MORPHOLOGICAL AND STRUCTURAL CHARACTERIZATION OF CNT/EPOXY NANOCOMPOSITES USING AFM AND FTIR

T.I. ORUJOVA
French-Azerbaijani University (UFAZ),
Azerbaijan State Oil and Industry University, Baku, Azerbaijan
Institute of Physics, Ministry of Science and Education, Baku, Azerbaijan
Email: taranaoruc@gmail.com

Carbon nanotube (CNT)-reinforced epoxy nanocomposites have attracted significant interest due to their potential in advanced structural and functional applications. In this study, thin-film nanocomposites containing 2 wt% multi-walled carbon nanotubes (MWCNTs) were prepared using a bisphenol-A–based epoxy resin (EDP) and a polyamine hardener. The morphology and chemical structure of the nanocomposites were investigated using Atomic Force Microscopy (AFM) and Fourier-transform infrared spectroscopy (FTIR). AFM images revealed a non-uniform dispersion of CNTs, where both nanoscale networks and agglomerated regions were observed. FTIR spectra indicated partial epoxy ring opening and confirmed the persistence of key functional groups in the cured matrix. The combined results demonstrate that CNT dispersion quality and matrix–filler interactions play a decisive role in defining the structural features of CNT/epoxy nanocomposites. These findings highlight the importance of optimizing preparation and mixing parameters to improve composite uniformity and functional performance.

Keywords: AFM, FTIR, carbon nanotube, epoxy nanocomposite, morphology
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1. Introduction

Polymer nanocomposites reinforced with carbon nanotubes (CNTs) have become one of the most promising classes of advanced materials due to their exceptional mechanical, electrical, and thermal properties. Owing to their high aspect ratio and excellent intrinsic conductivity, multi-walled CNTs are widely employed in applications such as aerospace structures, automotive components, sensors, and multifunctional coatings [1,2]. Epoxy resins, particularly bisphenol-A–based systems, exhibit outstanding mechanical strength, chemical resistance, and dimensional stability, making them a widely used matrix material in high-performance composites [3]. The overall properties of CNT/epoxy nanocomposites strongly depend on the dispersion quality of CNTs, their interfacial interaction with the matrix, and the fabrication conditions [4]. CNT agglomeration remains a critical challenge, as it adversely affects load transfer efficiency and electrical pathways. Atomic Force Microscopy (AFM) provides nanoscale topographical information and is highly suitable for studying CNT distribution and polymer surface morphology [6,7]. FTIR spectroscopy, on the other hand, enables identification of chemical interactions between CNTs and the polymer matrix [8]. In this work, CNT/epoxy nanocomposites containing 2 wt% MWCNTs were fabricated, and their surface morphology and structural interactions were characterized using AFM and FTIR techniques. The goal was to evaluate CNT dispersion quality and identify molecular-level interactions crucial for the functional properties of the material.

2. Materials and Methods

2.1. Materials

A commercial bisphenol-A–based epoxy resin (EDP) together with a polyamine hardener was used as the polymer matrix. Multi-walled carbon nanotubes (MWCNTs) synthesized via aerosol-assisted chemical vapor deposition (CVD) were employed as the nanofiller. The CNT loading was fixed at 2 wt% [9].

2.2. Preparation of Nanocomposites

MWCNTs (2 wt%) were dispersed in the epoxy resin using magnetic stirring at 45 °C for 4 hours to reduce agglomeration. After dispersion, the polyamine hardener was added according to manufacturer specifications, and the mixture was stirred for an additional 10 minutes. The resulting material was mechanically pressed to obtain thin-film samples and cured at room temperature.

2.3. AFM characterization

AFM measurements were performed using a Nanosurf FlexAFM Axiom microscope in tapping mode. Silicon cantilevers with a nominal radius <10 nm were used. Images were collected over scan areas of 1–10 µm with a scan rate of 0.8–1.2 Hz. Both topography and phase images were analyzed to evaluate CNT dispersion and surface morphology.

2.4. FTIR analysis

FTIR spectra were recorded in the range 4000–400 cm^{-1} with a resolution of 4 cm^{-1}, averaging 32 scans per spectrum. The analysis targeted identification of characteristic epoxy functional groups and their possible shifts or changes caused by CNT incorporation.

