix and with one another. Furthermore, Rai et al. [6] functionalized carbon fibers using hydrothermally produced ZnO nanostructures, producing polymer composites that increased their tensile strength by almost 50% and their impact absorption capacity by 76%. CuO nanostructured carbon fiber-reinforced polymer composites were the subject of additional research by Rai et al. [7], which showed notable improvements in properties. For CuO-coated WCF epoxy resin composites, these included a 74.8% improvement in impact energy absorption, a 52% rise in elastic modulus, a 42% increase in tensile strength, and a 32% improvement in in-plane shear strength. These results highlight how CuO nanostructures might improve composites' overall performance and lessen delamination. The enhanced interfacial surface area between the fibers and the matrix, which the CuO nanostructures give, is primarily responsible for the observed benefits and broadens the possible structural uses of these cutting-edge materials.

The development of epoxy resin composites reinforced with plain woven carbon fabric (WCF) and improved by the addition of CuO nanostructures is the focus of this study. To evaluate their characteristics, carbon fiber composites that were untreated and CuO-functionalized and made with different molar concentrations were examined. Examining how the shape of CuO nanostructures affects fracture propagation after impact and assessing the impact absorption capabilities of CuO/WCF nanocomposites are the main objectives of the study. To improve the interfacial bonding within WCF/epoxy resin composites without sacrificing the WCF's tensile strength, the carbon fibers were functionalized with CuO using a two-step, seed-assisted hydrothermal deposition process. The behavior of the nanostructures under various loading situations can be thoroughly understood through fractographic examination of the shattered surfaces. By adding a CuO nanostructured interphase, this work provides an affordable way to enhance the performance of plain carbon fiber polymer composites, increasing their appropriateness for sophisticated applications.

2. MATERIALS & METHODOLOGY

Unsized bidirectional plain woven carbon fiber fabric (T300 grade, 3000 filaments) provided by CF Composites, New Delhi, India, was used in the studies. All of the analytical-grade chemicals used were purchased from P.K. Enterprises in Dhanbad, India. The following essential chemicals were utilized exactly as supplied, without further purification: sodium hydroxide (NaOH, 98%), hexamethylenetetramine (HMTA, 99%), copper acetate monohydrate ($Cu(CH_3COO)_2{\cdot}H_2O$, 98%), copper nitrate trihydrate ($Cu(NO_3)_2{\cdot}3H_2O$, 98%), and absolute ethanol (C_2H_5OH, 99.9%). Using an overhead stirrer, a 2:1 weight ratio of the dimethyl aniline ($C_8H_{11}N$) hardener and bisphenol-A (BPA) epoxy resin ($(CH_3)_2C(C_6H_4OH)_2$), provided by Sakshi Dyes & Chemicals, New Delhi, were made. After desiccating the mixture to remove any air bubbles, it was allowed to cure for 48 hours in the open air. A seeding treatment and a growth treatment were the two steps in the hydrothermal method used to create CuO nanostructures on carbon fiber fabric. According to previous research, the reaction mixture for these phases was made by adding particular precursor chemicals [25,26]. A comprehensive factorial experimental design with three repeats for reliability was used to systematically investigate the effects of seeding cycles, growth length, and molar concentration. The vacuum-assisted resin transfer molding (VARTM) technique was used to insert samples of CuO-functionalized carbon fiber into composite materials. After cleaning the 9500×500×5 mm^3) flat glass plates using acetone to guarantee a clean surface, a release cloth was affixed with adhesive tape. The system was sealed using a rubber gasket. After covering the sample with a silk peel ply, the CuO-modified woven carbon cloth was applied. A plastic sheet produced a vacuum seal, and a distribution medium made sure that the resin was distributed evenly. A resin supply was linked to the intake, and a vacuum pump was connected to the output. 60 kPa of vacuum pressure was used to force resin into the mold. The system was sealed once enough resin had been infused, and the polymer matrix was allowed to cure at room temperature for 48 hours. Dimethyl aniline hardener and BPA epoxy resin were used as the polymer matrix in this investigation. Figure 1 shows a schematic representation of the experimental setup and fabrication procedure, which includes the creation of CuO nanostructured-WCF-epoxy composites.

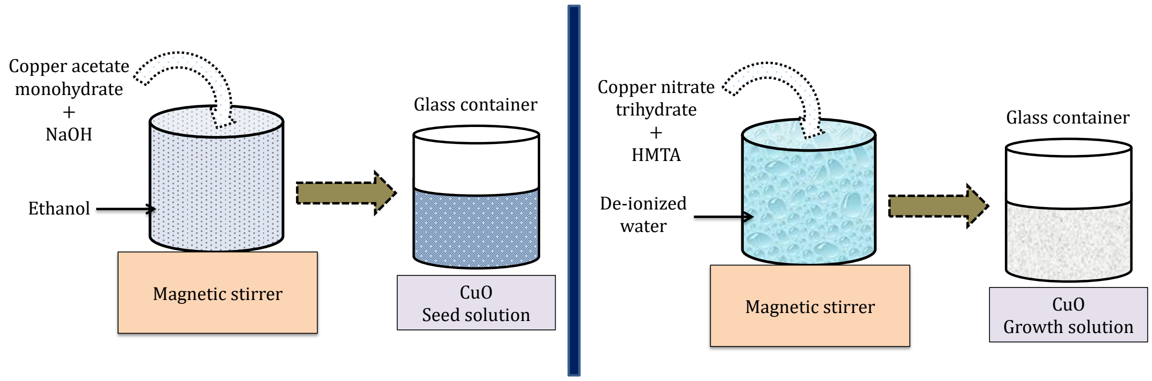


Figure 1. Synthesis of seed and growth solution for hydrothermal treatment of WCF.

