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*Article*

# Erosive Wear Behavior of Fiberglass Reinforced Epoxy Laminate Composites Modified with SiO<sub>2</sub> Nanoparticles Fabricated by Resin Infusion

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## Abstract

This work presents a study on the erosive wear behavior of laminated composites, manufactured using the vacuum assisted resin infusion (VARI) method with an epoxy matrix reinforced with glass fibers and modified with SiO<sub>2</sub> nanoparticles. Three materials were fabricated with SiO<sub>2</sub> nanoparticle concentrations of 0, 1.5, and 3 wt% to evaluate the effect of nanoparticle addition and dispersion on mechanical and microstructural properties, as well as erosion resistance. The results showed that the FG-1.5-SiO<sub>2</sub> composite, containing 1.5 wt% SiO<sub>2</sub> nanoparticles, exhibited the best nanoparticle dispersion, as evidenced by FTIR, GIXRD, and SEM analyses. This material displayed the lowest surface roughness ( $R_a = 0.215 \mu\text{m}$ ), the highest Vickers hardness (35.58), and the highest modulus of elasticity (19.66 GPa), indicating an effective load transfer and adequate interfacial interaction. In erosion tests, the FG-1.5-SiO<sub>2</sub> material demonstrated the lowest total mass loss (0.0261 mg) and the lowest erosion rate ( $2.3360 \times 10^{-5} \text{ mg/g}$ ), representing an approximately 38% improvement in erosion resistance compared to the reference material without nanoparticles (FG-0-SiO<sub>2</sub>). Profilometry and SEM analyses confirmed that this composite FG-1.5-SiO<sub>2</sub> exhibited less severe erosional damage, with shallower wear depth, characterized by less matrix removal and a stronger fiber-matrix interface. On the other hand, the composite with 3 wt% SiO<sub>2</sub> (FG-3-SiO<sub>2</sub>) showed poor dispersion and agglomeration, resulting in increased roughness, lower mechanical properties, and erosion resistance similar to that of the material without nanoparticle reinforcement. This was attributed to the agglomerates acting as stress concentrators and structural defects that facilitate material detachment.

**Keywords:** epoxy nanocomposites; erosive wear; SiO<sub>2</sub> nanoparticles; resin infusion; nanoparticle dispersion; erosion resistance

## 1. Introduction

Laminated composite materials have gained significant importance in sectors such as aerospace, aeronautics, automotive, energy, and marine in recent years due to their high strength-to-weight ratio, good thermal stability, corrosion resistance, and versatility in structural design [1–7]. However, when exposed to impact from solid particles, polymer matrix composites with fiber reinforcement experience surface material loss due to erosion. This phenomenon alters their morphology, generates microcracks, and negatively affects their mechanical properties, which can accelerate component failure and significantly shorten their service life [8,9]. Two intrinsic factors that limit their erosion

resistance compared to metallic or ceramic materials are the brittleness of thermoset matrices and the limited strength of the fiber-matrix interface [10].

One alternative to overcome these limitations is the incorporation of nanoparticles (NPs) into the polymer matrix, a strategy that has proven effective in improving the mechanical and tribological performance of these materials. This is because NPs, due to their high surface-to-volume ratio, promote better interfacial interaction with the polymer matrix, improving stress transfer, the degree of crosslinking, and beneficial microstructural modifications [11–15]. Various NPs such as  $\text{Al}_2\text{O}_3$ ,  $\text{TiO}_2$ ,  $\text{SiC}$ , and  $\text{SiO}_2$  have been studied as secondary reinforcements in epoxy matrices, showing improvements in hardness and wear resistance under erosion conditions [16–20]. Specifically, silicon dioxide ( $\text{SiO}_2$ ) NPs have generated great interest due to their chemical stability, high hardness, low cost, and excellent compatibility with epoxy polymer matrices [21]. In addition, surface protection strategies such as the application of hybrid coatings incorporating nanomaterials have also shown significant potential for mitigating erosive wear on composite substrates [22]. When properly dispersed,  $\text{SiO}_2$  NPs can form a microbarrier effect that restricts plastic deformation and microcrack propagation during impacts [23]. In addition, their surface hydroxyl groups can chemically interact with the epoxy matrix, improving interfacial adhesion and the overall load-bearing capacity of the composite [24].

Despite these advantages, most studies have focused on polymer nanocomposites without considering the synergistic influence of fiber reinforcement, or have analyzed the effects on mechanical properties rather than the mechanisms that arise due to erosional wear. Therefore, it is necessary to investigate how the addition and dispersion of  $\text{SiO}_2$  NPs affect the erosional wear behavior of glass fiber-reinforced epoxy systems, where both, the matrix and the fiber-matrix interface, play a fundamental role in energy absorption and material wear.

In this study, fiberglass-reinforced epoxy matrix laminates containing 0, 1.5 and 3 wt%  $\text{SiO}_2$  nanoparticles were fabricated using the resin infusion method. The main objective was to evaluate the effect of  $\text{SiO}_2$  nanoparticle concentration on the mechanical, microstructural, and erosion resistance properties of the nanocomposites. Dispersal of the NPs was achieved by ultrasonic stirring to minimize agglomeration and promote homogeneous distribution within the matrix.

Experimental results revealed that the composite with 1.5 wt%  $\text{SiO}_2$  exhibited the lowest rate of erosive wear, indicating that an optimal concentration of NPs and uniform dispersion can significantly improve the erosion resistance of epoxy/fiberglass laminates. The results of this research provide valuable information for the design of NPs-modified polymer composites for structural applications under erosive conditions.

## 2. Materials and Methods

### 2.1. Materials

Epilam 2015 epoxy resin (viscosity of 550 mPa·s at 25 °C), non-porous Skyspring  $\text{SiO}_2$  NPs (99.5% purity, diameter between 10 and 20 nm), and TBR600 fiberglass fabric (Type E glass, average filament diameter 15  $\mu\text{m}$ ) in bidirectional woven pattern with 5mm spacing were used to manufacture the composite materials.

The reference composite material was fabricated as shown in Figure 1 using the vacuum assisted resin infusion (VARI) method. The matrix was prepared by mixing epoxy resin and hardener in a 100:10 weight ratio. Eight layers (166.4 g per layer) of 150 x 220 mm bidirectional fiberglass fabric (Figure 2) were laid on a metal base, distribution mesh, and vacuum bag, which was then hermetically sealed with polyurethane tape. The resin was injected at a vacuum pressure of 50 kPa and a temperature of 25 °C, with an impregnation time of 25 min. Curing was achieved by heating the metal base to 70 °C for 4 h, resulting in a 150 x 220 mm laminate with a thickness of 4 mm.

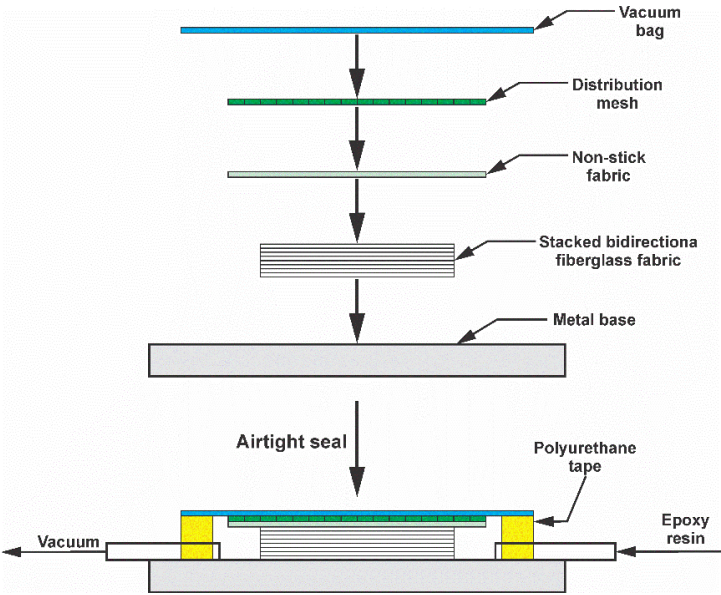


Figure 1. VARI method.

