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Research article

Correlation between fracture surface topography, skewness, and kurtosis with mechanical properties in epoxy-MgO nanocomposites

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Abstract: Epoxy resins are widely used in structural and protective coatings, but their brittleness and crack growth limit use in demanding applications. Improving toughness in epoxy and related polymers is still a challenge. In this work, epoxy-MgO nanocomposites were studied to evaluate their mechanical performance and fracture behavior. Tests included ultimate tensile strength, Young's modulus, and fracture surface analysis. In addition, skewness (Rsk) and kurtosis (Rku) were used as quantitative measures of the fracture surfaces. Results showed that adding MgO nanoparticles improved both strength and stiffness compared with pure epoxy, while the mid-range MgO contents gave the best results. Fracture surface observations confirmed that the nanoparticles created more uniform and less crack-sensitive morphologies than in pure epoxy. These findings indicate that MgO nanoparticles enhance the stability and fracture toughness of epoxy. Skewness and kurtosis provided useful parameters for characterizing fractures among the composites. This study also shows how statistical descriptions of surface morphology can be linked with mechanical behavior. The results offer guidance for optimizing nanoparticle design in structural and functional nanocomposite applications.

Keywords: MgO nanoparticles; nanocomposites; tensile; skewness; kurtosis

1. Introduction

Polymer matrix composites are widely used in structural and functional fields because they combine mechanical strength with low density, ease of processing, and chemical stability. Epoxy resins are among the most important materials in coatings, adhesives, and composite matrices, with their advantages including strong adhesion, excellent electrical insulation, and dimensional stability [1,2]. Despite these benefits, epoxies suffer from natural brittleness and low fracture toughness, which limit their use in applications that require resistance to crack propagation and energy absorption. To overcome these limitations, epoxy matrices have been reinforced with different nanomaterials and fillers to improve their mechanical properties [3–6]. Notably, the incorporation of silica nanoparticles [7], alumina nanoparticles [8], titanium dioxide nanoparticles [9], and carbon-based materials [10] has been reported to create significant improvements in mechanical performance substantially. Among these, magnesium oxide (MgO) nanoparticles are an attractive choice for improving both barrier and mechanical properties due to the combination of high thermal stability with a wide band gap and chemical inertness [11–13]. Therefore, interest in MgO-filled polymer composites has increased in recent years, but most studies have focused on thermal stability, dielectric behavior, and general mechanical properties such as tensile strength and hardness [11,14–16]. Less attention has been given to fractured behavior, despite the importance of understanding how nanoparticles influence surface morphology during fracture. Analysis of fracture surfaces provides key insights into energy dissipation mechanisms, crack propagation, and the quality of filler–matrix interfaces, all of which determine reliability under stress.

Traditional surface roughness parameters such as Ra and Rq describe average heights and deviations from the mean. However, they do not give insight into surface asymmetry or sharp localized features. While skewness (Rsk) and kurtosis (Rku) provide deeper statistical insight by characterizing the distribution of peaks and valleys across fracture surfaces, Rsk indicates whether surfaces contain more valleys or peaks, and Rku distinguishes between flatter, broad features and sharper, localized ones. This is especially relevant in nanocomposites, where crack growth and local energy absorption are strongly affected by small-scale irregularities. Although Rsk and Rku are not commonly applied in epoxy studies, their use offers greater sensitivity in linking nanoparticle reinforcement to shifts in failure mechanisms.

In this study, this deficiency is addressed by investigating the tensile properties of epoxy-MgO nanocomposites at different MgO concentrations and a detailed analyzing the fracture surface morphology. Both conventional roughness parameters (Ra and Rq) and statistical measures (Rsk and Rku) are compared, supported by grayscale surface profiling mapping and scanning electron microscope (SEM) imaging. Grayscale profiling adds an analytical dimension, allowing visualization of fracture complexity and confirming microscale roughness development. Consequently ‹results show that higher MgO content leads to rougher and more tortuous fracture surfaces, improved interfacial bonding, and fewer brittle failure features. Together, these methods provide both quantitative and visual evidence of nanoparticle reinforcement effects on fracture energy and toughness, thereby highlighting new directions for designing stronger polymer nanocomposites.