The study examined the structural, compositional, and morphological characteristics of CuO-functionalized woven carbon fiber (WCF) samples using sophisticated characterization techniques like field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDS), and high-resolution X-ray diffraction (HRXRD). For best results, WCF samples with the highest CuO deposition were used to create hybrid composites utilizing the vacuum-assisted resin transfer molding (VARTM) technique. A drop-weight impact tester was used to measure impact energy absorption in accordance with ASTM D5628-10 guidelines. Using energy levels ranging from 0 to 120 J, circular specimens of 45 mm in diameter and around 2.0 mm in thickness were dropped from a height of 0.75 m at an impact velocity of 3.84 m/s. The information gathered from first contact to penetration offered comprehensive understanding of the mechanical impact performance of the composites. A 100 kN load cell-equipped Instron 8801 universal testing equipment was used to test mechanical parameters, such as uniaxial tensile behavior and in-plane shear. One millimeter per minute was used as the constant displacement rate. The stress-strain response of composites reinforced with high-modulus fibers or woven textiles were examined using in-plane shear testing carried out in accordance with ASTM D3518. Elastic modulus and tensile strength were tested using ASTM D3039 guidelines. Five specimens per category were examined for each test, and outliers were eliminated to guarantee correct averages, standard deviations, and coefficients of variance, so ensuring the consistency and dependability of the results.

3. RESULT AND DISCUSSION

By adjusting process variables such seeding cycles, molar concentration, and growth treatment length, this study used a full factorial experimental design to maximize the growth of CuO nanostructures on woven carbon fiber (WCF) fabrics. The creation of CuO nanostructures was systematically investigated by 96 trials, each carried out in triplicate, as shown in Figure 3. This study highlights the mechanical performance and interfacial behavior of CuO-modified WCF polymer composites under mechanical loading conditions, whereas previous research concentrated on experimental results and parameter optimization [27].

Advanced analytical methods such as energy-dispersive X-ray spectroscopy (EDS), high-resolution X-ray diffraction (HRXRD), and field emission scanning electron microscopy (FESEM) were used to analyze the structural, compositional, and morphological properties of the CuO-modified WCFs. The vacuum-assisted resin transfer molding (VARTM) technique was then used to create hybrid composites, employing WCFs with ideal CuO deposition for enhanced functionality. By using circular specimens that were 45 mm in diameter and around 2 mm thick, impact resistance testing was performed in compliance with ASTM D5628-10 requirements. The specimens were exposed to energy levels ranging from 0 to 120 J. Using an Instron 8801 universal testing equipment, mechanical parameters, such as in-plane shear and tensile behavior, were assessed in accordance with ASTM standards. The outcomes highlighted the CuO-modified WCF composites' potential for cutting-edge applications by demonstrating improved mechanical performance and superior energy absorption capabilities.

3.1 Structural and Morphological Characterization

Field emission scanning electron microscopy (FESEM; Supra 55, Carl Zeiss, Germany) was used to examine the early development of CuO nanostructures on woven carbon fiber (WCF). The amounts of copper nitrate trihydrate and HMTA precursor solutions were adjusted between 10 mM and 60 mM in a two-step seed-mediated hydrothermal process in order to affect the shape of the final CuO nanostructures. Ultrafine CuO-growing samples were chosen for further mechanical characterization. As shown in Fig. 3(a–f), the ideal growth conditions were determined to be eight seeding cycles and a 12-hour growth treatment, with molar concentrations set at 10, 15, 25, 35, 45, and 60 mM. Figure 3(g) shows how differences in molar concentration relate to changes in the size of the CuO nanostructures. The nanostructures showed more surface exposure at lower molar concentrations. On the other hand, the nanostructures' height consistently increased but their width and thickness reduced as the molar concentration rose. This trend implies that the improved mechanical performance of the resultant composites may be greatly influenced by the increased surface area and density of CuO nanostructures per unit area of the WCF surface.