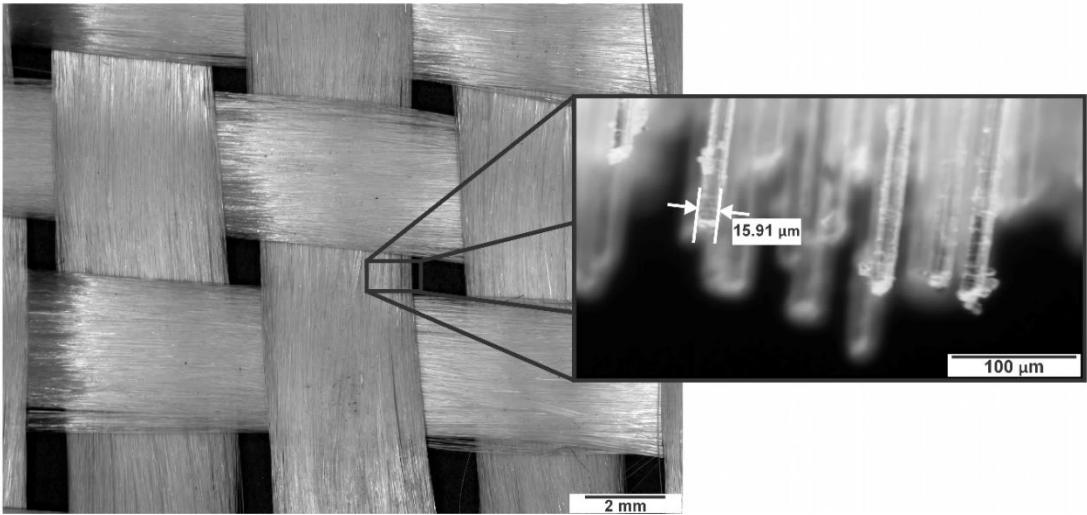


Figure 2. Fiberglass fabric.

The specimens showed a uniform distribution of fibers within the epoxy resin without apparent porosity or voids (Figure 3).

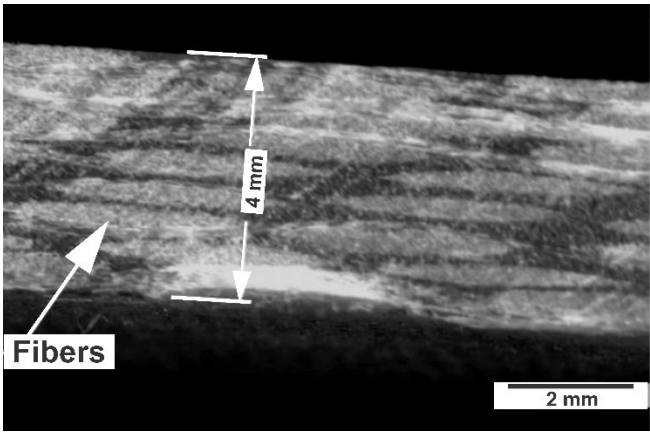


Figure 3. Cross section of the laminated composite.

2.2. Incorporation of SiO2 NPs

For the compounds with 1.5 and 3 wt% NPs relative to the resin, the NPs were dispersed in the epoxy resin using a 40 kHz ultrasonic bath for 5 min. The hardener was added, and an additional 7 min of ultrasonication was applied. The mixture was degassed for 7 minutes to reduce the presence of bubbles using this function of the ultrasonic bath. The same VARI and curing conditions as the reference laminate composite were applied to obtain the laminate composites with SiO2 NPs in the matrix. Three different fiberglass (FG) materials were produced, based on its NPs % concentration, see Table 1.

Table 1. Materials with different concentration of NPs.

| Material    | Concentration of SiO2 NPs, wt% |
|-------------|--------------------------------|
| FG-0-SiO2   | 0                              |
| FG-1.5-SiO2 | 1.5                            |
| FG-3-SiO2   | 3                              |

2.3. Erosive Particle

Silicon carbide (SiC) was used as the erosive particle, with a HV of 31 GPa. Figure 4 shows the SiC particles, which display polyhedral shapes with sharp angles. The selection of this particular abrasive is based on the size distribution and morphology with few variations, which guarantees reproducibility in erosion tests, minimizing variations due to the morphology or composition of the abrasive.

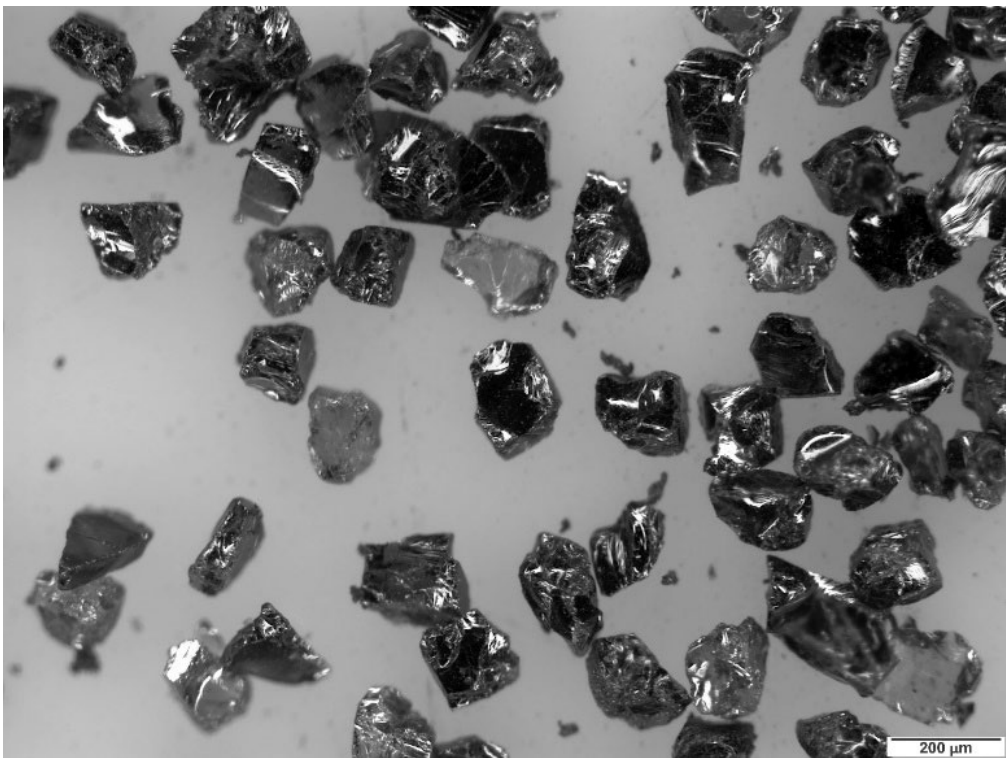


Figure 4. Erosive particle.

To determine the particle size distribution, static image analysis was used [25–27]. A total of 100 particle size measurements were taken from a series of images of the SiC particles captured by a stereoscope; with these data, a particle size distribution was made (Figure 5). Based on the results obtained, the particle size with the highest percentage was 249 μm.