2. Materials and methods

2.1. Materials

Polyprime EP, a solvent-free and colorless epoxy resin supplied by Polybit Co., was employed in this study as the control sample. The resin was cured with a polyamine-based hardener at a 2:1 weight ratio (resin: hardener), following the manufacturer's specifications. The resin and hardener were thoroughly mixed to achieve homogeneity, cast into molds, and cured at room temperature (25 ± 2 °C) for 24 h, a post-curing step at 60 °C for 2 h then was performed to ensure complete crosslinking. MgO nanoparticles were obtained from MTI Corporation. The nanoparticles had a purity of 99.9%, a particle size range of 20–25 nm, and a specific surface area exceeding 50 m^2/g. They appeared as a white powder with a bulk density of 0.13–0.16 g/cm^3 and a true density of 3.58 g/cm^3. The morphology and shape of the MgO nanoparticles were characterized and confirmed using transmission electron microscopy (TEM), as illustrated in Figure 1.

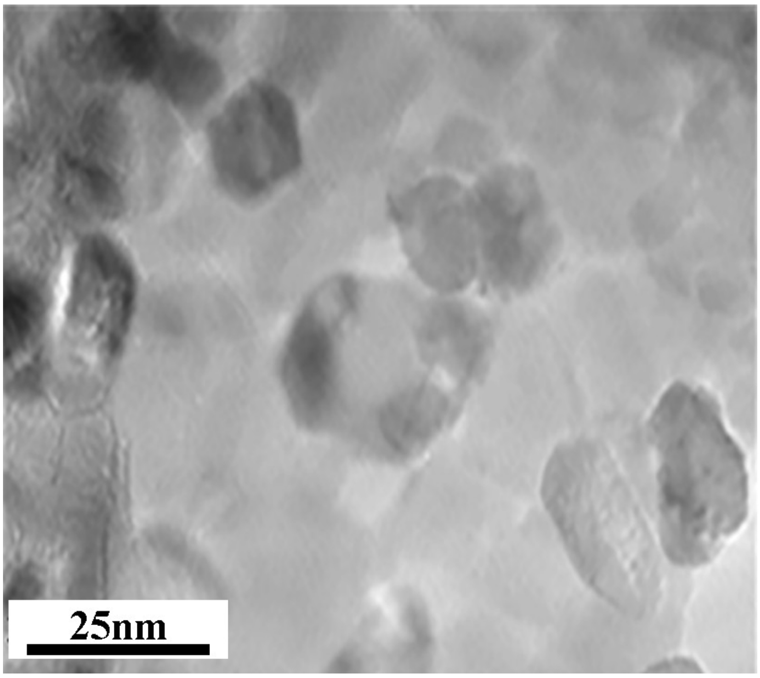

Figure 1. TEM image of MgO nanoparticles provided by the manufacturer (MTI Corporation).

2.1.1. Preparation method

MgO nanoparticles (0.5, 1.0, 1.5, 2.0, 2.5, and 3.0 wt.%) were blended with epoxy resin along with a neat epoxy (for the control sample). The epoxy and MgO nanoparticles were blended using ultrasonication for 20 min to allow for uniform dispersion of the nanoparticles and to prevent agglomeration of the nanoparticles. The mixing was done at 50 °C in order to keep the viscosity of the epoxy low and reduce the chance of agglomeration of the nanoparticles, and to create a uniform dispersion of the nanoparticles in the matrix. Air bubbles formed in the composite mixture during mixing were removed with a vacuum system. Optical microscopy was employed to examine the epoxy-MgO blend and verify the absence of large nanoparticle clusters. Once a uniform dispersion of MgO nanoparticles was confirmed, the hardener was added to the epoxy-MgO mixture.