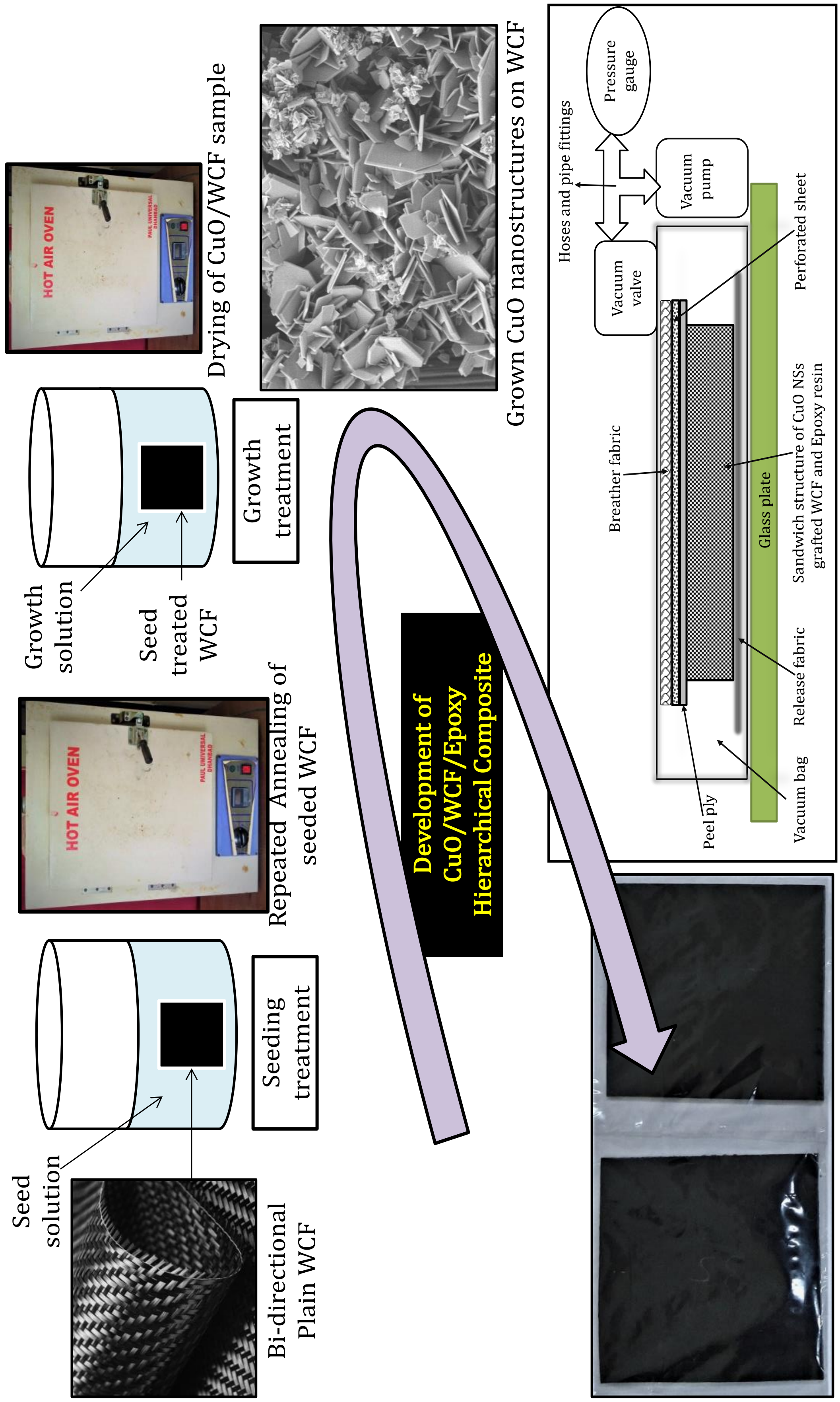