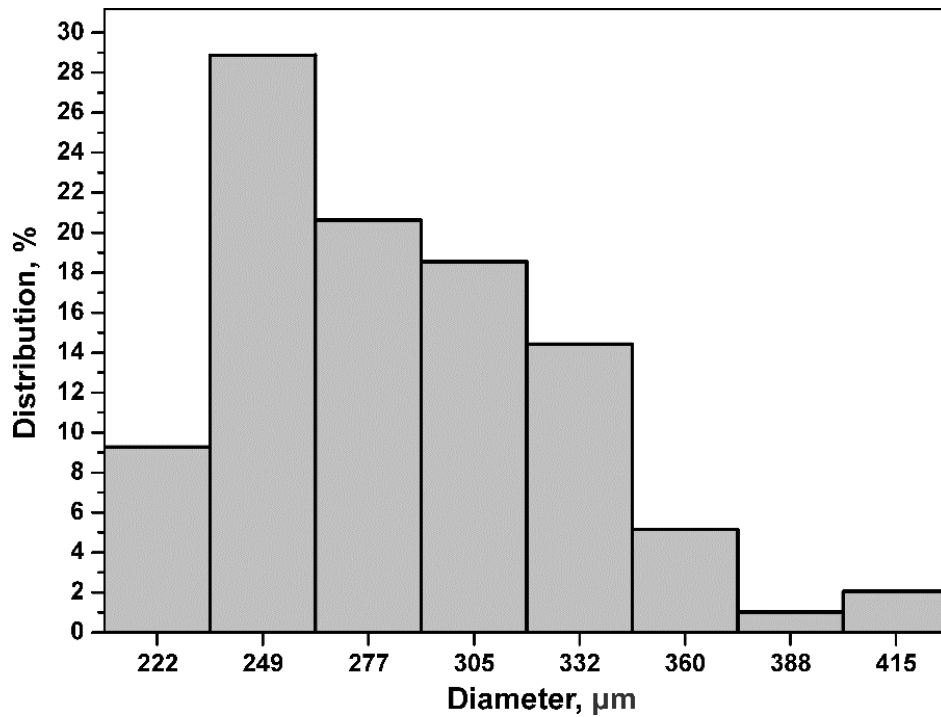


Figure 5. Erosive particle size distribution.

#### 2.4. Characterization

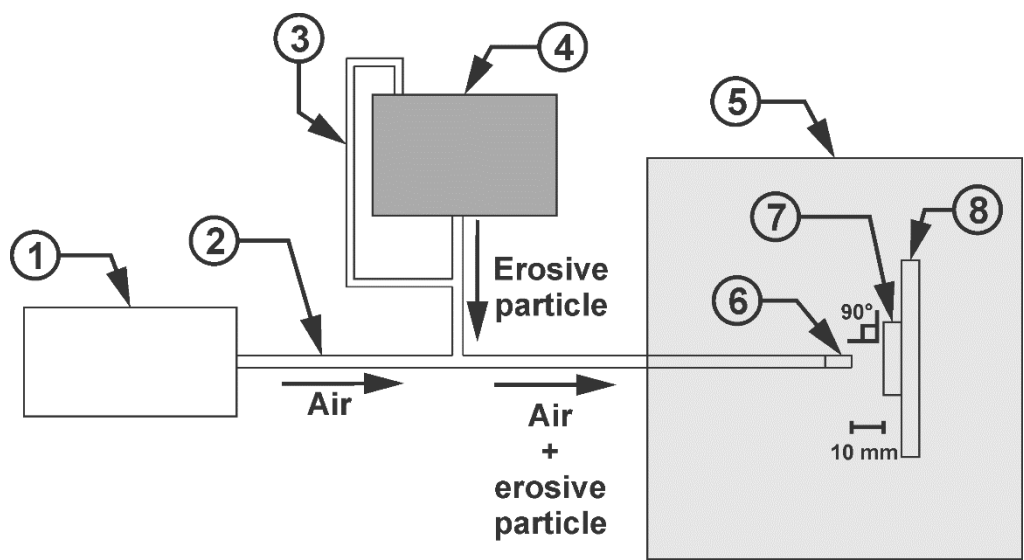
The chemical composition and distribution of the SiO<sub>2</sub> NPs were verified by Fourier transform infrared spectroscopy (FTIR) in transmission mode. Grazing incidence X-ray diffraction (GIXRD) was used as a complementary analysis to verify the presence and distribution of the nanoparticles in the resin matrix. XRD scans were performed in a  $2\theta$  range of  $5^\circ$  to  $80^\circ$  at a scan rate of  $2^\circ/\text{min}$  at room temperature. To determine the hardness and modulus of elasticity, nanoindentation tests were performed at a temperature of  $22.0 \pm 0.2^\circ\text{C}$ . All samples were subjected to a load of 50 mN for 10 seconds. The wear track profile and the roughness of the laminate composites were determined using a profilometer. A confocal microscope was used to identify the wear zone, and a scanning electron microscope was used to observe the wear mechanisms.

#### 2.5. Erosive Wear Tests

The specimens were mechanically cut to dimensions of  $20 \times 50$  mm. They were cleaned in a 40 kHz ultrasonic bath in soapy water for 10 minutes, followed by air drying. A homemade horizontal erosion test platform based on ASTM G76 [28] was used, and three tests were performed per sample. A simplified schematic diagram is shown in Figure 6. An air pressure of 45 Psi, a SiC erosion particle flow rate of approximately 0.838 kg/min and an impact velocity of 6 m/s, verified with an anemometer, were established. The nozzle used had an internal diameter of 8 mm and a separation distance of 10 mm from the sample. An impact angle of  $90^\circ$  was established due to the significant erosional damage it produces [29,30]. Before the tests, the initial mass of each sample was determined using an analytical balance, then the sample was removed every 20 seconds to record the mass loss and observe the effect of the SiO<sub>2</sub> NPs. This process was repeated for a total of 80 seconds.

The erosion rate ( $E$ ) was calculated by Equation 1 from the mass lost from the evaluated laminated composite material ( $\Delta w$ ) and the total mass of the erosive particle used in the test ( $\Delta e$ ) [31].

$$E = \frac{\Delta w}{\Delta e} \quad (1)$$



**Figure 6.** Schematic diagram of the horizontal erosion test platform, 1: Air compressor; 2: pipe; 3: feedback pipe; 4: erosive particle container; 5: erosion chamber; 6: nozzle; 7: sample; 8: sample holder.

3. Results and Discussion

3.1. Roughness, Hardness and Modulus of Elasticity

Table 2 presents the average roughness (Ra), Vickers hardness (VH) and modulus of elasticity (E) of FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub>, with their respective standard deviation (SD). The Ra values of FG-1.5-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub> were lower than those of the reference material, FG-0-SiO<sub>2</sub>. This reduction is attributed to the fact that the SiO<sub>2</sub> nanoparticles act as nanofillers for pores, microcracks, and surface defects present in the epoxy resin, generating a more homogeneous surface [32]. FG-1.5-SiO<sub>2</sub> exhibited the lowest roughness, suggesting an effective and homogeneous dispersion of the SiO<sub>2</sub> nanoparticles within the epoxy resin matrix [33]. In contrast, FG-3-SiO<sub>2</sub> showed a greater increase in roughness because its nanoparticle concentration promotes the formation of agglomerations [34]. This trend in FG-1.5-SiO<sub>2</sub> is validated by its higher VH and E values, indicating effective charge transfer and adequate interaction of the nanoparticles with the matrix [35,36]. In the case of FG-3-SiO<sub>2</sub>, its properties showed even lower values than the reference material FG-0-SiO<sub>2</sub>, confirming the presence of agglomerations that cause structural defects in the material [37].