2.1.2. Characterization and testing

The fracture surface morphology of the epoxy-MgO nanocomposites was analyzed using a TESCAN VEGA SEM. To observe surface features, examine crack propagation paths, and assess nanoparticle dispersion and matrix interaction. Mechanical properties were determined using a Laryee universal testing machine (Model UE34300, Beijing, China) in accordance with the ASTM D638 standard for tensile testing, with tensile tests performed at a crosshead speed of 2 mm/min. Surface roughness and grayscale profile analyses of the fracture surfaces were carried out using ImageJ software.

3. Results

3.1. Tensile properties of epoxy-MgO nanocomposites

The tensile properties of epoxy-MgO nanocomposites improved appreciably with potential improvements to the properties by incorporating the MgO nanoparticle, which was used in varying wt.% depending on the nanocomposite. As shown in Figure 2a, the unmodified epoxy had a low tensile strength (13.12 MPa) and modulus (0.24 GPa). After 0.5 wt.% MgO was incorporated, the tensile strength was found to be 45.15 MPa. However, the tensile strength improved to 52.67 MPa with 1.0 wt.% of MgO. With increasing concentration, it reached a maximum of 24.40 MPa at 3.0 wt.%. This is due to the agglomeration of nanoparticles may cause weak points in the matrix, leading to a reduction in tensile strength. The tensile modulus improved systematically with increasing wt.%, attaining a tensile modulus of 0.83 GPa at 1.0 wt.% and then reduced as the wt.% of MgO continued to increase until it obtained a peak of 2.92 GPa at 3.0 wt.%, where thermal degradation of the epoxy must have taken place to account for an observed increase in stiffness, although tensile strength drastically dropped. The force-deflection curves confirmed the mechanical performance of the samples with 1.0 wt.% MgO, as that sample had high load bearing capacity and acceptable ductile properties, and despite the low ductility at higher filler content, having had low deflection and low peak forces, this demonstrates a somewhat increase in brittleness (Figure 2b). The following results indicate the concentration of 1.0 wt.% MgO seemed to successfully balance strength, stiffness and toughness in epoxy nanocomposites. MgO nanoparticles in the epoxy matrix confine the chains by acting as solid physical barriers, restricting the mobility and chain length of the portion of the chain that was deflected in the applied mechanical stress. The larger the loading of MgO, the more confinement imposed by the nanoparticles and the more inter-chain interactions. The increasing stiffness due to structural confinement has a considerable bearing on the corresponding increase in tensile modulus and improved mechanical performance of the overall composite [3].