3. Results and Discussion

3.1. AFM analysis

AFM images revealed that CNT dispersion within the epoxy matrix was non-uniform. Smooth topographical

131, H.Javid ave, AZ-1073, Baku
Institute of Physics
E-mail: jophphysics@gmail.com

regions indicated relatively well-dispersed CNTs, whereas protrusions and bulges corresponded to CNT agglomerates. Nanoscale roughness values ranging from 20–50 nm suggested the presence of a CNT network, while larger protrusions reaching up to 200 nm reflected regions of intensified accumulation. Phase images also suggested partial CNT alignment or the influence of shear flow during sample preparation. These observations indicate that the mixing method provides partial dispersion, yet CNT agglomeration remains a challenge affecting both structural uniformity and potential conductive pathways.

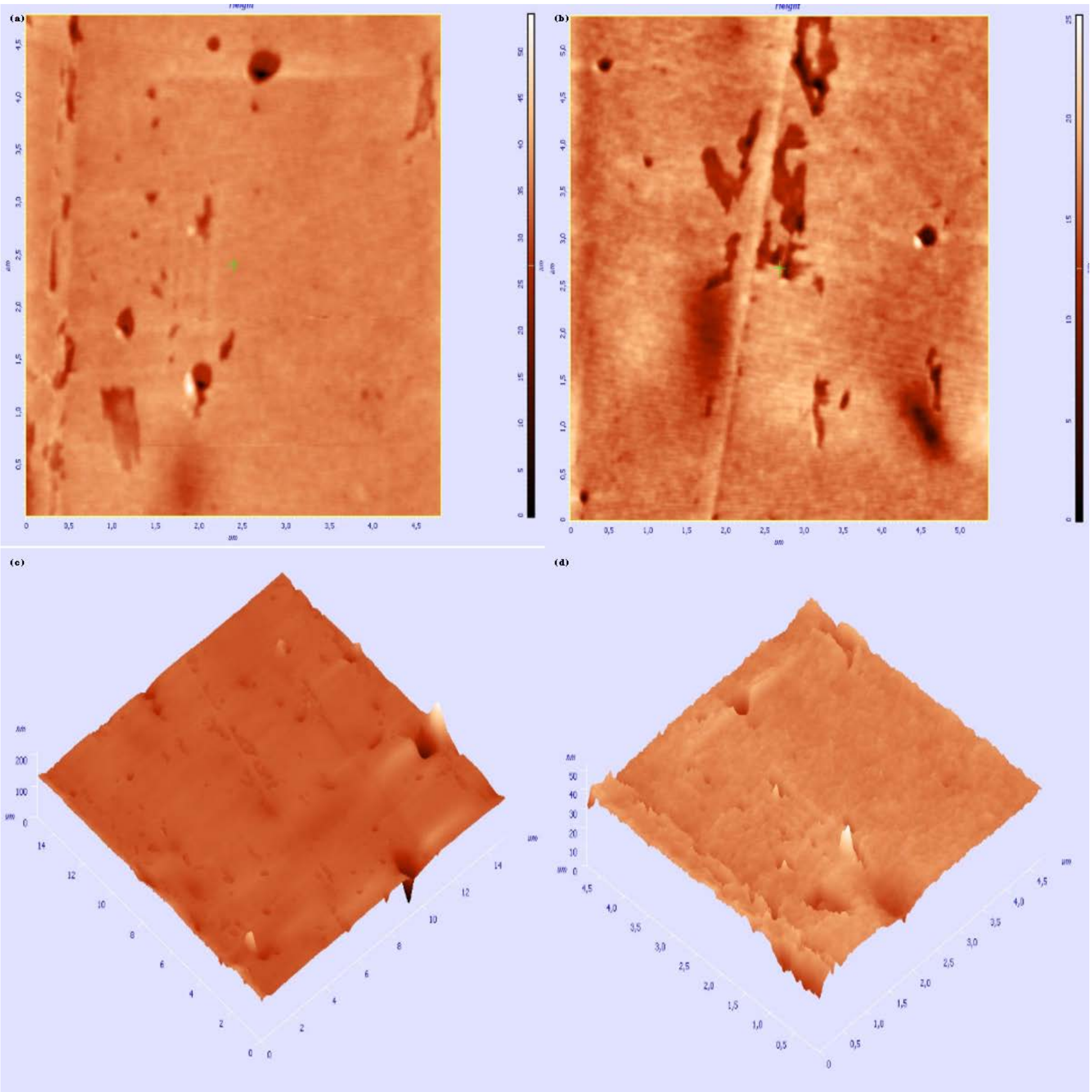

Figure 1. AFM images of the epoxy/CNT nanocomposite: (a–b) 2D height images, (c–d) 3D topographic images.

3.2. FTIR analysis

The FTIR spectra presented in Figure 2 provide information about the chemical structures of the Multi-Walled Carbon Nanotubes (MWCNTs), the epoxy composite, and their mutual interactions. The peak at 3780 cm^{-1} is attributed to the O–H stretching vibration of the epoxy structure, while the peak at 2900 cm^{-1} corresponds to the C–H stretching vibrations of CH groups. In addition, the peak at 1504 cm^{-1} is assigned to the C–C stretching vibrations