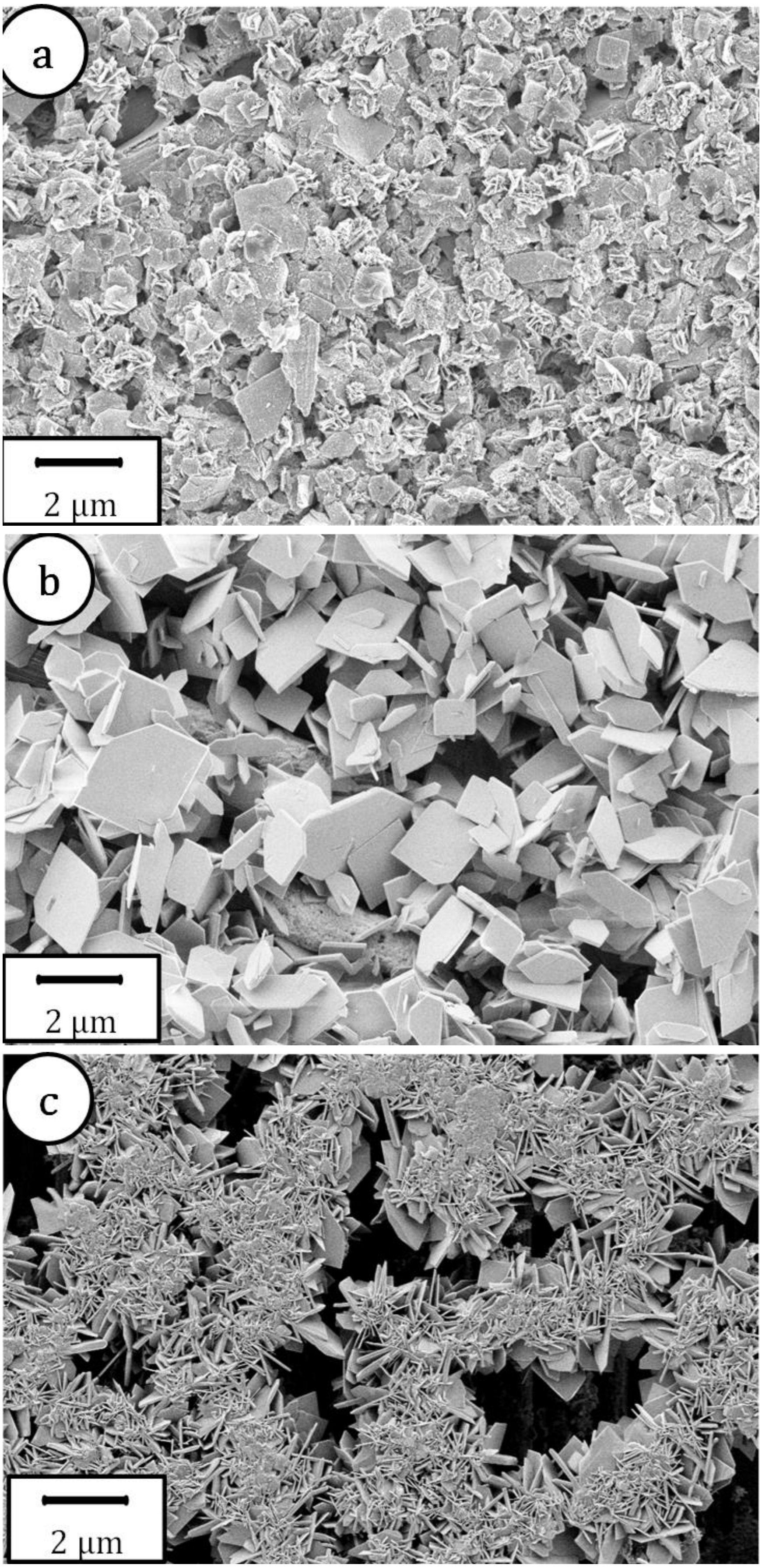