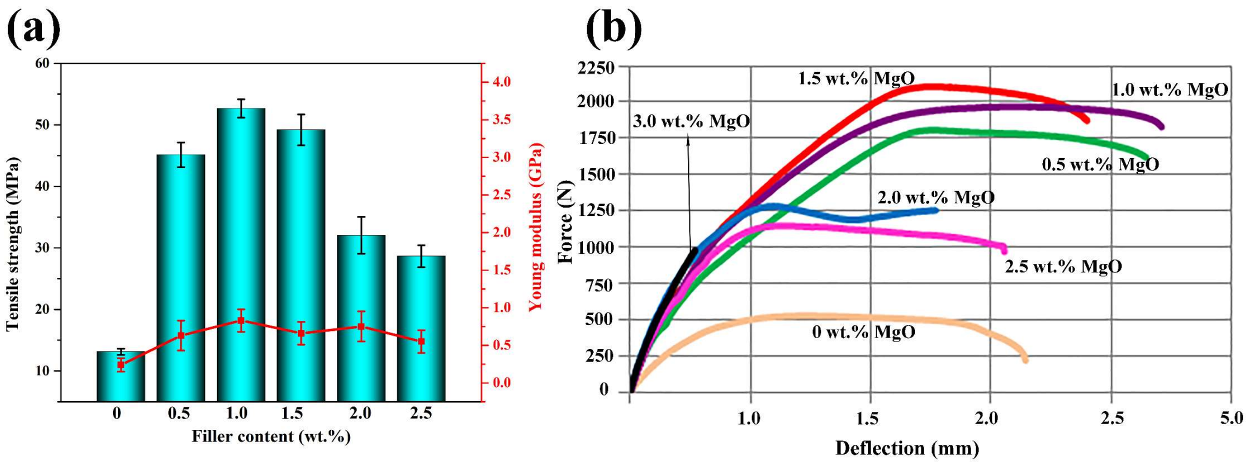

Figure 2. (a) Tensile strength and Young's modulus of epoxy-MgO nanocomposites at different MgO weight percentages, and (b) typical force–deflection curves for epoxy-MgO nanocomposites.

3.2. Fracture surface morphology of epoxy-MgO nanocomposite

The fracture surface morphology of epoxy-MgO nanocomposites was examined by SEM, as shown in Figure 3, to evaluate the influence of MgO nanoparticle content on failure mechanisms. The unfilled epoxy (0 wt.% MgO) sample (Figure 3a) exhibited a smooth, flat fracture surface characterized by linear cracks and clear signs of interfacial debonding, indicating brittle failure and limited energy dissipation, upon addition of 0.5 wt.% MgO concentration (Figure 3b), semi-parabolic cracks, and a distinct ductile zone were observed, suggesting partial stress transfer due to improved matrix–filler interaction. Which increases the concentration to 1.0 wt.% MgO (Figure 3c) resulted in a more aligned and prolonged fracture pattern, reflecting more homogeneous stress distribution, enhanced toughness, and ductility. Meanwhile, the sample continues 1.5 wt.% MgO (Figure 3d) exhibited rupture structures and rougher surfaces, indicating further improvement in crack propagation resistance. At 2.0 wt.% MgO (Figure 3e) features of cleavage were evident, suggesting a hybrid mode of brittle and cleavage failure. Further increasing the concentration to 2.5 wt.% MgO (Figure 3f) produced a coarser, more fragmented fracture surface compared with lower concentrations, indicating higher energy absorption during failure. Finally, the sample containing 3.0 wt.% MgO (Figure 3g), river lines and cleavage steps were observed, indicating complex crack propagation and extensive plastic deformation, although some features might also suggest nanoparticle agglomeration at this concentration. Overall, the SEM observations demonstrate a transition from brittle fracture toward more ductile-like behavior with increasing MgO content, with the most effective toughening occurring between (1.0 and 2.5 wt.%). The morphological findings were consistent with mechanical and roughness results, showing that improved nanoparticle dispersion and strong interfacial bonding enhanced the fracture resistance and overall mechanical performance of the epoxy-MgO nanocomposites.