**Table 2.** Summary of Ra, HV and E.

| Specimen                | Ra, $\mu\text{m}$ | SD, $\mu\text{m}$ | VH     | SD    | E, GPa | SD    |
|-------------------------|-------------------|-------------------|--------|-------|--------|-------|
| FG-0-SiO <sub>2</sub>   | 0.684             | 0.188             | 19.840 | 0.059 | 9.912  | 0.120 |
| FG-1.5-SiO <sub>2</sub> | 0.215             | 0.020             | 35.580 | 0.496 | 19.66  | 2.549 |
| FG-3-SiO <sub>2</sub>   | 0.475             | 0.230             | 13.830 | 0.208 | 5.491  | 0.052 |

3.2. FTIR

Figure 7 presents the FTIR spectra of specimens FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub>. Characteristic bands confirming the presence of SiO<sub>2</sub> containing groups are identified in all spectra. In FG-0-SiO<sub>2</sub>, these bands are attributed to the contribution of the glass fiber reinforcement, because this specimen does not contain NPs of SiO<sub>2</sub>. To differentiate the NPs contribution from the glass fiber signal in FG-1.5-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub>, the bending band ( $\delta$ ) of the O-Si-O bond, located between 450 and 500 cm<sup>-1</sup>, was analyzed [38]. As shown in the magnification, in FG-0-SiO<sub>2</sub> this band is observed at 479 cm<sup>-1</sup> with low intensity, corresponding to the silica in the fiber. In FG-1.5-SiO<sub>2</sub>, a slight shift to 470 cm<sup>-1</sup> is observed, maintaining low intensity. In contrast, in FG-3-SiO<sub>2</sub>, the band becomes wider and more intense, located at 472 cm<sup>-1</sup>. These shifts and changes reflect variations in the local chemical

environment due to interfacial interactions between the epoxy matrix and the NPs, which intensify with increasing NPs concentration [39]. The corresponding bands for symmetric ( $\nu_s$ ) and asymmetric ( $\nu_{as}$ ) stretching of Si–O–Si are located at  $830\text{ cm}^{-1}$  and  $1038\text{ cm}^{-1}$ , respectively [40]. Although no shifts are observed, their intensity increases markedly in FG-3-SiO<sub>2</sub>, this is attributed to the higher concentration of NPs and the possible formation of agglomerates, which, although contributing to the FTIR signal, may limit interfacial interaction [41]. The Si–OH band at  $936\text{ cm}^{-1}$  [42] also shows an increase in intensity in FG-3-SiO<sub>2</sub> compared to the other specimens. Although part of this increase is explained by the higher concentration of NPs, the marked intensity suggests the presence of aggregates containing Si–OH groups trapped at internal interfaces, reducing their accessibility and reactivity with the matrix [43]. In the band at  $3369\text{ cm}^{-1}$ , assigned to OH groups [44], a higher intensity is again observed in FG-3-SiO<sub>2</sub>. This is directly attributed to the surface silanol (Si–OH) groups of the NPs, whose signal is amplified by agglomeration and the consequent formation of hydrogen bonds between neighboring silanes [45]. This behavior is typical of nanocomposite systems where high concentration favors NPs agglomeration. Overall, the FTIR results indicate that FG-3-SiO<sub>2</sub> exhibits a marked tendency toward agglomeration, evidenced by the generalized increase in intensity of the Si–O–Si and Si–OH bands, along with morphological changes in the O–Si–O bending band. In contrast, FG-1.5-SiO<sub>2</sub> shows moderate changes compared to FG-0-SiO<sub>2</sub>, suggesting better NPs dispersion and more effective interfacial interaction, without significant alterations in the main SiO<sub>2</sub> bands.

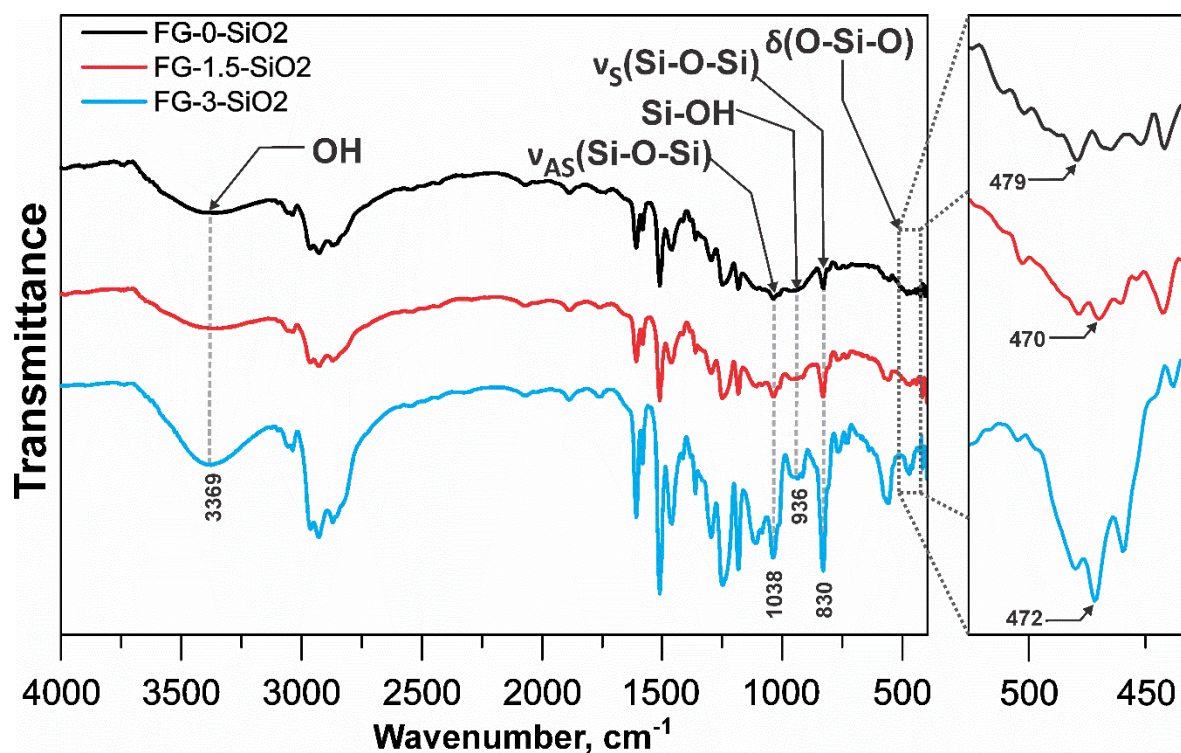


Figure 7. FTIR Spectrum and magnification.

### 3.3. GIXRD

Figure 8 shows the GIXRD patterns obtained for specimens FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub>. In all three spectra, the characteristic amorphous halo of SiO<sub>2</sub> is identified in the  $10\text{--}30^\circ$  region of  $2\theta$  [46,47]. In FG-0-SiO<sub>2</sub>, this halo is primarily attributed to the amorphous silica of the glass fiber, as it does not contain SiO<sub>2</sub> nanoparticles (NPs). In FG-1.5-SiO<sub>2</sub>, the intensity of the halo increases, reflecting the additional contribution of the amorphous SiO<sub>2</sub> NPs. This behavior indicates a homogeneous surface distribution of the NPs, which maximizes their contribution to X-ray scattering [48]. On the other hand, in FG-3-SiO<sub>2</sub>, a decrease in halo intensity is observed, even below that of FG-0-SiO<sub>2</sub>. This reduction, despite the higher concentration of NPs, indicates the presence of surface

agglomeration. The agglomerates formed may be partially or completely coated by the epoxy matrix, reducing their direct exposure to the incident beam [49]. Additionally, dense nanoparticle agglomerates tend to behave as regions of greater X-ray absorption, which decreases the diffuse signal from the amorphous silica and causes a reduction in the overall intensity of the halo [50–52].