in both epoxy and CNTs. The peak at 1602 cm^{-1} is associated with the C=C stretching vibrations of epoxy and CNTs. The C–O stretching peaks recorded in the 1250–950 cm^{-1} range confirm the presence of oxygen-containing functional groups on the nanotube surface, which contributes to improved adhesion with the epoxy matrix. The peaks at 818 and 561 cm^{-1} are correlated with the aromatic C–H out-of-plane bending (benzene ring) and the O–H out-of-plane vibration, respectively [10,11,12].

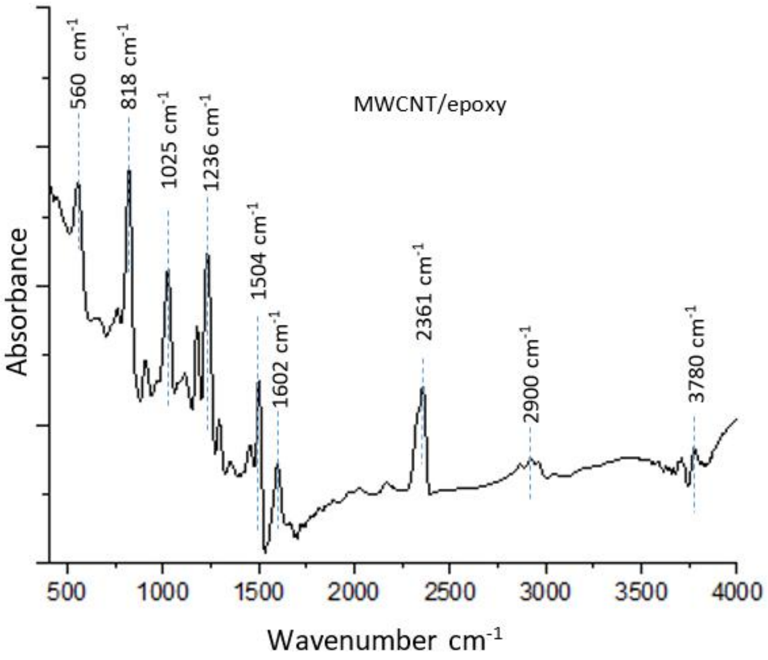

Figure 2. FTIR spectra of MWCNT/epoxy nanocomposite in the range 4000–400 cm^{-1}.

4. Conclusion

AFM and FTIR analyses provided detailed insights into the morphological and structural characteristics of 2 wt% MWCNT/epoxy nanocomposites. AFM imaging confirmed non-uniform dispersion with both nanoscale networks and agglomerated regions, indicating limited interfacial efficiency. FTIR results supported partial epoxy ring opening and confirmed the presence of characteristic functional groups, suggesting modest matrix–filler interactions. Overall, the study demonstrates that dispersion quality and interfacial behavior play critical roles in determining the structural properties of CNT/epoxy systems. Future improvements should focus on advanced dispersion strategies and surface functionalization of CNTs to enhance uniformity and improve composite performance

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