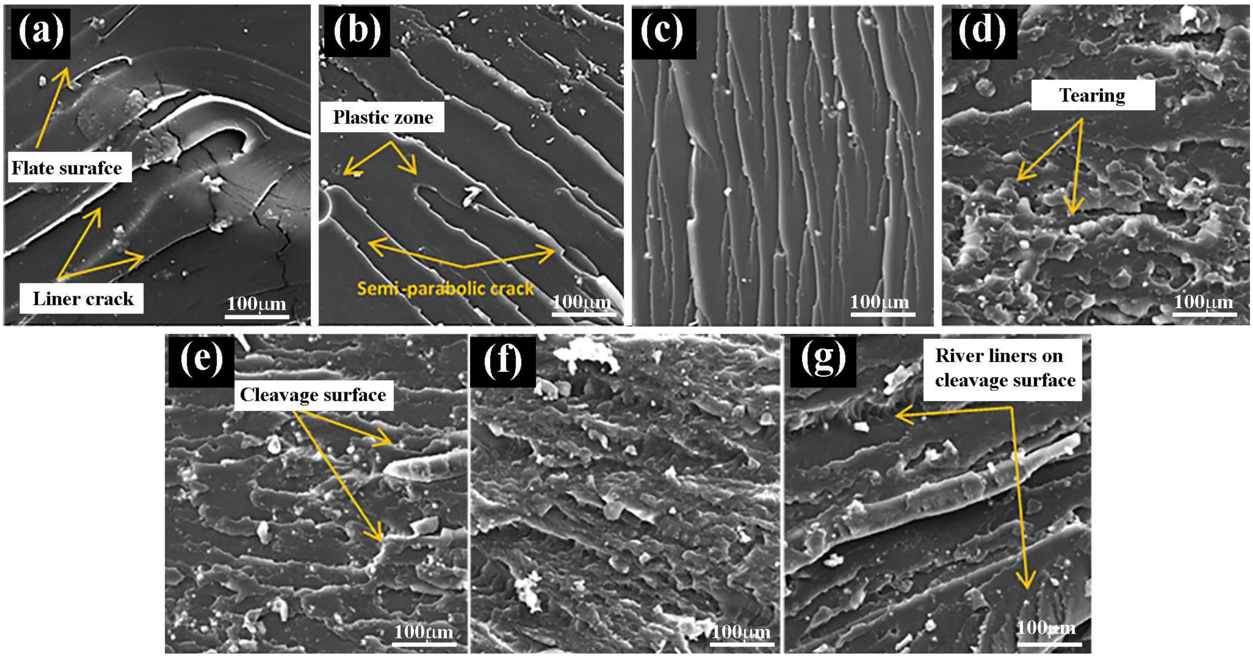

Figure 3. SEM images of the fracture surfaces of epoxy-MgO nanocomposites at different MgO weight percentages: (a) 0 wt.% (neat epoxy), (b) 0.5 wt.%, (c) 1.0 wt.%, (d) 1.5 wt.%, (e) 2.0 wt.%, (f) 2.5 wt.% showing irregular and rough morphology, and (g) 3.0 wt.%.

3.3. Effect of MgO content on fracture surface roughness

Evaluation of fracture surface roughness allows the material to respond to stress, absorb energy, and resist crack propagation. Additionally, quantitative changes in surface morphology, reflected by Ra and Rq parameters, indicate the effectiveness of nanoparticle dispersion and the strength of interfacial bonding. Three-dimensional (3D) surface topography images of epoxy–magnesium oxide nanocomposite fracture surfaces at different MgO concentrations are presented in Figure 4, along with the corresponding roughness measurements. The pure epoxy material (Figure 4a) displays the most even surface with Ra = 87.232 μm and Rq = 106.189 μm values, which indicate low energy absorption and poor crack resistance. The addition of 0.5 wt.% MgO (Figure 4b) leads to a slight increase in surface roughness, which results in Ra = 92.288 μm and Rq = 108.274 μm values. The surface texture increases at 1.0 wt.% MgO (Figure 4c) because of better nanoparticle dispersion, which leads to Ra = 99.565 μm and Rq = 116.903 μm values. The addition of 1.5 wt.% MgO (Figure 4d) produces a more complex fracture pattern with Ra = 104.497 μm and Rq = 116.375 μm values that indicate better crack deflection. The roughness values increase at 2.0 wt.% MgO (Figure 4e) to Ra = 105.368 μm and Rq = 121.275 μm before reaching their highest point at 2.5 wt.% MgO (Figure 4f) with Ra = 107.773 μm and Rq = 123.223 μm, where the highest surface irregularity and energy dissipation occur at 3.0 wt.% MgO (Figure 4g), where Ra reaches 115.327 μm and Rq reaches 132.054 μm. These results indicate that higher MgO content produces more complex fracture surfaces, which results in better toughness and stronger interfacial bonding in nanocomposites.