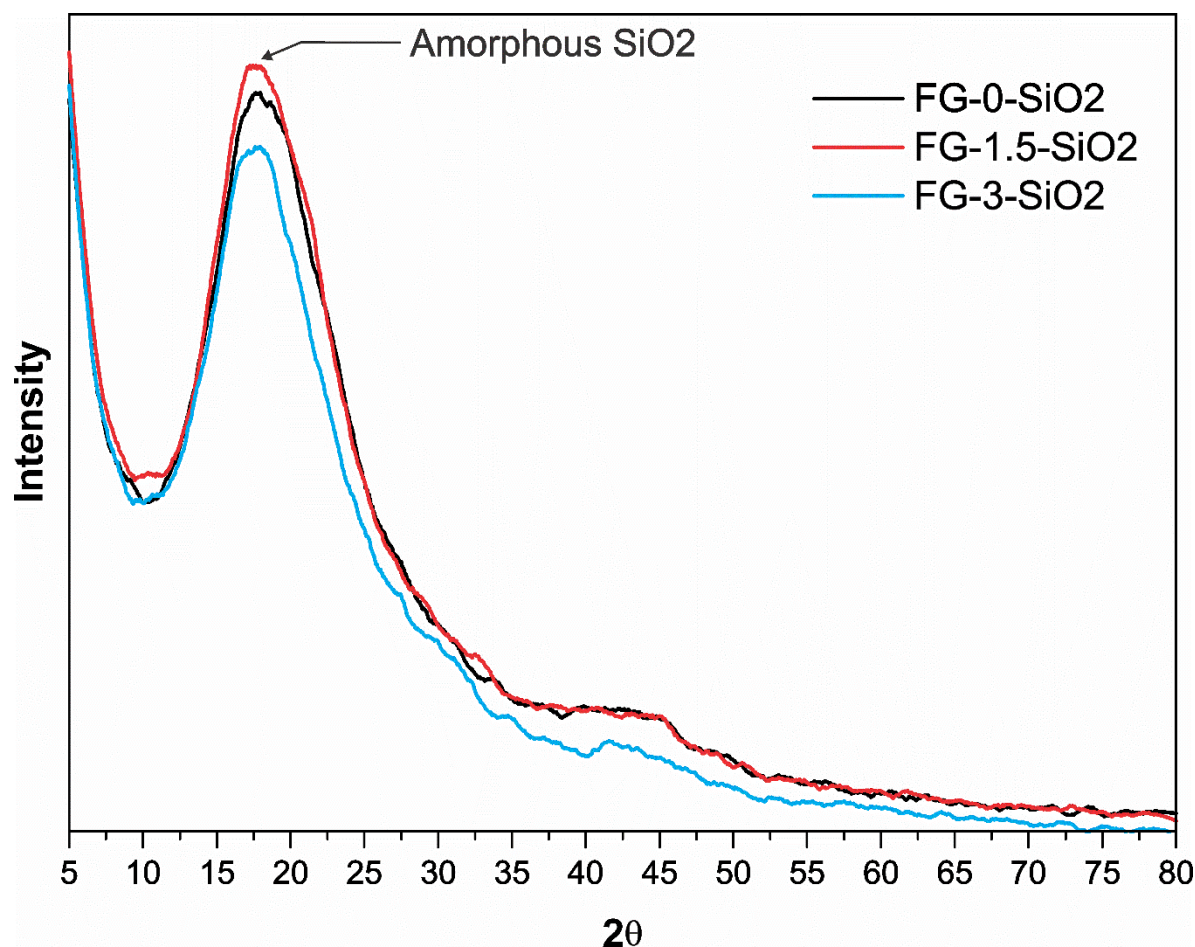


Figure 8. GIXRD pattern.

### 3.4. Topographic Analysis

Figure 9 shows scanning electron microscopy (SEM) images of the surfaces of specimens FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub>. FG-0-SiO<sub>2</sub> (Figure 9a) exhibits a surface with significant irregularities, attributable to the natural morphology of the glass fiber and the absence of SiO<sub>2</sub> nanoparticles. FG-1.5-SiO<sub>2</sub> (Figure 9b) displays a more homogeneous and uniform surface morphology, with no evidence of nanoparticle clumping or agglomeration. This suggests good dispersion of the SiO<sub>2</sub> NPs within the epoxy matrix, which is consistent with the results obtained for roughness, hardness, elastic modulus, FTIR, and GIXRD. On the other hand, in FG-3-SiO<sub>2</sub> (Figure 9c), regions with dense and heterogeneous clusters of NPs are observed, indicative of significant agglomeration. This non-homogeneous distribution confirms the trend observed in spectroscopic techniques, where the high concentration of NPs favors the formation of surface aggregates that can negatively affect the interfacial properties of the nanocomposite.

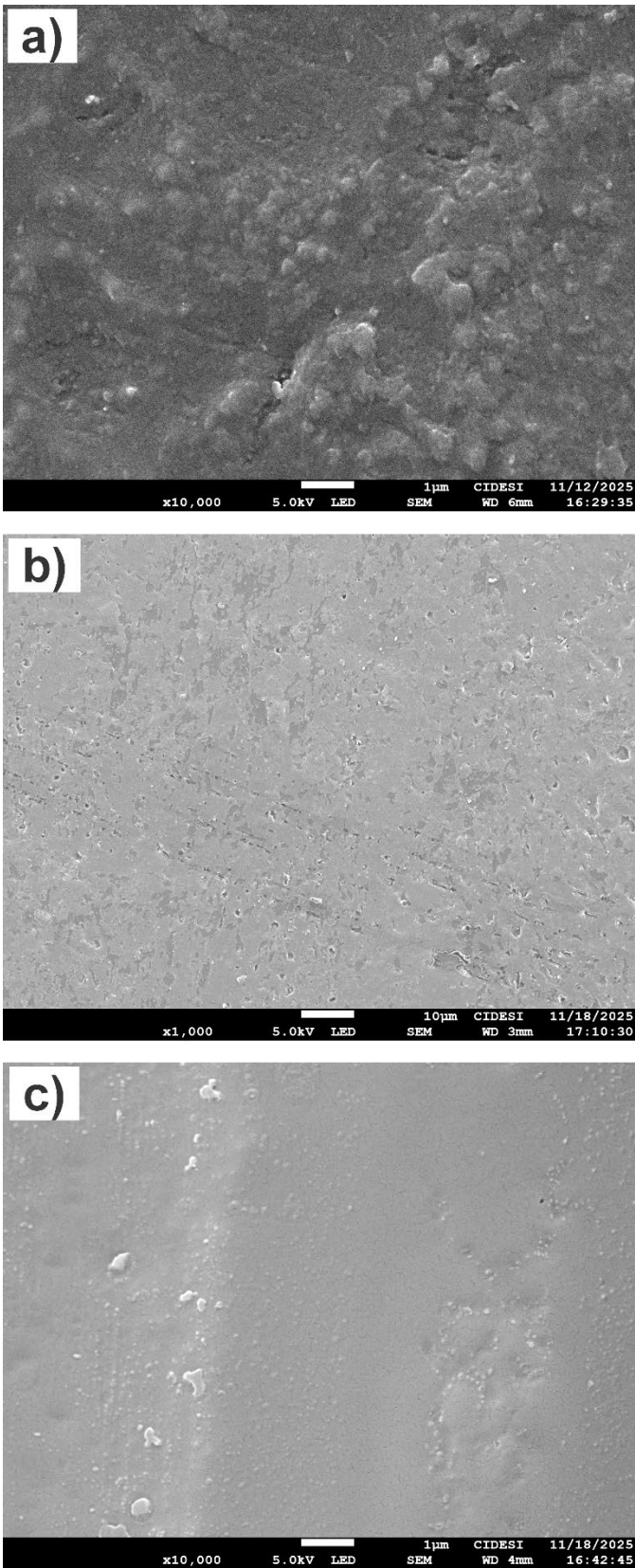


Figure 9. SEM micrographs of a) FG-0-SiO<sub>2</sub>, b) FG-1.5-SiO<sub>2</sub> and c) FG-3-SiO<sub>2</sub>.