Figure 2. Fabrication of CuO nanostructured CFRP composite samples.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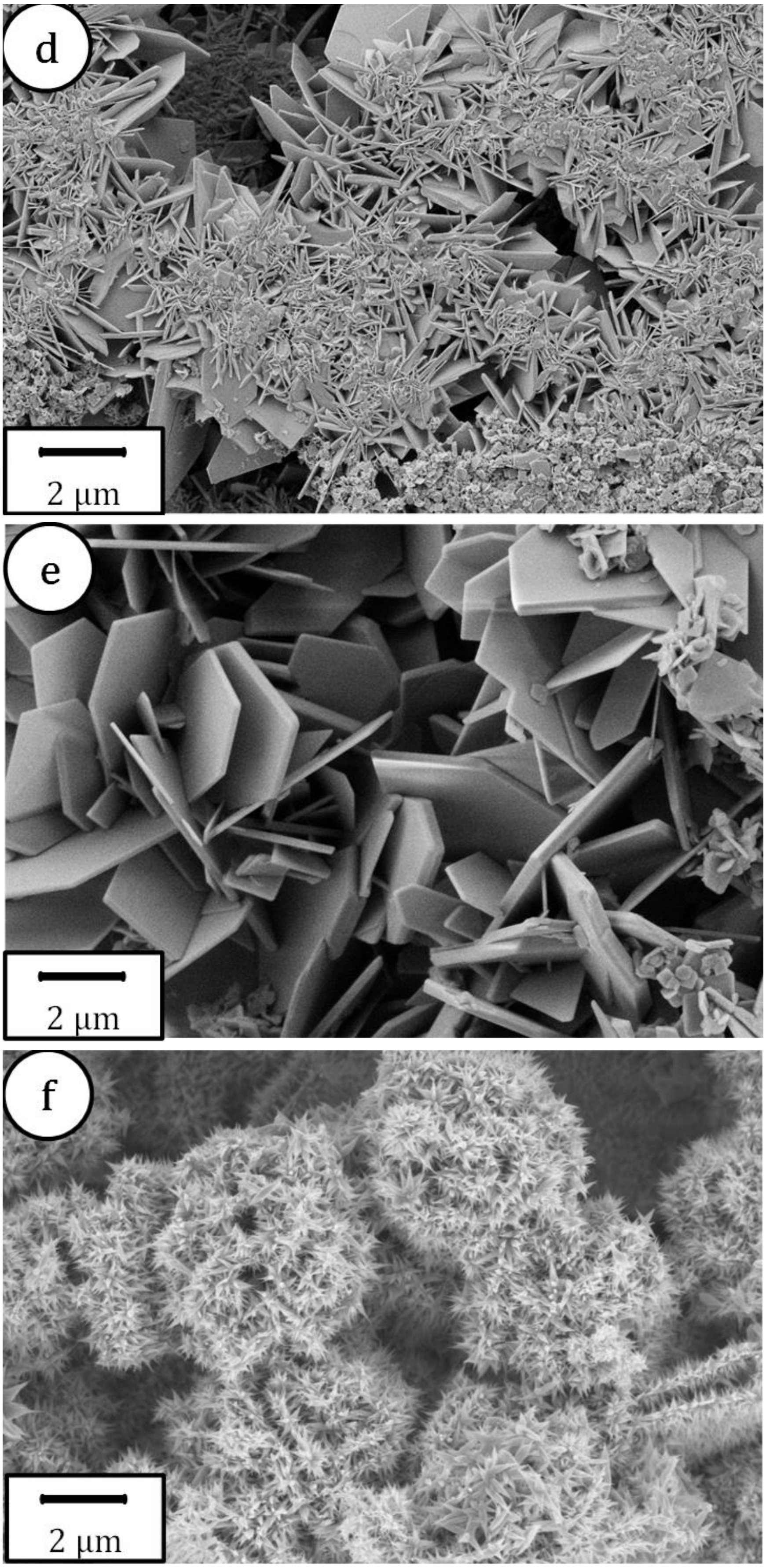
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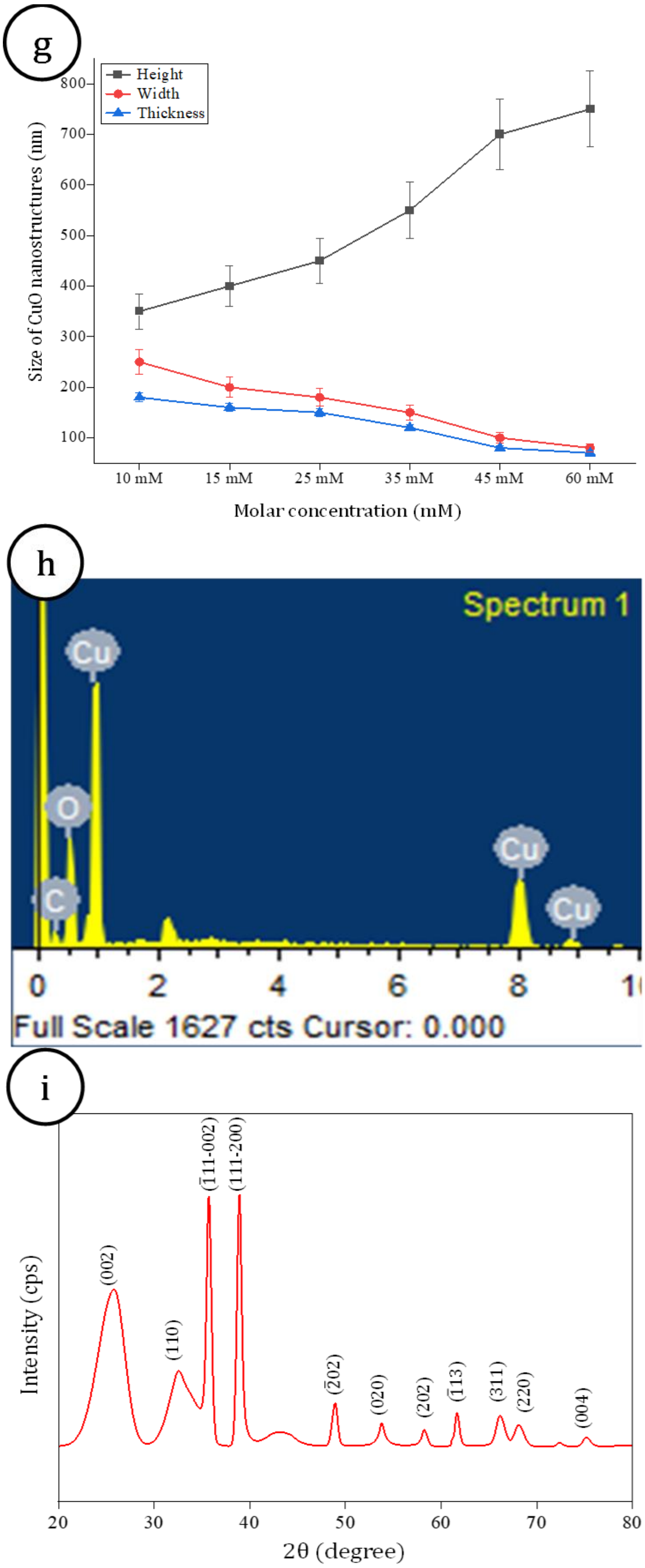