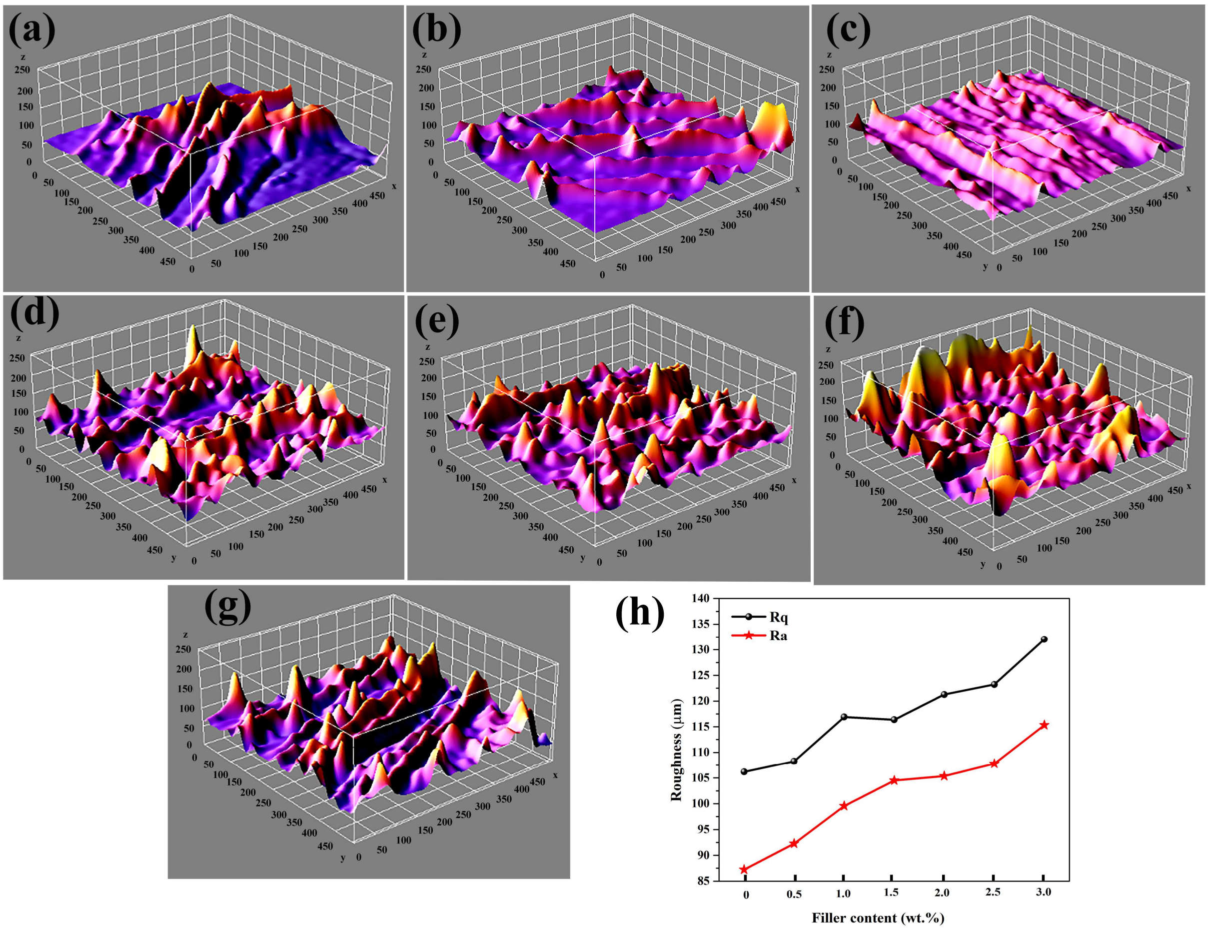

Figure 4. 3D surface topography of fracture surfaces for epoxy-MgO nanocomposites at different MgO weight percentages: (a) 0 wt.%, (b) 0.5 wt.%, (c) 1.0 wt.%, (d) 1.5 wt.%, (e) 2.0 wt.%, (f) 2.5 wt.%, and (g) 3.0 wt.%. (h) Corresponding roughness values (Ra and Rq).