3.5. Mass Loss, Profilometry and Erosion Rate

Figure 10 shows the erosion test results for FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub>, expressed as mass loss over time. For FG-0-SiO<sub>2</sub>, a pronounced mass loss is observed during the first 60 seconds, primarily attributed to the detachment of the epoxy resin matrix. Subsequently, the mass loss

stabilizes and remains minimal, indicating that the glass fibers have been reached due to their greater hardness and wear resistance, resulting in significantly less damage. FG-3-SiO<sub>2</sub> exhibits similar behavior to FG-0-SiO<sub>2</sub>, with a notable mass loss in the initial stage from 0 to 60 seconds and subsequent stabilization without significant changes. This suggests that the agglomeration of the NPs observed due to their concentration in previous techniques does not improve erosion resistance. Agglomeration limits the reinforcing properties of SiO<sub>2</sub> NPs, such as their high stiffness and hardness, since agglomerates act as stress concentrators and reduce the effective interfacial surface area, generating structural defects that facilitate matrix detachment. In contrast, FG-1.5-SiO<sub>2</sub> exhibits a behavior in which the greatest mass loss occurs within a 0-40 second interval, followed by progressive mass loss. This indicates that detachment of the epoxy resin matrix continues for a longer period, without reaching the fibers. This behavior is attributed to the optimal dispersion of the SiO<sub>2</sub> NPs, which, due to their high surface area and ability to chemically interact with the epoxy matrix through silanol groups, form a reinforced and cohesive interface. The adequate dispersion of the NPs allows them to act as barriers to the propagation of microcracks and dissipate impact energy during erosion, thus improving resistance to erosive wear compared to FG-0-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub>.

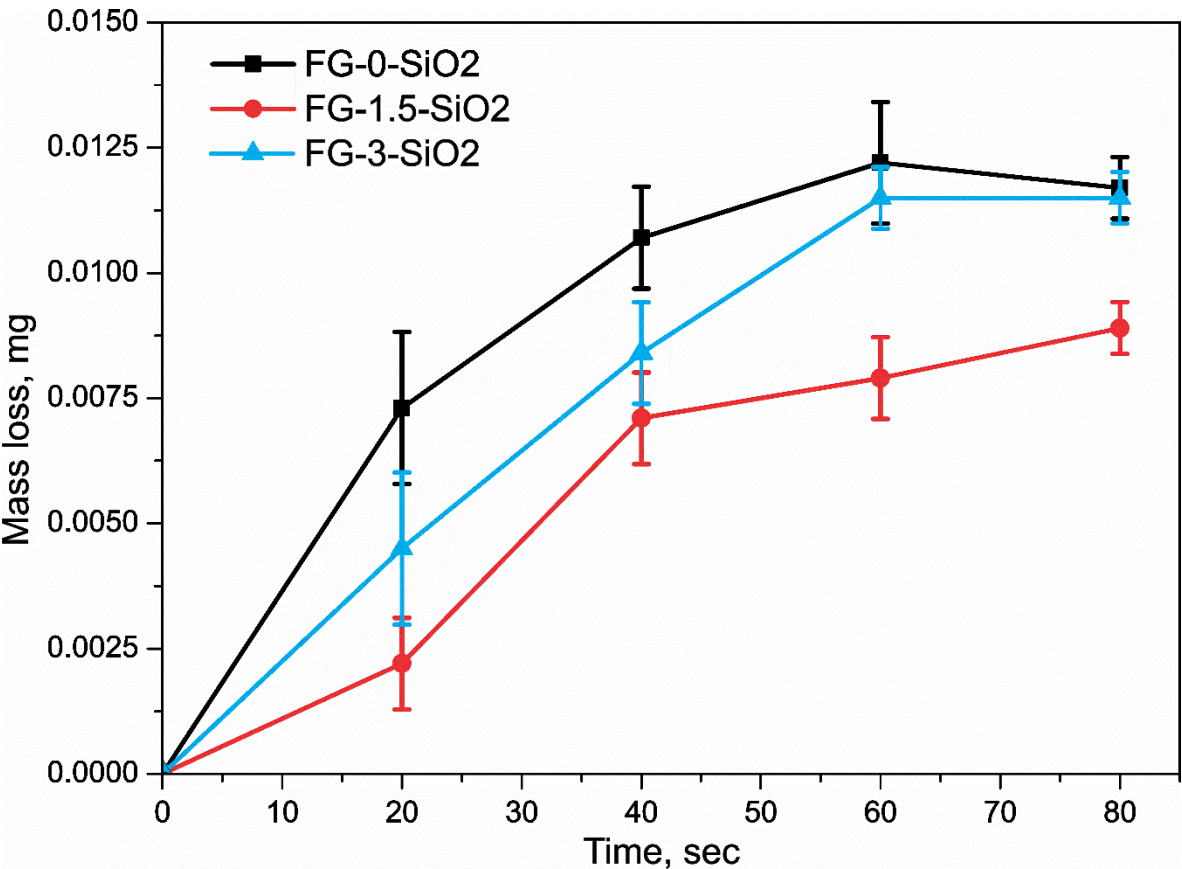


Figure 10. Mass loss over time.

Figure 11 presents the erosional wear zones and corresponding depth contrast images for specimens FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub>. Differences in the extent and severity of erosional damage can be observed among the samples. FG-1.5-SiO<sub>2</sub> exhibits slightly fewer deep regions and a smaller total wear zone compared to FG-0-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub>. This suggests greater resistance to penetration and propagation of erosional damage, which is consistent with the previously presented mass loss results. On the other hand, both FG-0-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub> exhibit deeper zones and a wider wear zone, indicating a lower capacity to resist erosion. In the case of FG-3-SiO<sub>2</sub>, it can again be attributed to the agglomeration of NPs, which generates structural heterogeneities and stress concentration sites that favor the detachment of material.

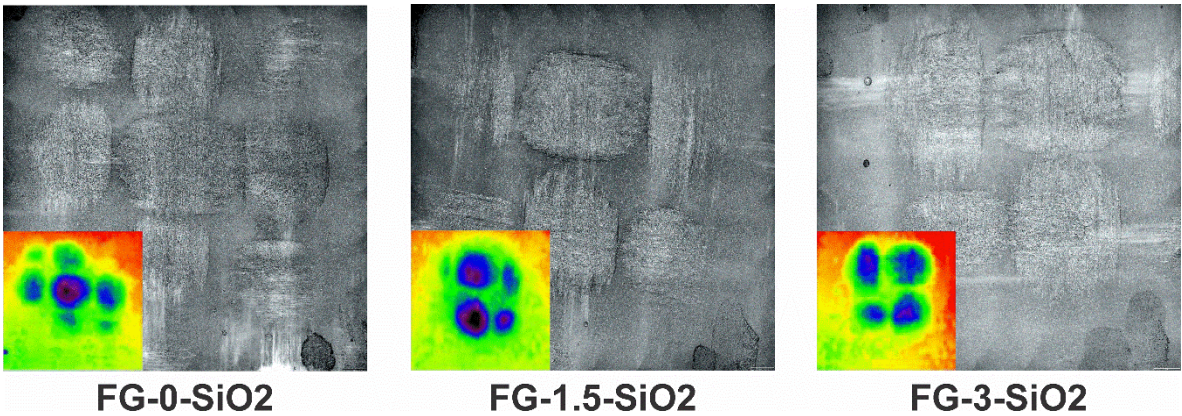


Figure 11. Wear zone and contrast image.