Figure 3. Illustration of developed morphologies of copper-oxide on carbon fiber through hydrothermal synthesis at varied molar concentration of (a) 10 mM, (b) 15 mM, (c) 25 mM, (d) 35 mM, (e) 45 mM, and (f) 60 mM; Variation in size (g), Elemental composition (h) and Crystalline structure (i) and of as grown CuO nanostructures on WCF.

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Energy dispersive spectroscopy (EDS) analysis confirmed a 1:1 stoichiometric ratio of copper to oxygen in the CuO nanostructures, verifying their successful growth on the WCF surface via the seed-assisted hydrothermal method. The EDS spectrum, shown in Fig. 3(h), revealed no presence of extraneous elements, indicating uniform and high-density deposition of CuO on the carbon fiber surface. The crystalline structure of the CuO-functionalized WCF samples was examined using a high-resolution X-ray diffractometer (HRXRD) (Rigaku SmartLab) with monochromatic Cu-Kα radiation. Scans were conducted at a rate of 5°/min over a 2θ range of 20°–80°. A significant diffraction peak at 25.8° on the (002) plane was attributed to the carbon in the fibers. The introduction of CuO nanostructures resulted in additional diffraction peaks associated with planes such as (110), (111), ($\bar{1}$11), (002), (200), ($\bar{2}$02), (020), (202), ($\bar{1}$13), (311), (220), and (004), spanning a 2θ range of 30°–80°, as depicted in Fig. 3(i). The observed lattice parameters (a = 4.68 Å, b = 3.43 Å, c = 5.13 Å, β = 99.5°) corresponded to the monoclinic CuO crystal phase, in alignment with the JCPDS database entry 05-0661, consistent with previous literatures [28–30]. The CuO-modified WCF samples were then utilized to fabricate CuO/WCF/epoxy hybrid composites. Using a vacuum bagging technique, five layers of CuO-modified WCF with the same molar concentration (e.g., five layers of WCF modified with 10 mM CuO) were assembled to produce composite samples for further analysis.

Mechanical Characterization of as Fabricated Samples

CFRP composites have a limited capacity to absorb energy, making them vulnerable to impact damage. Nonetheless, adding CuO nanostructures to carbon fibers greatly increases their resilience to impact failure. This section investigates the failure behavior of the composite samples under drop-weight impact tests as well as the energy absorption properties provided by CuO nanostructures. Increased surface interaction between CuO nanostructures, carbon fibers, and the polymer matrix is responsible for the hybrid composites' enhanced performance because it promotes stronger chemical bonding and more efficient mechanical load transmission. CuO nanostructures and the functional groups on carbon fibers—such as hydroxyl, carbonyl, and carboxyl groups—interact powerfully to form strong bonding sites with the polymer matrix. The maximum CuO nanostructure deposition was obtained under ideal growth circumstances, which included eight seeding cycles, a 12-hour growth period, and growth solution concentrations of 45 mM and 60 mM. This led to improved energy absorption. When compared to bare WCF/BPA epoxy composites, the energy absorption of the composites made under these circumstances increased by 66.7% and 74.8%, respectively. The inherent affinities of the functional groups on the carbon fiber surface further encourage these improvements. Table 1 summarizes the statistical analysis of the impact test findings, which shows a coefficient of variation of about 5%, indicating little data dispersion and dependable performance of the used approach. The stiffness of plain WCF/BPA epoxy composites and WCF/CuO/BPA epoxy composites at different CuO concentrations and morphologies was compared using tensile strength testing. Tensile tests were conducted on five specimens per sample category using an Instron-8801 universal testing machine with a 100kN load capacity, in accordance with ASTM D3039 standards, at a displacement rate of 1 mm/min. For additional analysis, the averages of these tests were employed. Because there were little interfacial contacts between the fibers and the epoxy, the plain WCF/BPA epoxy composites had the lowest tensile strength, elastic modulus, and in-plane shear strength. By promoting improved contact between the fibers, nanostructures, and polymer matrix, the addition of CuO nanostructures improved these characteristics [11]. The findings showed that better mechanical performance resulted from greater deposition of CuO nanostructure. CuO nanostructures grew more quickly, which improved load-sharing between the nanostructures and the fibers and raised the energy needed to break the fiber. The composites containing CuO nanostructures that were developed with eight seeding cycles, twelve hours of growth time, and a concentration of 60 mM growth solution had the maximum tensile strength (42%) and elastic modulus (52%). These enhancements are ascribed to improved interfacial interactions between the epoxide groups in the BPA epoxy resin, the CuO nanostructures, and the functional groups of carbon fiber. Furthermore, the CuO/WCF/BPA epoxy composites' in-plane shear resistance improved as the CuO molar concentration rose; the greatest improvement of 32% was noted at the highest concentration. Table 1 displays the data for tensile strength, elastic modulus, and in-plane shear strength as well as their averages, standard deviations, and coefficients of variance. The accuracy and dependability of the mechanical property data are confirmed by the low coefficient of variance (~5%), which further emphasizes how well the fabrication process works to produce enhanced CFRP composites.