Rsk and Rku are important statistical parameters for characterizing fracture surface properties. Rsk indicates the skewness of the fracture surface, such that larger values indicate sharp, irregular peaks associated with brittle failure, while Rku indicates the sharpness of the surface components, such that larger values indicate spiky, irregular surface profiles. Lower values of Rsk and Rku indicate more symmetric and flatter surfaces and are indicative of higher fracture toughness or more benign fracture propagation. From the data in Table 1, Rsk and Rku values reduce considerably as the amount of MgO nanoparticles increased in the epoxy matrix. The Rsk and Rku values provide an accurate assessment of the fracture surface properties of the epoxy matrix with increasing MgO nanoparticle content. The pure epoxy sample exhibited the highest Rsk (1.72) and Rku (3.573) values, reflecting an asymmetric and irregular fracture surface, a hallmark of brittle behavior, with the addition of MgO concentrations, Rsk values decreased from 1.531 at 1.0 wt.% to 1.42 at 3.0 wt.%, while Rku decreased from 3.573 (pure epoxy) to 2.31.

These decreases indicate a shift toward more symmetrical and less defined surface features, which may demonstrate improved fracture toughness. This trend is consistent with the roughness results (Ra and Rq), which increased with higher MgO content. Increasing Ra and Rq values indicated a greater degree of texture and irregularity in the fracture surface features, which is associated with increased energy absorption and resistance to crack propagation. Furthermore, Ra and Rq represent a measure of vertical deviation from the surface, but, unlike Rsk and Rku, they indicate a better evenness of surface elevations with less extreme topographic variations. Though previous measurements suggested an increase to the roughness of the surface features, the addition of MgO did not irregularly change the boundaries and positions of each fracture surface, which implied that the addition of MgO increases surface roughness and leads to a more uniform and controlled fracture surface. When using the surface roughness, skewness, and kurtosis. These results confirmed that MgO nanoparticles all contribute to tougher, less brittle fracture behaviour through maintaining mechanical integrity and improved morphological integrity of the nanocomposites.

Table 1. Rsk and Rku values of fracture surfaces for pure epoxy and epoxy-MgO nanocomposites at different MgO weight percentages.

Samples	Rsk	Rku
Pure epoxy	1.72	3.573
Epoxy + 0.5 wt.% MgO	1.621	3.211
Epoxy + 1.0 wt.% MgO	1.531	2.761
Epoxy + 1.5 wt.% MgO	1.471	2.559
Epoxy + 2.0 wt.% MgO	1.468	2.527
Epoxy + 2.5 wt.% MgO	1.456	2.486
Epoxy + 3.0 wt.% MgO	1.42	2.31

Figure 5 presents the grayscale surface roughness profiles of fracture surfaces for pure epoxy and epoxy-MgO nanocomposites at varying MgO contents. The grayscale profile is a representation of surface height variation across a scanned distance, where greater intensity fluctuations indicate higher surface irregularity and roughness. The pure epoxy sample consistently shows a relatively flat profile with minimal intensity change, confirming a smooth and uniform fracture surface associated with brittle failure. As MgO content increases, each nanocomposite profile demonstrates a noticeable increase in fluctuation amplitude and density. The 0.5 wt.% MgO sample begins to show minor intensity peaks, indicating the formation of small-scale surface irregularities. At 1.0 wt.% and 1.5 wt.% MgO samples, the grayscale curves exhibit sharper and more frequent peaks, suggesting improved fracture energy dissipation and more complex crack propagation paths. For 2.0 wt.% and 2.5 wt.% MgO, the intensity fluctuations are more distinct and sustained across the profile, which indicates greater surface deformation and plastic behavior during fracture. When the 3.0 wt.% MgO sample still exhibits increased roughness compared to pure epoxy, but with slightly reduced fluctuation intensity compared to mid-range concentrations, which may be related to particle agglomeration effects reducing the uniformity of the surface profile. Furthermore, the grayscale profiles show strong agreement with Ra, Rq, Rsk, and Rku, confirming that MgO incorporation increases fracture surface roughness and complexity. This indicates tougher and more energy-absorbing fracture mechanisms through improved stress transfer and crack deflection [17].