Figure 12 presents the results of total accumulative mass loss as a function of time and erosion rate for specimens FG-0-SiO2, FG-1.5-SiO2, and FG-3-SiO2. In Figure 12a, FG-1.5-SiO2 exhibited the lowest accumulative mass loss at the end of the test, indicating greater resistance to erosive wear of the epoxy matrix due to the good distribution of the NPs. Conversely, FG-0-SiO2 and FG-3-SiO2 showed a greater cumulative mass loss, indicating less protection against erosion. Figure 12b confirms that FG-1.5-SiO2 exhibited the lowest erosion rate, while FG-0-SiO2 showed the highest. The behavior of FG-3-SiO2 falls between the two, but is closer to that of FG-0-SiO2, suggesting that agglomerating NPs at higher concentrations does not significantly improve erosion resistance. Based on these results, it can be stated that the addition of 1.5 wt% SiO2 NPs increases erosion resistance by approximately 38% compared to FG-0-SiO2. This improvement is explained by the homogeneous dispersion of the nanoparticles, which reinforce the epoxy matrix through charge transfer, microcrack blocking, and impact energy dissipation, thus reducing material loss during the erosion test. Table 3 presents the erosion rate and total mass loss values for each specimen.

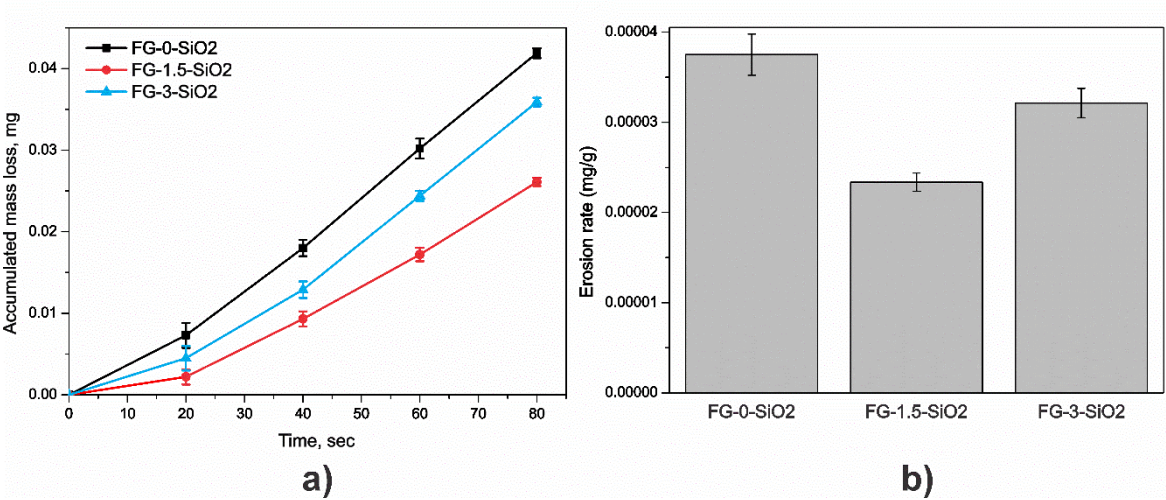


Figure 12. a) Accumulated mass loss and b) erosion rate.

Table 3. Erosion rate and total mass loss.

| Specimens   | Erosion rate, mg/g | SD, mg/g | Total mass loss, mg | SD, mg |
|-------------|--------------------|----------|---------------------|--------|
| FG-0-SiO2   | 3.7501E-5          | 2.279E-6 | 0.0419              | 0.0006 |
| FG-1.5-SiO2 | 2.3360E-5          | 1.007E-6 | 0.0261              | 0.0005 |
| FG-3-SiO2   | 3.2131E-5          | 1.621E-6 | 0.0359              | 0.0005 |

The profilometry performed in the erosional wear zone of FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub> is presented in Figure 13. The analysis shows the differences in erosion track depth among the samples. FG-0-SiO<sub>2</sub> and FG-3-SiO<sub>2</sub> exhibited the greatest wear depths, indicating lower erosion resistance, while FG-1.5-SiO<sub>2</sub> showed less pronounced wear depths, demonstrating better erosion resistance and good surface integrity under particle impact conditions. These results are consistent with the reported erosion rate, mass loss over time, and total cumulative mass loss.