Fractured Surface Topography

Figure 4 shows the topography and crack debris of fractured surfaces from the CuO/WCF/BPA epoxy hybrid composites as they were manufactured. This section explains the fracture processes found in the tested samples' FESEM study. As illustrated in Figure 4(a), the main fracture modes for plain CFRP composites (Sample-1) are fiber breaking, matrix cracking, debonding, and delamination. As shown in Figure 4(b), hybrid composites, on the other hand, show new failure modes like fiber pullout, crack debris, and fiber fracture, while having improved interfacial adhesion as a result of CuO nanostructure alterations. Additional failure modes that take place at the interface between the CFRP and the interlocked CuO nanorods are revealed by further analysis of hybrid composite samples.

These modes include nanostructure pullout, nanostructure breaking, and nanostructure debonding. These mechanisms are illustrated in Figure 4(c & d). The fracture points mainly shed light on fiber breakage and delamination. Energy interactions between the CuO nanostructures and the WCF surface take place prior to fracture, and the WCFs absorb delamination energy as well. The interactions between the CuO nanostructures and the growth regions on the WCF surface are responsible for variations in impact energy absorption. The relationship governing total impact energy absorption is described by Equation (1):

$$E_{total} = E_{rebound} + E_{absorbed} \quad (1)$$

The majority of the energy is absorbed by the resin and fibers in brittle composites because the rebound energy is low. Bending deformation and delamination energy contribute to the absorbed energy during low-velocity impacts. Because the composite is brittle, the majority of the impact energy is absorbed through fiber breaking, with the remainder being absorbed through shear-out, global deformation, and delamination. All samples were found to have a similar outward effect area. These findings show that, in comparison to conventional CFRP composites, the inclusion of CuO nanostructures at the interface greatly affects the fracture behavior and impact energy absorption of hybrid composites, increasing their resistance to damage [31].

Table 1. Mechanical characterization results of as fabricated plain CFRP and CuO-modified CFRP.

Test samples	**Absorbed impact energy (J)**			**Tensile stress (MPa)**			**Elastic strength (GPa)**			**In-plane shear stress (MPa)**		
	μ	***σ***	***CV (%)***	***μ***	***σ***	***CV (%)***	***μ***	***σ***	***CV (%)***	***μ***	***σ***	***CV (%)***
Plain CFRP	4.8	0.25	5.16	258	12.89	5.01	14.8	0.7375	5.01	162	8.1	5.00
10 mM CuO-CFRP	7.2	0.36	5.1	289	14.43	4.98	17.9	0.89137	5.00	168	8.4	5.01
15 mM CuO-CFRP	7.3	0.37	5.09	300	15.01	5.00	18.8	0.9368	4.99	176	8.82	5.01
25 mM CuO-CFRP	7.5	0.37	4.98	311	15.52	4.99	19.3	0.96462	5.00	183	9.14	4.99
35 mM CuO-CFRP	7.7	0.38	5.02	334	16.69	5.01	19.9	0.99035	5.01	192	9.58	4.98
45 mM CuO-CFRP	7.9	0.40	5.02	345	17.25	4.98	20.9	1.04147	4.98	206	10.31	4.99
60 mM CuO-CFRP	8.5	0.42	4.97	365	18.23	5.00	22.4	1.1175	5.01	214	10.7	5.00