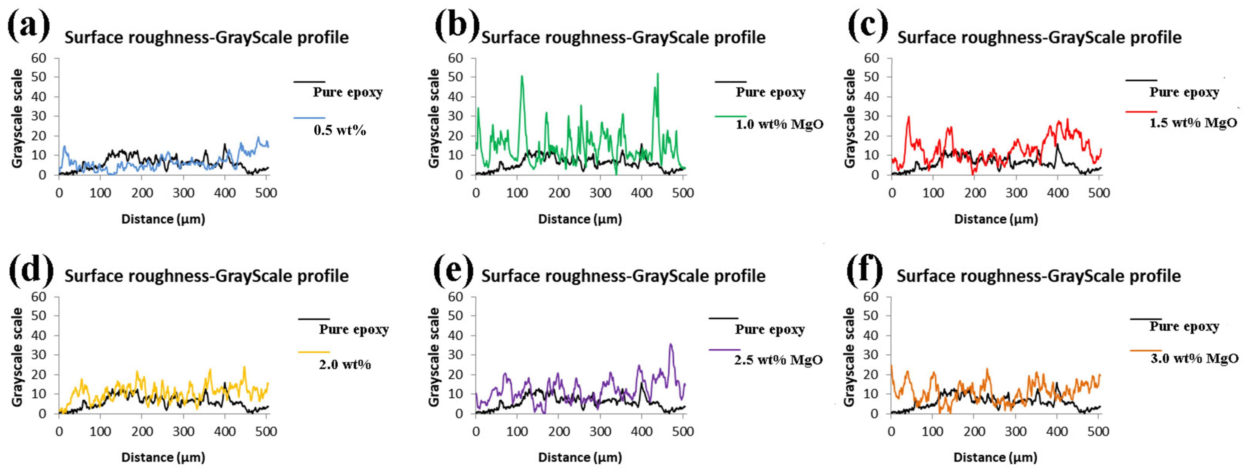

Figure 5. Grayscale surface roughness profiles of fracture surfaces for pure epoxy and epoxy-MgO nanocomposites at different MgO weight percentages: (a) 0.5 wt.%, (b) 1.0 wt.%, (c) 1.5 wt.%, (d) 2.0 wt.%, (e) 2.5 wt.%, and (f) 3.0 wt.%.

4. Conclusions

This study examined the influence of MgO nanoparticles on the tensile properties and fracture surface behavior of epoxy nanocomposites. The major findings are as follows:

1. Tensile strength increases from 13.12 MPa for pure epoxy to a maximum of 52.67 MPa at 1.0 wt.% MgO.

2. Young's modulus rose from 0.24 to 2.92 GPa at 3.0 wt.% MgO.

3. The surface roughness parameters (Ra and Rq) increase by the addition of MgO, indicating greater surface deformation and higher energy absorption.

4. SEM analysis revealed a transition from flat, brittle fracture surfaces in pure epoxy to more rough, curved fracture patterns in the composites, especially at 1.0–2.5 wt.% MgO.

5. Rsk decreased from 1.72 to 1.42, while Rku declined from 3.573 to 2.31, which reflected the formation of more symmetric and uniform fracture surfaces with increasing MgO content. Grayscale surface profiles further validated the roughness and statistical conclusions. Since MgO nanoparticles improved the fracture toughness, surface integrity, and stress distribution, 1.0–2.5 wt.% of MgO was found to be the optimum loading under which these aspects are best enhanced. All these results confirm MgO as an efficient nanofiller for the structural enhancement of epoxy composites.

Use of AI tools declaration

The authors declare they have not used Artificial Intelligence (AI) tools in the creation of this article.

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Conflict of interest

The authors declare no conflict of interest.

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