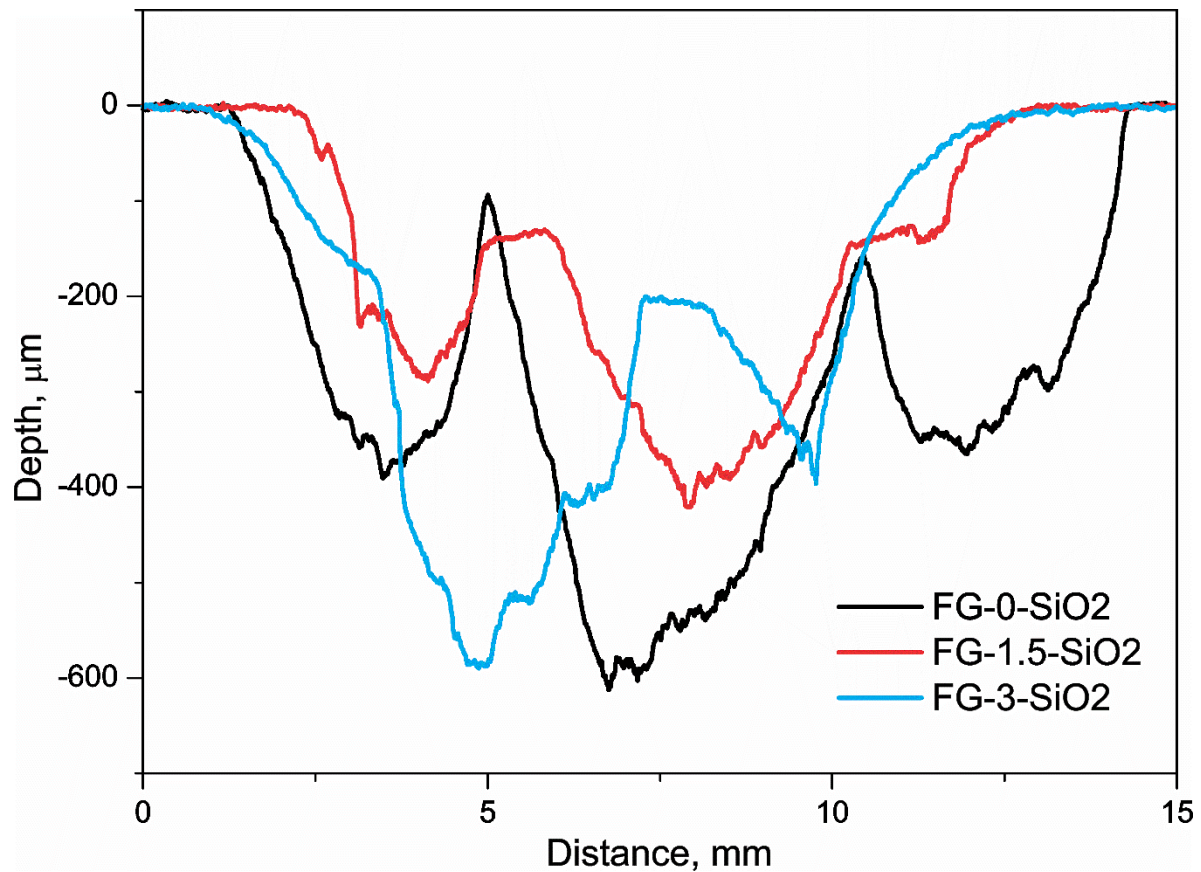
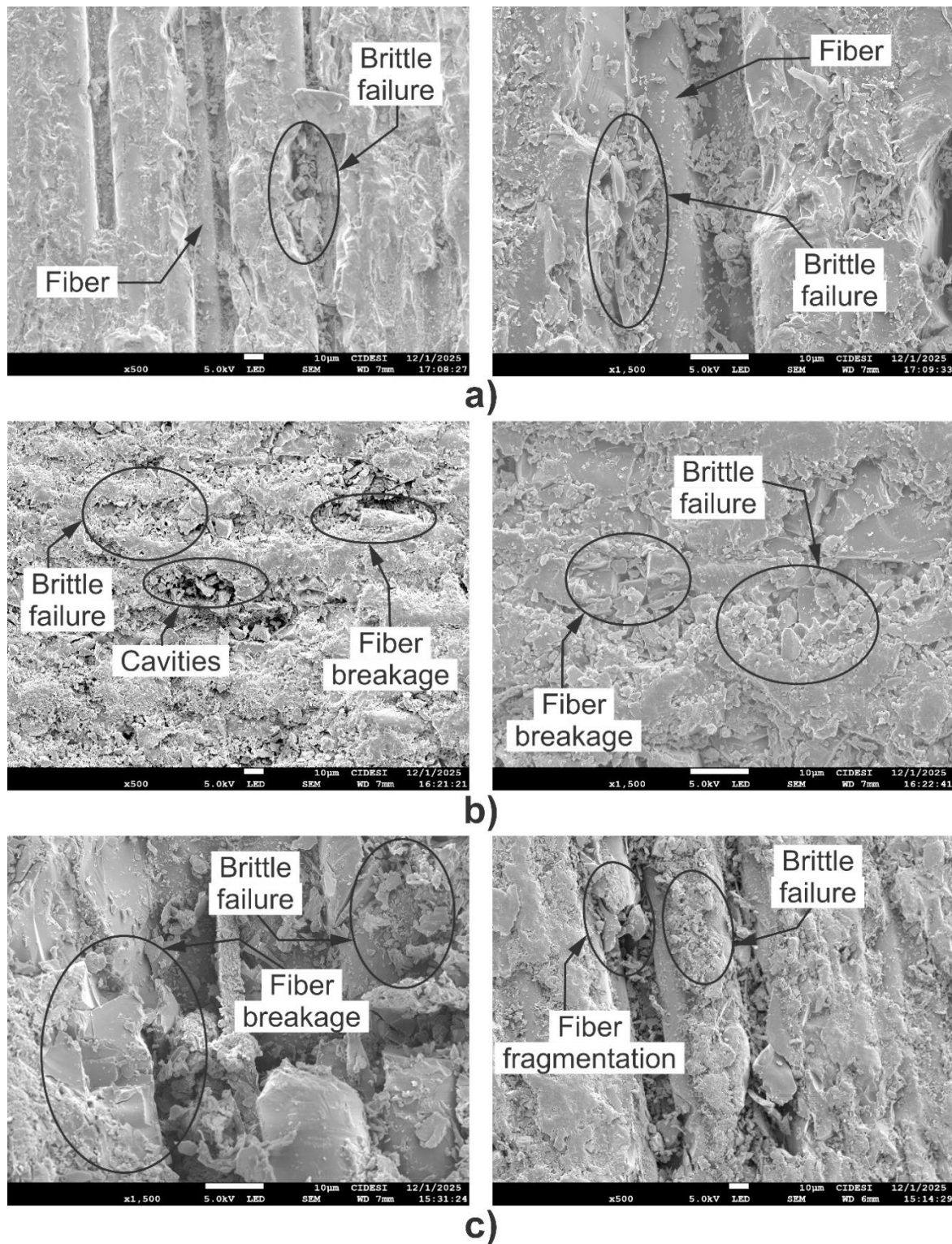


Figure 13. Perfilometry.

### 3.6. Wear Mechanisms

Figure 14 presents SEM images obtained at 500X and 1500X magnification showing the traces of erosive wear on specimens FG-0-SiO<sub>2</sub>, FG-1.5-SiO<sub>2</sub>, and FG-3-SiO<sub>2</sub>. To maximize surface damage, erosion tests were performed with a normal impact angle (90°) of the erosive agent. Figures 14a, 14b, and 14c show that all samples exhibit epoxy matrix detachment and fiber exposure. However, the severity and mechanisms of wear vary significantly among them. In FG-0-SiO<sub>2</sub> (Figure 14a), extensive regions of matrix removal are identified, exposing the reinforcing fibers and demonstrating a brittle failure mechanism characteristic of epoxy matrix composites. This behavior is attributed to the weak interface between the matrix and the fiber, and therefore, to the low wear resistance of the matrix not reinforced with SiO<sub>2</sub> nanoparticles. FG-3-SiO<sub>2</sub> (Figure 14c) also shows considerable matrix removal, accompanied by brittle fracture, fragmentation, and fiber breakage. These findings are consistent with previous results for hardness, elastic modulus, and wear rate, due to the agglomeration of SiO<sub>2</sub> nanoparticles, which generates areas of structural weakness and stress concentration that favor premature failure. FG-1.5-SiO<sub>2</sub> (Figure 14b) exhibits less matrix removal, a stronger interface, and a more controlled failure pattern, with small cavities and limited regions of fiber exposure and breakage. This confirms that the optimal dispersion of 1.5 wt% SiO<sub>2</sub> NPs strengthens the matrix, improves the interface, and mitigates erosive damage, as deduced from the mass loss and profilometry tests.



**Figure 14.** Wear mechanism at 500 and 1500X of a) FG-0-SiO<sub>2</sub>, b) FG-1.5-SiO<sub>2</sub> and c) FG-3-SiO<sub>2</sub>.

#### 4. Conclusions

Based on the results obtained in this study on the erosive wear behavior of fiberglass reinforced epoxy matrix laminated composites modified with SiO<sub>2</sub> NPs, the following conclusions are presented:

1. The incorporation of SiO<sub>2</sub> NPs into the epoxy matrix of fiberglass reinforced laminated composites improves resistance to erosive wear, but this effect depends directly on the concentration and homogeneous dispersion of the NPs.

2. An optimal concentration of 1.5 wt% of SiO<sub>2</sub> NPs, combined with an ultrasonic dispersion and degassing process, allows for a homogeneous distribution of the NPs within the epoxy matrix. This generates a more uniform surface, increases hardness and elastic modulus, and strengthens the interface between the matrix and the fiber.

3. The improvement in mechanical and tribological properties observed in the FG-1.5-SiO<sub>2</sub> composite is attributed to the well dispersed NPs, which act as barriers to microcrack propagation, improve stress transfer, and dissipate impact energy during the erosion process.

4. An excessive concentration of nanoparticles, such as the 3 wt% concentration found in FG-3-SiO<sub>2</sub>, causes agglomeration of NPs. This compromises the properties of the material by creating structural defects, reducing the effective interfacial area, and acting as stress concentration points, resulting in behavior similar to that of the material without NPs.

5. The results of this study demonstrate that there is an optimal concentration of SiO<sub>2</sub> NPs to significantly improve erosion resistance in laminated epoxy matrix and fiberglass composites. This provides valuable information for the design of laminated composite materials modified with NPs intended for structural applications in environments subject to wear from solid particles, where surface integrity and service life are critical.

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