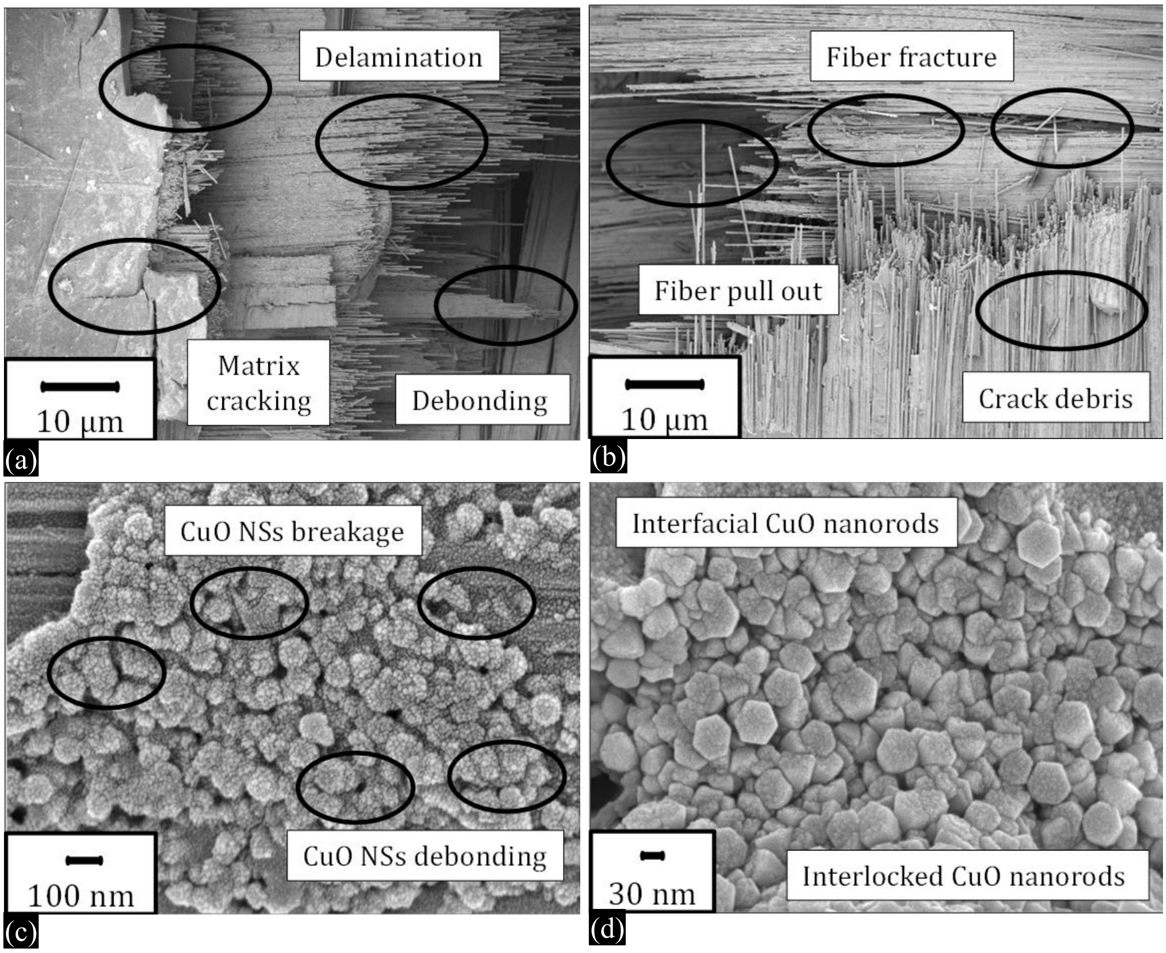

Figure 4. Fracture surface topography showing enhanced delamination resistance in CFRP by CuO surface functionalization.

One important finding was the unique structure of the impact holes, which resembled arches, in the composites at higher CuO molar concentrations. On the other hand, there was a direct and straight penetration of damage in the simple WCF/BPA epoxy composites. Because of the cross-linking action of the CuO nanostructures at the impact zone, the impact-damaged region of composites with higher CuO concentrations resembled an erupted volcano. The bonding energy between the WCFs and CuO nanostructures exceeded the epoxy resin's deformation energy when the CuO nanostructures spread into the fissures. As a result, although the damaged area was still very tiny, these nanostructures absorbed more impact energy. This suggests that composites with increased molar CuO concentrations demonstrated improved absorption of impact energy. Debonding and breaking of the nanostructure were among the failure mechanisms noted, indicating enhanced interfacial properties in the produced composites. As seen in Figure 4(c & d), FESEM examination of the damaged hybrid CFRP composite samples (S2–S7) showed surface evidence of CuO nanostructures. The existence of interlocked CuO nanorods at the failure zone interface is demonstrated by the close-up image in Figure 4(d). These results imply that the mechanical characteristics of the produced hybrid composite samples are greatly improved by the addition of CuO nanostructures to the WCF and their crosslinking at the interfacial area. This enhancement emphasizes how CuO nanostructures support the composites' structural integrity when subjected to impact loading.

CONCLUSIONS

Using a seed-assisted hydrothermal technique, monoclinic CuO nanostructures were successfully produced on WCF to enhance the interfacial bonding in plain WCF polymer composites. To determine the ideal process parameters for consistent CuO development, a full factorial experimental design was utilized. Analysis of the void content and volume fraction showed that, while keeping the fiber volume fraction constant, the CuO content grew in tandem with the precursor's molar concentration. The low void content and improved interfacial characteristics helped to improve the composite quality at higher CuO concentrations. Tensile and drop-weight impact tests were used to assess the composites' mechanical qualities. The findings showed that the hierarchical composites' capacity to absorb energy was much improved by the CuO nanostructures. CuO nanostructures' cross-linked network structure improved the composites' resistance to impact damage by promoting the diffusion of impact energy throughout the interfacial region. It was discovered that the CuO nanostructures improved load transfer between the components and strengthened the interfacial connection. According to impact tests, the WCF/CuO/BPA epoxy resin composites performed better as the CuO concentration rose and showed higher penetration thresholds than the ordinary WCF/BPA epoxy resin composites. In comparison to the plain composite, the composite with the highest CuO growth demonstrated a 166% decrease in fracture time and a 74.8% increase in impact energy absorption. Furthermore, compared to the ordinary composites, the CuO-modified composites showed greater tensile strengths and elastic moduli. In particular, the composite containing CuO modified at 8 seeding cycles, 12 hours of growth treatment, and 60 mM molar concentration shown improvements in in-plane shear strength of 32%, elastic modulus of 52%, and tensile strength of 42%. Overall, the composites' mechanical and thermal qualities were greatly improved by the improved interfacial interaction between CuO nanostructures, WCF fibers, and epoxy resin, which qualified them for structural uses.

Declaration of Interest

There is no potential conflict of interest.

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